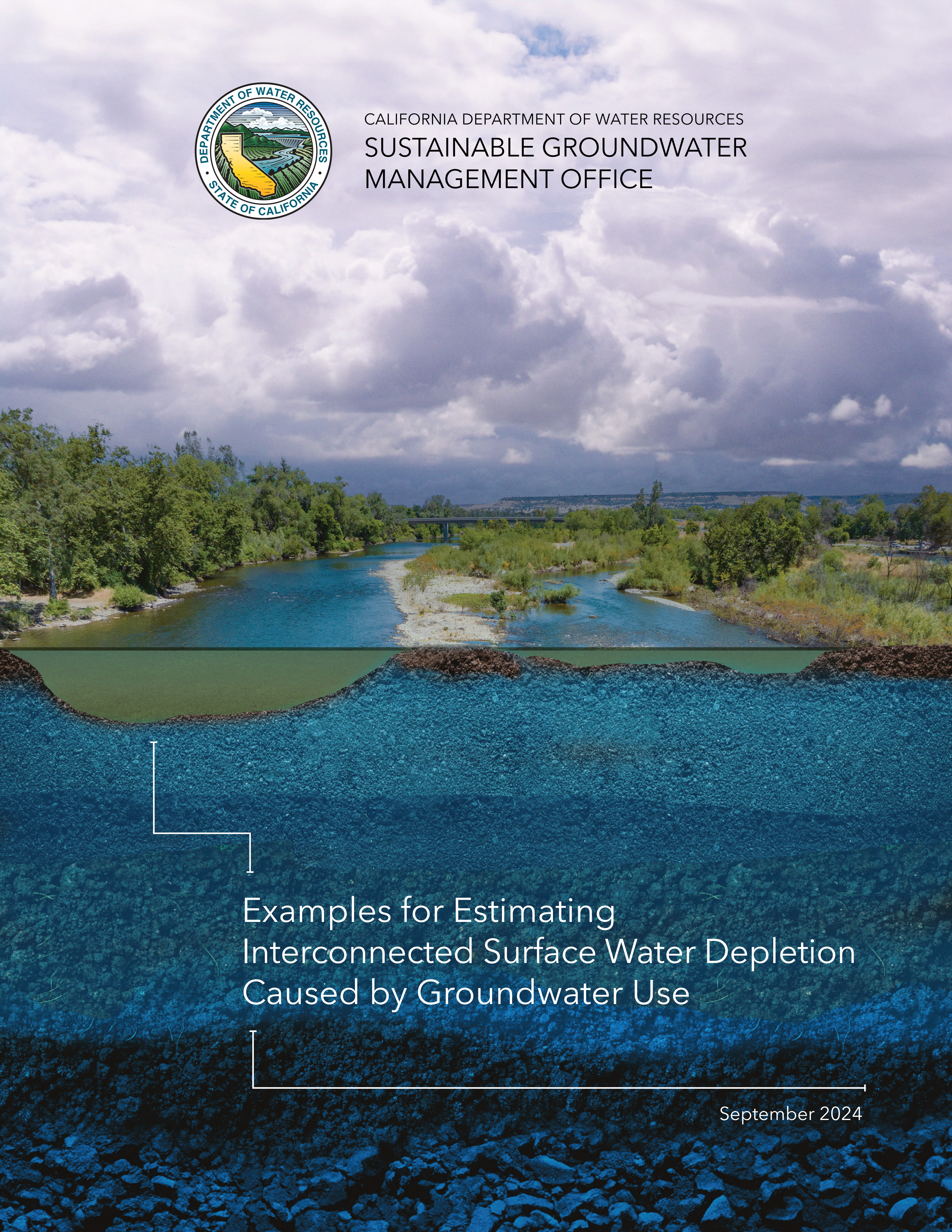
CALIFORNIA DEPARTMENT OF WATER RESOURCES

SUSTAINABLE GROUNDWATER
MANAGEMENT OFFICE



# Examples for Estimating Interconnected Surface Water Depletion Caused by Groundwater Use

September 2024

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# 1 Introduction

The California Department of Water Resources (DWR) developed a three-paper series on interconnected surface water (ISW) and depletion of ISW to provide water managers with the tools necessary to determine the location, quantity, and timing of ISW depletion caused by groundwater use. Paper 1, “Depletions of Interconnected Surface Water: An Introduction,” covered concepts associated with the interaction between surface water and groundwater and provided approaches for identifying ISW and defining depletion of ISW from groundwater pumping. Paper 2, “Techniques for Estimating Depletion of Interconnected Surface Water Caused by Groundwater Use,” discussed the data requirements for ISW depletion analyses, the methods that groundwater sustainability agencies (GSAs) or groundwater managers are likely to consider, and the general process that GSAs would follow to implement an ISW depletion analysis using a numerical groundwater model.

This paper continues and expands on concepts presented in Paper 2 by providing two detailed examples of using numerical models to evaluate ISW depletion. As described in Paper 2, ISW depletion caused by groundwater use is typically estimated using either numerical groundwater models or analytical methods. Numerical models are generally better able to accommodate complex groundwater, land surface, and surface water conditions than analytical methods. DWR has observed that more than 90 percent of basins with submitted groundwater sustainability plans (GSPs) used a numerical groundwater model in some way to support development of the GSP. Many of those basins will likely continue to use numerical models to estimate ISW depletion, so this paper focuses on examples using numerical models.

The examples discussed in this paper are hypothetical, but generally represent conditions found in many of California’s groundwater basins and subbasins. It is important to note that all basins and subbasins are unique, and groundwater managers will need to develop estimates of the location, quantity, and timing of ISW depletion that are appropriate for their conditions and consistent with the requirements of the Sustainable Groundwater Management Act (SGMA).

# 2 Examples of ISW Depletion Analyses

This section provides examples of ISW depletion analyses for two hypothetical basins intended to resemble typical groundwater basins in California.

1. Example Basin 1 is a groundwater basin subdivided into two subbasins with multiple streams and aquifers. It is intended to represent a basin with a relatively longer response time between pumping and ISW depletion, which is

characteristic of basins that are relatively larger, with greater hydrogeologic complexity (e.g., confining layers), pumping from deeper aquifers, and where pumping is more distant, both horizontally and vertically, from ISWs.

2. Example Basin 2 presents a relatively narrow alluvial groundwater basin with a single stream. In contrast with Example Basin 1, Example Basin 2 represents those basins with relatively shorter response times between pumping and ISW depletion. Shorter response times are characteristic of relatively smaller basins, basins composed of materials that more readily transmit water (e.g., coarser materials with fewer clay lenses and layers), and where pumping occurs relatively nearer to surface water bodies.

The hypothetical examples demonstrate the methodology for ISW depletion analyses and present the types of outputs from those analyses that groundwater managers can use to describe the location, quantity, and timing of ISW depletion. Readers should focus on the broadly applicable concepts and know that the specific details must be tailored to their basin.

## 2.1 Process to Evaluate ISW Depletion with a Numerical Model

As described in Paper 2, groundwater managers can use numerical models to estimate the location, quantity, and timing of ISW depletion. At a high level, and as explained by the USGS in Circular 1376 (Barlow and Leake, 2012), the process to estimate ISW depletion consists of the following steps:

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

This paper includes two hypothetical example basins, each with an associated numerical model. For both examples, ISW depletion is estimated over 100 years, with the first 50 years representing historical conditions and the second 50 years representing projected conditions. Multiple projected scenarios (e.g., with groundwater pumping expansion at historical rates [referred to in this paper as the *baseline scenario*] or with the implementation of various projects and management actions such as pumping limits) are shown for one of the examples. Note that groundwater managers may not need to develop a projected baseline scenario with the same assumptions used here (i.e., a status-quo scenario where future pumping rates continue to change in proportion to their historical trends) for GSP compliance purposes, but it is used in these papers to show how projects and management actions can modulate the amount of estimated ISW depletion.

For each example, a without-pumping scenario was developed. For simplicity in removing the pumping effects, the without-pumping scenario assumed groundwater-supplied agricultural land was converted to native land, and the associated pumping and irrigation recharge was set to zero. Groundwater managers will need to carefully consider the appropriate assumptions when developing a without-pumping scenario for their basin, keeping in mind the purpose of supporting an analysis of the depletion of ISW caused by groundwater pumping. When using the relatively complex, integrated groundwater and surface water models used for many of California's groundwater basins, groundwater managers could, for instance, assume that agricultural demands would be met by a hypothetical surface water source, resulting in no groundwater pumping. The decisions that go into setting up the without-pumping scenario will vary on a case-by-case basis but should be fully described in a basin's GSP. In this paper and where applicable, urban pumping was also assumed to be zero for the without-pumping scenarios, assuming that the urban groundwater supply was replaced by imported water.

## 2.2 Example Basin 1

Example Basin 1 (Basin 1) is a hypothetical groundwater basin subdivided into two subbasins. The hydrology, hydrogeology, and water use for Basin 1 are intended to be similar to those of (sub)basins with relatively longer response times between pumping and ISW depletion.

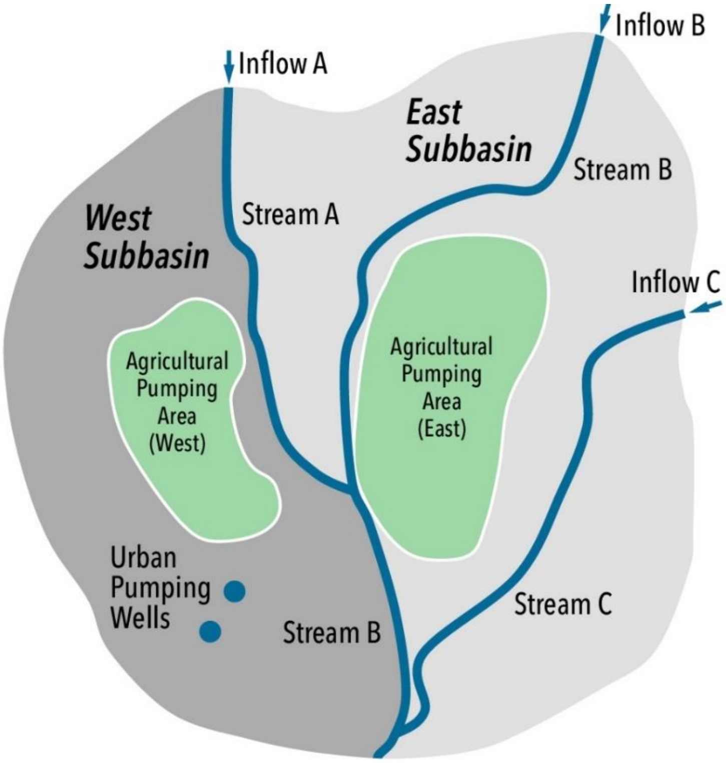
### 2.2.1 Basin Setting

Basin 1 is subdivided into two subbasins, West and East, with an area of 12,000 acres and 19,000 acres, respectively, and it has three perennial streams (**Figure 1**). Stream B is the primary stream flowing from north to south through the basin, and Streams A and C are tributaries to Stream B. Each stream has portions in the upper reaches that do not have a hydraulic connection with the groundwater system. The West Subbasin is the portion of Basin 1 west of Stream A and west of Stream B below its confluence with Stream A. The East Subbasin is the portion of Basin 1 east of Stream A and east of Stream B below its confluence with Stream A.

Basin 1 has two aquifers: a shallow, unconfined aquifer and a deep aquifer. The two aquifers are separated by a confining clay unit covering only a portion of the basin, resulting in semi-confined conditions for the deep aquifer.

Each subbasin has an agricultural area which relies on groundwater within its boundaries. The West Subbasin also includes an urban area that relies on groundwater for its supplies.

*Figure 1: Map of Example Basin 1.*



## 2.2.2 With-Pumping Scenario

Following the stepwise method (presented in Paper 2) for using a numerical model to estimate ISW depletion noted above, the numerical model for Basin 1 was first run for a with-pumping scenario. In this example, the with-pumping scenario includes 50 years of historical pumping and 50 years of projected pumping, and pumping in the projected period is set to increase at the same rate as pumping increased during the historical period.  The historical and projected periods are combined into one scenario, named the *baseline scenario*. **Figure 2** shows the annual pumping and net stream gain for the *baseline scenario*. Pumping rates steadily increased in the basin, and net stream gain decreased correspondingly. Water from the aquifer entered the streams at an average of 10,000 acre-feet per year during the historical period, with the highest net annual stream gain of approximately 20,000 acre-feet during the early portion of the historical period. There were short periods towards the end of the historical period where, on an annual basis and at a basinwide scale, the streams periodically lost surface water to the groundwater. As pumping continued to increase during the projected baseline period, the streams switched to mostly losing conditions.

*Figure 2: Annual pumping and net stream gain throughout Basin 1 for the baseline scenario.*

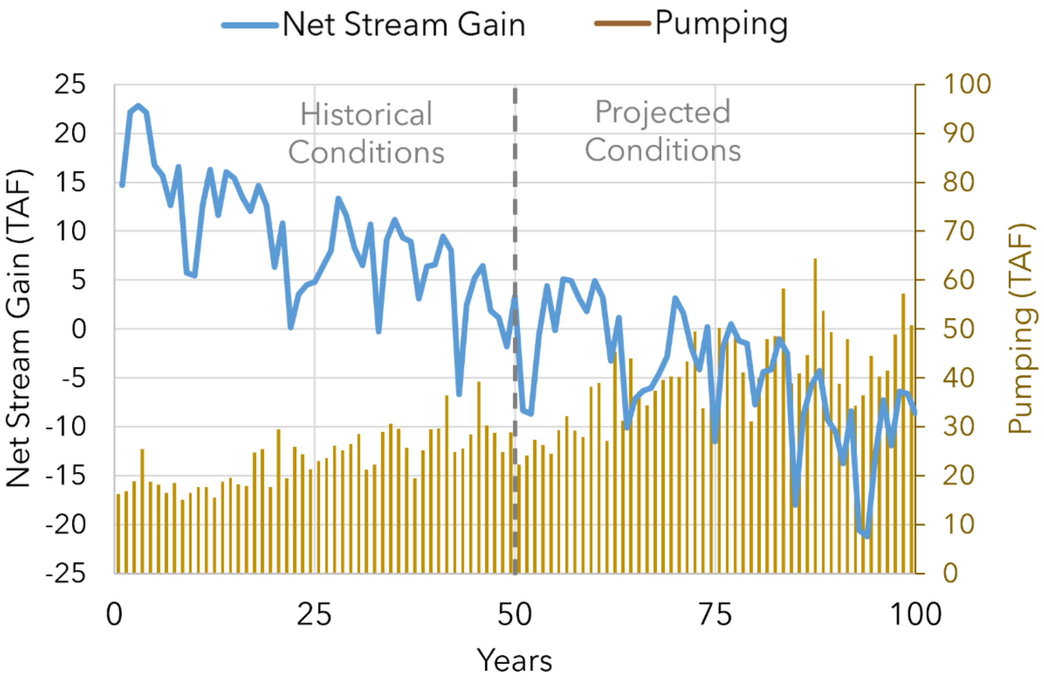


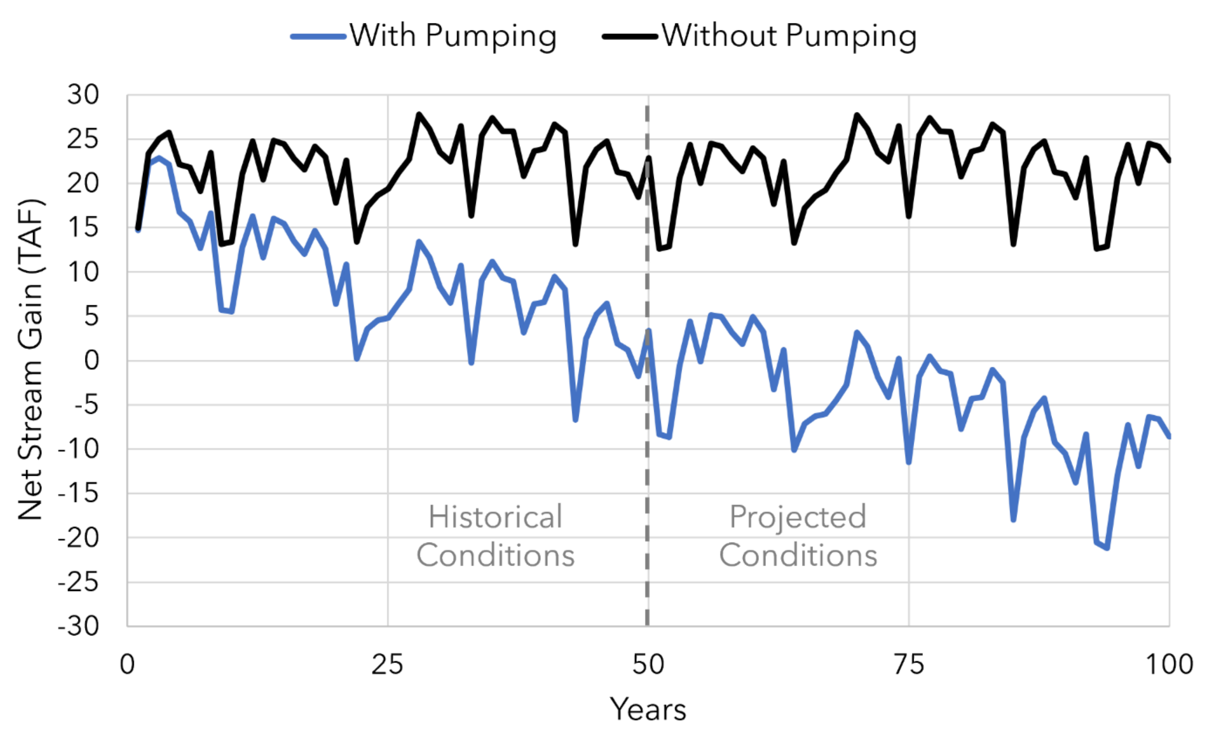
**Figure 2** illustrates the general relationship between increased pumping and changes in net stream gain. However, net stream gain can be affected by several factors, including seasonal and annual hydrology, rainfall runoff, tributary flows, groundwater operations, surface water diversion, irrigation tailwater, and return flows. Therefore, estimating the effects of ISW depletion caused by groundwater pumping requires additional analyses, as described in the three-step process outlined in Section 2.1.

### 2.2.3 Basinwide Without-Pumping Scenario and Estimated ISW Depletion

A hypothetical, 100-year *without-pumping scenario* was run to quantify the depletion of ISWs by basinwide groundwater pumping. The *without-pumping scenario* represents how flows between the stream and groundwater would occur without the effects of groundwater pumping. As described above, in this example, the *without-pumping scenario* assumes that the agricultural land is converted to native land with no associated pumping and, thus, no recharge from applied irrigation. Groundwater recharge from other sources (e.g., from precipitation) is the same between the with-pumping and the without-pumping scenarios.

**Figure 3** shows the net stream gain for the *without-pumping scenario* compared with the net stream gain from the *baseline scenario* (i.e., the same net stream gain information shown in **Figure 2**). Without basinwide groundwater pumping, the numerical model estimates that the streams would gain approximately 15-20 thousand acre-feet per year for the historical and projected periods. The resultant difference between the net stream gain in the *without-pumping scenario* and the *baseline scenario* is the depletion caused by basinwide groundwater pumping, which is shown in **Figure 4**.[1]

*Figure 3: Annual net stream gain throughout Basin 1 for the baseline scenario and the without-pumping scenario.*



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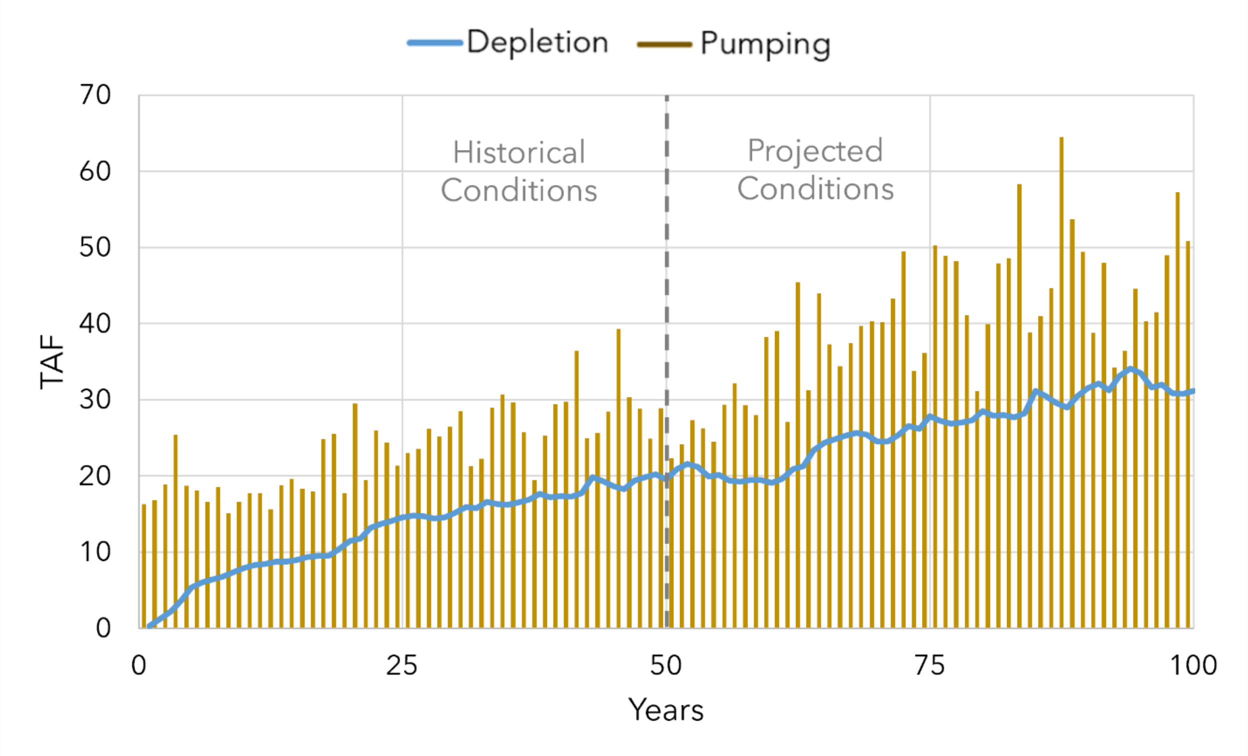
[1] For simplicity in the remainder of this document, depletion is often referred to as being from a particular *with-pumping scenario*. In reality, the depletion is calculated as the difference between net stream gain for a *without-pumping scenario* and a *with-pumping scenario*.

*Figure 4: Annual pumping and stream depletion throughout Basin 1 for the baseline scenario.*

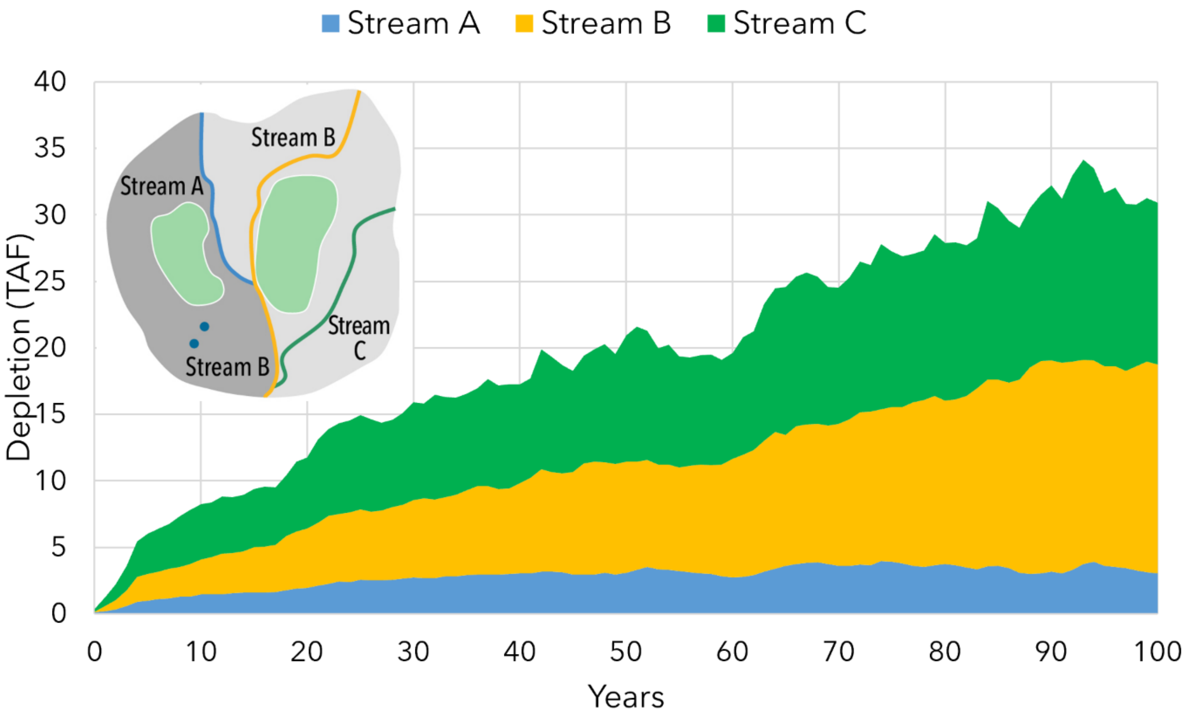


### 2.2.3.1 Location of Depletion Due to Basinwide Pumping

While **Figure 4** displays depletion from all streams in Basin 1, the depletion occurs in the different streams at different times and quantities. **Figure 5** shows the amount of depletion from each of the three streams in Basin 1 for the *baseline scenario* as a series of stacked curves. Stream A is higher in elevation, and for much of its length, except a quarter mile stretch near the confluence with Stream B, it is disconnected from the groundwater system. In the context of ISW depletion, disconnection means changes in groundwater pumping do not affect the net stream gain (see Paper 1). Because most of Stream A is disconnected, groundwater pumping in the basin depletes Stream A the least. Streams B and C are disconnected in the upper reaches and connected in the lower reaches (approximately the lower three miles)–groundwater pumping in the basin has the greatest depletion impact on both these streams.

Although not shown in the paper, numerical models lend themselves well for further refinement of depletion locations within subsections of a stream. Groundwater managers can use these same techniques to evaluate depletion along a specific reach of an ISW if warranted in their basin (e.g., if a particular reach of an ISW is sensitive to reduced flow).

*Figure 5: Stacked annual depletion from each stream in Basin 1 for the baseline scenario.*



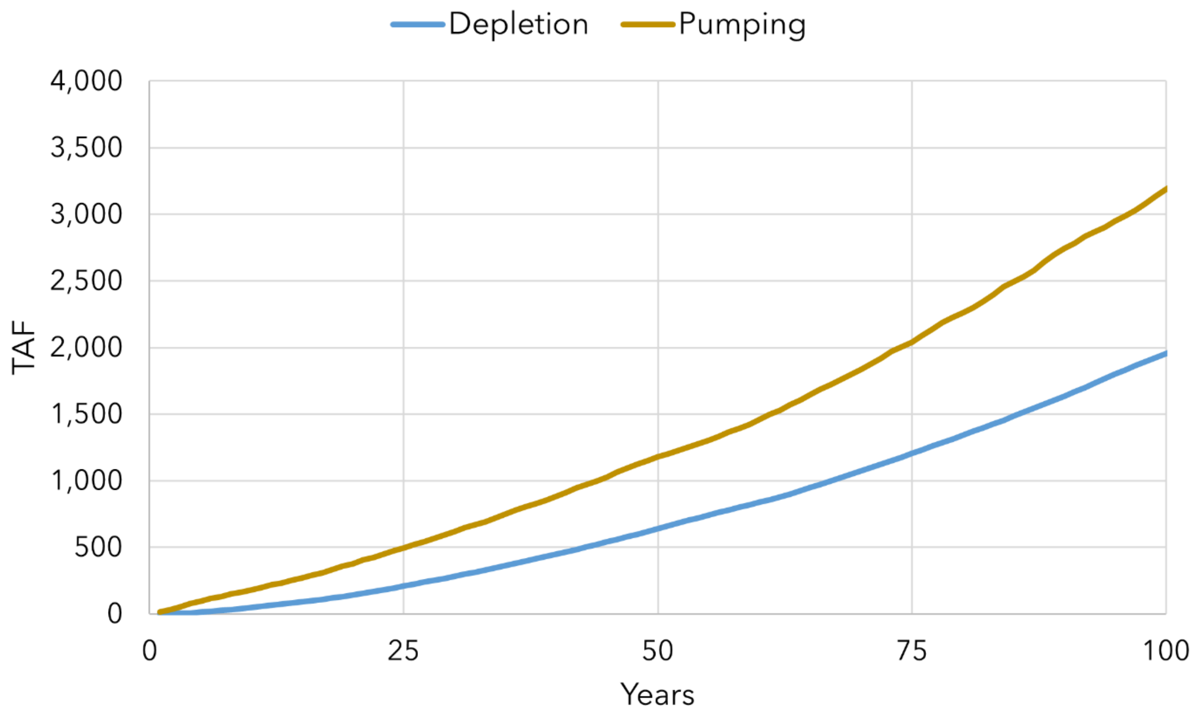
### *2.2.3.2 Time Lag Between Pumping and ISW Depletion*

This subsection discusses one component of the timing of ISW depletion – how to interpret information about the time lag between pumping and depletion.

Without pumping, groundwater in aquifers flows toward and eventually discharges from outflow points (e.g., ISW, locations where groundwater is subject to direct evapotranspiration by phreatophyte vegetation, or outflows to adjacent basins). When groundwater is pumped and consumptively used, it results in a one-for-one capture of groundwater that would otherwise be discharged to those outflow points. When groundwater pumping starts in a basin, the pumped water initially comes from aquifer storage. In basins with ISWs, stream depletion begins as the groundwater levels decline over a larger area and begin to change the steam-aquifer interaction (i.e., increasing stream losses or decreasing stream gains). There will be a lag between the timing of the groundwater pumping and the start of stream depletion. This lag is a function of characteristics such as distance between the wells and the ISWs, pumping depths, and aquifer and streambed properties.

**Figure 4** shows this lag; as the simulation period (and thus, pumping) begins, ISW depletion starts at zero. Depletion begins to ramp up despite a relatively steady pumping quantity in the first 10 to 15 years. As pumping rates increase, the amount of ISW depletion also increases, but it doesn't "catch up" with the pumping rates due to the lag. An alternate way to visualize this phenomenon is to examine the cumulative amount of depletion. As **Figure 6** shows, the cumulative quantity of groundwater pumped after a specific time (e.g., 1.2 million acre-feet by year 50) is significantly ahead of the amount of depletion (which doesn't reach 1.2 million acre-feet until approximately year 75).

*Figure 6: Cumulative pumping and depletion throughout Basin 1 for the baseline scenario.*



Another way to understand the lag between pumping and depletion is to use the numerical model to evaluate a *projected-no-pumping scenario* instead of the *baseline scenario* used in the above examples. In the *projected-no-pumping scenario*, pumping in the 50-year historical period is included, but pumping in the 50-year projected period is turned off. The difference between the *projected-no-pumping scenario* and the 100-year *without-pumping scenario* (**Figure 7**) shows how historical pumping activities impact future quantities of depletion. As **Figure 7** shows, depletion caused by historical pumping practices slowly decreases over time but extends more than 25 years into the future. **Figure 7** helps illustrate two important points. First, the quantity of depletion shown during the projected period, which others have referred to as residual depletion,[2] is effectively "locked in." That is to say,

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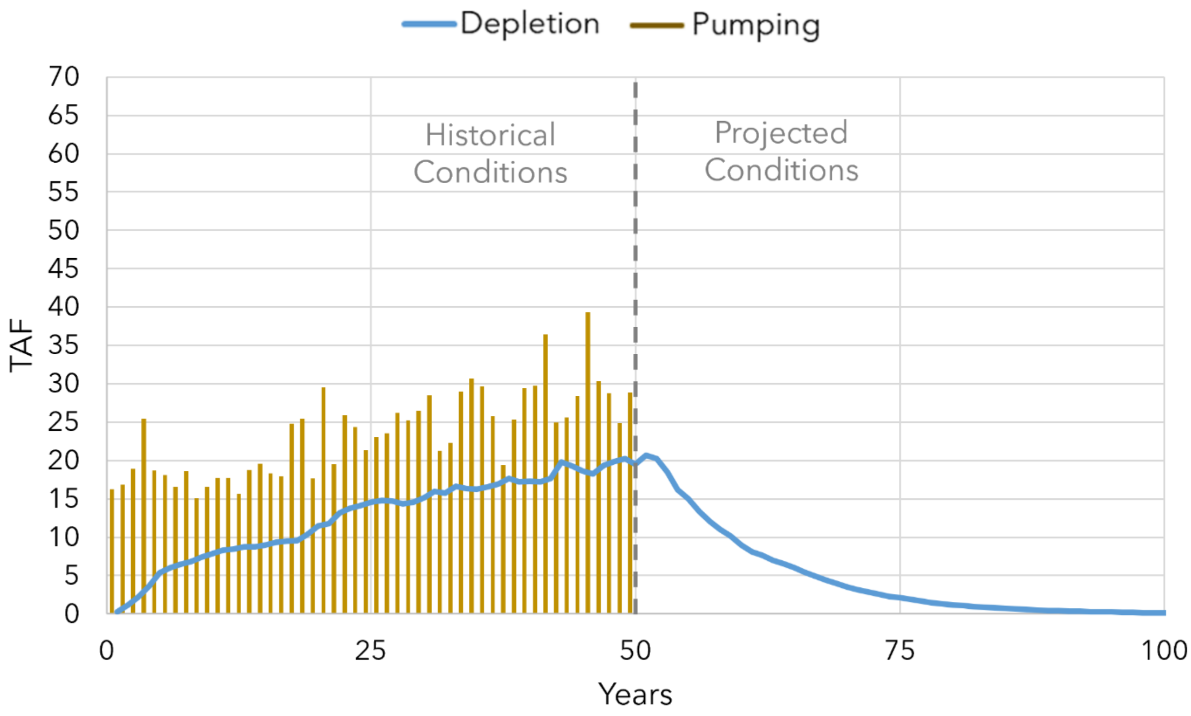
[2] See e.g., Nebraska Department of Natural Resources, 2010, Number 5, Water Matters Newsletter, "Stream Depletion and Groundwater Pumping Part Two: The Timing of Groundwater Depletions", [https://dnr.nebraska.gov/sites/dnr.nebraska.gov/files/doc/water-planning/water-matters/WaterMatters_No5.pdf](https://dnr.nebraska.gov/sites/dnr.nebraska.gov/files/doc/water-planning/water-matters/WaterMatters_No5.pdf)

a groundwater manager in Basin 1 who was trying to manage depletion for a future management period (the 50-year projected period, in this case) would know that there was nothing they could effectively do to reduce the residual depletion; it is entirely caused by historical pumping practices, which cannot be changed. The second point, which is related to the first, is that projects or management actions implemented early in the management period (i.e., early in the 50-year projected period) may have a limited impact on the quantity of depletion in that same early time. The depletion quantity early in the management period is predominately comprised of residual depletion.

*Figure 7: Annual pumping and depletion throughout Basin 1 for the projected-no-pumping scenario.*

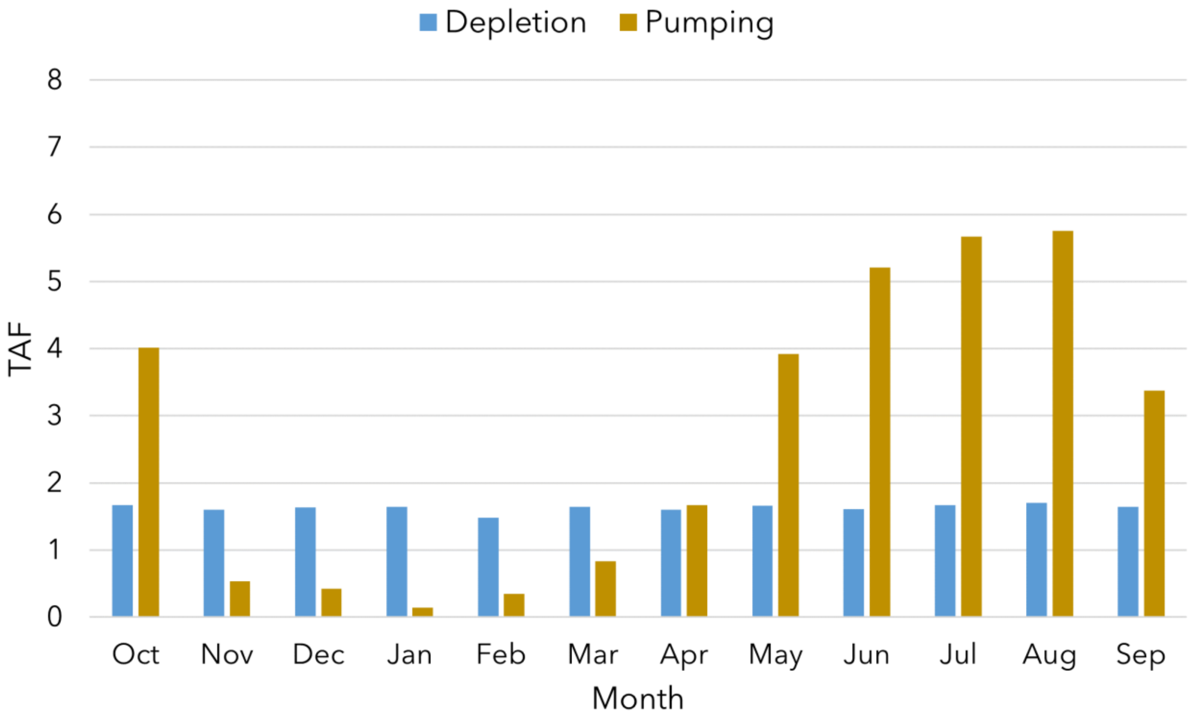


The figures above show that the groundwater and surface water systems in Basin 1 are not in equilibrium during the historical or projected baseline periods. Groundwater and surface water systems would be in equilibrium when the quantity of groundwater withdrawal (pumping) is equivalent to the amount of captured surface water flow (depletion in this example; pumping can also capture other surface discharges like direct evapotranspiration of groundwater, but that is not applicable in Basin 1). Once a basin is in a state of equilibrium, changes in pumping would disrupt the equilibrium, and the time it would take to return to equilibrium following subsequent stabilization of pumping would depend on the lag described above. With Basin 1 as the example and using the end of the historical period as the point of examination (which could, for example, represent the "current" state of the system), a groundwater manager would observe that the basin is not in a state of equilibrium between pumping and ISW depletion because groundwater pumping is generally increasing and, as **Figure 6** shows, the quantity of depletion lags the quantity of pumping by roughly 25 years. In that example, the groundwater manager should assume that ISW depletion will continue to increase until pumping quantities stabilize and, subject to the time lag, a new equilibrium is reached.

#### *2.2.3.3 Timing of ISW Depletion by Season and Year Type*

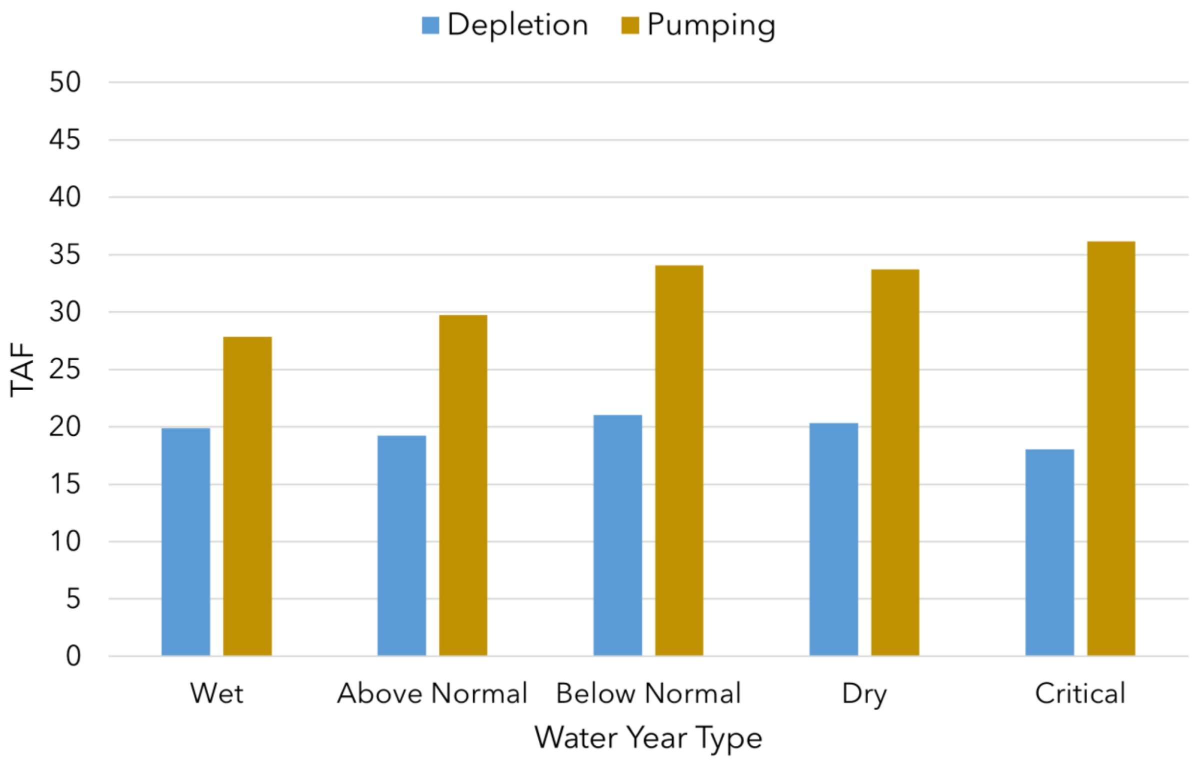
**Figure 8** shows the monthly average of depletion and pumping over the 100-year *baseline scenario*. The annual cycle of groundwater pumping in Basin 1 is typical of agricultural areas, with higher pumping in the irrigation season (May through October) and lower pumping in the winter and early spring. The depletion pattern, however, is relatively steady, which is explained by the lag effect noted above. Because the pumping wells are spread horizontally within the relatively large basin and vertically within the basin's aquifers, and because the quantity of pumping increases relatively steadily (i.e., there are no years of high groundwater pumping followed by years of no groundwater use), the depletion is effectively spread out to a relatively steady rate across all months. This phenomenon is expected to be present in many of California's larger basins and subbasins.

*Figure 8: Distribution of average pumping and depletion by month in Basin 1 for the 100-year baseline scenario.*



Similarly, **Figure 9** shows patterns of pumping and depletion for Basin 1 in different water-year types. Pumping in the basin increases in relatively drier years (below normal, dry, and critical year types), but depletion remains relatively stable. Again, this phenomenon is related to the lag between pumping and depletion. The depletion caused by increased pumping in drier water-year types may take years to occur and, therefore, may occur in years that are not dry.

*Figure 9: Distribution of average pumping and depletion by water-year type in Basin 1 for the 100-year baseline scenario.*



Evaluating whether there are seasonal or water-year-type trends in ISW depletion is not an explicit requirement of the GSP Regulations; although, it may be helpful in areas where groundwater managers identify the need to manage depletion for specific periods or specific hydrologic conditions. **Figure 8** and **Figure 9** show, however, that in cases like Basin 1, *basinwide* management strategies that are responsive to specific periodic or hydrologic conditions are unlikely to be effective. For example, suppose groundwater managers in Basin 1 are interested in limiting the quantity of depletion of the Basin's streams during the summer months of dry and critically dry years. In that case, the time lag and diffuse pumping mean there is no particular time when basinwide pumping reductions would have that intended effect. Instead, a basinwide pumping reduction would modulate the relatively flat depletion curve downward, reducing depletion across all months and water year types. Focused management strategies, which could include pumping management actions at targeted groups of wells, may be needed, and these types of strategies are discussed below in Section 2.2.5.3.

**Figure 8** and **Figure 9** help to illustrate another important point—that depletion due to historical pumping continues despite the occurrence of relatively wetter periods. It may be a common misconception that ISW depletion is reset or erased following a wet year. Depletion due to past pumping does not disappear or substantially reduce during wet months or wet years in most basins with groundwater levels well below the land surface. Wet years can cause more recharge to occur, but that increased recharge would happen regardless of pumping, and the amount of recharge does not depend on groundwater levels (i.e., groundwater recharge doesn't increase if groundwater levels are lower). Depletion of ISW does, however, increase with increasing pumping, either by increasing the flow from the stream to the aquifer, reducing the flow from the aquifer to the stream, or both. Although depletion due to past pumping does not reduce in wet years, the effect of that depletion on beneficial users of surface water may be reduced in wet years when those users are less sensitive to the reduction in surface water flows or stage.

### 2.2.4 Process for Estimating Depletion Caused by Pumping from a Specified Portion of a Basin

The previous section describes the estimation of ISW depletion due to pumping throughout Basin 1. This section explores the depletion caused by pumping within the individual subbasins. The discussion focuses on the effects of pumping in one subbasin on the streams within Basin 1 and, importantly, on streams within the neighboring subbasin. It is important to note that the process described is the same that could be used if Basin 1 had not been subdivided into subbasins but instead had two GSAs (e.g., West GSA and East GSA) or two management areas.

**Figure 10** displays annual pumping from the West Subbasin and the corresponding depletion throughout Basin 1 caused by that pumping. The process used to estimate the West Subbasin's depletion is the same three-step process described in Section 2.1. The West Subbasin first runs its numerical model in a *baseline scenario*, the same scenario described in Section 2.2.2. They then run a *without-pumping scenario* in which pumping in the West Subbasin is turned off; pumping in the remainder of the Basin (i.e., in Subbasin East) is left on, which allows West Subbasin to isolate the depletion caused by pumping within their subbasin. **Figure 11**, correspondingly, displays the annual pumping from the East Subbasin and the depletion throughout Basin 1 caused by that pumping.

*Figure 10: Depletion for all streams in Basin 1 due to pumping in the West Subbasin.*

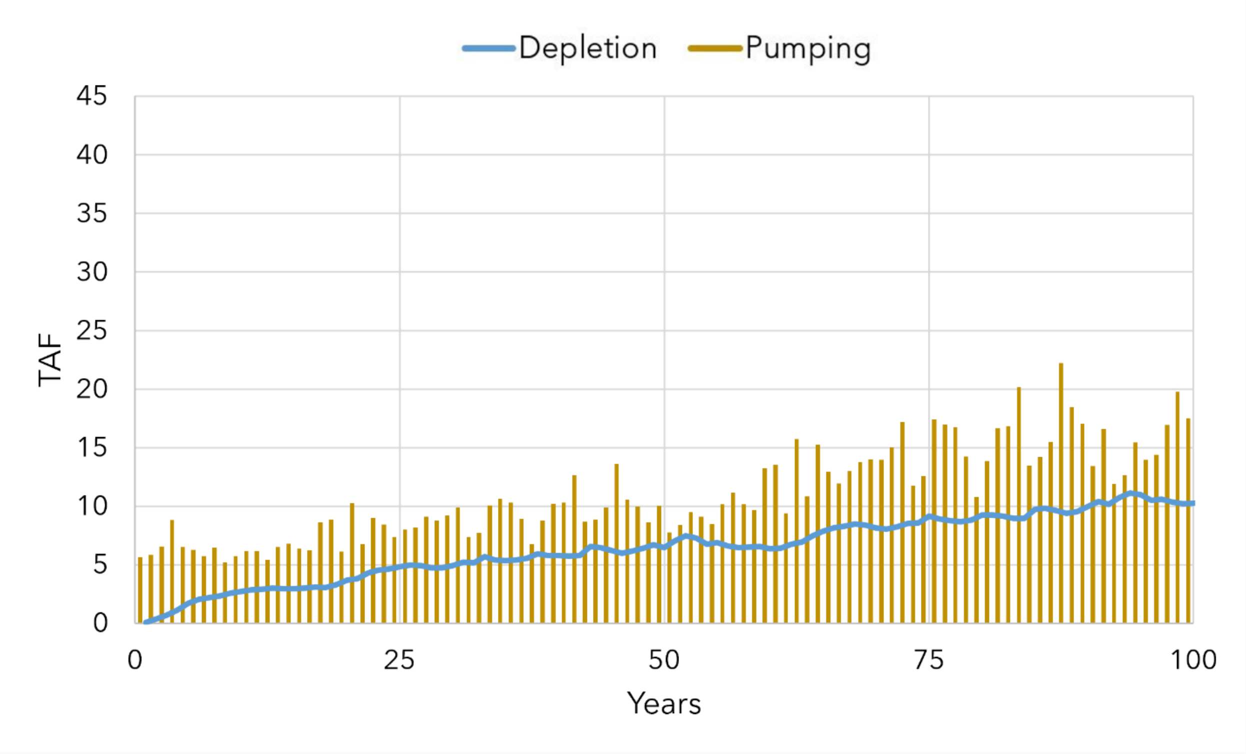
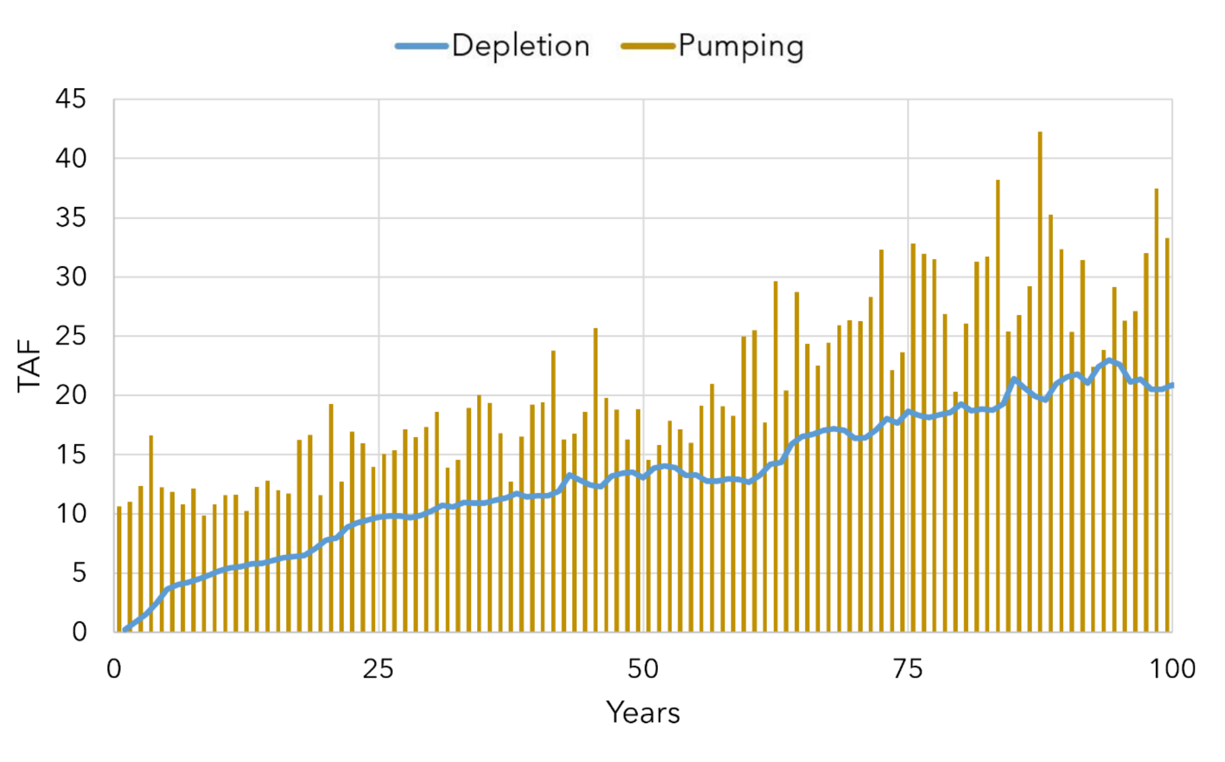


*Figure 11: Depletion for all streams in Basin 1 due to pumping in the East Subbasin.*



The West and East subbasins contribute approximately one-third and two-thirds, respectively, of the total pumping in Basin 1. Pumping in the two subbasins also causes depletion in the same proportion, with approximately 10,000 and 20,000 acre-feet per year of depletion in Year 100 caused by the West and East subbasins, respectively.

Depletion caused by pumping from each subbasin on the three streams in Basin 1 is shown in **Figure 12** through **Figure** 14. **Figure 12** and **Figure 13** show the quantity of depletion from each stream caused by pumping in the West and East subbasin, respectively. **Figure 14** shows the total amount of depletion for each stream but separates the total into the portion attributable to pumping in each subbasin. The figures show that, of the three streams, groundwater pumping depletes Stream A the least. As noted above, Stream A is disconnected for much of its length, with the only hydraulically connected portion being the lower reach near the confluence with Stream B. Wells in the agricultural pumping area of the East Subbasin are located nearer to the connected portion of Stream A than wells in the agricultural pumping area of the West Subbasin. Therefore, **Figure 14** shows that the majority of the depletion of Stream A is caused by pumping from the East Subbasin.

*Figure 12: Stacked annual depletion for individual streams in Basin 1 caused by pumping in the West Subbasin.*

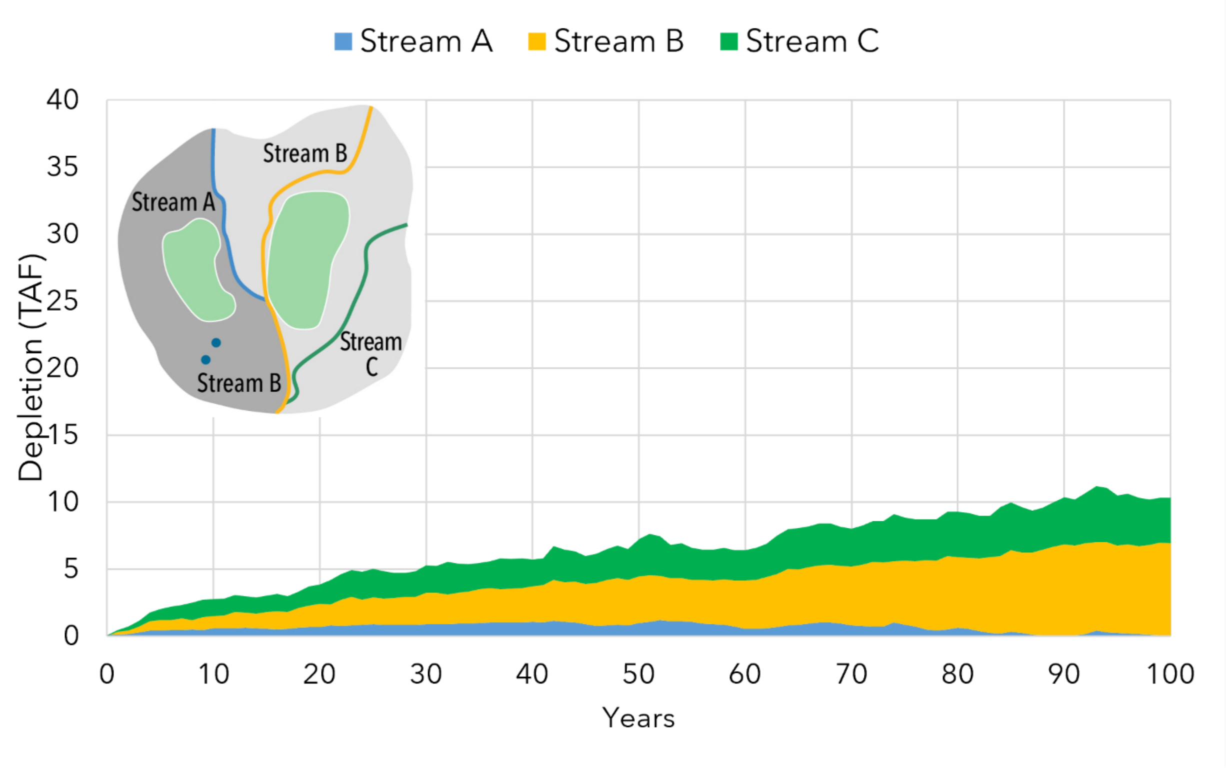
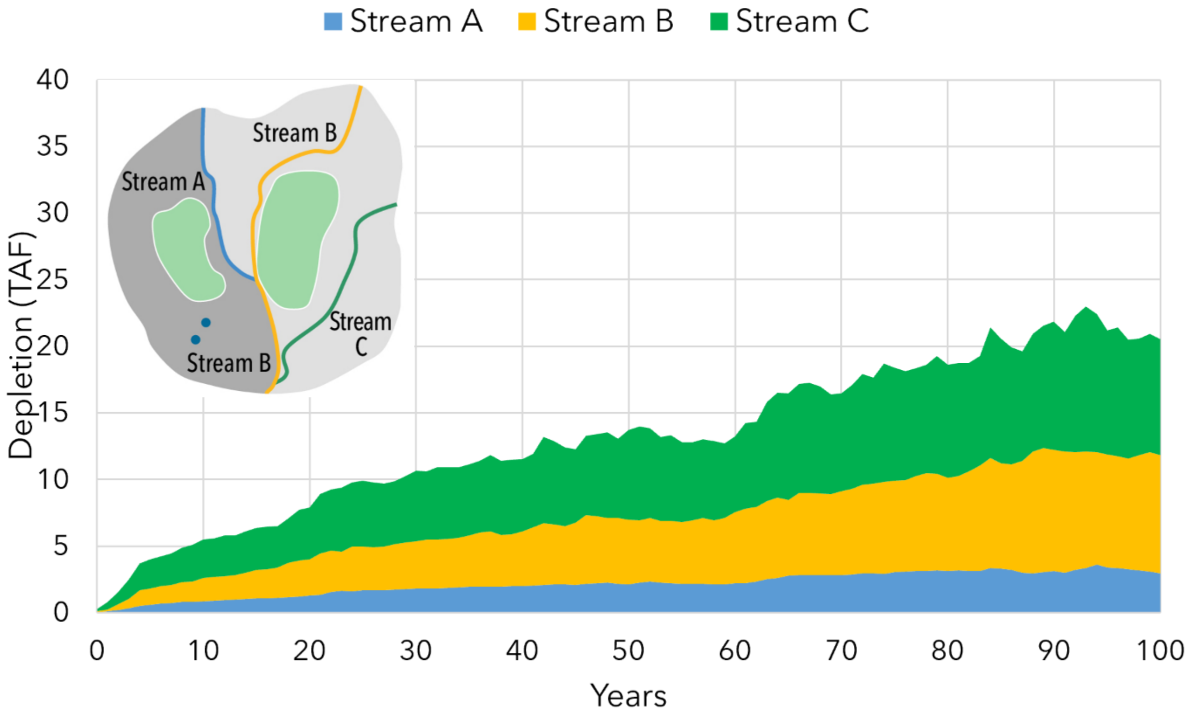


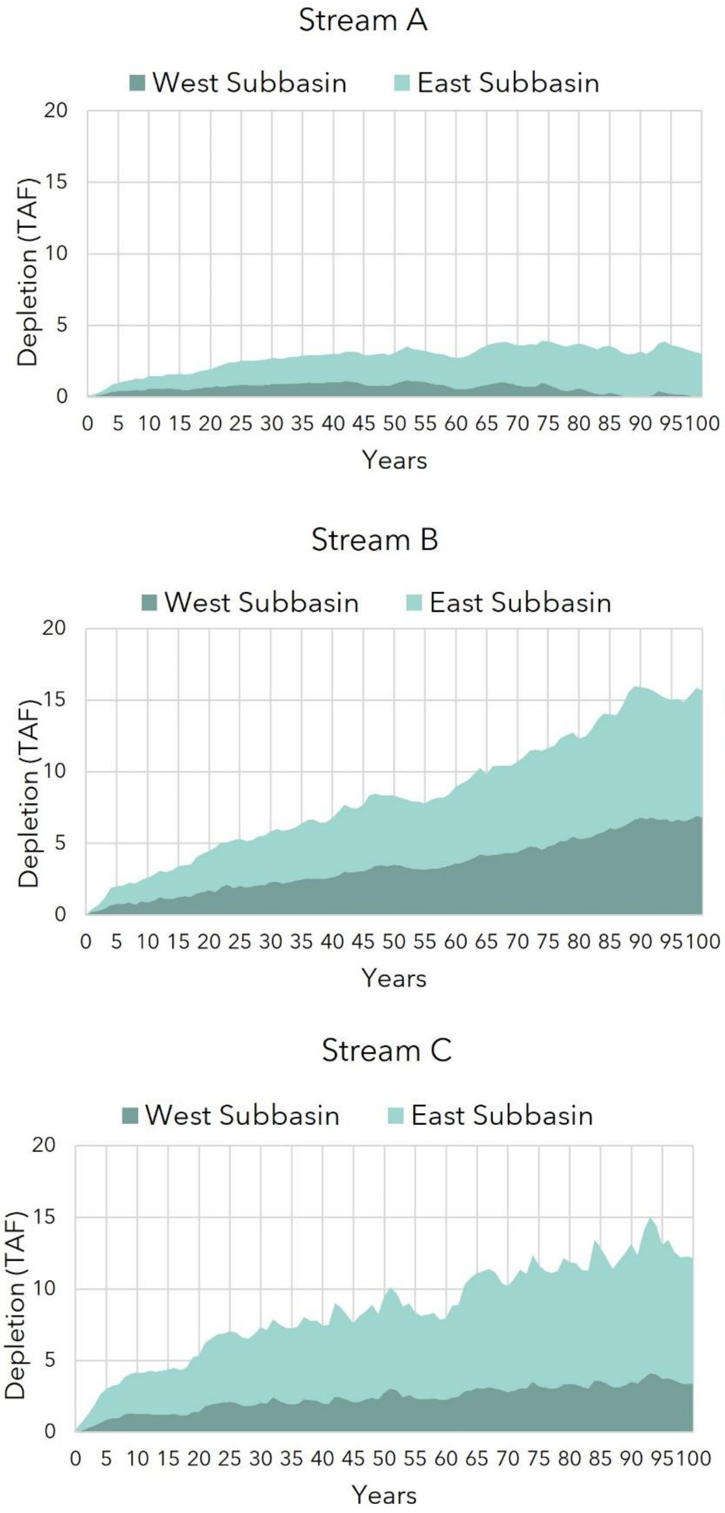
*Figure 13: Stacked annual depletion for individual streams in Basin 1 caused by pumping in the East Subbasin.*

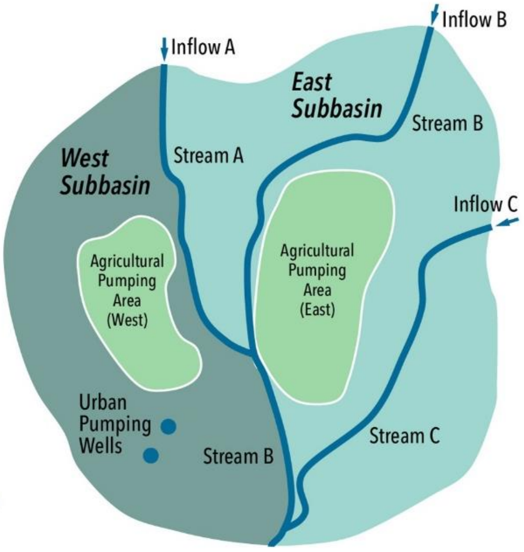


The lower reach of Stream B is aligned with the boundary of the two subbasins. Unsurprisingly, Stream B is depleted due to pumping in both subbasins in approximately the same proportion as the pumping.

**Figure 12** and **Figure 14** both show that pumping in the West Subbasin results in the depletion of Stream C. This may appear counterintuitive initially because Stream C is wholly located within the East Subbasin and is separated from the West Subbasin by Stream B, a hydrological boundary. However, the numerical model indicates that the lowered heads caused by the West Subbasin's pumping extend into areas in the adjacent subbasin beyond Stream B, crossing the shallow hydrological subbasin boundary. This result is noteworthy because it demonstrates the potential importance of looking beyond subbasin (and GSA, management area, etc.) boundaries when evaluating ISW depletion. Although not illustrated in this example, the extent of these spatial effects is not limited to streams regionally downgradient from the pumping; depletion can occur in streams that are upgradient of pumping areas.

*Figure 14: Stacked depletion of each stream caused by pumping from the West and East subbasins.*





These results highlight the importance of selecting the spatial extent of numerical models. In this example, groundwater managers in the West Subbasin could only assess the effect of their subbasin's pumping on Stream C because the numerical model included the additional area in Basin 1 outside their boundary. As noted in Paper 2, many subbasins in California have developed models that, for valid reasons, only include their subbasins or limited surrounding areas within the larger basin they reside in. Those models will be limited in their ability to assess ISW depletion outside the extent of the modeled area. Although not shown in this paper, if the West Subbasin had only developed a model for their area (i.e., excluding the East Subbasin), they likely would have used some type of head-dependent boundary condition along or near Streams A and B. In that case, they would need to use caution in estimating the depletion from Streams A and B, particularly for the projected period, and they could not use the methods described in this paper to estimate the depletion from Stream C. Rather, if the model's boundary conditions are appropriately developed, they might be able to assess the out-of-basin depletion quantity by evaluating the changes in the simulated subsurface flow along the subbasin boundary. The location and timing of the out-of-basin depletion would, however, be unknown.

### 2.2.5 Potential Management Strategies

This subsection describes how numerical models can be used to evaluate how changes in groundwater management, including implementing projects and management actions, can modulate the estimated ISW depletion. This type of analysis can be useful for groundwater managers to identify whether their projects and management actions are sufficient to avoid exceeding their identified minimum thresholds. This paper does not address how minimum thresholds or other sustainable management criteria should be developed, and the management-scenario examples are included for illustrative purposes only.

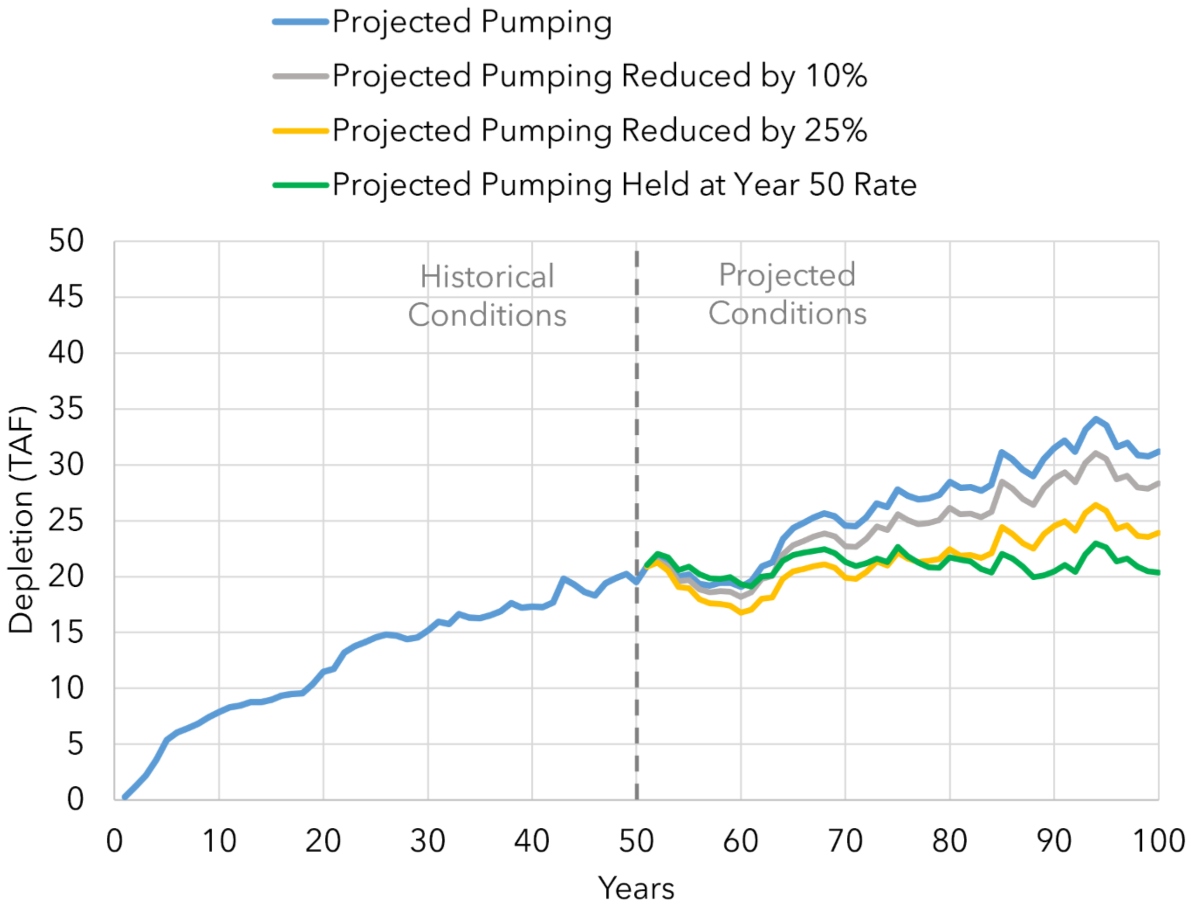
The management scenario examples presented here are categorized as demand-based, supply-based, and focused strategies. Each of the management scenarios is focused on pumping within Basin 1 and its cumulative effects on the streams, but the same concepts could be extended to evaluate the management of smaller groups of wells, e.g., within only one of the subbasins or in a management area, or to assess the effects on a particular stream or a smaller portion of a stream.

#### *2.2.5.1 Demand-Based Strategies*

To evaluate the effects of various potential demand-management scenarios, the numerical model was run so that the with-pumping scenario included reduced pumping rates for the projected period (i.e., from year 51 through 100). Recall that the *baseline scenario* assumed that groundwater pumping would increase at a rate similar to the rate of increase for the historical period. Two of the demand management scenarios evaluated here assumed that the projected pumping increase was reduced, relative to the baseline projection, by 10 percent and 25 percent, respectively. Another demand management scenario was performed that maintained a constant pumping rate at the same value used for year 50, the end of the historical period (i.e., no pumping increase).

**Figure 15** shows annual depletion estimates for each scenario. The 10- and 25-percent reduction scenarios represent an increase in pumping relative to the historical period, albeit at a reduced rate relative to the baseline projection. The resultant depletion continues to increase at a correspondingly reduced rate. Even the no-expansion scenario, which caps pumping at the rate from the end of the historical period, shows a moderate increase in depletion, resulting from the lag effect discussed earlier in this paper.

*Figure 15: Comparison of depletion under a variety of projected pumping scenarios.*



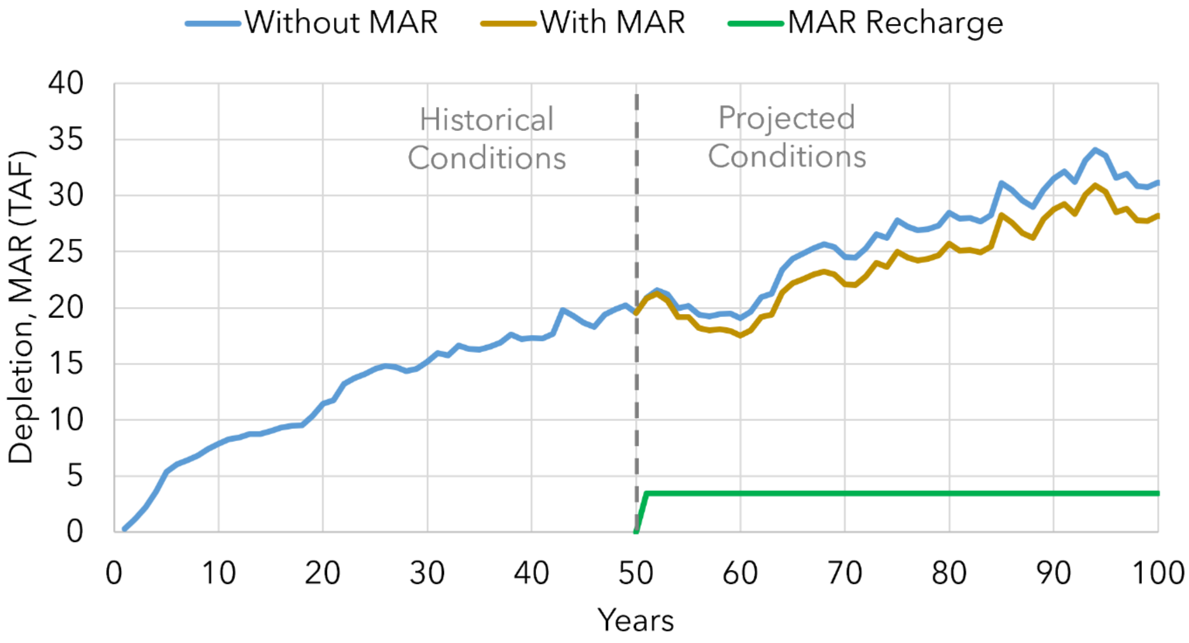
#### *2.2.5.2 Supply-Based Strategies*

This subsection demonstrates how the techniques described above to analyze ISW depletion can be used to evaluate the effects of a supply-focused management action like managed aquifer recharge (MAR) on ISW. Conceptually, because groundwater recharge (addition of water to an aquifer) is the opposite of groundwater pumping (removal of water from an aquifer), ISW flows that can be depleted by pumping can also be increased by recharge. In practice, however, it is important to note that a unit of MAR will rarely, if ever, result in a one-for-one offset to a unit of pumping in terms of the quantity, timing, and location of ISW depletion. This is because the locations and timing of MAR activities do not typically coincide with the pumping locations, particularly for MAR activities that target shallow, surficial aquifers.

A *MAR scenario* was developed in which a portion of the agricultural area in the West Subbasin was used to infiltrate water into the shallow, unconfined aquifer. The *MAR scenario* assumed 3,500 acre-feet of water was recharged from December through April each year during the 50-year projected period. The pumping quantity between the *MAR scenario* and the *baseline scenario* was unchanged.

**Figure 16** compares stream depletion for the *baseline scenario* (the same depletion curve shown in Figure 4) and the *MAR scenario*. The difference between the *MAR scenario* and the *baseline scenario* quantifies the benefits of MAR activities regarding streamflow accretion, which could interest groundwater managers if they wish to offset depletion with projects like MAR.

*Figure 16: Annual MAR volumes and depletion throughout Basin 1 for a MAR scenario compared to the baseline scenario.*



### 2.2.5.3 *Focused Management Strategies*

This subsection provides a conceptual discussion regarding using numerical models to evaluate focused groundwater management strategies to address ISW depletion. In contrast to basinwide groundwater management strategies, focused strategies could include managing targeted wells or pumping areas to alleviate ISW depletion on specific stream reaches during periods of interest. For example, pumping from specific near-stream wells, which correspondingly could cause ISW depletion at time scales ranging from days to months, could be reduced or eliminated during dry and critical years to reduce depletion.

Identifying targeted wells for managing pumping is an important step before implementing a focused management strategy. Using the techniques described in this paper, numerical models can estimate the impact of removing pumping from a group of wells, or even an individual well, on ISW depletion. This can be achieved by evaluating each well individually using a numerical model or, more practically, by only evaluating potential wells with the maximum likelihood of causing ISW depletion at the time scale of interest (e.g., high-capacity and/or shallow pumping wells near streams). An individual well or a group of wells can be turned off as a targeted well scenario in the numerical model. The difference between the with-pumping conditions and the targeted-well without-pumping scenario would provide the location, quantity, and timing of depletion caused by the well(s) of interest.

## 2.3 Example Basin 2

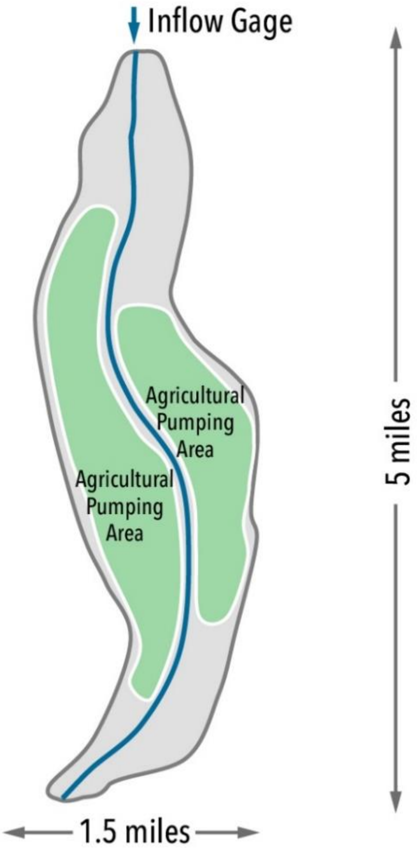
Example Basin 2 (Basin 2) is a hypothetical river valley groundwater basin. Its hydrology, hydrogeology, and water use are intended to be similar to (sub)basins with relatively shorter response times between pumping and ISW depletion. This example contrasts with the previous example in terms of the spatial and temporal scale of depletion.

### 2.3.1 Basin Setting

Basin 2 is approximately 3,000 acres and comprises an alluvial valley carved within impermeable bedrock formations by a single stream that runs from north to south (**Figure 17**). Basin 2 is approximately 5 miles long along the stream and 1.5 miles wide in the central portion of the valley. The only groundwater production in Basin 2 is pumping for agriculture.

Basin 2 comprises a single alluvial aquifer of sandy, silty, and clayey materials with uniform properties. For modeling purposes, the aquifer was divided into two layers: the first includes the shallow portion of the aquifer, where groundwater is interconnected with the stream, and the second layer consists of the deeper portion of the aquifer, where groundwater production occurs.

*Figure 17: Map of Example Basin 2*

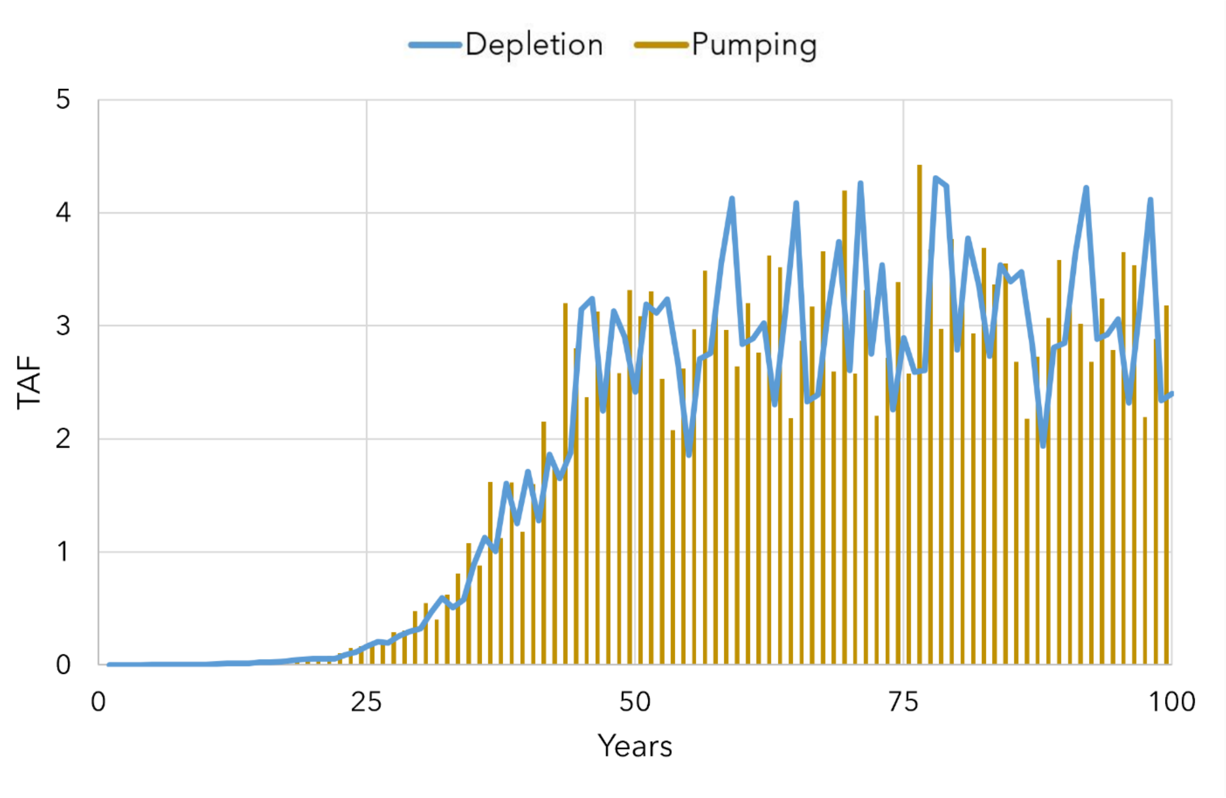


### 2.3.2 With-Pumping Scenario

Depletion in Basin 2 was estimated using the same process utilized for Example Basin 1, with the first step consisting of running the with-pumping scenario. **Figure 18** shows pumping during the 100-year *baseline scenario* in Basin 2 and the associated changes in net stream gain. As the figure shows, there was minimal pumping in the basin during the first half of the historical period, followed by a ramping up in pumping volume to approximately 3,000 acre-feet per year, on average, by year 50. The *baseline scenario* assumes that pumping volumes increase marginally in the first 10 years (years 51 through 60) and then remain stable for the remainder of the projected period (years 61 through 100).

During the first approximately 30 years of the historical period, the stream gained at all times (i.e., water from the aquifer entered the stream, with the amount of stream gains varying based on dry or wet hydrologic conditions). As pumping increased at the end of the historical period and into the projected period, the average flow reversed so that the stream lost at most times (i.e., it discharged water to the aquifer).

*Figure 18: Annual pumping and net stream gain in Basin 2 for the baseline scenario.*

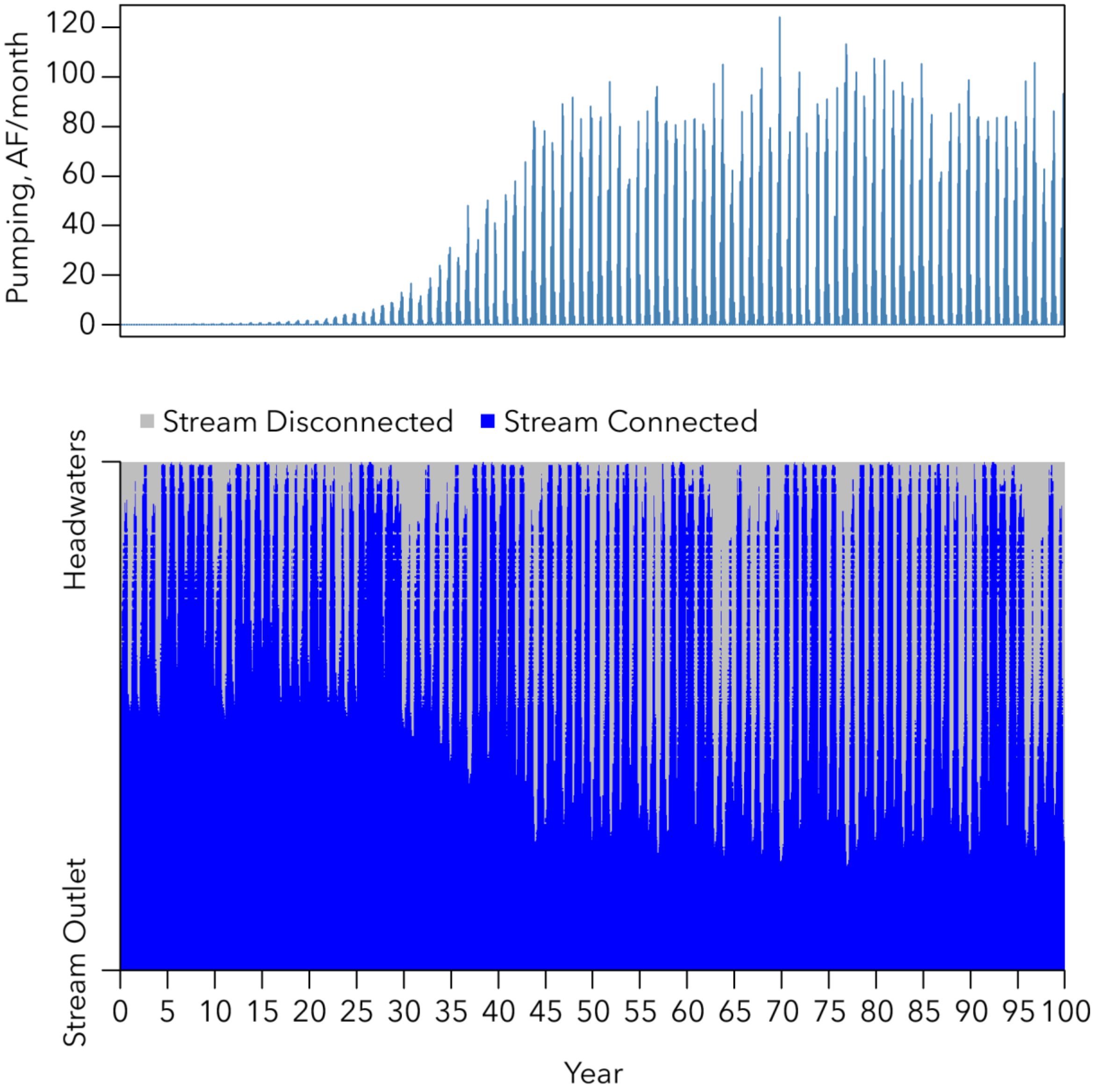


### 2.3.3 Using Numerical Models to Estimate the Variability of ISW Conditions in Time and Space

While this document mainly focuses on estimating ISW depletion, this section describes the potential utility of numerical models in estimating the extent of ISW conditions along a stream reach through time. The extent of the stream in Basin 2 that is interconnected with the underlying groundwater varies along its reach through time as a function of groundwater pumping and other factors like changes in hydrology in wetter or drier years. **Figure 19** shows the locations along the entire stream reach where the numerical model for Basin 2 calculates the stream is interconnected with groundwater for every month in every year of the 100 years simulated in the *baseline scenario*. For this purpose, the stream was determined to be disconnected whenever the simulated groundwater level in the model cell declined below the bottom elevation of the streambed.

**Figure 19** shows that there are periods when the stream in Basin 2 was interconnected along its entire length (i.e., times when the vertical blue lines extend to the top of the chart) and also periods where it was disconnected from groundwater for up to roughly half of its length (i.e., times when the blue line ends roughly halfway up the y-axis of the chart) during the early portion of the historical period, before the introduction of significant groundwater pumping in the Basin. As pumping rates increased throughout the historical period and into the projected period, the stream's interconnection with groundwater decreased in terms of the length of the stream that is interconnected during dry periods. After year 60, when pumping rates reach their maximum, there are still periods when the entire stream reach is interconnected but it is also relatively common for the stream only to be connected for the lower quarter of its length during dry periods.

*Figure 19: Interconnection of the stream and groundwater in Basin 2 for the baseline scenario.*



### 2.3.4 Without-Pumping Scenario and Estimated ISW Depletion

A hypothetical *without-pumping scenario* was run to estimate the depletion of the stream caused by groundwater pumping in Basin 2. **Figure 20** shows the net stream gain for the 100-year *without-pumping scenario* and the *baseline scenario*. Without groundwater pumping, the stream remains a gaining stream throughout the 100-year period, with the amount of stream gains varying with dry or wet hydrologic conditions. The difference in the net stream gain between the two scenarios is the depletion caused by groundwater pumping, shown in **Figure 21**.

*Figure 20: Annual net stream gain in Basin 2 for the baseline scenario and the without-pumping scenario.*

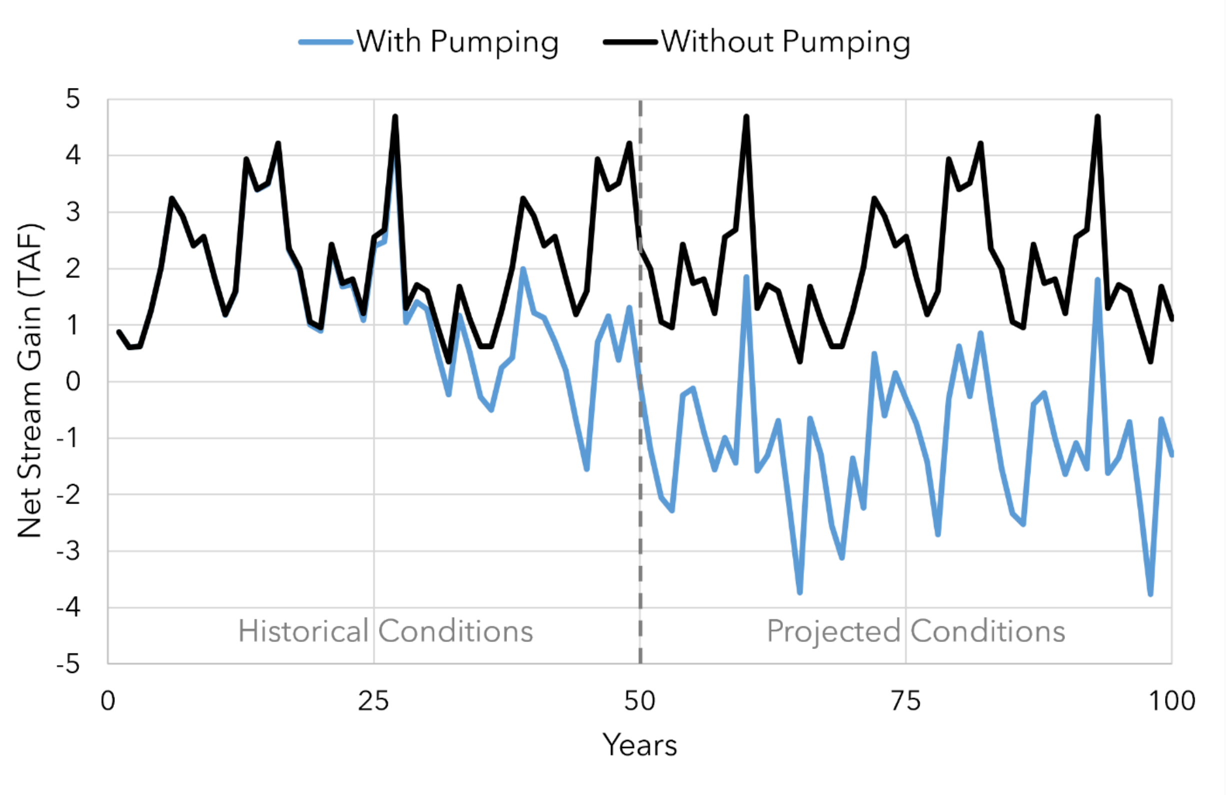
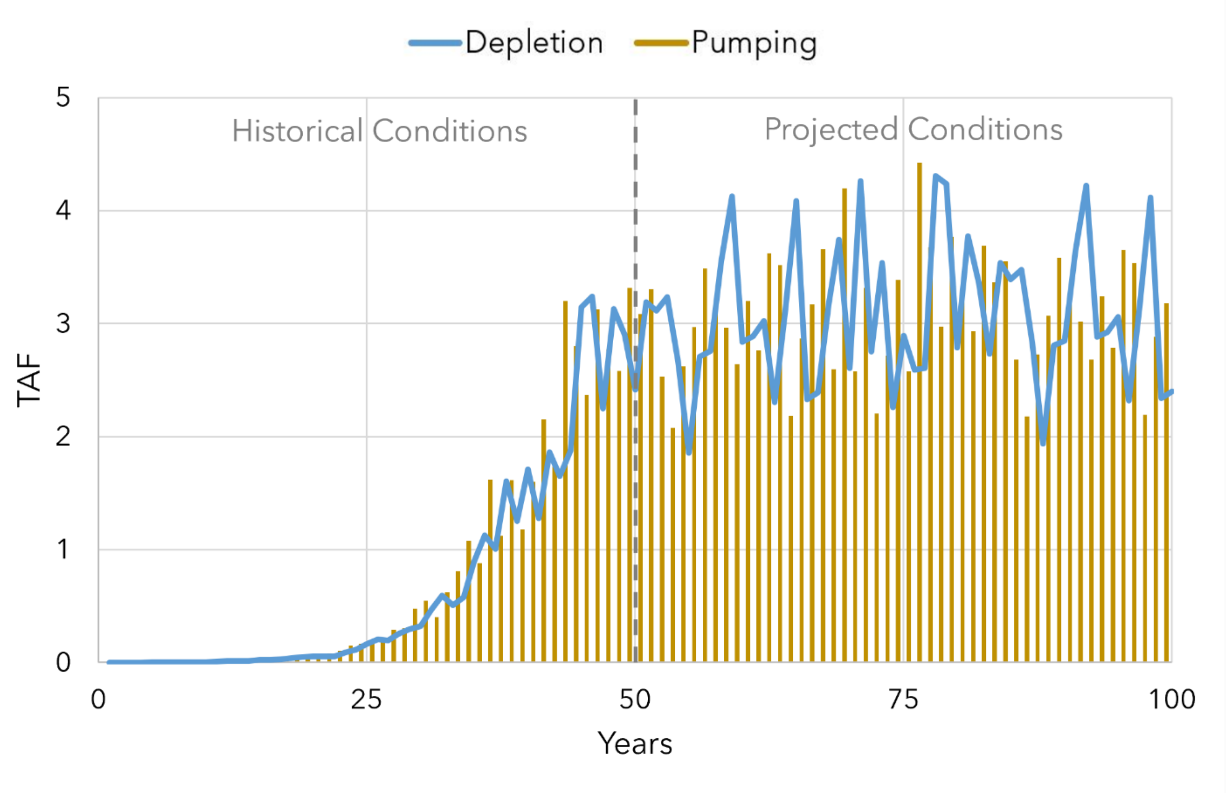
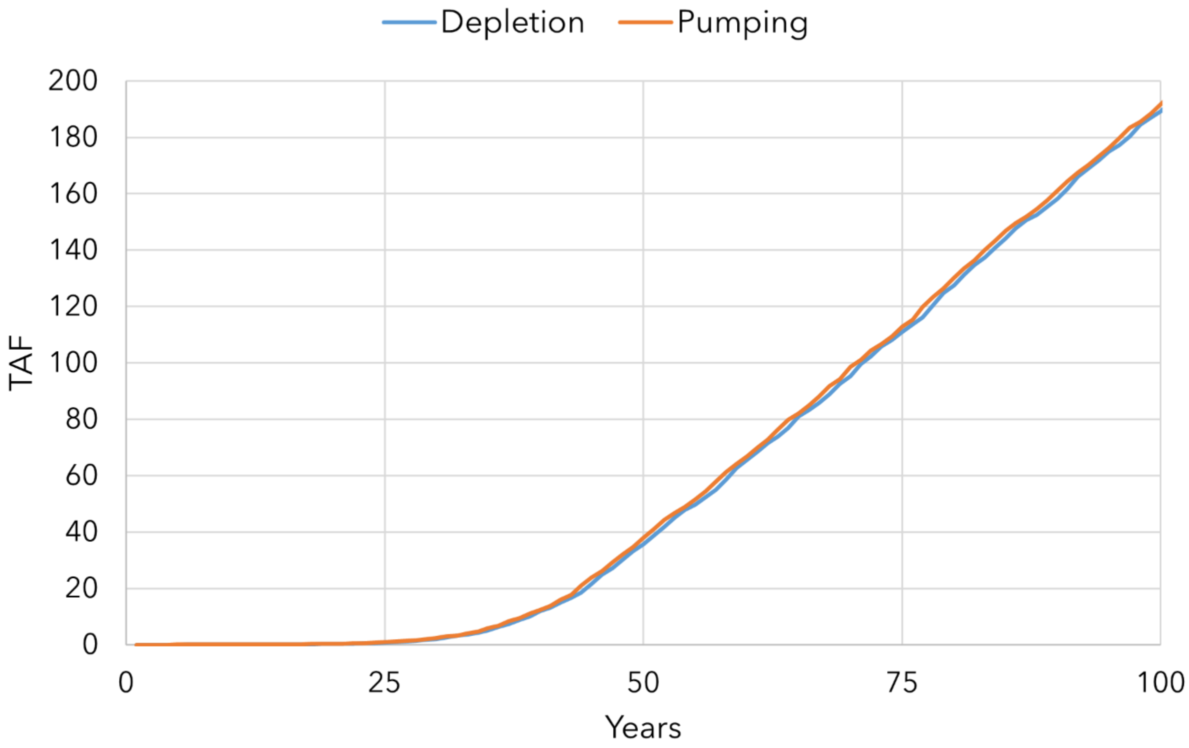


*Figure 21: Annual pumping and stream depletion in Basin 2 for the baseline scenario.*



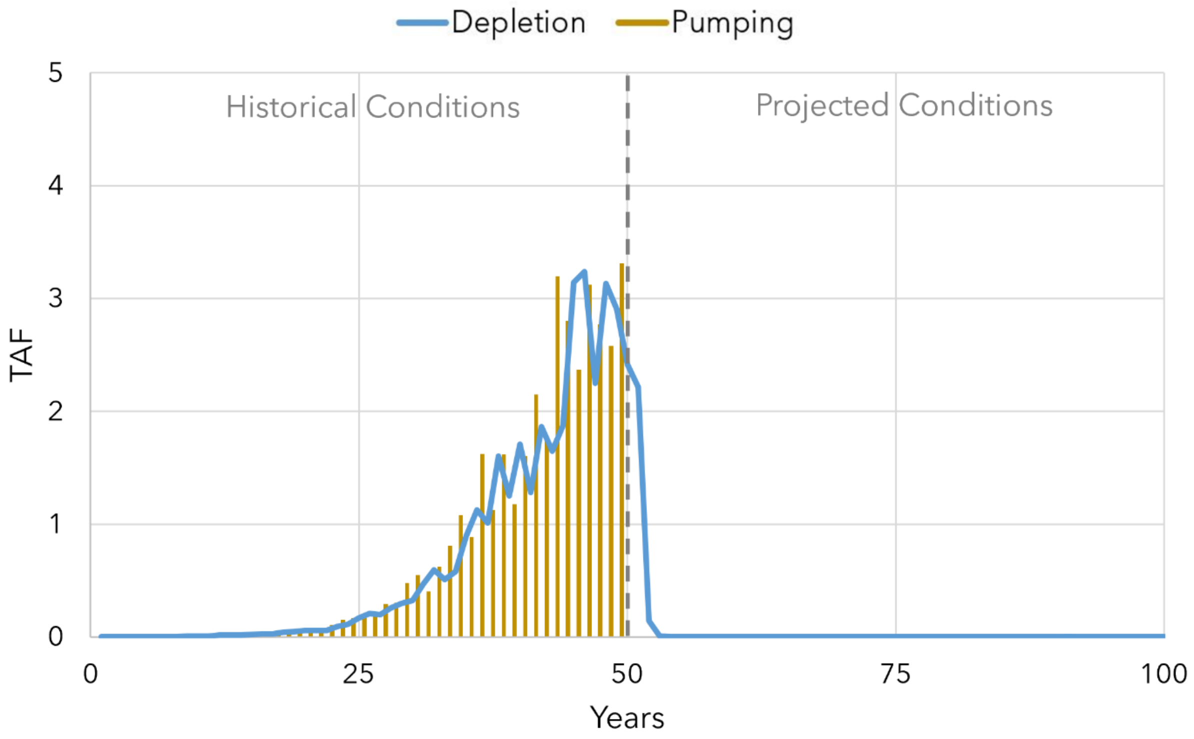
Depletion in Basin 2 closely follows groundwater pumping. As seen in **Figure 22**, the time lag between pumping and depletion is much smaller for Basin 2 than for Basin 1 (shown in **Figure 6**). The relatively rapid response is a function of both the short distance between pumping areas and the stream and the properties of the aquifer, which lacks semi-confining or confining layers and other complexities present in Basin 1.

*Figure 22: Cumulative pumping and stream depletion in Basin 2 for the baseline scenario.*



A comparison of a *projected-no-pumping scenario* with the 100-year *without-pumping scenario* (**Figure 23**) shows the effect that historical pumping practices have on depletion occurring during the projected period. Compared to Basin 1 (shown in **Figure 7**), residual depletion in Basin 2 decreases more rapidly in time, approaching zero by roughly year five.

*Figure 23: Annual pumping and depletion in Basin 2 for the projected-no-pumping scenario.*



### 2.3.5 Timing of ISW Depletion by Season and Water Year Type

**Figure 24** shows the average monthly pumping and depletion distribution in Basin 2 for the 100-year *baseline scenario*. Because of the short lag times noted above, monthly patterns of ISW depletion emerge that were not observed in Basin 1 (refer to the discussion in Section 2.2.3.3). **Figure 25** shows the average pumping and depletion distribution by water-year type for the same scenario. There does not appear to be a discernable trend in depletion by water-year type. This is likely because the lag in Basin 2, while shorter than Basin 1, is long enough that increased pumping during drier years causes stream depletion that, on average across the basin, occurs in subsequent years that may not be dry.

*Figure 24: Distribution of average pumping and depletion by month in Basin 2 for the 100-year baseline scenario.*

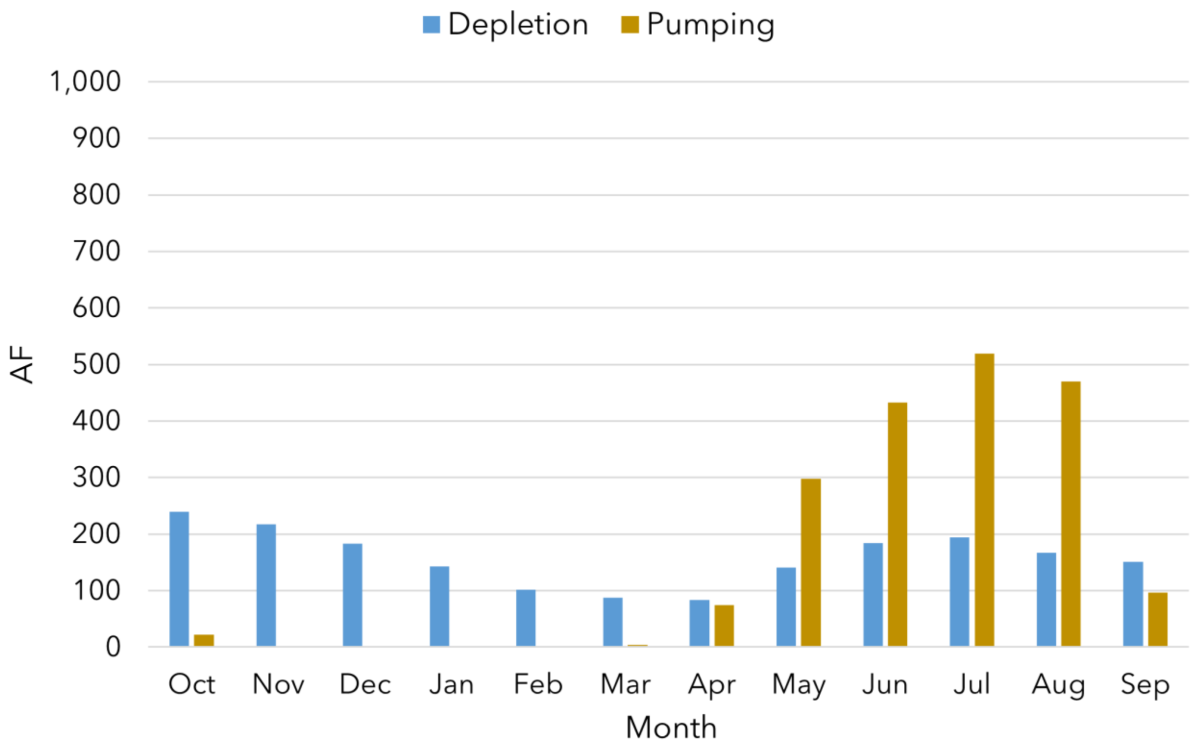
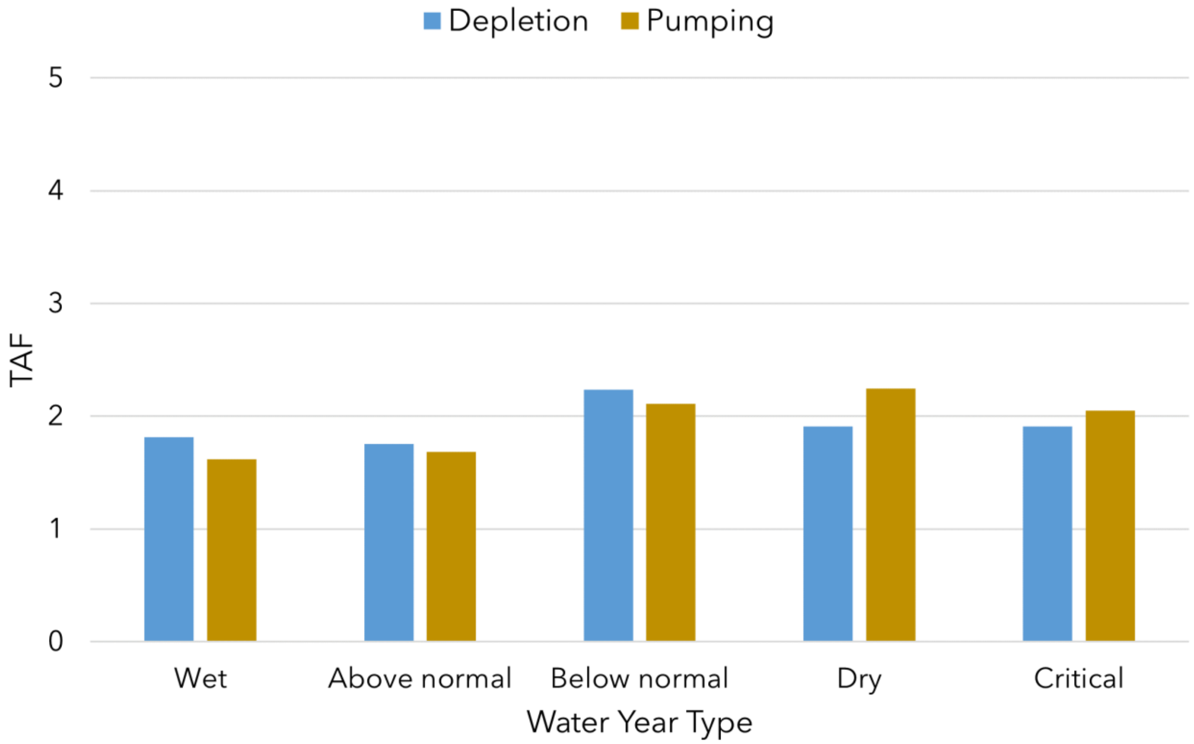


*Figure 25: Distribution of average pumping and depletion by water-year type throughout Basin 2 for the 100-year baseline scenario.*



# 3 Summary

This paper provides examples of how groundwater managers can use numerical models to estimate the location, quantity, and timing of ISW depletion. Numerical models provide a comprehensive approach to integrating the hydrologic cycle components and evaluating stream-aquifer interaction for different scenarios to estimate the ISW depletion caused by groundwater pumping. Most basins have access to existing numerical models, and as described in Paper 2, the GSP Regulations require a numerical model unless the groundwater sustainability plan identifies and describes an equally effective method, tool, or analytical model to quantify surface water depletion and meet the requirements of the regulations.[3]

The example basins discussed in this paper are representative of groundwater basins in California. Basin 1 represents basins with relatively long response times between depletion and pumping and also represents jurisdictional and management complexities that can arise in basins with multiple subbasins, GSAs, or management areas. Basin 2 represents basins with relatively shorter response times and limited jurisdictional and management complexity.

Both examples show how ISW depletion can be estimated for historical and projected conditions and how historical pumping can affect depletion in future projected periods. The analyses show how ISW depletion can vary—or not—over months, years, and by different water-year types. They also demonstrate how groundwater pumping within one subbasin can result in ISW depletion in streams completely outside that subbasin.

The estimates of ISW depletion under various projected pumping and management scenarios in Basin 1 show how groundwater managers can assess whether projected development and groundwater operations may affect future ISW depletion.

Both examples demonstrate the importance of the time lag between pumping and depletion, which can vary based on the characteristics of the basin and the location, quantity, and timing of pumping.

As noted in the paper, these are only examples; groundwater managers must tailor their approaches to the unique situations and challenges they face in their basins. For example, groundwater managers may need to evaluate specific portions of a river reach or may need to evaluate pumping management at specific sets of wells within their basin, neither of which was explicitly shown in this paper. However, the methods they would use for those types of analyses are fundamentally the same as the methods used in the examples contained in this document.

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[3] CCR § 354.28(c)(6)((B).

# 4 Conclusions

This paper concludes DWR's three-paper series on ISW and depletion of ISW caused by groundwater use. The papers are written for groundwater managers, especially those in California's groundwater basins that are required to develop and implement GSPs, who are faced with the challenge of (1) understanding ISW conditions in their basin, (2) determining the location, quantity, and timing of ISW depletion caused by groundwater pumping, and, ultimately, (3) managing groundwater resources to eliminate significant and unreasonable impacts to beneficial uses and users of the ISW caused by groundwater pumping. The three-paper series aims to help address the first two elements of the list above by describing what ISW conditions are and how they can be depleted by groundwater pumping (Paper 1), identifying the types of data and methodologies commonly used to estimate ISW depletion (Paper 2), and, finally, providing examples of how to use numerical groundwater models, which likely will be the most common and defensible method, for ISW depletion estimation (Paper 3).

As described in the series, the location, quantity, and timing of ISW depletion cannot be directly measured, and estimating depletion is, inherently, a technical process that relies on other types of data – principally, the properties of the pumping (including the location, quantity, and timing) in the basin and the properties of the aquifers and surface water beds through which water flows. In nearly any basin, there is likely to be uncertainty in those data sets, as well as other data that may be needed to calibrate and apply the tools and methods necessary to estimate depletion of ISW caused by groundwater pumping. Despite those challenges, groundwater managers who are required to do so by SGMA should leverage the data they do have to begin the process of estimating ISW depletion, which will form the basis for subsequent steps to sustainably manage ISW depletion. The initial ISW depletion estimates should also inform future efforts to improve those estimates and reduce uncertainty (e.g., by addressing data gaps). On that topic and because ISW depletion is a function of pumping, one potential data need or data gap that groundwater managers should focus on is the location and quantity of pumping. Without an adequate understanding of pumping occurring throughout the basin there is no way to understand the depletion that the pumping causes.

Additionally, the series of papers documents that ISW depletion may not always be intuitive. For example, there can be a significant time lag between pumping and the resulting depletion. Because of that lag, basins may experience ongoing increases in ISW depletion due to historical pumping patterns despite efforts to stabilize current and future pumping. Additionally, pumping within one area, such as a subbasin or a GSA area, may deplete ISW outside of that area. It will take the expertise of groundwater professionals to estimate ISW depletion, qualify those estimates with descriptions of uncertainty, and make plans to improve the estimates over time.

Addressing ISW depletion for a GSP may require groundwater managers to coordinate with surface water users in ways they did not before SGMA, coordinate with groundwater and surface water users outside of the GSP or subbasin area, and carefully consider how to convey the concepts and results to interested parties in the basin.

# 5 References

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Nebraska Department of Natural Resources, 2010, Number 5, Water Matters Newsletter, “Stream Depletion and Groundwater Pumping Part Two: The Timing of Groundwater Depletions”, https://dnr.nebraska.gov/sites/dnr.nebraska.gov/files/doc/water-planning/water-matters/WaterMatters_No5.pdf

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