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California Department of Water Resources
Sustainable Groundwater Management Program

October 2016

Best Management Practice Framework

Introduction to Best Management Practices

Chapter 7 of the Sustainable Groundwater Management Act (SGMA), in Water Code Section 10729(d), states that, "*By January 1, 2017, the department shall publish on its internet Web site best management practices for the sustainable management of groundwater*." Prior to the completion of a best management practices (BMPs) document, the Department of Water Resources (DWR) was required to adopt regulations for evaluating groundwater sustainability plans (GSPs), the implementation of GSPs, and coordination agreements by June 1, 2016 (GSP Regulations), and Alternatives.

"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.

–GSP Regulations §351(h)

The GSP Regulations adopted in May 2016 are part of the California Code of Regulations in Title 23, Division 2, Chapter 1.5, Subchapter 2. The GSP Regulations address BMPs in Section 352.2 (Monitoring Protocols) and Section 352.4 (Data and Reporting Standards). Other than BMPs addressing monitoring protocols and monitoring sites, SGMA and the GSP Regulations provide no direction or limitation with respect to what type of BMPs or additional guidance should be developed to assist groundwater sustainability agencies (GSAs) with making sustainable groundwater management decisions.

DWR elected to publish two categories of information that can assist GSAs with developing GSPs – **BMPs** and **Guidance Documents**.

Best Management Practices (BMPs)

BMPs are intended to provide clarification, guidance, and examples to help GSAs develop the essential elements of a GSP. BMPs rely on technical information from other groundwater management efforts, existing standards, or other guidance or reference reports. The BMP categories include the following:

- **BMP 1:** Monitoring Protocols, Standards, and Sites
- **BMP 2:** Monitoring Networks and Identification of Data Gaps
- **BMP 3:** Hydrogeologic Conceptual Model
- **BMP 4:** Water Budget
- **BMP 5:** Modeling

Guidance Documents

Guidance Documents are prepared for topic areas unique to SGMA, for either topics where no established practices in the water management industry exist or to provide suggestions with supporting graphics to aid GSAs in developing certain GSP components. The Guidance Documents in development for 2016 include the following:

- Preparation Checklist for GSP Submittal
- GSP Annotated Outline
- Establishing Sustainable Management Criteria (*In development*)
- Engagement with Tribal Governments (*In development*)
- Stakeholder Engagement and Communication (*In development*)

How to Utilize BMPs and Guidance Documents

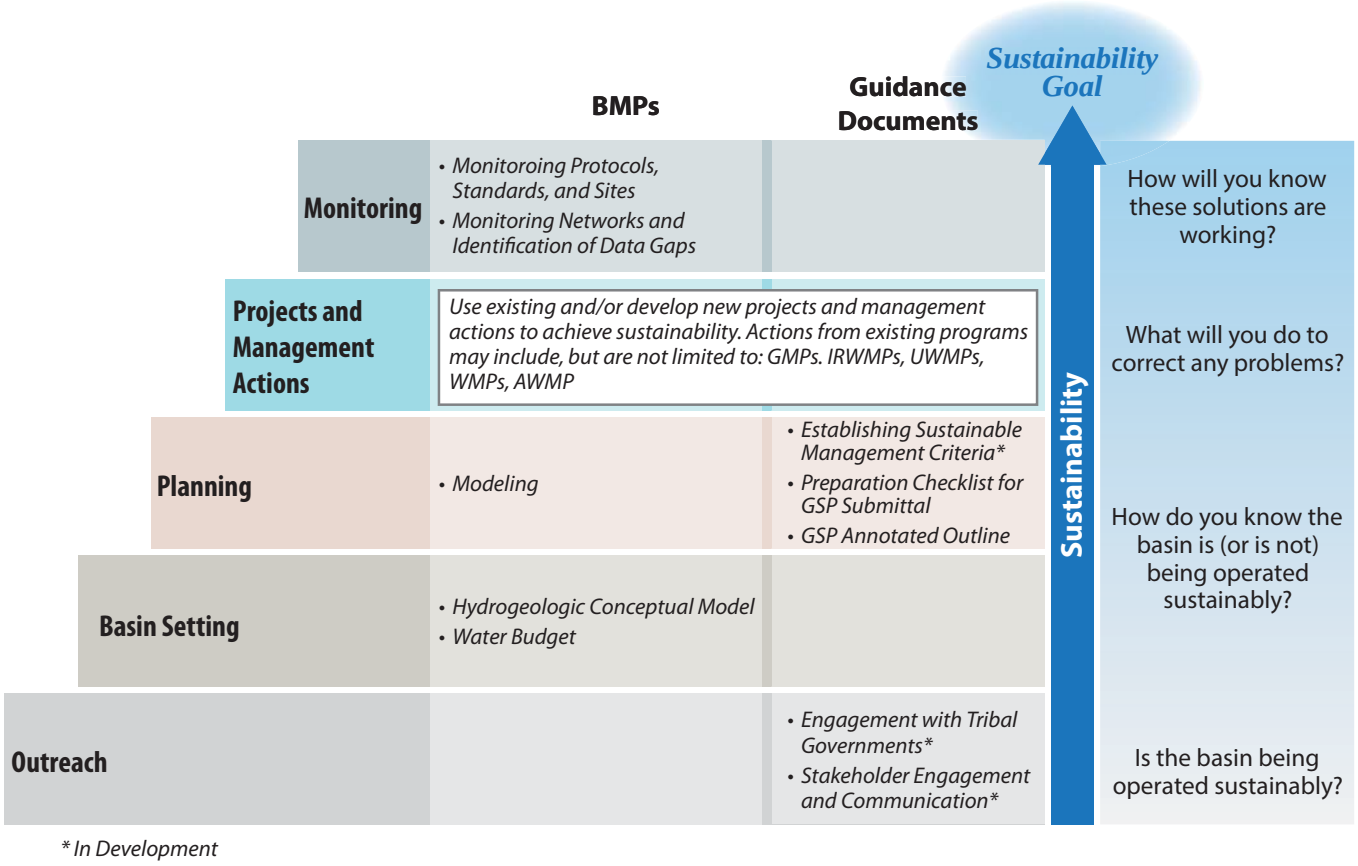
BMPs and Guidance Documents are organized to follow a logical progression of SGMA compliance activities. **Figures 1 and 2** illustrate the general progression of work flow that GSA's will likely follow in preparing and implementing their basin-wide GSPs. DWR recommends that BMPs be utilized by GSAs in this order as they are preparing GSPs.

The BMPs and Guidance Documents are only intended to provide technical or general guidance to GSAs and other stakeholders. GSAs and other stakeholders have the option of using this material, but the content provided in these documents does not create any new requirements or obligations for the GSA or other stakeholders.

The BMPs and Guidance Documents do not serve as a substitute for the GSP Regulations or the provisions in SGMA. Those GSAs submitting a GSP are strongly encouraged to fully read the (GSP Regulations) and the text of the (SGMA). In addition, using these BMPs to develop a GSP does not equate to an approval determination by DWR.

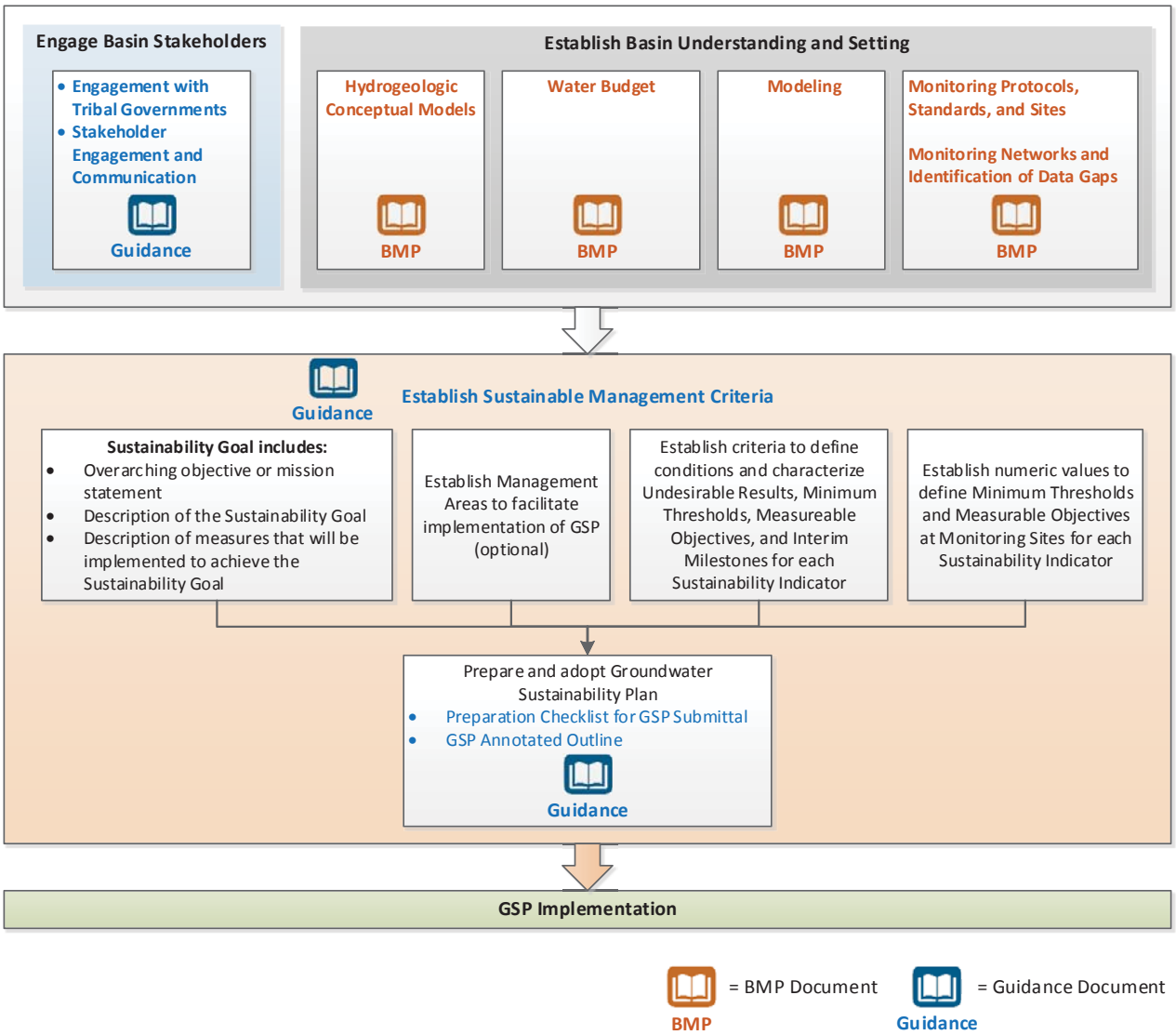
The generalized workflow diagram shown in **Figure 2** identifies some of the key steps that may be used to establish, achieve, and maintain a groundwater basin's sustainability goal. This diagram refers to the initial set of BMPs and Guidance Documents presented in **Figure 1**, while focusing on how that information can be used to establish a sustainability goal and the criteria used to evaluate the basin's condition and progress toward achieving sustainability.

Figure 1. Steps to Sustainability and related BMPs and Guidance Documents



** In Development*

Figure 2. Interrelationship of BMPs and Guidance Documents in Generalized Workflow for Developing a Basins' Groundwater Sustainability Goal



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

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Groundwater Monitoring Protocols, Standards, and Sites
Best Management Practice

California Department of Water Resources
Sustainable Groundwater Management Program
1416 Ninth Street
P.O. Box 942836
Sacramento, CA 94236-0001

www.water.ca.gov/groundwater

Groundwater Monitoring Protocols, Standards, and Sites Best Management Practice

1. Objective

The objective of this Best Management Practice (BMP) is to provide technical assistance on the development of Monitoring Protocols in accordance with Groundwater Sustainability Plan (GSP) Emergency Regulations (Regulations). Information provided in this BMP is meant to provide technical assistance and guidance to establish consistent data collection approach for each of the sustainability indicators.

This BMP includes the following sections:

1. Objective. A brief description of how and where monitoring protocols are required under SGMA and the overall objective of this BMP.
2. Use and Limitations. A brief description of the use and limitations of this BMP.
3. Monitoring Protocol Fundamentals. A description of the general approach and background of groundwater monitoring protocol.
4. Relationship of Monitoring Protocol to other BMPs. A description of how this BMP is connected with other BMPS.
5. Technical Assistance. Technical content of BMP providing guidance for regulatory sections.
6. Key Definitions. Descriptions of those definitions identified in the GSP Regulations, SGMA, or Basin Boundary Regulations.
7. Related Materials. References and other materials that provide supporting information related to the development of Groundwater Monitoring Protocol.

This BMP provides guidance to Groundwater Sustainability Agencies (GSAs) on groundwater monitoring protocols that provide accurate and reproducible data. The desired outcome of this BMP is for GSAs to adopt a set of sampling and measuring procedures that will yield similar data regardless of the monitoring personnel.

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2. USE AND LIMITATIONS

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

3. MONITORING PROTOCOL FUNDAMENTALS

Establishment of protocol or convention for the collection of data in support of demonstration of successful implementation of SGMA is essential and should be based on the best available scientific methods. The use of protocol that can be applied consistently across all basins within the state will provide for the collection of comparable data. Consistency of the data collection methods will reduce uncertainty in the comparison of data and provide for a more robust set of observations to facilitate communication within basins as well as between basins.

Providing a basic minimum technical standard for accuracy will provide quality data to support implementation of GSPs to meet sustainability goals.

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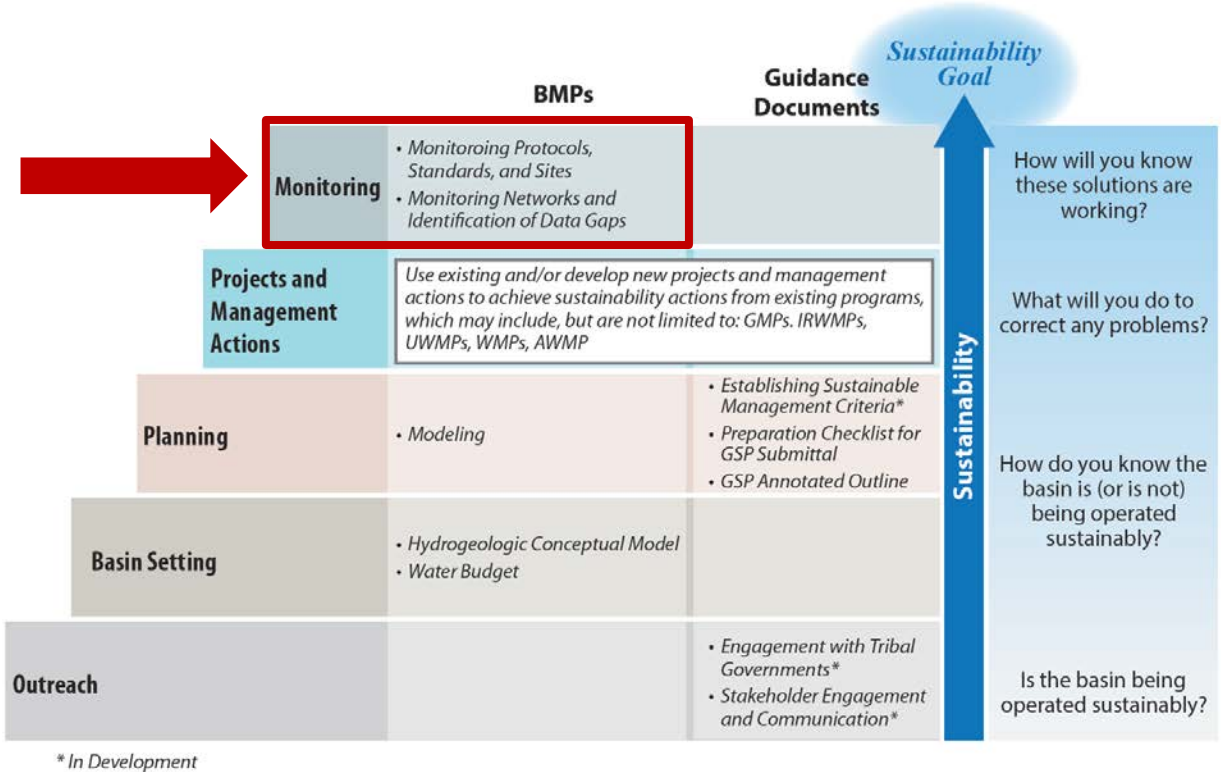
4. Relationship of Monitoring Protocol to other BMPs

Groundwater monitoring is a fundamental component of the SGMA as each GSP must include a sufficient network that provides the data that demonstrate the measured progress toward the achievement of the sustainability goal for each basin. For this reason, a standard set of protocols need to be developed and utilized to accomplish this fundamental component of SGMA.

Because the methods used to collect and report the data are fundamental to manage the basin and provide proof of sustainability, it is important that data is developed in a manner consistent with the basin setting, planning, and projects/management actions steps identified on **Figure 1** and the Regulations. The inclusion of monitoring protocols in the Regulations also emphasizes the importance of quality empirical data to support GSPs and provide comparable information from basin to basin.

Figure 1 provides an illustration as to how monitoring protocol is linked to other related BMPs. This figure also provides the context of the BMPs as they relate to various steps to sustainability as outlined in the regulations. The monitoring protocol BMP is part of the Monitoring development step in the regulations.

Figure 1 - Steps to Sustainability under SGMA



5. TECHNICAL ASSISTANCE

> *§ 352.2. Monitoring Protocols Each Plan shall include monitoring protocols adopted by the Agency for data collection and management, as follows:*
> *(a) Monitoring protocols shall be developed according to best management practices.*
> *(b) The Agency may rely on monitoring protocols included as part of the best management practices developed by the Department, or may adopt similar monitoring protocols that will yield comparable data.*
> *(c) Monitoring protocols shall be reviewed at least every five years as part of the periodic evaluation of the Plan, and modified as necessary.*

The Regulations specifically call out the need to utilize protocols identified in this BMP or develop similar protocols. The following technical protocols provide guidance based upon existing professional standards and are commonly adopted in various groundwater related programs. The intent of these protocols is to provide clear techniques that yield quality data for use in the various components of the GSP. These protocols can be further elaborated on by individual GSAs in the form of standard operating procedure which reflect specific local requirements as they may relate to local conditions.

PROTOCOLS FOR ESTABLISHING MONITORING SITES

The protocol for establishment of monitoring sites should be evaluated in conjunction with the Monitoring Network and Identification of Data Gaps BMP, but in general some specific protocols can be applied and are described below.

- Monitoring locations should be established with clear long term access agreements in place. Each location should be accessible year round to address any need for increased monitoring frequency.
- Each monitoring location must have a unique identifier developed with a general written description of the location, date established, access concerns and point of contact (if necessary), type of information to be collected, latitude, longitude, and elevation.
    - Each monitoring location should also track all modifications to the site in a modification log.
- Where wells are being installed, the following should be performed:
    - Log borehole cuttings under the supervision of a California Professional Geologist. Where possible collection of samples in chip trays will aid in developing comparative analysis tools within the basin.

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- Develop written criteria for logging of borehole cuttings for comparison to known geologic formations, principal aquifers and aquitards/aquicludes, or specific marker beds.
- Conduct borehole geophysical surveys of resistivity, spontaneous potential, spectral gamma, or other method as appropriate for the conditions. A caliper log should also be performed to evaluate borehole diameter.
- Prepare and submit state well completion report, include geophysical logs, detailed geologic log, and formation identification as attachment.

PROTOCOLS FOR MEASURING GROUNDWATER LEVELS

Groundwater level measuring protocols should ensure that:

- Groundwater level data are taken from the correct location, including well id, screen interval depth.
- Groundwater level data are accurate and reproducible
- Groundwater level data represent conditions that inform appropriate basin management
- All salient information is recorded to normalize, if necessary, and compare data
- Data are handled in a way that preserves data integrity

The following BMPs must be incorporated into a GSP's monitoring protocols for collecting groundwater elevation data. A GSP that adopts protocols that deviate from these BMPs must demonstrate that the adopted protocols will yield comparable data.

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General Well Monitoring Information

- Groundwater elevations will form the basis of basin-wide piezometric maps, and should approximate conditions at a specific point in time. Therefore, all groundwater levels in a basin should be collected within as short a time as possible, preferably within a few days.
- Each well used for measuring groundwater levels must have a unique identifier. This identifier must appear on the well housing or the well casing to avoid confusion.
- Depth to groundwater must be measured relative to an established Reference Point (RP) on the well casing. The RP is usually identified with a permanent marker, paint spot, or a notch in the lip of the well casing. By convention in open casing monitoring wells, the RP reference point is located on the north side of the well casing. If no mark is apparent, the person performing the measurement should measure the depth to groundwater from the north side of the top of the well casing.
- The elevation of the RP of each well must be surveyed by a license surveyor to the North American Vertical Datum of 1988 (NAVD88), or a local datum that can be converted to NAVD88. The elevation of the RP must be accurate to within 0.5 feet. It is preferable for the RP elevation to be accurate to 0.1 feet or less.
- The sampler should remove the appropriate cap, lid, or plug that covers the monitoring access point. For dedicated monitoring wells, this may entail removing the entire well cap. For irrigation wells or municipal wells, this may entail removing a plug or cap to an access port.
- Where the well has been tightly capped and is under pressure, the sampler should allow groundwater elevations to equilibrate to atmospheric conditions. This will take a variable amount of time based on well condition and aquifer properties.
- The sampler must use a measuring device capable of measuring depth to groundwater to an accuracy of 0.1 foot to obtain the depth to groundwater below the RP. It is preferable to measure depth to groundwater to an accuracy of 0.01 feet. Common measuring devices include electronic sounders and chalked steel survey tapes. Other measuring devices may provide similarly accurate data: each device should be assessed to ensure that the data are of sufficient accuracy to conform to the Emergency Regulations, and that the data are reproducible. Air lines and poppers generally do not provide depth to groundwater information at accuracy of 0.1 foot or better and therefore are not recommended for use as it relates to this BMP.
- The sampling device should be cleaned to avoid introducing oil or other contaminants into a well. If monitoring wells are part of a groundwater remediation program, the sampling device must be disinfected in accordance with the remediation program's sampling plan.

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Measuring Groundwater Levels

- Measure depth to water in the well using procedures appropriate for the measuring device. All equipment must be operated and maintained in accordance with manufacturer's instructions.
    - For electrical sounders, lower the sounder probe into the well until an audio signal, light indicator, or meter deflection is noted. Note, or pinch with fingers, the location on the sounder cable that corresponds to the well RP. For sounders that are not marked in 0.01 ft. intervals, use an engineer's measuring tape, marked in decimal feet, to measure the distance from the above-noted sounder cable location to the nearest mark on the cable, and calculate the depth to water. In situations where the electrical sounder is marked in 0.01' intervals, using an engineer's measuring tape is not necessary.
    - For steel tapes, coat the lower 5 to 10 feet of tape with carpenters chalk. Lower the tape into the well until the bottom 1 to 2 feet of tape is submerged and an even foot mark is at the elevation of the RP. Historic depth to water readings in the well will give you an idea of the approximate groundwater level in a particular well. By lowering the tape slowly in intervals of approximately 2 to 3 feet, the contact of the tape's weight with the water's surface can often be heard. For wells with deep water levels, it may be necessary to approximately know the depth to water, or to make several measurement attempts to ensure that the tape is submerged within its chalked length and a representative water mark is observed. Record the whole foot mark held at the RP, then slowly reel the tape in until the start of wetted tape is observed, as indicated by wet chalk. Record the measurement where the wetted tape began (i.e., the length of wetted tape, as indicated by wet chalk). The depth to water is determined by subtracting the length of wet tape from the total length of tape lowered into the well below the RP.
- For measuring wells that are under pressure, allow a period approximately 10 minutes for the water levels to stabilize. After allowing for equalization of pressure differential, collect and note an initial depth to water measurement, the sampler should obtain a second depth to water measurement to ensure that the groundwater elevation has equilibrated to atmospheric conditions, and has not changed from the first reading. If the depth to water has changed by more than 0.1 feet, the sampler should continue to take measurements until the depth to water varies by less than 0.1 feet between successive measurements. Every effort should be made to ensure that a representative stable depth to groundwater is recorded. If a well does not stabilize, the quality of the value should be noted indicating the measurement is questionable.

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- The sampler should calculate the groundwater elevation as:

$$GWE = RPE - DTW$$

  Where:
  GWE = Groundwater Elevation
  RPE = Reference Point Elevation
  DTW = Depth to Water
  The sampler must ensure that all measurements are in consistent units of feet, tenths of feet, and hundredths of feet. Measurements and RPEs should not be recorded in feet and inches.

Recording Groundwater Levels

- The sampler should record the well identifier, date, time (24-hour format), RPE, height of RP above or below ground surface, DTW, GWE, and comments regarding any factors that may influence the depth to water readings such as weather, nearby irrigation, flooding, or well condition. If there is a questionable measurement or the measurement can't be obtained, it should be noted. An example of a field sheet with the required information is shown below. It includes questionable measurement and no measurement codes that should be noted.
- The sampler should replace any well caps or plugs, and lock any well buildings or covers.
- All data should be entered into the GSA data management system (DMS) as soon as possible. Care should be taken to avoid data entry mistakes and the entries should be checked by a second person.

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THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES

WELL DATA

STATE WELL NUMBER	COUNTY	REFERENCE POINT ELEV.	MEASURING AGENCY
			DWR

NO MEASUREMENT	QUESTIONABLE MEASUREMENT
0. Measurement discontinued 1. Pumping 2. Pump house locked 3. Tape hung up 4. Can't get tape in casing 5. Unable to locate well 6. Well has been destroyed 7. Special 8. Casing leaky or wet 9. Temporarily inaccessible	0. Caved or deepened 1. Pumping 2. Nearby pump operating 3. Casing leaky or wet 4. Pumped recently 5. Air or pressure gauge measurement 6. Other 7. Recharge operation at or nearby well 8. Oil in casing

DATE	N M	Q M	TAPE AT RP	TAPE AT WS	RP to WS	OBSR VR	COMMENTS

DWR 1213

Pressure Transducers

Groundwater elevations may be recorded using pressure transducers equipped with data loggers that are permanently installed in monitoring wells. When installing such pressure transducers, care must be exercised to ensure that the data recorded by the transducers is confirmed with hand measurements. The following general protocols must be followed when installing a pressure transducer in a monitoring well.

- The sampler must use an electronic sounder or chalked steel tape and follow the protocols listed above to calculate the groundwater elevation in the monitoring well.
- The sampler must note the well identifier, the associated transducer serial number, transducer range, transducer accuracy, and cable serial number.
- The transducer range is the length of water column above the submerged transducer that it is capable of reading. This is determined by the highest and the lowest groundwater levels recorded in the well. The transducer should be set in the well below the lowest recorded water level and have the capability to measure the pressure of the highest recorded water level. Transducer range is given in pounds per square inch (psi). The sampler should convert these to feet using the formula:

  $$Range_{Feet} = 2.31 \times Range_{PSI}$$

  Transducer accuracy is often given in percentage. The sampler should convert these to feet using the formula:

  $$Accuracy_{Feet} = \frac{Range_{Feet} \times Range_{Percentage}}{100}$$

  Transducers with an accuracy of greater than 0.1 feet should not be used.
- The sampler must note whether the pressure transducer uses a vented or non-vented cable for barometric compensation. Vented cables are preferred.
- The sampler must estimate likely or anticipated groundwater level fluctuations. The depth of the selected transducer must be greater than the lowest anticipated groundwater elevation, as noted above.
- The sampler must set the correct transducer conversion factors, including factors such as range, linearity, and offset for proper conversion of electric signal to feet of water.
- The sampler should set and note in the field notes if the transducer is reporting depth to water or groundwater elevation.
- The sampler should check the accuracy of the transducer and the conversion factors using the following procedure:
  - Lower the transducer into the well until it is submerged to approximately half its full range. For example, a 100 PSI transducer (231-foot range) should be submerged under approximately 115 feet of water.

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- Record the depth to water transmitted by the transducer.
- To validate the transducer functionality:
    - Using a measuring tape position, raise the cable and transducer 1.00 ft.
    - Record the depth to water transmitted by the transducer and verify that it is 1.00 ft. higher.
    - Lower the cable 2.00 feet, so the transducer is one foot below its original position.
    - Record the depth to water transmitted by the transducer and verify that it is 1.00 ft. lower.
    - Each measurement should be within about 0.02 ft. of the 1.00 ft. raising and lowering increments.

- Measure the cable length for placing the transducer at the correct depth. The depth of the transducer below the water surface can also be checked by reading the transducer. The transducer should be positioned so that it is below the lowest expected water level, but not so low that the transducer range cannot account for the highest expected water level. If this can't be accomplished, a transducer with a greater range and longer cable is required. However, if the accuracy of the readings exceed 0.1 ft. due to a high range of water levels and required transducer pressure range, a transducer may not be practical for this particular monitoring well.
- Secure the cable to the well head with a well dock or another reliable method. Mark the cable at the elevation of the reference point with tape or an indelible marker. This will allow estimates of future cable slippage.
- Re-measure the depth to water with a steel or electric tape. The transducer cable may stretch when it is installed (particularly new cables which have been on a spool for a length of time), and the transducer reading may not match the hand measured reading. Either re-position the transducer, or set the correct reference depth in data logger. In some cases, stretch in the cable may take over night to equilibrate. In this case, the transducer will need to be reset the following day.
- The transducer data should periodically be checked against hand measured data to monitor electronic drift or cable movement. This should be happen during routine site visits.
- Follow manufacture specifications for data storage capacity to ensure data downloads are performed prior to filling. Each time data downloads are performed a check of the depth measurement should be performed and evaluation of the data logger software specifically date and time.
- The data should be downloaded a minimum of two times per year and entered into the basin's DMS as soon as possible. The downloaded data should be graphed and analyzed to look for any anomalies or unexplained drift in data.

Data collected with non-vented data logger cables should be barometrically compensated. After the sampler is confident that the transducer data have been safely downloaded and stored, the data should be deleted from the data logger to ensure that adequate data logger memory remains.

PROTOCOLS FOR SAMPLING GROUNDWATER QUALITY

The following BMPs must be incorporated into a GSP's monitoring protocols for collecting groundwater quality data. More detailed sampling procedures and protocols are included in the standards and guidance documents listed at the end of this BMP. A GSP that adopts protocols that deviate from these BMPs must demonstrate that the adopted protocols will yield comparable data.

Groundwater sampling procedures should attempt to replicate the sampling and analysis methods of other groundwater quality in the basin's DMS. For example, if groundwater quality data in the DMS are derived from municipal well reports to the California Division of Drinking Water, the groundwater sampling protocols should replicate the sampling procedures and analysis methods used for drinking water quality reporting.

As part of compliance it may be necessary to collect additional samples for various water quality analyses. All analyses should be performed by a State certified Environmental Laboratory Accreditation Program. The specific analytical methods are beyond the scope of this BMP, but should be commiserate with other programs evaluating water quality within the basin for comparative purposes.

Groundwater quality sampling protocols should ensure that:

- Groundwater quality data are taken from the correct location
- Groundwater quality data are accurate and reproducible
- Groundwater quality data represent conditions that inform appropriate basin management
- All salient information is recorded to normalize, if necessary, and compare data
- Data are handled in a way that preserves data integrity

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Standardized protocols include the following:

- Prior to sampling, the sampler must contact the laboratory to schedule laboratory time, obtain appropriate sample containers, and clarify any sample holding times or sample preservation requirements.
- Each well used for groundwater quality monitoring must have a unique identifier. This identifier must appear on the well housing or the well casing to avoid confusion.
- Samples should be collected at or near the wellhead. Samples should not be collected from storage tanks, at the end of long pipe runs, or after any water treatment.
- The sampler should clean the sampling port and/or sampling equipment and the sampling port and/or sampling equipment must be free of any contaminants.
- The sampler must decontaminate any sampling equipment used at multiple well sites to avoid cross-contamination between samples.
- The groundwater elevation in the well should be measured, following appropriate protocols.
- For any well not equipped with low-flow or passive sampling equipment, an adequate volume of water must be purged from the well to ensure that the groundwater sample represents native groundwater. Purging three to five well casing volumes is generally considered adequate. If pumping causes a well to be evacuated (go dry), it is not necessary to continue purging.
- The pH and electrical conductivity of the purging groundwater should stabilize before sampling. Stabilization occurs when, for at least three consecutive measurements, the pH remains constant within 0.1 Standard Unit (SU) and specific conductance varies no more than approximately 3 percent. Measurements of pH should only be measured in the field, lab analysis are typically unachievable due to short hold times. Other parameters, such as; oxidation-reduction potential (ORP), dissolved oxygen (DO) (in situ measurements preferable), or turbidity, may also be used as a purge adequacy parameter. All field instruments should be calibrated daily and evaluated for drift throughout the day.
- Sample containers should be labeled prior to sample collection. The sample label must include: the sample date, sample time, sample location, and sample constituents.
- Samples should be collected under laminar flow conditions. This may require reducing pumping rates prior to sample collection.
- Samples should be collected according to appropriate standards such as those listed in the *Standard Methods for the Examination of Water and Wastewater* or other appropriate guidance. The specific sample collection procedure should reflect the type of analysis to be performed.

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- All samples requiring preservation must be preserved as soon as practically possible, ideally at the time of sample collection. Assure that, samples are appropriately filtered as recommended for the specific analyte. Entrained solids can be dissolved by preservative leading to inconsistent results of dissolve analytes. Specifically, samples to be analyzed for metals should be field filtered prior to preservation; do not collect an unfiltered sample in preserved container.
- Samples should be chilled to 4 °C to prevent degradation, as necessary. The laboratory's Quality Assurance Management Plan should detail appropriate chilling and shipping requirements.
- Samples must be shipped under chain of custody documentation to the appropriate laboratory promptly to avoid violating holding time restrictions.
- The sampler must record the sample location, sample date, sample time, number and type of sample containers, and any other pertinent data in a sampling log.
- Instruct laboratory to use reporting limits that are equal or less than the applicable water quality objectives/screening levels.

Special protocols for low-flow sampling equipment

In addition to the protocols listed above, sampling using low-flow sample equipment should adopt the following protocols derived from EPA's *Low-flow (minimal drawdown) ground-water sampling procedures* (Puls and Barcelona, 1996). These protocols apply to low-flow sampling equipment that generally pumps between 0.1 and 0.5 liters per minute. These protocols are not intended for bailers.

Special protocols for passive sampling equipment

In addition to the protocols listed above, passive diffusion samplers should follow protocols set forth in USGS Fact Sheet 088-00.

PROTOCOLS FOR MONITORING SEAWATER INTRUSION

Monitoring seawater intrusion requires analysis of the chloride concentrations within groundwater of each principal aquifer. While no significant standardized approach exists, the methodologies described above for degraded water quality can be applied for the collection of groundwater samples. In addition to the protocol described above, the following protocols should be followed:

- Water quality samples will be collected and analyzed at least semi-annually. Samples will be analyzed for dissolved chloride at a minimum. In areas of high groundwater extraction more frequent sampling may be necessary.
    - The development of surrogate measures of chloride concentration may facilitate cost-effective means to monitor more frequently to observe the

range of conditions and variability of the flow dynamics controlling seawater intrusion.

- Water levels will be collected at a frequency adequate to characterize changes in head in the vicinity of the leading edge of degraded water quality. Frequency may need to be increased in areas of known preferential pathways, groundwater pumping, or efficacy evaluation of mitigation projects.

The use of geophysical surveys, electrical resistivity, or other methods, may provide for identification of preferential pathways and optimize monitoring well placement.

PROTOCOLS FOR MEASURING STREAMFLOW

All streamflow measurements should be collected, analyzed, and reported in accordance with the procedures outlined in USGS Water Supply Paper 2175, *Volume 1. - Measurement of Stage Discharge* and *Volume 2. - Computation of Discharge.*

PROTOCOLS FOR MEASURING SUBSIDENCE

Evaluating and monitoring inelastic land subsidence can utilize multiple data sources with increasing complexity to evaluate the specific conditions and associated causes. To the extent possible, the use of existing data should be collected and analyzed. Subsidence can be estimated from numerous techniques, including level surveying tied to known stable benchmarks or benchmarks located outside the area being studied for possible subsidence, installing and tracking changes in borehole extensometers, obtaining data from continuous GPS (CGPS) locations, static GPS surveys or Real-Time-Kinematic (RTK) surveys, or analyzing Interferometric Synthetic Aperture Radar (InSAR) data. No standard procedures exist for collecting data from the potential subsidence monitoring approaches, however, an approach may include:

- Identification of land subsidence conditions
    - Evaluate existing regional long-term levelling surveys of regional infrastructure, i.e. roadways, railroads, canals, and levees.
    - Inspect existing County and State well records where collapse has been noted for well repairs or replacement.
    - Identify potential for land subsidence by evaluation of geologic logs and the hydrogeologic conceptual model to determine if significant fine grained layers exist such that could suggest the potential for collapse of the units should significant depressurization occur.
    - Collect regional remote-sensing information such as InSAR, commonly provided by USGS and NASA. Data availability is limited currently, but future resources are being developed.

- Monitor regions of suspected subsidence where potential exists
    - Establish CGPS network to evaluate changes in land surface elevation, or
    - Establish leveling surveys transects to observe changes in land surface elevation, or
    - Establish extensometer network to observe land subsidence.

Various standards and guidance documents that must be adhered to when collecting data from the various approaches include:

- Levelling surveys must follow surveying standards set out in the California Department of Transportation's *Caltrans surveys Manual*.
- GPS surveys must follow surveying standards set out in the California Department of Transportation's *Caltrans surveys Manual*.
- The USGS has been performing subsidence surveys within several areas of California. These studies are sound examples for appropriate methods and should be utilized to the extent possible and where available:
    - http://ca.water.usgs.gov/land_subsidence/california-subsidence-measuring.html
- Instruments installed in borehole extensometers must follow the manufacturer's instructions for installation, care, and calibration.
- Availability of InSAR data is improving and will increase as programs are developed. This method requires expertise in analysis of the raw data and will likely be made available as an interpretative report for specific regions.

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6. KEY DEFINITIONS

IMPORTANT DEFINITIONS

§ 351 (h) "Best available science" refers to 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.

§ 351 (i) "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.

SGMA REFERENCE

§ 10727.2. REQUIRED PLAN ELEMENTS (f) Monitoring protocols that are designed to detect changes in groundwater levels, groundwater quality, inelastic surface subsidence for basins for which subsidence has been identified as a potential problem, and flow and quality of surface water that directly affect groundwater levels or quality or are caused by groundwater extraction in the basin. The monitoring protocols shall be designed to generate information that promotes efficient and effective groundwater management.

GSP REFERENCE

§ 352.2. Monitoring Protocols
Each Plan shall include monitoring protocols adopted by the Agency for data collection and management, as follows:

(a) Monitoring protocols shall be developed according to best management practices.

(b) The Agency may rely on monitoring protocols included as part of the best management practices developed by the Department, or may adopt similar monitoring protocols that will yield comparable data.

(c) Monitoring protocols shall be reviewed at least every five years as part of the periodic evaluation of the Plan, and modified as necessary.

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7. Related Materials

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Holmes, R.R. Jr., P.J. Terrio, M.A. Harris, and P.C. Mills, 2001. *Introduction to field methods for hydrologic and environmental studies*, open-file report 01-50, USGS, Urbana, Illinois, 241 p. https://pubs.er.usgs.gov/publication/ofr0150

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Vail, J., D. France, and B. Lewis. 2013. Operating Procedure: Groundwater Sampling SESDPROC-301-R3. https://www.epa.gov/sites/production/files/2015-06/documents/Groundwater-Sampling.pdf

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

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Monitoring Networks and Identification of Data Gaps
Best Management Practice

California Department of Water Resources
Sustainable Groundwater Management Program
1416 Ninth Street
P.O. Box 942836
Sacramento, CA 94236-0001

www.water.ca.gov/groundwater

Monitoring Networks and Identification of Data Gaps
Best Management Practice

1. Objective

The objective of this Best Management Practice (BMP) is to provide technical assistance for the development of monitoring networks in accordance with Groundwater Sustainability Plan (GSP) Emergency Regulations (Regulations). Information provided in this BMP is designed to aid in the development of a network that is capable of providing sustainability indicator data of sufficient accuracy and quantity to demonstrate that the basin is being sustainably managed. In addition, this BMP is intended to provide information on how to identify and plan to resolve data gaps to reduce uncertainty that may be necessary to improve the ability of the GSP to achieve the sustainability goal for the basin.

This BMP includes the following sections:

1. Objective. A brief description of how and where monitoring networks are required under Sustainable Groundwater Management Act (SGMA) and the overall objective of this BMP.
2. Use and Limitations. A brief description of the use and limitations of this BMP.
3. Monitoring Network Fundamentals. A description of the general approach and background of groundwater monitoring networks.
4. Relationship of Monitoring Network to other BMPs. A description of how this BMP is connected with other BMPS.
5. Technical Assistance. Technical content of BMP providing guidance for regulatory sections.
6. Key Definitions. Descriptions of those definitions identified in the GSP Regulations, SGMA, or Basin Boundary Regulations.
7. Related Materials. References and other materials that provide supporting information related to the development of Groundwater Monitoring Networks.

2. Use and Limitations

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

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3. MONITORING NETWORK FUNDAMENTALS

Monitoring is a fundamental component necessary to measure progress toward the achievement of any management goal. A network for groundwater management that identifies adequate collection, both spatial distribution and temporal frequency, of multiple datasets, including, groundwater levels, water quality information, land surface elevation, and surface water discharge conditions, allows for the proper characterization of changes to the groundwater system.

Within SGMA, this characterization is necessary to establish and track locally defined significant and unreasonable conditions for each of the sustainability indicators.
In addition, the collection of data from a sufficient network is required to assure that uncertainty is appropriately reduced during the analysis of these datasets. The collection of data in an organized and consistent manner will aid in assuring that the interpretations of the data are as accurate as possible. Also, the consistency of the types, methods, and timing of data collection facilitate the sharing of data across basin boundaries or within basins.

Analyzing data from an adequate monitoring network within a basin can lead to refinement of the understanding of the dynamic flow conditions leading to the optimization of sustainable groundwater management, continuing the use of groundwater in a manner that achieves the sustainability goal for each basin.

4. RELATIONSHIP OF MONITORING NETWORKS TO OTHER BMPS

Groundwater monitoring is a fundamental component of SGMA as each GSP must include a sufficient network that provides data that demonstrate measured progress toward achievement of the sustainability goal for each basin. For this reason, a sufficient network will need to be developed and utilized to accomplish this fundamental component of SGMA.

Because data provided by the monitoring network is the fundamental component used to manage the basin and provide proof of sustainability, it is important that the monitoring network is developed in a manner consistent with the basin setting, planning, and projects/management actions steps identified on **Figure 1** and in the Regulations. The inclusion of a monitoring network in the Regulations also emphasizes the importance of quality empirical data to support GSPs and to provide comparable information from basin to basin.

Figure 1 provides an illustration as to how monitoring networks are linked to other related BMPs. This figure also provides the context of the BMPs as they relate to

various steps to sustainability as outlined in the Regulations. The monitoring network BMP is part of the monitoring development step in the Regulations.

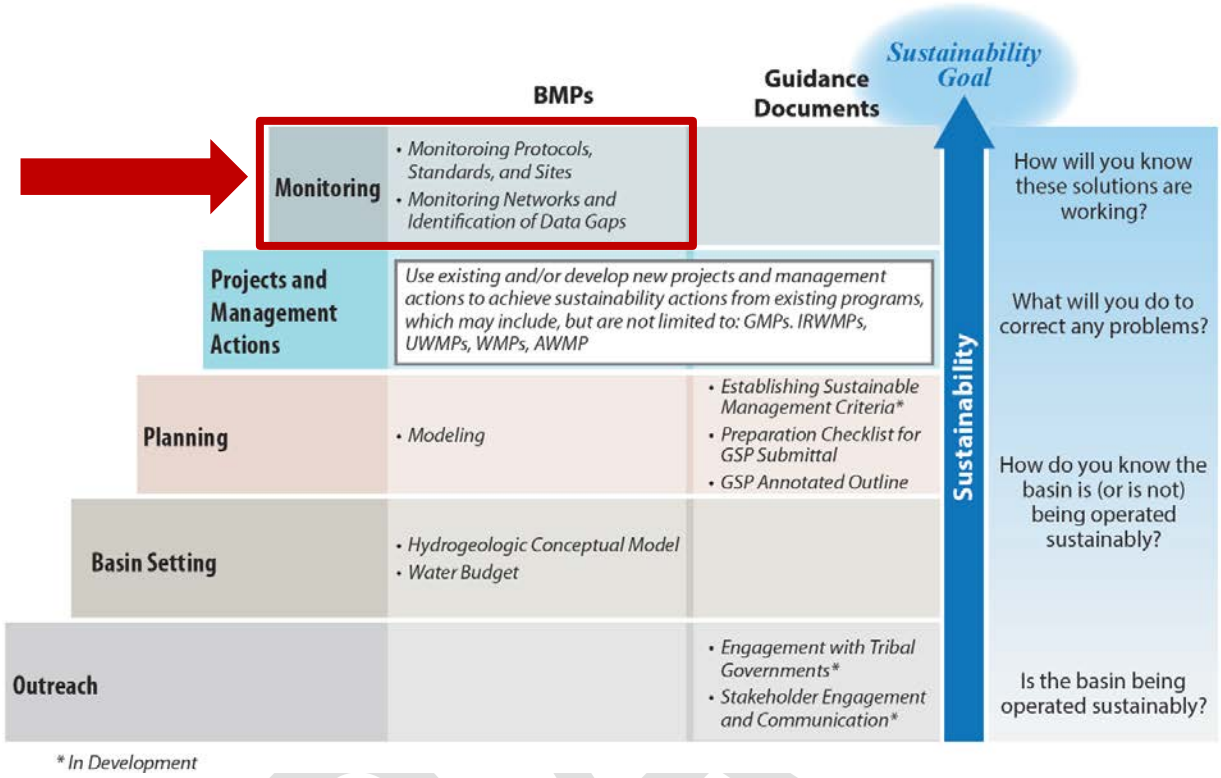

Figure 1 - Steps to Sustainability under SGMA

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5. TECHNICAL ASSISTANCE

GENERAL MONITORING NETWORKS

§354.32 Intro Monitoring Networks §354.34(a) and (b)

> *§ 354.32. Introduction to Monitoring Networks This Subarticle describes the monitoring network that shall be developed for each basin, including monitoring objectives, monitoring protocols, and data reporting requirements. The monitoring network shall promote the collection of data of sufficient quality, frequency, and distribution to characterize groundwater and related surface water conditions in the basin and evaluate changing conditions that occur through implementation of the Plan.*
>
> *§ 354.34. Monitoring Network (a) Each Agency shall develop a monitoring network capable of collecting sufficient data to demonstrate short-term, seasonal, and long-term trends in groundwater and related surface conditions, and yield representative information about groundwater conditions as necessary to evaluate Plan implementation. (b) Each Plan shall include a description of the monitoring network objectives for the basin, including an explanation of how the network will be developed and implemented to monitor groundwater and related surface conditions, and the interconnection of surface water and groundwater, with sufficient temporal frequency and spatial distribution to evaluate the affects and effectiveness of Plan implementation. The monitoring network objectives shall be implemented to accomplish the following: (1) Demonstrate progress toward achieving measurable objectives described in the Plan. (2) Monitor impacts to the beneficial uses or users of groundwater. (3) Monitor changes in groundwater conditions relative to measurable objectives and minimum thresholds. (4) Quantify annual changes in water budget components.*

GSAs are required to develop a monitoring network according to the requirements in the Regulations. The monitoring network must be capable of capturing data on a sufficient temporal frequency and spatial distribution to demonstrate short-term, seasonal, and long-term trends in basin conditions for each of the sustainability indicators and provide enough information to evaluate GSP implementation. If the monitoring network is developed in such a way that it does help GSAs achieve sustainability then it will have demonstrated progress toward achieving measureable objectives, monitored changes in groundwater conditions, and helped quantify annual changes in water budget components.

GSAs should start by evaluating their existing monitoring network and existing datasets when developing the monitoring network for their GSP, such as the California Statewide Groundwater Elevation Monitoring (CASGEM) program. The *Assessment and*

Improvement of Monitoring Network Section of the Regulations describes a process by which GSAs can identify and fill and gaps in their monitoring network. Other considerations for developing a monitoring network include:

- Degree of monitoring. The degree of monitoring should be consistent with the level of groundwater use. Areas that are subject to greater groundwater pumping or greater fluctuations in conditions may require more monitoring (temporal and/or spatial) than areas that experience less pumping or are more static.
- Access Issues. When identifying existing or future monitoring sites, GSAs may have to deal with access issues such as unwilling landowners, access agreements, destroyed wells, or other safety concerns with accessing a monitoring site.
- Adjacent Basins. Understanding of conditions at or across basin boundaries is important. GSAs should coordinate with adjacent basins on monitoring efforts to be consistent both temporally and spatially. Coordinated efforts and shared data will help GSAs understand their basins' conditions better and potentially better understand groundwater flow conditions across boundaries.
- Consider all sustainability indicators. GSAs should look for ways to efficiently use monitoring sites to collect data for more than one or all of the sustainability indicators. Similarly, when installing a new monitoring site, GSAs should take that opportunity to gather as much information about the subsurface conditions as possible.

There are many other considerations that GSAs must understand when developing their monitoring network that are specific to the various sustainability indicators: chronic lowering of groundwater levels, reduction of groundwater storage, seawater intrusion, degraded water quality, land subsidence, or depletions of interconnected surface waters. These considerations are discussed below.

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SPECIFIC MONITORING NETWORKS

§354.34(d)-(j)
(d) The monitoring network shall be designed to ensure adequate coverage of sustainability indicators. If management areas are established, the quantity and density of monitoring sites in those areas shall be sufficient to evaluate conditions of the basin setting and sustainable management criteria specific to that area.
(e) A Plan may utilize site information and monitoring data from existing sources as part of the monitoring network.
(f) The Agency shall determine the density of monitoring sites and frequency of measurements required to demonstrate short-term, seasonal, and long-term trends based upon the following factors:
(1) Amount of current and projected groundwater use.
(2) Aquifer characteristics, including confined or unconfined aquifer conditions, or other physical characteristics that affect groundwater flow.
(3) Impacts to beneficial uses and users of groundwater and land uses and property interests affected by groundwater production, and adjacent basins that could affect the ability of that basin to meet the sustainability goal.
(4) Whether the Agency has adequate long-term existing monitoring results or other technical information to demonstrate an understanding of aquifer response.
(g) Each Plan shall describe the following information about the monitoring network:
(1) Scientific rationale for the monitoring site selection process.
(2) Consistency with data and reporting standards described in Section 352.4. If a site is not consistent with those standards, the Plan shall explain the necessity of the site to the monitoring network, and how any variation from the standards will not affect the usefulness of the results obtained.
(3) For each sustainability indicator, the quantitative values for the minimum threshold, measurable objective, and interim milestones that will be measured at each monitoring site or representative monitoring sites established pursuant to Section 354.36.
(h) The location and type of each monitoring site within the basin displayed on a map, and reported in tabular format, including information regarding the monitoring site type, frequency of measurement, and the purposes for which the monitoring site is being used.
(i) The monitoring protocols developed by each Agency shall include a description of technical standards, data collection methods, and other procedures or protocols pursuant to Water Code Section 10727.2(f) for monitoring sites or other data collection facilities to ensure that the monitoring network utilizes comparable data and methodologies.
(j) An Agency that has demonstrated that undesirable results related to one or more sustainability indicators are not present and are not likely to occur in a basin, as described in Section 354.26, shall not be required to establish a monitoring network related to those sustainability indicators.

Groundwater monitoring data provide the basis for demonstrating that undesirable results are avoided and are necessary for adequately managing the basin. The undesirable result associated with each sustainability indicator is based on a unique set of representative monitoring points. Therefore, a single monitoring network may not be appropriate to address all sustainability indicators. The monitoring network will consist of an adequate magnitude of monitoring locations that will characterize the groundwater flow regime dynamic such that a GSA will have the ability for predict sustainability indicator responses to management actions and document those results. In addition to understanding the dynamic responses to management actions, the data collected from these networks will be the foundation for communication to other connected basins as one may affect another. The transparent availability of data is intended to alleviate conflict by demonstrating conditions in a consistent manner such that assessment of the sustainability indicators is relatively consistent from basin to basin.

The use of existing monitoring networks established during implementation of CASGEM http://www.water.ca.gov/groundwater/casgem/ , Irrigated Lands Reporting Program (IRLP), http://www.waterboards.ca.gov/centralvalley/water_issues/irrigated_lands/ , Groundwater Ambient Monitoring and Assessment Program (GAMA) http://www.swrcb.ca.gov/gama/ , National Groundwater Monitoring Network http://cida.usgs.gov/ngwmn/splash.jsp , Existing Groundwater Management Planning, and other local programs could be used for a base monitoring network from which to build. These networks should be evaluated for compliance with Data and Reporting Standards of the Regulations §352.4.

This section addresses the design and installation of monitoring networks and sites. Agencies must address a number of issues prior to designing the monitoring site including, but not limited to, establishing the reason for installing the monitoring site, obtaining access agreements, assessing how the monitoring site may improve the basin conceptual model, assessing how the monitoring site may reduce uncertainty, etc. Where management areas are established, each area must be considered when developing the monitoring network for each sustainability indicator.

The following sections describe specific considerations for each of the sustainability indicators. These considerations should be applied to the network as a whole to assure the quality of the data is consistent and reliable; and so that sound representative monitoring locations can be established, as described in the Representative Monitoring Points section of this BMP.

A. Chronic Lowering of Groundwater Levels

§354.34(c)(1)
(1) Chronic Lowering of Groundwater Levels. Demonstrate groundwater occurrence, flow directions, and hydraulic gradients between principal aquifers and surface water features by the following methods:
(A) A sufficient density of monitoring wells to collect representative measurements through depth-discrete perforated intervals to characterize the groundwater table or potentiometric surface for each principal aquifer.
(B) Static groundwater elevation measurements shall be collected at least two times per year, to represent seasonal low and seasonal high groundwater conditions.

The observation and collection of groundwater level data is the cornerstone of data collected for SGMA compliance. The use of groundwater levels as a surrogate for other sustainability indicators will require reliable, consistent, high quality, defendable data. Collection of this information will be dependent upon the initial hydrogeologic conceptual model and will likely undergo refinement both temporally and spatially as management in the basin progresses. This isn't to say that the monitoring network will continually expand, but rather, through increased understanding be more refined to gather the necessary information in the most efficient way possible to demonstrate sustainability and exercise the basin to maintain conditions consistent with the sustainability goal and sustainable yield of the basin.

All wells that are part of the monitoring program should be dedicated groundwater monitoring wells with known construction information. The selection of wells should be aquifer-specific and wells which are screened across more than one aquifer should not be candidates for selection. Development of the monitoring well network must evaluate and consider both unconfined and confined aquifers and assess where pumping wells are screened that affect monitoring at these locations. Agricultural or municipal wells can be used temporarily until either dedicated monitoring wells can be installed or an existing well can be identified that meets the above criteria. If agricultural or municipal wells are used for monitoring, the wells must be screened across a single water-bearing unit, and care must be taken to ensure that pumping drawdown has sufficiently recovered before collecting data from a well.

Each well selected for inclusion in the monitoring network should be evaluated to ensure that water level and water quality data obtained from that well are not influenced by factors related to other wells in the vicinity. Well construction details and pumping information for all active and inactive wells located in the area of the selected monitoring well location should be reviewed to determine whether construction details

or pumping activity at those wells could affect water level or water quality data for the selected monitoring site.

There is no definitive rule for the density of groundwater monitoring points needed in a basin. **Table 1** was adopted from the *CASGEM groundwater elevation monitoring guidelines* (DWR, 2010). This table summarizes existing publications references to quantify the density of monitoring wells per hundred square miles. While these estimates from other studies may provide guidance, the necessary monitoring point density for GSP development and implementation will depend on local geology, extent of groundwater use, and how the GSPs define undesirable results. The use of Hopkins (1984) analysis incorporates a relative well density based on the degree of groundwater use within a given area.

Table 1. Monitoring Well Density Considerations

Reference	Monitoring Well Density (wells per 100 miles^2)
Heath (1976)	0.2 - 10
Sophocleous (1983)	6.3
Hopkins (1984)	4.0
Basins pumping more than 10,000 acre-feet/year per 100 miles^2	
Basins pumping between 1,000 and 10,000 acre-feet/year per 100 miles^2	2.0
Basins pumping between 250 and 1,000 acre-feet/year per 100 miles^2	1.0
Basins pumping between 100 and 250 acre-feet/year per 100 miles^2	0.7

In addition to consideration of the monitoring well network density, one must also take into account the frequency of monitoring these wells to characterize the groundwater dynamics within a basin or area. The discussion presented in the *National Framework for Ground-water Monitoring in the United States* (ACWI, 2013) also utilizes a degree of groundwater use and aquifer characteristics to aid in determining an appropriate frequency. The following **Figure 2** (ACWI, 2013) and **Table 2** (ACWI, 2013) describe these considerations and provide recommended frequency of long-term monitoring. It should be noted that the initial characterization is not included; the initial characterization of a monitoring location will require more frequent monitoring to establish the dynamic range and identification of external stresses affecting the groundwater level. An understanding of the full range of monitoring well conditions should be reached prior to establishing a long-term monitoring frequency.

Figure 2. Factors Determining Frequency of Monitoring Groundwater Levels (Taylor and Alley, 2001, adapted from ACWI, 2013)

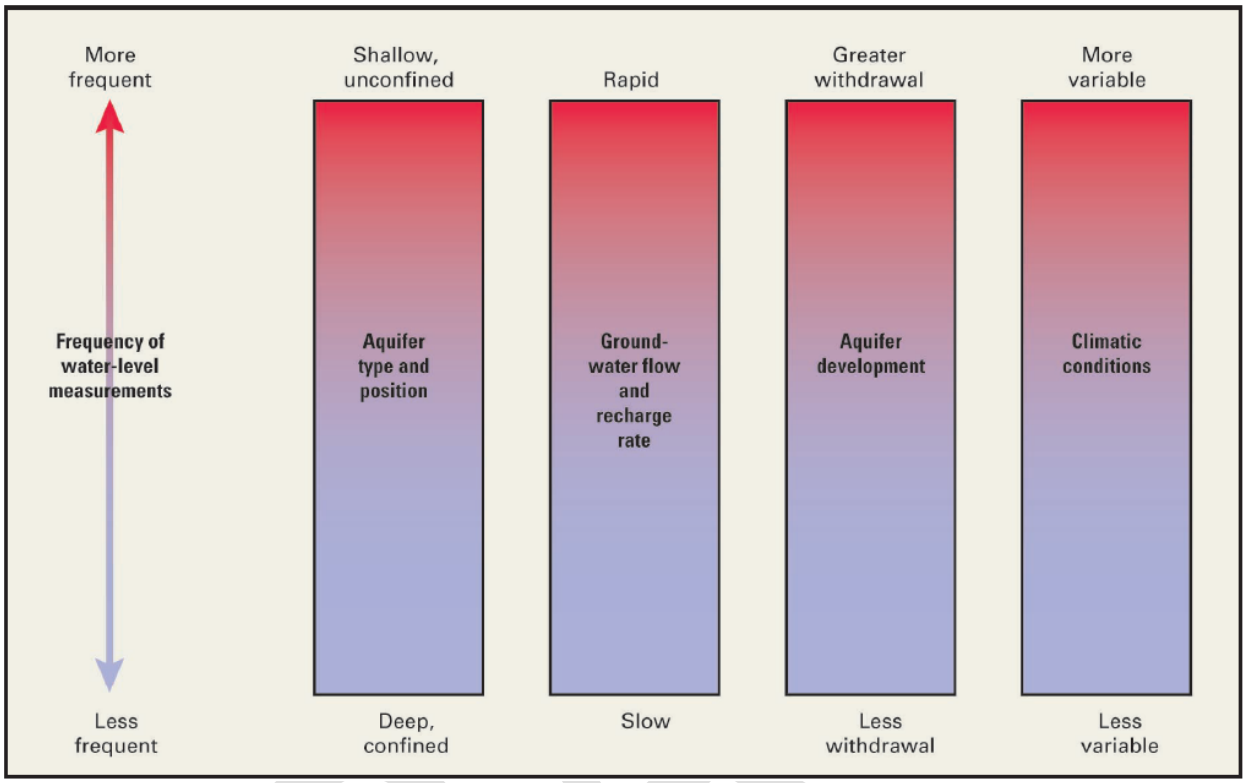

Table 2. Monitoring Frequency Based on Aquifer Properties and Degree of Use (adapted from ACWI, 2013)

[in/yr, inches per year; ft/d, feet per day]

Monitoring Category	Aquifer Type	Nearby Long-Term Aquifer Withdrawals		
		Small Withdrawals	Moderate Withdrawals	Large Withdrawals
Trend Monitoring Category	**Unconfined**			
	"low" recharge (<5 in/yr)	Once per quarter	Once per quarter	Once per month
	"high" recharge (>5 in/yr)	Once per quarter	Once per month	Once per day
	Confined			
	"low" hydraulic conductivity (<200 ft/d)	Once per quarter	Once per quarter	Once per month
	"high" hydraulic conductivity (>200 ft/d)	Once per quarter	Once per month	Once per day
Surveillance Monitoring Category	**Unconfined**			
	"low" recharge (<5 in/yr)	Every three years	Once per year	Twice per year
	"high" recharge (>5 in/yr)	Every three years	Twice per year	Once per quarter
	Confined			
	"low" hydraulic conductivity (<200 ft/d)	Every three years	Every two years	Once per year
	"high" hydraulic conductivity (>200 ft/d)	Every three years	Every two years	Once per year

The discussion below provides specific management practices to be applied during implementation of the GSP; where the general approaches for considering monitoring network density and frequency described above provide some guidance for the expectations for network design.

- All wells must meet applicable well installation standards set in California Department of Water Resources Bulletin 74-81 and 74-90, or as updated.
- Groundwater level data will be collected from each significant water principal aquifer in the basin.
- Water level data must be sufficient to produce seasonal maps of potentiometric surfaces or water table surfaces throughout the basin that clearly identify changes in groundwater flow direction and gradient.
- Water levels will be collected during the middle of October and March, corresponding to season lows and highs, respectively.
    - While semi-annual monitoring is required, more frequent, quarterly, monthly, or daily monitoring may be necessary to provide a more robust understanding of groundwater dynamics within the system.
    - Agencies will need to adjust the monitoring frequency to address uncertainty, such as in specific places where sustainability indicators are of concern; or to track specific management actions and projects as they are implemented.
- Data must be sufficient for mapping groundwater depressions, recharge areas, and along margins of basins where groundwater flow is known to enter or leave a basin.
- Data must be able to demonstrate the relationship between shallow groundwater and surface water bodies.
- Data must be able to map the effects of management actions, i.e. managed aquifer recharge or hydraulic seawater intrusion barriers.
- Data must be able to demonstrate conditions at basin boundaries.
    - Agencies may consider coordinating monitoring efforts with adjacent basins to provide consistent data across basin boundaries.
- Data must be able to characterize conditions as they may affect the beneficial uses and users identified within the basin.

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Additional Information:

Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data
http://pubs.usgs.gov/circ/circ1217/pdf/circ1217_final.pdf

A National Framework for Ground-Water Monitoring in the United States
Fact Sheet: http://acwi.gov/sogw/NGWMN_InfoSheet_final.pdf
Full Report: http://acwi.gov/sogw/ngwmn_framework_report_july2013.pdf

Statistical Design of Water-Level Monitoring Networks
http://pubs.usgs.gov/circ/circ1217/pdf/pt4.pdf

Design of Ground-Water Level Observation-Well Programs
http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6584.1976.tb03635.x/epdf

B. Reduction of Groundwater Storage

§354.34(c)(2)
(2) Reduction of Groundwater Storage. Provide an estimate of the change in annual groundwater in storage.

While reduction in groundwater storage is inconsistent with a specific measureable condition, it does rely heavily on the collection of groundwater levels as described in the preceding section. This section is included to provide additional consideration to the identification in the hydrogeologic conceptual model of the discrete aquifer units and surrounding aquitard and their potential to release water from storage. These changes in groundwater levels reflect changes in storage and can thus be estimated with assumptions of thickness of unit, porosity, and connectivity.

Estimates of changes in storage are available, but they should be used cautiously as they tend to be much more regional in nature and may not provide the level of accuracy necessary to fully determine the conditions within the basin and may limit the GSA's ability to exercise the basin to meet sustainability goals. The National Aeronautics and Space Administration (NASA) mission, Gravity Recovery and Climate Experiment (GRACE) satellites, provides analysis results of differential gravity response associated with changes in groundwater occurrence and terrestrial water storage, http://www.nasa.gov/mission_pages/Grace/#.WATU_fkrKUk .

C. Seawater Intrusion

> *§354.34(c)(3)*
> *(3) Seawater Intrusion. Monitor seawater intrusion using chloride concentrations, or other measurements convertible to chloride concentrations, so that the current and projected rate and extent of seawater intrusion for each applicable principal aquifer may be calculated.*

The monitoring network for seawater intrusion should be adequate to capture changes in water quality conditions associated with the dynamic seawater-freshwater interface along the many coastal aquifers of California. This system is largely controlled by differences in water density and hydraulic head to maintain the advancement of the seawater front. A robust understanding is necessary to identify the preferential flow pathways where seawater can intrude inland and associate with freshwater groundwater extractions or declines in head. The following management practices should be considered at a minimum to provide data supporting assessment of seawater intrusion:

- Monitoring of Groundwater elevation in all sea water intrusion specific monitoring locations should be conducted consistent with water level monitoring network and protocols described in this and the Monitoring Protocol BMPs.
- Monitor groundwater quality data from each principal aquifer in the basin that is currently, or may in the future, be impacted by seawater intrusion.
    - The spatial density must be adequate to map an isocontour of chloride advancement front as a representation of seawater
    - Monitoring should occur at least quarterly and correspond with seasonal highs and lows, or more frequent as appropriate.
    - The above points do not include initial characterization, where more frequent monitoring may be necessary to evaluate the full dynamic range of aquifer response and associated seawater intrusion.
- Collect groundwater quality data from each principal aquifer in the basin that is currently, or may in the future be, impacted by degraded water quality.
    - Agencies should use, to the greatest degree possible, existing water quality monitoring data. For example, these could include ILRP, GAMA, existing Regional Water Quality Control Board (RWQCB) monitoring and remediation programs, and drinking water source assessment programs.
    - Collection of water quality samples are required to be analyzed for chloride concentration.
        - Additional analytes may be desirable for characterization and planning of mitigation measures.

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        - The use of a surrogate must be demonstrated through correlative analysis, and should be periodically quantitatively assessed following implementation of use.
- Define the three-dimensional extent of any existing seawater intrusion, or degraded water quality.
- Samples should be sufficient for mapping movement of seawater or degraded water quality.
- Samples should be sufficient to assess groundwater quality impacts to beneficial uses and users

The spatial distribution of monitoring locations may be optimized by inclusion of geophysical techniques to identify the preferential pathways controlling seawater intrusion and target critical connections to existing water supply wells and mitigation efforts.

D. Degraded Water Quality

§354.34(c)(4)
(4) Degraded Water Quality. Collect sufficient spatial and temporal data from each applicable principal aquifer to determine groundwater quality trends for water quality indicators, as determined by the Agency, to address known water quality issues.

Groundwater quality monitoring networks should be designed to demonstrate that the degraded water quality sustainability indicator is being observed for the purpose of meeting the sustainability goal. The monitoring network should consist largely as supplemental monitoring locations where known groundwater contamination plumes under existing regulatory management and monitoring exist, and additional safeguards for plume migration are necessary. In addition, some monitoring may be necessary to address other degraded water quality issues in which migration could impact beneficial uses of water including, but not limited to; unregulated contaminant plumes and naturally occurring water quality impacts. Seawater intrusion and degraded water quality are naturally related, as many best management practices are interchangeable. The following represent specific practices to be employed in the execution of the GSP:

- Monitor groundwater quality data from each principal aquifer in the basin that is currently, or may in the future be, impacted by degraded water quality.
    - The spatial distribution must be adequate to map or supplement mapping of known contaminants.
    - Monitoring should occur at seasonal highs and lows, or more frequent as appropriate.

        - Where regulated plumes exist, monitoring should coincide with regulatory monitoring for plume migration comparison purposes.
        - Where unregulated degraded water quality occurs, monitoring should be consistent with degree of groundwater use in the regions of the known impacts.
- Collect groundwater quality data from each principal aquifer in the basin that is currently, or may in the future be, impacted by degraded water quality.
    - Agencies should use to the greatest degree possible existing water quality monitoring data. For example, these could include ILRP, GAMA, existing RWQCB monitoring and remediation programs, drinking water source assessment programs.
- Define the three-dimensional extent of any existing degraded water quality impact.
- Data should be sufficient for mapping movement of degraded water quality.
- Data should be sufficient to assess groundwater quality impacts to beneficial uses and users

Additional References:

Framework for a ground-water quality monitoring and assessment program for California (GAMA)
http://pubs.usgs.gov/wri/wri034166/

Estimation of aquifer scale proportion using equal area grids: Assessment of regional scale groundwater quality
http://ca.water.usgs.gov/projects/gama/pdfs/Belitz_etal_2010_wrcr12701.pdf

E. Land Subsidence

> *§354.34(c)(5)*
> *(5) Land Subsidence. Identify the rate and extent of land subsidence, which may be measured by extensometers, surveying, remote sensing technology, or other appropriate method.*

The occurrence of inelastic land subsidence has been recognized in California for many decades. Observation of land subsidence sustainability indicator can utilize numerous techniques, including levelling surveying tied to known benchmarks, installing and tracking changes in borehole extensometers, monitoring continuous global position system (CGPS) locations, or analyzing interferometric synthetic aperture radar (InSAR) data. As with most sustainability indicators, conditions of subsidence, or lack thereof,

can be correlated to groundwater levels as a surrogate. Each of these approaches uses different measuring points and techniques, and is tailored for specific data needs and geologic conditions.

The use of existing data should be utilized to the greatest extent. The USGS has conducted numerous studies and much of the data can be located through their webpage and reports: http://ca.water.usgs.gov/land_subsidence/index.html . In addition, DWR has developed supporting studies and data available in the Groundwater Information Center interactive maps and reports: http://www.water.ca.gov/groundwater/gwinfo/index.cfm . The use of existing regular surveys of State infrastructure may also present a record of historical changes in elevation along roadways and canals.

Prior to development of a specific subsidence monitoring network a screening level analysis should be conducted. The screening of subsidence occurrence should include:

- Review of the hydrogeologic conceptual model and understanding of grain size distributions and potential for subsidence to occur.
- Review of any known regional or correlative geologic conditions where subsidence has been observed.
- Review of historic range of groundwater levels in the principal aquifers of the basin.
- Review of historic records of infrastructure impacts including, but not limited to: damage to pipelines, canals, roadways, bridges, canals, or well collapse potentially associated with changes in land surface elevation changes.
- Review of remote sensing results such as InSAR or other land surface monitoring data.
- Review of existing CGPS surveys.

In general, the network should be designed to provide consistent, accurate, and reproducible results. Where subsidence conditions are occurring or believed to occur, a specific monitoring network should be established to observe the sustainability indicator such that the sustainability goal can be met. The following approaches can be used independently or in coordination with multiple methods and should be evaluated with the specific conditions and objectives in mind. Various standards and guidance documents that must be adhered to when developing a monitoring network include:

- Levelling surveys must follow surveying standards set out in the California Department of Transportation's *Caltrans surveys Manual*. Specific Sites where additional information can be found include:
    - http://www.dot.ca.gov/hq/row/landsurveys/
    - http://www.ngs.noaa.gov/datasheets/

- https://www.ngs.noaa.gov/FGCS/tech_pub/1984-stds-specs-geodetic-control-networks.htm#3.5

- CGPS surveys must follow surveying standards set out in the California Department of Transportation's *Caltrans surveys Manual*. Specific sites where additional data can be found include:
  - http://www.dot.ca.gov/hq/row/landsurveys/
  - http://www.ngs.noaa.gov/CORS/
  - http://www.unavco.org/instrumentation/networks/status/pbo
  - http://www.dot.ca.gov/dist6/surveys/CVSRN/sitemap.htm
  - http://sopac.ucsd.edu/map.shtml

- The construction and use of borehole extensometers can yield information about total and unit-specific subsidence rates depending upon construction and purpose. Specific sites where additional data can be found include:
  - Extensometer methods commonly used by the USGS http://hydrologie.org/redbooks/a151/iahs_151_0169.pdf
  - Extensometry principles (p. 20-29) http://wwwrcamnl.wr.usgs.gov/rgws/Unesco/
  - Examples of extensometer construction, instrumentation, and data interpretation
    - Single-stage pipe extensometer (Edwards Air Force Base, CA; 1990), p. 20-23: http://pubs.usgs.gov/wri/2000/wri004015/
    - Dual-stage pipe extensometer (Lancaster, CA; 1995), p. 8-12: http://pubs.usgs.gov/of/2001/ofr01414/
    - Dual-stage pipe extensometer (San Lorenzo, CA; 2008), p. 12-13: https://pubs.er.usgs.gov/publication/ds890

- The use of InSAR data can be useful for screening and regular monitoring, especially as the technology becomes more widely available and usable. Specific sites where additional data can be found include:
  - Interferometric Synthetic Aperture Radar (InSAR) techniques are an effective way to measure changes in land-surface altitude over large areas. Some basic information about InSAR can be found here:
    - https://pubs.usgs.gov/fs/fs-051-00/pdf/fs-051-00.pdf
    - http://pubs.usgs.gov/fs/fs06903/pdf/fs06903.pdf
  - Raw data (not processed into interferograms) is available from a variety of foreign space agencies or their distributors at variable costs (including free):
    - European Space Agency http://www.esa.int/ESA
    - Japanese Space Exploration Agency http://global.jaxa.jp/

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        - Italian Space Agency http://www.asi.it/en
        - Canadian Space Agency http://www.asc-csa.gc.ca/eng/
        - German Aerospace Center http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10002/
    - Data Processing: Processing raw data to high-quality InSAR data is not a trivial task.
        - Open source/research-grade software packages and commercially-available software packages. A list of available software can be found here: http://www.unavco.org/software/data-processing/sar-software/sar-software.html
        - There are commercial companies that process InSAR data.
        - Processing raw data to quality-controlled InSAR data is an essential part of InSAR processing because of the numerous common sources of error. Discussions of these error sources are found here:
            - http://pubs.usgs.gov/sir/2014/5075/
            - https://pubs.er.usgs.gov/publication/sir20135142

F. Depletion of Interconnected Surface Water

§354.34(c)(5)
(6) Depletions of Interconnected Surface Water. Monitor surface water and groundwater, where interconnected surface water conditions exist, to characterize the spatial and temporal exchanges between surface water and groundwater, and to calibrate and apply the tools and methods necessary to calculate depletions of surface water caused by groundwater extractions. The monitoring network shall be able to characterize the following:
(A) Flow conditions including surface water discharge, surface water head, and baseflow contribution.
(B) Identifying the approximate date and location where ephemeral or intermittent flowing streams and rivers cease to flow, if applicable.
(C) Temporal change in conditions due to variations in stream discharge and regional groundwater extraction.
(D) Other factors that may be necessary to identify adverse impacts on beneficial uses of the surface water.

Monitoring of the interconnected surface water depletions requires the use of tools, commonly modeling approaches, to estimate the depletions associated with groundwater extraction. The use of models requires assumptions to be made to constrain the numerical model solutions. These assumptions should be based on

empirical observations determining the extent of connection of the surface water and groundwater systems, the timing of those connections, the flow dynamics of both the surface water and groundwater systems, and hydrogeologic properties of the geologic framework connecting these systems.

The following components should be included in the establishment of a monitoring network:

- Use existing stream gaging and groundwater level monitoring networks to the extent possible.
- Establish stream gaging along sections of known surface water groundwater connection.
    - All streamflow measurements should be collected, analyzed, and reported in accordance with the procedures outlined in USGS Water Supply Paper 2175, *Volume 1. - Measurement of Stage Discharge* and *Volume 2. - Computation of Discharge.*
        - https://pubs.er.usgs.gov/publication/wsp2175_vol1
        - https://pubs.er.usgs.gov/publication/wsp2175
    - Specific Sites where additional information can be found include:
        - General source: http://water.usgs.gov/nsip/
        - Standards for the Analysis and Processing of Surface-Water Data and Information Using Electronic Methods https://pubs.er.usgs.gov/publication/wri20014044
        - USGS Streamflow Information
            - Real-time Streamflow Data for the Nation
            - Historical Streamflow Data for the Nation
            - WaterWatch
            - StreamStats
    - Selection of a stream gaging locations where differential observations are anticipated, location selection must account for surface water diversions and return flows; or select gaging locations and reaches over which no diversions or return flows exist.
- Establish a shallow groundwater monitoring well network to characterize groundwater levels adjacent to connected streams and hydrogeologic properties.
    - Network should extend perpendicular and parallel to stream flow to provide adequate characterization to constrain model development.
    - Monitor to capture seasonal pumping conditions in vicinity of the wells.
- Identify and quantify both timing and volume of groundwater pumping within approximately 3 miles of the stream or as appropriate for the flow regime.
- Establish qualitative monitoring by use of GPS survey of the timing and position along stream where ephemeral or intermittent streams cease to flow. Should be conducted annually or as appropriate to capture stream flow change.

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It may be beneficial to conduct other initial characterization surveys to establish an appropriate monitoring method to develop assumptions for a model or other technique to estimate depletion of surface water. These may include:

- Stream bed conductance surveys
- Aquifer testing for hydrogeologic properties
- Isotopic studies to determine source areas
- Geochemical studies to determine source areas
- Geophysical techniques to determine connectivity to stream channels and preferential flow pathways.

REPRESENTATIVE MONITORING POINTS

§ 354.36. Representative Monitoring (a)-(c)
Each Agency may designate a subset of monitoring sites as representative of conditions in the basin or an area of the basin, as follows:
(a) Representative monitoring sites may be designated by the Agency as the point at which sustainability indicators are monitored, and for which quantitative values for minimum thresholds, measurable objectives, and interim milestones are defined.
(b) Groundwater elevations may be used as a proxy for monitoring other sustainability indicators if the Agency demonstrates the following: (1) Significant correlation exists between groundwater elevations and the sustainability indicators for which groundwater elevation measurements serve as a proxy. (2) Measurable objectives established for groundwater elevation shall include a reasonable margin of operational flexibility taking into consideration the basin setting to avoid undesirable results for the sustainability indicators for which groundwater elevation measurements serve as a proxy.
(c) The designation of a representative monitoring site shall be supported by adequate evidence demonstrating that the site reflects general conditions in the area.

Undesirable results can be assessed based on data from Representative Monitoring Points (RMPs), which are a subset of a basin's complete monitoring network, as demonstrated in **Figure 3**. In this figure, the complete monitoring network is represented by black dots. The RMPs for each sustainability indicator are indicated by various colored bull's-eyes. In this example, the network of RMPs is unique for each sustainability indicator. Agencies can adopt a single network of RMPs, or have a unique set of RMPs for each sustainability indicator.

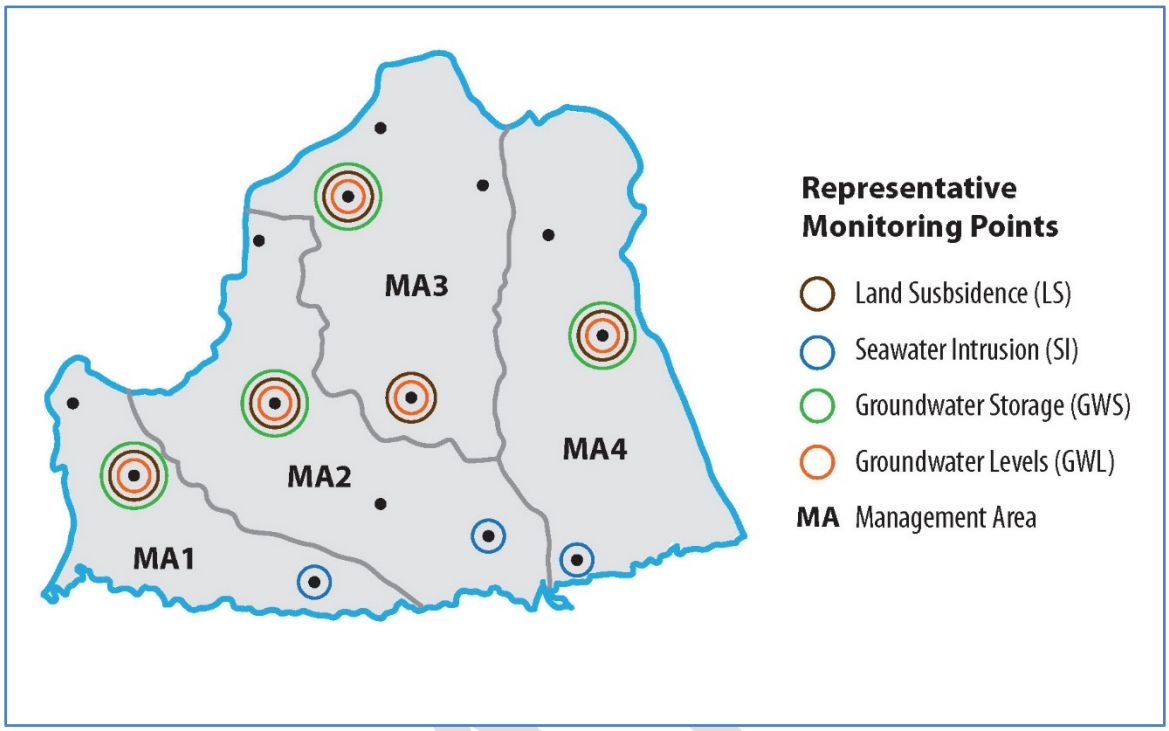

Figure 3: Representative Monitoring Points

If RMPs are used to represent groundwater elevations from a number of surrounding monitoring wells, the GSP should demonstrate that each RMP's historical measured groundwater elevations, groundwater elevation trends, and seasonal fluctuations are similar to the historical measurements in the surrounding monitoring wells. If RMPs are used to represent groundwater quality from a number of surrounding monitoring wells, the GSP should demonstrate that each RMP's historical measured groundwater quality and groundwater quality trends are similar to historical measurements in the surrounding monitoring wells.

The use of groundwater levels as a proxy may be utilized where clear correlation can be made for each sustainability indicator. The use of the proxy can facilitate the illustration of where minimum thresholds and measureable objective occur. A series of RMPs or a single RMP may be adequate to characterize a management area or basin. Use of the RMP should include identification and description of possible interference with the monitoring objective.

NETWORK ASSESSMENT AND IMPROVEMENTS

§ 354.38. Assessment and Improvement of Monitoring Network (a)-(e)
a) Each Agency shall review the monitoring network and include an evaluation in the Plan and each five-year assessment, including a determination of uncertainty and whether there are data gaps that could affect the ability of the Plan to achieve the sustainability goal for the basin.
(b) Each Agency shall identify data gaps wherever the basin does not contain a sufficient number of monitoring sites, does not monitor sites at a sufficient frequency, or utilizes monitoring sites that are unreliable, including those that do not satisfy minimum standards of the monitoring network adopted by the Agency.
(c) If the monitoring network contains data gaps, the Plan shall include a description of the following: (1) The location and reason for data gaps in the monitoring network. (2) Local issues and circumstances that limit or prevent monitoring.
(d) Each Agency shall describe steps that will be taken to fill data gaps before the next five-year assessment, including the location and purpose of newly added or installed monitoring sites.
(e) Each Agency shall adjust the monitoring frequency and distribution of monitoring sites to provide an adequate level of detail about site-specific surface water and groundwater conditions and to assess the effectiveness of management actions under circumstances that include the following: (1) Minimum threshold exceedances. (2) Highly variable spatial or temporal conditions. (3) Adverse impacts to beneficial uses and users of groundwater. (4) The potential to adversely affect the ability of an adjacent basin to implement its Plan or impede achievement of sustainability goals in an adjacent basin.

Network assessment and improvements are commonly identified as 'data gaps' in the monitoring network and refer to *"a lack of information that significantly affects the understanding of basin setting or evaluation of the efficacy of the Plan implementation, and could limit the ability to assess whether a basin is being sustainably managed."* Therefore, the monitoring network is a key component in the development of Plans and will influence the development and understanding of the basin setting, including the hydrogeologic conceptual model, groundwater conditions, and water budget; and proposed minimum thresholds and measurable objectives. It should be noted that GSAs should consider previous analyses of data gaps of their monitoring network through existing programs, such as CASGEM monitoring plans. **Figure 4** shows a flowchart that demonstrates a process that GSAs should use to identify and address data gaps.

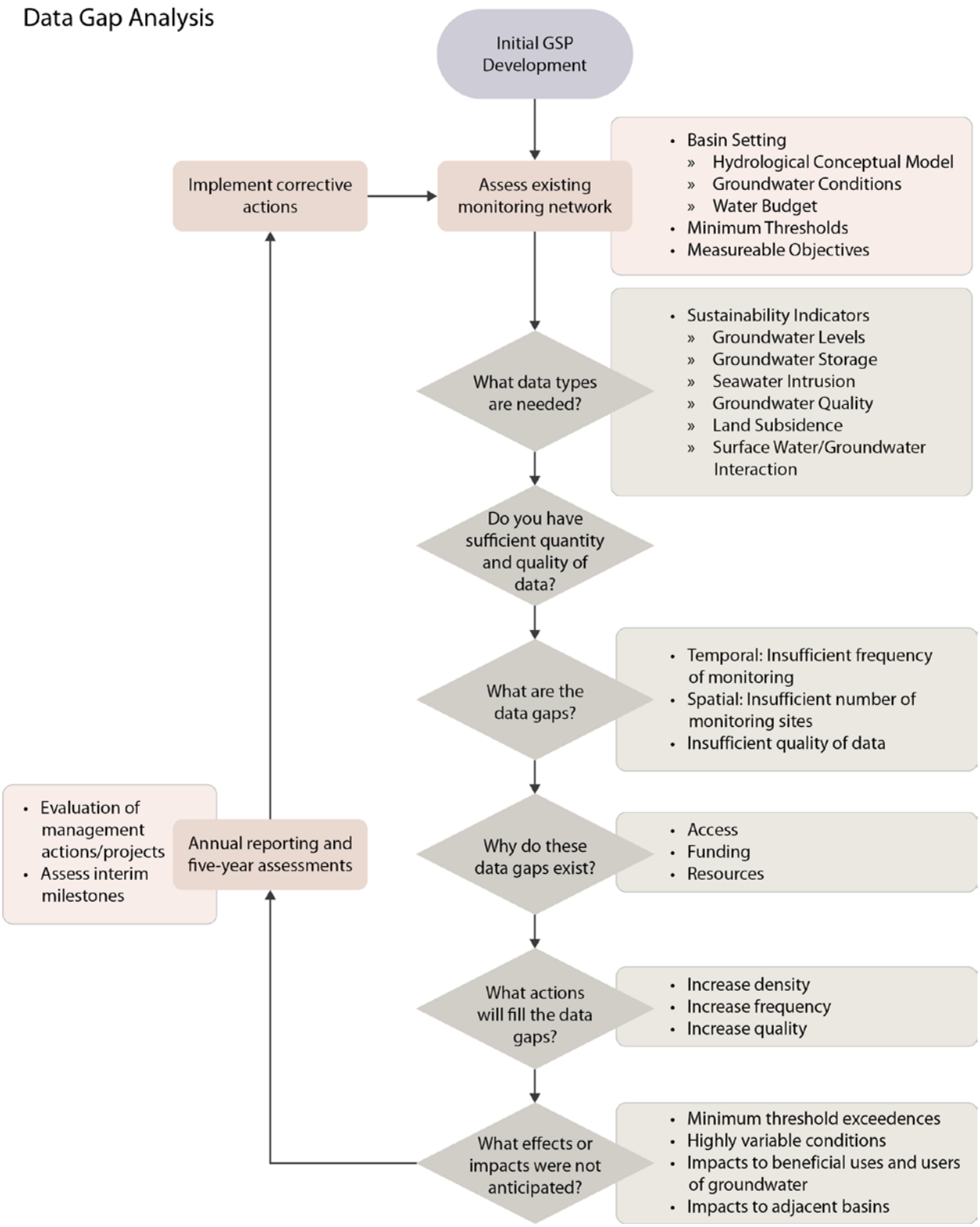

Figure 4. Data Gap Analysis Flow Chart

The various data sets that GSAs will need to monitor include those related to the sustainability indicators: chronic lowering of groundwater levels, reduction in groundwater storage, seawater intrusion, degraded water quality, land subsidence, and depletions of interconnected surface water. Judgment will be needed from GSAs to identify possible data gaps in their monitoring network of the sustainability indicators. Data gaps can result from information from monitoring that is not of sufficient quantity or quality.

Data of insufficient quantity typically result from missing or incomplete information, either temporally or spatially. Examples of temporal data gaps include a hydrograph with data that is too infrequent, has inconsistent intervals, or a short historical record, as shown in **Figure 5**. Spatial data gaps may occur from a monitoring network with low or uneven density in three dimensions, as shown in **Figure 6**.

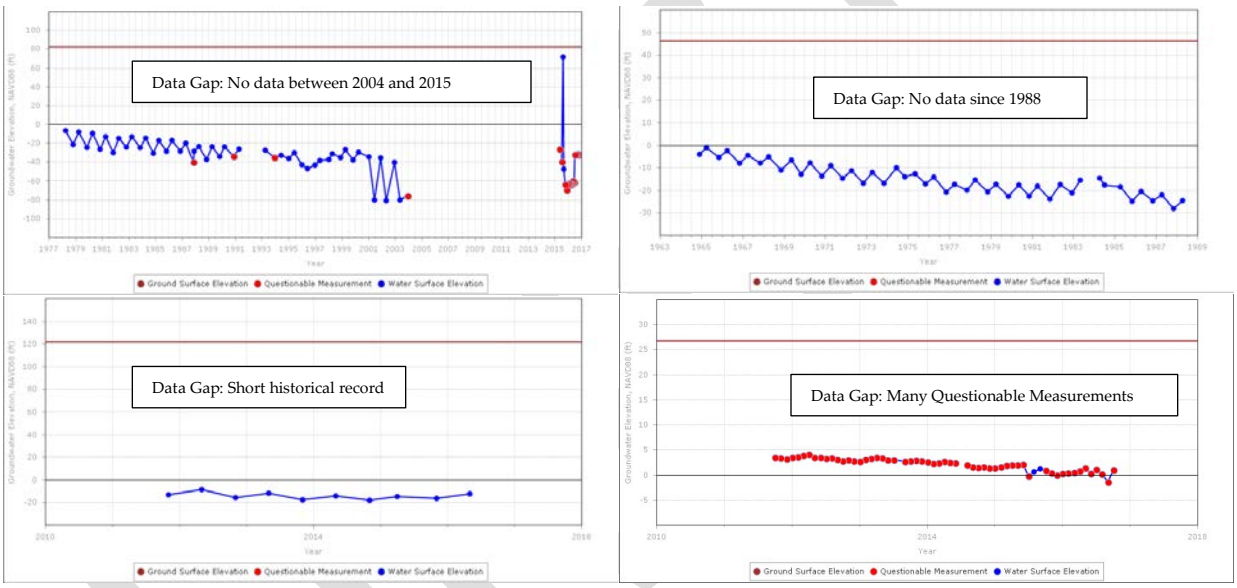

Figure 5. Examples of Hydrographs with Temporal Data Gaps

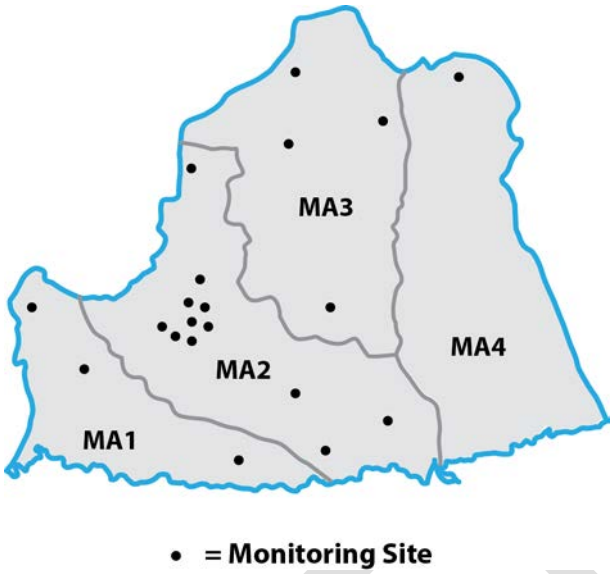

Figure 6. Example Monitoring Network with Spatial Data Gaps

Poor quality data may also be the cause of data gaps. Data must be of sufficient quality to enable scientifically defensible decisions. Poor quality data may at times be worse than no data because it could lead to incorrect assumptions or biases. Some things to consider when questioning the quality of data include: collection conditions and methods, sampling quality assurance/quality control, and proper calibration of meters/equipment. As part of the CASGEM program, DWR reports groundwater elevation data from local agencies, which include the option for "Questionable Measurement Codes." These codes are one way of identifying poor quality data.

There may be various reasons for data gaps including: site access, funding, and lack of staffing resources. By identifying and correcting the reasons behind data gaps, GSAs may be able to avoid further data gaps.

Direct actions GSAs could take to fill data gaps include:

- Increasing the frequency of monitoring. For instance, some groundwater elevation measurements are taken twice a year in the spring and fall, but perhaps those measurements need to be increased to quarterly, monthly, or more frequently if needed.
- Increasing the spatial distribution and density of the monitoring network.
- Increasing the quality of data through improved collection methods and data management methods.

As GSPs are implemented, GSAs may identify other data gaps, especially if there are minimum threshold exceedances, highly variable spatial or temporal conditions, adverse impacts to beneficial uses and users of groundwater, and impacts to adjacent

basins' ability to achieve sustainability. Any or all of these conditions may indicate a need to refine the monitoring network.

Agencies are required to assess their monitoring networks every five years. During those assessments, data gaps may also be identified as agencies monitor the progress of their management actions/projects and the status of their interim milestones. These regular assessments will allow the GSAs to adaptively manage, focus, and prioritize future monitoring.

DATA REPORTING

> *§ 352.6. Data Management System*
> *Each Agency shall develop and maintain a data management system that is capable of storing and reporting information relevant to the development or implementation of the Plan and monitoring of the basin.*

The use of a Data Management System (DMS) is required for all GSPs. The DMS should include clear identification of all monitoring sites and a description of the quality assurance and quality control checks performed on the data being entered. Uploading of the collected data should occur immediately following collection to address any quality concerns in timely manner and prevent potential for development of data gaps. Coordination of data structures between adjacent basins will facilitate data sharing and increase data transparency.

DWR will be providing an update to this BMP as the suggested data structure is developed, as necessary.

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6. KEY DEFINITIONS

SGMA DEFINITIONS (CA WATER CODE SECTION 10721)

(r) "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.

(u) "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.

(v) "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.

(w) "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.

(x) "Undesirable result" means 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 groundwater 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.

DRAFT

GSP REGULATIONS DEFINITIONS (CALIFORNIA CODE OF REGULATIONS SECTION 351)

(l) "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.

(o) "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.

(q) "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.

(s) "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.

(t) "Minimum threshold" refers to a numeric value for each sustainability indicator used to define undesirable results.

(u) "NAD83" refers to the North American Datum of 1983 computed by the National Geodetic Survey, or as modified.

(v) "NAVD88" refers to the North American Vertical Datum of 1988 computed by the National Geodetic Survey, or as modified.

(y) "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.

(aa) "Principal aquifers" refer to aquifers or aquifer systems that store, transmit, and yield significant or economic quantities of groundwater to wells, springs, or surface water systems.

(ab) "Reference point" refers to a permanent, stationary and readily identifiable mark or point on a well, such as the top of casing, from which groundwater level measurements are taken, or other monitoring site.

(ac) "Representative monitoring" refers to a monitoring site within a broader network of sites that typifies one or more conditions within the basin or an area of the basin.

(ad) "Seasonal high" refers to the highest annual static groundwater elevation that is typically measured in the Spring and associated with stable aquifer conditions following a period of lowest annual groundwater demand.

(ae) "Seasonal low" refers to the lowest annual static groundwater elevation that is typically measured in the Summer or Fall, and associated with a period of stable aquifer conditions following a period of highest annual groundwater demand.

(ag) "Statutory deadline" refers to the date by which an Agency must be managing a basin pursuant to an adopted Plan, as described in Water Code Sections 10720.7 or 10722.4.

DRAFT

(ah) "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).
(ai) "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

NETWORK DESIGN

- Design of a Real-Time Ground-Water Level Monitoring Network and Portrayal of Hydrologic Data in Southern Florida
  - http://fl.water.usgs.gov/PDF_files/wri01_4275_prinos.pdf

- Optimization of Water-Level Monitoring Networks in the Eastern Snake River Plain Aquifer Using a Kriging-Based Genetic Algorithm Method
  - http://pubs.usgs.gov/sir/2013/5120/pdf/sir20135120.pdf

GUIDANCE

California Department of Water Resources, 2010. *California statewide groundwater elevation monitoring (CASGEM) groundwater elevation monitoring guidelines*, December, 36 p. http://www.water.ca.gov/groundwater/casgem/documents.cfm

Heath, R. C., 1976. *Design of ground-water level observation-well programs*: Ground Water, V. 14, no. 2, p. 71-77.

Hopkins, J., 1994. *Explanation of the Texas Water Development Board groundwater level monitoring program and water-level measuring manual*: UM-52, 53 p.
http://www.twdb.texas.gov/groundwater/docs/UMs/UM-52.pdf

Sophocleous, M., 1983. *Groundwater observation network design for the Kansas groundwater management districts, USA*: Journal of Hydrology, vol.61, pp 371-389.

Subcommittee on ground water of the advisory committee on water information, 2013. A National Framework for Ground-Water Monitoring in the United States, 168 p.
http://acwi.gov/sogw/ngwmn_framework_report_july2013.pdf

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

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Hydrogeologic Conceptual Model Best Management Practice

California Department of Water Resources
Sustainable Groundwater Management Program
1416 Ninth Street
P.O. Box 942836
Sacramento, CA 94236-0001

www.water.ca.gov/groundwater

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Hydrogeologic Conceptual Model Best Management Practice

1. Objective

The objective of this Best Management Practice (BMP) is to provide technical assistance on the preparation of a hydrogeologic conceptual model (HCM) in accordance with the Groundwater Sustainability Plan (GSP) Emergency Regulations (Regulations) that supports the long-term sustainability of the basin under the Sustainable Groundwater Management Act (SGMA). Information provided in this BMP is meant to provide technical assistance to Groundwater Sustainability Agencies (GSAs) and other stakeholders on how to address HCM requirements outlined in the Regulations, including identifying available resources to support development of HCMs.

This BMP includes the following sections:

1. Objective. The objective and brief description of the contents of this BMP.
2. Use and Limitations. A brief description of the use and limitations of this BMP.
3. HCM Fundamentals. A description of HCM fundamental concepts.
4. Relationship of HCM to other BMPS. A description of how the HCM relates to other BMPs and is the basis for development of other GSP requirements.
5. Technical Assistance. A description of technical assistance to support the development of a HCM and potential sources of information and relevant datasets that can be used to further define each component.
6. Key Definitions. Definitions relevant for this BMP as provided in the GSP and Basin Boundary Regulations and in SGMA.
7. Related Materials. References and other materials that provide supporting information related to the development of HCMs.

2. Use and Limitations

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

3. HCM Fundamentals

A HCM provides an understanding of the general physical characteristics of the basin setting, provides the context to develop a mathematical (analytical or numerical) model

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and monitoring network, and provides a tool for stakeholder outreach and communication. A HCM also provides a foundation for understanding potential uncertainties of the physical characteristics of a basin which can be useful for identifying data gaps necessary to further refine the understanding of the hydrogeologic setting. An example of a HCM depiction as a three-dimensional block diagram is provided in **Figure 1**.

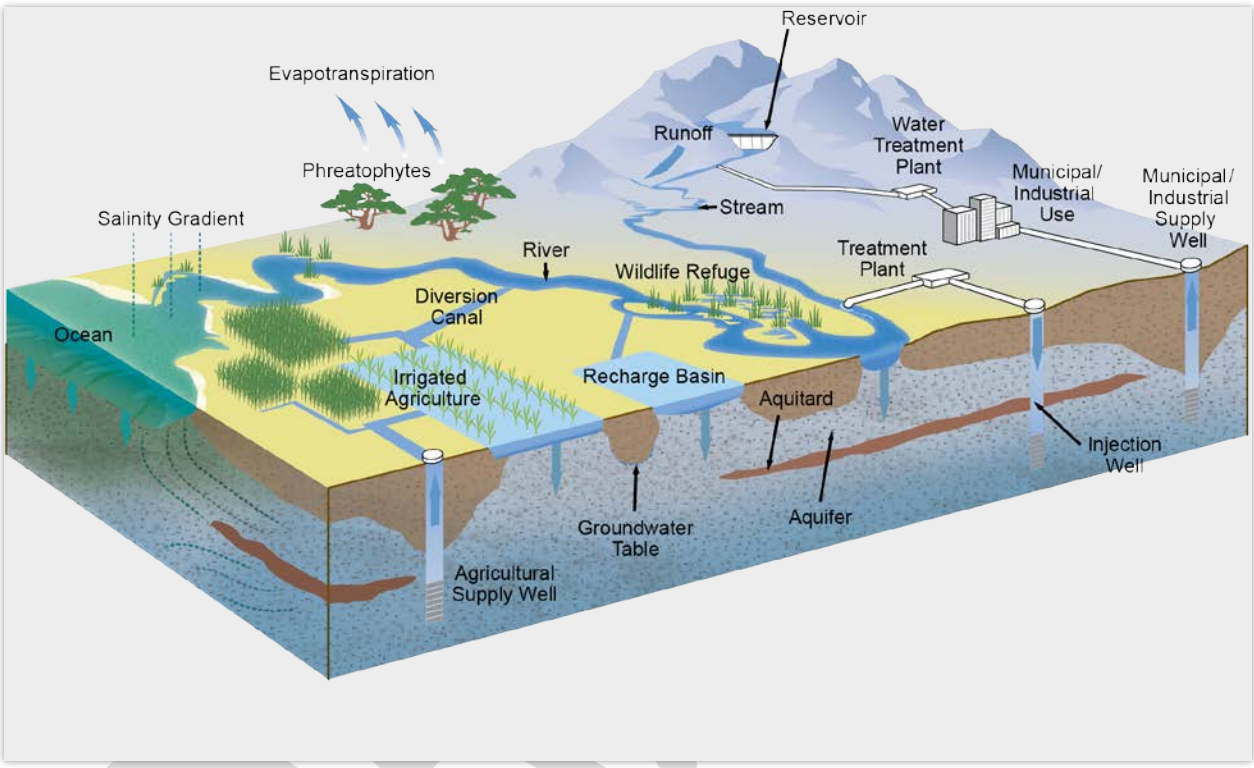

Figure 1 – Example 3-D Graphic Representing a HCM.

COMMON HCM USES

The following provides a limited list of common HCM uses:

- Develop an understanding and description of the basin to be managed, specifically the structural and physical characteristics that control the flow and storage of surface and groundwater
- Identify general water budget components
- Identify areas that are not well understood (data gaps)
- Inform monitoring requirements
- Facilitate or serve as the basis for the development, construction, and application of a mathematical (analytical or numerical) model
- Refine the understanding of the basin characteristics over time, as new information is acquired from field investigation activities, monitoring networks and modeling results

- Provide often highly technical information in a format more easily understood to aid in stakeholder outreach and communication of the basin characteristics to local water users
- Help identify potential projects and management actions to achieve the sustainability goal within the basin

HCM IN REFERENCE TO THE GSP REGULATIONS

§354.14 (a): Each Plan shall include a descriptive hydrogeologic conceptual model of the basin based on technical studies and qualified maps that characterizes the physical components and interaction of the surface water and groundwater systems in the basin.

The regulations[1] require that each GSP include a HCM for the basin reported in a narrative and graphical form that provides an overview of the physical basin characteristics, uses of groundwater in the basin, and sets the stage for the basin setting (§354.14(a)). The Regulations identify the level of detail to be included for the HCM to aid in describing the basin setting for the GSP development and sustainability analysis.

The HCM requirements outlined pertain to two main types of information:

1. The narrative description is accompanied by a graphical representation of the basin that clearly portrays the geographic setting, regional geology, basin geometry and general water quality and consumptive water uses in the basin.
2. A series of geographic maps and scaled cross-sections to provide a vertical layering representation and a geographic view of individual datasets including, the topography, geology, soils, recharge and discharge areas, source and point of delivery of imported water supplies, and surface water systems that are significant to management of the basin.

A HCM differs from a mathematical (analytical or numerical) model in that is does not compute specific quantities of water flowing through or moving into or out of a basin, but rather provides a general understanding of the physical setting, characteristics, and processes that govern groundwater occurrence within the basin. In that sense, the HCM forms the basis for mathematical (analytical or numerical) model development, and sets the stage for further quantification of the water budget components.

[1] http://www.water.ca.gov/groundwater/sgm/pdfs/GSP_Emergency_Regulations.pdf

The intent of requiring HCMs in the Regulations is not to provide a direct measure of sustainability, but rather to provide a useful tool for GSAs to develop their GSP and meet other requirements of SGMA.

4. Relationship of HCM to other BMPS

The purposes of the HCM in the broader context of SGMA implementation include supporting the evaluation of undesirable results and development of minimum thresholds; supporting identification and development of potential projects and management actions to address undesirable results that exist or are likely to exist in the future; and supporting the development of monitoring protocols, networks, and strategies to evaluate the sustainability of the basin over time.

The HCM is also linked to other related BMPs as illustrated in **Figure 2**. This figure also provides the context of the BMPs as they relate to various steps to sustainability as outlined in the Regulations. The HCM BMP is part of the Basin Setting development step in the Regulations.

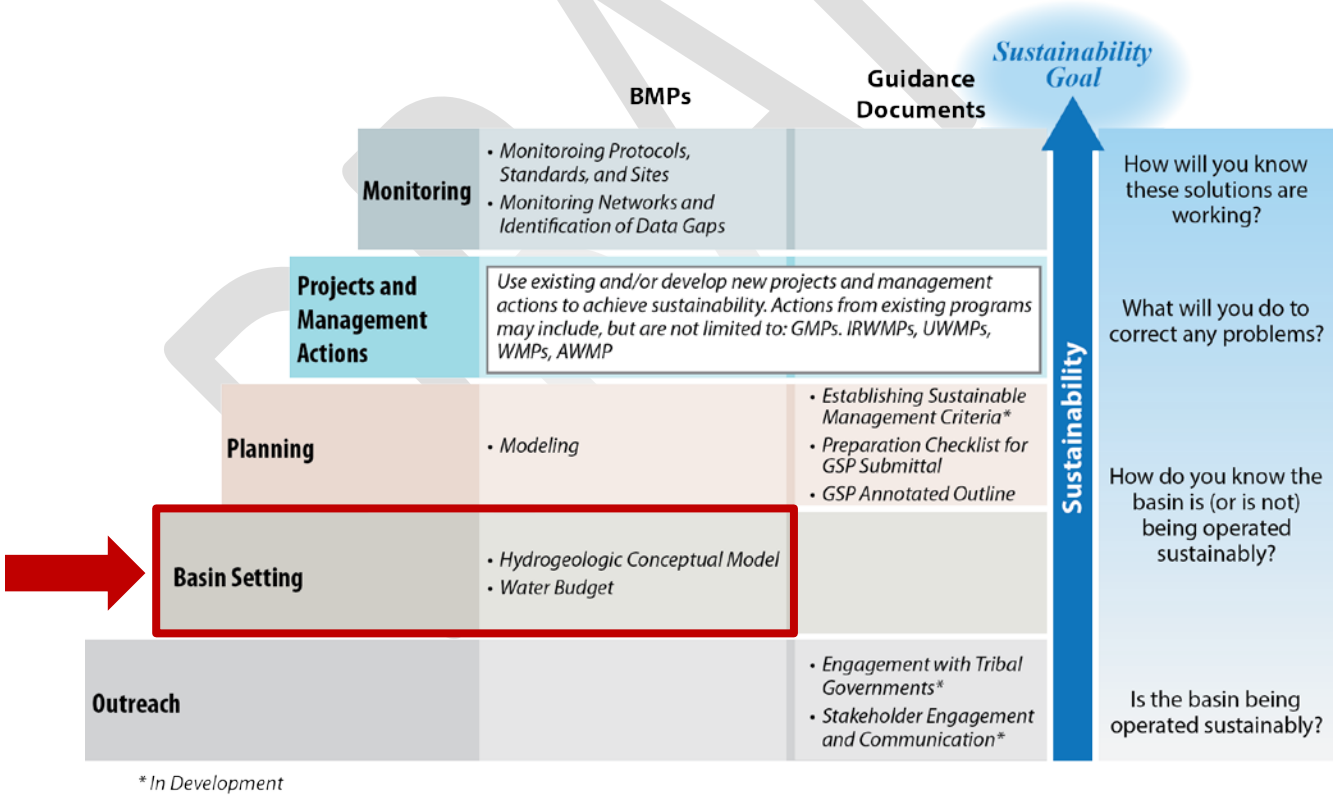

Figure 2 - Steps to Sustainability under SGMA

HCM development is the first step to understanding and conveying the GSP basin setting. The HCM is also linked to other GSP components (and applicable related BMPs) as illustrated **Figure 3**. For example, the HCM supports the development of the monitoring networks and activities needed to better understand the distribution and movement of water within a basin, which leads to the initial development and quantification of a water budget. Once the HCM and water budget have been developed, a mathematical (analytical or numerical) model may be built to further evaluate sustainability indicators, assess the probability of future undesirable results, and support basin management decisions as necessary to avoid the occurrence of undesirable results.

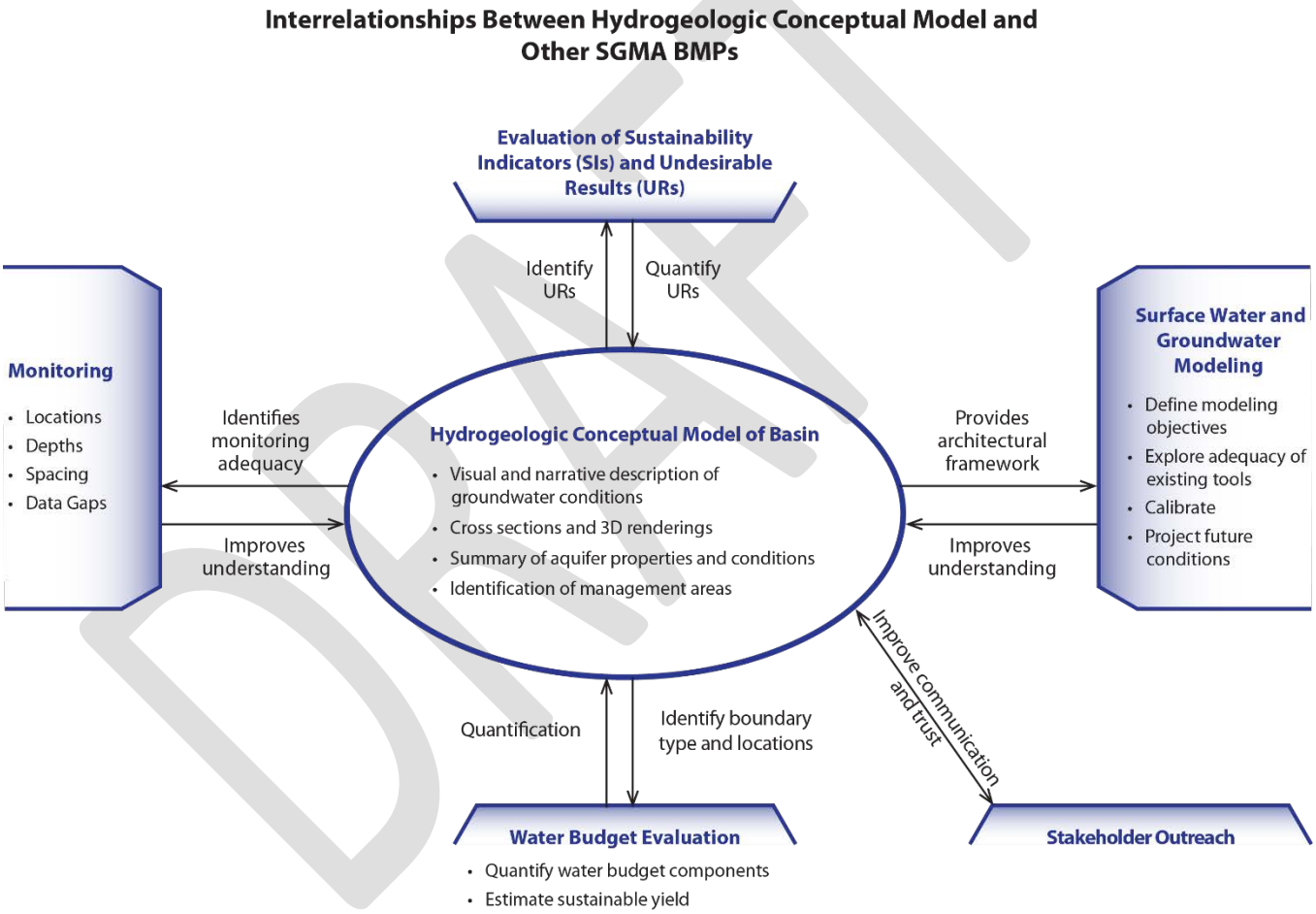

Figure 3 – Interrelationship between HCM and Other BMPs

5. TECHNICAL ASSISTANCE

This section provides technical assistance to support the development of a basin HCM under SGMA and the Regulations including potential sources of information and relevant datasets that can be used to develop each HCM requirement. As described in the Regulations section 354.12, the Basin Setting shall be prepared by or under the direction of a professional geologist or professional engineer.

CHARACTERIZING THE PHYSICAL COMPONENTS

Each section below is related to the specific Regulation requirements and provides additional technical assistance for the GSA's consideration.

§354.14 (b)(1): The regional geologic and structural setting of the basin including the immediate surrounding area, as necessary for geologic consistency.

The regional geologic and structural setting of a basin describes the distribution, extent, and characteristics of the geologic materials present in the basin along with the location and nature of significant structural features such as faults and bedrock outcrops that can influence groundwater behavior in the basin. This type of information can often be found in existing geologic maps and documents published by the Department (specifically Bulletin 118 and 160), the United States Geological Survey (USGS), and other local government agencies (references are also provided in Section 7). Groundwater Management Plans and other technical reports prepared for the basin may also include information of this type.

§354.14 (b)(2): Lateral basin boundaries, including major geologic features that significantly affect groundwater flow.

Basin boundaries are often geologically controlled and may include bedrock boundaries that define the margins of the alluvial groundwater aquifer system, and therefore represent barriers to groundwater flow. For a map of the Department's Bulletin 118 groundwater basins and subbasins refer to the Department's basin boundary website.

Other basin boundaries may include rivers and streams, or structural features such as faults. Information on these types of boundaries can also be found in reports prepared by state (California Geological Survey) or federal agencies (USGS) or by local agencies or districts. In addition, the presence of seawater along the coastal margin can also reflect the boundary of a coastal basin.

§354.14 (b)(3): Definable bottom of the basin

Several difference techniques or types of existing information can be used in the evaluation of the definable bottom of the basin and extent of freshwater.

Defining the Basin Bottom based on Physical Properties

The bottom of the basin may be defined as the depth to bedrock also recognized as the top of bedrock below which no significant groundwater storage occurs. This type of information may be found from reviewing geologic logs from wells drilled for water extraction, as well as from oil and gas exploration wells which tend to be drilled deeper into the aquifer.

Defining the Basin Bottom based on Field Techniques

Common field techniques used to define the bottom of alluvial basins can be subdivided into techniques utilizing direct measurements and those utilizing indirect measurements. The most common ones are listed below.

Direct measurement approaches typically involve drilling of multiple wells through the freshwater bearing alluvial aquifer sediments and into the underlying lithologic units whether it be bedrock, or alluvium containing groundwater that does not meet the criteria for potable water or an USDW. Once each borehole has been constructed, several different approaches can be taken to estimate the depth to the basin bottom at that location. Compilation of data from multiple wells can then be used to prepare a contour map of the depth to the basin bottom. Typical direct techniques include:

- Installation of multi-port well systems or installation of a nested well array
- Continuous profiling of lithology/groundwater quality using TDS, conductivity, or other downhole geophysical techniques
- Mapping depth to bedrock from borehole

Indirect measurement approaches are typically employed along the ground surface or from helicopters or fixed-wing aircraft. The most common methods used are geophysical techniques or surveys. Typical geophysical techniques that can be used to estimate bedrock depth or groundwater quality profiles include:

- Seismic refraction/reflection surveys
- Gravity surveys
- Magnetic surveys
- Resistivity surveys
- Radar, including ground penetrating radar
- Electromagnetic techniques

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§354.14 (b)(4): Principal aquifers and aquitards, including the following information:
(A) Formation names, if defined.
(B) Physical properties of aquifers and aquitards, including the vertical and lateral extent, hydraulic conductivity, and storativity, which may be based on existing technical studies or other best available information.
(C) Structural properties of the basin that restrict groundwater flow within the principal aquifers, including information regarding stratigraphic changes, truncation of units, or other features.
(D) General water quality of the principal aquifers, which may be based on information derived from existing technical studies or regulatory programs.
(E) Identification of the primary use or uses of each aquifer, such as domestic, irrigation, or municipal water supply.

Aquifer information is available in geologic reports from the Department and the USGS, as well as Bulletin 118 and local groundwater management plans and groundwater studies. Links to applicable reports are provided below. The USGS maintains very detailed reports and datasets for groundwater quality throughout the state that can be downloaded from their California Water Science Website (http://ca.water.usgs.gov/). The State Water Quality Control Board also collects and maintains groundwater quality data, accessible through their GeoTracker GAMA website. (http://www.waterboards.ca.gov/gama/geotracker_gama.shtml)

In many basins of the Central Valley, freshwater is underlain by saltier or brackish water that is a remnant of the marine conditions that were present when the Valley was flooded in the geologic past. Several standards exist that can be used to define the base of freshwater:

- Base of freshwater maps in the Central Valley published by the Department
- SWRCB secondary water quality standards
- United States Environmental Protection Agency (US EPA) definition for Underground Source of Drinking Water (USDW)

The Department plans to release a freshwater map for the Central Valley that depicts the useable bottom of the alluvial aquifer. This map assumes that the base of freshwater is defined by the Title 22 SWRCB upper secondary maximum contaminant level recommendation of 1,000 milligrams per liter (mg/L) total dissolved solids (TDS).

The USGS has two base of fresh water maps available in the Central Valley based on 3,000 mg/L TDS.

An alternative threshold available to define the bottom of the groundwater basin is the US EPA USDW standard of less than 10,000 mg/L TDS. In some basins, oil and gas aquifers underlie the potable alluvial aquifer or USDW (defined as < 10,000 ppm total dissolved solids in Title 40, Section 144.3, of the Code of Federal Regulations). In basins where produced water from underlying oil and gas operations is beneficially used within the basin, or injected into the basin's USDW, the HCM can further characterize the geologic boundaries that separate the USDW from the oil and gas aquifers, and identify the "exempted aquifer" portion of the groundwater basin that has been permitted for underground injection control by the State Water Resources Control Board or the Division of Oil, Gas and Geothermal Resources (DOGGR).

Uses of groundwater can be found within agricultural water management plans (AWMP) and urban water management plans (UWMP) which detail the use of water by agency and by types of beneficial uses.

§354.14 (b)(5): Identification of data gaps and uncertainty within the hydrogeologic conceptual model.

An assessment of the uncertainty in the HCM components along with the identification of data gaps of the physical system and water use practices in the basin are all necessary elements of the HCM. Typical data gaps and uncertainties related to the HCM include the hydraulic properties of the aquifer and aquitard materials, the depth and thickness of various geologic layers, and adequate geographic distribution of groundwater quality data, among others. It is important to adequately evaluate data gaps and uncertainties within a HCM as these data gaps often drive the types and locations of monitoring that needs to be conducted to reduce uncertainties in these conceptual model components.

For example, a portion of a groundwater basin may not be well characterized from previous studies and historic monitoring activities, and therefore there is less readily available information to define the HCM in that portion of the basin. Specific data collection activities to address these data gaps could then be considered in the development of the GSP.

§354.14 (c): The hydrogeologic conceptual model shall be represented graphically by at least two scaled cross-sections that display the information required by this section and are sufficient to depict major stratigraphic and structural features in the basin.

In addition to the narrative description of the HCM, another Regulation requirement is to include graphical representations of the HCM components in the form of at least two geologic cross-sections. A cross-section depicts the vertical layering of the geology and

major subsurface structural features in a basin in addition to other HCM features such as the general location and depth of existing monitoring and production wells, the interaction of streams with the aquifer, etc.

The locations selected for cross-section development in a basin are best informed by the sustainability indicators most critical to that basin, as well as the potential for undesirable results to occur. For example, if subsidence is a known issue in a basin, construction of cross-section(s) may be focused in areas where subsidence has occurred or is at risk of occurring. An example of a cross-section is provided below in **Figure 4**.

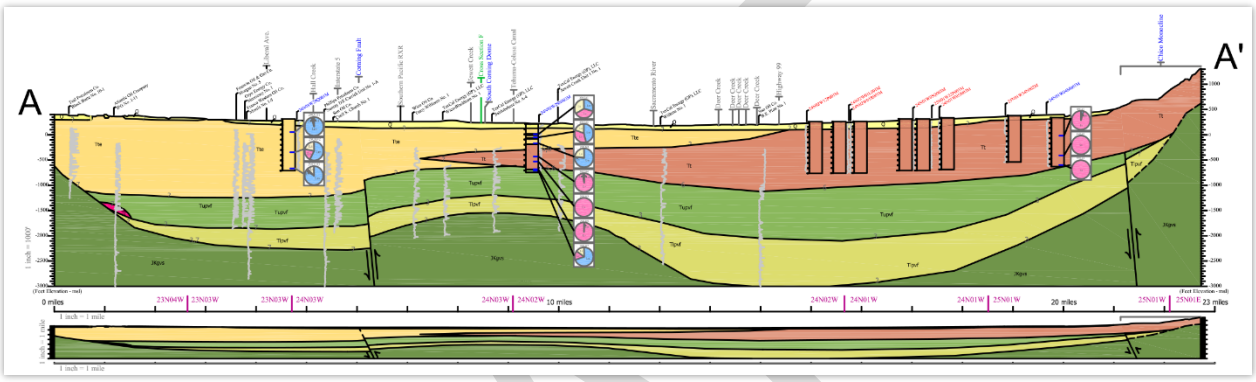

Figure 4 – Example Scaled Cross-Section

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MAPPING REQUIREMENTS

§354.14 (c): (b) The hydrogeologic conceptual model shall be summarized in a written description that includes the following:
(1) The regional geologic and structural setting of the basin including the immediate surrounding area, as necessary for geologic consistency.
(2) Lateral basin boundaries, including major geologic features that significantly affect groundwater flow.
(3) The definable bottom of the basin.
(4) Principal aquifers and aquitards, including the following information:
(A) Formation names, if defined.
(B) Physical properties of aquifers and aquitards, including the vertical and lateral extent, hydraulic conductivity, and storativity, which may be based on existing technical studies or other best available information.
(C) Structural properties of the basin that restrict groundwater flow within the principal aquifers, including information regarding stratigraphic changes, truncation of units, or other features.
(D) General water quality of the principal aquifers, which may be based on information derived from existing technical studies or regulatory programs.
(E) Identification of the primary use or uses of each aquifer, such as domestic, irrigation, or municipal water supply.

Geographical representations of the distribution of major data elements in a groundwater basin in map form helps illustrate the layout of data and information presented in the HCM. The data for these maps are generally available from various sources such as GIS Shapefiles that can be overlain on a basin-wide base map.

As stated in the Regulations, the following physical characteristics of the basin need to be displayed on maps. Information is provided on the types of datasets readily available for mapping.

- Topographic information can be found from online USGS topographic maps or more detailed high resolution Digital Elevation Model (DEM) mapping GIS datasets. There are several sources of topographic and DEMs available online, such as the ones provided in Section 8.

- In addition, the ESRI ArcGIS platform also includes DEM data available for use in conjunction with the ESRI GIS software.

- Surficial Geologic information can be downloaded from the California Geological Survey (CGS) and USGS from their interactive mapping tool.
    - (CGS - http://maps.conservation.ca.gov/cgs/gmc/)
    - (USGS - http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html)

  The map that is produced to illustrate the surficial geology of the basin shall also include the location of the cross-sections.

- The National Resource Conservation Service (NRCS; part of the USDA) maintains soil data and Shapefiles nationwide on a county basis downloadable at no charge from their website:
  http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx.
  For additional related soil characteristics in California, see the UC Davis soil interactive maps (http://casoilresource.lawr.ucdavis.edu/).

- Recharge and discharge areas of groundwater are not always well mapped. This type of information may be available from local and regional groundwater management planning documents, or larger reports form the Department and USGS. Additional recharge maps in California have been developed by UC Davis (get official title) – The following link is to their interactive recharge map http://casoilresource.lawr.ucdavis.edu/sagbi/

- Surface water mapping data can be downloaded from ESRI base maps within ArcGIS, or downloaded from the National Hydrography Datasets (NHD) datasets: http://viewer.nationalmap.gov/viewer/nhd.html?p=nhd

- Water supplies imported into a basin from state, federal, or local projects need to be mapped for the HCM. This information is generally available from the major suppliers of surface water such as the Department, United States Bureau of Reclamation (USBR), and local water and irrigation districts.

- Groundwater elevation contour maps should be created from water level data collected from wells that are screened within the same principal aquifers.

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An example of a geologic map is provided in **Figure 5** below.

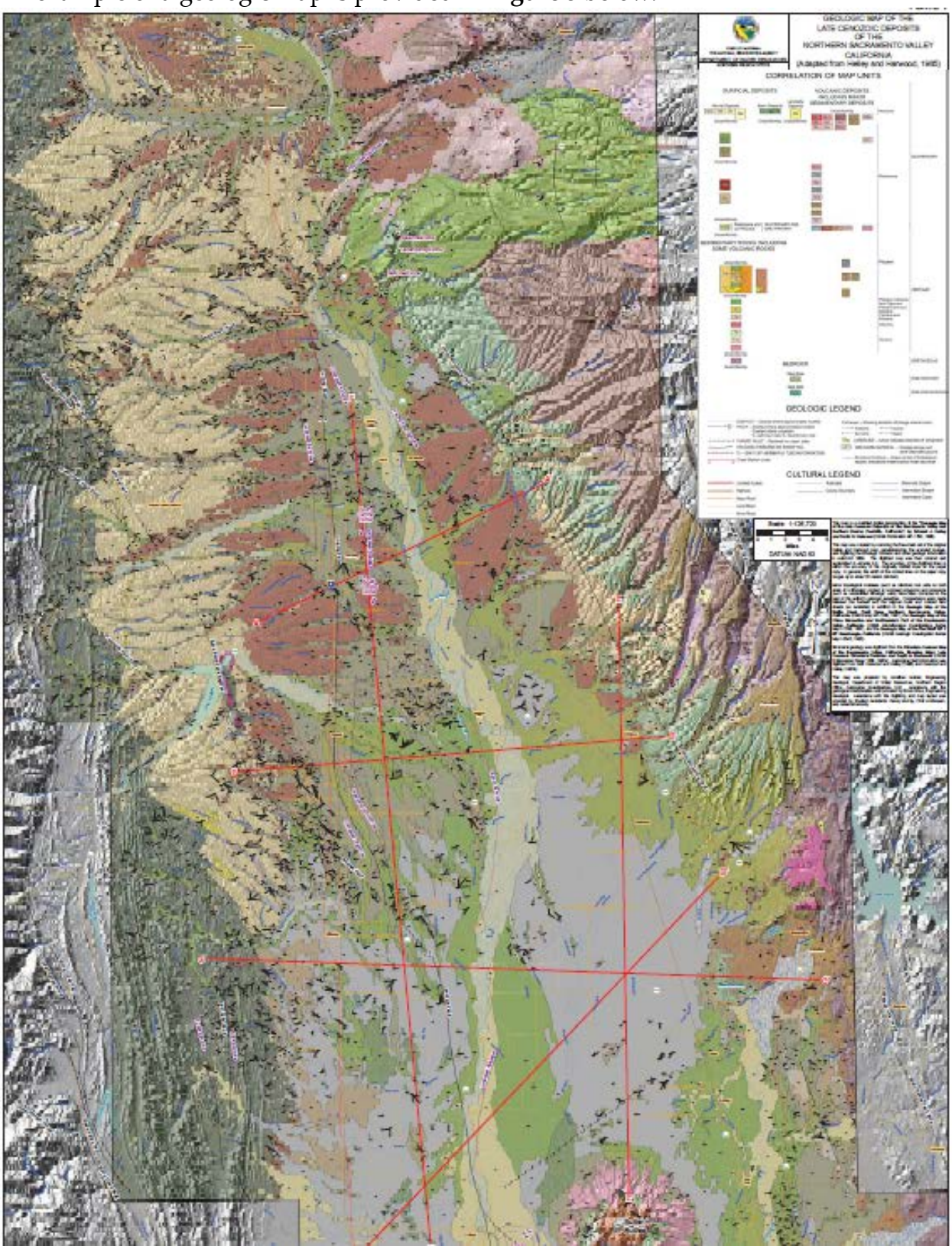

Figure 5 – Example Geologic Map

SUMMARY

In summary, the HCM requirements outlined in the GSP Regulations pertain to two main types of information:

1. Narrative description of the basin, which can be accompanied by a three-dimensional graphic illustration of the HCM to complement the narrative, and
2. At least two scaled cross-sections and geographic maps to provide vertical layering representation and a geographic view of individual datasets, respectively.

The typical flow of graphical HCM development is presented in **Figure 6**. This figure shows the level of technical representation and detail, from basic cartoon-type representation on the left, to a geographic representation map, to a scaled vertical cross-section that provides more subsurface detail for the HCM.

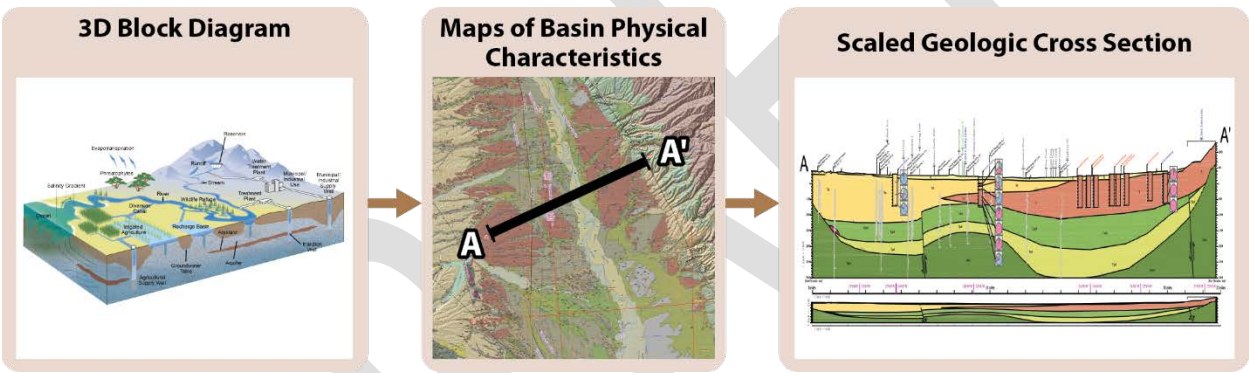

Figure 6 – Steps to Developing Graphic Representations of the HCM.

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6. KEY DEFINITIONS

The key definitions related to HCM development outlined in applicable SGMA code and regulations are provided below for reference.

SGMA Definitions (California Water Code 10721)

- "Groundwater recharge" or "recharge" means the augmentation of groundwater, by natural or artificial means.

- "Recharge area" means the area that supplies water to an aquifer in a groundwater basin.

Groundwater Basin Boundaries Regulations (California Code of Regulations 341)

- "Aquifer" refers to a three-dimensional body of porous and permeable sediment or sedimentary rock that contains sufficient saturated material to yield significant quantities of groundwater to wells and springs, as further defined or characterized in Bulletin 118.

- "Hydrogeologic conceptual model" means a description of the geologic and hydrologic framework governing the occurrence of groundwater and its flow through and across the boundaries of a basin and the general groundwater conditions in a basin or subbasin.

- "Qualified map" means a geologic map of a scale no smaller than 1:250,000 that is published by the U. S. Geological Survey or the California Geological Survey, or is a map published as part of a geologic investigation conducted by a state or federal agency, or is a geologic map prepared and signed by a professional geologist that is acceptable to the Department.

- "Technical study" means a geologic or hydrologic report prepared and published by a state or federal agency, or a study published in a peer-reviewed scientific journal, or a report prepared and signed by a professional geologist or by a professional engineer.

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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" refers to 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.

- "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.

- "Principal aquifers" refer to aquifers or aquifer systems that store, transmit, and yield significant or economic quantities of groundwater to wells, springs, or surface water systems.

- "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.

- "Water source type" represents the source from which water is derived to meet the applied beneficial uses, including groundwater, recycled water, reused water, and surface water sources identified as Central Valley Project, the State Water Project, the Colorado River Project, local supplies, and local imported supplies.

- "Water use sector" refers to categories of water demand based on the general land uses to which the water is applied, including urban, industrial, agricultural, managed wetlands, managed recharge, and native vegetation.

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7. Related Materials

This section provides a list of related materials including associated SGMA BMPs, general references, standards, guidance documents, and selected case studies and examples pertinent to the development of HCMs. For the items identified, available links to access the materials are also provided. In addition, common data sources and links to web-materials are also provided.

Standards

- ASTM D5979 – 96 (2014) Standard Guide for Conceptualization and Characterization of Groundwater Systems

Guidance and References

European Commission. 2010. *Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Guidance Document No. 26. Guidance on Risk Assessment and the Use of Conceptual Models for Groundwater.* Technical Report – 2010-042.

Fulton, J.W., et. al. 2005. *Hydrogeologic Setting and Conceptual Hydrologic Model of the Spring Creek Basin, Centre County, Pennsylvania, June 2005.* USGS Scientific Investigation Report 2005-5091.
http://pubs.usgs.gov/sir/2005/5091/sir2005-5091.pdf

Teresita Betancur V., Carlos Alberto Palacio T. and John Fernando Escobar M. 2012. *Conceptual Models in Hydrogeology, Methodology and Results - A Global Perspective*, Dr. Gholam A. Kazemi (Ed.), ISBN: 978-953-51-0048-5, InTech, Available from: http://www.intechopen.com/books/hydrogeology-a-globalperspective/conceptual-models-in-hydrogeology-methodologies-and-results

Toth, J. 1970. *A conceptual model of the groundwater regime and the hydrogeologic environment.* Journal Of Hydrology, Volume 10, Issue 1. February. doi:10.1016/0022-1694(70)90186-1

Data Sources

- **Geology reports**:
  Geology of the Northern Sacramento Valley, CA:
  http://www.water.ca.gov/pubs/geology/geology_of_the_northern_sacramento_valley__california__june_2014-web/geology_of_the_northern_sacramento_valley__california__june_2014__updated_09_22_2014__website_copy_.pdf

- **DEMs**:
  http://www.opendem.info/opendem_client.html

  http://viewer.nationalmap.gov/basic/?basemap=b1&category=ned,nedsrc&title=3DEP%20View

  http://www.brenorbrophy.com/California-DEM.htm.

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

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Water Budget
Best Management Practice

California Department of Water Resources
Sustainable Groundwater Management Program
1416 Ninth Street
P.O. Box 942836
Sacramento, CA 94236-0001

www.water.ca.gov/groundwater

Water Budget Best Management Practice

1. Objective

The objective of this Best Management Practice (BMP) is to provide technical assistance to Groundwater Sustainability Agencies (GSAs) and other stakeholders on the preparation of a water budget in accordance with requirements of the Groundwater Sustainability Plan (GSP) Emergency Regulations (Regulations) and the long-term groundwater sustainability goal of the Sustainable Groundwater Management Act (SGMA). The information provided in this BMP also identifies available resources to support development, implementation, and reporting of water budget information for the basin.

This BMP includes the following sections:

1. Objective. The objective and brief description of the contents of this BMP.
2. Use and Limitations. A brief description of the use and limitation of this BMP.
3. Water Budget Fundamentals. A description of fundamental water budget concepts
4. Relationship of Water Budgets to other BMPS. A description of how the water budget BMP relates to other BMPs and how water budgets information may be used to support development of other GSP requirements.
5. Technical Assistance. A description of technical assistance to support the development a water budget, potential sources of information, and relevant datasets that can be used to further define each component.
6. Key Definitions. Definitions relevant for this BMP as provided in the GSP Regulations, Basin Boundary Regulations, the SGMA, and DWR Bulletin 118.
7. Related Materials. References and other materials that provide supporting information related to the development of water budget estimates.

2. Use and Limitations

This BMP is only intended to provide technical assistance to GSAs and other stakeholders. GSAs and other stakeholders have the option of using this BMP; the content provided in this BMP does not create any new requirements or obligations for the GSA or other stakeholders.

This BMP does not serve as a substitute for the GSP Regulations and the SGMA. Those submitting a GSP are strongly encouraged to read the GSP Regulations and the SGMA. In addition, using this BMP to develop a GSP does not equate to an approval by the Department.

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3. WATER BUDGET FUNDAMENTALS

Earth's water is moved, stored, and exchanged between the atmosphere, land surface, and the subsurface according to the hydrologic cycle (**Figure 1**). The hydrological cycle begins with evaporation from the ocean. As the evaporated water rises, the water vapor cools, condenses, and ultimately returns to the Earth's surface as precipitation (rain or snow). As the precipitation falls on the land surface, some water may infiltrate into the ground to become groundwater, some water may runoff and contribute to streamflow, some will evaporate, and some may be used by plants and transpired back into the atmosphere to continue the hydrologic cycle (Healy, R.W., et.al., 2007).

The water budget takes into account the storage and movement of water between the three components of the hydrologic cycle, the atmosphere, the land surface, and the subsurface. A water budget is a foundational tool used to compile or estimated water inflows (supplies) and outflows (demands) into an accounting of the total groundwater and surface water entering and leaving a basin, and to calculate the difference between inflows and outflows as a change in the amount of water stored.

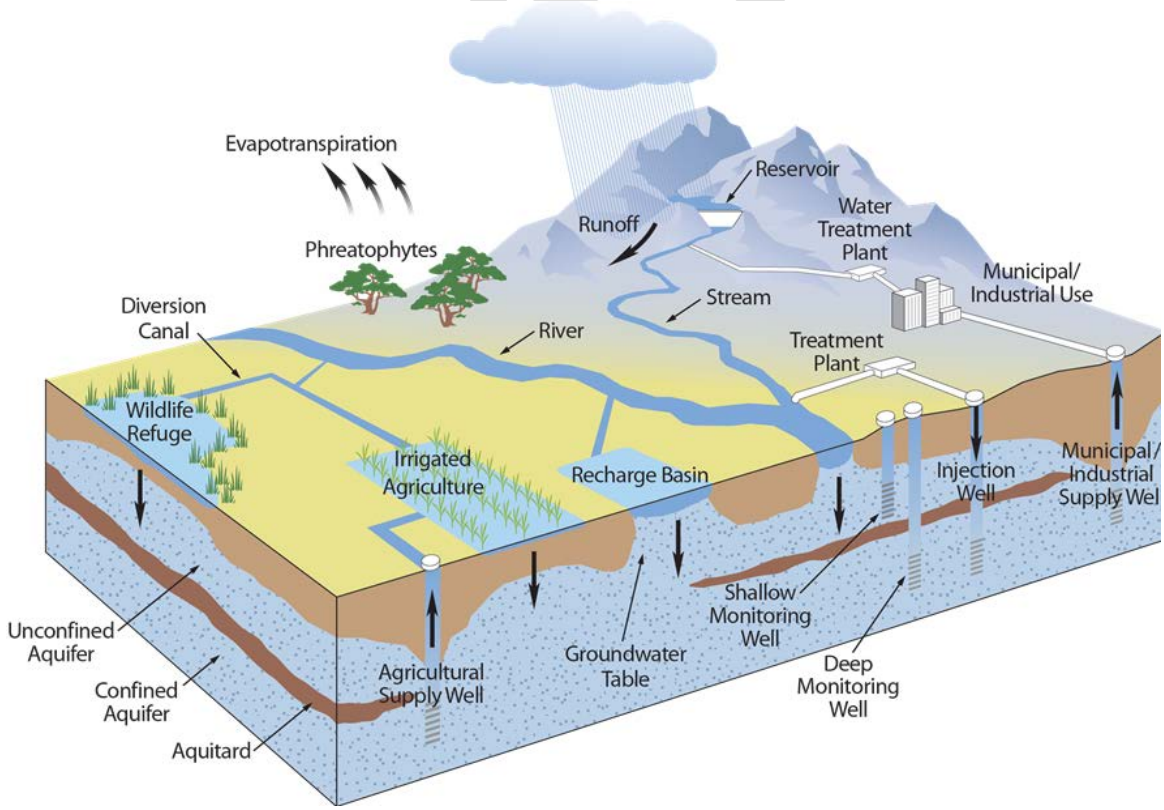

Figure 1 –The Hydrologic Cycle (updated figure in development)

In the world of resource management, it's often said you can't manage what you don't measure. Similar to a checking account, water budget deposits (inflows) and withdrawals (outflows) are tracked and compared over a given time period to help identify if the ending account balance is positive (increase in amount of water stored) or negative (decrease in the amount of water stored). During periods when inflows exceed outflows, the change in volume stored is positive. Conversely, during periods when inflows are less than outflows, the change in aquifer storage is negative. Surpluses from previous budget periods can act as a buffer towards isolated annual water budget deficits, but a series of ongoing negative balances can result in conditions of long-term overdraft.

In some basins, precipitation may be the largest contributor to groundwater recharge. In other basins, leading sources of recharge may stem from infiltration of irrigation water, conveyance systems, septic systems, and various surface water systems (streams, lakes, reservoirs, etc.). In areas where the groundwater levels are above the surface water systems and the direction of groundwater flow is towards the surface water system, the surface water system will receive water from the groundwater system.

In principle, a water budget is a simple concept that measures, evaluates, and takes into consideration water inflow and outflow from all parts of the atmosphere, land surface and subsurface components of a basin. In reality, it can be difficult to accurately measure and account for all components of the water budget for a given area. Some water budget components may be estimated independent of the water budget, while others may be calculated based on the fundamental principle that the difference between basin inflows and outflows are balanced by the change in water in storage. This principle is quantified according to the following water budget equation.

$$\text{Inflows (a, b, c)} - \text{Outflows (a, b, c)} = \text{Change in Storage}$$

Equation 1 – Water Budget Equation

Because groundwater basin inflows and outflows are balance by a change in amount of water in storage, the above equation may be rearranged to calculate, or back into, an unknown component of the water budget equation. For example, if one wishes to determine unknown Outflow component "a", and all other components of the water budget for the groundwater system have been determined, outflow(a) can be calculated by rearranging the above water balance as follows:

$$\text{Outflow (a)} = \text{Inflow (a, b, c)} - \text{Outflow (b, c)} - \text{Change in Storage}$$

To illustrate this example, consider an annual groundwater budget where total inflow from components (a, b, and c) equal 100 units of water, and total outflow from all components other than "a" equals 40 units of water, and the annual change in storage identified through groundwater level measurements is approximately equal to +10 units of water. An estimate of outflow(a) during this period may be calculated from the above water budget equation as follows:

Outflow (a)	=	Inflow (a, b, c)	–	Outflow (b, c)	–	Change in Storage
50 units	=	100 units	–	40 units	–	10 units

Identifying which water budget components are most appropriate to estimate through balancing of the water budget equation will depend on the local ability to independently measure or estimate the remaining water budget components and on the relative importance, versus *uncertainty*, associated with each component in the overall water budget. A higher level of water budget uncertainty often translates to a higher risk that the proposed projects and management actions being evaluated, based on future water budget projections, may not achieve the intended outcome within the intended timeframe.

An important water budget component that needs to be considered when implementing sustainable water resource management is the interaction between groundwater and surface water systems. Groundwater flow naturally moves down-gradient, from areas of groundwater recharge to areas of groundwater discharge. In areas where groundwater levels have dropped below the surface water system, the direction of groundwater flow will be from the surface water system and to the groundwater system. Streams which receive water from the groundwater system are called "gaining" streams and those that lose water to the groundwater system are called "losing" streams (see associated text box). The gaining or losing character of streamflow may be consistent throughout a stream system or it may be highly variable based on stream reach location and the seasonal versus annual changes in local climatic conditions and the water inflow (recharge) or outflow (groundwater extraction) for the basin.

Unless additional inflows or supplies are developed, ongoing increases in groundwater extraction will eventually result in a complete disconnection between the surface water and groundwater systems. Once surface water and groundwater systems become disconnected, all further extraction from the groundwater system will be largely balanced through a decline of groundwater in storage and/or a reduction of subsurface outflow from the basin.

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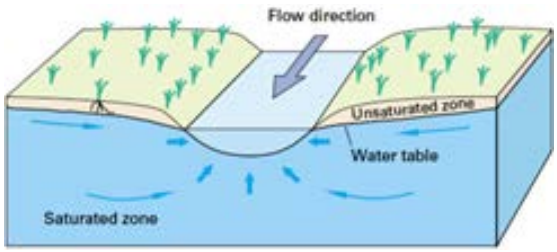
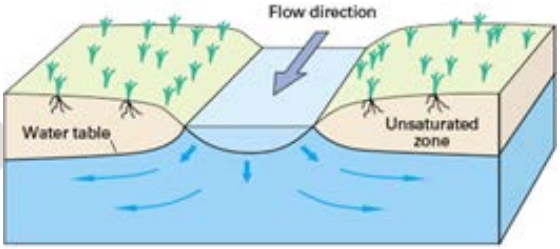
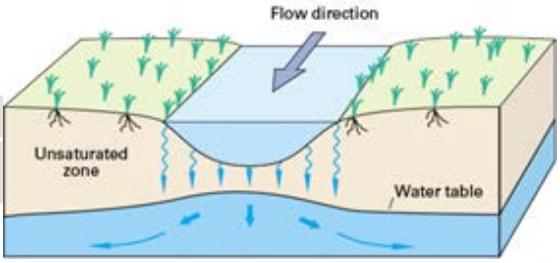
Another important water budget consideration is stream depletion due to groundwater pumping. In basins with *interconnected surface water* systems, if inflows (recharge) to the basin remain fixed while the amount of groundwater extraction increases, the increased volume of groundwater extraction won't necessarily express itself as a one-to-one decline in the volume of aquifer storage. Instead, the amount of groundwater extraction will be offset through the direct or indirect depletion of surface water systems. Shallow production wells in close proximity to surface water systems commonly capture flow directly from the surface water system through induced recharge. Stream depletion associated with pumping wells further removed from surface water systems is more commonly the result of the indirect capture of groundwater flow that would otherwise have discharged to the surface water system sometime in the future. In both situations, streamflow depletion will continue until a new equilibrium between the outflow associated with groundwater extraction and the inflow from surface water depletion is established. The time lag to reach this new equilibrium is directly related to the location and construction of production wells, the thickness and hydrologic conductivity of the aquifer system, and the capacity and timing of the groundwater extraction wells. In many basins, stream depletion due to groundwater extraction will continue for decades prior to reaching a new equilibrium (Barlow, P.M., and Leake, S.A., 2012).



Gaining Stream



Losing Stream



Losing Stream that is Disconnected from the Water Table

(*Source: Winter, T.C., et.al., 1998*)

In order to accurately identify and evaluate the various inflow and outflow components of the water budget, it is important to adequately characterize the interaction between surface water and groundwater systems through sufficient monitoring of groundwater levels and streamflow conditions. The Monitoring Networks and Monitoring Protocol BMPs have additional information regarding GSP monitoring requirements.

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Due to the complexities of characterizing stream depletion due to groundwater extraction, integrated groundwater - surface water models are commonly used to assist with water budget accounting and forecasting. Additional information regarding consideration of models under the GSP Regulations is provided in the Modeling BMP and in Section 5 of this BMP (*Technical Assistance*).

Common Water Budget Uses

Water budget accounting may be very general or very detailed, depending on the hydrologic complexities of the basin, the scale and intent of water budget accounting, and the importance of understanding the individual water budget components to support water resource decision making. Some of the general and GSP Regulation-specific water budget uses and applications are provided below.

General Water Budget Uses:

- Develop an accounting and spatial distribution of inflows and outflows to a watershed, groundwater basin, or management area.
- Identify the primary beneficial uses and users of water and determine which water budget components are most critical to the area.
- Improve communication between the local land use planners and water resource managers.
- Estimate water budget components that are not easily measured or well understood.
- Evaluate how the surface and groundwater systems respond to the seasonal and long-term changes to supplies, demands, and climatic conditions.
- Identify the timing and volume of inflows and outflows that will result in a balanced water budget condition for a management area.
- Develop a water supply assessment of future conditions to better understand the effects of proposed land and water use changes to the local and regional water budget.
- Inform additional monitoring needs.
- Identify the interaction between surface water and groundwater systems.

GSP-Related Water Budget Uses:

The SGMA requires local agencies to develop and implement GSPs that achieve *sustainable groundwater management* by implementing projects and management actions intended to ensure that the basin is operated within its *sustainable yield* by avoiding *undesirable results*. A key component in support of this effort is an accounting and

assessment of the current, historical, and projected water budgets for the basin. The following provides a partial list of GSP-related water budget applications and uses:

- Develop an accounting and spatial distribution of inflows and outflows to the basin by *water source type* and *water use sector,* to identify the main beneficial uses and users and determine which water budget components are most critical to achieving sustainable groundwater management.
- Assess how annual changes in historical inflows, outflows, and change in basin storage vary by *water year type* (hydrology) and water supply reliability.
- Develop an understanding 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.
- Improve coordination and communication between the GSA and water supply or management agencies, local land use approval agencies, and interested parties who may be subject to sustainable groundwater management fees.
- Facilitate coordination of water budget data and methodologies between agencies preparing a GSP within the basin (intra-basin) or between basins (inter-basin).
- Identify data gaps and *uncertainty* associated with key water budget components and develop an understanding of how these gaps and uncertainty may affect implementation of proposed projects and water management actions.
- Evaluate how the surface and groundwater systems respond to the annual historical changes in the water budget inflows and outflows.
- Determine the rate and volume of surface water depletion caused by groundwater use that has adverse impacts on the beneficial uses of the surface water and may lead to undesirable results.
- Identify which water budget situations commonly result in *overdraft conditions*.
- Estimate the sustainable yield for the basin
- Forecast projected inflows and outflows to the basin over the *planning and implementation horizon*.
- Evaluate the effect of proposed projects and management actions on future water budget projections.
- Evaluate future scenarios of water demand uncertainty associated with projected changes in local land use planning, population growth, and climate.
- Inform monitoring requirements.
- Inform development and quantification of sustainable management criteria, such as the *sustainability goal*, undesirable results, *minimum thresholds*, and *measureable objectives*.
- Help identify potential projects and management actions to achieve the sustainability goal for the basin within twenty years of GSP implementation.

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Water Budgets in Reference to the GSP Regulations

As previously mentioned, water budgets are a foundational tool used to account for the various inflows, outflows, and change in storage over a given area and time period. With respect to the GSP Regulations, developing a water budget that accurately identifies and tracks changing inflows and outflows to the basin will be a critically important tool to support decision making regarding the implementation of sustainable management actions and projects.

The simplicity or complexity of water budgets will vary by groundwater basin according to the local complexities of the basin hydrology, physical setting, spatial distribution of supplies and demands, historical water management practices and the presence or absence of undesirable result. Ongoing parallel efforts to monitor and verify water budget components will help improve accuracy; however, some level of uncertainty is inherent in each water budget. An important objective of water budget accounting under the GSP Regulations is to develop an understanding of what level of water budget uncertainty and detail is sufficient for making effective basin management decisions.

The GSP water budget requirements are not intended to be a direct measure of groundwater basin sustainability; rather, the intent is to quantify the water budget in sufficient detail so as to build local understanding of how historical changes to supply, demand, hydrology, population, land use, and climatic conditions have affected the six *sustainability indicators* in the basin and ultimately utilize this information to predict how these same variables may affect or guide future management actions. Building a coordinated understanding of the interrelationship between changing water budget components and aquifer response will allow local water resource managers to effectively identify future management actions and projects most likely to achieve and maintain the sustainability goal for the basin.

Another important aspect of documenting water budget information in the GSP is to ensure DWR is provided with sufficient information to demonstrate the GSP conforms to all the SGMA and GSP Regulation requirements and, when implemented, is likely to achieve the sustainability goal in the basin within 20 years of the GSP implementation.

4. RELATIONSHIP OF THE WATER BUDGET TO OTHER BMPS

Quantifying the current, historical, and projected water budget for the basin is just one of several interrelated GSP elements the GSAs will use to help understand the basin setting, evaluate groundwater conditions, determine undesirable results, develop

sustainability criteria, establish appropriate monitoring networks, and ultimately identify future projects and management actions that are likely to achieve and maintain the sustainability goal for the basin. **Figure** 2 illustrates the relationship of the water budget BMP to the other BMPs, and to the overall steps towards achieving sustainability under SGMA and the GSP Regulations.

Figure 2 identifies the water budget BMP as part of the Basin Setting portion of the GSP Regulations (§354.12). However, the water budget BMP also directly supports, or is supported, by several other BMPs such as, stakeholder outreach, development of the Hydrogeologic Conceptual Model (HCM), modeling, monitoring networks, monitoring protocols, and establishing sustainable management criteria. Basin monitoring feeds into the understanding of the HCM and groundwater conditions, which helps support the understanding and quantification of the water budget and model development, and ultimately supports evaluation of sustainability indicators, undesirable results, and basin management decisions to achieve the sustainability goal for the basin.

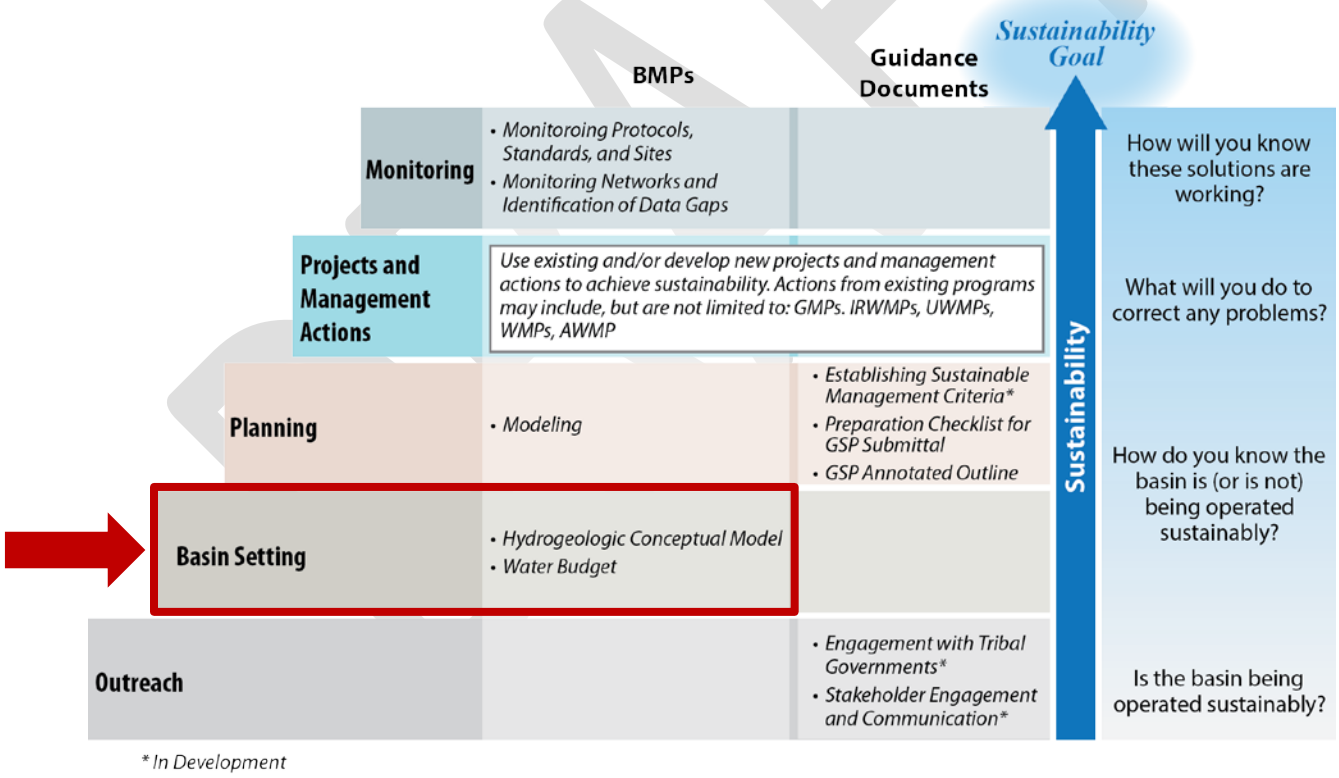

Figure 2 - Steps to Sustainability under SGMA

5. TECHNICAL ASSISTANCE

Implementing sustainable groundwater management under SGMA and the GSP regulations requires development of a water budget that can accurately identify and account for basin inflows, outflows, and change in storage over changing temporal and spatial conditions of supply, demand, and climate. This section provides technical assistance and guidance to support the development of a water budget under SGMA and the GSP Regulations, including potential sources of information, reporting formats, and relevant datasets that can be used to further quantify and estimate the various water budget components.

GENERAL WATER BUDGET REQUIREMENTS:

The following section highlights and provides guidance and technical assistance on the general requirements for all GSP-developed water budgets.

Professional Certification:

> ***Subarticle 2. Basin Setting***
> ***§354.12: Introduction to Basin Setting***
> *Information provided pursuant to this Subarticle shall be prepared by or under the direction of a professional geologist or professional engineer.*

Water budget requirements are provided in Subarticle 2, under the Basin Setting portion of the GSP Regulations. Introduction to the basin setting stipulates that GSP water budget information, and all information provided under Subarticle 2 of the GSP Regulations, is to be prepared by, or under the direction of, a professional geologist or professional engineer. The qualifications and requirements for professional engineers and geologists are governed by the Professional Engineers Act (Business and Professions Code §6700) and the Geologist and Geophysicist Act (Business and Professions Code §8700). Information regarding the professional codes and licensing lookup are provided below.

- **Professional Engineers Act:** http://www.bpelsg.ca.gov/laws/pe_act.pdf
- **Professional Geologist and Geophysicist Act:** http://www.bpelsg.ca.gov/laws/gg_act.pdf
- **Professional License Lookup:** http://www.bpelsg.ca.gov/consumers/lic_lookup.shtml

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Water Budget Data, Information, and Modeling Requirements:

> ***§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.*

Water Budget Data Requirements: GSP Regulations stipulate the need to use the best available information and the *best available science* to quantify the water budget for the basin. Best available information is common terminology that is not defined under SGMA or the GSP Regulations. Best available science refers to 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.

It is understood that initial steps to compile and quantify water budget components may be constrained by GSP timelines and limited funding, and may consequently need to rely on the best available information that is obtainable at the time the GSP is developed. Information describing potential sources of data to support the quantification of water budget components is provided later in this BMP under *Water Budget Data Resources*. This section also includes a listing of data to be provided by the Department as part of DWR's technical assistance in support of GSAs developing GSP water budget components.

As GSAs compile and assess the various water budget components for the basin, it is also understood and expected each GSA will work to identify, prioritized, and fill data gaps as an ongoing effort to further refine water budget data and information based on the best available science.

Successful achievement of the sustainability goal for the basin will ultimately depend on the GSAs ability to manage the basin within the identified uncertainty of water budget information to meet the locally defined objectives and thresholds of the outcome-based sustainable management criteria identified in §354.22. However, the initial approval of the GSP by the Department will require GSAs to gather and present a level and quality of water budget information that will demonstrate the GSP will likely

achieve the sustainability goal for the basin under the substantial compliance requirements in Section §355.2 of the GSP Regulations.

Use of Models to Determine Water Budgets: GSP Regulations do not require the use of a model to quantify and evaluate the projected water budget conditions and the potential impacts to beneficial uses and users of groundwater. However, if a model is not used, the GSA is required to describe in the GSP an equally effective method, tool, or analytical model to evaluate projected water budget conditions.

Groundwater basins characterized by balanced water budget conditions, an absence of undesirable results, and limited proposed changes to future groundwater demands may be able to identify and describe equally effective methods or tools to quantify and forecast future water budget conditions in sufficient detail to develop sustainable management criteria and meet the overall GSP requirement of substantial compliance.

In most basins subject to SGMA, historical supplies and demands have already adversely impacted one or more sustainability indicators, resulting in undesirable results and a need for a more active approach to sustainable management to mitigate or curtail potential escalation of undesirable results in the future. In addition, basins with *interconnected surface water* systems or complex spatial and temporal variations in water budget components, will find quantification and forecasting of streamflow depletion and other water budget components extremely difficult without the use of a numerical groundwater and surface water model. Modeling results may also be an effective tool for outreach and communication, and can prove instrumental in analyzing and quantifying some of the more difficult to measure water budget components.

Additional information regarding the requirements, application, and availability of models and modeling data is provided in the Modeling BMP.

Defining Basin Area and Water Budget Systems

> ***§354.18(a):*** *Each Plan shall include a water budget for the basin that provides an accounting and assessment of the total annual volume of groundwater and surface water entering and leaving the basin, including historical, current and projected water budget conditions, and the change in the volume of water stored. Water budget information shall be reported in tabular and graphical form.*

Basin Area: Prior to developing a water budget for the basin, GSAs must first identify the physical boundaries and three dimensional area of the basin as described under the HCM (§354.14) portion of the GSP Regulations. The HCM is based on technical studies

and qualified maps that characterize the physical basin area and the interaction of the surface water and groundwater systems in the basin. It requires evaluation of the regional geology, structural setting, water quality, principal aquifers, and principal aquitards in the basin. Additional information regarding development of the HCM may be found in the HCM BMP.

The lateral boundaries of the basin are determined by the Department and conform to those boundaries provided in Bulletin 118. The vertical basin boundary, or definable bottom of the basin, is determined by the GSA and may be delineated by either, 1) a structural barrier to groundwater flow as determined by local geology, or 2) the base of fresh water as determined by ground water quality information. Basin boundaries may be periodically modified through SGMA under §10722.

Surface Water Systems: The surface water system is represented by water on the land surface within the lateral boundaries of the basin. Surface water systems include lakes, streams, canals, springs, and conveyance systems. Near-surface processes such as infiltration from surface water systems or outflow due to evapotranspiration from the root zone are often included for convenience as part of the surface water accounting. **Figure** 3 illustrates the conceptual basin boundaries, including the surface water and groundwater systems.

Groundwater System: The groundwater system is represented by that portion of the basin from the ground surface to the definable bottom of the basin and extending to the lateral boundary of the basin. The groundwater system will be characterized by one or more *principal aquifers* and represents the physical basin area used to quantify the annual change in volume of groundwater stored, as required in the water budget. The same three-dimensional basin area should also be used for GSAs to optionally identify the volume of groundwater in storage or the groundwater storage capacity, as necessary, to assist in the determination of sustainable yield.

Required components of the water budget include inflows and outflows across the basin boundary, and inflows and outflows to and from the surface water system and the groundwater system. Some inflows and outflows do not cross the basin boundary, but instead represent exchanges between these systems (**Figure** 3). In **Figure** 3, the solid black line represents the water budget accounting volume encompassing the surface and groundwater systems, while the dashed line represents the interface between the surface water system and the groundwater system. Solid arrows represent inflows to and outflows from the basin, while dashed arrows represent exchanges between the surface water and groundwater systems within the basin.

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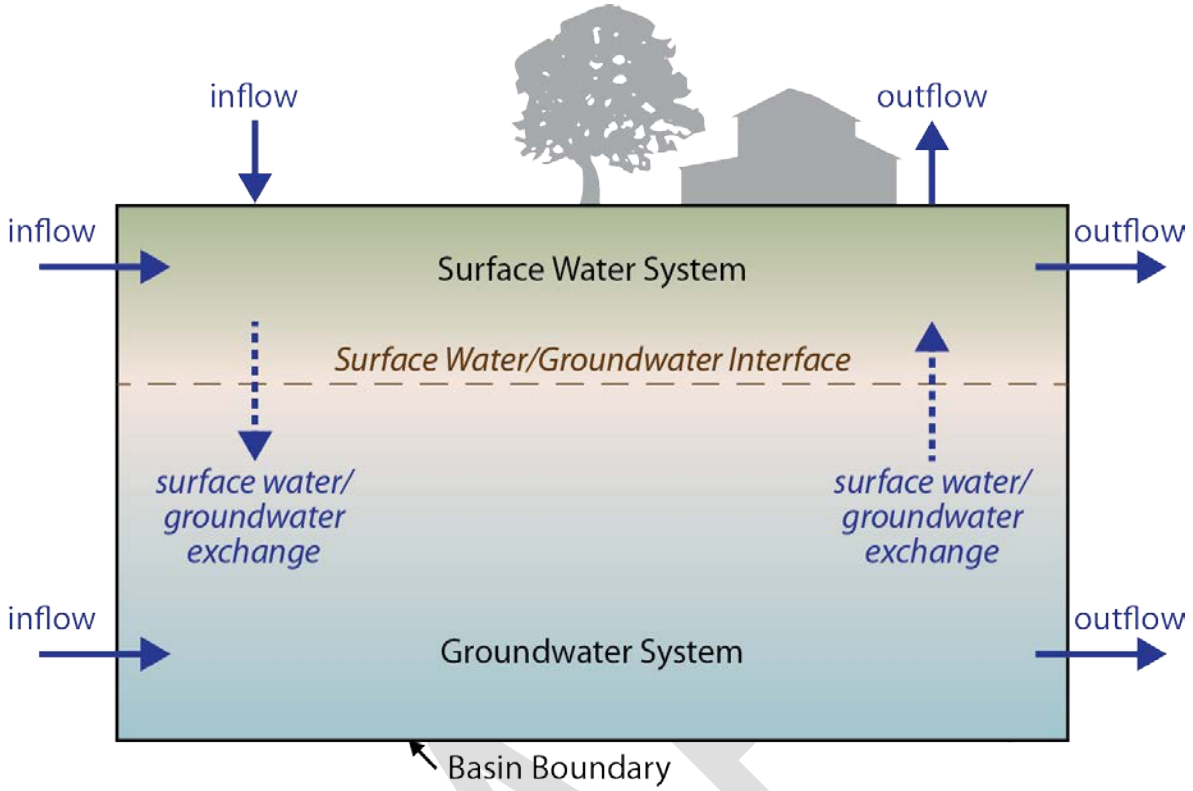

Figure 3 - Conceptual Basin Boundary, Surface Water and Groundwater Systems, and Inflows and Outflows

Management Areas: Although the GSP Regulations only require quantification of water budget components for the basin, each GSA may choose to further subdivide and report the water budget by one or more management areas to help facilitate GSP implementation, and to help demonstrate GSP substantial compliance to the Department under §355.2 of the GSP Regulations. Management areas are defined and further characterized in Sections §351 and §354.20 of the GSP Regulations. If management areas are developed, additional information and graphics will be needed to define the name, location, and distribution of management areas within the basin. Graphical representation of the physical setting and characteristics of the basin will be largely provided under HCM requirements in §354.14 of the Regulations.

Coordination of Water Budget Data: When one or more GSPs are being develop for the same basin by one or more GSAs, Section §10727(b)(3) of the SGMA requires a coordination agreement between all GSAs developing a GSP within the basin. In addition, Section §10727.6 of the SGMA requires that each GSP developed by the coordinating agencies utilize the same data and methodologies for the following water budget related components:

- Groundwater extraction data
- Surface water supply
- Total water use
- Change in groundwater storage
- Water budget
- Sustainable Yield

When presenting water budget information for basins with one or more GSPs, all the GSPs for the basin need to identify and describe the existing coordination agreements for the basin, the point of contact of each agreement, how the individual coordinating agencies have taken steps to ensure that each GSP for the basin is utilizing the same data and methodologies for the above water budget components, and how the GSP is fulfilling the coordination requirements identified under Section §357.4 of the GSP Regulations.

In addition, for many basins within the Central Valley, Salinas Valley and elsewhere, not all the lateral basin boundaries serve as a barrier to groundwater or surface water flow. In situations where a basin is adjacent or contiguous to one or more additional basins, or when a stream or river serve as the lateral boundary between two basins, it is highly recommended that water budget accounting in adjacent basins develop "interbasin" agreements to facilitate exchange of water budget information, as described in Section §357.2 of the GSP Regulations.

Accurate accounting and water budget forecasting of surface water and groundwater flows across the basin boundaries, application of best available data and the best available science, and the GSP Regulation requirement that GSP implementation will not adversely affect an adjacent basin's ability to implement its GSP or impede the ability to achieve its sustainability goal, will in most cases also require coordination and sharing of water budget data and assumptions between contiguous basins. In these interbasin situations, it is highly recommend that water budget accounting should describe how individual coordinating agencies have taken steps to ensure that each GSP for the basin is utilizing similar data and compatible methodologies for the water budget components identified under interbasin coordination in Section §357.4 of the GSP Regulations.

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Accounting and Quantification of Water Budget Components:

> *§354.18(b): The water budget shall quantify the following, either through direct measurements or estimates based on data:*
>
> *(1) Total surface water entering and leaving a basin by water source type.*
>
> *(2) Inflow to the groundwater system by water source type, including subsurface groundwater inflow and infiltration of precipitation, applied water, and surface water systems, such as lakes, streams, rivers, canals, springs and conveyance systems.*
>
> *(3) Outflows from the groundwater system by water use sector, including evapotranspiration, groundwater extraction, groundwater discharge to surface water sources, and subsurface groundwater outflow.*
>
> *(4) The change in the annual volume of groundwater in storage between seasonal high conditions.*
>
> *(5) If overdraft conditions occur, as defined in Bulletin 118, the water budget shall include a quantification of overdraft over a period of years during which water year and water supply conditions approximate average conditions.*
>
> *(6) The water year type associated with the annual supply, demand, and change in groundwater stored.*
>
> *(7) An estimate of sustainable yield for the basin*

Accounting of the water budget components includes an annual quantification of inflows and outflows across the basin boundaries, inflows and outflows to and from the surface water and groundwater systems, and the associated change in groundwater in storage. Surface water entering and leaving the basin and inflow to the groundwater system must be accounted for by *water source type*. Outflows from the groundwater system must be accounted for by *water use sector*. Accounting of the annual change in surface water and groundwater in storage is also required under the GSP Regulations.

The GSP water budget components are conceptually illustrated in Figure 4. Figure 4 expands upon Figure 3 by depicting the individual water budget components identified by the GSP Regulation. In the same manner as Figure 3, the solid black line represents the basin boundary, while the dashed line represents the interface between the surface water system and the groundwater system. Solid arrows represent inflows to and outflows from the basin, while dashed arrows represent exchanges between the surface water and groundwater systems within the basin.

Quantification of the basin inflows, outflows, and change in storage is to be generated through direct measurements or estimates based on data. As previously discussed, quantification of the water budget must also be based on best available information and best available science. Methods to quantify water budget components may vary

depending on basin-specific conditions, best available information, and the consideration of uncertainties associated with each method. It is anticipated that the quantification methods may change over time as monitoring networks are improved and data gaps are filled.

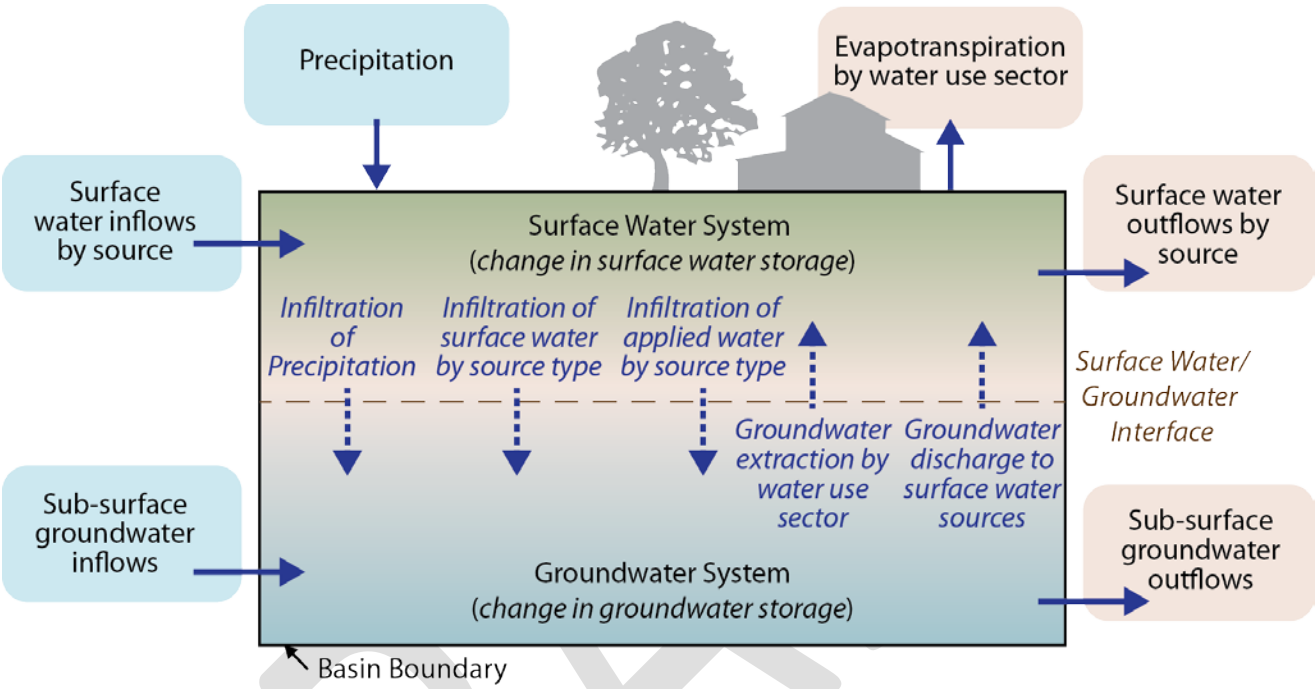

Figure 4 – Required Water Budget Components

Additional discussion regarding consideration of direct and indirect approaches to quantify water budget components is provided below under *Identifying and Selecting Methodologies to Estimate Water Budget Components*. Information describing potential data sources to support quantification of change in storage is provided later in this section under *Water Budget Data Resources*, including data to be provided by DWR specifically for the purpose of supporting GSP water budget development.

A breakdown of the specific water budget components requirements listed in Section §354.18(b) of the GSP Regulations is provided below.

(1) Total surface water entering and leaving the basin by water source type.

Surface water entering (inflow) and leaving (outflow) the basin is required to be annually quantified for the basin as a total annual volume in acre-feet per year (af/yr) according to the surface water body (name) and the water sources type. Water source type represents the source from which water is derived to meet the applied beneficial uses. Surface water sources should be identified as one of the following:

- Central Valley Project,
- State Water Project,
- Colorado River Project,
- Local supplies, and
- Local imported supplies.

Much of the surface water flowing into the basin is diverted and applied to meet the beneficial uses within the basin. It is recommended that total annual volume of applied surface water (af/yr) also be quantified according to the appropriate water use sector and the total applied water area (acres). For urban water suppliers, the diverted and applied surface water use should include the total annual volume of use for all urban areas within the basin and the average daily gallons of per capita use (gpcd) for the basin. A breakdown of the applied surface water accounting by basin and by water use sector is provided as follows:

- Urban: total annual volume (af/yr) and the average daily per capita use (gpcd).
- Industrial: total annual volume (af/yr) and total applied water area (acres)
- Agricultural: total annual volume (af/yr) and applied water area (acres)
- Managed Wetlands: total annual volume (af/yr) and applied water area (acres)
- Managed Recharge: total annual volume (af/yr) and applied water area (acres)
- Native Vegetation: total annual volume (af/yr) and applied water area (acres)
- Other (as needed): total annual volume (af/yr) and applied water area (acres)

Applied surface water supply may be further subdivided by *management area* as needed to facilitate water budget accounting and to help demonstrate GSP substantial compliance under Section §355.2 of the GSP Regulations.

Surface Water Available for Groundwater Recharge or In-Lieu Use: In addition to the above GSP Regulation requirement to include an accounting of the total surface water entering and leaving the basin, Section §10727.2(d)(5) of SGMA requires the GSP include a description of the surface water supply used, or available for use, for groundwater recharge or in-lieu use.

As part of the Department's technical assistance under SGMA, the Department is currently estimating, based on available information, the volume of water available for replenishment of the groundwater in the State. The statewide evaluation of water available for replenishment is being conducted on a regional basis. The regional estimates of water available for replenishment provided by the Department will not fulfill the SGMA requirement to identify the surface water supply used, or available for use, for groundwater recharge or in-lieu use at the basin level. However, the

Department's documentation of the process, methods, and sources of data for evaluating surface water supply availability should provide valuable assistance to GSAs who are also estimating surface water supply available for recharge information at the basin level. The Department's report on Water Available for Replenishment is currently under development. A draft release is scheduled for the end of December, 2016.

(2) Inflow to the groundwater system by water source type, including subsurface groundwater inflow and infiltration of precipitation, applied water, and surface water systems, such as lakes, streams, rivers, canals, springs and conveyance systems.

Inflows to the groundwater system are to be annually quantified for the basin as the total annual volume (af/yr) according to the water source type and water use sector.

An accounting of inflows to the groundwater systems should include, but may not be limited to, the following:

- Subsurface Groundwater Inflow (af/yr)
- Infiltration of precipitation (af/yr)
- Infiltration of applied water (af/yr)
- Infiltration from surface water systems (af/yr).

Infiltration of oil field-produced water should be identified as a separate source of imported source of water, if applicable (see text box discussion of oil field-produced water considerations).

For areas having Urban Water Management Plans (UWMP) or Agricultural Water Management Plans (AWMP), the GSP water budget assessment of urban and agricultural areas should be consistent with the water

Oil & Gas Field-Produced Water

Significant quantities of water are produced as a by-product of oil and gas extraction in some basins. Where applicable, it is important to characterize this water in terms of aquifer depletion, beneficial use, quality, and reliability.

- Aquifer Depletion. Oil and gas-bearing formations are often at a depth below the groundwater flow system. Is the quantity of produced water accounted for in the hydrogeologic conceptual model? Will depletion of this water cause Undesirable Results such as subsidence?
- Beneficial Use. Describe the uses for the produced water. Is the produced water being supplied as a beneficial use such as irrigation or recharge, or is it being evaporated? If so, it should be included as a water supply type in the water budget accounting.
- Quality. Describe the quality of the produced water, existing use permits, and any treatment processes employed. Describe the use or discharge relative to RWQCB Basin Plan Objectives.
- Reliability. Availability of produced water will fluctuate with oil and gas production. Oil fields have limited production durations which may be incompatible with long-term groundwater sustainability. Oil field-produced water will generally not be an acceptable supply for establishing sustainability, but may be a component of an initial basin recovery effort. The reliability of produced water should be characterized in the GSP if it is being use as a source of supply.

budget reporting in the most recent UWMPs and AWMPs, unless more recent information is available.

(3) ***Outflows from the groundwater system by water use sector, including evapotranspiration, groundwater extraction, groundwater discharge to surface water sources, and subsurface groundwater outflow.***

An annual accounting of groundwater outflow from the basin is to be quantified as the total volume (ac-ft) by water source type and water use sector. Sources of groundwater outflow should include, but may not be limited to, the following:

- Evapotranspiration: (af/yr)
- Groundwater discharge to surface water sources (af/yr)
- Subsurface groundwater outflow (af/yr)
- Groundwater extraction by water use sector:
    - Urban: (af/yr) and (gpcd)
    - Industrial: (af/yr)
    - Agricultural: (af/yr)
    - Managed Wetlands: (af/yr)
    - Managed Recharge: (af/yr)
    - Infiltration from the following: (af/yr)
    - Native vegetation: (af/yr)
    - Other (as needed): Note: if oil and gas production wells are producing or applying water within the basin, as defined in the HCM, an accounting of the produced water is to be included as a source of applied water.

Outflows from the groundwater system may be further subdivided by management area as needed to facilitate water budget accounting and to help demonstrate GSP substantial compliance under Section §355.2 of the GSP Regulations.

(4) The change in the annual volume of groundwater in storage between seasonal high conditions.

In addition to the inflow and outflow components of the water budget, the annual change in the volume of groundwater in storage (af/yr) is required to be provided in tabular and graphical form according to water year type and according to the associated total annual volume of groundwater extraction for the basin. In addition, the GSP should provide some level of discussion regarding the relationship and variation between annual change of groundwater in storage versus annual changes in surface water supply reliability, water year type, water use sector, sustainable yield and overdraft conditions (if present or are potentially present, i.e., negative change in

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annual groundwater storage is occurring, but overdraft conditions are still unconfirmed).

The change in groundwater in storage is to be determined as the total change in storage between *seasonal high* conditions, which typically occurs in the spring. It is recommended that the change in storage estimates be based on observed changes in groundwater levels within the basin. However, change in groundwater storage may also be calculated as the difference between annual inflows and outflows according to the water budget equation in Section 3, where all inflows and outflows can be reliably measured or estimated.

Similar to other water budget components, the method to quantify change in storage will likely vary depending on basin-specific conditions and available information, and include consideration of uncertainties associated with each method.

Assessment of change in storage under future water budget projections will likely require the use and application of a groundwater flow model. If a model is used to estimate future changes in groundwater storage, the modeling requirements and principles identified in the Model BMP should be followed.

Changes in surface water storage (reservoirs, lakes, and ponds) will also be an important water budget component in some basins. For these basins, change in storage should be identified as change in groundwater in storage and change in surface water storage.

The annual change in groundwater storage may also be further subdivided according to *management areas, as* needed, to help facilitate water budget accounting and to help demonstrate GSP substantial compliance under Section §355.2 of the GSP Regulations.

(5) ***If overdraft conditions occur, as defined in Bulletin 118, the water budget shall include a quantification of overdraft over a period of years during which water year and water supply conditions approximate average conditions****.*

The GSP water budget must include an assessment of groundwater overdraft conditions. Determination of overdraft conditions requires the evaluation of current and historical water budget conditions. As described in DWR Bulletin 118, overdraft occurs when groundwater extraction exceeds groundwater recharge over a period of years, resulting in a decrease in groundwater storage.

Overdraft conditions are to be assessed by calculating change in groundwater storage over a period of years during which water year and water supply conditions

approximate average conditions. Assessment of overdraft conditions should include an evaluation of changes in groundwater storage by water year type. For basins without an existing water year index, water year types will be developed, classified, and provided by DWR based on annual precipitation as a percentage of the previous 30-year average precipitation for the basin. Water year classifications will be divided into five categories ranging from wet, above normal, below normal, dry, to critically dry conditions.

Single-year reduction in groundwater storage during critical, dry or below normal water years may not represent overdraft conditions. Reductions in groundwater storage in above normal or wet years or over a period of average water year conditions may indicate overdraft conditions. All annual change in groundwater storage estimates from water budget accounting should be included and discussed in the GSP.

If overdraft conditions are identified, the GSP shall describe projects or management actions, including a quantification of demand reduction or other methods, for the mitigation of overdraft, as required under Section §354.44(b)(2) of the GSP Regulations.

When evaluating if the GSP is likely to achieve the sustainability goal for the basin, the Department will consider whether the GSP includes a reasonable assessment of overdraft conditions and a reasonable means to mitigate overdraft as required under Section §354.4(b)(6) of the GSP Regulations.

(6) The water year type associated with the annual supply, demand, and change in groundwater stored.

In order for local resource managers to develop an understanding of the relationship between changing hydrologic conditions and the associated aquifer response to changing water supply, demand, and storage, the GSP water budget accounting must be reported according to water year type. Even though the GSP Regulations only require annual water budget accounting and reporting, in order for local water resource managers to adequately understand the timing and distribution of water supply and demand and to implement effective water management actions, it is highly recommended that local water budget accounting be conducted on a monthly or more frequent basis. As mentioned in the overdraft discussion, water year types will be developed, classified, and provided by DWR for those basins not having an existing water year index. GSP reporting of supply, demand, and change in groundwater stored according to water year type will help facilitate assessment of overdraft conditions and estimates of sustainable yield for the basin.

(7) An estimate of sustainable yield for the basin

Estimating sustainable yield includes evaluating current, historical, and projected water budget conditions. Sustainable yield is defined in the SGMA legislation and refers to 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. Water budget accounting information should directly support an estimate of sustainable yield. However, by definition, additional information will be needed to clarify how locally developed criteria to define undesirable results supports the estimate of sustainable yield for the basin. Additional information should include an explanation of the relationship or linkage between the water budget information and the sustainability indicators, undesirable results, measureable objectives, and minimum thresholds will be required to support the GSP estimate of sustainable yield.

TABULAR AND GRAPHICAL REPRESENTATION OF THE WATER BUDGET COMPONENTS:

The above water budget information is to be developed in tabular and graphical form. Tabular and graphical presentation of the data may take many forms depending on the sources of water inflow and outflow to the basin and the water use sectors within the basin.

A sample water budget tabulation is illustrated in Table 1. Table 1 includes a listing of required water budget components in to support a complete accounting of groundwater basin inflows and outflows, additional water budget components not explicitly listed in the Regulations may be required for some basins. For example, in basins where treated produced water generated from oil and gas operations is used as a source of supply, the annual volume of the produced water being applied for beneficial use should be quantified and described according to water supply type and water use sector. Although produced water being injected beneath the defined basin bottom does not need to be included in the water budget accounting, a description of the location and annual injection volumes should be described and quantified in the basin setting.

Additional tables depicting a breakdown of water budget accounting by water use sector and water source type will also likely be need in order to better understand the individual supplies and demands for the basin, and the percent of total supply that is met by each water source type. Supplementary example tables are being developed and will be provided as part of the Departments technical assistance.

Multiple graphical depictions of the various water budget components will be needed to fully illustrate the water budget accounting. The graphics should include charts and

maps to show the trends and spatial distribution of the various water budget components. A general graphic summarizing the inflows, outflows and change in storage by water year type will be needed to provide an understanding of the overall water balance for the basin by water year type. In addition, more detailed maps and figures that separately depict basin inflows and outflows by water source type, water use sector, and water year will be needed to better understand the relationship and overall importance of the various water sources and water use sectors.

Water Year:
Water Year Type:

INFLOWS		OUTFLOWS	
Inflow Source	Volume (af/yr)	Outflow Sink	Volume (af/yr)
Surface Water Inflow\1		Surface Water Outflow\1	
Precipitation		Evapotranspiration\4	
Subsurface Groundwater Inflow		Subsurface Groundwater Outflow	
Total Basin Inflow		Total Basin Outflow	
Subsurface Groundwater Inflow		Subsurface Groundwater Outflow	
Infiltration of Precipitation		Groundwater Extraction\1	
Infiltration from Surface Water Systems\2		Discharge to surface water systems\2	
Infiltration of Applied Water\3			
Total Groundwater Inflow		Total Groundwater Outflow	
	Change in Surface Storage Volume		
	Change in Groundwater Volume		

\1 by water source type
\2 lakes, streams, canals, springs, conveyance systems
\3 includes applied surface water, groundwater, recycled water, and reused water
\4 by water use sector

Table 1 - Simple Water Budget Tabulation Example

A sample paired bar graphic illustrating balanced water budgets for both the basin and the groundwater system including the required water budget components is presented as Figure 5. Each pair of bars shows inflows on the left and outflows on the right. In this illustration, more water comes into the basin than flows out during the water year, with the difference stored as carry-over surface storage. Similarly, groundwater outflows exceed groundwater inflows, resulting in an annual reduction in groundwater storage.

Additional graphical examples depicting water supplies and water use by water year type are provided in the Department's *California Water Plan Update 2013* (*Volume 1, Chapter 3, pages 3-33 - 3-40)*, and the *California Groundwater Update 2013 (Chapter 2, pages*

17-22). Online links to these reports are provided in Section 7, under *Guidance and General References.* Supplementary example graphics are being developed and will be provided as part of the Departments technical assistance.

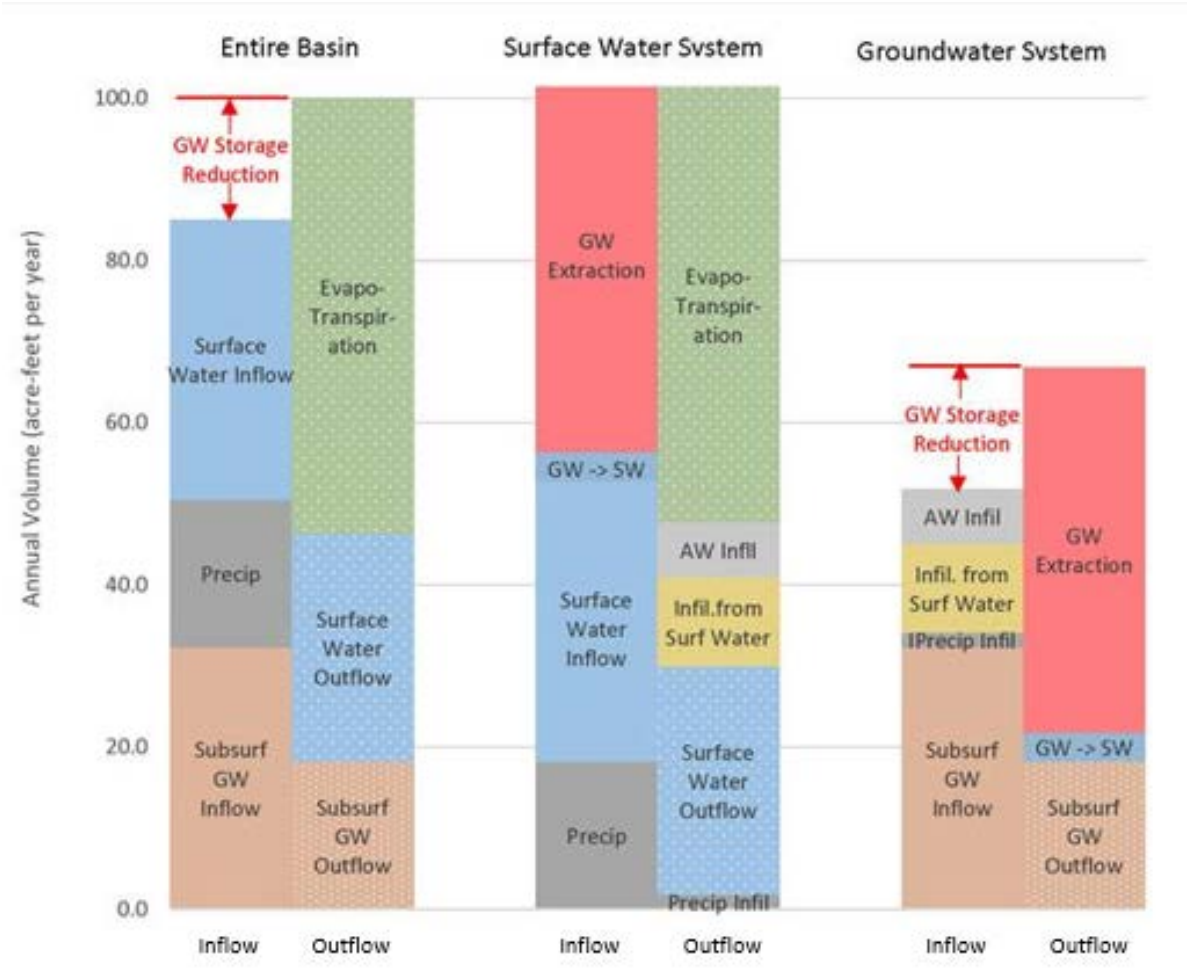

Figure 5 – Paired Bar Water Budgets Illustrating Balanced Water Budget

DEFINING WATER BUDGET TIME FRAMES:

> §354.18(c): Each Plan shall quantify the current, historical, and projected water budget for the basin…

The GSP Regulations require quantification of a water budget for current, historical, and projected basin conditions. A description of the current, historical, and projected water budget requirements are provided below.

Current Water Budget Assessment §354.18(c)(1)

The GSP is required to provide an accounting of current water budget conditions to inform local resource managers and help the Department understand the existing

supply, demand and change in storage under the most recent population, land use, and hydrologic conditions. The current water budget is required to quantify all seven of the general water budget requirements listed in §354.18(b).

Historical Water Budget Assessment §354.18(c)(2)

The historical water budget accounting is required to evaluate how past water supply availability or reliability has previously affected aquifer conditions and the ability of the local resource managers to operate the basin within sustainable yield. The historical assessment is specifically required to include the following:

- Utilize the most recent ten years of surface water supply information to quantify the availability or reliability of historical surface water supply deliveries. The reliability of historical surface water deliveries is to be calculated based on the planned versus actual annual surface water deliveries, by surface water source, and water year type.
- Quantify and assess the most recent ten years of historical water budget information by water year type. The ten years of historical water budget information is to be used to help estimate the projected future water budgets and future aquifer response to the sustainable groundwater management projects and actions being proposed over the GSP planning and implementation horizon. The intent of the historical water budget evaluation is also to provide the necessary data and information to calibrate the tools or methods used to project future water budget conditions. Depending on the historical variability of supplies, demands, and land use; the level of historical groundwater monitoring in the basin; and the type of tool being used to estimate future projects and associated aquifer response; additional historical water budget information may be needed for adequate calibration.
- Utilizing the most recent ten years of water supply reliability and water budget information, the GSP is required to describe how the historical conditions concerning hydrology, water demand, and surface water supply availability or reliability have impacted the ability of the local agency to operate the basin within sustainable yield. To assist in the evaluation, it is recommended that the assessment of safe yield be evaluated by water year type, as previously described in *An estimate of sustainable yield for the basin.*

Projected Water Budget Assessment §354.18(c)(3)

The projected water budget accounting is used to quantify the estimated future baseline conditions of supply, demand, and aquifer response to GSP implementation. The projected water budget assessment in the GSP is also required to evaluate and identify the level of uncertainty in the projected water budget estimate, and to include historical water budget information to estimate future baseline conditions concerning hydrology,

water demand and surface water supply reliability over the 50-year planning and implementation horizon. Methods used to estimate the project water budget include the following three requirements:

- Utilize 50 years of historical precipitation, evapotranspiration, and stream flow information as the future baseline hydrology conditions, while taking into consideration uncertainties associated with the estimated climate change and sea level rise projections.
- Utilize the most recent land use, evapotranspiration, and crop coefficient information as the baseline condition for estimating future water demands, while taking into account future water demand uncertainty associated with projected changes in local land use planning, population growth, and climate.
- Utilize the most recent water supply information as the baseline condition for estimating future surface water supply, while applying the historical surface water supply reliability identified in 354.18(c)(2) and taking into consideration the projected changes in local land use planning, population growth, and climate.

Time frames required for the evaluation of current, historical, and projected water budget conditions are illustrated graphically in Figure 6. The illustration also includes a description of data to be supplied by DWR. Additional discussion of data and data sources is discussed in greater detail in subsequent sections of this BMP (*Water Budget Data Resources)*.

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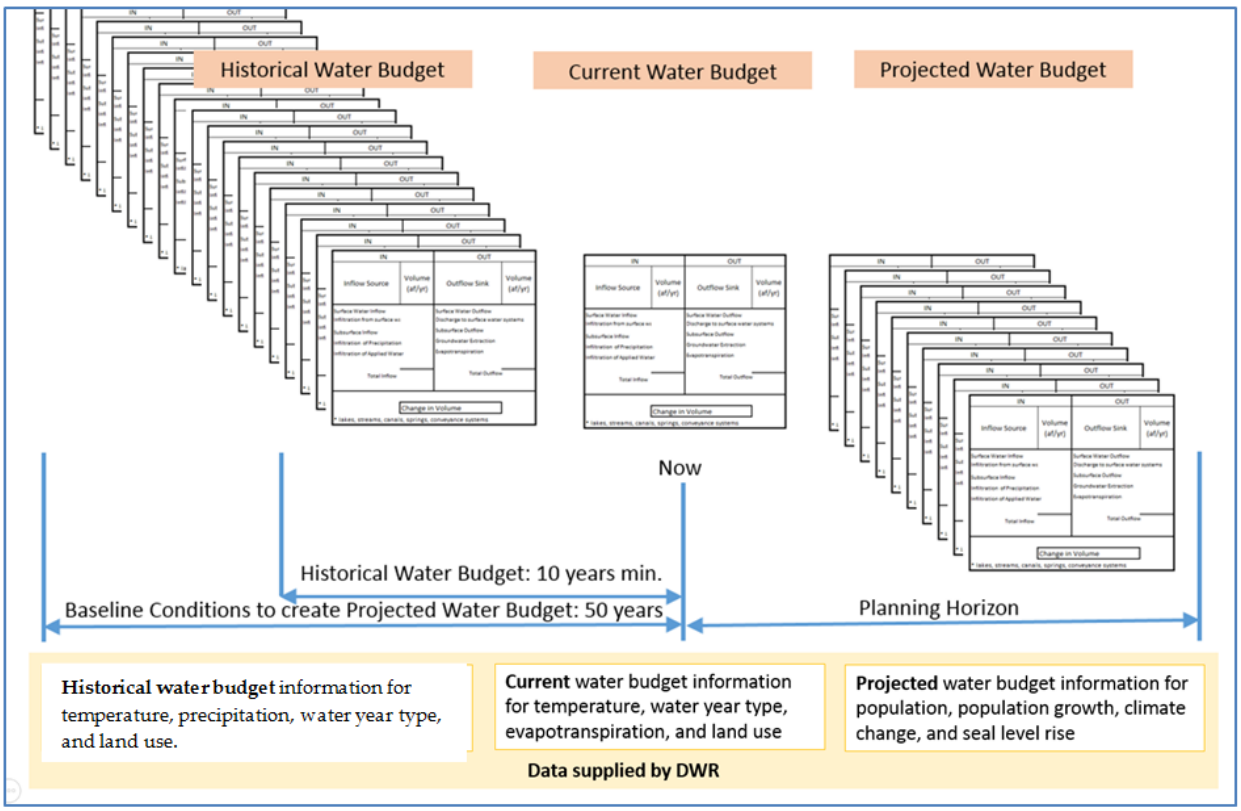

Figure 6 - GSP Water Budget Time Frames

Although the GSP Regulations only require annual quantification of the current, historical, and projected water budget information, it is anticipated that many GSAs will want to perform water budget accounting on a monthly or even a daily basis, especially if a groundwater model is used to compile and assess future water budget and aquifer conditions. In these situations, model results can be aggregated to annual values to support the GSP and subsequent annual reporting. Water budget accounting for shorter than annual time periods provides information necessary to support sustainable management of the basin through more timely evaluation of the water supply and demands by water use sector, of the potential undesirable results, and of the associated need for potential projects and management actions.

IDENTIFYING AND SELECTING METHODOLOGIES TO ESTIMATE WATER BUDGET COMPONENTS

As discussed above, individual components of the water budget may be estimated independently or based on estimates of other water budget components using the water budget equation. A comprehensive review of methodologies for each water budget component is beyond the scope of this BMP; however the reader is encouraged to

review water budget data resources described under *Water Budget Data Resources* and related materials referenced in Section 7. Selection of a methodology for a particular water budget component should consider the following:

- 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.
- Past and current approaches to quantifying water budget components in the basin.
- Alternative approaches representing the best available information and the best available science.
- Data available to support application of the methodology.
- The methodology used for other GSPs within the basins or adjacent basins.
- The magnitude of the water budget component relative to other components in the basin.
- Accuracy and uncertainty associated with the methodology and supporting data

Some water budget components lend themselves to direct monitoring and measurement more than others. For example, physical processes at the ground surface, such as surface water diversion, groundwater extraction, and precipitation can be directly measured with a high degree of accuracy, certainty, and reliability using various meters, dataloggers, and other readily available monitoring devices. In addition, these approaches to monitoring support utilization of the best available science, reflect industry standards, and result in defensible data that meets the uncodified finding of SGMA to collect data necessary to resolve disputes regarding sustainable yield, beneficial uses, and water rights (SGMA Uncodified Findings (b)(3)).

In contrast, other processes such as infiltration and subsurface *groundwater flows* across basin boundaries cannot be measured directly and must be estimated using other approaches.

The methodologies, assumptions and data sources used to quantify water budget components are to be documented in the GSP. Much of the information needed to quantify a component of the water budget may be available in existing planning documents and on-line data sources (see *Water Budget Data Resources* below).

As described in the *Coordination of Water Budget Data* section in this BMP, for situations where basin boundaries are adjacent or contiguous to one or more additional basins, or when a stream or river serve as the lateral boundary between two basins, it is highly recommended that water budget accounting in adjacent basins develop "interbasin" agreements to facilitate exchange of water budget information, as described in Section §357.2 of the GSP Regulations..

EVALUATING ACCURACY AND UNCERTAINTY OF WATER BUDGET COMPONENTS

Careful consideration should be given to documenting the accuracy and uncertainty of the data being used and in selecting which components are estimated independently versus estimated based on the principle of mass balance, as described above. In all cases, any components estimated based on the water budget equation (Equation 1) should be examined closely for reasonableness. For example, if past experience suggests that a typical value for infiltration of precipitation is around 5 to 10 percent of the total inflow for a given basin, but solution of the water budget equation for infiltration of precipitation results in an estimate of 50 percent of total inflow from infiltration of precipitation, additional examination of the other water budget components is warranted.

Evaluation of accuracy and uncertainty associated with individual water budget components is important because it improves understanding of the sensitivity and range of uncertainty of the various water budget components, which subsequently helps support and inform development of GSP sustainable management criteria (§354.22) and projects and management actions (§354.44) that are being implemented and proposed to achieve sustainability.

WATER BUDGET DATA RESOURCES

Data resources to assist in development a water budget will vary according to past water management studies and water resource investigations conducted in the region. However, several sources of potentially useful information have been identified and are described below. These sources include data to be provided by DWR as part of technical assistance to support GSP development and sustainable water management, as well as other available sources of information.

Data Provided by DWR (§354.18(d) and (f))

Data to be provided by DWR to develop the water budget identified in the Regulations includes the following (§354.18(d) and (f)):

- **Historical Information:** Monthly minimum, maximum, and mean temperature and precipitation; water year type for areas outside the Central Valley; and Central Valley land use information.
- **Current Information:** Monthly minimum, maximum, and mean temperature; water year type; evapotranspiration, and statewide land use information

- **Projected Information:** Population, population growth, climate change, and sea level rise.
- **Modeling Support**: The California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) and Integrated Water Flow Model (IWFM)

Agencies developing a water budget may choose to use other data of comparable quality, as allowed by Regulation §354.18(d). As mentioned previously, 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 plan (§354.18(e)). A water budget completed outside of a model may be useful as part of model calibration to confirm the reasonableness of water budget produced by the model.

Climate Change and Sea Level Rise. GSP Regulations require future water budget estimates to take into consideration changing climate and sea level rise when evaluating water supply, demand, and reliability for the basin over the planning and implementation horizon. Due to the spatial and temporal complexities associated with evaluating the basin response to changing climate, land use, and proposed projects, it is anticipated that most GSAs will utilize a hydrologic model to evaluate the various potential future basin conditions. In an effort to support consistent GSP analysis of future sustainability conditions, DWR will provide GSAs with the methods and data to be used in their analysis of future conditions. One of these datasets will include a range of future supply variability resulting from changing climate effects on temperature, precipitation, runoff, and sea level rise. The methods and analysis used to evaluate the future climate effects on water supply availability will be consistent with the data and methods used in the Proposition 1 Water Storage Investment Program Grant Application Process. The data and methods will be provided online by DWR in a separate document, and will not assume implementation of the Delta Fix Program.

Additional Data and Resources

Several other data sources exist in addition to those data specifically identified in the Regulation to be provided by DWR. Some of these include data available from DWR not specifically listed in the Regulation. A summary of data available to support water budget development is provided in Table 2. The table is not intended to provide an exhaustive list of data and sources to support water budget development, but rather to provide a reference to data that may be helpful. Specific data selected to support water budget development will depend on methodologies selected to estimate water budget components.

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Table 2 – Potential Data Sources to Support Water Budget Development

Data Type	Data Sources	Notes
Air Temperature	DWR, PRISM, CIMIS, NOAA, USBR	Historical and current conditions available from DWR, PRISM, CIMIS, and NOAA. Projected future conditions available from DWR and USBR.
Precipitation	DWR, PRISM, CIMIS, NOAA, NASA, USBR	Historical and current conditions available from DWR, PRISM, CIMIS, NOAA, and NASA. Projected future conditions available from DWR and USBR.
Water Year Type	DWR	
Land Use	DWR, USDA, County General Plans, Local Agencies	Historical and current conditions available from DWR, USDA CDL, county general plans, and local agencies (including county agricultural commissioners).
Evapotranspiration	DWR, CIMIS, CalSIMETAW, UCCE	Historical and current conditions include reference evapotranspiration, total evapotranspiration, and amount of evapotranspiration derived from applied irrigation water. Could include traditional approaches and/or satellite remote sensing approaches.
Population	DWR, State Dept. of Finance, U.S. Census Bureau, UWMPs	Historical and current conditions from Dept. of Finance, U.S. Census, and UWMPs. Projected future conditions from DWR and UWMPs.
Climate Change	DWR, USBR	May include projected temperature, precipitation, evapotranspiration, streamflows, projected project supplies, etc.
Sea Level Rise	DWR	
Applied Water	AWMPs, UWMPs, UCCE, DWR	Historical and current applied irrigation water demands reported in AWMPs, UCCE publications, and DWR reports. Historical, current, and projected urban demands described in UWMPs.
Groundwater Level	DWR, USGS, Local Agencies	DWR sources include GIC and WDL.
Aquifer Thickness and Layering	DWR, USGS, Local/Regional Studies	DWR and USGS sources include C2VSIM and CVHM models and other studies. Local and regional studies and models may also be available.
Aquifer Hydraulic Conductivity	DWR, USGS, Local/Regional Studies	DWR and USGS sources include C2VSIM and CVHM models and other studies. Local and regional studies and models may also be available.
Digital Elevation Model	USGS	Utilized to estimate surface water runoff from precipitation.
Streamflow	DWR, USGS, Local Agencies	DWR sources include CDEC and WDL.
Surface Water Diversions	Local Agencies, SWRCB eWRIMS, DWR, USBR	

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Data Type	Data Sources	Notes
Municipal/Industrial Groundwater Pumping	UWMPs	
Agricultural Groundwater Pumping	AWMPs, DWR, USGS	
Specific Yield	DWR, USGS, Local/Regional Studies	DWR and USGS sources include C2VSIM and CVHM models and other studies. Local and regional studies and models may also be available.
Surface Soil Properties	NRCS	
Per-Capita Water Use	UWMPs, DWR, USGS	

Tabled Acronyms:

AWMP – Agricultural Water Management Plan
C2VSIM – California Central Valley Groundwater-Surface Water Simulation Model
CalSIMETAW – California Simulation of Evapotranspiration of Applied Water Model
CDEC – California Data Exchange Center
CIMIS – California Irrigation Management Information System
CVHM – Central Valley Hydrologic Model
DWR – Department of Water Resources
eWRIMS – Electronic Water Rights Information Management System
GIC – Groundwater Information Center
NASA – National Aeronautics and Space Administration
NOAA – National Oceanic and Atmospheric Administration
NRCS – Natural Resources Conservation Service
PRISM –Parameter-elevation Relationships on Independent Slopes Model
SWRCB – State Water Resources Control Board
UCCE – University of California Cooperative Extension
USBR – United States Bureau of Reclamation
USDA – United States Department of Agriculture
USGS – United States Geological Survey
UWMP – Urban Water Management Plan
WDL – Water Data Library

Additional Data Sources:

Additional sources of available information include data from state and federal agencies, research institutions, local water resource management entities, and other local data collection and sharing activities. A partial list of data sources associated with existing water resource management programs are provided below:

- Urban Water Management Plans (UWMPs) [http://www.water.ca.gov/urbanwatermanagement/]
- Agricultural Water Management Plans (AWMPs), [http://www.water.ca.gov/wateruseefficiency/agricultural/agmgmt.cfm]

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- Groundwater Management Plans (GWMPs), [http://water.ca.gov/groundwater/groundwater_management/GWM_Plans_inCA.cfm]
- Integrated Regional Water Management Plans (IRWMPs), [http://water.ca.gov/irwm/stratplan/]
- Groundwater Ambient Monitoring and Assessment Program (GAMA), [http://www.swrcb.ca.gov/gama/]
- Irrigated Lands Regulatory Program (ILRP) http://www.waterboards.ca.gov/centralvalley/water_issues/irrigated_lands/

A comprehensive list of all available sources of water budget data from state and federal agencies, research institutions, and local water management entities is beyond the scope of this BMP. Some additional sources of water budget-related information from select state and federal agencies are provided below.

Department of Water Resources:

- Groundwater Information Center (GIC): http://water.ca.gov/groundwater/gwinfo/index.cfm
- California Statewide Groundwater Elevation Monitoring Program (CASGEM): http://water.ca.gov/groundwater/casgem/
- Water Data Library (WDL) http://www.water.ca.gov/waterdatalibrary/
- California Data Exchange Center (CDEC) http://cdec.water.ca.gov/
- California Irrigation Management Information System (CIMIS) http://wwwcimis.water.ca.gov/cimis/welcome.jsp
- Land Use Surveys: http://www.water.ca.gov/landwateruse/lusrvymain.cfm
- Groundwater –Surface Water Simulation Model: The following DWR Bay-Delta site list information for the C2VSim Central Valley Groundwater-Surface water simulation model. This same website contains additional links to DWR water budget tools such as:
    - Integrated Water Flow Model (IWFM)
    - Irrigation Demand Calculator (IDC)
    - CalLite: Central Valley Water Management Screening Model
    - Water Resource Integraded Modeling System (WRIMS) model engine (formally named CALSIM)
    - Delta Simulation Model II (DSM2)

  http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/index_C2VSIM.cfm
- Bulletin 118: http://water.ca.gov/groundwater/bulletin118/index.cfm

- California Groundwater Update 2013:
- http://www.water.ca.gov/waterplan/topics/groundwater/index.cfm
- California Water Plan Update 2013: http://www.water.ca.gov/waterplan/cwpu2013/final/index.cfm
- Additional DWR Data Topics: http://water.ca.gov/nav/index.cfm?id=106

State Water Resources Control Board:

- Electronic Water Rights Information Management System (eWRIMS) http://www.swrcb.ca.gov/waterrights/water_issues/programs/ewrims/
- GeoTracker: https://geotracker.waterboards.ca.gov/

United States Geological Survey:

- Central Valley Hydrologic Model (CVHM): http://ca.water.usgs.gov/projects/central-valley/central-valley-hydrologic-model.html
- Water Data Discovery: http://water.usgs.gov/data/
- Surface Water Information: http://water.usgs.gov/osw/
- Groundwater Information Pages: http://water.usgs.gov/ogw/

Additional USGS Water budget Related Materials by Topic

Developing a Water Budget:

This USGS Circular is a general reference for developing a water budget; it includes the key components of the water budget, exchanges of water between these components, and case studies of water-budget development and the use of water budgets in managing hydrologic systems. http://pubs.usgs.gov/circ/2007/1308/

Recharge Estimation:

Modeling, field-based, and other methods have been used to estimate recharge. Those included here are examples of methods potentially applicable to relatively large areas. A comprehensive overview of recharge estimation methods is available in this book: https://pubs.er.usgs.gov/publication/70156906.

This USGS report is a compilation of methods and case studies for recharge estimation in the arid and semiarid southwestern U.S., including eastern and southeastern California: http://pubs.usgs.gov/pp/pp1703/index.html

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Modeling of Recharge:

The Basin Characterization Model (BCM) was developed by the USGS for use in estimating natural recharge, and has been applied to all of California and other regions in the western US and internationally. This regional water-balance model differs from rainfall-runoff models because it incorporates estimates of shallow bedrock permeability to spatially distribute in-place natural recharge across the landscape. Content on the website below describes the model and associated methods, and provides links to output datasets available for historical and future projections of climate, and to associated publications of applications. The BCM is currently undergoing revisions to further improve the accuracy of recharge estimates for California; these revisions will be completed in mid-2017.
http://ca.water.usgs.gov/projects/reg_hydro/projects/dataset.html

The Farm Process: is a tool developed by the USGS to improve the estimation of recharge (and pumping) associated with irrigated agriculture. It is available in various versions of MODFLOW; the most recent version is in MODFLOW-OWHM.

- Primary documentation, Version 1: http://pubs.usgs.gov/tm/2006/tm6A17/
- Documentation of Version 2: http://pubs.usgs.gov/tm/tm6a32/
- Version 3 is in MODFLOW-OWHM: http://water.usgs.gov/ogw/modflow-owhm/

GSFLOW: Is a coupled ground-water and surface-water flow model developed by the USGS and based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005). Features of both PRMS and MODFLOW aid in recharge estimation. http://pubs.usgs.gov/tm/tm6d1/

SWB: Is a modified Thornthwaite-Mather soil-water-balance code developed by the USGS for estimating groundwater recharge. http://pubs.usgs.gov/tm/tm6-a31/

INFIL: Is a grid-based, distributed-parameter watershed model developed by the USGS, for estimating net infiltration below the root zone. The link below provides documentation of the model, the associated software, and examples of applications.
http://water.usgs.gov/nrp/gwsoftware/Infil/Infil.html

Case Studies for Recharge Estimation using Modeling:

MODFLOW: Natural recharge estimates, and uncertainty analysis of recharge estimates, using a regional-scale model of groundwater flow and land subsidence, Antelope Valley, California. https://pubs.er.usgs.gov/publication/70155814

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INFIL: Estimating spatially and temporally varying recharge and runoff from precipitation and urban irrigation in the Los Angeles Basin, California
http://dx.doi.org/10.3133/sir20165068

Geophysical Methods for Estimating Recharge:
This USGS report describes many geophysical methods for investigating groundwater recharge; it includes case studies and a list of references for further information.
http://pubs.usgs.gov/pp/pp1703/app2/pp1703_appendix2.pdf

Surface-Water/Groundwater Interactions:

- This USGS Circular is a general reference for groundwater and surface water, and their interdependence: http://pubs.usgs.gov/circ/circ1139/
- This USGS Circular describes the process of streamflow depletion by wells, and ways of understanding and managing the effects of groundwater pumping on streamflow: http://pubs.usgs.gov/circ/1376/
- This USGS document outlines *Field Techniques for Estimating Water Fluxes Between Surface Water and Ground Water*: http://pubs.usgs.gov/tm/04d02/
- This USGS document identifies methodologies for *Using Diurnal Temperature Signals to Infer Vertical Groundwater-Surface Water Exchange*: http://onlinelibrary.wiley.com/doi/10.1111/gwat.12459/abstract

Baseflow Analysis:

- General link to USGS software associated with baseflow analysis http://water.usgs.gov/software/lists/groundwater#flow-based

- U.S. Geological Survey Groundwater Toolbox, A Graphical and Mapping Interface for Analysis of Hydrologic Data (Version 1.0)—User Guide for Estimation of Base Flow, Runoff, and Groundwater Recharge From Streamflow Data: http://pubs.usgs.gov/tm/03/b10/ and http://water.usgs.gov/ogw/gwtoolbox/

Streamflow Trend Evaluation:
User Guide to Exploration and Graphics for RivEr Trends (EGRET) and dataRetrieval: R Packages for Hydrologic Data: http://pubs.usgs.gov/tm/04/a10/

Water Use:
Guidelines for preparation of State water-use estimates for 2005:
http://pubs.usgs.gov/tm/2007/tm4e1/

Climate-related Analysis:
HydroClimATe: Hydrologic and Climatic Analysis Toolkit:
http://pubs.usgs.gov/tm/tm4a9/

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BCM Time Series Graph Tool: Enabling analyses of climate and hydrology variables, including recharge and runoff, for all HUC-8 watersheds in California for historical and future climates:http://climate.calcommons.org/article/about-bcm-time-series-graph-tool

Climate Smart Watershed Analyst: Enabling analyses of climate and hydrology variables, for time series and seasonality for planning watersheds in the San Francisco Bay Area for historical and future climates: http://geo.pointblue.org/watershed-analyst/

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6. KEY DEFINITIONS

The key definitions related to Water Budget development outlined in applicable SGMA code and regulations are provided below for reference.

SGMA DEFINITIONS (CALIFORNIA WATER CODE 10721):

(b) "Basin" means a groundwater basin or subbasin identified and defined in Bulletin 118 or as modified pursuant to Water Code § 10722.

(c) "Bulletin 118" means the department's report entitled "California's Groundwater: Bulletin 118" updated in 2003, as it may be subsequently updated or revised in accordance with § 12924.

(r) "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.

(t) "Recharge area" means the area that supplies water to an aquifer in a groundwater basin.

(v) "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.

(w) "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.

(x) "Undesirable result" means 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 groundwater 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.

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(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.

(y) "Water budget" means an accounting of the total groundwater and surface water entering and leaving a basin including the changes in the amount of water stored.

(aa) "Water year" means the period from October 1 through the following September 30, inclusive

GROUNDWATER BASIN BOUNDARIES REGULATIONS (CALIFORNIA CODE OF REGULATIONS 341):

(f) "Aquifer" refers to a three-dimensional body of porous and permeable sediment or sedimentary rock that contains sufficient saturated material to yield significant quantities of groundwater to wells and springs, as further defined or characterized in Bulletin 118.

(q) "Hydrogeologic conceptual model" means a description of the geologic and hydrologic framework governing the occurrence of groundwater and its flow through and across the boundaries of a basin and the general groundwater conditions in a basin or subbasin.

GROUNDWATER SUSTAINABILITY PLAN REGULATIONS (CALIFORNIA CODE OF REGULATIONS 351):

(b) "Agricultural water management plan" refers to a plan adopted pursuant to the Agricultural Water Management Planning Act as described in Part 2.8 of Division 6 of the Water Code, commencing with Section 10800 et seq.

(d) "Annual report" refers to the report required by Water Code Section 10728.

(e) "Baseline" or "baseline conditions" refer to historic information used to project future conditions for hydrology, water demand, and availability of surface water and to evaluate potential sustainable management practices of a basin.

(g) "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.

(h) "Best available science" refers to 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.

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(l) “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.

(n) “Groundwater flow” refers to the volume and direction of groundwater movement into, out of, or throughout a basin.

(a) “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.

(c) “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.

(d) “Management area” refers to an area within a basin for which the Plan may identify different minimum thresholds, measurable objectives, monitoring, or projects and management actions based on differences in water use sector, water source type, geology, aquifer characteristics, or other factors.

(e) “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.

(f) “Minimum threshold” refers to a numeric value for each sustainability indicator used to define undesirable results.

(aa) “Principal aquifers” refer to aquifers or aquifer systems that store, transmit, and yield significant or economic quantities of groundwater to wells, springs, or surface water systems.

(ad) “Seasonal high” refers to the highest annual static groundwater elevation that is typically measured in the Spring and associated with stable aquifer conditions following a period of lowest annual groundwater demand.

(ae) “Seasonal low” refers to the lowest annual static groundwater elevation that is typically measured in the Summer or Fall, and associated with a period of stable aquifer conditions following a period of highest annual groundwater demand.

(af) “Seawater intrusion” refers to the advancement of seawater into a groundwater supply that results in degradation of water quality in the basin, and includes seawater from any source.

(ah) “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).

(ai) “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.

(aj) "Urban water management plan" refers to a plan adopted pursuant to the Urban Water Management Planning Act as described in Part 2.6 of Division 6 of the Water Code, commencing with Section 10610 et seq.

(ak) "Water source type" represents the source from which water is derived to meet the applied beneficial uses, including groundwater, recycled water, reused water, and surface water sources identified as Central Valley Project, the State Water Project, the Colorado River Project, local supplies, and local imported supplies.

(al) "Water use sector" refers to categories of water demand based on the general land uses to which the water is applied, including urban, industrial, agricultural, managed wetlands, managed recharge, and native vegetation.

(am) "Water year" refers to the period from October 1 through the following September 30, inclusive, as defined in the Act.

(an) "Water year type" refers to the classification provided by the Department to assess the amount of annual precipitation in a basin.

BULLETIN 118 DEFINITIONS

"Groundwater overdraft" refers to the condition of a groundwater basin in which the amount of water withdrawn by pumping exceeds the amount of water that recharges the basin over a period of years during which water supply conditions approximate average conditions.

"Groundwater in storage" refers to the quantity of water in the zone of saturation.

"Groundwater Storage Capacity" refers to the volume of void space that can be occupied by water in a given volume of a formation, aquifer, or groundwater basin.

"Safe yield" refers to the maximum quantity of water that can be continuously withdrawn from a groundwater basin without adverse effect

"Saturated zone" refers to the zone in which all interconnected openings are filled with water, usually underlying the unsaturated zone.

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7. Related Materials

This section provides a list of related materials including associated SGMA BMPs, general references, and selected case studies and examples pertinent to the development of water budgets. For the items identified, available links to access the materials are also provided.

GUIDANCE AND GENERAL REFERENCES:

- Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey, Circular 1376. [http://pubs.usgs.gov/circ/1376/]
- Healy, R.W., Winter, T.C., LaBough, J.W., and Franke, L.O., 2007, Water Budgets: Foundations for Effective Water-Resources and Environmental Management. U.S. Geological Survey, Circular 1308. [http://pubs.usgs.gov/circ/2007/1308/]
- Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground Water and Surface Water, A Single Resource. U.S. Geological Survey, Circular 1139. [http://pubs.usgs.gov/circ/circ1139/#pdf]
- California Water Plan Update 2013. Department of Water Resources, 2013.[http://www.water.ca.gov/waterplan/cwpu2013/final/index.cfm]
- California's Groundwater Update 2013, Department of Water Resources, 2013.[http://www.water.ca.gov/waterplan/topics/groundwater/index.cfm]

SELECTED CASE STUDIES AND EXAMPLES:

- Development and Calibration of the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG. DWR Technical Memorandum. California Department of Water Resources (DWR) Bay-Delta Office. 2013. [http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/download/C2VSim_Model_Report_Final.pdf]
- Groundwater Availability of the Central Valley, California. Professional Paper 1766. USGS. 2009. [http://pubs.usgs.gov/pp/1766/PP_1766.pdf]
- Scott Valley Integrated Hydrologic Model: Data Collection, Analysis, and Water Budget. Final Report. University of California – Davis, Department of Land, Air, and Water Resources. 2013. [http://groundwater.ucdavis.edu/files/165395.pdf]

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- Selected Approaches to Estimate Water-Budget Components of the High Plains, 1940 through 1949 and 2000 through 2009. Scientific Investigations Report 2011–5183. USGS. 2011. [http://pubs.usgs.gov/sir/2011/5183/pdf/sir2011-5183.pdf]

- Simulated Effects of Ground-Water Withdrawals and Artificial Recharge on Discharge to Streams, Springs, and Riparian Vegetation in the Sierra Vista Subwatershed of the Upper San Pedro Basin, Southeastern Arizona. Scientific Investigations Report 2009-5207. USGS. April, 2014. [http://pubs.usgs.gov/sir/2008/5207/sir2008-5207.pdf]

- Evaluation of Simulations to Understand Effects of Groundwater Development and Artificial Recharge on Surface Water and Riparian Vegetation, Sierra Vista Subwatershed, Upper San Pedro Basin Arizona. Open-File Report 2012-1206. USGS. 2012. [https://pubs.usgs.gov/of/2012/1206/of2012-1206.pdf\

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

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Modeling
Best Management Practice

California Department of Water Resources
Sustainable Groundwater Management Program
1416 Ninth Street
P.O. Box 942836
Sacramento, CA 94236-0001

www.water.ca.gov/groundwater

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Modeling Best Management Practice

1. Objective

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

This BMP includes the following sections:

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

2. Use and Limitations

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

3. Modeling Fundamentals

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

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

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

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

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

GENERAL TYPES OF MODELS AND MODELING SOFTWARE

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

TYPES OF MODELS

Conceptual Models

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

Mathematical Models

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

Analytical Models and Tools

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

Numerical Models and Tools

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

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Integrated Groundwater and Surface Water Models

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

Coupled Groundwater and Surface Water Models

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

Contaminant Transport Models

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

TYPES OF MODELING SOFTWARE

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

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

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

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

COMMON MODEL USES

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

General Uses (modified from Barnett and others, 2012)

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

GSP-Related Uses

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

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

MODELS IN REFERENCE TO THE GSP REGULATIONS

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

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

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

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

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

4. Relationship of Modeling to other BMPs

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

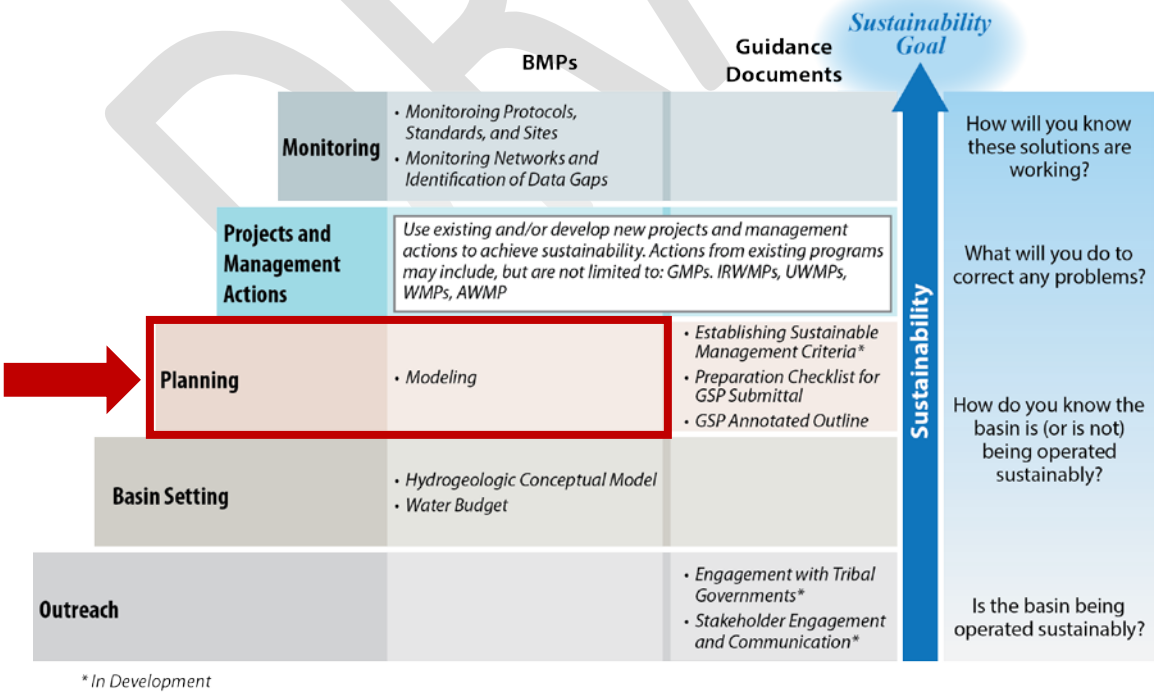

Figure 1 - Steps to Sustainability under SGMA

5. TECHNICAL ASSISTANCE

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

GUIDING PRINCIPLES FOR MODELS USED IN SUPPORT OF GSPs

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

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

GENERAL MODELING REQUIREMENTS

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

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

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

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

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

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

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

1. An explanation of the modeling code, the physical processes simulated by the code, associated mathematical equations, and assumptions, which are typically found in publicly available user instructions or manuals. This information should be referenced by the model user in their documentation of the model application.

2. A description of the model application, including the construction of the model by the GSA that describes model development, assumptions, data inputs, boundary conditions, calibration, uncertainty analysis, and other applicable model application elements. This documentation should be a component of a GSP, and included as an appendix to characterize the technical work that went into developing and applying the model for GSP development and implementation. The California Water and Environmental Modeling Forum (CWEMF) has developed a framework for documenting and archiving a groundwater flow model application that can be tailored for GSA use (CWEMF, 2000).

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

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

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

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

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

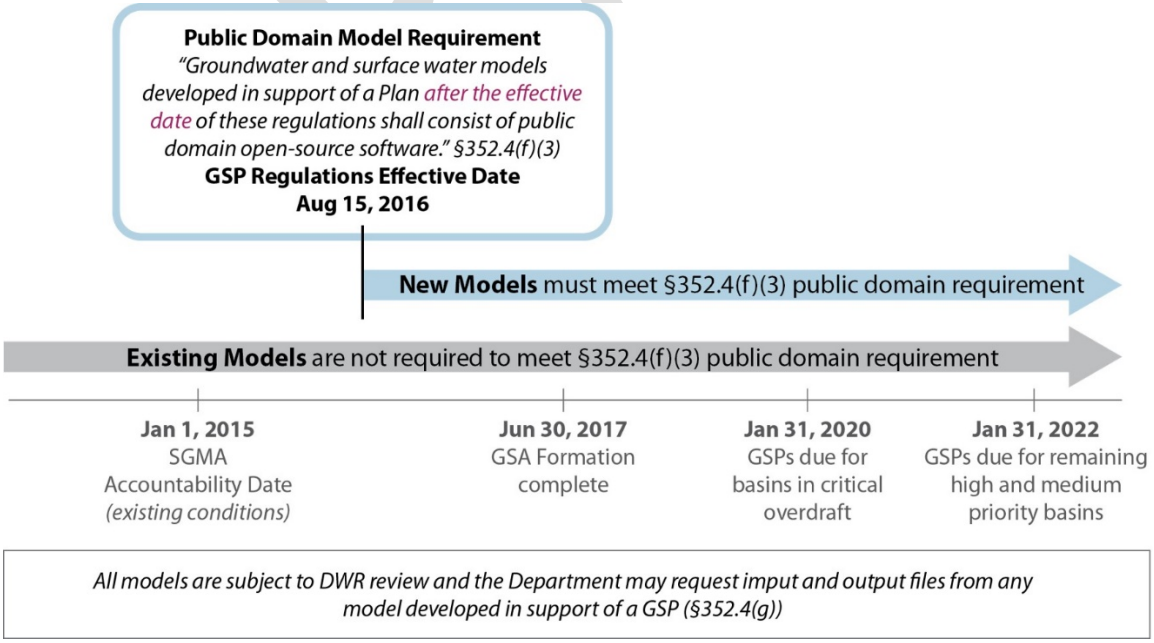

Figure 2 - GSP Regulations Effective Date and Model Development Timeline

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

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

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

MODELING CONSIDERATIONS

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

Addressing Sustainability Indicators

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

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

Lowering of Groundwater Levels

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

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

Reduction of Groundwater Storage

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

Seawater Intrusion

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

Degraded Water Quality

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

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Land Subsidence

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

Depletion of Interconnected Surface Water

354.28 (b) The description of minimum thresholds shall include the following:
(1) The information and criteria relied upon to establish and justify the minimum thresholds for each sustainability indicator. The justification for the minimum threshold shall be supported by information provided in the basin setting, and other data or models as appropriate, and qualified by uncertainty in the understanding of the basin setting.
…
(6) Depletions of Interconnected Surface Water. The minimum threshold for depletions of interconnected surface water shall be the rate or volume of surface water depletions caused by groundwater use that has adverse impacts on beneficial uses of the surface water and may lead to undesirable results. The minimum threshold established for depletions of interconnected surface water shall be supported by the following:

> *(A) The location, quantity, and timing of depletions of interconnected surface water.*
> *(B) A description of the groundwater and surface water model used to quantify surface water depletion. <u>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.</u>*

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

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

Developing Water Budgets

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

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

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

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

Forecasting Future Conditions

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

Assessing Impacts of Potential GSP Projects and Management Actions

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

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

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.

Identifying Data Gaps and Monitoring Needs

Modeling 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 how the parameter uncertainty affects the ability to achieve sustainability. Results from a model's uncertainty analysis can be used to prioritize data collection activities according to which parameters are most influential on various sustainability indicators. For example, if modeling results indicate that achieving sustainability is heavily dependent on infiltration of surface water, it will be important to focus characterization activities on better understanding the rate and variability of surface water infiltration, and what actions influence these processes.

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

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

Assessing Impacts on Adjacent Basins

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

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

Model Adaptability

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

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

Spatial Extent of the Model

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

Data Availability

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

Importance of Land Use Practices in Agricultural Basins

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

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

Model Results Presentation

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

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

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

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THE GROUNDWATER MODELING PROCESS

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

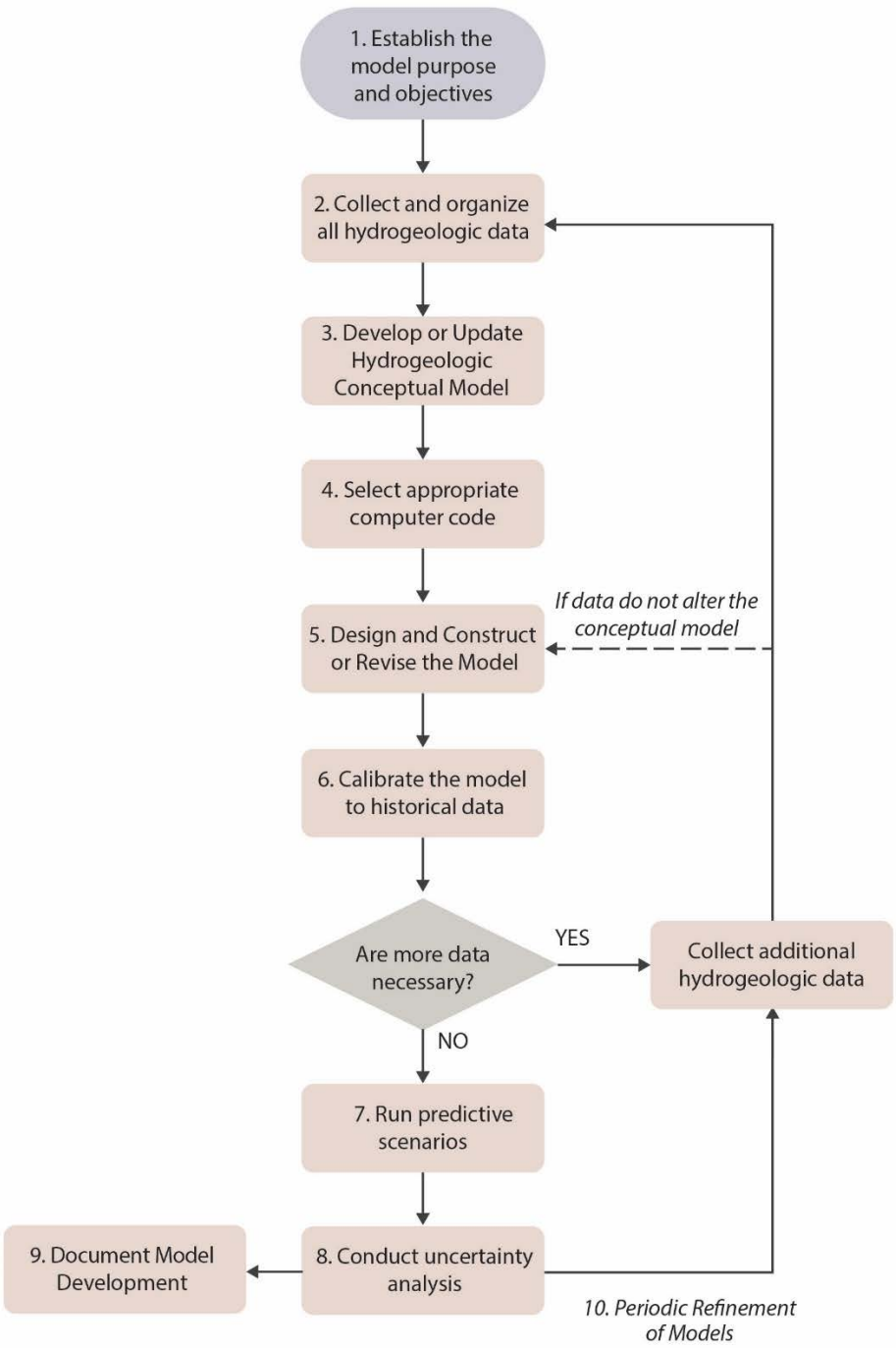


Figure 3: General Modeling Process

1. **Establish the model's purpose and intended use**. Models generally cannot reliably answer all questions about groundwater behavior. For the purposes of SGMA, the GSA should assess which sustainability indicators need to be simulated by the model (or models), and develop the model purpose to address these. GSAs should also establish protocols at this stage for where the model will be housed, how the model will be updated, and the terms of model use by various GSA members. Stakeholder input is an important component of model development. Specifically, during the early planning phase of model development when the purpose and objectives of the model are being considered.

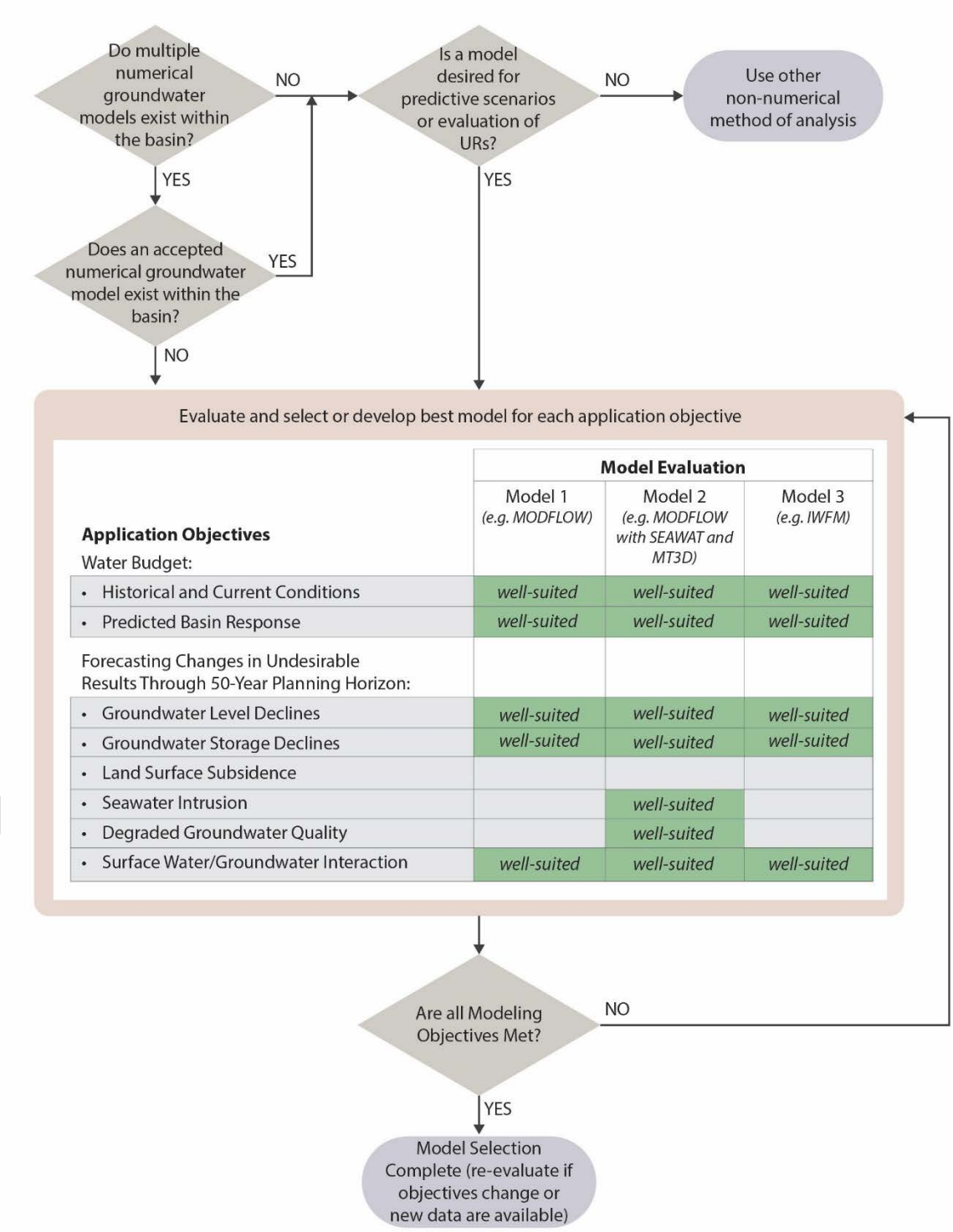
2. **Collect and organize all hydrogeologic data**. The amount of available data and accuracy of available data will drive the complexity and detail included in both the conceptual model and mathematical model. All GSA members should, to the degree possible, provide data of similar accuracy and completeness to ensure that the entire model reflects a similar level of data collection. Raw data collected as part of the basin setting and HCM development should be organized at this stage. Once these data are organized into a database, they are processed into input files for modeling, with specific file formats as required by the chosen code. As an example, the Central Valley Hydrologic Model (CVHM) website has a framework for the organization of the raw data with links to the data sources, as well as related GIS shapefiles and CVHM input files of the processed data (http://ca.water.usgs.gov/projects/central-valley/central-valley-spatial-database.html).

3. **Develop a conceptual model of the basin**. A conceptual model allows for the narrative interpretation and graphical representation of a basin based on known characteristics and current management actions. Conceptual models do not necessarily include quantitative values. For more details on developing a conceptual model, please refer to the HCM BMP.

4. **Select the appropriate computer code**. The selected computer code must be able to simulate all the processes that might significantly influence the various sustainability indicators. However, modelers should practice pragmatism and avoid unnecessary model complexity. For example, it may be practical to analyze future land subsidence with one-dimensional analytical calculations, rather than selecting a three-dimensional model that includes land subsidence.

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

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



Application Objectives	Model Evaluation: Model 1 (e.g. MODFLOW)	Model 2 (e.g. MODFLOW with SEAWAT and MT3D)	Model 3 (e.g. IWFM)
Water Budget:			
• Historical and Current Conditions	well-suited	well-suited	well-suited
• Predicted Basin Response	well-suited	well-suited	well-suited
Forecasting Changes in Undesirable Results Through 50-Year Planning Horizon:			
• Groundwater Level Declines	well-suited	well-suited	well-suited
• Groundwater Storage Declines	well-suited	well-suited	well-suited
• Land Surface Subsidence			
• Seawater Intrusion		well-suited	
• Degraded Groundwater Quality		well-suited	
• Surface Water/Groundwater Interaction	well-suited	well-suited	well-suited

Figure 4: Model Code Selection Flowchart

5. **Design and construct the model**. In this step, the conceptual model developed in step three is implemented in the selected model code. This step includes developing model layers, developing the model grid, populating the model with hydrogeologic parameters, developing boundary conditions, and adding water budget components to the model. Models should maintain simplicity and parsimony of hydrogeologic parameters, while simultaneously simulating the important hydrogeologic details that will drive basin sustainability.

6. **Calibrate the numerical model to historical data**. Model calibration is required by the GSP Regulations (352.4(f)(2)). Calibration is performed to demonstrate that the model reasonably simulates known, historical conditions. Calibration generally involves iterative adjustments of various model aspects until the model results match historical observations within an agreed-to tolerance. Hydrogeologic parameters such as hydraulic conductivity and specific yield are often modified during model calibration. Aspects of the water budget such as recharge rate or pumping depth may also be modified during calibration.

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

7. **Develop and run predictive scenarios** that establish expected future conditions under varying climatic conditions, and implementing various projects and management actions. Predictive scenarios should be designed to assess whether the GSP's projects and management actions will achieve the sustainability goal, and the anticipated conditions at five-year interim milestones. Predictive scenarios for the GSP should demonstrate that the sustainability goal will be maintained over the 50-year planning and implementation horizon.

8. **Conduct a predictive uncertainty analysis to identify the impact of parameter uncertainty on the use of model's ability to effectively support management decisions**. Predictive uncertainty analysis provides a measure of the likelihood that a reasonably constructed and calibrated model can still yield uncertain results that drive critical decisions. It is important that decision makers understand the implications of these uncertainties when developing long-term basin management strategies. As discussed in other sections of this BMP, this type of analysis can also identify high-value data gaps that should be prioritized to improve confidence in model outputs, and yield a tool that has an increased probability of providing useful information to support effective basin management decisions.

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9. **Document model code and model application development**. The GSP needs to include documentation on the modeling tools used for the sustainability analysis. This documentation can be provided in the form of a technical appendix to the GSP and should include both information on the model code (referenced from user manuals, for instance) and detailed descriptions of he model application development. Model code information should include an explanation of the modeling code, associated mathematical equations, and assumptions, which is typically found in publicly available user instructions or manuals. This information should be referenced by the model user in their documentation of the model application. The description of the model application should include detailed information on the model conceptualization, assumptions, data inputs, boundary conditions, calibration, sensitivity and uncertainty analysis, and other applicable modeling elements such as model limitations. In addition, all final model files used for decision making in the GSP should be packaged for release to DWR.

10. **Revise model regularly during implementation**. After GSP development and during the implementation of the GSP, new data will be available through monitoring and collection from local agencies. As new data are made available through annual updates and the 5-year review process, models can be updated and refined. These new data will be useful for regular model updates and recalibration to reduce model uncertainties and better assess the future effects of management actions on the basin's sustainability indicators.

6. KEY DEFINITIONS

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

SGMA Definitions (CALIFORNIA WATER CODE 10721):

- "Basin" refers to a groundwater basin or subbasin identified and defined in Bulletin 118 or as modified pursuant to Chapter 3 (commencing with Section 10722).

- "Coordination agreement" means a legal agreement adopted between two or more groundwater sustainability agencies that provides the basis for coordinating multiple agencies or groundwater sustainability plans within a basin pursuant to this part.

- "Condition of long-term overdraft": The condition of a groundwater basin where the average annual amount of water extracted for a long-term period, generally 10 years or more, exceeds the long-term average annual supply of water to the basin, plus any temporary surplus. Overdraft during a period of drought is not sufficient to establish a condition of long-term overdraft if extractions and recharge are managed as necessary to

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

- "Groundwater" refers to water beneath the surface of the earth within the zone below the water table in which the soil is completely saturated with water, but does not include water that flows in known and definite channels.

- "Groundwater recharge" refers to the augmentation of groundwater, by natural or artificial means.

- "Planning and implementation horizon" means a 50-year time period over which a groundwater sustainability agency determines that plans and measures will be implemented in a basin to ensure that the basin is operated within its sustainable yield.

- "Recharge area" is the area that supplies water to an aquifer in a groundwater basin.

- "Sustainability goal" means the existence and implementation of one or more groundwater sustainability plans that achieve sustainable groundwater management by identifying and causing the implementation of measures targeted to ensure that the applicable basin is operated within its sustainable yield.

- "Sustainable groundwater management" means the management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results.

- "Sustainable yield" means the maximum quantity of water, calculated over a base period representative of long-term conditions in the basin and including any temporary surplus, that can be withdrawn annually from a groundwater supply without causing an undesirable result.

- "Undesirable result" refers to: One or more of the following effects caused by groundwater conditions occurring throughout the basin:

  1. Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply if continued over the planning and implementation horizon. Overdraft during a period of drought is not sufficient to establish a chronic lowering of groundwater levels if extractions and recharge are managed as necessary to ensure that reductions in groundwater levels or storage during a period of drought are offset by increases in groundwater levels or storage during other periods.

  2. Significant and unreasonable reduction of groundwater storage.

  3. Significant and unreasonable seawater intrusion.

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

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

6. Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water.

- "Water budget" is an accounting of the total groundwater and surface water entering and leaving a basin including the changes in the amount of water stored.

- "Water year" refers to the period from October 1 through the following September 30, inclusive.

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

- "GIS": Geographic Information System that collects, stores, analyzes, and displays spatial or geographically referenced data.

- "Hydrogeologic conceptual model" is a description of the geologic and hydrologic framework governing groundwater flow through and across the boundaries of a basin and the general groundwater conditions in a basin.

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

- "Basin setting" refers to the information about the physical setting, characteristics, and current conditions of the basin as described by the Agency in the hydrogeologic conceptual model, the groundwater conditions, and the water budget, pursuant to Subarticle 2 of Article 5.

- "Best available science" means the use of sufficient and credible information and data, specific to the decision being made and the time frame available for making that decision that is consistent with scientific and engineering professional standards of practice.

- "Best management practice" refers to a practice, or combination of practices, that are designed to achieve sustainable groundwater management and have been determined to be technologically and economically effective, practicable, and based on best available science.

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- "Data gap" refers to a lack of information that significantly affects the understanding of the basin setting or evaluation of the efficacy of Plan implementation, and could limit the ability to assess whether a basin is being sustainably managed.

- "Groundwater flow" refers to the volume and direction of groundwater movement into, out of, or throughout a basin.

- "Interconnected surface water" refers to surface water that is hydraulically connected at any point by a continuous saturated zone to the underlying aquifer and the overlying surface water is not completely depleted.

- "Interim milestone" refers to a target value representing measurable groundwater conditions, in increments of five years, set by an Agency as part of a Plan.

- "Measurable objectives" refer to specific, quantifiable goals for the maintenance or improvement of specified groundwater conditions that have been included in an adopted Plan to achieve the sustainability goal for the basin.

- "Minimum threshold" refers to a numeric value for each sustainability indicator used to define undesirable results.

- "Plan implementation" refers to an Agency's exercise of the powers and authorities described in the Act, which commences after an Agency adopts and submits a Plan or Alternative to the Department and begins exercising such powers and authorities.

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

- "Uncertainty" refers to a lack of understanding of the basin setting that significantly affects an Agency's ability to develop sustainable management criteria and appropriate projects and management actions in a Plan, or to evaluate the efficacy of Plan implementation, and therefore may limit the ability to assess whether a basin is being sustainably managed.

7. Related Materials and Key Definitions

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

STANDARDS

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

GUIDANCE

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

Barnett B., L.R. Townley, V. Post, R.E. Evans, R.J. Hunt, L. Peeters, S. Richardson, A.D. Werner, A. Knapton, and A. Boronkay, 2012. *Australian groundwater modelling guidelines*, National Water Commission, Canberra, June, 191 p. http://archive.nwc.gov.au/library/waterlines/82

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

Merz, S.K. 2013. *Australian groundwater modelling guidelines: companion to the guidelines*, National Water Commission, Canberra, July, 31 p. http://archive.nwc.gov.au/library/waterlines/82

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

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

Reilly, T.E., 2001. *System and boundary conceptualization in groundwater flow simulation*: Techniques of water resource investigations of the United States geological survey, book 3, applications of hydraulics, Chapter B8, Reston, VA, 38 p. http://pubs.usgs.gov/twri/twri-3_B8/

Reilly, T.E., and A.W. Harbaugh, 2004. *Guidelines for evaluating ground-water flow models*: USGS scientific investigations report 2004-5038, Reston, VA, 30 p. http://pubs.usgs.gov/sir/2004/5038/PDF.htm

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APPENDIX A - EXISTING MODEL CODES AND MODEL APPLICATIONS

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

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

DWR developed, maintains, and regularly updates C2VSim. It has been used for several large-scale Central Valley studies. C2VSim is an integrated numerical model based on the finite element grid 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 primarily subsurface and limited-surface hydrologic processes over the Central Valley at a uniform grid-cell spacing of 1 mile on a monthly basis using data from April 1961 to September 2003. CVHM simulates surface water flows, groundwater flows, and land subsidence in response to stresses from water use and climate variability throughout the Central Valley. It uses the MODFLOW-2000 (USGS, 2000) finite-difference groundwater flow model code combined with a module called the farm process (FMP) (USGS, 2006) to simulate groundwater and surface water flow, irrigated agriculture, and other key hydrologic processes. It can be used in a similar manner to C2VSim.
http://ca.water.usgs.gov/projects/central-valley/central-valley-hydrologic-model.html

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

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Summary of the most commonly used groundwater models in California water resources management.					
Model Code or Application	**Description**	**Download**	**Documentation**	**Maintained by**	**Applicability to SGMA Undesirable Results**
MT3D	Modular 3-D Multi-Species Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems. Post-processing code to MODFLOW for transport modeling.	http://hydro.geo.ua.edu/mt3d/	Zheng, Chunmiao, 2010, *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
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
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

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Summary of the most commonly used groundwater models in California water resources management.					
Model Code or Application	**Description**	**Download**	**Documentation**	**Maintained by**	**Applicability to SGMA Undesirable Results**
IWFM	Finite-element code for integrated water resources modeling.	http://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
C2VSIM	IWFM application for the Central Valley Aquifer.	http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/index_C2VSIM.cfm	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.	DWR	Groundwater levels Storage Interconnected SW/GW Subsidence
MicroFEM	*Finite-element groundwater flow code.*	*http://www.microfem.com/*	*Hemker, C.J., MicroFEM for Windows – Short User's Guide*	*Dr. C.J. Hemker*	*Groundwater levels* *Storage* *Interconnected SW/GW*
SACFEM	*MicroFEM application for the Sacramento Valley Groundwater Basin.*		*USBR. 2015. SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model User's Manual*	*CH2M*	*Groundwater levels* *Storage* *Interconnected SW/GW*
INFIL 3.0	Watershed model to estimate net infiltration below the root zone.	http://water.usgs.gov/nrp/gwsoftware/Infil/Infil.html	U.S. Geological Survey, 2008, Documentation of computer program INFIL3.0-A distributed-parameter watershed model to estimate net infiltration below the root zone: U.S. Geological Survey Scientific Investigations Report 2008-5006.	USGS	

Notes:

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

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