The State Water Project Delivery Capability Report 2023 Addendum

Impacts of Subsidence

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State of California

Natural Resources Agency

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CASP	California Aqueduct Subsidence Program
CASS	California Aqueduct Subsidence Study
CVP	Central Valley Project
DAPP	Dos Amigos Pumping Plant
DCR	Delivery Capability Report
DWR	Department of Water Resources
EPP	Edmonston Pumping Plant
HCC	Hydraulic conveyance capacity
LOC	Levels of concern
NESP	Non-Exceedance Subsidence Percentile
O&M	Operations and Maintenance
SFM	Subsidence Forecast Model
SJFD	San Joaquin Field Division
SLC	San Luis Canal
SLFD	San Luis Field Division
SOD	South of Delta
SWP	State Water Project

Section 1. Introduction

The purpose of this addendum is to show how ongoing subsidence effects on the California Aqueduct will impact operation of the State Water Project (SWP). The addendum provides information to SWP water users about a potential range of water delivery impacts over the next 20 years if no corrective action is taken to address the subsidence effects. However, the California Department of Water Resources (DWR) is committed to restore the conveyance capacity of the California Aqueduct and has an engineering plan for near-term fixes. DWR is also working with its partners to secure additional funding sources for this work. DWR is confident that the California Aqueduct capacity will be restored and the SWP will not see the impacts outlined in this addendum. Thus, long-term water supply planning activities by water users should rely on the potential future SWP allocation results presented in the 2023 Delivery Capability Report (DCR 2023) released in 2024: https://data.cnra.ca.gov/dataset/finaldcr2023.

The 2023 Delivery Capability Report provided estimates of both current and potential future delivery capabilities of the SWP. Those estimates were based on the latest available data concerning hydrology, climate change, regulations, water demands, and other factors critical to SWP operations. However, as noted in that report, DCR 2023 did not account for the effects of subsidence in its current or future delivery capability estimates.

The SWP relies on the San Luis Canal (SLC) and the California Aqueduct (Aqueduct) in the San Joaquin Valley to transport water from the Sacramento-San Joaquin Delta to various water agencies, districts, counties, and other SWP contractors. Differential land subsidence along the alignments of these gravity conveyances affects the ability of that infrastructure to function as designed.

To estimate the impacts of subsidence on the delivery capability of the SWP, this addendum builds on previous studies conducted by DWR. Since 2017, DWR has been monitoring subsidence and evaluating its effects on the SWP. Some of these studies are highlighted in Section 2 of this addendum. Section 3 presents the development of subsidence scenarios for CalSim3, their application, and the corresponding estimates of delivery capability.

Summary of Findings

1. Subsidence has already occurred and DWR has responded by adapting the operating criteria of the SLC and Aqueduct. Even with this current adaptation, 2023 levels of subsidence reduce the long-term average delivery capability of the SWP by 3%.

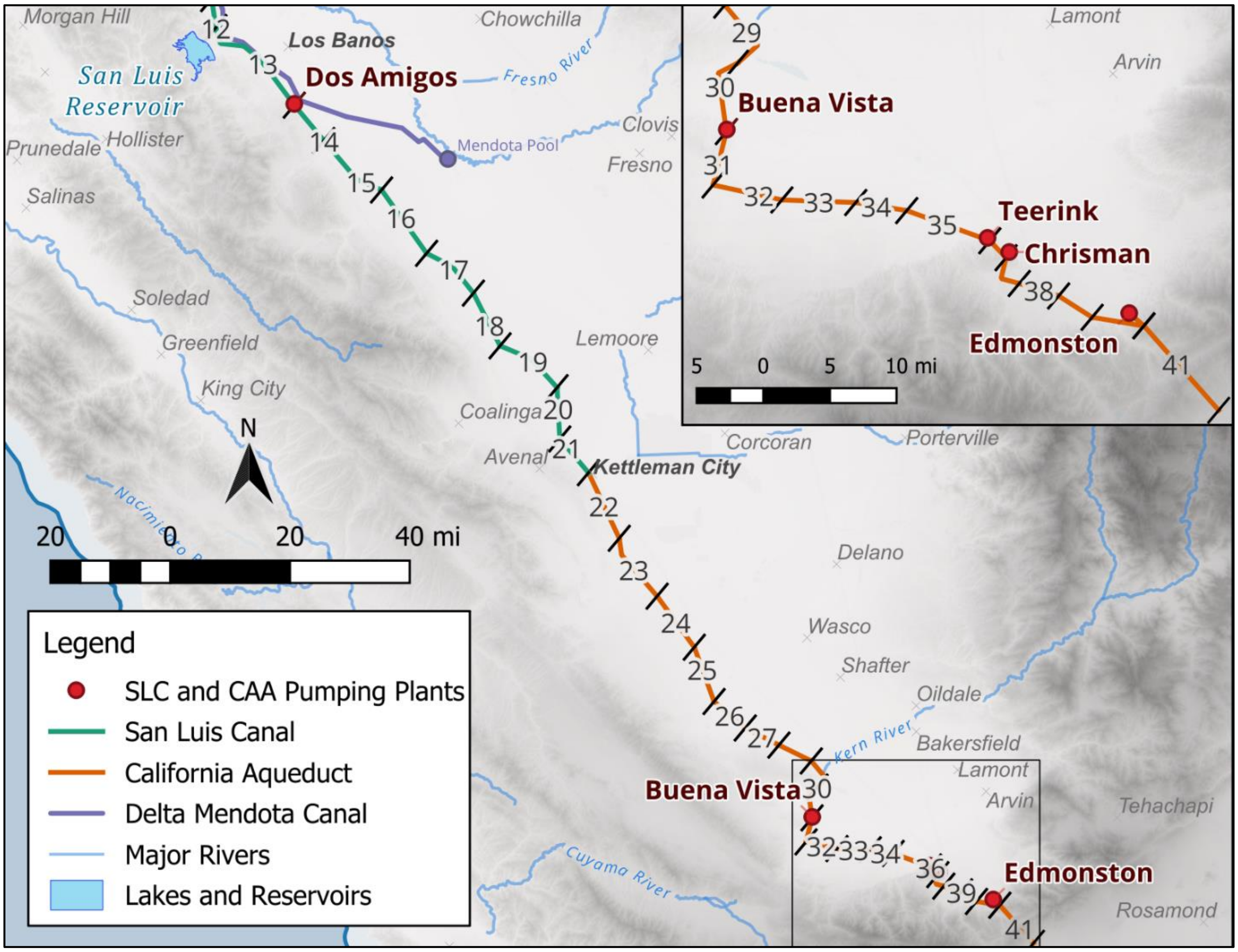
2. Without additional operational adaptations or infrastructure improvements, estimates predict that long-term average delivery capability of the SWP could be reduced by 18% to 87% by 2043.
3. The estimates of delivery capability presented in this addendum contain a high degree of uncertainty. Even so, they demonstrate that subsidence has the potential to cause fundamental changes to the operations of the SWP. Future studies will be designed to improve understanding of this uncertainty and evaluate how the SWP could adapt its infrastructure and operations to potential future subsidence.

Section 2. Studies of Subsidence and State Water Project Facilities

The body of literature on subsidence in the San Joaquin Valley is extensive and includes analyses beyond the scope of this report. To gain a comprehensive understanding of the relationships between hydrology, human activity, and subsidence, it is recommended to consult those broader resources. However, the following studies are particularly relevant when assessing the impacts of subsidence on joint use and SWP facilities. The analyses presented in this addendum are built upon the data, assumptions, and conclusions from these studies.

It is also essential to understand the scope of the analyses discussed below. While the impacts of subsidence are not limited to the San Joaquin Valley, or to the infrastructure of the SWP, this addendum and the studies referenced below focus on those areas. Figure 1 shows the parts of the SWP that are the focus of this addendum, labeled by pool.

Figure 1. Portions of San Luis Canal and the California Aqueduct in the Study Area



California Aqueduct Subsidence Study

In 2017, the California Aqueduct Subsidence Study (CASS) was conducted in response to changes in the operational flexibly of the SLC and Aqueduct. In 2006, the San Luis Field Division (SLFD) of the California DWR Division of Operations and Maintenance began to see a reduction in flow capacity through Pools 20 and 21 of the SLC. Subsidence had lowered portions of the SLC and Aqueduct and caused the concrete liner freeboard (the vertical distance between the water surface and the top of the concrete liner) to be reduced from its normal of three feet to less than one foot. Subsidence had also decreased the ability to store water in those pools, which is normally done to add operational flexibility and to manage pumping at the SLC and Aqueduct pumping plants.

The purpose of CASS was to research and study existing subsidence reports and data, and to understand and summarize the magnitude, location, and effects on the SLC and Aqueduct. The CASS report summarized the information found and presented the results of the analyses performed with that data. The report is found at https://cawaterlibrary.net/wp-content/uploads/2017/11/Aqueduct_Subsidence_Study-FINAL-2017.pdf.

In 2019, the California Aqueduct Subsidence Study Supplemental Report (CASS Supplemental Report) was published. The CASS Supplemental Report presented new data compilation, analysis, and modeling to supplement the original CASS report. The CASS Supplemental Report addressed land use within a 10-mile-wide study corridor centered on the SLC and Aqueduct in the SLFD and the San Joaquin Field Division south of San Luis Reservoir; subsidence in the Lost Hills oil field west of the SLC and Aqueduct; modeling of SLC and Aqueduct performance using the U.S. Army Corps of Engineers' Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydraulic model; and predictions of future subsidence.

The CASS Supplemental Report also included multiple estimates of future subsidence based on linear extrapolations of recent observations. These models were used to estimate cumulative future subsidence in 2040 under multiple scenarios. The CASS Supplemental Report can be found here: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Engineering-And-Construction/Files/Subsidence/CASS_Supplement_final_a_1119.pdf

California Aqueduct Subsidence Program

Since release of the 2019 CASS Supplemental Report, additional subsidence has continued to affect factors that influence SLC and Aqueduct operations, including the Aqueduct's hydraulic conveyance capacity, available freeboard, and turnout operations. As a result, DWR has conducted further investigations into the effects of subsidence on SLC and Aqueduct operations under an initiative called the California Aqueduct Subsidence Program (CASP). The purpose of the CASP is to develop and implement corrective and preventive measures to mitigate the effects of subsidence, while planning the cost-beneficial remediation of anticipated future subsidence of the SLC and Aqueduct. In so doing, the CASP intends to improve the resiliency of SWP water delivery via the SLC and Aqueduct.

Hydraulic Model Improvements

The CASP built upon the base hydraulic model used in the CASS and the CASS Supplemental Report. The hydraulic model update efforts conducted by the CASP produced what is essentially a new model. The hydraulic model includes the latest terrain data available at the time of this report, refined gate operations, geo-referenced line work, and additional geometric components such as critical overchutes, bridges, pumping plants, forebays, and concrete liner raises. The hydraulic model extends from the Dos Amigos Pumping Plant (DAPP) discharge to the forebay of the Edmonston Pumping Plant (EPP).

The hydraulic model has been applied to calculate hydraulic conveyance capacity (HCC). This is defined as the maximum steady flow rate at which water can be conveyed through a pool while meeting a set of specified operational criteria. The work of updating the hydraulic model is documented in detail in the California Aqueduct Hydraulic Model Development Report here: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Engineering-And-Construction/Files/Subsidence/2023_CaliforniaAqueductModelUpdate_ADA_Document.pdf

Probabilistic Subsidence Forecast Model

A physically based model that can calculate changes in land surface in response to changes in groundwater pumping patterns under different future scenarios at the scale necessary to evaluate the performance of the SLC and Aqueduct does not exist at the time of developing these studies. To prepare estimates of future subsidence of the SLC and Aqueduct that also capture a reasonable range of uncertainty for risk evaluation, CASP developed a probabilistic Subsidence Forecast Model (SFM). The SFM development process, and projections of future subsidence are presented in the “Probabilistic Subsidence Forecast Model for the California Aqueduct Subsidence Program” report here: https://water.ca.gov/-/media/DWR-

Website/Web-Pages/Programs/Engineering-And-Construction/Files/Subsidence/CASP_SSHAC_Rept_Rev1_241010-3_ADA_combined.pdf

Hydraulic Conveyance Capacity

In October 2024, the CASP developed a set of future subsidence scenarios for use in this analysis and in the SWP Climate Adaptation Plan being conducted by DWR's SWP Climate Action Program. These scenarios include the use of updated climate model parameters prepared by the DWR Climate Change Program in early 2024, as well as the addition of precise survey data from 2022 and 2023 to the analysis. These scenarios are the most up-to-date estimates of future subsidence that utilize the same climate model parameters as the DCR 2023. While this report explores a range of subsidence conditions at 2043, under 2023 operating regulations, the SWP Climate Adaptation Plan will place a sub-set of the scenarios in the context of potential SWP climate adaptation scenarios at 2043 and 2085 using expected future operating regulations. A description of the scenarios used is provided in Section 3. Subsidence levels, hydraulic model assumptions, SFM assumptions, and tables of HCC can be found in the "Subsidence and Hydraulic Conveyance Capacity Information for Use in the Climate Adaptation Study" report, which is included as Technical Appendix A to this addendum.

Section 3. Impacts of Subsidence on Delivery Capability

The DCR 2023 assesses the delivery capability of the SWP under both current and potential future conditions. In that report, the terms “current” and “potential future” should be understood to reference 2023 and a 20-year future projection to 2043. To evaluate the impact of subsidence, it is essential to apply the appropriate levels of subsidence for each planning horizon. The sections below describe these subsidence scenarios, and the results of the CalSim3 studies that employ them.

Changes to Hydraulic Conveyance Capacity

In all scenarios in this addendum, the CalSim3 assumptions are kept as similar as possible to the nearest equivalent scenario in the DCR 2023. All changes in assumptions are related to subsidence of the San Luis Canal and the California Aqueduct, together referred to as “SLC and Aqueduct”. Primarily, the HCC in the SLC and Aqueduct was no longer assumed to be equal to the original design capacity (as it is in the DCR 2023 main report). Instead, multiple HCC scenarios were developed by CASP for use in this addendum. For information on the development of these HCC scenarios, see the “Subsidence and Hydraulic Conveyance Capacity Information for Use in the Climate Adaptation Study” report.

CalSim3 Updates and Changes to Assumptions

As mentioned above, all changes to CalSim3 were related to subsidence, and the ability to simulate its impact on the operations of the Aqueduct. The following major updates were made; changes are relative to the DCR 2023 model.

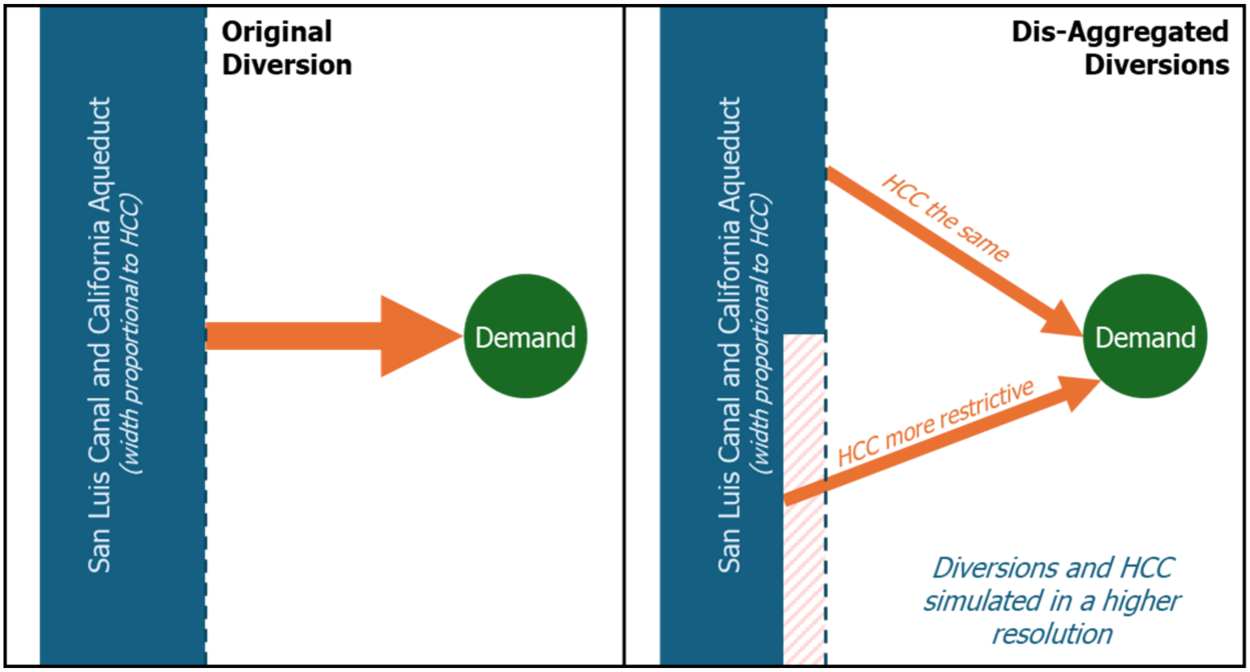
- The SLC and Aqueduct spatial resolution from the DAPP to the EPP was modified to distinctly represent Pool 14 (DAPP discharge) through Pool 40 (forebay to EPP).
- Demands along SLC and Aqueduct for Pools 14 through 40 were disaggregated or consolidated, as appropriate, to conform to the modified spatial resolution. This disaggregation was done where the total of all demands from the SLC and Aqueduct remained the same as in the DCR 2023, and the spatial proportions reflected historical diversion patterns for the different contractors. Historical data from the last 10 years was used.
- Separate arcs were established for SWP and CVP portions of the SLC to enable distinct accounting of conveyance capacity, demands, water conveyance, and deliveries.
- Monthly varying HCC for SLC and Aqueduct Pools 14 through 40 was

enabled to represent the range of operating conditions under the DWR Standing Operating Order 600.22 (May 20, 2020, hereafter 2020 SOO) and Special Conditions that specify water elevations at checks that enable diversions to the Coalinga Canal and the Coastal Branch of the California Aqueduct.

- Hydraulic Conveyance Capacity for Pools 14 through 40 are defined month-by-month in a lookup table. Pools 14 through 21 comprise the San Luis Canal (SLC) portion of the Aqueduct, which conveys both SWP and CVP water supplies in a single physical channel. HCC for each pool in the SLC is allocated to the SWP and CVP based on the percentages in the 1961 Joint Use Facilities Agreement.

The disaggregation of the SLC and Aqueduct and water demands was required because the prior version of the model aggregated demands across multiple pools which experienced different levels of subsidence impacts. Figure 2 shows how the disaggregation allows for the simulation of varying HCC values, and how that variation can impact the diversions from the SLC and Aqueduct.

Figure 2. Conceptual diagram showing the spatial disaggregation of the SLC and Aqueduct, its modeled Hydraulic Conveyance Capacity, and corresponding diversions



One 2023 condition HCC scenario and multiple potential 2043 HCC scenarios were developed by the CASP group. These scenarios utilize the same climate parameters as the DCR 2023 potential future climate change analyses. The CASP group developed more HCC scenarios than are used in this addendum.

The resulting HCC values for each scenario used by this addendum are shown in the sections below.

CalSim3 Applications Under Major Infrastructure Changes

Certain assumptions are important to consider when predicting the impacts of major changes to infrastructure, such as the reductions in HCC caused by subsidence. This is especially true for “no adaptation scenarios” like those used in the DCR main report and this addendum. In reality, certain major infrastructure changes would likely necessitate some form of adaptation. For example, the scenarios presented here assume the demand patterns for water deliveries remain the same as historical trends. Extreme infrastructure changes would likely change those demand patterns. The utility of “no adaptation scenarios” is not to predict the future, but rather to establish a benchmark for comparing the performance of potential adaptations.

In addition to the above, CalSim3 currently does not include alternative methods for allocating deliveries or adjusting operations when parts of the SLC or Aqueduct have zero capacity to convey water. The allocation methods used in the DCR 2023 report are used here. If future studies need to evaluate alternative operations and their impact on the performance of the SWP when portions of the SLC and Aqueduct are assumed inoperable, those additional assumptions will need to be developed.

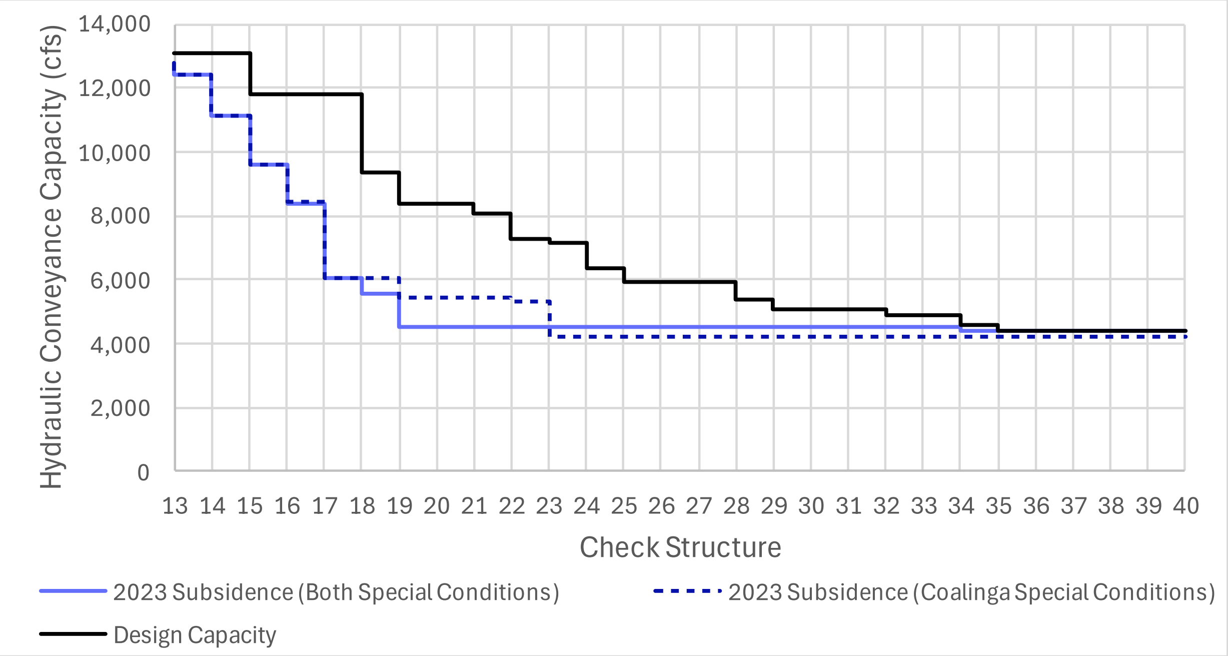
It is important to note that no estimates of HCC can be developed for the 95% Non-Exceedance Subsidence Percentile (NESP) scenario without violating the 2020 SOO and special conditions. At that level of subsidence the SLC and Aqueduct cannot be operated without additional adaptations or additional maintenance. This situation is described in detail in the “Subsidence and Hydraulic Conveyance Capacity Information for Use in the Climate Adaptation Study” report. Operations of the SLC and Aqueduct under 2023 guidelines would not be possible without physical modifications to the infrastructure under this subsidence scenario. Due to this, the impacts of subsidence under this scenario are discussed qualitatively in the section “Potential 2043 Conditions” below. It is also important to note that the subsidence levels predicted in the 75% NESP scenario are near the limit where operations under the existing guidelines is still possible.

Even without quantitative evaluation, the 95% NESP scenario establishes a benchmark for future studies to compare against. Future studies could potentially utilize the 95% NESP values for vertical land subsidence and include potential adaptations that allow for the operations of the SLC and Aqueduct under those elevation profiles. Those future studies could use the discussions in this report as a baseline.

2023 Conditions

As discussed in Section 2, the CASP group developed estimates of 2023 HCC using Precise Survey data from along the SLC and Aqueduct alignment. Figure 3 presents the 2023 HCC values for the SLC and Aqueduct from that report. The sequential numbering of the Aqueduct pools is coincident with the check structure number at the downstream end of a pool. For example, Check Structure 14 is located at the downstream end of Pool 14.

Figure 3. Estimated 2023 Hydraulic Conveyance Capacity of the SLC and Aqueduct



Potential 2043 Conditions

Potential 2043 HCC values were developed by the CASP group using the probabilistic SFM under the same climate parameters as the DCR 2023 potential future scenarios.

It is important to distinguish between the risk-informed metrics used for hydrology development and those used for subsidence level development. In the DCR 2023, potential future hydrology scenarios were based on levels of concern (LOC) tied to the April to July 8 River Index. In other words, climate parameters were developed without factoring in the risks related to subsidence. On the other hand, the probabilistic SFM assesses risk through the metric of "additional subsidence". This metric is influenced by historical subsidence rates, the uncertainty regarding implementation of the Sustainable Groundwater Management Act, and changes in water deliveries in response to climate change. As a result, the development of potential 2043 subsidence levels is semi-independent of the hydrology risk level.

This addendum attempts to estimate the range of potential impacts of subsidence on delivery capability over the same planning horizon as the DCR 2023 main report. In this report, the same non-exceedance values are applied to both hydrology and subsidence. Said another way, the 50% LOC Climate Scenario is paired with the 50% NESP profile, and the 75% LOC Climate Scenario is paired with the 75% NESP. Pairing the non-exceedance values to each other minimized the number of scenarios, while still exploring a wide range of potential impacts due to subsidence.

Future studies could explore the impacts of subsidence under different hydrology and subsidence combinations—for instance, evaluating an extreme climate (e.g., the 95% LOC Climate Change scenario) alongside minimal additional subsidence (e.g., a 5% NESP scenario).

In this report, when a scenario is presented as "with subsidence", it uses the same non-exceedance value as the selected hydrology LOC. The climate change scenario parameters and paired subsidence scenarios are shown in Table 1 below.

Table 1. Hydrologic and Subsidence Parameters for each 2043 Climate Change Scenario by Level of Concern

Parameter	2043, 50% Level of Concern	2043, 75% Level of Concern	2043, 95% Level of Concern
Change in Temperature (°C)	1.5	1.7	1.8
Change in Average Precipitation (%)	+1.5%	+0.1%	-1.8%
Change in Precipitation Intensification (%)	+11%	+12%	+13%
Sea Level Rise (cm)	15	30	30
NESP (%)	50%	75%	95%[1]

1 This subsidence scenario does not have HCC values associated with it. See the discussion in the section "CalSim3 Applications Under Major Infrastructure Changes" above.

Figure 4 and Figure 5 show the HCC values for the 50% NESP and 75% NESP scenarios, respectively. Both figures show the original design capacity of the SLC and Aqueduct for reference. The sequential numbering of the Aqueduct pools is coincident with the check structure number at the downstream end of a pool. For example, Check Structure 14 is located at the downstream end of Pool 14.

Figure 4. 2043 50% Level of Concern Hydraulic Conveyance Capacity of the California Aqueduct

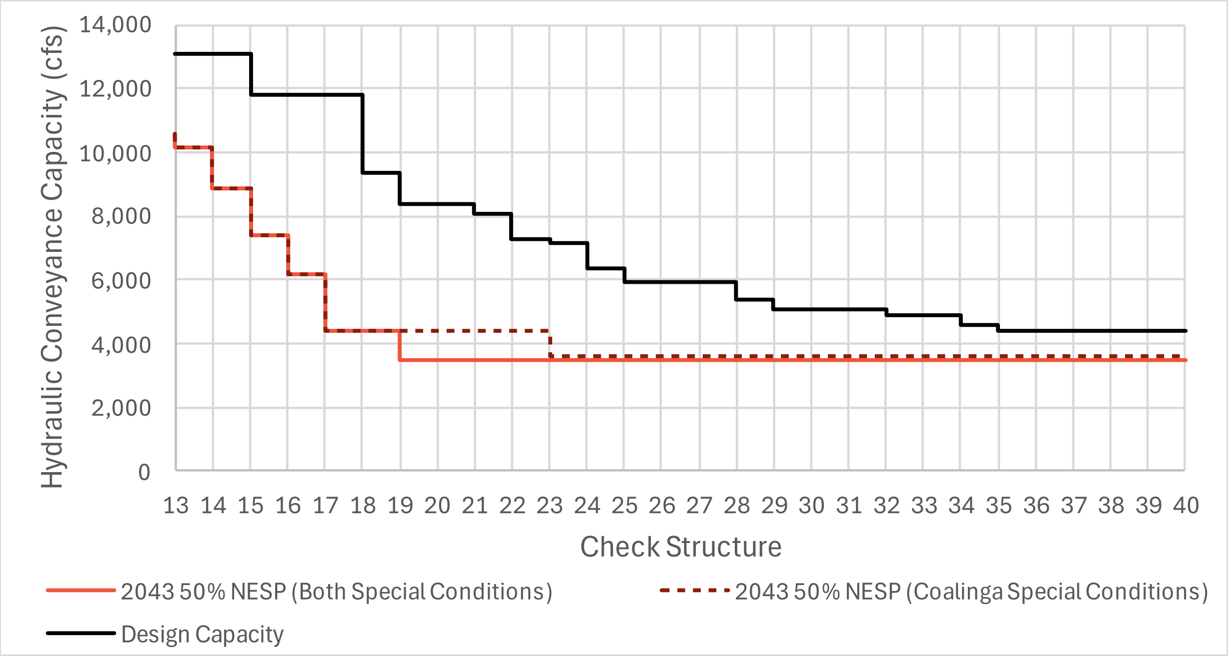
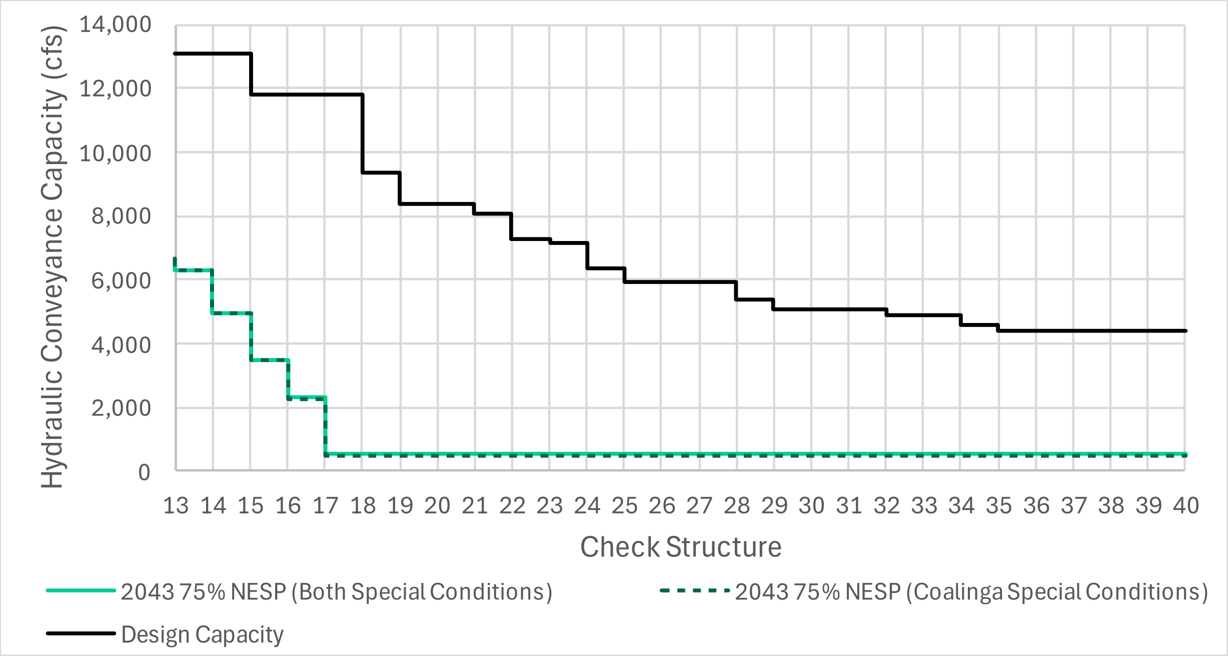


Figure 5. 2043 75% Level of Concern Hydraulic Conveyance Capacity of the California Aqueduct



Summary of Subsidence Impacts on Delivery Capability

The cumulative effects of subsidence reduce the delivery capability of the SWP. The effect of 2023 levels of subsidence can already be observed in the need for alternative operating procedures. Even with the interim operating procedures described in the 2020 SOO, the long-term average delivery capability of the SWP is reduced by 3% compared to estimates from the DCR 2023 main report. Looking to 2043, the long-term average delivery capability is reduced by 18% to 87% compared to the DCR 2023 Baseline. These reductions are summarized in Table 2 below.

Table 2. Reductions in Long-Term Average Table A Deliveries due to Subsidence (TAF/year)

Metric	Baseline (2023)	2043, 50% LOC	2043, 75% LOC
DCR 2023 Long-Term Average Table A Deliveries (TAF)	2,202	1,921	1,812
Long-Term Average Table A Deliveries under Subsided conditions (TAF)	2,125	1,797	295
Reductions in Long-Term Average Table A Deliveries relative to the Same Climate Conditions in DCR 2023 (%)	-3%[1]	-6%[1]	-84%[1]
Reductions in Long-Term Average Table A Deliveries relative to DCR 2023 Baseline (%)	-3%[2]	-18%[3]	-87%[3]

TAF: thousand acre-feet

1. These values could be interpreted as "reductions due to potential subsidence alone".
2. This value, and its calculation is identical to the value and calculation above it. It is included for completeness.
3. These values could be interpreted as "reductions due to potential subsidence and potential future climate change".

The largest impact is seen in months where the SLC and Aqueduct would typically operate at or near their design capacity. These months typically occur during wet years where allocations are high. Due to the lower hydraulic conveyance capacity due to subsidence, the capability of the SLC and Aqueduct to deliver water to meet demands is diminished in these months. Said another way, the ability of the SWP to fully utilize the water available in wet periods is reduced due to the "bottleneck" created by the diminished capacity of the SLC and Aqueduct.

Additionally, the operational flexibility of the SLC and Aqueduct is reduced in these wet years. In order to meet annual demands in these years, the subsided SLC and Aqueduct tends to operate at capacity later into the year. This reduces the ability of the SLC and Aqueduct to carry other flows, or to change the timing of deliveries.

As previously mentioned, like the DCR main report this analysis does not include any adaptation actions. As such, this analysis does not change the water demand patterns to accommodate for these lower capacities. Said another way: demand patterns in the model are assumed to follow historical trends, but the actual patterns could change in the future to accommodate reduced operational flexibility. Future studies could evaluate the impact of altered demand and delivery patterns under subsidence conditions.

Table 3 shows the range of estimated SWP Table A deliveries under 2023 conditions for both the DCR 2023 main report (which assumed design capacity) and 2023 subsidence scenarios.

Table 3. Deliveries of Table A Water under 2023 Conditions

Scenario	Long-Term Average Table A Deliveries (TAF)	Maximum Single Year Table A Deliveries (TAF)	Minimum Single Year Table A Deliveries (TAF)
DCR 2023 Baseline	2,202	3,904	184
DCR 2023 Baseline with 2023 levels Subsidence	2,125	3,674	210[1]

1. The increase in minimum delivers is due to an increase in SOD storage in most years. Since delivery capability decreases in these scenarios, water tends to stay in storage more often than in the non-subsidence scenarios. Since the SLC and Aqueduct are capacity constrained, more water stays in San Luis. This allows for higher deliveries in subsequent years. This is discussed in more detail in later sections.

Table 4 and Table 5 show the range of SWP Table A deliveries under potential future climate change and subsidence conditions. The DCR 2023 Baseline, which assumed design capacity is also included in these tables for reference. It should be noted that the impacts to long-term average Table A deliveries due to climate change without considerations of subsidence are smaller than the impacts of climate change when subsidence is also considered. Said another way, including subsidence in the analysis further reduces the delivery capability of the SWP. The impact of subsidence and climate change is also much larger than that of climate change alone, especially in the "2043, 75% LOC, 75% NESP" scenario.

Table 4. Deliveries of Table A Water under Potential 2043 Conditions, 50% Level of Concern Scenario

Scenario	Long-Term Average Table A Deliveries (TAF)	Maximum Single Year Table A Deliveries (TAF)	Minimum Single Year Table A Deliveries (TAF)
DCR 2023 Baseline	2,202	3,904	184
2043, 50% LOC	1,921[1]	3,848	75
2043, 50% LOC with 50% NESP	1,797[2]	3,368	176[3]

1. This is 281 taf lower than the DCR 2023 Baseline.
2. This is 405 taf lower than the DCR 2023 Baseline.
3. The increase in minimum delivers is due to an increase in SOD storage in most years. Since delivery capability decreases in these scenarios, water tends to stay in storage more often than in the non-subsidence scenarios. Since the SLC and Aqueduct are capacity constrained, more water stays in San Luis. This allows for higher deliveries in subsequent years. This is discussed in more detail in later sections.

Table 5. Deliveries of Table A Water under Potential 2043 Conditions, 75% Level of Concern Scenario

Scenario	Long-Term Average Table A Deliveries (TAF)	Maximum Single Year Table A Deliveries (TAF)	Minimum Single Year Table A Deliveries (TAF)
DCR 2023 Baseline	2,202	3,904	184
2043, 75% LOC	1,812[1]	3,834	97
2043, 75% LOC with 75% NESP	295[2]	602[3]	199[4]

1. This is 390 taf lower than the DCR 2023 Baseline.
2. This is 1,907 taf lower than the DCR 2023 Baseline.
3. Table A deliveries include water that is not conveyed through the SLC and Aqueduct. Deliveries reported here include water conveyed through the North and South Bay Aqueducts, as well as water withdrawn from storage facilities in Southern California, such as Lake Perris, Castaic Lake, and Pyramid Lake. The value of 602 TAF/year is larger than capacity of the SLC and Aqueduct for this scenario. In this scenario, the SLC and Aqueduct delivered 362 TAF in 1983, which is equivalent to a continuous 500 cfs.
4. The increase in minimum deliveries is due to an increase in SOD storage in most years. Since delivery capability decreases in these scenarios, water tends to stay in storage more often than in the non-subsidence scenarios. Since the SLC and Aqueduct are capacity constrained, more water stays in San Luis. This allows for higher deliveries in subsequent years. This is discussed in more detail in later sections.

Note that a quantitative analysis cannot be done for the 95% NESP scenario. Under that subsidence scenario the SLC and Aqueduct cannot be operated using the 2020 SOO. As such HCC cannot be estimated by the CASP models. Due to this, no CalSim3 model can be constructed either. The locations and characteristics of these limits are described in the "Subsidence and HCC Information for Use in the Climate Adaptation Study" report.

In the absence of a quantitative estimate of the impacts to delivery capability, the following information should be kept in mind. The spatial locations with the highest levels of subsidence are similar under the 50% NESP, 75% NESP, and 95% NESP scenarios. Additionally, the magnitude of subsidence in the 95% NESP is larger than both the 50% NESP and 75% NESP scenarios. The actual magnitudes of subsidence for each scenario are presented in the “Subsidence and Hydraulic Conveyance Capacity Information for Use in the Climate Adaptation Study” report. It is expected that larger magnitudes of subsidence would further reduce the delivery capability of the SWP. It is then expected that the impacts of the 95% NESP subsidence levels would be greater than an 87% reduction in long-term average Table A deliveries.

Impacts of 2023 Levels of Subsidence on Delivery Capability

The cumulative effects of 2023 levels of subsidence reduce the delivery capability of the SWP. As discussed in Section 2, DWR monitors actual subsidence rates along the alignment of the SLC and Aqueduct. Those measurements were used to develop the 2023 level of subsidence scenarios discussed below. Estimated impacts to both SWP Table A and Article 21 deliveries are presented below. For definitions of Table A and Article 21 deliveries, see the DCR 2023.

Estimates of SWP Table A Water Deliveries

The likelihood of different levels of Table A deliveries is presented in Figure 6. Impacts of subsidence in 2023 reduce the likelihood of the highest deliveries. In these high allocation years, the lowered HCC of the SLC and Aqueduct limits the operations of the SWP. This lower HCC also alters the monthly pattern of deliveries. Figure 7 shows that the SLC and Aqueduct operate at their highest combined delivery capacity later into the year. Even when water is available in high allocation years, the SLC and Aqueduct lack the capacity to convey that water to users. Instead, that water remains in storage in San Luis Reservoir. These reduced deliveries in sequential wet or above normal years leads to higher beginning-of-year storage in San Luis Reservoir at the end of those periods. This higher storage also reduces the amount of water exported from the Delta because less water is needed to meet the storage targets in San Luis Reservoir. As a result, additional water may be stored north of the Delta in Oroville. The operational response to subsidence is that high deliveries happen less frequently due to capacity limits and average storage levels increase as a result. This in turn leads to fewer years with low allocations. Figure 6 shows this effect in the reduced likelihood of low deliveries. Figure 8 and Figure 9 show the corresponding increases in San Luis and Oroville Storage.

Figure 6. Estimated Likelihood of SWP Table A Water Deliveries (Excluding Butte County, Yuba City, Plumas County FCWCD), by Increments of 500 TAF under 2023 Levels of Subsidence

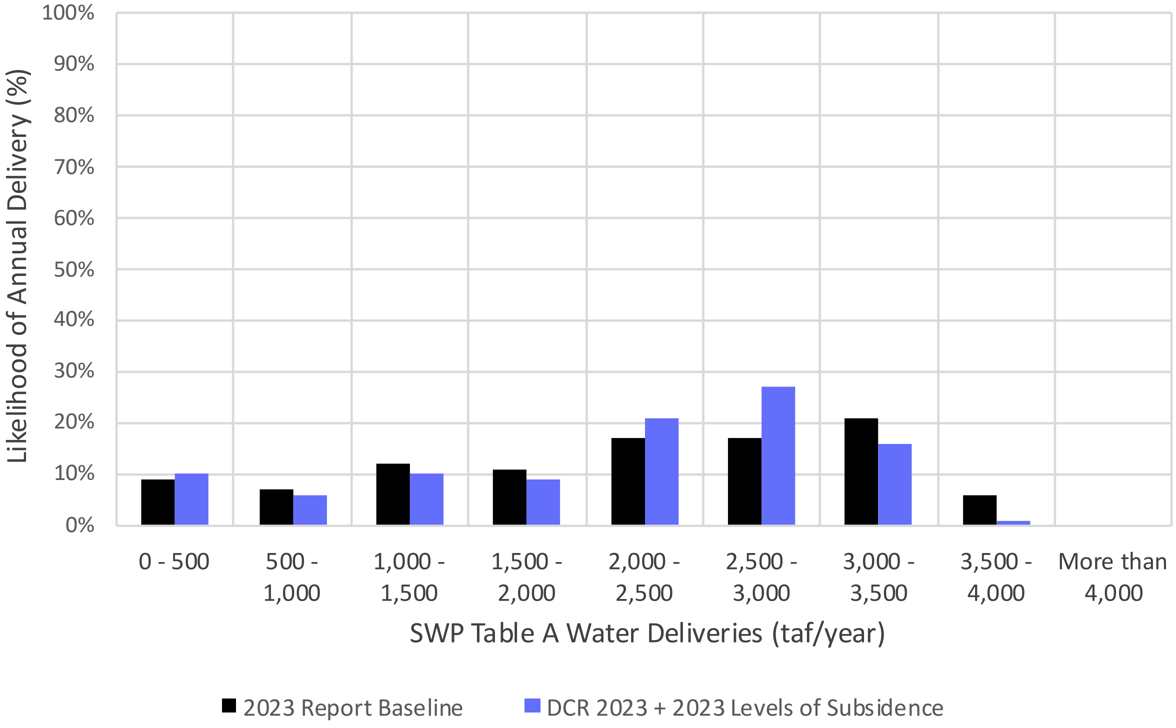


Figure 7. Monthly Patterns of Table A Deliveries under 2023 Levels of Subsidence

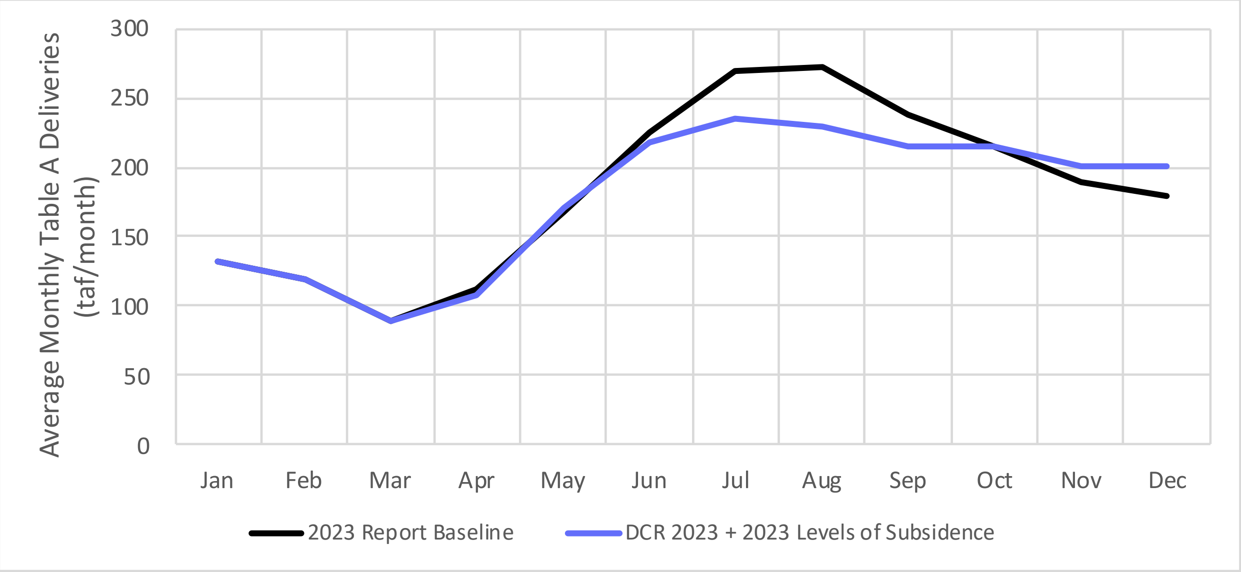


Figure 8. Total Storage in the State Water Project Portion of San Luis Reservoir under 2023 Levels of Subsidence

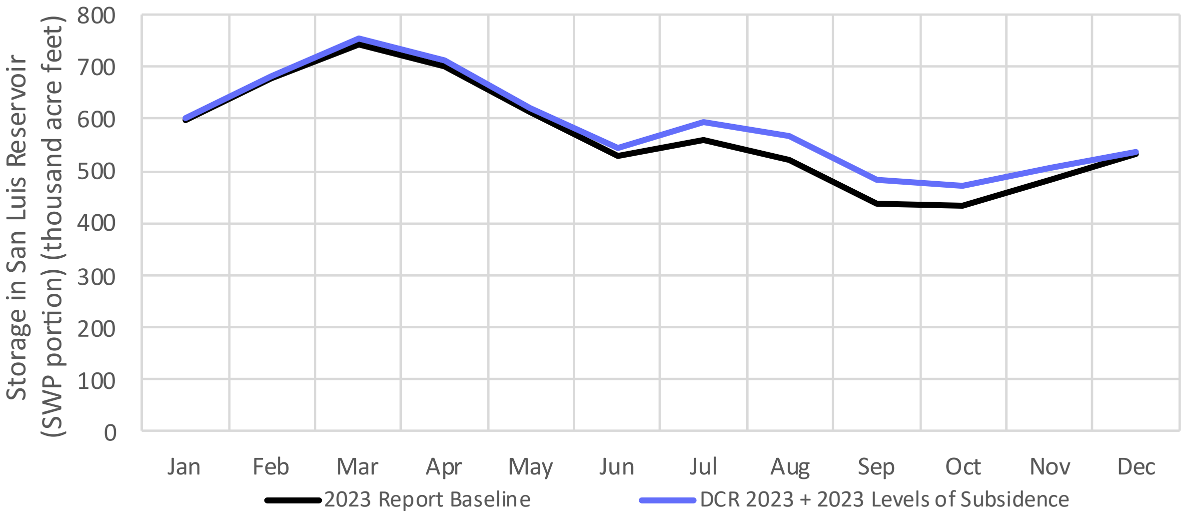


Figure 9. Total Storage in Lake Oroville under 2023 Levels of Subsidence

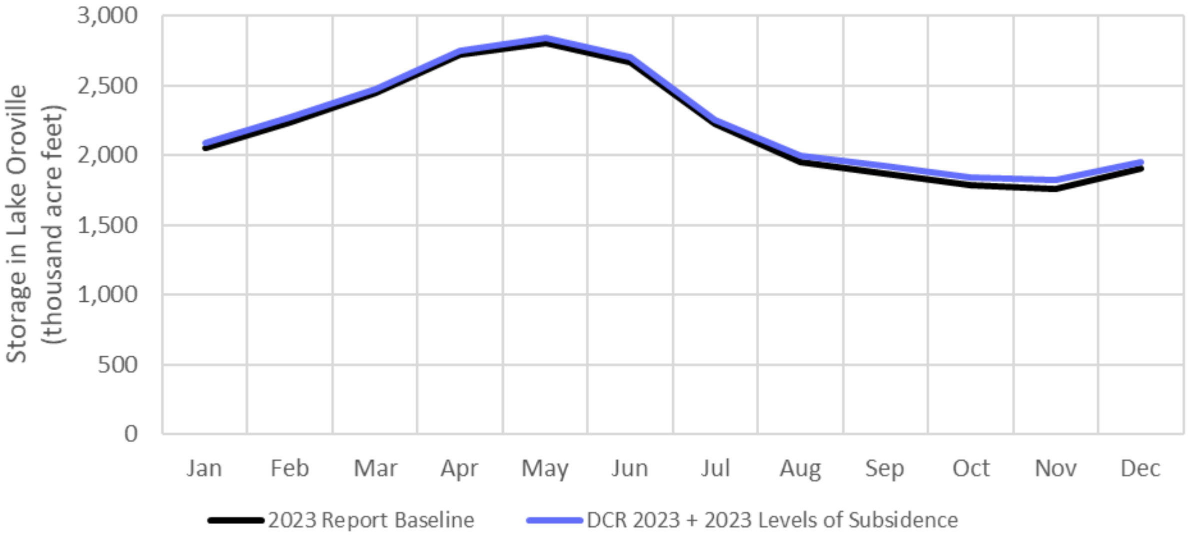


Table 6 and Figure 10 show the estimated annual Table A deliveries for selected wet periods from the model simulation period. Wet periods show the largest reductions in SWP deliveries compared to the DCR 2023 Baseline. This change is due to the reduction in HCC in the SLC and Aqueduct. The wettest years see reductions around 500 taf/year.

Table 6. Estimated Average and Wet Period Deliveries of SWP Table A Water under 2023 Levels of Subsidence (in TAF/year) and Percent of Maximum SWP Table A Amount, 4,133 TAF/year

Period	DCR 2023 Baseline, Design HCC Scenario (1922–2021)	Estimated 2023 HCC Scenario (1922–2021)
Long-Term Average	2,202 (53%)	2,125 (51%)
Single Year (1983)	3,794 (92%)	3,674 (89%)
Single Year (1998)	3,904 (94%)	3,322 (80%)
2-Year (1982-1983)	3,605 (87%)	3,221 (78%)
4-Year (1980-1983)	3,110 (75%)	2,974 (72%)
6-Year (1978-1983)	3,060 (74%)	2,914 (70%)
10-Year (1978-1987)	2,849 (69%)	2,785 (67%)
Single Year (2017)	3,372 (82%)	2,781 (67%)

Figure 10. Estimated Wet Period SWP Table A Water Deliveries under Current Subsidence (Excluding Butte County, Yuba City, Plumas County FCWCD)

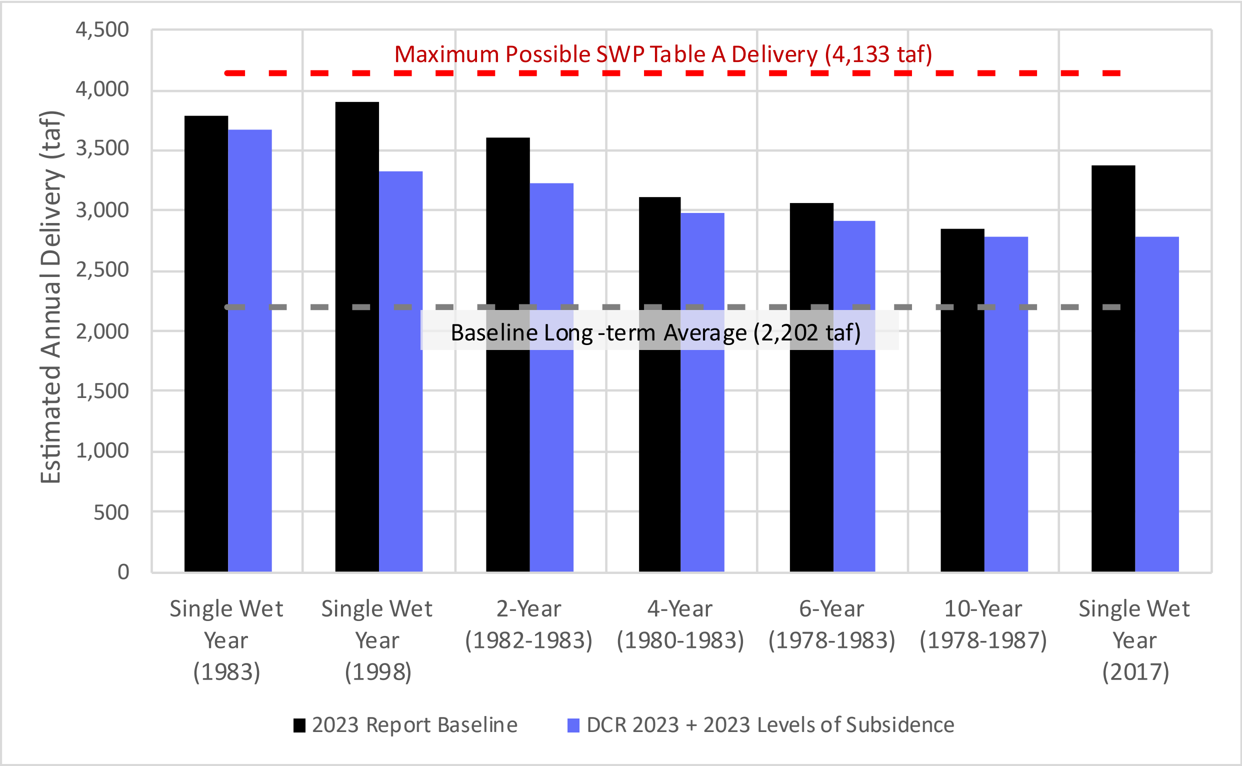


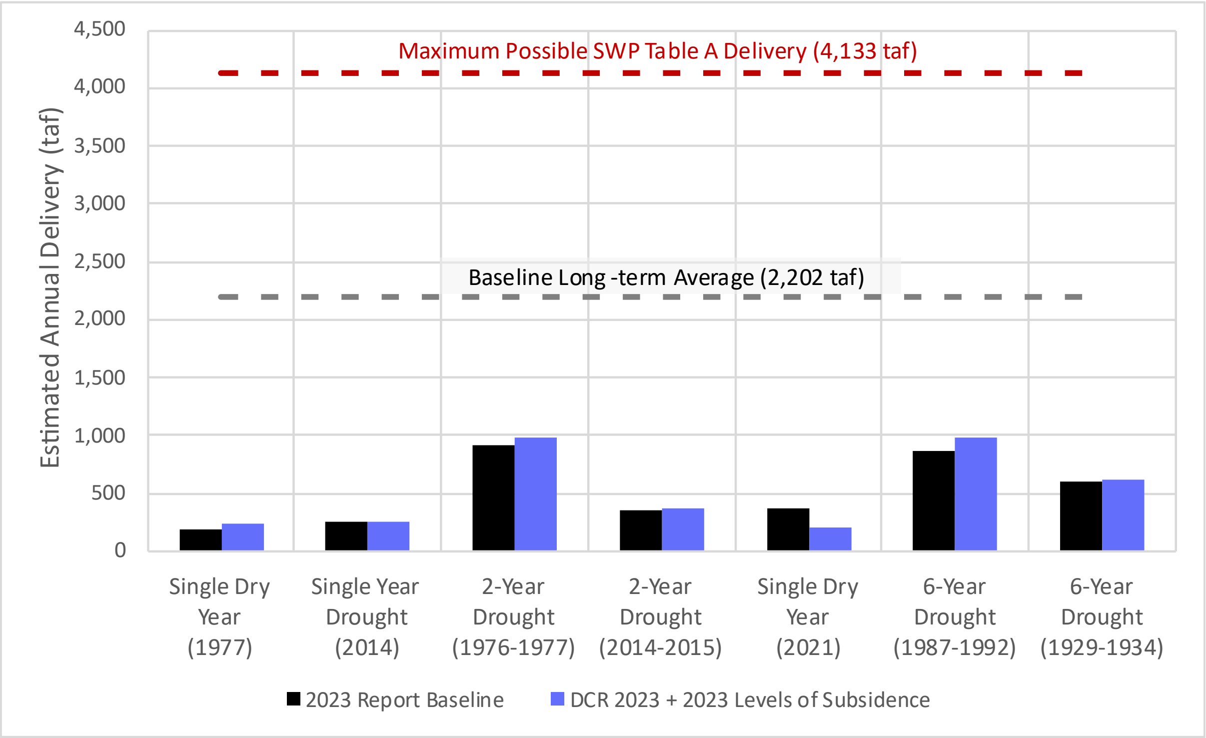
Table 7 and Figure 11 show the estimated annual Table A deliveries for selected dry periods from the model simulation period. Dry periods show small increases in SWP deliveries compared to the DCR 2023 Baseline. This change is due to increased storage in San Luis due to the inability to deliver water in preceding years. The driest years see increases around 50 TAF/year.

Note that this increase is an order of magnitude smaller than the corresponding decrease in wet period deliveries.

Table 7. Estimated Average and Dry Period Deliveries of SWP Table A Water under 2023 Levels of Subsidence (in TAF/year) and Percent of Maximum SWP Table A Amount, 4,133 TAF/year.

Period	DCR 2023 Baseline, Design HCC Scenario (1922–2021)	Estimated 2023 HCC Scenario (1922–2021)
Long-Term Average	2,202 (53%)	2,125 (51%)
Single Year (1977)	184 (4%)	243 (6%)
Single Year (2014)	251 (6%)	254 (6%)
2 Year (1976-1977)	922 (22%)	987 (24%)
2 Year (2014-2015)	360 (9%)	365 (9%)
6 Year (1987-1992)	860 (21%)	980 (24%)
6 Year (1929-1934)	597 (14%)	611 (15%)

Figure 11. Estimated Dry Period SWP Table A Water Deliveries under 2023 Levels of Subsidence (Excluding Butte County, Yuba City, Plumas County FCWCD)



Estimates of SWP Article 21 Water Deliveries

Article 21 deliveries tend to decrease under 2023 levels of subsidence. This is because Article 21 deliveries are “surplus” deliveries and occur only after Table A deliveries. When capacity is limited in the SLC and Aqueduct, Table A deliveries occupy the entire capacity of the Aqueduct. With 2023 levels of subsidence, it is less likely for capacity to be available at the same time when water is available to be delivered as Article 21.

Table 8 and Figure 12 show the estimated annual Article 21 deliveries for selected wet periods from the model simulation period. Most periods see a reduction in Article 21 deliveries. The wettest years see a reduction of about 400 TAF/year.

Table 8. Estimated Average and Wet Period Deliveries of SWP Article 21 Water under 2023 Levels of Subsidence (in TAF/year)

Period	DCR 2023 Baseline, Design HCC Scenario (1922–2021)	Estimated 2023 HCC Scenario (1922–2021)
Long-Term Average	101	72
Single Year (1983)	1,025	729
Single Year (1998)	271	201
2-Year (1982-1983)	878	479
4-Year (1980-1983)	564	321
6-Year (1978-1983)	385	225
10-Year (1978-1987)	269	145
Single Year (2017)	353	369

Figure 12. Estimated Wet Period Deliveries of SWP Article 21 Water under 2023 Levels of Subsidence (in TAF/year)

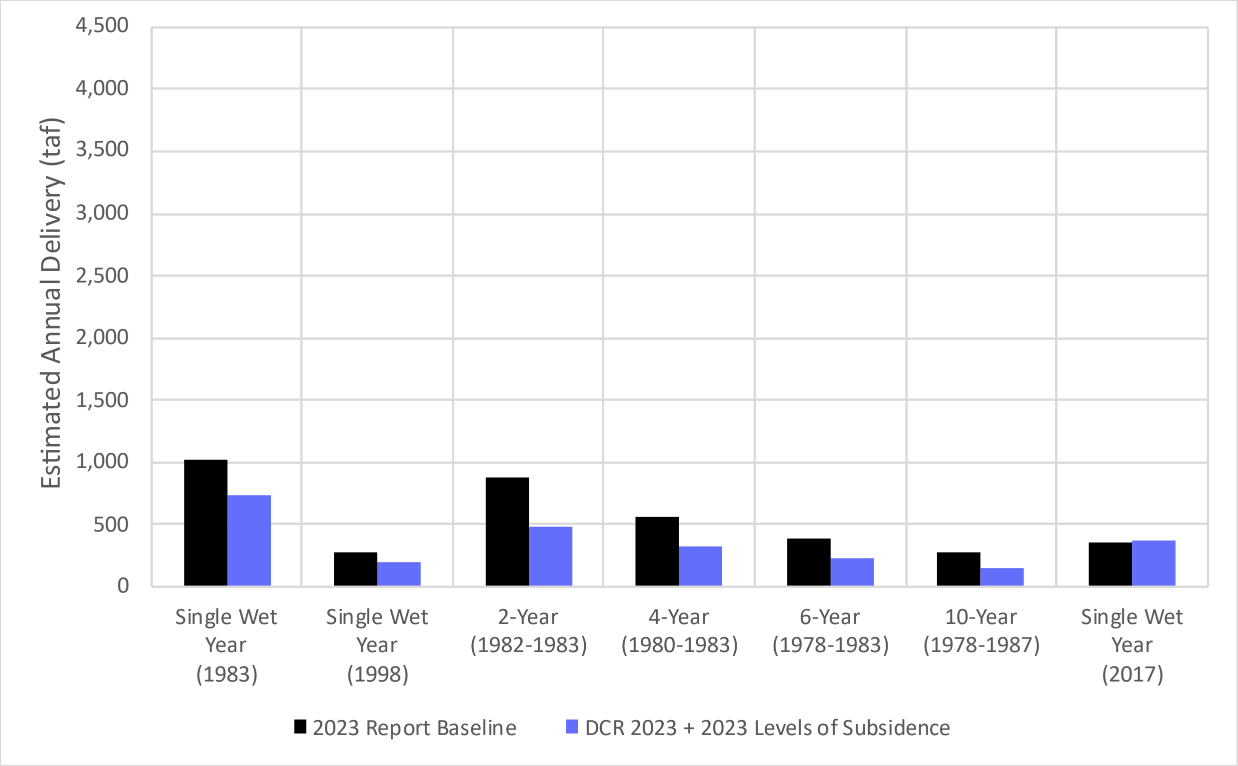
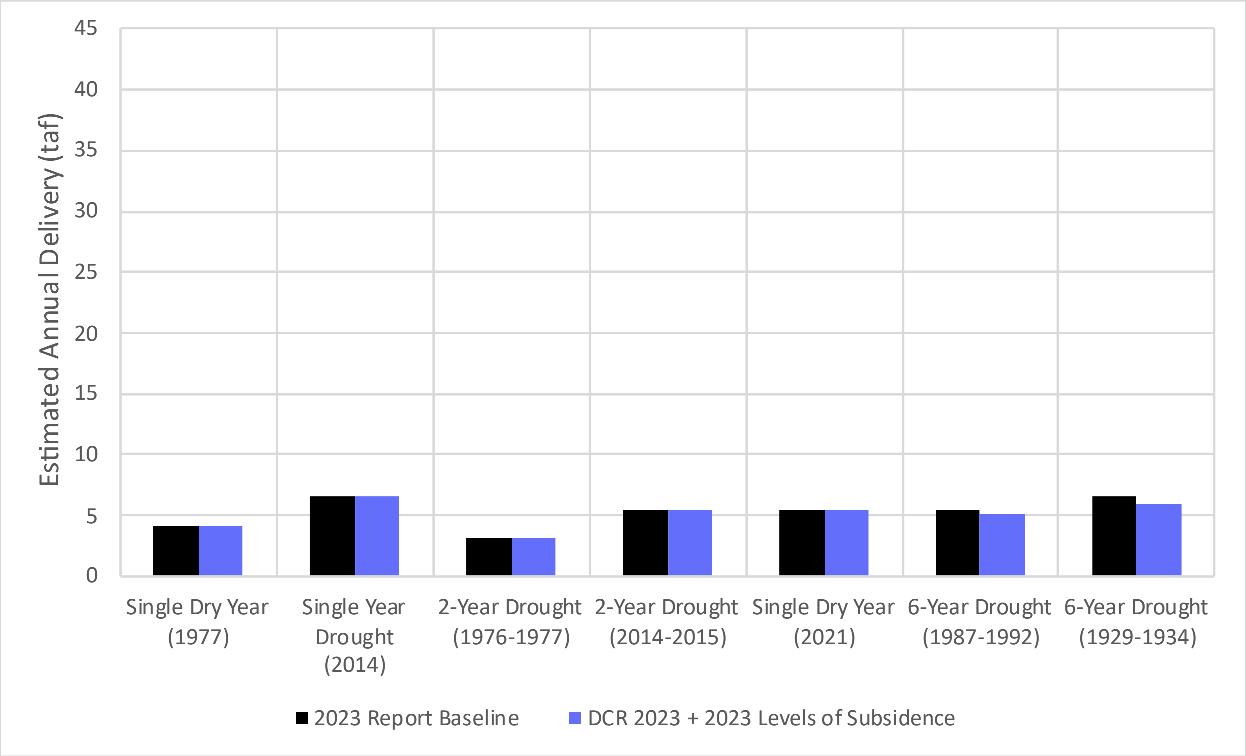


Table 9 and Figure 13 show the estimated annual Article 21 deliveries for selected dry periods from the model simulation period. Most dry periods see no significant change in Article 21 deliveries, as surplus water availability is the limiting factor even if capacity exists in the SLC and Aqueduct.

Table 9. Estimated Average and Dry Period Deliveries of SWP Article 21 Water under 2023 Levels of Subsidence (in TAF/year)

Period	DCR 2023 Baseline, Design HCC Scenario (1922–2021)	Estimated 2023 HCC Scenario (1922–2021)
Long-Term Average	101	72
Single Year (1977)	4	4
Single Year (2014)	7	7
2-Year (1976-1977)	3	3
2-Year (2014-2015)	5	5
6-Year (1987-1992)	5	5
6-Year (1929-1934)	7	6

Figure 13. Estimated Dry Period Deliveries of SWP Article 21 Water under 2023 Levels of Subsidence (in TAF/year)



Impacts of Potential 2043 Subsidence on Delivery Capability

The cumulative effects of potential 2043 levels of subsidence reduce the delivery capability of the SWP. As discussed above, the potential 2043 subsidence scenarios presented below demonstrate the wide range of potential impacts on the SWP delivery capability. It is essential to remember that no adaptations are implemented in these scenarios, and that the estimates of impacts are intended to be a first step in assessing the vulnerability of the SWP to subsidence.

Estimates of SWP Table A Water Deliveries

The likelihood of different levels of Table A deliveries is presented in Figure 14. Impacts of potential 2043 subsidence levels differ dramatically from each other. The 50% NESP scenario tends to reduce the likelihood of high deliveries compared to the 50% LOC scenario without subsidence.

The 75% NESP scenario, however, dramatically reduces the likelihood of any deliveries greater than 500 TAF/year. This is because of the low HCC values in the SLC and Aqueduct. At these low HCC values, the SWP only delivers more than 500 taf/year in 1% of years. This also dramatically impacts the monthly pattern of deliveries and the average monthly storage in San Luis Reservoir and lake Oroville (as seen in Figure 15, Figure 16, and Figure 17 respectively). The reasons for the changes in monthly patterns and average storage levels are similar to those discussed in the 2023 section above.

Figure 14. Estimated Likelihood of SWP Table A Water Deliveries (Excluding Butte County, Yuba City, Plumas County FCWCD), by Increments of 500 TAF under Potential 2043 Conditions

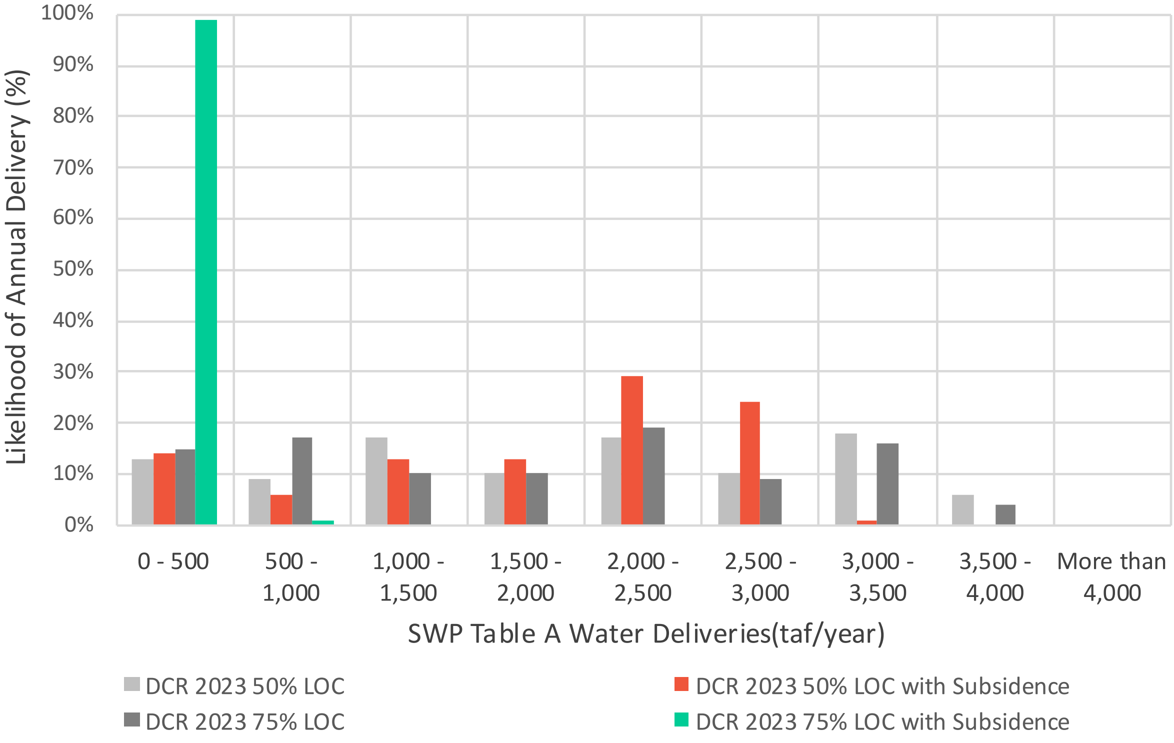


Figure 15. Monthly Patterns of Table A Deliveries under Potential 2043 Conditions

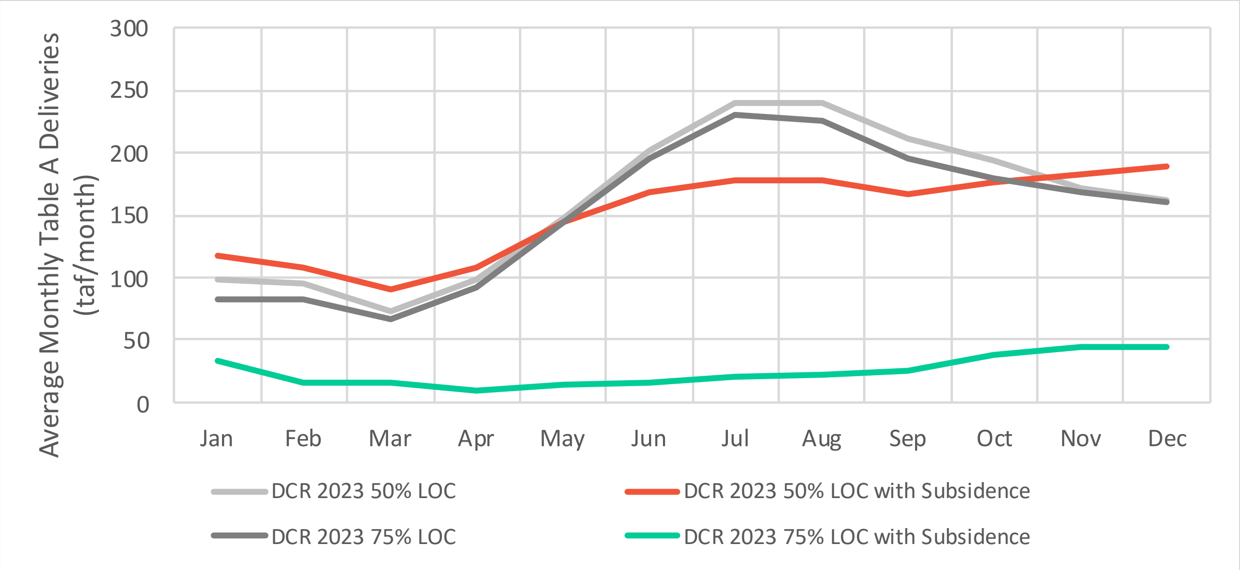


Figure 16. Total Storage in the State Water Portion of San Luis Reservoir under Potential 2043 Conditions

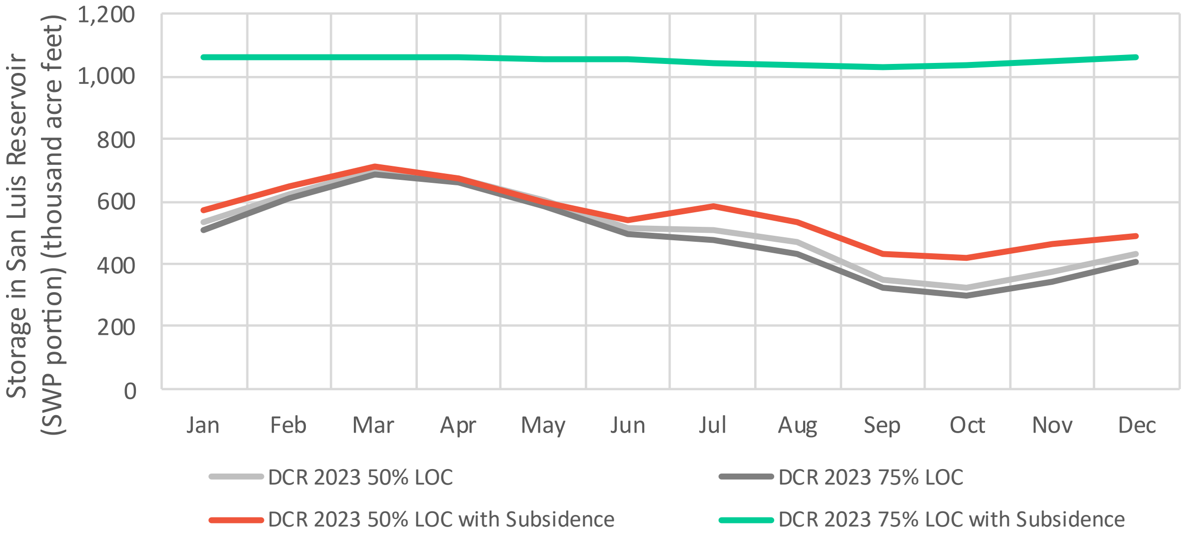


Figure 17. Total Storage in Lake Oroville under Potential 2043 Conditions

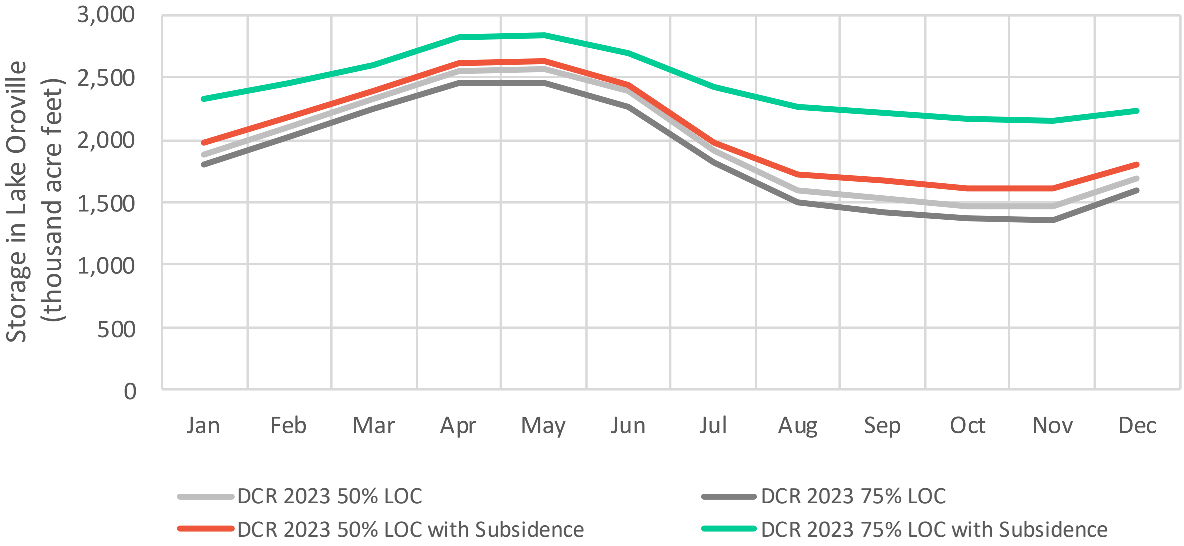


Table 10 and Figure 18 show the estimated annual Table A deliveries for selected wet periods from the model simulation period. Evaluating the two scenarios that use the 50% LOC Climate Change scenario, the wettest years see reductions around 500 TAF/year due to subsidence.

Evaluating the two scenarios that use the 75% LOC Climate Change scenario, the wettest years see reductions around 2,800 TAF/year due to subsidence.

Table 10. Estimated Average and Wet Period Deliveries of SWP Table A Water under Potential 2043 Conditions (in TAF/year) and Percent of Maximum SWP Table A Amount, 4,133 TAF/year

Period	2043 50% LOC Without Subsidence	2043 50% LOC With Subsidence	2043 75% LOC Without Subsidence	2043 75% LOC With Subsidence
Long-Term Average	1,921 (46%)	1,797 (43%)	1,812 (44%)	295 (7%)
Single Year (1983)	3,790 (92%)	3,368 (81%)	3,790 (92%)	602 (15%)
Single Year (1998)	3,848 (93%)	2,910 (70%)	3,834 (93%)	299 (7%)
2-Year (1982-1983)	3,595 (87%)	2,889 (70%)	3,592 (87%)	448 (11%)
4-Year (1980-1983)	2,849 (69%)	2,656 (64%)	2,722 (66%)	383 (9%)
6-Year (1978-1983)	2,773 (67%)	2,567 (62%)	2,669 (65%)	361 (9%)
10-Year (1978-1987)	2,459 (59%)	2,369 (57%)	2,422 (59%)	335 (8%)
Single Year (2017)	3,505 (85%)	2,517 (61%)	3,357 (81%)	262 (6%)

Figure 18. Estimated Wet Period SWP Table A Water Deliveries under Potential 2043 Conditions (Excluding Butte County, Yuba City, Plumas County FCWCD)

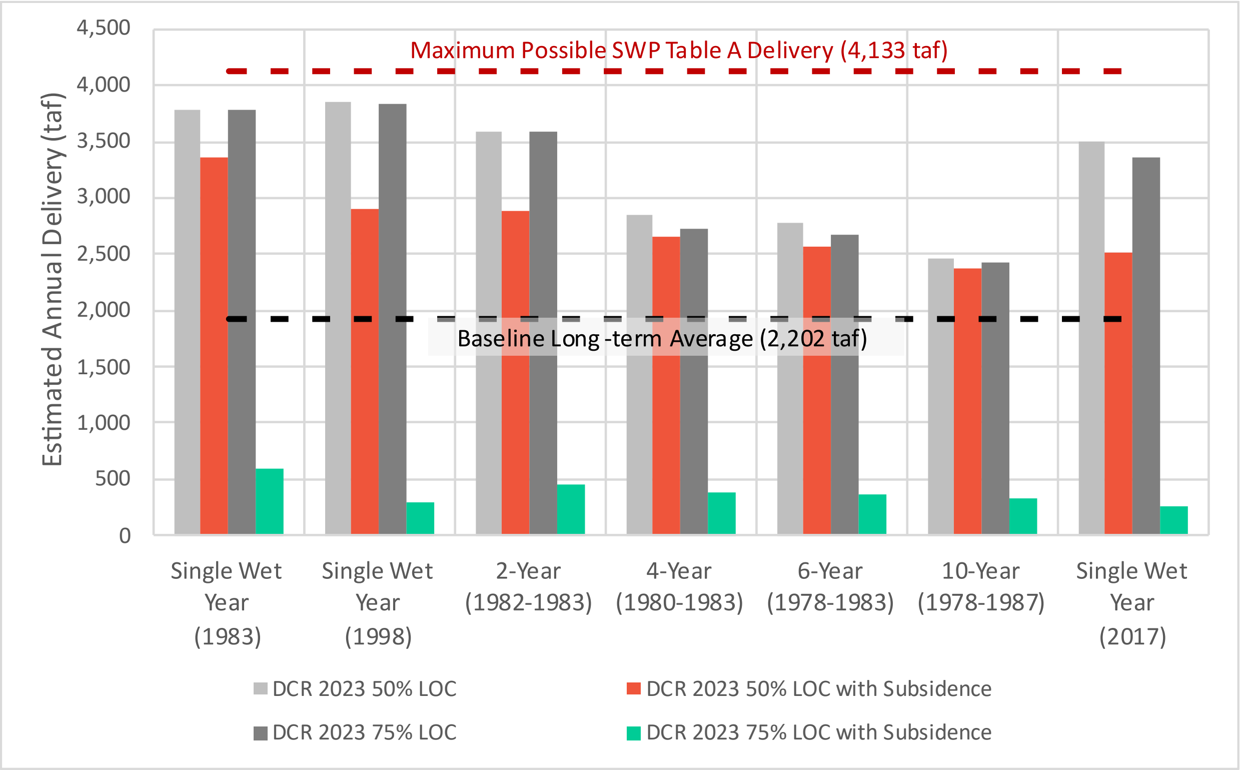


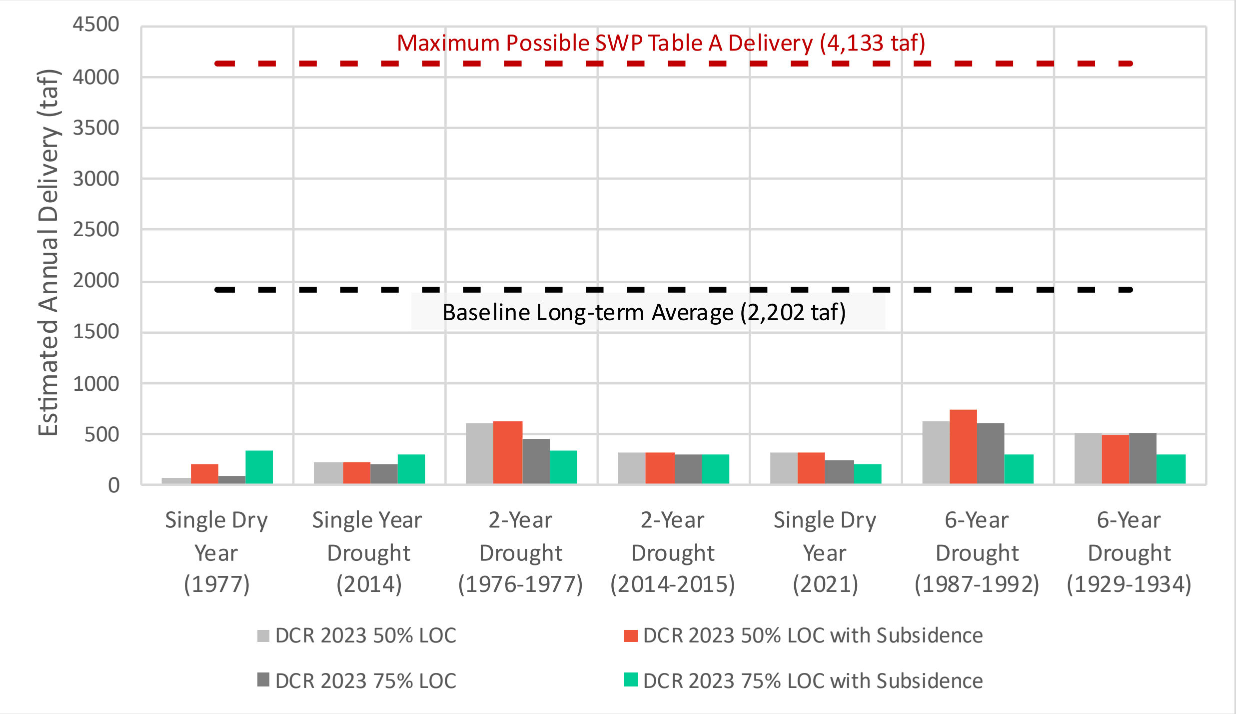
Table 11 and Figure 19 show the estimated annual Table A deliveries for selected dry periods from the model simulation period. Evaluating the two scenarios that use the 50% LOC Climate Change scenario, dry periods see similar or slightly higher deliveries under subsided conditions. This increase is often due to the higher storage levels in San Luis and Oroville at the beginning of these periods. Often, this higher reservoir storage is due to the inability to deliver this water in the years prior, meaning less water is released in the first place.

Evaluating the two scenarios that use the 75% LOC Climate Change scenario, a different pattern is seen. Only in the exceptionally dry year of 1977 (and the coupled 2-year period 1976-1977) do we observe this increase. The lack of increases is due to the low HCC values in the SLC and Aqueduct. Even if additional water is available in storage, it still cannot be conveyed in these dry years as they were in the 2043 75% LOC without Subsidence scenario.

Table 11. Estimated Average and Dry Period Deliveries of SWP Table A Water under Potential 2043 Conditions (in TAF/year) and Percent of Maximum SWP Table A Amount, 4,133 TAF/year

Period	2043 50% LOC Without Subsidence	2043 50% LOC With Subsidence	2043 75% LOC Without Subsidence	2043 75% LOC With Subsidence
Long-Term Average	1,921 (46%)	1,797 (43%)	1,812 (44%)	295 (7%)
Single Year (1977)	75 (2%)	202 (5%)	97 (2%)	338 (8%)
Single Year (2014)	221 (5%)	222 (5%)	213 (5%)	308 (7%)
2-Year (1976-1977)	604 (15%)	623 (15%)	464 (11%)	340 (8%)
2-Year (2014-2015)	321 (8%)	323 (8%)	297 (7%)	298 (7%)
6-Year (1987-1992)	625 (15%)	737 (18%)	602 (15%)	300 (7%)
6-Year (1929-1934)	520 (13%)	500 (12%)	504 (12%)	306 (7%)

Figure 19. Estimated Dry Period SWP Table A Water Deliveries under Potential 2043 Conditions (Excluding Butte County, Yuba City, Plumas County FCWCD)



Estimates of SWP Article 21 Water Deliveries

Table 12 and Figure 20 show the estimated annual Article 21 deliveries for selected wet periods from the model simulation period. Evaluating the two scenarios that use the 50% LOC Climate Change scenario, wet periods see a dramatic reduction in Article 21 deliveries. Since the HCC is limiting deliveries in these years, deliveries of Article 21 water are not made as frequently, as Table A deliveries take priority.

Evaluating the two scenarios that use the 75% LOC Climate Change scenario, the same pattern is seen. The impact of subsidence in this case is much more drastic. In the subsidence scenario, Article 21 deliveries are never estimated to be larger than 75 TAF/year. This is notable because this maximum value is lower than the average value from the comparable 2043 75% LOC without Subsidence scenario (83 taf/year).

Table 12. Estimated Average and Wet Period Deliveries of SWP Article 21 Water under Potential 2043 Conditions (in TAF/year)

Period	2043 50% LOC Without Subsidence	2043 50% LOC With Subsidence	2043 75% LOC Without Subsidence	2043 75% LOC With Subsidence
Long-Term Average	97	40	87	51
Single Year (1983)	1,026	384	1,011	73
Single Year (1998)	208	76	100	63
2-Year (1982-1983)	881	227	840	68
4-Year (1980-1983)	546	158	424	61
6-Year (1978-1983)	436	154	304	59
10-Year (1978-1987)	314	97	264	56
Single Year (2017)	458	199	434	62

Figure 20. Estimated Wet Period Deliveries of SWP Article 21 Water under Potential 2043 Conditions (in TAF/year)

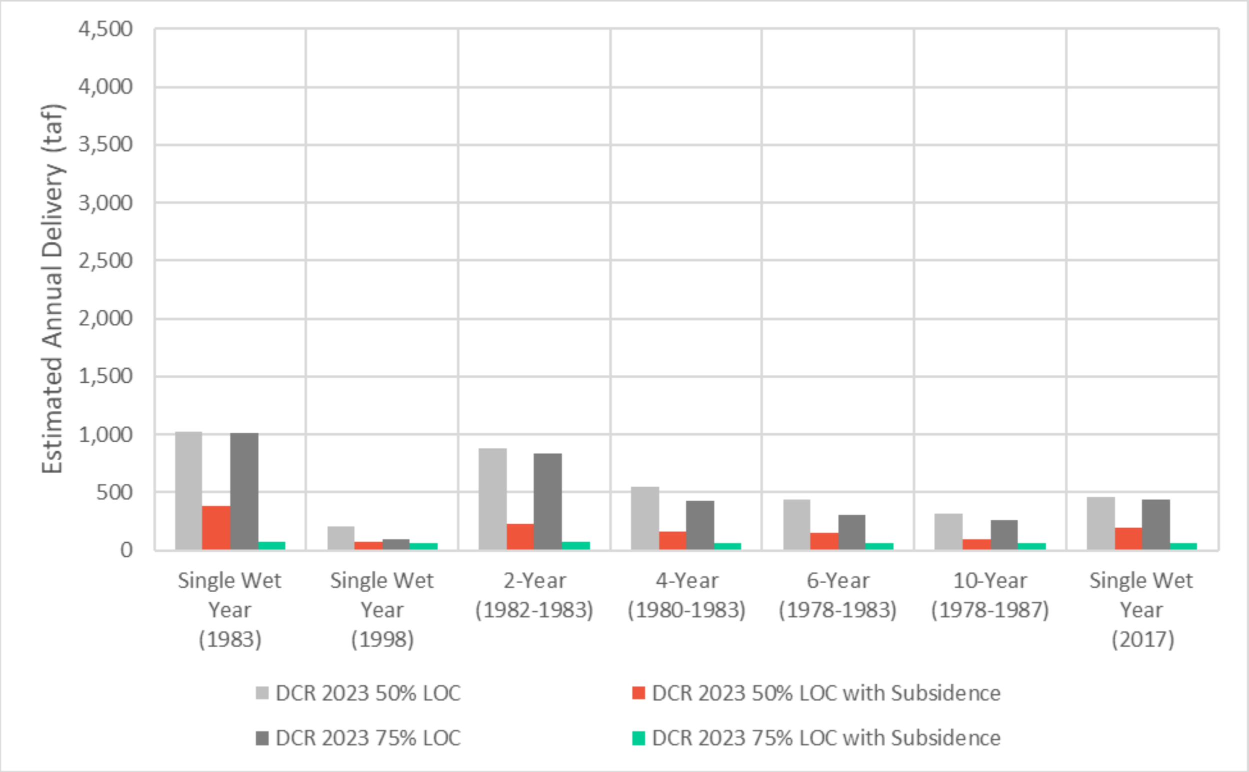


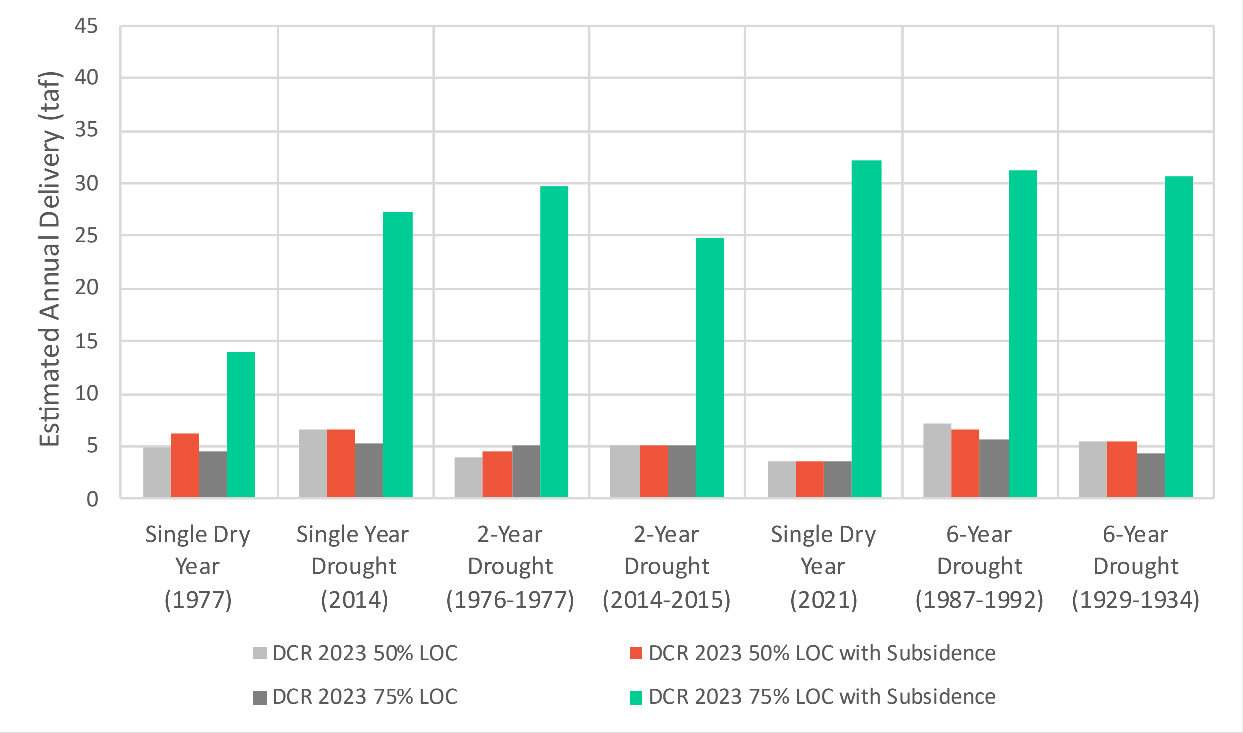
Table 13 and Figure 21 show the estimated annual Article 21 deliveries for selected dry periods from the model simulation period. Evaluating the two scenarios that use the 50% LOC Climate Change scenario, dry periods see little change. Some periods can see shifts of 1 TAF/year in either direction.

Evaluating the two scenarios that use the 75% LOC Climate Change scenario, a different pattern is seen. Dry year deliveries of Article 21 water increase dramatically. This is due to the fact that the estimated deliveries in the comparable 2043 75% LOC without Subsidence scenario are very low due to a lack of water availability. Since the limiting factor in that scenario is not SLC and Aqueduct HCC, and the fact that San Luis Reservoir tends to have higher storage at the beginning of these periods, more water is delivered as Article 21 rather than used to fill San Luis.

Table 13. Estimated Average and Dry Period Deliveries of SWP Article 21 Water under Potential 2043 Conditions (in TAF/year)

Period	2043 50% LOC Without Subsidence	2043 50% LOC With Subsidence	2043 75% LOC Without Subsidence	2043 75% LOC With Subsidence
Long-Term Average	97	40	87	51
Single Year (1977)	5	6	5	14
Single Year (2014)	7	7	5	27
2-Year (1976-1977)	4	4	5	30
2-Year (2014-2015)	5	5	5	25
6-Year (1987-1992)	7	6	6	31
6-Year (1929-1934)	5	6	4	31

Figure 21. Estimated Dry Period Deliveries of SWP Article 21 Water under Potential 2043 Conditions (in TAF/year)



Attachment

The following is an attachment of the January 25, 2024 technical memorandum prepared by the California Aqueduct Subsidence Program team, titled: “Subsidence and Hydraulic Conveyance Capacity Information for Use in the DCR 2023 Report”. It is included to provide supporting technical detail relevant to the analysis presented in this report. Minor formatting modifications have been made to improve accessibility for screen readers and other assistive technologies.

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
CALIFORNIA AQUEDUCT SUBSIDENCE PROGRAM
TECHNICAL MEMORANDUM

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DATE: January 25, 2024

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SUBJECT: Subsidence and Hydraulic Conveyance Capacity Information for Use in the DCR 2023 Report

Introduction

This technical memorandum (TM) provides information developed by the California Aqueduct Subsidence Program (CASP) for use in preparing the 2023 Delivery Capability (DCR 2023) Report. The initial release of the DCR 2023 Report will present the delivery capability of the State Water Project (SWP) based on the assumption that the hydraulic conveyance capacity (HCC) of the California Aqueduct (Aqueduct) is the original design capacity. Following the initial release, DCR 2023 will be amended to include a supplemental evaluation of the effects of current and forecasted future subsidence of the Aqueduct in the San Joaquin Valley on the delivery capability of the SWP.

CASP has developed a set of analytical tools and methods to evaluate the effects of current and potential future subsidence on the performance of the SWP and Central Valley Project (CVP). Relevant CASP information for use in DCR 2023 presented in this TM include:

- Subsidence Profiles
    - Subsidence in the San Joaquin Valley
    - Current and Projected Future Subsidence

  - Subsidence Forecast Model Description
  - Subsidence Displacements for Use in DCR 2023
- HCC
  - Hydrologic Engineering Center's-River Analysis System (HEC-RAS) Model Description
  - Application of the 2020 Standing Operating Order (SOO) and Special Conditions
  - Hydraulic Conveyance Capacities for Use in DCR 2023

Subsidence Profiles

Subsidence in the San Joaquin Valley

The Aqueduct is a key element of the SWP and the federal CVP. Regional land subsidence, caused primarily by groundwater overdraft, has reduced the HCC and operational flexibility of the Aqueduct in the San Joaquin Valley, and additional subsidence is expected to continue into the foreseeable future. In 2014, California enacted the Sustainable Groundwater Management Act (SGMA), which requires the development and implementation of Groundwater Sustainability Plans (GSP) that describe planned actions to achieve sustainable groundwater management practices by 2040 and avoid undesirable consequences of overdraft, including land subsidence. Subsidence in the San Joaquin Valley is expected to continue while recently formed Groundwater Sustainability Agencies (GSA) develop and gradually implement their GSPs to comply with SGMA.

Significant uncertainty exists regarding the specifics of how SGMA implementation will occur. Additional uncertainty exists regarding future climatic conditions and their effects on water deliveries to SWP and CVP contractors, which in turn can affect when and how rapidly full SGMA implementation will occur. CASP has been established to formulate, analyze, evaluate, recommend, and implement near-term and long-term actions to address the consequences of subsidence of the Aqueduct in the San Joaquin Valley on the operation and performance of the SWP and CVP.

Current and Projected Future Subsidence

Subsidence has been occurring in the San Joaquin Valley for many decades and has gradually lowered the elevation of the Aqueduct at several locations. The Department of Water Resources (DWR) performs annual surveys of several locations along the Aqueduct (commonly referred to as “Precise Surveys”) and periodically prepares regional surveys of the greater San Joaquin Valley. This information was used to prepare the existing profile of the Aqueduct. Profiles reflecting future subsided conditions were prepared using a Subsidence Forecast Model (SFM) to calculate a range of potential additional displacements.

Subsidence Forecast Model Description

The SFM was developed by CASP to quantify a range of potential future land subsidence conditions in consideration of uncertainty regarding the implementation of SGMA and future climate. The SFM is primarily based on empirical relationships between historical subsidence rates and annual water deliveries from the CVP and SWP to federal and state water contractors in the San Joaquin Valley. The SFM is a series of subsidence calculations at Precise Survey locations and is based on the following key assumptions:

- The rate of groundwater overdraft, which contributes to loss of aquifer storage and permanent land subsidence, is correlated with CVP and SWP deliveries and specifically with higher groundwater storage loss during severe drought years.
- Historical subsidence rates will continue as groundwater levels decline, even when extraction may be coming from deeper parts of the aquifer system than has occurred in the past.
- Subsidence will continue to occur at locations that have experienced historical subsidence.
- Modifications to groundwater pumping patterns to comply with SGMA will occur in a similar manner at all locations that have caused historical subsidence, meaning that the variability of future subsidence along the Aqueduct will be proportional to the variability of historical subsidence.

If the geology, aquifer properties, or SGMA response behaviors differ dramatically from these assumptions, then these new conditions may have an unmodeled impact on future subsidence rates.

The SFM considers the three following conditions that determine the rates of future subsidence at modeled locations along the Aqueduct:

- A No SGMA condition, during which the behavior of subsidence is represented by a statistical model based on historical patterns;
- A Partial SGMA Implementation condition, during which the parameters of the statistical model are tapered down; and
- A Cessation of Overdraft condition, during which only the natural geologic and background subsidence rates and elastic fluctuations are represented.

The SFM accounts for random (aleatory) variability in the annual subsidence rate during both severe drought and other climate conditions and also considers the frequency and duration of severe drought periods during which water deliveries are low to non-existent and the subsidence rate is expected to be much higher. The SFM also accounts for anticipated future reductions in land subsidence rates associated with the implementation of SGMA, which requires the high-priority groundwater basins to be in balance by 2040. All groundwater basins that underly subsided portions of the Aqueduct in the CASP area of interest are classified under SGMA as high-priority basins. The timing of onset and speed of implementation of SGMA are uncertain and thus are treated as epistemic variables in the forecast model.

The SFM outputs probability distributions of additional land subsidence at each calculated location (Precise Survey points) for each year in the SFM simulation. These outputs are then processed to prepare longitudinal profiles of additional subsidence (subsidence profiles) at selected non-exceedance percentiles for specific years. The percentiles account for both aleatory variability and epistemic (incomplete knowledge) uncertainties. Subsidence profiles are calculated for every year through 2080 and for non-exceedance percentiles of 1, 2, 3, 4, 5, 10, 15,…, 90, 95, 96, 97, 98, and 99. The higher percentiles are associated with more severe conditions (i.e., greater subsidence).

More information on the development of the SFM is available in the Probabilistic Subsidence Forecast Model For The California Aqueduct Subsidence Program San Joaquin Valley, California Report, included as Attachment 2 (DWR 2023a).

Subsidence Profiles for Use in DCR 2023

The subsidence profiles from the SFM were calculated for the year 2043 based on a starting year of 2023 to correspond with the DCR planning horizon of 2023 through 2043. Based on discussion with the DCR team, 50th, 75th, and 95th percentile non-exceedance subsidence profiles were selected to be combined with the 50th, 75th, and 95th percentile climate change forecasts used in DCR 2023 for evaluation of a range of potential delivery capabilities in 2043.

The existing (2023) profile of the Aqueduct from the Dos Amigos Pumping Plant (DAPP) to the Edmonston Pumping Plant (EPP), reflecting existing subsidence, was prepared by modifying a regional light detection and ranging (LiDAR) survey from 2021 with measured displacements determined through Precise Surveys from 2021 to 2023. Figure 1 shows several profiles along the portion of the Aqueduct extending from DAPP to Buena Vista Pumping Plant (BVPP), including the 2023 Precise Survey points from the top of concrete liner on the east and west banks of the Aqueduct a single representation of the original design top of the concrete liner profile, and the original design water surface elevation (WSEL) profile. Whereas the overall profile extends from DAPP to EPP, the geographic extent shown in Figure 1 is limited to the section from DAPP to BVPP to demonstrate the vertical elevation changes without limiting graphic resolution.

Figures 2, 3, and 4 show a single profile similar to Figure 1 that reflects the 2023 Precise Survey points from the top of concrete liner elevations for the east and west banks, the same original design top of liner and water surface shown in Figure 1, and the minimum top of liner elevations for the projected 50th, 75th, and 95th non-exceedance subsidence percentiles for 2043 from DAPP to BVPP. Minimum top of liner projections for 2043 were prepared by applying calculated displacements corresponding to the 50th, 75th, and 95th non-exceedance subsidence percentiles for 2043 to the 2023 Precise Survey points from the top of concrete liner.

Figure 5 combines Figures 2, 3, and 4 to help demonstrate the variability of projected subsidence for 2043. SFM displacements and corresponding elevations for the Aqueduct from DAPP to EPP are provided in Attachment 1, Subsidence Forecast Model Displacements and Elevations.

Figure 1 **2023 Top of Liner Profile with Original Design WSEL and Original Design Top of Liner Profiles**

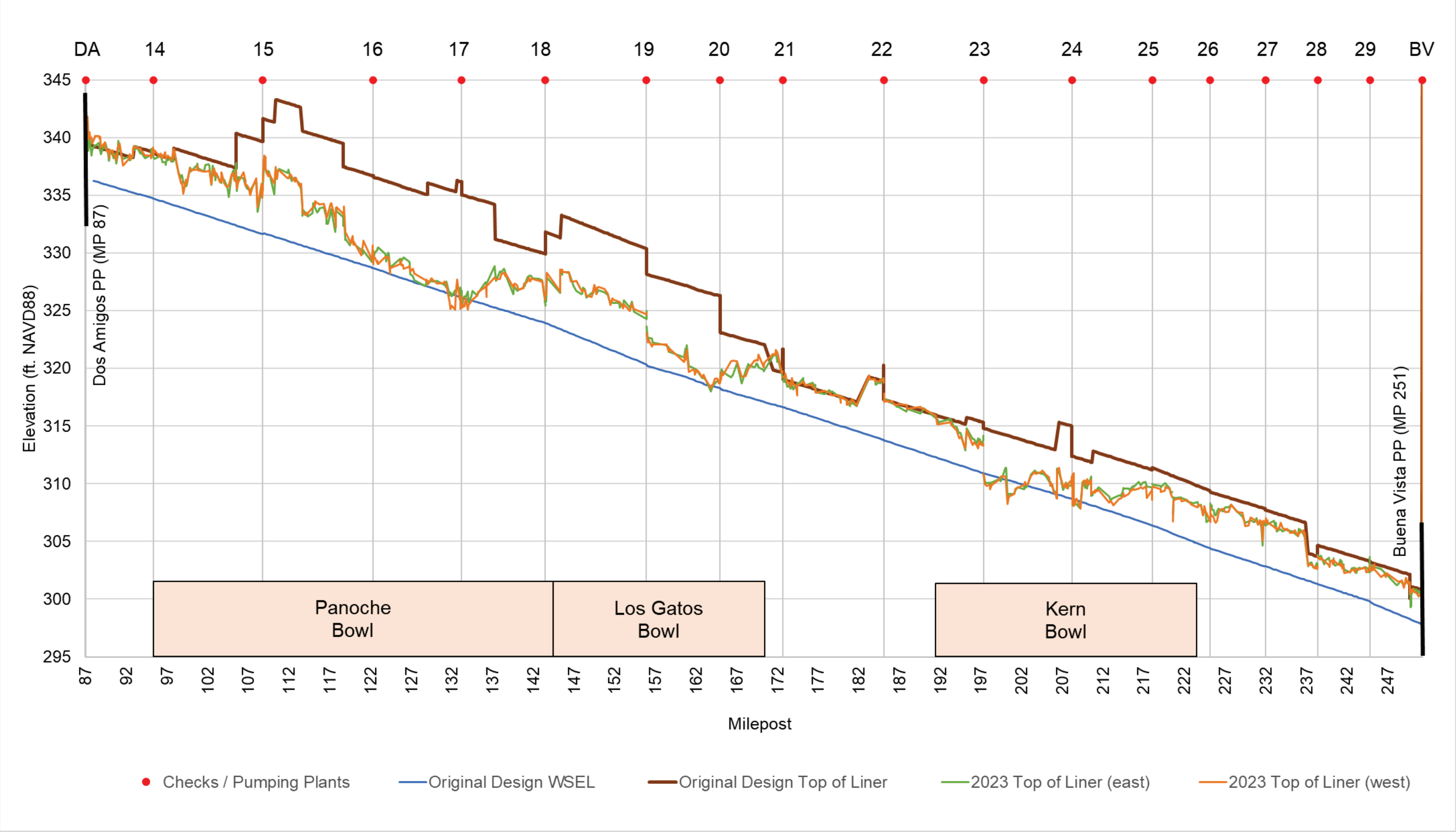


Figure 2 **2043 50th Non-exceedance Subsidence Percentile Top of Liner Profile with 2023 Top of Liner, Original Design WSEL, and Original Design Top of Liner Profiles**

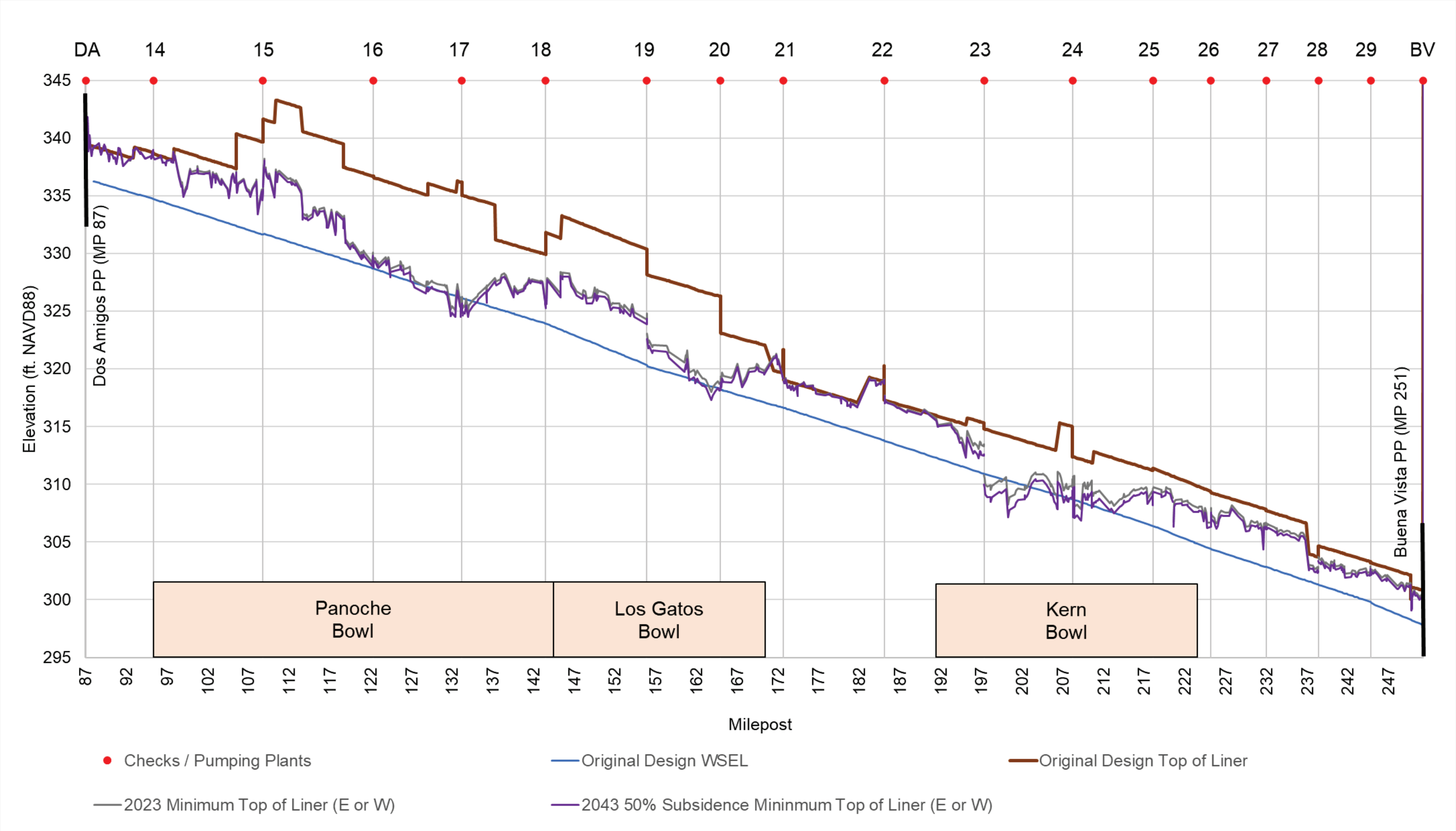


Figure 3 **2043 75th Non-exceedance Subsidence Percentile Top of Liner Profile with 2023 Top of Liner, Original Design WSEL, and Original Design Top of Liner Profiles**

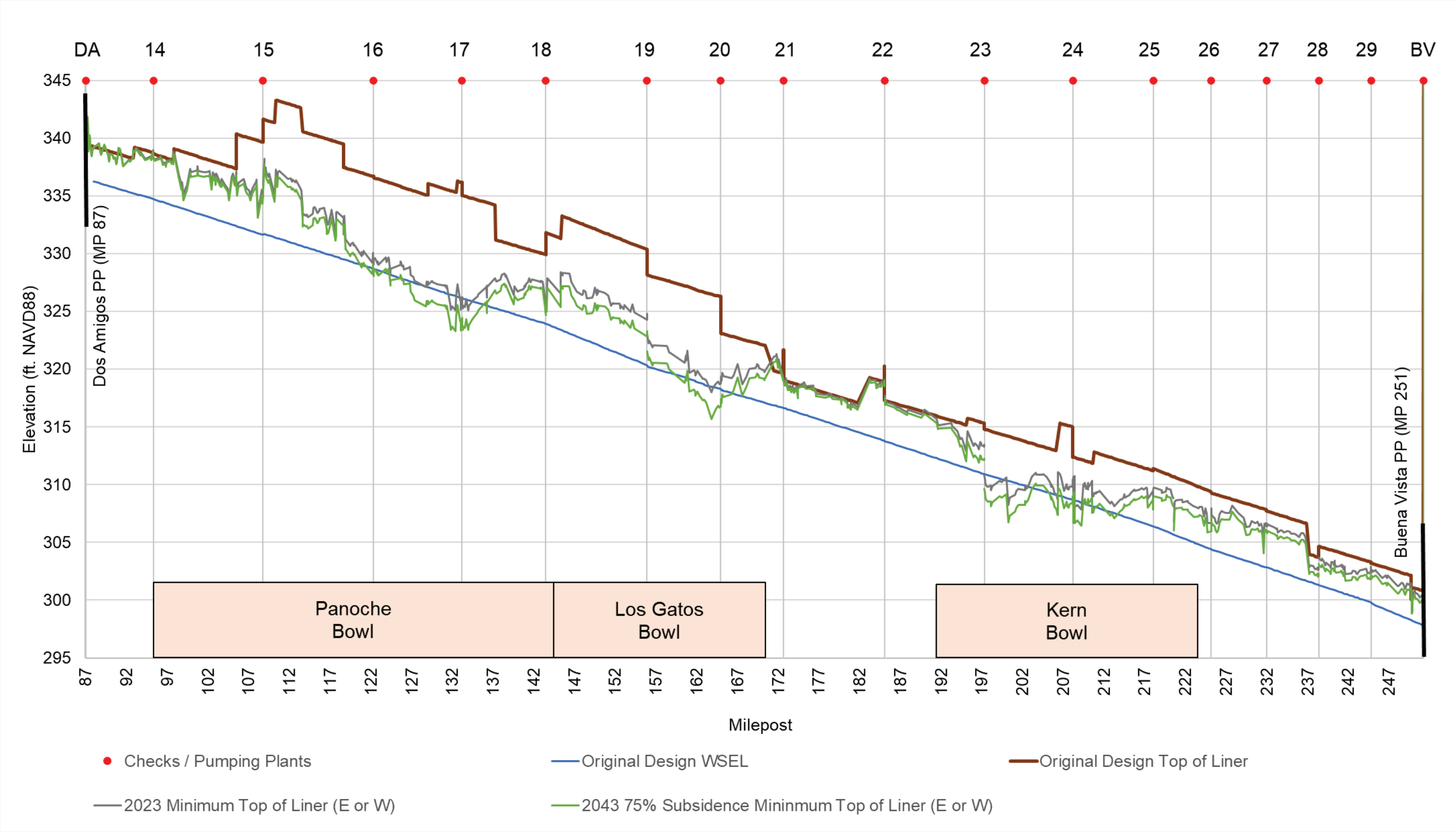


Figure 4 **2043 95th Non-exceedance Subsidence Percentile Top of Liner Profile with 2023 Top of Liner, Original Design WSEL, and Original Design Top of Liner Profiles**

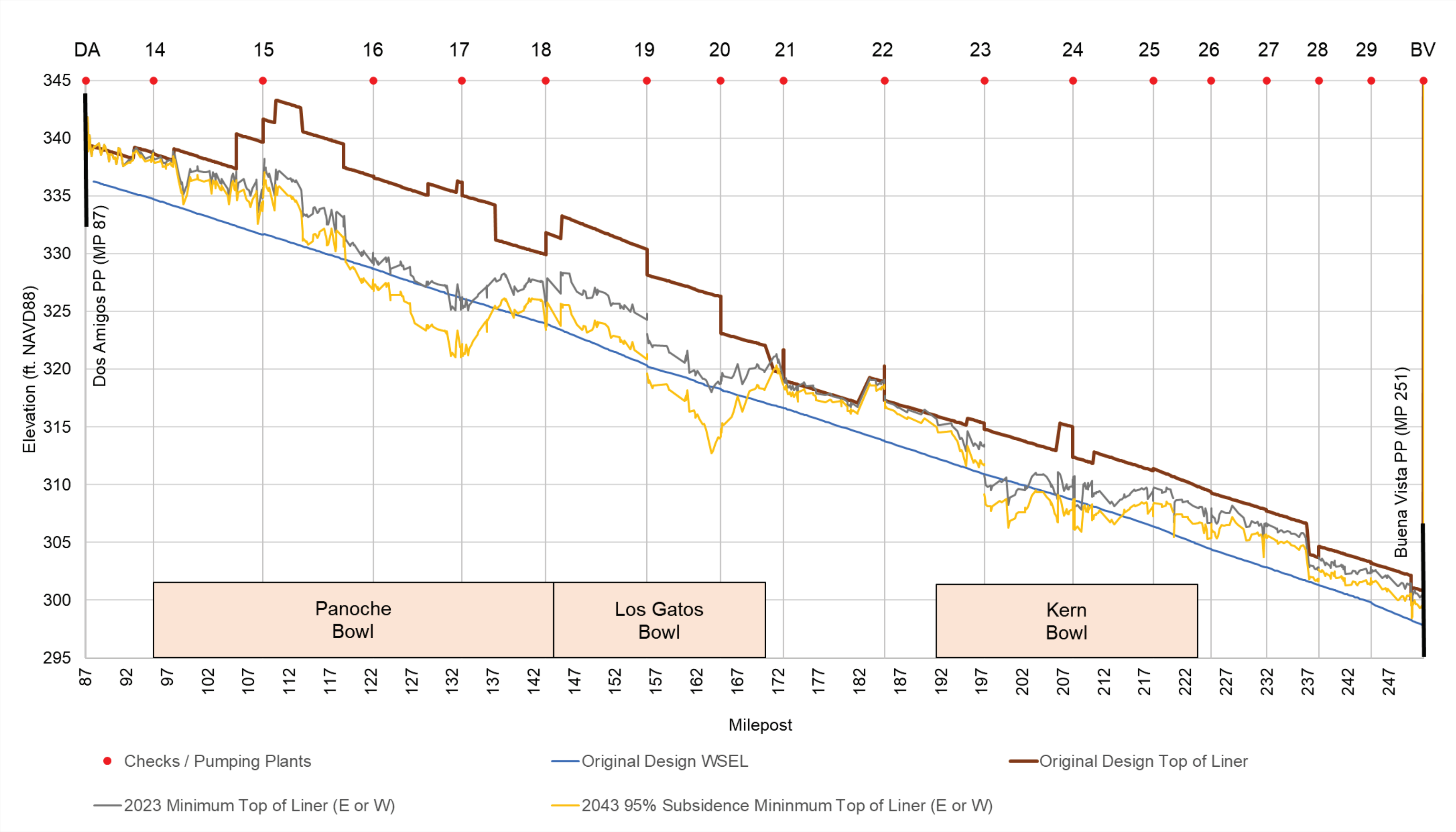
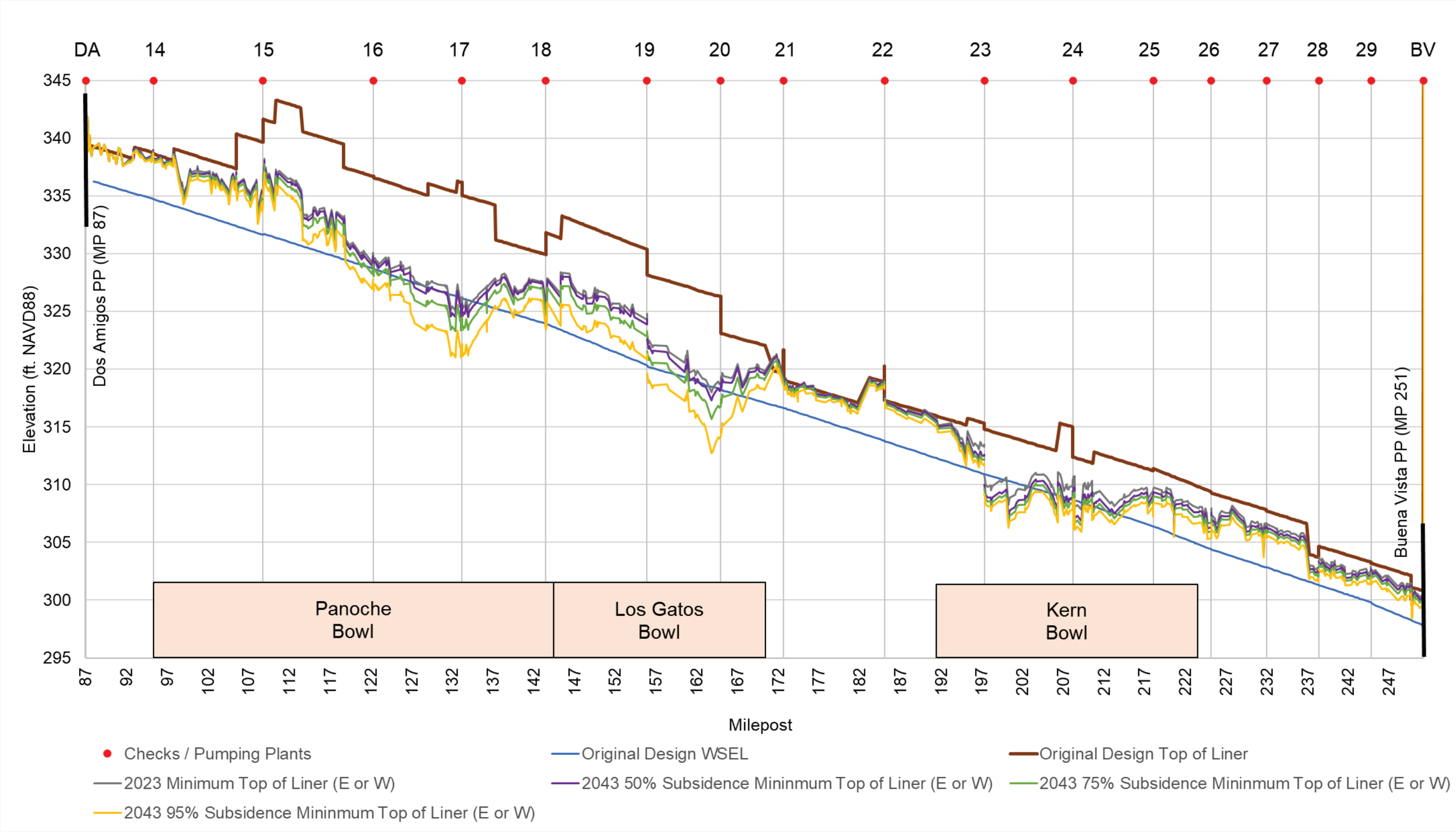


Figure 5 50th, 75th, and 95th Non-exceedance Subsidence Percentile Top of Liner Profile with 2023 Top of Liner, Original Design WSEL, and Original Design Top of Liner Profiles



Hydraulic Conveyance Capacity

HCC is the calculated maximum steady-state flow rate at which water can be conveyed through an Aqueduct pool or section (such as a check), given a specified physical condition, and set of operational criteria. HCC is typically represented in cubic feet per second (cfs). When calculated for a pool in this TM, the HCC represents the flow rate at the upstream end of the given pool.

HEC-RAS Model Description

The California Aqueduct Hydraulic Model L21PS23-V6.2-01 was used to compute the HCC estimates presented in this TM. This model is a detailed hydraulic model of the Aqueduct that represents its current physical features, including recent changes caused by subsidence. The L21PS23 label in the model's name indicates that the model elevations are based on 2021 LiDAR updated with 2023 Precise Survey; Version (V)6.2 indicates that the model was executed using HEC-RAS software V6.2; and 01 indicates this is the first model version with this combination of data. Additional details about the model, along with technical modeling approach considerations, are documented in the California Aqueduct Hydraulic Model Development Report (DWR, 2023b).

Application of 2020 Standing Operating Order and Special Conditions

The calculated value of the HCC depends on many factors, including the analytical method used to calculate the HCC, the physical conditions represented in the hydraulic model used, and the operating criteria applied. The physical condition of the Aqueduct varies between 2023 and 2043 to represent current subsidence (2023) or the selected 2043 non-exceedance percentile estimated displacement.

In all scenarios evaluated for DCR 2023, the analytical method used is held constant. DWR SOO 600.22 on May 20, 2020 (hereinafter 2020 SOO), established modified criteria to operate a subsided Aqueduct. In addition to the 2020 SOO, two special conditions are used during Aqueduct operations to maintain water levels at two specific locations. The Coalinga Canal Special Condition establishes water levels at Check 18 for diversion into the Coalinga Canal, and the Coastal Branch Special Condition establishes water levels at Check 22 for diversion into the Coastal Branch of the Aqueduct. Applying each of these special conditions affects the HCC of the Aqueduct. All scenarios presented herein are based on simulated operations within the normal operating range, per the 2020 SOO, with special conditions and no physical modifications to existing Aqueduct facilities to address subsidence.

The special conditions described above are applied depending on the time of year. DWR Field Division operations and maintenance staff have reported to CASP staff that the Coalinga Canal Special Condition is typically in effect year-round, and that the Coastal Branch Special Condition generally becomes effective each year in the April to June timeframe and continues through the September to November timeframe.

To simulate the water delivery capability of the SWP and CVP for DCR 2023, the CalSim model applies HCC values that correspond to the SOO and applicable special conditions for the months they would be in effect. In CalSim simulations of current operating practices, the HCC calculated with the Coalinga Canal Special Condition should be applied in November through April, and the HCC calculated with both the Coalinga Canal and Coastal Branch Special Conditions should be applied in May through October each year to generally represent their application as communicated by operations staff.

Additional information on the development of the HCCs presented herein is presented in the attached California Aqueduct Hydraulic Conveyance Capacity Report (DWR 2023c).

Hydraulic Conveyance Capacities for Use in DCR 2023

Table 1 presents the HCC for the 2023 conditions when operated under the 2020 SOO with the Coalinga Canal Special Condition, and with both the Coalinga Canal and Coastal Branch Special Conditions, to provide input to the CalSim model. Figures 6 and 7 show the original design capacity, the two HCCs presented in Table 1, respectively, and the choke points as described in DWR (2023c).

Table 2 presents the HCC for 2043 at the 50th non-exceedance subsidence percentile when operated under the 2020 SOO with the Coalinga Canal Special Condition and with both the Coalinga Canal and Coastal Branch Special Conditions. Figures 8 and 9 show the original design capacity, the two HCCs presented in Table 2, and the associated choke points.

Simulations of the 75th and 95th non-exceedance subsidence percentiles in 2043 with the application of the 2020 SOO with the Coalinga Canal and Coastal Branch Special Conditions and no physical modifications to existing Aqueduct facilities to address subsidence produce hydraulically infeasible conditions and therefore are not provided here.

Table 1 Calculated 2023 Subsidence Conditions Hydraulic Conveyance Capacity

Pool	2023 Subsidence with 2020 SOO with Coalinga Canal Special Condition (cfs)	2023 Subsidence with 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions (cfs)
14	12,518	12,550
15	12,129	12,157
16	10,828	10,856
17	9,343	9,370
18	8,137	8,164
19	6,003	6,001

Pool	2023 Subsidence with 2020 SOO with Coalinga Canal Special Condition (cfs)	2023 Subsidence with 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions (cfs)
20	6,003	5,536
21	5,411	4,506
22	5,411	4,506
23	5,411	4,506
24	5,295	4,506
25 – 40	4,198	4,506

Source: California Aqueduct Hydraulic Conveyance Capacity annual report (DWR, 2023c)
Key:
cfs = cubic foot per second
SOO = Standing Operating Order

Figure 6 **2023 HCC Profile with 2020 SOO with Coalinga Canal Special Condition**

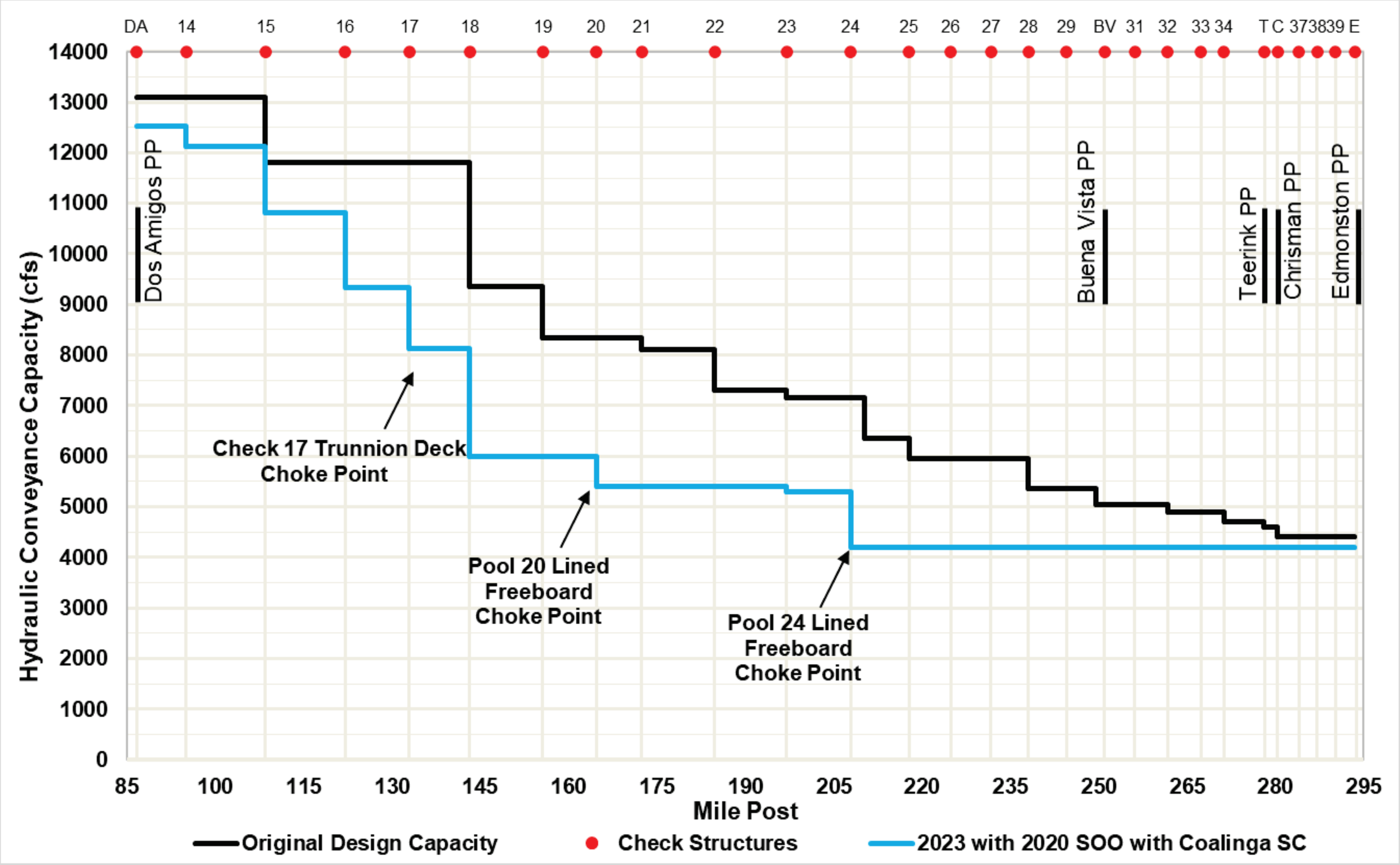


Figure 7 **2023 HCC Profile with 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions**

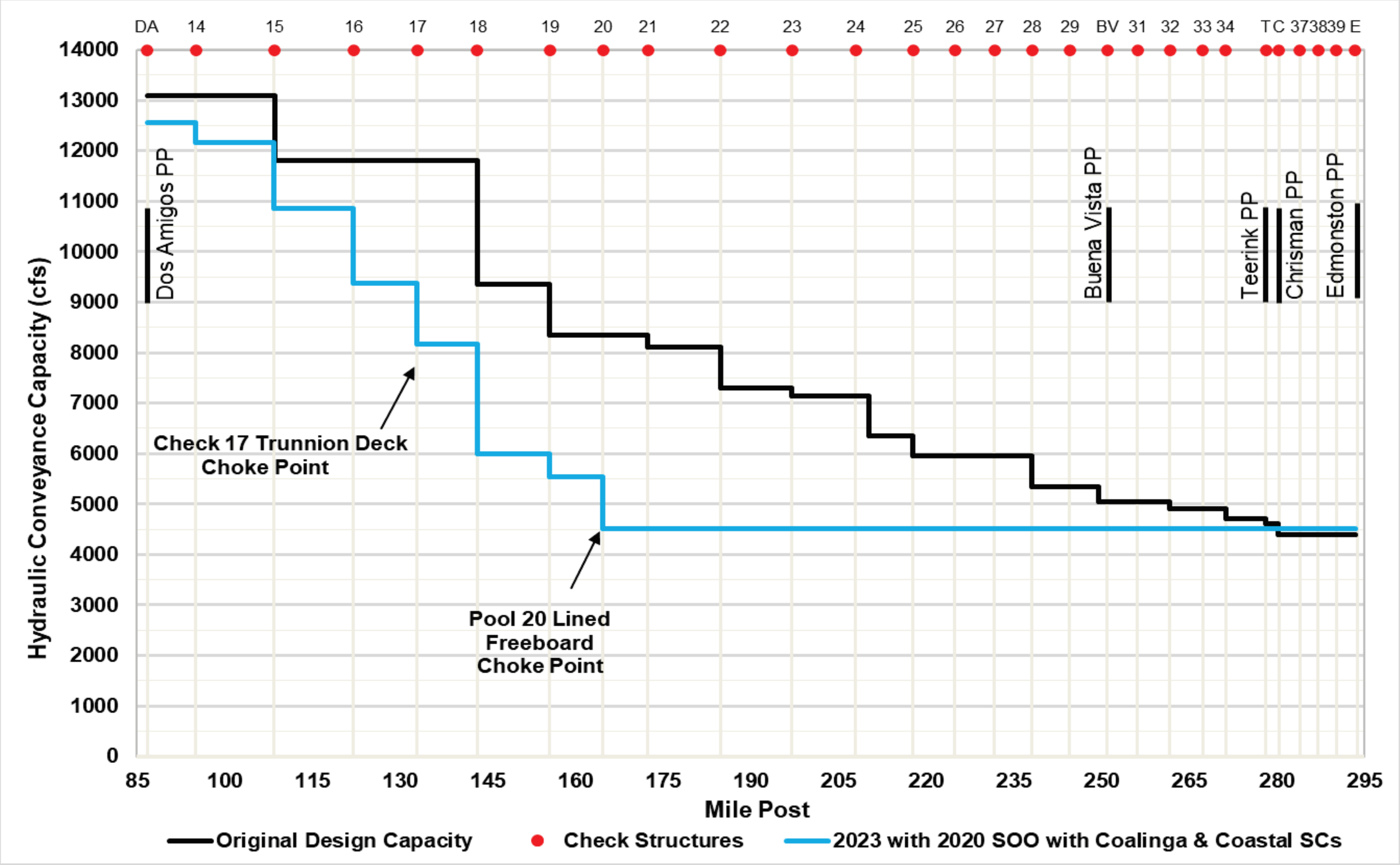


Table 2 Calculated 2043 50th Non-exceedance Subsidence Percentile Conditions Hydraulic Conveyance Capacity

Pool	2043 50th Non-exceedance Subsidence Percentile with 2020 SOO and Coalinga Canal Special Condition (cfs)	2043 50th Non-exceedance Subsidence Percentile with 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions (cfs)
14	10,410	10,413
15	10,016	10,025
16	8,716	8,724
17	7,230	7,237
18	6,025	6,031
19	3,658	3,664
20	3,658	3,663
21 – 40	3,658	3,580

Key:
cfs = cubic foot per second
SOO = Standing Operating Order

Figure 8 **2043 HCC Profile with 50th Non-exceedance Subsidence Percentile, 2020 SOO, and Coalinga Canal Special Condition Hydraulic Conveyance Capacity**

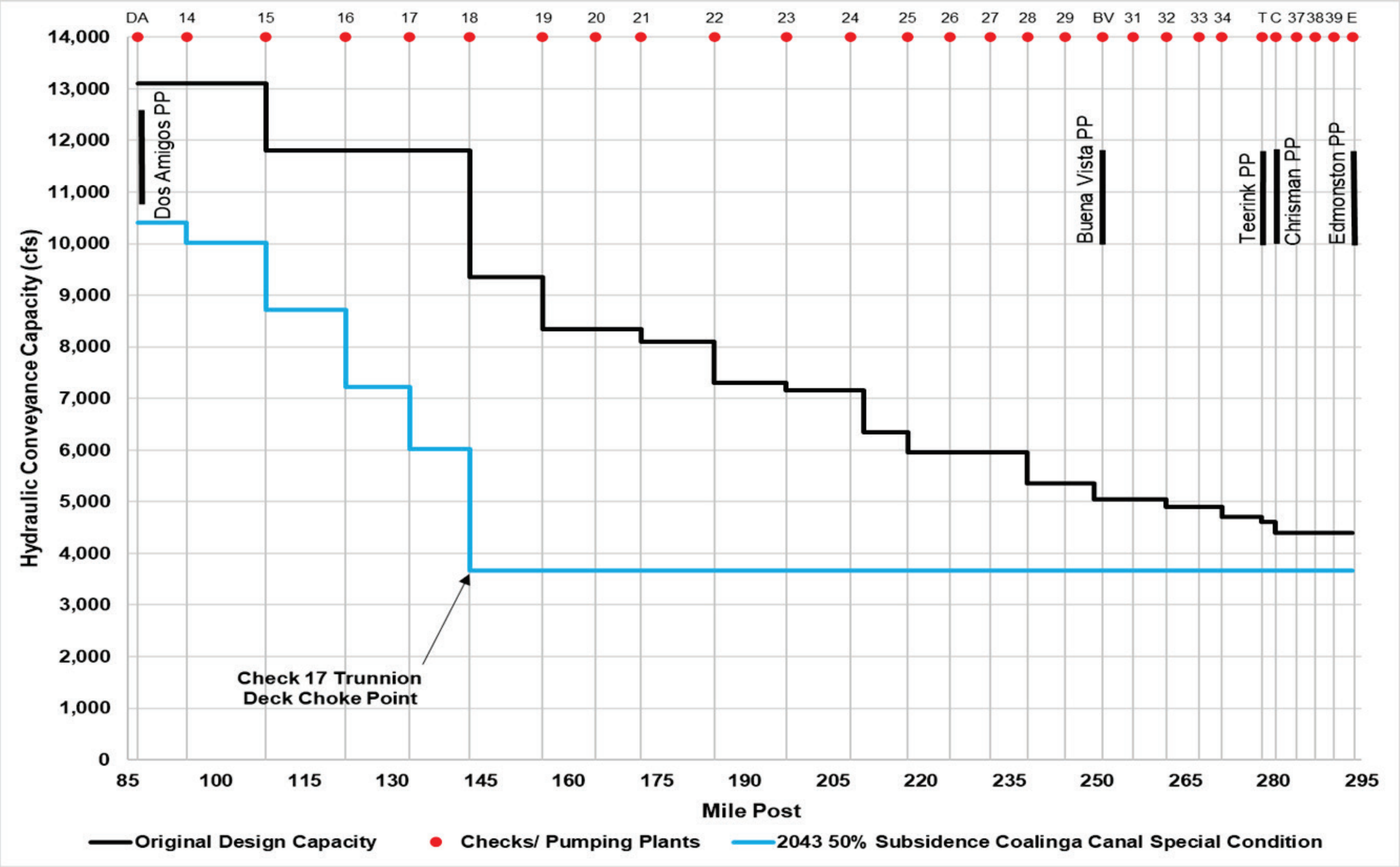
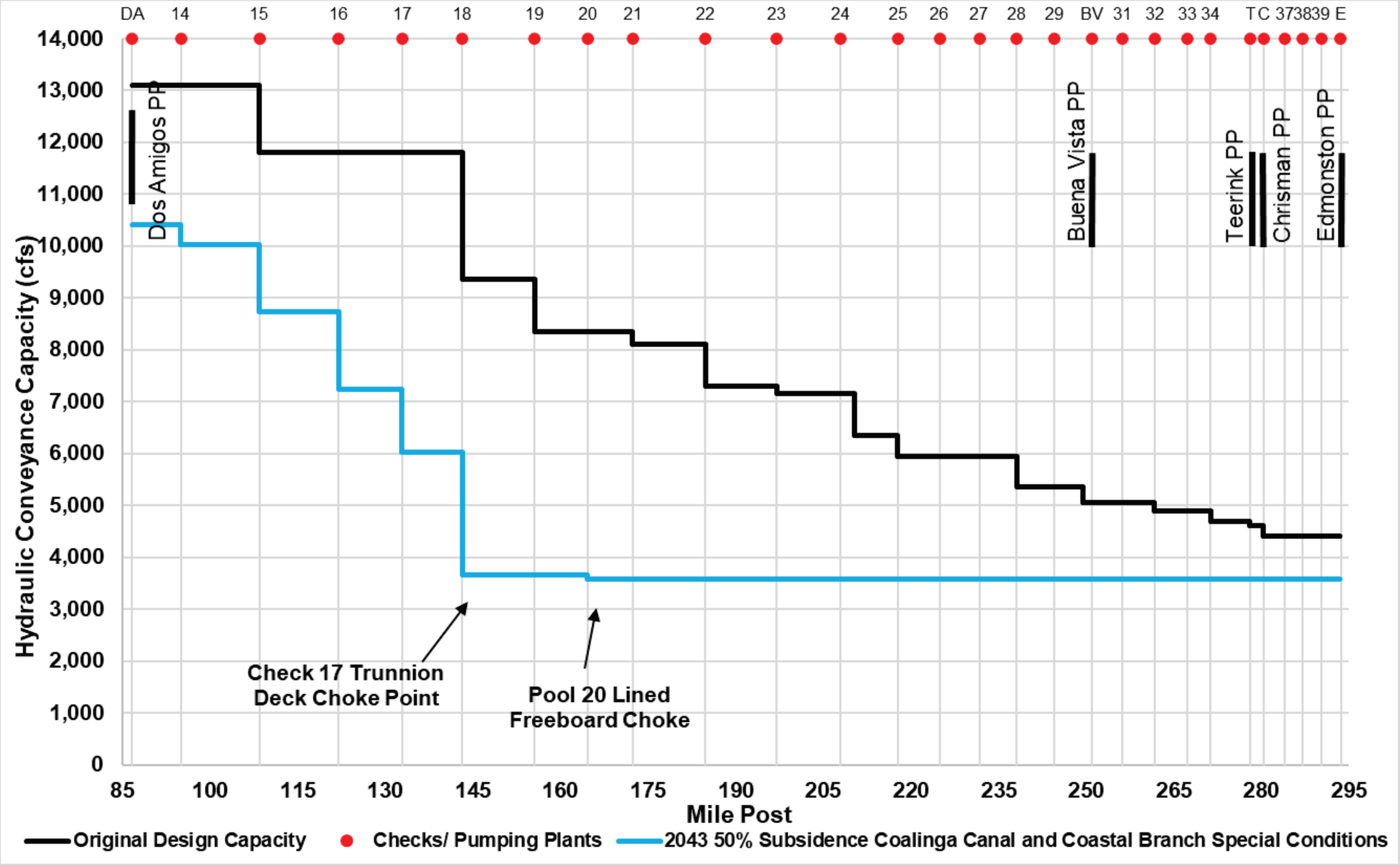


Figure 9 2043 HCC Profile with 50th Non-exceedance Subsidence Percentile, 2020 SOO, and Coalinga Canal and Coastal Branch Special Conditions Hydraulic Conveyance Capacity



Abbreviations and Acronyms

Aqueduct	California Aqueduct
BVPP	Buena Vista Pumping Plant
CASP	California Aqueduct Subsidence Program
cfs	cubic feet per second
CVP	Central Valley Project
DAPP	Dos Amigos Pumping Plant
DCR 2023	2023 Delivery Capability Report
DWR	Department of Water Resources
EPP	Edmonston Pumping Plant
GSA	Groundwater Sustainability Agencies
GSP	Groundwater Sustainability Plans
HCC	hydraulic conveyance capacity
HEC-RAS	Hydrologic Engineering Center's-River Analysis System
LiDAR	light detection and ranging
SFM	Subsidence Forecast Model
SGMA	Sustainable Groundwater Management Act
SOO	Standing Operating Order
SWP	State Water Project
TM	technical memorandum
WSEL	Water Surface Elevation

References

California Department of Water Resources (DWR). August 18, 2023a. *Probabilistic Subsidence Forecast Model for the California Aqueduct Subsidence Program, San Joaquin Valley, California*. Sacramento (CA).

California Department of Water Resources (DWR). 2023b. *California Aqueduct Hydraulic Model Development Report.* Sacramento (CA).

California Department of Water Resources (DWR). December 2023c. *California Aqueduct Hydraulic Conveyance Capacity.* Sacramento (CA).

Attachments

1. Subsidence Forecast Model Displacements and Elevations
2. Probabilistic Subsidence Forecast Model for The California Aqueduct Subsidence Program San Joaquin Valley, California Report
3. 2023 California Aqueduct Hydraulic Conveyance Capacity Report

Attachment 1 Subsidence Forecast Model Displacements and Elevations

Attachment 2 Probabilistic Subsidence Forecast Model For The California Aqueduct Subsidence Program San Joaquin Valley, California Report

State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES

PROBABILISTIC SUBSIDENCE FORECAST MODEL FOR THE CALIFORNIA AQUEDUCT SUBSIDENCE PROGRAM, SAN JOAQUIN VALLEY, CALIFORNIA

August 18, 2023

State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES
Division of Engineering

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Daniel Whisman	Principal Engineer
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This report was prepared under the supervision of

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By

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*This report is the result of a much larger team of individuals both within the Department and those consulting for the Department. From each of us listed above, thank you to all those that contributed to the success of this project and your assistance in preparing this report

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State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES
Division of Engineering

Probabilistic Subsidence Forecast Model for the California Aqueduct Subsidence Program, San Joaquin Valley, California

Design Report

ENGINEERING CERTIFICATION

This report has been prepared under our direction as licensed professionals in direct responsible charge of the work, in accordance with the provisions of the Professional Engineers Act of the State of California.

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REPORT CONTENTS

APPENDICES

LIST OF TABLES

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List of Acronyms and Abbreviations

Short form	Long form
AIC	Akaike Information Criterion
CASP	California Aqueduct Subsidence Program
CBR of the TDI	Center, Body and Range of Technically Defensible Interpretations
CVP	Central Valley Project
GSA	Groundwater Sustainability Agency
GSP	Groundwater Sustainability Plan
DWR	California Department of Water Resources
MAF	Millions of acre-feet
PDF	Probability Density Function
SGMA	Sustainable Groundwater Management Act
SJFD	San Joaquin Field Division
SLFD	San Luis Field Division
SSHAC	Senior Seismic Hazard Analysis Committee
SWP	State Water Project
TAF	Thousands of acre-feet
TI Group	Technical Integrator Group

EXECUTIVE SUMMARY

This report documents development of a probabilistic subsidence forecast model for simulating a plausible range of future land-surface altitude conditions along the California Aqueduct in the San Joaquin Valley, with emphasis on areas of localized subsidence (i.e., “subsidence bowls”). The model forecasts will be used to inform long-term planning and on-going analyses of potential investments needed to provide a suitable level of performance of the California Aqueduct. The forecast model is primarily based on an empirical relationship between historical subsidence rate and annual water deliveries from the Central Valley Project (CVP) and State Water Project (SWP) to users in the San Joaquin Valley. A key assumption of the model is that the rate of groundwater overdraft, which contributes to loss of aquifer storage and permanent land subsidence, is correlated with CVP and SWP deliveries, and specifically with higher groundwater storage loss during severe drought years. Another key assumption is that the same rates of subsidence will continue even when groundwater levels and extraction may be coming from deeper parts of the system as groundwater levels decline. If the geology and/or aquifer properties change dramatically, then these new conditions may have an unmodeled impact on future rates.

The forecast model considers three conditions that determine the rate of subsidence, beginning with the No SGMA condition, during which the behavior of subsidence is represented by a statistical model based on historical patterns, followed by Partial SGMA Implementation, during which the parameters of the statistical model are tapered down, and a Cessation of Overdraft condition, during which only the natural geologic and background subsidence rate and elastic fluctuations are represented. The model accounts for random (aleatory) variability in annual subsidence rate during both severe drought and other climate conditions, and it considers the frequency and duration of severe droughts during which deliveries are low to non-existent and the subsidence rate is expected to be much higher. The model also accounts for anticipated future reductions in subsidence rate associated with implementation of the Sustainable Groundwater Management Act (SGMA), which requires the high-priority groundwater basins to be in balance by 2040. The times of onset and speed of implementation of SGMA are uncertain, and thus are treated as epistemic variables in the forecast model.

The output from the probabilistic forecast model provides the distribution of forecast subsidence magnitudes, rendered as profiles of elevation along the Aqueduct, for any year of interest through the 2080 CASP planning horizon. Compared to earlier trend extrapolations (i.e., regression analysis), the present model better represents the structure of uncertainties underlying forecasts of subsidence and allows a better understanding of how those uncertainties affect future subsidence.

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1.0 Introduction

The California Aqueduct (Aqueduct) is a key element of the California State Water Project (SWP) and the federal Central Valley Project (CVP). Regional land subsidence caused primarily by groundwater overdraft has reduced the hydraulic conveyance capacity and operational flexibility of the Aqueduct in the San Joaquin Valley, and additional subsidence is expected to continue into the foreseeable future. In 2014, California passed the Sustainable Groundwater Management Act (SGMA), which requires the development and implementation of Groundwater Sustainability Plans (GSPs) that intend to achieve sustainable groundwater management practices by 2040 and avoid undesirable consequences of overdraft, such as land subsidence. In the near term, subsidence in the San Joaquin Valley is expected to continue as recently formed Groundwater Sustainability Agencies (GSAs) develop and gradually implement their GSPs to comply with SGMA. As of 2022, there is significant uncertainty in exactly when and how SGMA implementation will occur. Additionally, there is uncertainty in future climatic conditions and their impacts on water deliveries to SWP and CVP contractors, which may affect when and how rapidly full SGMA implementation occurs. The California Aqueduct Subsidence Program (CASP) has been established to formulate, analyze, evaluate, recommend, and implement actions to address the consequences of subsidence of the Aqueduct in the San Joaquin Valley on the operation and performance of the SWP and CVP. The evaluation of potential actions will be based on multiple criteria that include monetary return on investment, safety, resiliency, adaptability, operational flexibility, contractual and legal obligations, and other considerations.

The evaluation of future conditions and the performance of potential actions to address the consequences of subsidence on the Aqueduct require an estimate of future subsidence of the Aqueduct in the San Joaquin Valley. A physically based model that can calculate changes in land surface in response to changes in groundwater pumping patterns under different future scenarios, at the scale necessary to evaluate the performance of the Aqueduct, does not exist at the present time. To prepare estimates of future subsidence of the Aqueduct that also capture a reasonable range of uncertainty for risk evaluation, CASP opted to develop a probabilistic subsidence forecast model.

This report documents development of a probabilistic subsidence forecast model for evaluating future performance of the Aqueduct under a “no-action condition”; i.e., the assumption that no future actions (structural or non-structural) will be implemented (beyond those actions expected to be taken by GSAs to fulfill their GSPs) to alter the rate of subsidence anticipated in the GSPs, or to restore Aqueduct hydraulic conveyance capacity or operational flexibility that has been or will be lost due to subsidence. The model will also allow generation of subsidence forecasts based on potential non-structural actions to reduce subsidence-inducing groundwater pumping. Because the subsidence forecast model will be used for long-term planning, engineering design, and risk analysis, the CASP and interested parties must have reasonable confidence that the model is defensible and has been developed in a transparent manner. Specifically, the model forecasts need to be considered “stable”; i.e., if another group set out independently to develop a similar model, using a similar methodology, the results would not differ significantly. To accomplish these objectives, the forecast model was developed using the structured approach described by Budnitz *et al*. (1997) for representing relevant data, models, and informed expert opinion in a probabilistic framework to capture aleatory (randomness) and epistemic (incomplete knowledge) uncertainty in natural hazards; in this case, about future subsidence conditions.

In the following sections, this report describes: the Budnitz *et al*. (1997) methodology applied in developing the CASP probabilistic subsidence forecast model (Chapter 2); the conceptual framework and physical basis for the model (Chapter 3); the specific physical and behavioral conditions represented by the model (Chapter 4); the model form (Chapter 5), including branches of the logic tree and their weights; subsidence forecast results (Chapter 6), including sensitivity analyses and comparison with predictions from linear regression of survey data; and a summary with conclusions (Chapter 7). Additional data and documentation of the process of model development are provided in multiple Appendices to this report.

1.1 Chapter References

Budnitz, R.J., Apostolakis, G., Boore, D.M., Cluff, L.S., Coppersmith, K.J., Cornell, C.A., and Morris, P.A., 1997. *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*: Washington, D.C., US Nuclear Regulatory Commission, NUREG/CR-6372, p. 278

2.0 SSHAC Process and Study Organization

2.1 Description of the SSHAC Process

The CASP subsidence forecast model was developed through the process recommended by Budnitz *et al*. (1997) for use of data, models, and expert opinion in probabilistic analyses of natural hazards. The Budnitz *et al*. working group that developed the methodology for the Nuclear Regulatory Commission (NRC), Department of Energy (DOE) and Electric Power Research Institute (EPRI), is known as the Senior Seismic Hazard Analysis Committee (SSHAC), and the methodology is generally referred to as the "SSHAC process". As described by Morgan (2014), SSHAC is "a set of deliberative processes designed to support a group of experts in developing a composite probability distribution that reflects the overall informed scientific community." In SSHAC parlance, the modeled distribution should represent the "center, body and range of technically defensible interpretations" (the "CBR of the TDI"). The "informed community" may include stakeholders and other technical experts in addition to scientific specialists. The SSHAC process was originally designed to capture epistemic uncertainty in input parameters for probabilistic seismic hazard analysis, but it can be applied to probabilistic analyses of other hazards with uncertain rates and sizes of occurrence such as tsunamis and volcanic eruptions (Ake *et al*., 2018). For this study, the SSHAC process is applied to represent a natural hazard (subsidence) that has been accelerated by land use practices, and thus the model must incorporate uncertainty in the anthropogenic (behavioral) drivers of future subsidence rate.

The essential features of a SSHAC study, which are described in more detail in following sections, include the following:

- **Clearly defined roles for all participants, including the responsibilities and attributes associated with each role.** For CASP, the SSHAC process was carried out by a Technical Integrator (TI) Group that evaluated data, models and information from Resource Experts and Proponent Experts. The work of the TI Group and its adherence to the SSHAC process was monitored by a Participatory Peer Review Panel (PPRP). DWR served as the overall Project Sponsor for the study.

- **Objective evaluation of data, models, and methodologies.** The evaluation process involved the consideration of a broad range of data, models and methods proposed by the larger technical and stakeholder community relevant to evaluating future subsidence in the San Joaquin Valley that may potentially impact the California Aqueduct. The evaluation process was performed by the TI Group, and included: (a) compilation and review of relevant literature (e.g., DWR documents and publications; peer-reviewed research papers; relevant geologic and other data; etc.); (b) discussions with current researchers and stakeholders (i.e., Resource and Proponent Experts) regarding technical, social and political issues that are potentially relevant to evaluating future land subsidence; and (c) evaluation of the data, models, and interpretations with respect to their representation in the subsidence forecast model.

- **Integration of the data evaluation into a model that captures the "CBR of the TDI".** The goal of the integration process is to develop a model that reflects the best estimate of each element of the hazard input with the current state of knowledge, and the associated uncertainty. For CASP, this involved construction of a subsidence hazard model that addresses both aleatory variability (randomness) and epistemic uncertainties (incomplete knowledge). The construction of this model consisted of two parts, namely (1) the specification of the model structure and functional form, and (2) the specification of model parameters and their uncertainties. Given the very simple structure of the model, it is not necessary to consider alternative model forms, so that only uncertainty in the parameters is considered. The TI Group was responsible for integrating relevant data and expert opinion into the model form and parameters. This process required exercise of expert judgement by the TI Group.

- **Independent Peer Review.** The primary objective of the peer review was to ensure that the SSHAC process was followed and that the technical results adequately characterize the CBR of the TDI considering all available data, methods, and models. The peer review for a SSHAC study is intended to be "participatory"; i.e., conducted during the course of the study while data are being evaluated and the model is developed, rather than limited to the end stage of the study as part of the reporting process.

- **Documentation of Process.** As described in NRC (2012), documentation is an integral component of the SSHAC process in that it provides a record of the final technical results, how they were reached, and how the SSHAC process was implemented including participatory peer review. In addition, the documentation provides the basis for review by any pertinent regulatory officials and/or stakeholder groups, if needed. The documentation must justify in sufficient detail the technical interpretations that support the subsidence forecast model, and it must be sufficiently detailed to allow the analysis to be reproduced by an external reviewer (Ake *et al*., 2018).

The SSHAC process is appropriate for structured development of the CASP subsidence forecast model because the data, interpretations, methods, and models bearing on future subsidence are imbued with significant complexity and uncertainty, and they require detailed evaluation and integration by technical experts, necessitating some degree of judgment. As noted by Ake *et al.* (2018), "there is no quantitative test available to prove that the center, body, and range of technically defensible interpretations ("CBR of the TDI") has been properly represented" for evaluations of natural hazards like earthquakes and volcanic eruptions. In the case of land subsidence, uncertainty in both natural (geologic) and behavioral drivers of subsidence rate are important considerations for representation of the CBR of the TDI. The SSHAC process is designed to develop reliable and stable estimates of natural hazards in the absence of certainty afforded by such a test. Confidence that the CBR of the TDI has been captured comes from the evaluation, questioning and challenging of data and judgements by and among the TI Group;

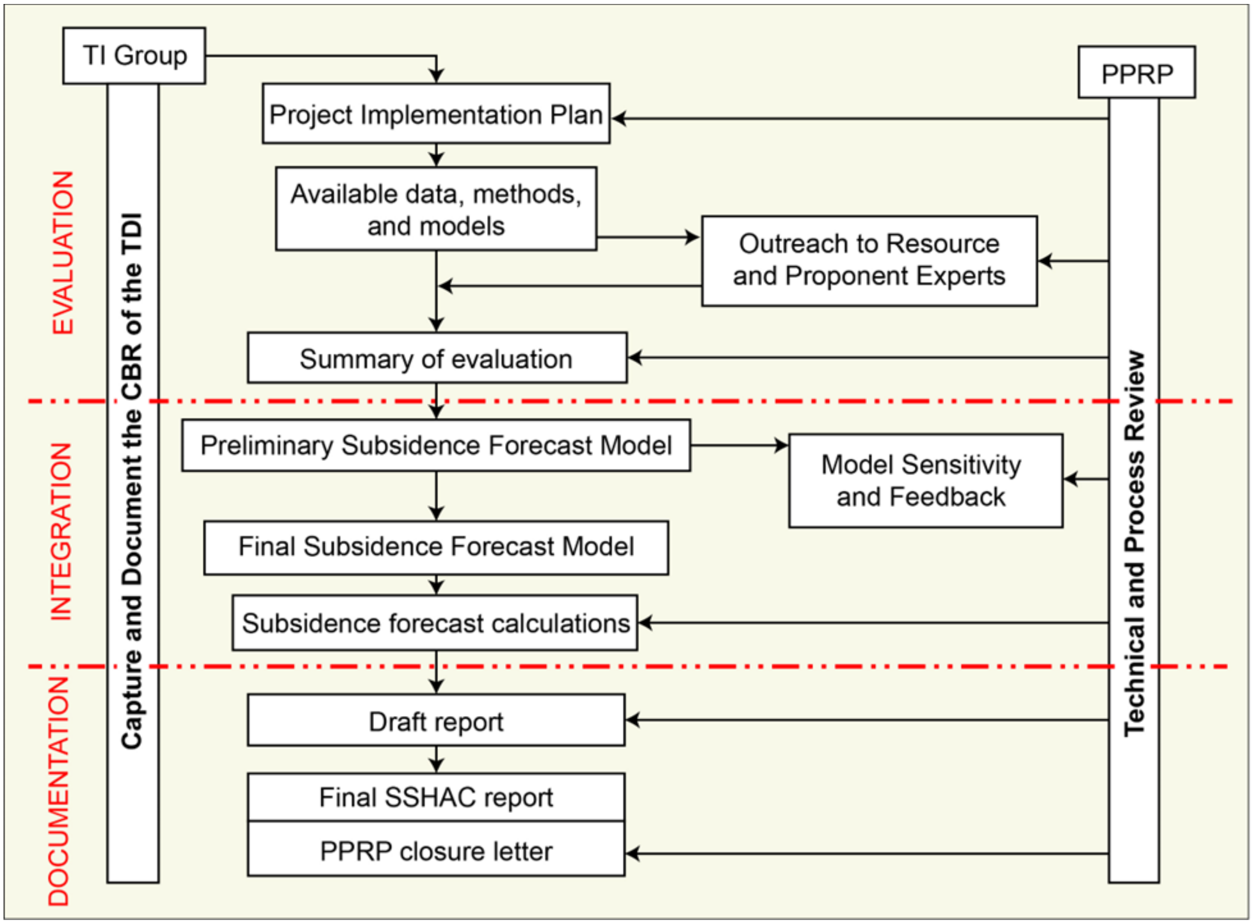
technical review and feedback from the PPRP while the study is being conducted; and the endorsement from the PPRP that the study follows the principles of the SSHAC process (Ake *et al*., 2018).

2.2 Selection of SSHAC Level 2 Study

Budnitz *et al*. (1997) describe four levels of increasingly complex SSHAC studies, with Level 1 being the least complex. The selection of appropriate level for the study depends on the nature of the project and governing regulatory requirements (if any). For CASP, the subsidence forecast model was developed following recommendations for a SSHAC Level 2 study, per guidance provided in NUREG/CR 6372 (Budnitz *et al*., 1997), NUREG-2117 (NRC, 2012) and NUREG-2213 (Ake *et al*., 2018). The elements of a SSHAC Level 2 study are illustrated in the flowchart in Figure 2-1 (modified from Ake *et al*., 2018).

A Level 2 process was chosen because the CASP study required formal structured outreach to external Resource and Proponent experts to obtain information and insights into relevant data, models, and methods, and to ensure that a broad range of information is considered as part of the evaluation and model development process. These efforts exceed the scope of a Level 1 study. The Level 2 process also provided for review and feedback from the PPRP regarding the preliminary and final subsidence forecast models. The more elaborate processes for structured outreach in a SSHAC Level 3 study (e.g., multiple public workshops; structured working meetings of the TI Group attended by the PPRP) were determined to be unnecessary for this study.

Figure 2-1. Flowchart showing elements and sequence of a SSHAC level 2 study. Modified from Ake et al. (2018)



2.3 Project Scope

The following sections describe key tasks of the CASP SSHAC Level 2 study.

2.3.1 Development of Project Implementation Plan

The Project Implementation Plan (PIP) describes the SSHAC Level 2 objectives and process; the project organization, including specified roles and responsibilities of each of the SSHAC project team members; the project activities and key tasks; and anticipated project schedule. The PIP provides the implementation guidance for completion of the SSHAC Level 2 study and was distributed to all project participants for review in advance of the project kick-off meeting.

2.3.2 Project Kick-Off Meeting

During the project kick-off meeting, the PIP was discussed in detail so that all project participants understood the objectives of the study and their roles in it. The participants also reviewed potential sources of cognitive bias, as summarized in Ake *et al*. (2018), to help the TI Group avoid such biases throughout the evaluation and integration phases of the project.

2.3.3 TI Group Evaluation

The TI Group met 24 times in 2021 to develop the subsidence forecast model. The TIG compiled, reviewed, and discussed the available data, methods and models that are relevant to developing the functional form of the subsidence forecast model and capturing the CBR of TDI of model inputs. A bibliography of references that were evaluated for this study is included in Appendix A of this report. The TI Group defined the terms used in formulating and characterizing the model, and it interpreted physical processes and causal linkages represented in the model (separating representations of physical/geologic and behavioral processes as much as is practicable). As part of the evaluation, the TI Group reviewed information from interviews with 14 Resource and Proponent experts conducted in 2020 by CASP, prior to initiation of the SSHAC study. The expert interviews are documented in Appendix B of this report.

2.3.4 Integration of Data in a Preliminary Subsidence Forecast Model

The TI Group developed a preliminary subsidence forecast model to capture the CBR of the TDI. The model development process was informed by sensitivity analyses to assess the relative significance of parameters in the model.

2.3.5 PPRP Review

The minutes of each SSHAC TI Group meeting, along with PowerPoint slides used to facilitate the TIG discussion, were documented in memos that were submitted to the PPRP for review during the study. In addition, the PPRP was given two briefings on the progress of the model development prior to completion of the preliminary model. The TIG formally presented the preliminary subsidence forecast model to the PPRP on 5 November 2021. The PPRP reviewed the preliminary model and transmitted a memo with feedback and comments to the TI Group on 12 November 2021.

2.3.6 Preparation of Final Model

The preliminary subsidence forecast model was revised to address PPRP comments and finalized in 2022.

2.3.7 Reporting and Documentation

An initial draft of the SSHAC Level 2 report (‘Rev 0”) was prepared by Dr. Unruh and Dr. Toro in late 2022. The “Rev 0” report was reviewed by Mr. Hans AbramsonWard, a Certified Engineering Geologist with LCI. A revised version of the report (“Rev 1”) was prepared to address Mr. AbramsonWard’s comments. Upon Mr. AbramsonWard’s acceptance of the revisions, the “Rev 1” report was distributed to the TIG for review and comment in early 2023. The version of the report incorporating all TIG comments (“Rev 2”) was submitted to the PPRP for review in March 2023.

This final SSHAC Level 2 report (“Rev 3”) was prepared to address the PPRP comments in July 2023. PPRP comments and TI Group resolution of the comments are documented in an annotated version of the Rev 3 report, which was submitted to DWR and CASP as part of the final project deliverables.

2.3.8 PPRP Closure Letter

Upon acceptance of the final technical report, the PPRP drafted a closure letter and submitted it to the DWR Project Manager. The closure letter is attached as Appendix C of this report.

2.4 Project Organization

The project organization for the CASP SSHAC Level 2 study is shown on Figure 2-2. The specific roles for the project participants are described in the following sections.

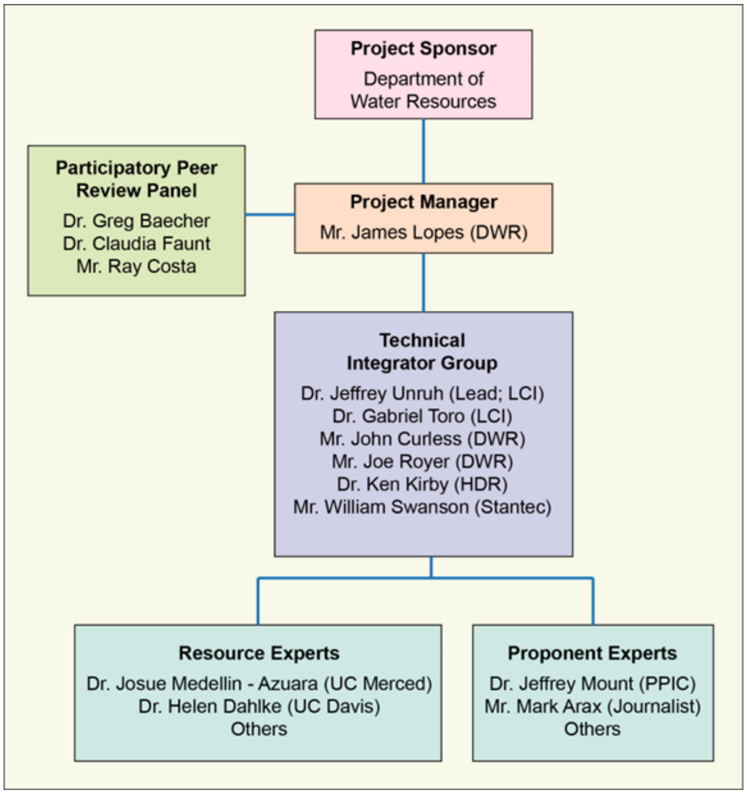
2.4.1 Project Sponsor

The Department of Water Resources (DWR) is the Project Sponsor. Mr. James Lopes served as the Project Manager for the SSHAC Level 2 study on behalf of DWR.

2.4.2 Technical Integration Group

The TI Group for the SSHAC Level 2 update included Dr. Jeffrey Unruh (TI Lead, LCI), Dr. Gabriel Toro (Lead Analyst, LCI), Mr. Joe Royer (DWR), Mr. John Curless (DWR), Dr. Ken Kirby (HDR) and Mr. William Swanson (Stantec) (Figure 2). Members of the TI Group collectively have knowledge of the hydrogeologic, engineering and public policy issues relevant to evaluating future land subsidence in the San Joaquin Valley, and Unruh and Toro have prior experience conducting SSHAC Level 2 studies.

Figure 2-2. Organizational chart for the CASP SSHAC level 2 study



2.4.3 Resource and Proponent Experts

The TI Group evaluated Resource and Proponent Expert opinion as appropriate to capture the CBR of the TDI. With respect to the CASP study, "Resource Experts" are responsible for providing unique and/or comprehensive data sets and/or have individual knowledge that is relevant to forecasting future land subsidence in the San Joaquin Valley. "Proponent Experts" are responsible for providing well-formed opinions about issues relevant to forecasting subsidence and may advocate for preferred models or interpretations over others. Both Resource and Proponent experts generally have knowledge of on-going work and research by others in their fields of specialty, and thus their informed input contributes to the efforts of the TI Group to fully characterize the CBR of the TDI.

2.4.4 Participatory Peer Review Panel

The PPRP consisted of Dr. Gregory Baecher (University of Maryland, Chair), Dr. Claudia Faunt (USGS), and Mr. Ray Costa (Independent Engineer). These individuals collectively have expert knowledge in land subsidence and hydrogeology in the San Joaquin Valley, application of probabilistic methods to natural hazard evaluation, and geotechnical engineering. The PPRP provided a "technical review" of the study as well as a "process review" that the TI Group has properly implemented the SSHAC Level 2 process, as described in Ake *et al*. (2018).

2.5 Report Authorship

The first draft of this report was written by Dr. Jeffrey Unruh and Dr. Gabriel Toro of LCI. The content of the report was developed over the course of the SSHAC study by the TI Group and reflects significant contributions from Dr. Ken Kirby (HDR), Mr. William Swanson (Stantec), Mr. John Curless (DWR) and Mr. Joe Royer (DWR). The first draft of the report was collectively reviewed by the TI Group, and a revised version that addresses edits and comments from the TI Group was prepared and submitted to the PPRP for review. The TI Group collectively addressed the PPRP review comments and participated in preparing the final version.

2.6 Chapter References

Ake, J., Munson, C., Stamatakos, J., Juckett, M., Coppersmith, K., and Bommer, J., 2018, *Updated implementation guidelines for SSHAC hazard studies: NUREG-2213, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission*, Washington D.C.

Budnitz, R.J., Apostolakis, G., Boore, D.M., Cluff, L.S., Coppersmith, K.J., Cornell, C.A., and Morris, P.A., 1997. *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*: Washington, D.C., US Nuclear Regulatory Commission, NUREG/CR-6372, p. 278

Morgan, M.G., 2014, *Use (and abuse) of expert elicitation in support of decision making for public policy*: PNAS, v. 111, no. 20, p. 7176-7184.

NRC, 2012, *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies*: Washington D.C., US Nuclear Regulatory Commission, NUREG 2117, Revision 1.

3.0 Conceptual Framework

3.1 Physical Model For Land Subsidence

3.1.1 Natural Geologic Subsidence

Long-term geologic subsidence of the San Joaquin Valley has occurred in late Quaternary time, primarily due to compaction and consolidation of Pliocene-Pleistocene Tulare Formation deposits in the upper 600-900 m (2000 ft to 3000 ft) of the valley sedimentary column (see discussion in DWR, 2019). This compaction is recorded in relief on the buried surface of the 0.62-million-year-old Corcoran clay (Figure 3-1), which was originally deposited on the floor of a freshwater lake as an approximately horizontal stratum. Deep borings in the San Joaquin Valley have documented up to about 240 m (800 ft) of relief on the upper surface of the Corcoran clay due to compaction of it and underlying deposits (Figure 3-2). This natural compaction is the initial stage of the transformation of unconsolidated sediment into sedimentary rock, and the process has been well studied in sedimentary basins around the world (e.g., Kooi and de Vries, 1998). The average rate of subsidence during the past 0.62 million years due to compaction of Tulare Formation sediments (and possibly older deposits) below the Corcoran clay is estimated to be about 0.2 mm/yr (DWR, 2019). This geologic or natural background rate of subsidence is about two orders of magnitude lower than the maximum historic rates (several cm/yr or more) that have been attributed to groundwater withdrawal (DWR, 2019).

3.1.2 Induced (Anthropogenic) Subsidence

Land subsidence rates higher than background geologic rates have been recognized in the San Joaquin Valley and studied since the 1920's (Poland *et al*., 1975). Although multiple contributing mechanisms to land subsidence have been identified, including shallow hydrocompaction of soils (reduction of pore air volume when wetted) and oil and gas extraction, the consensus of the informed technical community is that the dominant physical cause of historically observed subsidence in the central and southern San Joaquin Valley since the 1930's is overdraft of groundwater from the aquifer below the Corcoran clay (see discussion in DWR, 2017, 2019, and references cited therein) (Figure 3-3). Artesian pressure in the sub-Corcoran aquifer contributes to buoyant support of the overlying sedimentary column. The *effective normal stress* on the skeleton of this deep confined aquifer is the vertical lithostatic stress minus the pore pressure in the aquifer (Galloway *et al*., 1999). Reduction in artesian pressure in the deep aquifer through loss of groundwater storage increases the effective normal stress on the aquifer, which responds with a combination of elastic and inelastic deformation. The elastic deformation is accommodated by compression of quartz, feldspar and other silicate mineral grains that are in point contact with each other in the coarse-grained beds of the aquifer. The inelastic deformation primarily is accommodated by dewatering and depressurizing of bedded silts and clays in the aquifer. As the fine-grained beds dewater, the platy clay minerals respond to the increase in effective normal stress by rotating to sub-horizontal orientations (at a high angle to the vertical normal stress), which eliminates pore space and reduces the bed thickness

(Galloway *et al*., 1999). Although the elastic deformation, or "elastic change", is potentially recoverable when water pressures in the aquifer increase and reduce the effective normal stress, the compaction of clay layers is generally non-recoverable and contributes to permanent subsidence of the land surface. The latter permanent subsidence due to anthropogenic dewatering is here referred to as "induced subsidence" to distinguish it from subsidence associated with the natural geologic compaction described in Section 3.1.1.

It should be noted that groundwater in an unconfined aquifer also provides buoyant support of the aquifer skeleton, and that lowering of groundwater surface elevation in an unconfined aquifer can produce elastic and inelastic deformations. Thus, while much of the technical literature on subsidence in the San Joaquin Valley has focused on the relationship between water pressure and compaction in the confined sub-Corcoran aquifer, reduction in groundwater elevations in the overlying semi-confined to unconfined aquifer also may contribute to both elastic change and permanent subsidence.

The relationship between progressive groundwater storage loss and land surface subsidence in the San Joaquin Valley over the past several decades is illustrated in Figure 3-4. Cumulative groundwater overdraft (i.e., basin-wide storage loss; gray line) between 1988-2017 is estimated by Escriva-Bou (2019) to be about 60 million acre-feet (Maf). Although there have been short periods of minor storage recovery (e.g., late 1990's; Figure 3-4), the multi-decade trend is characterized by net storage loss, particularly after 2006 (Famiglietti *et al.*, 2011). The time series of groundwater storage change is punctuated by relatively higher rates of storage loss during droughts (e.g., 2012-2016) (Figure 3-4).

California Aqueduct Mile Post (MP) 160.45 was selected as a key reference location for developing the CASP subsidence forecast model because it is in one of the areas along the Aqueduct alignment most affected by induced subsidence, and because of the number of historical subsidence measurements available at this location. The time history of subsidence at MP 160.45 also is plotted on Figure 3-4 (blue line) for comparison with the basin-wide storage loss. When subsidence at MP 160.45 is plotted against cumulative basin-wide storage loss in the same year, the result shows a good linear correlation (Figure 3-5). With the caveat that subsidence at a point is being compared to an estimate of basin-wide storage loss in Figure 3-4, it is apparent that increases in local subsidence rate at MP 160.45 are temporally coincident with increases in the rate of regional groundwater storage loss during multi-year dry and drought periods (see additional data and discussion in Section 3.2 that show the historical variations in subsidence rate at MP 160.45 generally are observed elsewhere in the basin). The causal relationships implied in Figures 3-4 and 3-5 are that: 1) the basin-wide average rate of groundwater pumping increases during multi-year dry and drought periods; 2) subsidence rates generally are correlated with groundwater pumping rates; and 3) pumping-induced subsidence occurs when groundwater levels are reduced below historical low levels. This latter point is further discussed in Section 3.1.3.

Figure 3-1. Buried relief on the top of the Pleistocene Corcoran Clay in the San Joaquin Valley subsurface. The boundaries and extents of the primary historical subsidence bowls also are shown. Modified from DWR (2019)

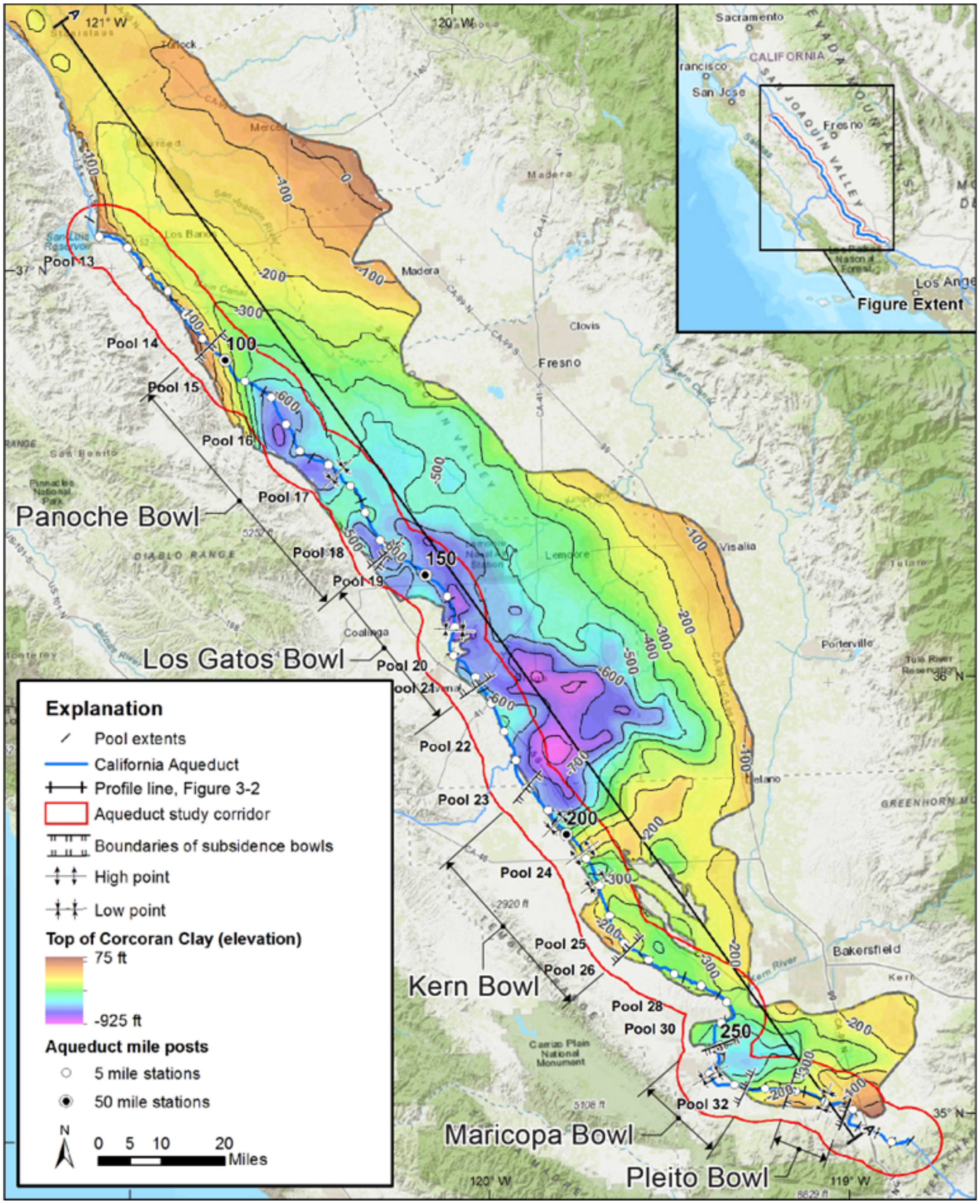


Figure 3-2. Profile of buried relief on the surface of the Corcoran Clay illustrating geologic compaction of underlying deposits in the past 620,000 years. See Figure 3-1 for location of profile. Modified from DWR (2019)

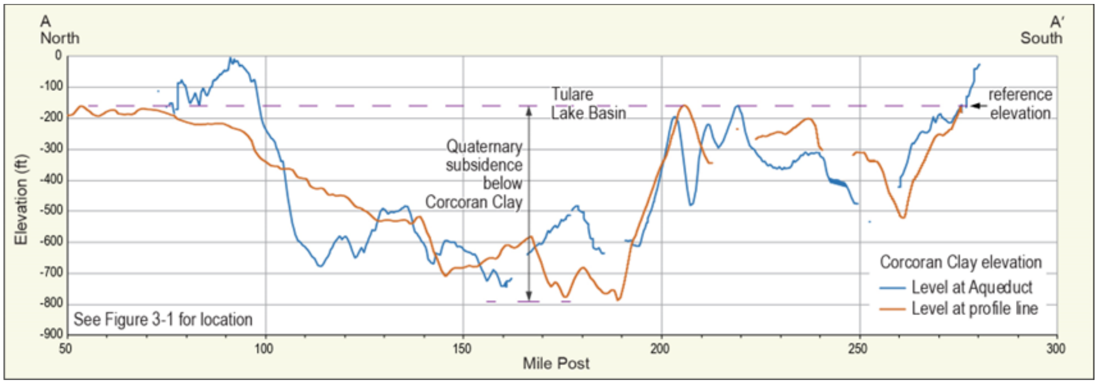


Figure 3-3. Schematic geologic sections showing pre- and post-development (top and bottom, respectively) groundwater flow and head conditions in the San Joaquin Valley. The Corcoran clay (Figures 3-1 and 3-2) is a confining layer that separates the upper and lower parts of the fresh groundwater aquifer system. From Faunt et al. (2009)

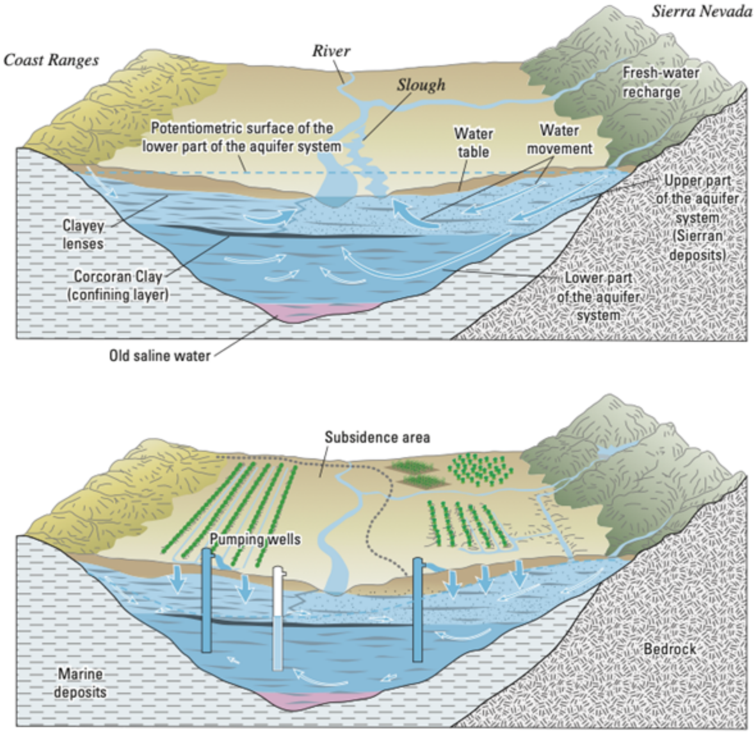


Figure 3-4. Time history of land subsidence at MP 160.45 (blue line), and coeval San Joaquin cumulative basin-wide overdraft/ groundwater storage loss (gray line; data from Escriva-Bou, 2019). Orange bands indicate multi-year dry and drought periods

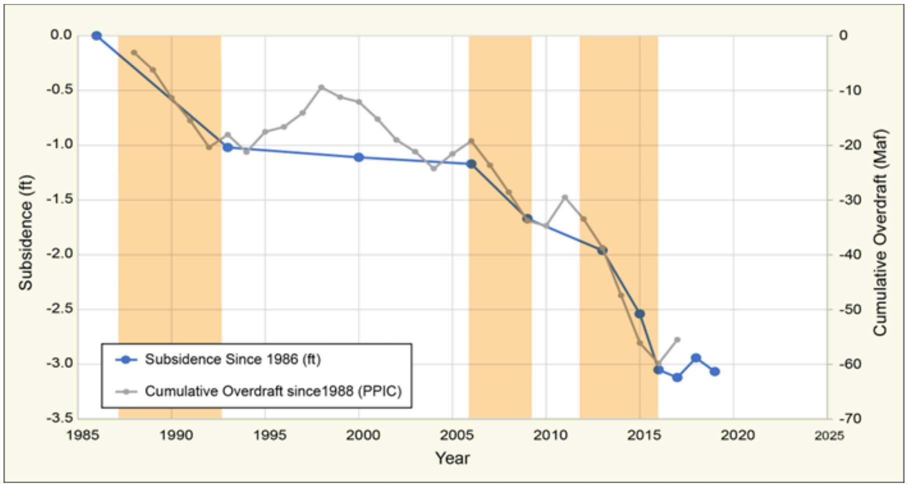
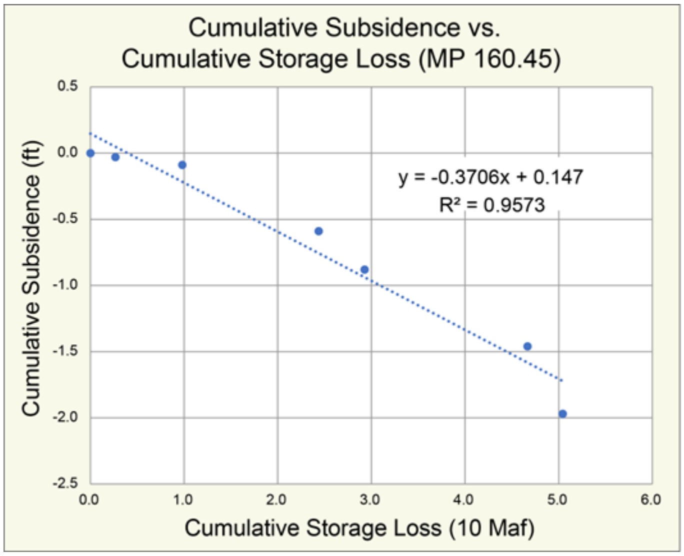


Figure 3-5. Cumulative subsidence at MP 160.45 vs. cumulative basin-wide storage loss between 1998-2017, with linear regression trend line and R2 value. Same data as in Figure 3-3, but with cumulative subsidence and storage loss shown relative to their 1998 values



3.1.3 Preconsolidation Stress

The maximum vertical effective stress that an aquifer skeleton has sustained at any time in the past is commonly referred to as the *preconsolidation stress* (Sneed and Galloway, 2000; Armenti, 2017; Smith *et al*., 2017). If the aquifer has accommodated both elastic and inelastic deformation in response to the applied preconsolidation stress, then no additional permanent compaction will occur until the effective normal stress, which is the total vertical stress minus the pore pressure, increases above the preconsolidation stress. Variations in the effective normal stress less than the preconsolidation stress may produce elastic changes in the aquifer thickness, but the preconsolidation stress is a threshold stress that must be exceeded before new inelastic (permanent) compaction of the aquifer can occur.

Because the effective normal stress at a given depth in a confined aquifer is directly proportional to the hydraulic head, it is convenient to refer to a "preconsolidation head" as a proxy for the preconsolidation stress (see discussion in Armenti, 2017). If it is assumed that the lithostatic overburden load is constant, then changes in effective normal stress at a given depth are primarily related and proportional to changes in pore pressure, and thus to changes in head. The preconsolidation stress can be related to a specific value of head in the aquifer. Reduction in head that increases effective normal stress above the preconsolidation stress will potentially induce new permanent compaction of the aquifer. Under these conditions, the preconsolidation head is the threshold groundwater elevation for inducing new permanent subsidence.

In discussions to develop the subsidence forecast model (documented in the TI Group meeting minutes), the TIG used the informal term "inducing head" as a synonym for the preconsolidation head, specifically to relate it to "inducing pumping"; i.e., groundwater pumping *behavior* that lowers the artesian head in the deep aquifer below the elevation required to raise the effective normal stress to the preconsolidation stress, and which triggers new permanent subsidence.

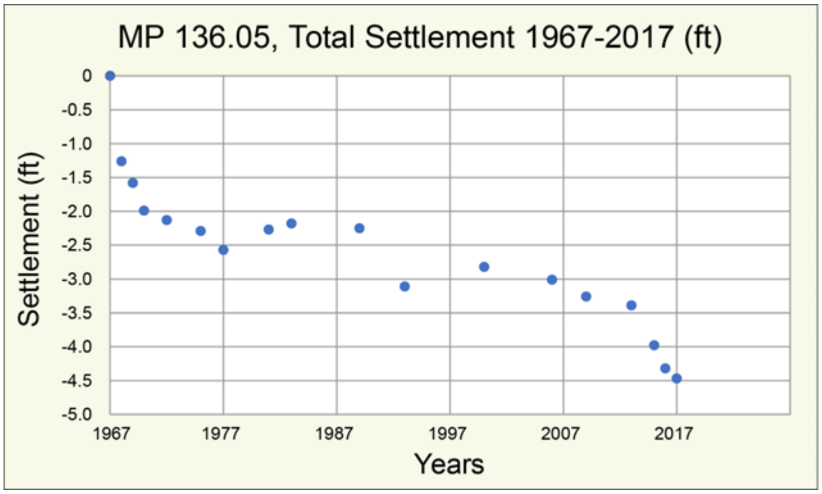
3.1.4 Residual Subsidence

Fine-grained clay layers have lower hydraulic conductivity than coarser-grained sand and gravel horizons in an aquifer, and consequently they drain more slowly in response to reductions in average pore pressure. The rate of drainage from the fine-grained layers is proportional to the difference in pore pressure between them and the surrounding aquifer. The pressure difference declines as drainage progresses, resulting in a decrease in drainage rate from these layers with time. This phenomenon can be modeled using a one-dimensional differential diffusion equation (see summary in Smith *et al*., 2017, and references cited therein). The implication is that a static reduction in average aquifer pore pressure may trigger viscous aquifer deformation (i.e., a *rate* of aquifer compaction in response to an increase in effective normal stress), and land subsidence that occurs with a decaying, time-dependent rate.

It can be inferred that aquifer compaction resulting from draining of aquitards may occur and be expressed by a time-dependent decline in land subsidence rate. In discussions to develop the subsidence forecast model, the SSHAC TI Group used the informal term "lagging subsidence" to describe this process because it can continue at a declining rate after an initial elastic response to a discrete reduction in groundwater elevations below the inducing head. Prokopovich (1969) previously recognized this phenomenon in the San Joaquin Valley and described it as "residual subsidence". For consistency and continuity with Prokopovich's work, the term "residual subsidence" is used to refer to subsidence associated with time-dependent draining of aquitards, while noting its equivalence to the term "lagging subsidence" in other SSHAC documentation for this study.

Examples of residual or lagging subsidence are potentially captured in land survey data along the Aqueduct in DWR's San Luis Field Division (SLFD). As shown by the time history for land elevation at MP 136.05 (Figure 3-6), the subsidence rate progressively declined for a decade after the California Aqueduct came into service in 1967. It is inferred that the decline in rate during that time was due to growers replacing pumped groundwater with surface water deliveries from the Aqueduct for irrigation; in fact, groundwater elevations in this region began to recover rapidly from historic lows after 1967 and continued to rise until at least 1976 (Ireland *et al.*, 1980; also, see discussion in DWR, 2017 and 2019). The time history of subsidence between 1967-1977 for MP 136.05 can be reasonably well approximated using an exponential function where the subsidence rate decreases with time (Figure 3-7). To illustrate this in more detail, the annual subsidence rate between 1967-1977 is plotted on a semi-log graph in Figure 3-8; note that the subsidence rate declined by about an order of magnitude within the decade.

Figure 3-6. Time history of subsidence, MP 136.05



Following the decay in subsidence rate between 1967-1977, the time history for MP 136.05 reveals a modest increase in land surface elevation after 1978 (Figure 3-6). These data suggest the increase in average aquifer pore pressure associated with rising water levels after 1967 (Ireland *et al*., 1980) reduced the effective stress on the aquifer skeleton below the preconsolidation stress, thereby arresting residual subsidence and triggering elastic rebound. On this basis, it appears that residual subsidence in the SLFD largely ceased in the mid- to late 1970's because artesian head rose above the inducing head. Some additional draining of fine-grained layers like the Corcoran clay may have been occurring in the mid- to late-70's, but at rates too low to produce measurable subsidence along the Aqueduct.

Figure 3-7. Exponential fit to decay in subsidence rate at MP 136.05 in the first decade after the Aqueduct came into service (1967-1977)

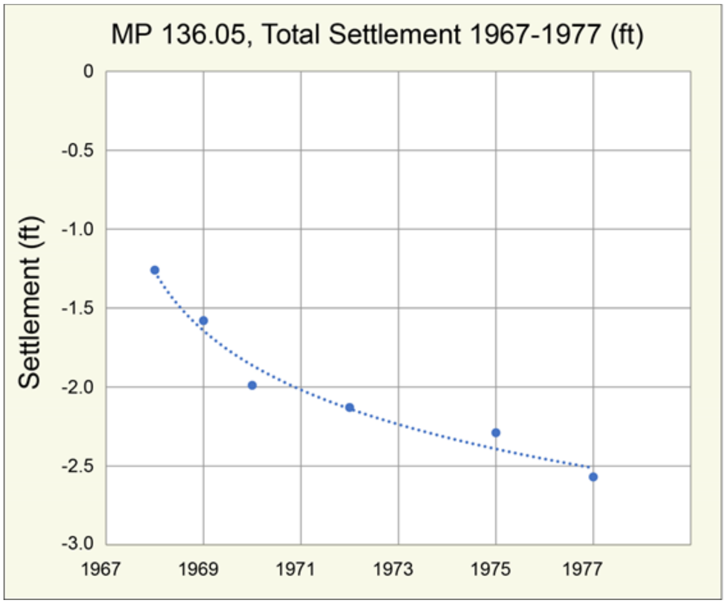
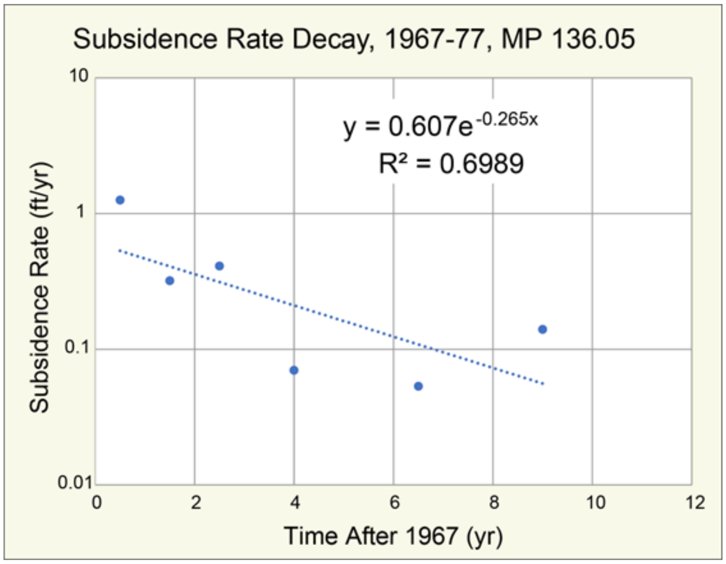


Figure 3-8. Subsidence rate as a function of time at MP 136.05, 1967-77. Note semi-log plot



3.2 Surface Water Availability, Pumping Behavior and Subsidence Rate

The TI Group reviewed data presented in DWR (2017; 2019) and concluded that there is a correlation between subsidence rate and annual availability of surface water to growers who can also pump groundwater from the aquifers that contribute to subsidence in the vicinity of the Aqueduct. For example, Figure 3-9 is a plot from DWR (2019) that shows: 1) annual allocations to Central Valley Project (CVP) south of Delta (SOD) agricultural water service contractors from the late 1970's to 2017; 2) the Sacramento Valley water year hydrologic classification (an index used by the U.S. Bureau of Reclamation in making water allocations); and 3) time histories of subsidence at several low points within the main SLFD subsidence bowls. The plot shows that consistent 100% CVP SOD agricultural water service contract allocations from 1977 to 1989 corresponded with associated stability or minor rebound of the land surface beneath the Aqueduct during this period. The consistency and magnitude of CVP allocations declined after 1989, following a 1986 California Appeals Court decision that led to the State Water Resources Control Board imposing limitations on freshwater exports from the Delta to maintain water quality in the Bay-Delta system (Hannemann and Dyckman, 2009), as well as the implementation of requirements of the 1992 Central Valley Project Improvement Act and for Endangered Species Act protective actions for Chinook salmon and Delta smelt. Since about 1989, water allocations to CVP SOD agricultural water service contractors have been reduced to 50% or less of contract amounts during multi-year dry and drought periods (indicated by vertical beige bands and red columns on Figure 3-9), and the rate of subsidence has increased during these periods. The average subsidence rate was zero or very low during extended periods of wet weather when CVP allocations were 50% or greater (e.g., 1995-2006). In the decades since 1989, the highest observed subsidence rates occurred during the 2012-2016 drought (Figure 3-10), which was characterized by extremely dry conditions and two consecutive years of zero allocations to CVP SOD agricultural water service contractors (Figure 3-9). Data on annual water exports from the Delta to the San Joaquin Valley provided to the TI Group from the DWR Climate Group (Figure 3-11) document that the most severe deficits in surface water deliveries between 1968-2017 occurred during the 2012-2016 drought.

The TI Group interpreted the historical association of higher subsidence rates with reduced CVP water contract allocations (Figure 3-9) to indicate that growers use groundwater to partially replace deficits in contract water deliveries. The highest subsidence rates between 1968 and 2017 occurred during the 2012-2016 drought, which was accompanied by severe CVP and State Water Project (SWP) delivery deficits (Figure 3-11), and by rapid basin-wide storage loss (Figure 3-4). Although the direct physical correlation of land subsidence is with groundwater storage loss (Section 3.1.2), the TI Group assesses that the high subsidence rate in 2012-2016 also is correlated with severe delivery deficits because growers rely on pumping additional groundwater to replace at least some of the reductions in CVP and SWP water deliveries.

Figure 3-9. Subsidence time histories for selected mileposts in the SLFD, annual allocations to CVP South of Delta Agricultural water service contractors, and Sacramento Valley water year index. From DWR (2019)

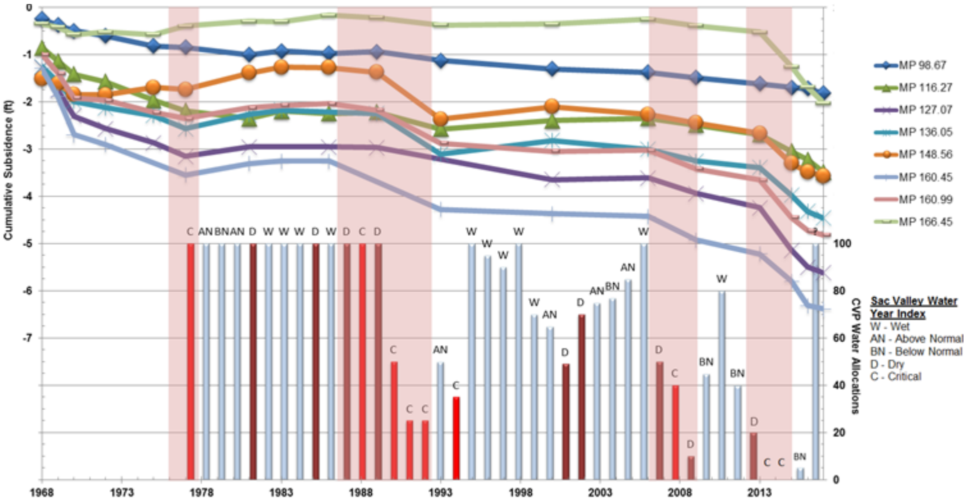
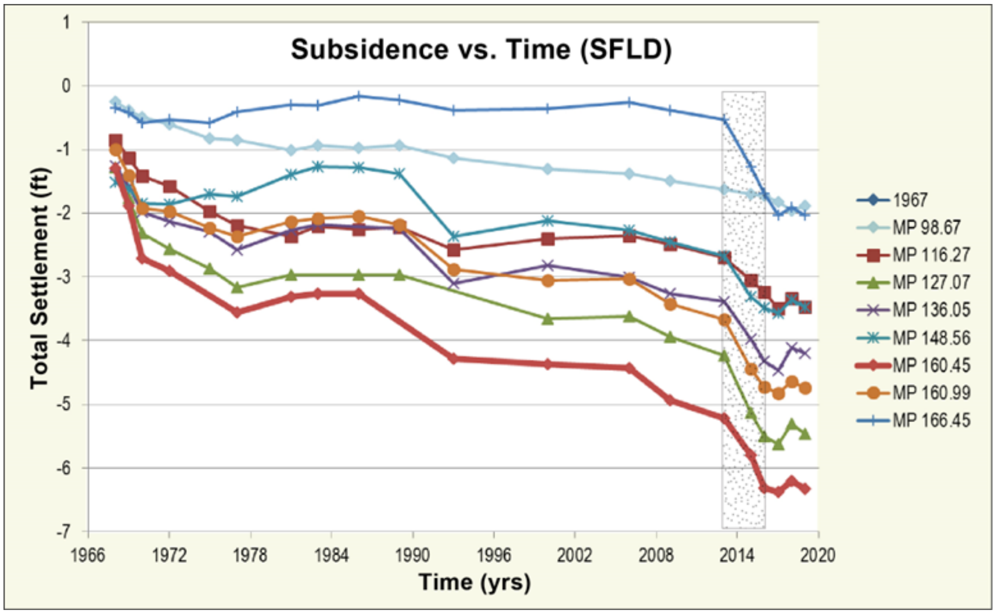


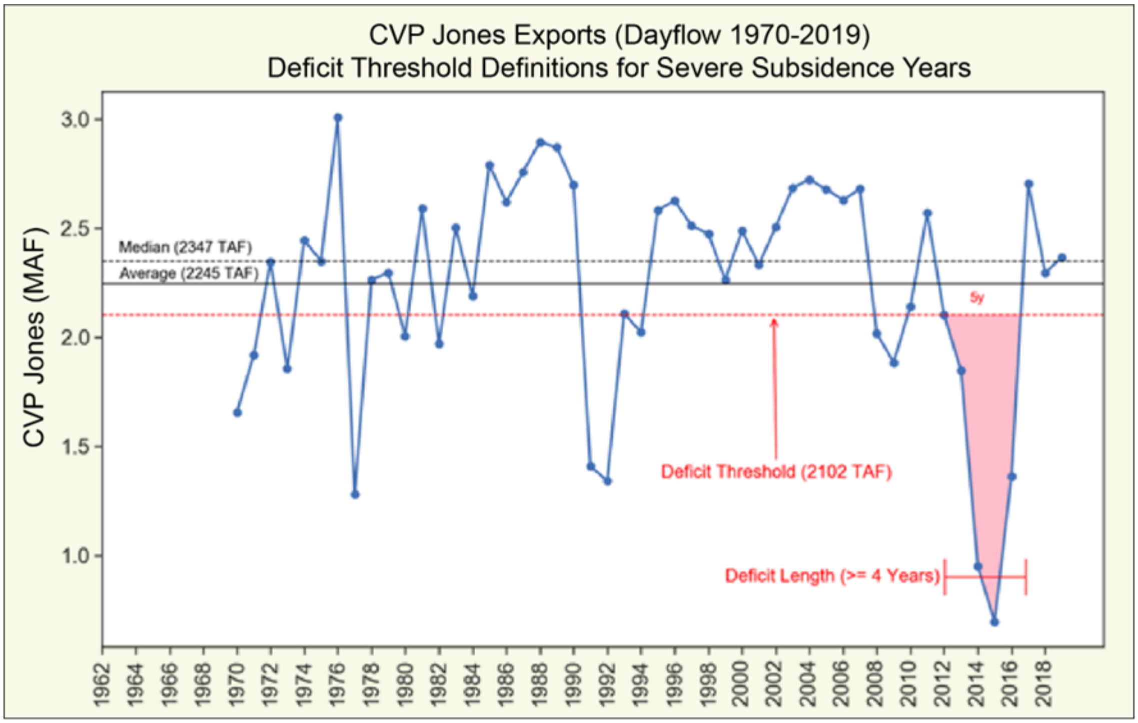
Figure 3-10. Subsidence time histories for selected mileposts in the SLFD, with high rates during the 2012-2016 drought highlighted



3.3 SGMA Implementation

The Sustainable Groundwater Management Act (SGMA), passed by the California legislature and signed into law by Governor Edmund G. Brown, Jr. in 2014, mandates that groundwater users implement changes to bring the most severely over-drafted groundwater basins into balance by 2040 (Hanak *et al*., 2019). To come into full compliance with SGMA, groundwater users will need to transition from current patterns of periodic inducing pumping to sustainable levels of pumping that do not trigger additional induced subsidence. The SGMA law provides for groundwater users to form Groundwater Sustainability Agencies (GSAs) and locally manage groundwater resources through development of Groundwater Sustainability Plans (GSPs) that describe management actions, metrics, and timetables for achieving sustainable groundwater use by 2040 (Hanak *et al*., 2019). Initial GSPs were required to be provided to DWR for review no later than January 2020. See Appendix B for additional context.

Figure 3-11. Time history of exports from the Delta at the CVP Jones pumping plant, 1969-2019. Note severity of deficit in surface water exports during the 2012-2016 drought relative to previous decades. Plot provided by DWR Climate Group. TAF =Thousands of Acre-Ft; MAF = Millions of Acre-Ft



The multi-decade timeline for SGMA implementation allows the GSAs to develop and implement projects and management actions that will reduce overdraft of groundwater within their basins between 2020 and 2040. During this period of partial SGMA implementation, "recent" patterns and rates of groundwater pumping associated with the last several decades of agricultural land use are expected to be replaced by "transitional" patterns of groundwater pumping at lower rates. The reduction in pumping rate is expected to initially reduce the rate of induced subsidence, and then eventually eliminate induced subsidence with full achievement of sustainable conditions. The anticipated transitional pumping during partial SGMA implementation has been described as a "glide path" to sustainable groundwater use and full SGMA implementation by 2040 (e.g., Arvin-Edison Water Storage District, 2019; also, see summaries of expert elicitations in Appendix B). As noted by the Public Policy Institute of California ("Learning the Language of Groundwater"; PPIC blog post, 18 June 2019), a "glide path" approach implies that "groundwater elevations will continue to decline, but at a decreasing rate, until they reach long-term balance" (see https://www.ppic.org/blog/learning-the-language-of-groundwater/; last accessed 18 July 2023). Because induced subsidence rates are proportional to overdraft rates (Figure 3-5; Section 3.2), the TI Group infers that subsidence rates would progressively decline during a period of partial SGMA implementation until they reach natural or background rates upon cessation of overdraft and resolution of any residual subsidence (while recognizing and representing within the model that some uncertainty exists as to whether full SGMA implementation will be achieved).

3.4 Summary

Anthropogenic land subsidence in the San Joaquin Valley is primarily caused by overdraft of groundwater and associated loss of storage in the major groundwater aquifers. Although the deep, confined freshwater aquifer below the Corcoran clay has been the focus of much subsidence research, reduction in groundwater elevations in the overlying semi-confined aquifer also experiences induced compaction as well, including elastic changes and permanent subsidence. Permanent subsidence is primarily due to dewatering and compaction of fine-grained (silt and clay) beds, and it occurs when groundwater elevations are drawn down below the preconsolidation or "inducing" head. Draining and compaction of fine-grained beds in response to static reduction in groundwater elevation below the inducing head is a time-dependent process that can contribute to residual ("lagging") compaction at a declining rate after groundwater elevations are stabilized. This may be virtually instantaneous or take many years or decades to stabilize.

The objective of SGMA is for groundwater users to sustainably manage groundwater resources and eliminate overdraft in the most significantly impacted basins by 2040. Informed experts and stakeholders anticipate that "transitional" groundwater pumping at reduced rates relative to the previous several decades will occur during a period of partial SGMA implementation prior to 2040 (Appendix B), resulting in a declining rate of overdraft with a corresponding decline in subsidence rate (i.e., the "glide path" scenario). Groundwater overdraft is anticipated--and required by law--to cease upon full implementation of SGMA, which will result in the decline of subsidence rates to natural geologic or background rates and the cessation of other adverse effects associated with groundwater overdraft.

3.5 Chapter References

Armenti, T., 2017, *Land rebound and preconsolidation head in the Houston Ship Channel area*: M.S. thesis, University of Houston, 109 p.

Arvin-Edison Water Storage District, 2019, Executive Summary, Management Area Plan, Kern Sub-Basin, 14 p., available from https://aewsd.org/wp-content/uploads/AEWSD-GSP-FINAL-executive-summary-only.pdf (last accessed 1/10/22).

Department of Water Resources, 2017, *California Aqueduct Subsidence Study*.

Department of Water Resources, 2019, *California Aqueduct Subsidence Study: Supplemental Report*.

Escriva-Bou, A., 2019, *Technical Appendix A: Updated Assessment of San Joaquin Valley's Water Balance, in Hanak, E., et al., Water and the future of the San Joaquin Valley*: Public Policy Institute of California, available from https://www.ppic.org/wp-content/uploads/0219ehr-appendix-a.pdf (last accessed 1/5/21).

Famiglietti, J.S., Lo., M., Bethune, J., Anderson, K.L., Syed, T.H., Swenson, S.C., de Linage, C.R., and Rodell, M., 2011, *Satellites measure recent rates of groundwater depletion in California's Central Valley*: Geophyscial Research letters, v. 38, no.3, L03403, doi:10.1029/2010GL046442.

Galloway, D.L., Jones, D.R., and Ingebritsen, S.E., 1999, *Land subsidence in the United States*: United States Geological Survey Circular 1182, 177 p.

Hanak, E., and 9 co-authors, 2019, *Water and the future of the San Joaquin Valley: Public Policy Institute of California*, 100 p. plus technical appendices and overview, available from https://www.ppic.org/publication/water-and-the-future-of-the-san-joaquin-valley/ (last accessed 1/4/21).

Hanemann, M., and Dyckman, C., 2009, *The San Francisco Bay-Delta: a failure of decision-making capacity*: Environmental Science and Policy, v. 12, p. 710-725.

Ireland, R.L., Poland, J.F., and Riley, F.S., 1980, *Land Subsidence in the San Joaquin Valley, California, as of 1980*: United States Geological Survey Professional Paper 437-I, 93 p.

Kooi, H. and de Vries, J.J., 1998, *Land subsidence and hydrodynamic compaction of sedimentary basins*: Hydrology and Earth System Sciences, v.2, no. 2-3, p. 159-171.

Poland, J.F,. Lofgren, B.E., Ireland, R.L., and Pugh, A.G., 1975, *Land subsidence in the San Joaquin Valley, California, as of 1972*: United States Geological Survey Professional Paper 437-H, 78 p. (http://pubs.usgs.gov/pp/0437h/report.pdf; last accessed 1/12/22).

Prokopovich, N., 1969, "*Prediction of Future Subsidence along Delta- Mendota and San Luis Canals, Western San Joaquin Valley, California," U.S. Bureau of Reclamation*, Sacramento, California.

Smith, R.G., Knight, R., Chen, J., Reeves, J.A., Zebker, H.A., Farr, T., and Liu, Z., 2017, *Estimating the permanent loss of groundwater storage in the southern San Joaquin Valley, California*: Water Resources Research, v. 53, p. 2133–2148; doi:10.1002/2016WR019861.

Sneed, M., and Galloway, D. L., 2000, *Aquifer-System Compaction and Land Subsidence: Measurements, Analyses, and Simulations-the Holly Site, Edwards Air Force Base, Antelope Valley, California (No. 2000-4015)*: United States Geological Survey Water Resources Investigation Report 00-4015

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4.0 Forecast Model Conditions

4.1 Introduction

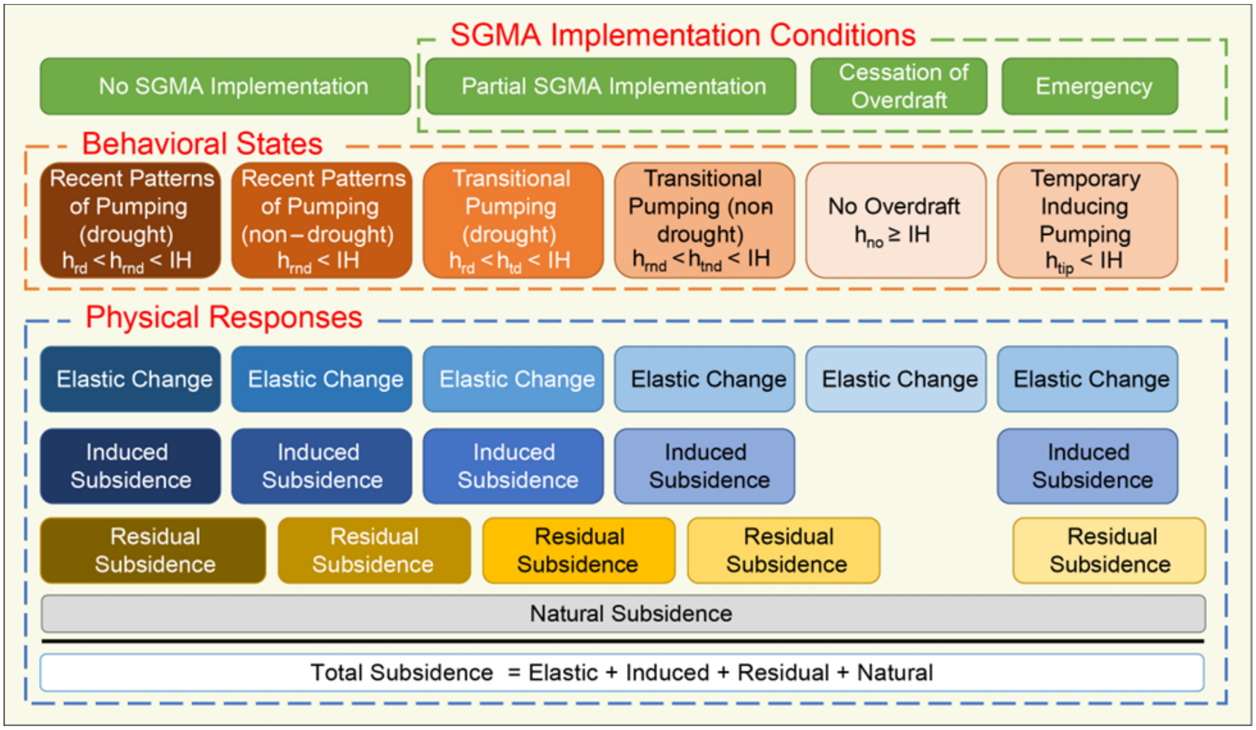
Based on the conceptual framework outlined in Chapter 3, the TI Group posits that the annual rate of groundwater overdraft, and thus the annual rate of subsidence, is correlated with deficits in annual water deliveries to CVP and SWP contractors. The highest rates of subsidence in the SLFD between 1968 and 2017 are associated with multi-year dry or drought periods, during which annual allocations to CVP SOD agricultural water service contractors were less than 50% of maximum contracted volumes (Figure 3-9). Higher rates of groundwater pumping during these periods led to reductions in groundwater storage below previously low levels, which consequently induced higher rates of aquifer compaction and associated land subsidence.

The CASP study area currently lacks a fully parameterized physical model for predicting subsidence at scales required for engineering evaluation of the Aqueduct. Consequently, the CASP subsidence forecast model applies an empirical relationship between surface water delivery deficits and relatively higher subsidence rates during severe droughts to develop stochastic realizations of future subsidence. The implementation of this empirical relationship in the model is described in detail in the following sections. For the purposes of the forecast model, "severe droughts" are defined by multi-year delivery deficits equal to or greater than those documented at CVP/SWP Jones pumping plant during the 2012-2016 drought (Figure 3-11; see discussion in Section 3.2).

The subsidence forecast model represents a set of discrete alternative future conditions, associated behavioral states, and physical responses that jointly determine the rate of subsidence, as illustrated in Figure 4-1. For the purposes of the model, land subsidence over the past several decades along the Aqueduct is primarily attributed to groundwater storage loss and induced aquifer compaction; other physical processes that could potentially contribute to future subsidence, such as hydrocompaction of shallow soils, are assessed to be less significant and are not explicitly included in the conceptual model (although they may be included implicitly via the historical subsidence data). The model conditions (top row, Figure 4-1) include groundwater pumping in the absence of SGMA implementation; groundwater pumping during partial implementation of SGMA; cessation of overdraft upon full implementation of SGMA; and a possible future emergency condition.

Reading the chart in Figure 4-1 vertically, each of the model conditions is associated with assumed groundwater pumping behavioral states that control groundwater elevations (hydraulic head), and specifically determine whether the groundwater surface elevation is above or below the inducing head (IH) (equivalent to the preconsolidation head; see discussion in Section 3.1.3) for triggering new permanent subsidence. For a given model condition and pumping behavioral state, the forecast model considers the potential for different physical responses of the aquifer, including induced permanent subsidence, positive and negative elastic changes in the aquifer thickness, and potential residual (i.e., "lagging") subsidence.

Figure 4-1. Potential future subsidence conditions represented by the forecast model. See text and Table 4-1 for discussion and additional explanation



The following sections describe the major conditions, the associated pumping behavioral states, and the physical aquifer responses (Figure 4-1) represented by the forecast model.

4.2 No SGMA Implementation Condition

The No SGMA Implementation condition assumes no action is taken by GSAs to achieve SGMA sustainability goals, and that groundwater pumping behavior characteristic of the past several decades continues indefinitely. The No SGMA Implementation condition assumes that total acreage in the SJV currently planted in permanent crops remains constant and does not increase over time (i.e., demand hardening for irrigation water does not increase). Given the relationship between pumping behavior and subsidence rate discussed in Section 3.2, continuation of historical pumping patterns implies continuation of historical subsidence rates, with their associated variability, into the future.

As discussed in Section 3.1.2, cumulative net overdraft of groundwater in the San Joaquin Valley has occurred over the past several decades in response to pumping by agricultural users to replace deficits in surface water deliveries. Up until about 1988, the CVP and SWP consistently delivered 100% of contract allocations to water users. After 1988, annual contract allocations generally were less than 100% and varied significantly from year to year, sometimes by more than 50%. In response to water shortages and increased costs to acquire partial replacement supplies through market transfers, the period between 1988 and 2020 also was characterized by widespread planting of high-value permanent orchards and vineyards in the San Joaquin Valley. In addition to their value as agricultural commodities, permanent crops provide higher revenue to growers to cover the costs of purchasing additional water to offset shortfalls in contract allocations in addition to greater crop establishment costs. The progressive increase in permanent crops over the past several decades contributed to "demand hardening" for groundwater to replace surface water deficits during drought periods (DWR, 2019). Annual subsidence rates observed over the past three decades were affected by these trends in surface water availability and land use, and thus are more likely to represent future conditions in the absence of SGMA implementation than subsidence rates observed during the period prior to about 1988 when CVP and SWP deliveries were consistently at 100% (Figure 3-9), and a lower percentage of agricultural land was planted in permanent crops (DWR, 2019).

Table 4-1. Explanation of acronyms for hydraulic head conditions associated with pumping behavioral states in Figure 4-1

Hydraulic Head Associated With Pumping Behavioral States In Figure 4-1	Explanation
h_{rnd}	Recent hydraulic head in non-drought years
h_{rd}	Recent hydraulic head in drought years
h_{tnd}	Hydraulic head during transitional pumping in non-drought years
h_{td}	Hydraulic head during transitional pumping in drought years
h_{no}	Hydraulic head associated with a no-overdraft condition
h_{tip}	Hydraulic head during temporary inducing pumping
h_{rnd}	Recent hydraulic head in non-drought years

The forecast model for the No SGMA condition makes a distinction between pumping behavior and subsidence rates during severe droughts like the 2012-2016 drought (referred to as "drought") and other periods (referred to as 'non-drought'). The TI Group assumes that the statistical variability in annual subsidence rate for the past several decades, exclusive of the years 2012-2016, captures expected future variability in the absence of SGMA implementation (and status quo in land use practices) during years other than those in severe drought. Patterns of pumping since 1989 have resulted in net storage loss and subsidence, and thus on average have resulted in reduction in groundwater elevations below the inducing head. In Figure 4-1, this is represented by showing the recent artesian head during non-drought years (h_{rnd}) as generally being lower than the inducing head (IH). In the five decades since the Aqueduct came into service, the 2012-2016 drought is anomalous in terms of the severity of the total CVP delivery deficit (Figure 3-9) and magnitude of the subsidence rate (Figure 3-10). As documented in DWR (2019), groundwater elevations dropped locally below historic 1967 lows in parts of the SLFD during the 2012-2016 drought, and associated subsidence rates were the highest documented since the late 1960's (Figure 3-9). Based on observations of recent patterns of pumping, therefore, artesian head during the severe drought years (h_{rd}) is inferred to be lower than artesian head during non-drought years (h_{rnd}), resulting in more rapid storage loss and higher subsidence rates after groundwater levels drop below the inducing head (Figure 4-1).

Total subsidence for the No SGMA condition at any given time is interpreted to be a sum of physical responses from elastic change, induced subsidence, residual subsidence and natural subsidence (Figure 4-1). As documented by DWR's periodic land surveys along the Aqueduct (Figure 3-9), the time history of subsidence over the past several decades for selected points in the SLFD generally is characterized by periods of induced permanent subsidence alternating with either no subsidence or minor rebound. The rebound is temporally associated with abrupt increases in annual CVP allocation after several successive years of deliveries below 50% (Figure 3-9), and it is here interpreted to be an elastic response of the aquifer to recovery of groundwater elevations after a reduction in pumping rate. The elastic rebound is typically a minor fraction of the induced permanent subsidence (Figure 3-9).

The time histories in Figures 3-9 and 3-10 exhibit no evidence for significant residual subsidence following periods of rapid subsidence, which might be expected from time-dependent draining of aquitards in parts of the aquifer that had been subjected to increases in effective stress greater than the preconsolidation stress (Section 3.1.3). Based on the fact that the high subsidence rate during the 2012-2016 drought was abruptly arrested during the wet 2017 water year, and then followed by minor rebound in 2018 (Figure 3-10), the TI Group posits that water levels rapidly recovered above the inducing head between 2017 and 2018, triggered local elastic rebound, and resolved any residual subsidence that may have occurred between the dates of the annual surveys.

4.3 Patrial SGMA Implementation Condition

The Partial SGMA Implementation condition represents a transition from a No SGMA implementation condition, to a Cessation of Overdraft condition (Figure 4-1). The Partial SGMA Implementation condition begins when the long-term-average rate of groundwater pumping proximal to the Aqueduct is reduced due to actions taken by GSAs to comply with SGMA. The TI Group assumes there will be a finite time over which GSAs implement management actions, progressively reduce pumping rates, and bring groundwater use into balance (i.e., the "glide path" scenario for SGMA implementation discussed in Section 3.3). Partial SGMA implementation concludes when proximate overdraft ceases, and the basin is in balance.

The behavioral state associated with Partial SGMA Implementation is here referred to as “transitional pumping”, and it is assumed to occur at a lower average rate than recent historical patterns of pumping in the absence of SGMA implementation. The TI Group makes a distinction between transitional pumping during non-drought and severe drought years (Figure 4-1). For transitional pumping during non-drought years, the average pumping rate is less than the historical rate of pumping during non-drought years. Transitional pumping is still expected to draw proximate groundwater elevations below the inducing head ($h_{tnd} < IH$; Figure 4-1), but the rate of storage loss is anticipated to be lower than during the No SGMA condition. Consequently, permanent subsidence will continue to accumulate, but at a lower rate than historic rates. Similarly, the TI Group assumes that transitional pumping rates during a future extended drought will be higher than transitional pumping rates during years that are not in extended drought, but lower than during an extended drought in a No SGMA condition because GSAs will have undertaken management actions to reduce overdraft during the period of Partial SGMA Implementation

Total subsidence that occurs during the Partial SGMA Implementation condition is the sum of physical responses from elastic change, induced subsidence, residual subsidence, and natural subsidence (Figure 4-1). The TI Group assumes that aquifer response to transitional pumping behavior will be similar to pumping during the No SGMA condition but lower in magnitude, resulting in lower average subsidence rates. The TI Group assumes that if GSAs pursue a “glide path” approach to complying with SGMA, then subsidence rates generally will decline over the duration of the Partial SGMA Implementation condition (Section 3.1.1).

4.4 No Overdraft Condition

The No Overdraft condition begins once GSAs have taken sufficient actions to cease groundwater overdraft. The associated pumping behavioral state is No Overdraft (Figure 4-1), which is here understood to be the rate or rates of pumping that will occur when GSAs fully implement measures to comply with SGMA and operate within the sustainable yield of the basin. Groundwater elevations proximal to the California Aqueduct during this condition (h_{NO}) are expected to be managed by GSAs to remain above the inducing head ($h_{NO} > IH$; Figure 4-1). Anticipated total subsidence during the No Overdraft condition includes the sum of physical responses from elastic change, natural subsidence, and may include residual subsidence following from previous induced subsidence.

4.5 Emergency Condition

The TI Group defines an Emergency Condition as a temporary situation in which a groundwater basin that had previously achieved Cessation of Overdraft resumes subsidence-inducing pumping for some reason in response to an emergency, such as extremely severe drought or water infrastructure failure. The associated pumping behavioral state during an Emergency Condition is “Temporary Inducing Pumping”, in which the head in the deep aquifer (h_{TIP}) is temporarily drawn down below the inducing head (IH: Figure 4-1). Total subsidence during an Emergency Condition includes the sum of physical responses from elastic change, induced subsidence (for some discrete period), natural subsidence, and may include residual subsidence for some period based on previous or new induced subsidence (Figure 4-1).

4.6 Chapter References

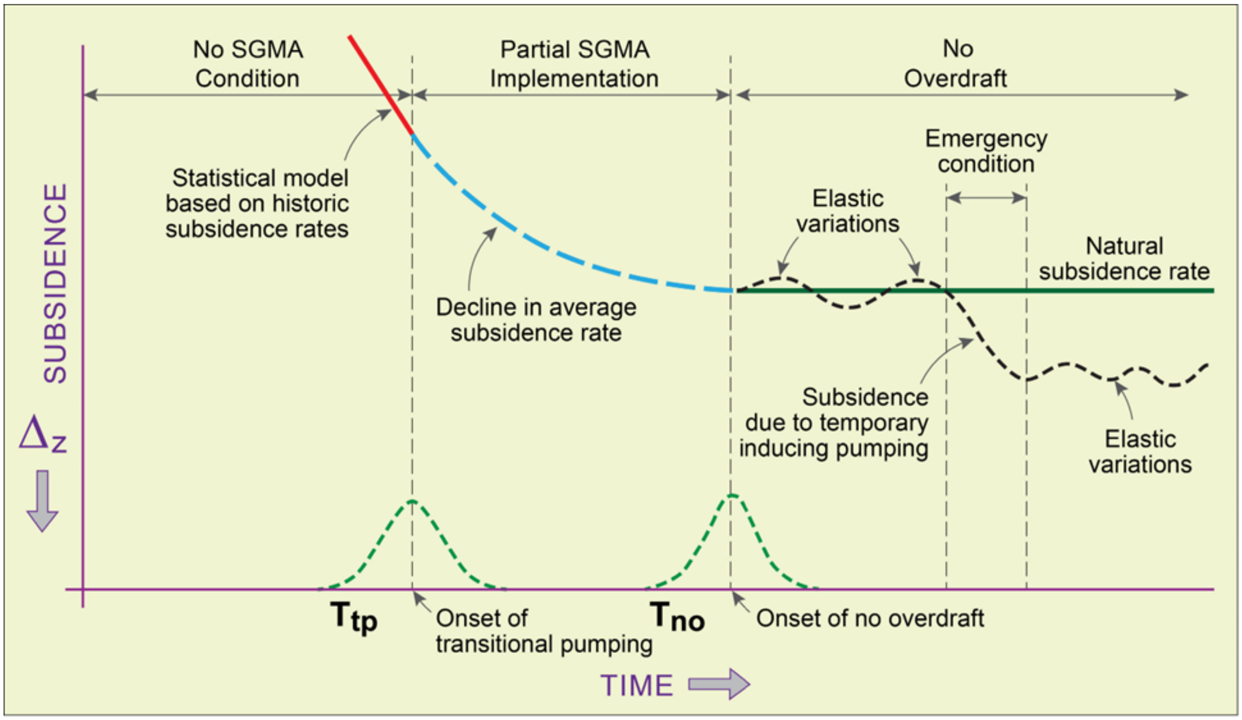
Department of Water Resources, 2019, *California Aqueduct Subsidence Study: Supplemental Report*.

5.0 Model Structure

5.1 Overview

The forecast model incorporates both aleatory (randomness) and epistemic (incomplete knowledge) uncertainty about future subsidence rates during the potential future conditions described in Section 4: the No SGMA condition; the Partial SGMA Implementation condition; and the No Overdraft condition (Figure 5-1). Although the TI Group recognized there is a potential for a future Emergency Condition (Section 4.5) to occur during the CASP planning horizon, this condition was not explicitly included in the forecast model because the nature of the emergency and its likelihood, duration, and impact on subsidence rate cannot be anticipated and characterized in a defensible manner. The Emergency Condition is included in Figure 5-1 to schematically demonstrate the TI Group's assessment that temporary inducing pumping after cessation of overdraft could increase permanent subsidence.

Figure 5-1. Schematic representation of forecast model elements



Annual subsidence rate and cumulative subsidence during the No SGMA condition are represented by a statistical model that extrapolates the range of annual subsidence rates for both non-drought and drought conditions into the future (red line, Figure 5-1). The No SGMA model assumes that present land use practices continue unchanged into the future. The model treats the variability in annual subsidence rates, as well as the occurrence of severe droughts (with associated higher mean subsidence rates), as random processes, and uses a stochastic approach to create simulated time histories ("realizations") of future subsidence based on statistical sampling of historic subsidence rate data from non-drought and drought periods at a given site. Future subsidence realizations are developed at specific mileposts and other stations along the Aqueduct for which historical subsidence data are available. This method is used to generate a large population of randomly generated future subsidence realizations, from which the mean, standard deviation, and percentiles of subsidence at specified future dates can be extracted. Thus, aleatory uncertainty in both subsidence rates and the occurrence of severe droughts is captured.

Subsidence during the Partial SGMA Implementation condition is modeled as a progressive decline in the rate predicted by the stochastic model for the No SGMA condition (blue dashed curve, Figure 5-1). The modeled decline in subsidence rate during Partial SGMA Implementation is intended to represent the "glide-path" transition from historical patterns of pumping and groundwater overdraft to full SGMA implementation and no overdraft that is anticipated by many experts and stakeholders (Section 3.3). The period of Partial SGMA Implementation is determined by the year in which GSAs begin transitional patterns of pumping (Ttp), and the year in which No Overdraft is achieved (Tno). Once Ttp and Tno are specified for a given model realization, the rate of subsidence is modeled to progressively decline from the rate given by the No SMGA condition at Ttp (red line, Figure 5-1), to the geologic background rate at Tno (flat green line, Figure 5-1). Given that the time of onset and duration of Partial SGMA Implementation are currently unknown, Ttp and Tno are treated as epistemic variables in the forecast model. As discussed in Section 5.3 below, the TI Group acted in its SSHAC role as an integrator of data, models, and interpretations (Section 2.3.4) to develop probability distributions for Ttp and Tno that represent the center, body, and range of informed opinion about the timing and implementation of SGMA. This integration included evaluation of CASP interviews with 14 experts and stakeholders conducted before the initiation of the SSHAC study (see Appendix B for a summary of the interviews).

The Cessation of Overdraft condition assumes that by the end of the Partial SGMA Implementation period GSAs will have modified land use and water management practices to bring groundwater basins in balance, and, per requirements of SGMA, halt groundwater storage loss and associated induced land subsidence. The forecast model assumes that the State of California will enforce SGMA after it is fully implemented, and thus no new permanent induced subsidence will occur after time Tno, excepting potential emergency conditions that are not represented in the forecast model. The forecast model allows for potential positive and negative changes in land surface elevation during the Cessation of Overdraft condition due to elastic response of the aquifer to annual variations in groundwater elevation above the Inducing Head. The magnitude and sign (up or down) of annual elastic land surface changes is treated as a random variable that is constrained by statistical sampling of historical leveling data along stable reaches of the Aqueduct outside of the main subsidence bowls.

The following sections describe elements for the three model conditions in detail.

5.2 Statistical Model for the No SGMA Condition

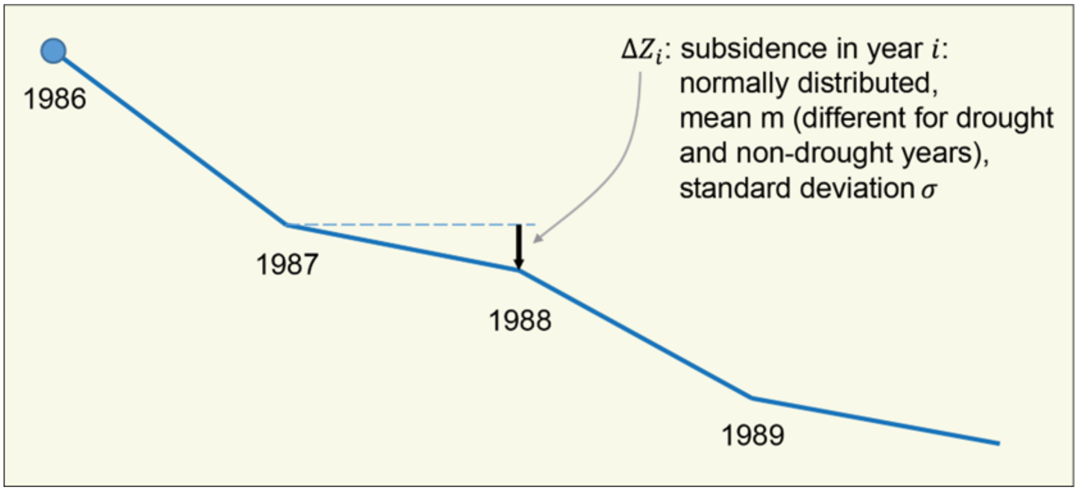
The model for the no SGMA condition was initially developed and explored for MP 160.45, located within the Los Gatos subsidence bowl in the SLFD, and then applied to all locations with sufficient historical-record survey data. The available data for MP 160.45 and other locations include all precise survey data obtained between the years 1986 to 2021, which encompass the 2012-2016 severe-drought period discussed earlier. Survey data were not available for every year within that period. There were intervals of up to seven years during which data were unavailable. In addition, the pattern of data availability was not the same for all locations. The typical number of survey measurements at each milepost was 12.

Data from years prior to 1986 are not included in the model because they represent periods of time in which groundwater levels were rapidly recovering after the Aqueduct came into service (i.e., approximately 1967-1975), and many successive years during which CVP and SWP deliveries were approximately 100% of contract value (approximately 1977-1989 in the SLFD; Figure 3-9). The TI Group assessed that these conditions are not likely to occur again over the CASP planning horizon that the forecast model is intended to simulate. Additionally, the most recent approximately three decades have been characterized by a significant expansion of permanent crops in the San Joaquin Valley, leading to development of "demand hardening" conditions for groundwater use that largely did not exist prior to the mid-1980's (DWR, 2019). For these reasons, the TI Group assessed the survey data from 1986-2021 to be most representative of current and potential future land use conditions for use in the forecast model.

The statistical model adopted by the TI Group is a "random-walk" model (Figure 5-2), in which the subsidence increment Z_i in year i is a normal random variable where the mean (i.e., the mean annual subsidence rate) is different for drought and non-drought years, and the standard deviation (common for drought and non-drought years) takes a value σ.

The mean annual subsidence rate is much higher for drought than for non-drought years. This model is the simplest possible model that is consistent with the data. More complex alternatives, which would have different standard deviations for drought or non-drought years, or assume a correlation between the Z_i residuals in subsequent years, were evaluated using the Akaike Information Criterion (AIC; Akaike, 1974) and rejected. The AIC criterion balances the goodness of fit (which is measured by a high value of the likelihood function of the fitted model) against the number of parameters in the model. A model with many parameters will almost always yield a higher likelihood, but this may lead to overfitting, which is undesirable. A larger number of parameters in a statistical model usually leads to higher statistical uncertainty in the parameters (given the same data set), which reduces the model's predictive value for future occurrences. As a limiting case, a statistical model in which the number of parameters is the same as the number of observations may fit the data perfectly, but it has no predictive value. As mentioned earlier, the typical number of survey measurements at each location was 12. Furthermore, at most three measurements correspond to years severe drought.

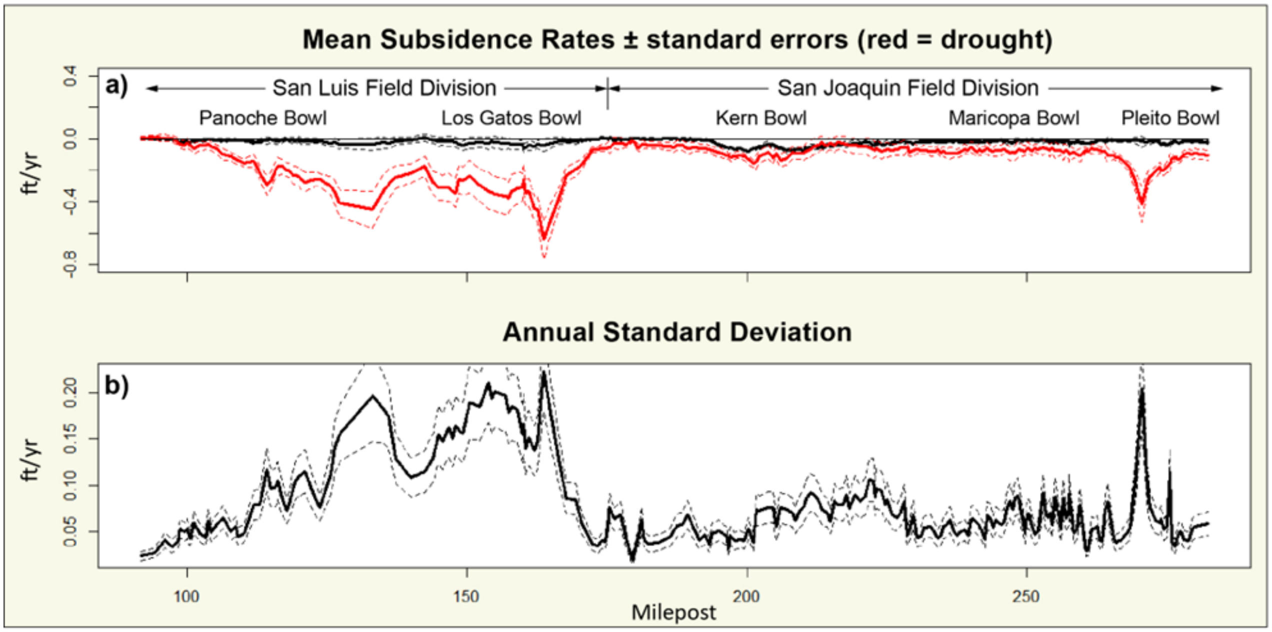
Figure 5-2. Stochastic random walk model used to generate artificial time histories (“realizations”) of future subsidence. Total subsidence for a given realization is the cumulation of i annual subsidence increments, each selected randomly from a normal distribution with mean m and standard deviation s. Different values of the mean m are defined for “severe drought” and “non-drought” years



The choice of a normal distribution shape is also made for simplicity, as the sample size at each milepost is insufficient for the investigation of the distribution shape. A shape other than normal could have been chosen based on physical arguments, but this was not done for this project. This choice of distribution shape has a negligible effect on the final results, because the purpose of this model is to forecast the probability distribution of cumulative subsidence after many years. As predicted by the Central Limit Theorem, the sum of many independent random quantities with finite mean and standard deviation will approach a normal distribution, regardless of the underlying distribution of the individual quantities being summed. Another advantage of assuming a normal distribution is that it simplifies the treatment of missing observations because the sum of multiple normally distributed annual subsidence increments is also normal. The three parameters in the random-walk model described above (and their uncertainties) are calculated using the maximum likelihood method. This is done using numerical optimization, although a closed-form solution was also obtained and used as verification.

Figure 5-3 shows the random-walk parameters calculated for all mileposts; namely, the calculated mean annual subsidence rates (upper plot) for drought (red) and non-drought (black) years, and the standard deviation σ (lower plot) for all locations considered. Only locations with survey measurements in 1986 (the starting year for the analysis) and with two or more survey measurements during the 2012-2016 drought were considered. The dashed lines indicate the ± 1 standard error range (i.e., the statistical uncertainty, or how well the parameter is known given the data) for each estimate. This figure shows that the mean subsidence rate is much higher for drought than for non-drought years throughout both the SLFD and SJFD. The standard errors have a negligible effect on the results because they are much smaller than the standard deviation σ.

Figure 5-3. Statistical parameters for the No SGMA stochastic model, as derived from precise land survey data from mileposts along the Aqueduct in the SLFD and SJFD, from 1986-2021



To simulate a future subsidence history with this random-walk model, it is necessary to also simulate the possible future occurrence and duration of severe droughts (similar in severity to the 2012-2016 drought) during the 2023-2080 time period. The DWR Climate Group developed these inputs using a "decision scaling" approach. The Climate Group utilized CalLite 3.0 modeling results for the SWP/CVP, using: 1) paleo-reconstructed river flows representing more than a millennium of interannual climate variability; 2) traces of monthly inflows representative of current climate conditions (1950-2012); and 3) incrementally perturbed climates of average annual temperature (+0°C to +4°C) and precipitation (-20% to +30%). Results for year t are obtained as the average of results during the 30 years centered on year t, weighted by their agreement with the Global-Climate Model projections for that time period.

The Climate Group noted that the range of possible warming projected by climate models for 2080 extends beyond the maximum +4ºC warming that has been used for CalLite simulations to date. Consequently, the magnitude of potential change represented by the updated parameters (based on existing CalLite simulations of +4ºC or less) may underestimate the true range near the 2080 CASP planning horizon. The Climate Group also reiterated their concerns about the divergence of the various climate scenarios near the end of the projected period. The TIG and Climate Group agreed that the current delivery deficit parameters provide a sufficient representation of uncertainty for the intended use of the subsidence forecast model, given the substantial uncertainties about land use, enforcement of SGMA, operation of the State Water Project, etc., beyond about 2040 that are only implicitly addressed in the model at present.

To generate the inputs required for the random walk model, the DWR Climate Group defined a severe drought as a period of four years or more during which the exports from the Jones pumping plant to CVP SOD agricultural water contractors are less than 2,102 TAF per year; i.e., a drought with associated delivery deficits comparable to those during the 2012-2016 drought (see Figures 3-8 and 3-10). The Climate Group selected data from Jones pumping plant to parameterize future severe droughts for several reasons: 1) the correlations in Figure 3-9 among subsidence rate in the SLFD, exports to CVP contractors from Jones pumping plant, and occurrence of drought; 2) the assumption that "severe export deficits" from Jones to CVP contractors are a reasonable proxy for "severe droughts" that reduce surface water availability for the entire state; and 3) the fact that the Climate Group has the computational tools to estimate the frequency and duration of future "severe export deficits" at Jones under different climate scenarios using CalLite simulations.

The annual rate λ and mean duration $\bar{T}$ of severe droughts were calculated for each climate condition simulated in CalLite for the 1,100-year paleo-informed record. The climate-change-condition-specific drought parameters were then calculated as a function of time (Figures 5-4 and 5-5) by weighted averaging according to projected changes in temperature and precipitation of global climate models for each future 30-year period (stepping forward one year at a time). They also fit a distribution shape for the drought duration (also called mean deficit length) T, such that the quantity $T - 4$ has a discrete Boltzmann distribution. The TI Group simplified this distribution to a geometric distribution (see Benjamin and Cornell, 1971), whose only parameter is the mean drought duration. The geometric and Boltzmann distributions differ because the latter has a truncated upper tail.

Figure 5-4. Forecasted annual rate of drought periods through 2080 (courtesy of DWR Climate Group). See text for discussion.

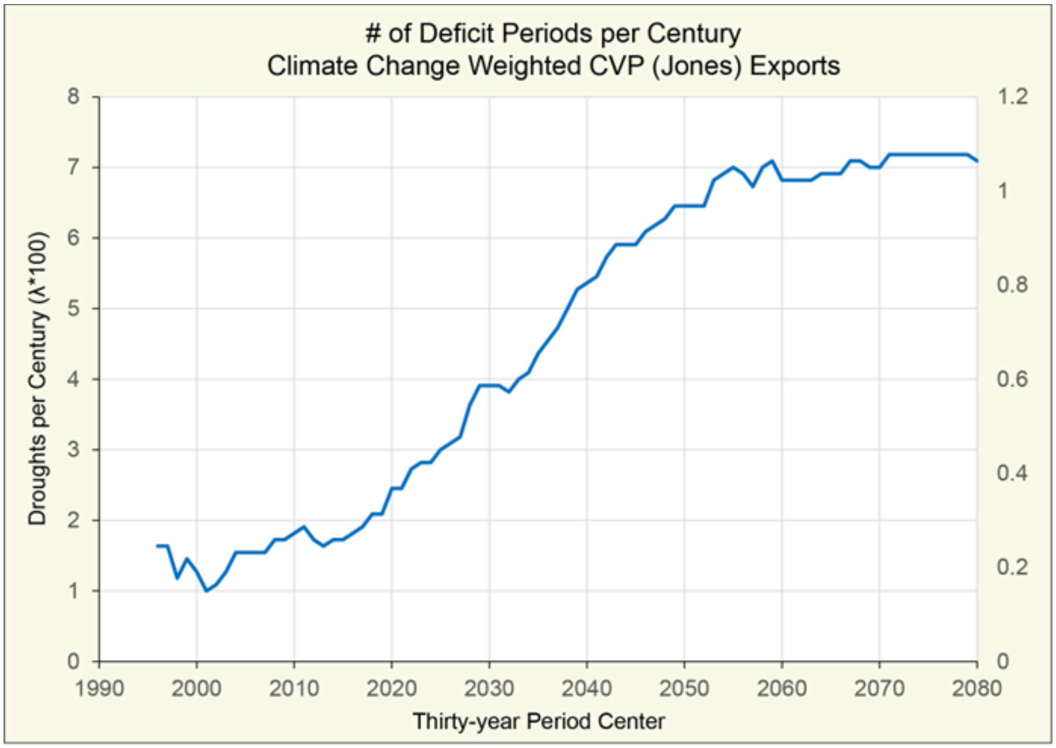
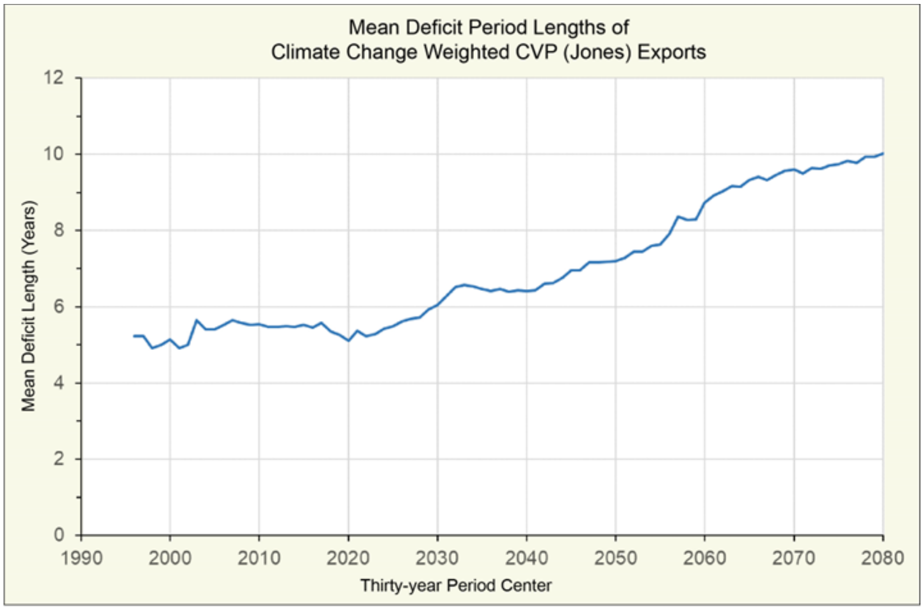


Figure 5-5. Forecasted duration of drought periods as a function of time through 2080 (courtesy of DWR Climate Group). See text for discussion



To represent the range of possible subsidence histories during the period of no-SGMA implementation, the TI Group simulated many future realizations of the subsidence history. The steps to generate each realization for each location are described below (and shown diagrammatically in Figure 5-6):

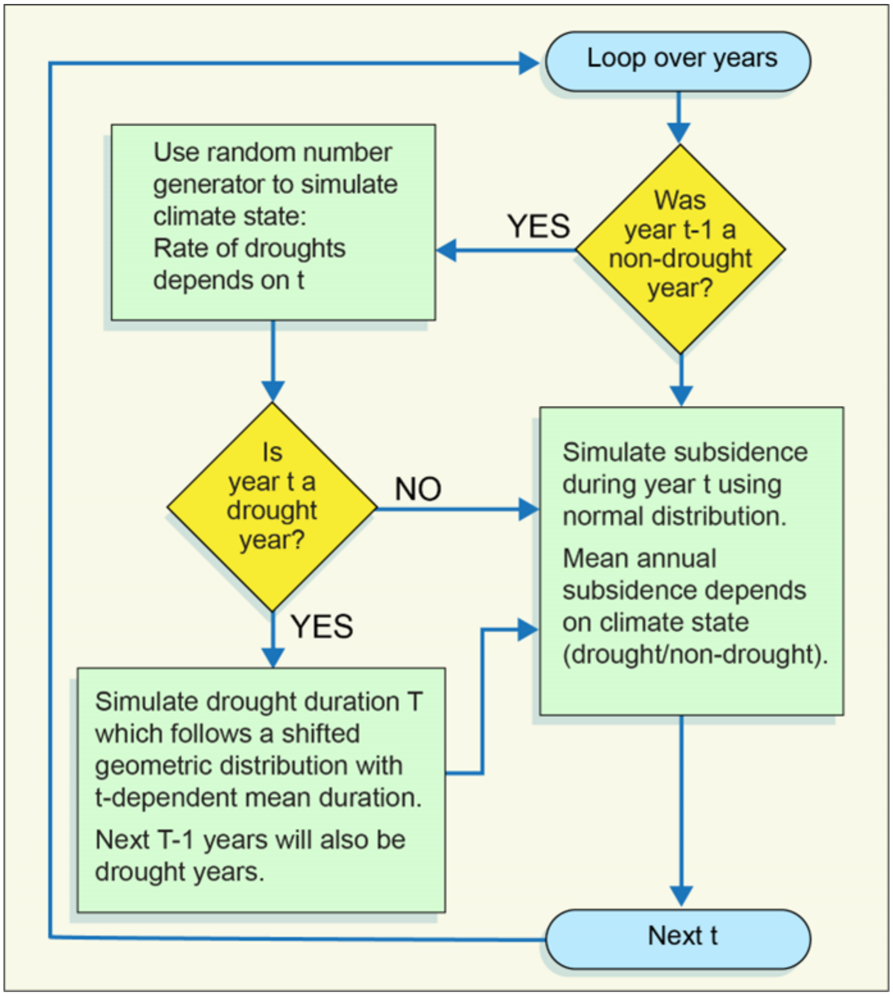
Loop over years t between 2023 and 2080.

- Simulate climate state for year t. If year t is not the continuation of a severe drought, then it has probability $\lambda/(1+\lambda\bar{T})$ of being the beginning of a multi-year severe drought. Use a uniform random-number generator: if the random number is smaller than $\lambda/(1+\lambda\bar{T})$, then year t is the beginning of a severe drought. If so, then also simulate the duration of this drought (4-year shifted geometric distribution, with mean value $\bar{T}$) using a random-number generator. Both the rate λ and the mean duration $\bar{T}$ increase with time due to climate change (per Figures 5-4 and 5-5).

- Simulate subsidence for year t using a normal random-number generator. The mean of the year-t subsidence depends on the climate state (drought vs. non-drought), but the standard deviation is the same. The means and the standard deviation are for each location correspond to the historic data available at that location (see upper plot of Figure 5-3).

These calculations are performed separately for each location, without any assumption about spatial dependence or independence between annual subsidence increments in neighboring locations. The anticipated future use of the subsidence forecast results for hydraulic analysis of the Aqueduct (i.e., working with percentile subsidence profiles of lining elevation) implies perfect probabilistic dependence of subsidence among locations. The assumption of perfect correlation is a reasonable one because the common logic-tree branches and the common climate forcing introduce strong correlation in subsidence. In addition, a joint statistical analysis of the historical subsidence residuals at all locations (not documented in this report) shows a strong within-bowl correlation and significant overall correlation, which are attributed to similar within-bowl pumping patterns and geology. Consideration of partial correlation would introduce significant complexity to the hydraulic analysis, requiring hydraulic calculations for a much larger number of subsidence profiles.

Figure 5-6. Flow chart showing analytical steps in the stochastic model for the No SGMA condition



5.4 Partial SGMA Implementation Condition

5.3.1 Basin-Wide Onset and Duration of Partial SGMA Implementation Condition

The dates for onset of Transitional Pumping (Ttp) and No Overdraft (Tno) determine the time and duration of the Partial SGMA Implementation condition in the probabilistic model (Figure 5-1). These dates are unknown and highly uncertain, and thus are treated as epistemic variables. Working primarily in 2021, the TI Group developed probability distributions for Ttp and Tno through the following process:

1) In SSHAC meetings 1 through 5, the TI Group reviewed available data and expert opinion on implementation of SGMA. In particular, the TI Group reviewed and discussed interviews conducted with 14 resource and proponent experts on topics relevant to implementation of SGMA. These interviews were conducted prior to the initiation of the SSHAC study. See Appendix B of this report for interview notes and documentation of the process.

2) Drawing on information obtained from technical literature and the expert interviews from 2020, members of the TI Group independently developed strawman probability distributions to represent their assessment of the range of expert and stakeholder opinion for Ttp and Tno.

3) During SSHAC meeting 6, the TIG members presented their individual strawman Ttp and Tno distributions for discussion and debate among the entire group. The following key issues were raised in this discussion:

    - Several TIG members placed higher weight on Partial SGMA Implementation beginning in the 2030-2040 decade than in the 2020-2030 decade, citing comments in the expert interviews that the magnitude of land use changes required to reduce groundwater pumping likely works against rapid implementation of SGMA. As noted by some experts in the interviews, many of the first-round draft GSPs submitted to the state for review focus on “supply-side” approaches for obtaining additional surface water rather than “demand-side” issues that contribute to groundwater overdraft. The TIG interpreted this focus to indicate that developing and implementing pumping reductions will not happen rapidly.

    - Several TIG members placed a combined weight of 16% or higher on Transitional Pumping beginning after 2040 to represent the possibility that SGMA implementation may be delayed by litigation or a repeat of the 2012-2016 drought, as noted in several expert interviews. An alternative view (reflected in no weight given to Partial Implementation after 2040) is that if Transitional Pumping does not at least begin by 2040 as mandated by SGMA, then the law may never be implemented or enforced as currently codified.

- All TIG members placed significant combined weight on Cessation of Overdraft beginning after 2040, consistent with opinion of several interviewed experts that there is a 20%-30% or greater likelihood that groundwater overdraft will not be eliminated basin-wide by 2040. TIG members noted that a transitional "ramp down" in pumping rate begun late in the 2030-2040 decade could extend into the 2040 decade; that a repeat of a 2012-2016-type drought may result in delay in reaching a No Overdraft condition until after 2040; and that litigation could halt or slow implementation of SGMA.

- Most TIG members assigned progressive decreases in weight to Cessation of Overdraft beginning in succeeding decades from 2040 and beyond. One TIG member assigned progressively increasing weights to succeeding decades to reflect a proponent view that implementing and enforcing SGMA may be more difficult than for previous statewide water initiatives that ultimately failed or fell short in meeting their policy objectives.

- The TIG discussed the possibility of self-policing among GSA members to enforce SGMA and prevent groundwater overdraft and "undesirable consequences" such as damage to the California Aqueduct from occurring after 2040. Although litigation is a potential tool that state water contractors could use against individual growers who may be causing subsidence-related damage to the Aqueduct by local groundwater pumping, the TIG assumed that the SGMA law itself will probably not facilitate this.

- The TIG noted that in most cases the questions posed to experts in the interviews (Appendix B) addressed SGMA implementation very generally, with no questions about when groundwater pumping reductions would begin in specific sub-basins. Several experts indicated their belief that most land fallowing to reduce groundwater use will occur in the southern San Joaquin Valley (Kern and Tulare basins), and hence these areas may be among the last to come into balance, but the experts did not cite specific GSPs in support of this view. The TIG concluded that expert opinion expressed in the interviews should be viewed as applying generally to the entire San Joaquin Valley groundwater basin.

4) The individual TIG weighting scenarios for the San Joaquin Valley basin were aggregated and discussed again during SSHAC meeting 7, at which time the TIG developed marginal distributions for Ttp and Tno that reflected a consensus assessment of the community distribution of expert and stakeholder opinion on basin-wide timing of Partial SGMA Implementation and Cessation of Overdraft (blue bars in Figure 5-7). Key points that emerged in the discussion include:

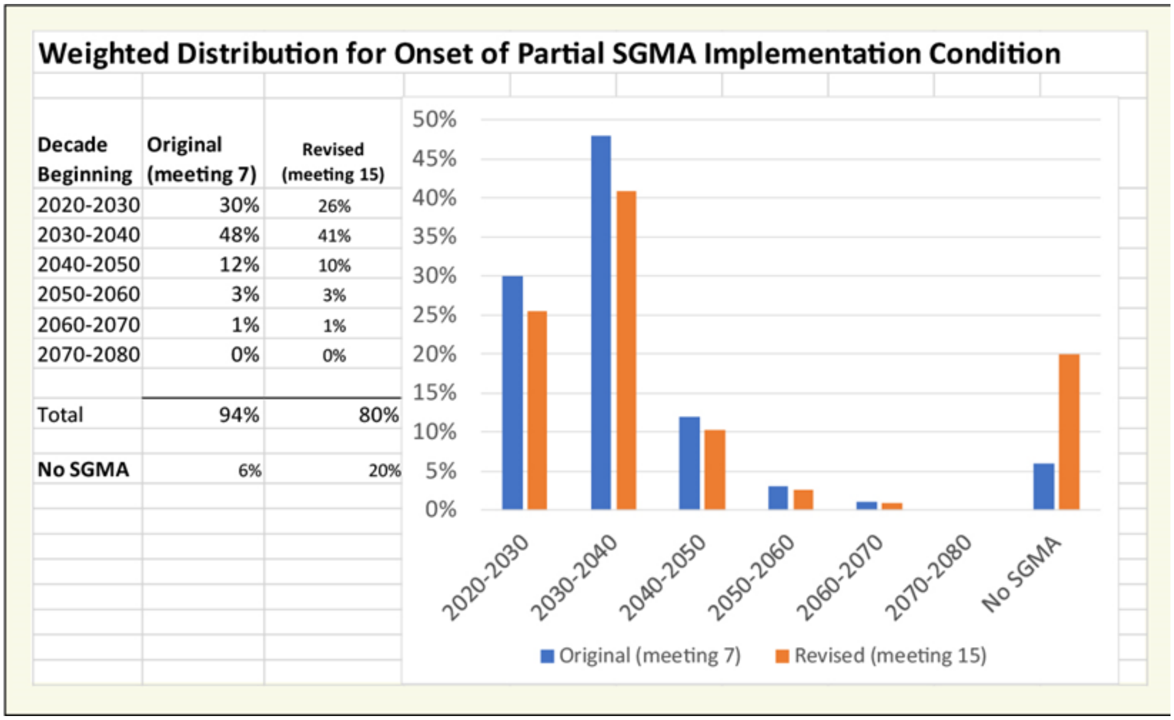
   - The marginal distribution of decadal weights for onset of Partial SGMA Implementation (Ttp) aligns with expert opinion that although GSAs will likely begin taking management actions to comply with SGMA by 2040, implementation will be slow (i.e., more likely to occur in the 2030 decade than in the 2020 decade). The TIG assigned a cumulative weight of 16% to the possibly that Ttp will occur during the 2040 decade or later due to recurring drought, infrastructure failure, litigation, legislative action and/or regulatory failure. The TIG assigned a low weight (6%) to the scenario where the No SGMA condition continues after 2070 to represent minority expert opinion that the law could be effectively challenged in court and never implemented.

- The consensus distribution for Cessation of Overdraft placed the highest weight on the 2030 decade, consistent with the preponderance of expert opinion in the CASP interviews is that GSAs would generally be in balance, or close to balance, by 2040. The cumulative 34% weight given to the Cessation of Overdraft occurring in the 2040 and later decades reflects the opinion of some experts that it may take 10-15 years after 2040 to reach Cessation of Overdraft. The weights assigned to the 2050 and 2060 decades (4% and 2%, respectively) are intended to represent minority expert opinion that litigation could delay implementation of SGMA for 10-30 years.

5) After further discussion during SSHAC meeting 15, the TI Group concluded that higher weight should be given to the No SGMA condition to represent new information that was not available to the 2020 expert interviewees. Specifically, the CASP interviewees were not aware of modeling by the DWR Climate Group (discussed in Section 5.2) that suggests drought conditions and associated delivery deficits similar those in 2012-2016 may occur approximately 60% of the time by the year 2070, and they were not asked to consider what effect this could have on implementation of and compliance with SGMA. The TI Group believes that this information significantly increases uncertainty about the timing and efficacy of SGMA implementation prior to the 2040 legislative deadline, and about behavioral responses to the modeled increase in the frequency and duration of severe droughts after 2040. Given these considerations, the TI Group increased the weight given to the No SGMA condition in a basin-wide forecast model from 6% to 20%. The weights that were specified earlier for the 2020-2070 bins in the distributions of Ttp and Tno were reduced in an approximately proportional manner, as shown by the red bars in Figure 5-7.

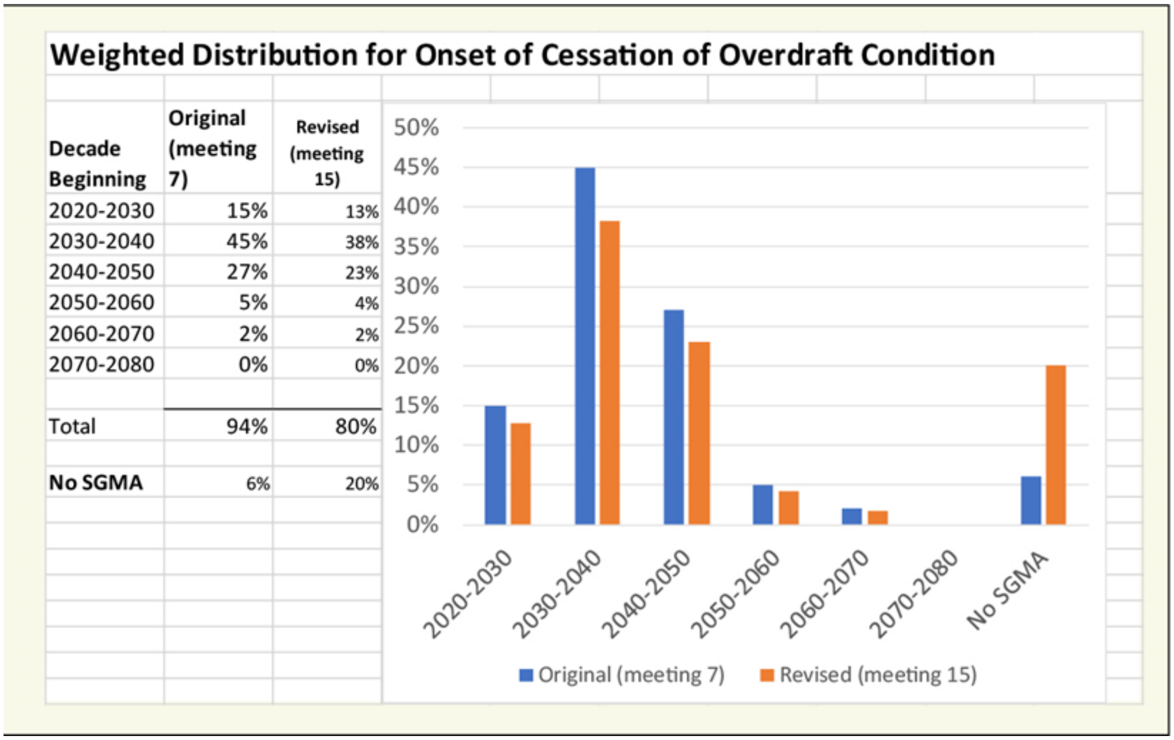
Although the marginal distributions in Figure 5-7 represent the TI Group's consensus assessment in late 2021 of the CBR of expert opinion for Ttp and Tno, the distributions cannot be implemented directly in the probabilistic model. Specifically, the two marginal distributions are not fully independent because Tno could occur prior to Ttp in some instances if both are chosen at random from their respective distributions. For use in the probabilistic model, it was necessary to have their joint distribution, which can also be written as the product of the marginal distribution of Ttp and the conditional distribution of Tno given Ttp. The process to generate a joint distribution of Ttp and Tno generally requires the modification of one or both distributions and the imposition of additional conditions (Tno≥Ttp, unimodality of conditional distributions, etc.). The TI Group reasoned that Ttp was more fully explicated in the expert interviews than Tno, and thus the TI Group decided to keep the consensus distributions for Ttp unchanged and modify the distribution of Tno as needed to satisfy the requirements for a joint distribution (the required modifications were small). Dr. Gabriel Toro, TI Group Analyst, prepared revised conditional distributions of Tno (Figure 5-8), which were reviewed and approved by the TI Group.

Figure 5-7. Distributions developed by the TI Group for Ttp and Tno. Original consensus marginal distributions developed in SSHAC meeting 7 are indictated by blue bars. Subsequent TI Group revisions developed in SSHAC meeting 15 to represent additional uncertainty in SGMA implementation associated with potential future drought conditions are represented by the orange bars



Weighted Distribution for Onset of Partial SGMA Implementation Condition

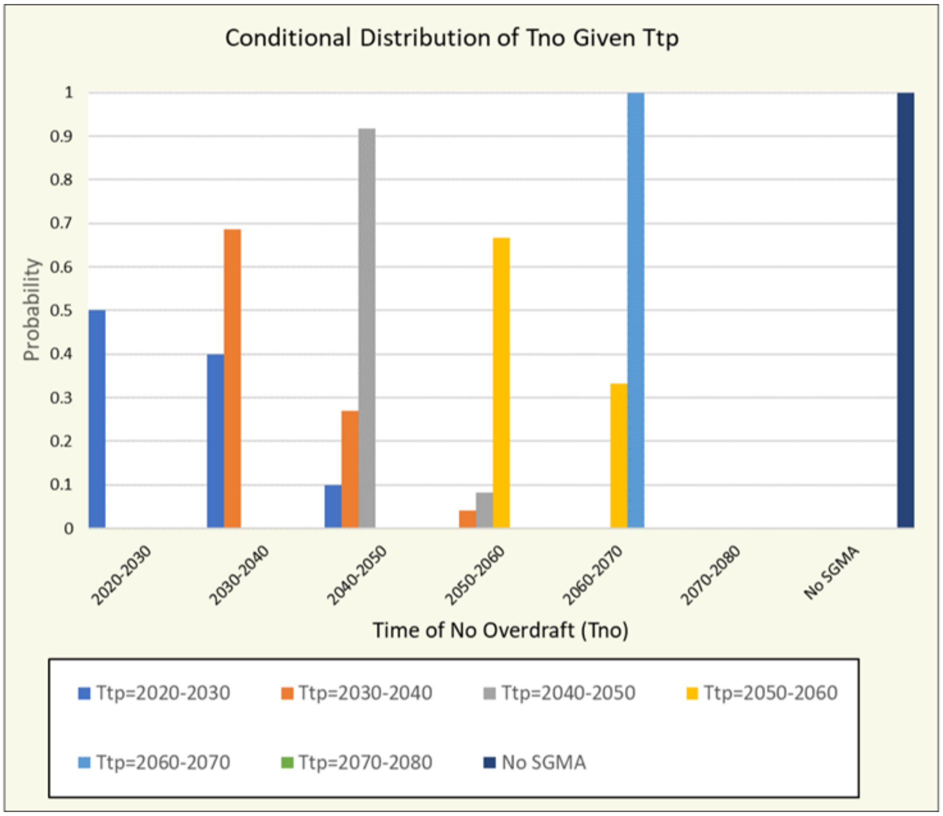
Decade Beginning	Original (meeting 7)	Revised (meeting 15)
2020-2030	30%	26%
2030-2040	48%	41%
2040-2050	12%	10%
2050-2060	3%	3%
2060-2070	1%	1%
2070-2080	0%	0%
Total	94%	80%
No SGMA	6%	20%



Weighted Distribution for Onset of Cessation of Overdraft Condition

Decade Beginning	Original (meeting 7)	Revised (meeting 15)
2020-2030	15%	13%
2030-2040	45%	38%
2040-2050	27%	23%
2050-2060	5%	4%
2060-2070	2%	2%
2070-2080	0%	0%
Total	94%	80%
No SGMA	6%	20%

Figure 5-8. Conditional distributions for Tno given Ttp, Basin-Wide scenario. Bars of the same color indicate the probability distribution of Tno for a given Ttp



5.3.2 Onset and Duration of Partial SGMA Implementation Condition, Westside Sub-Basin

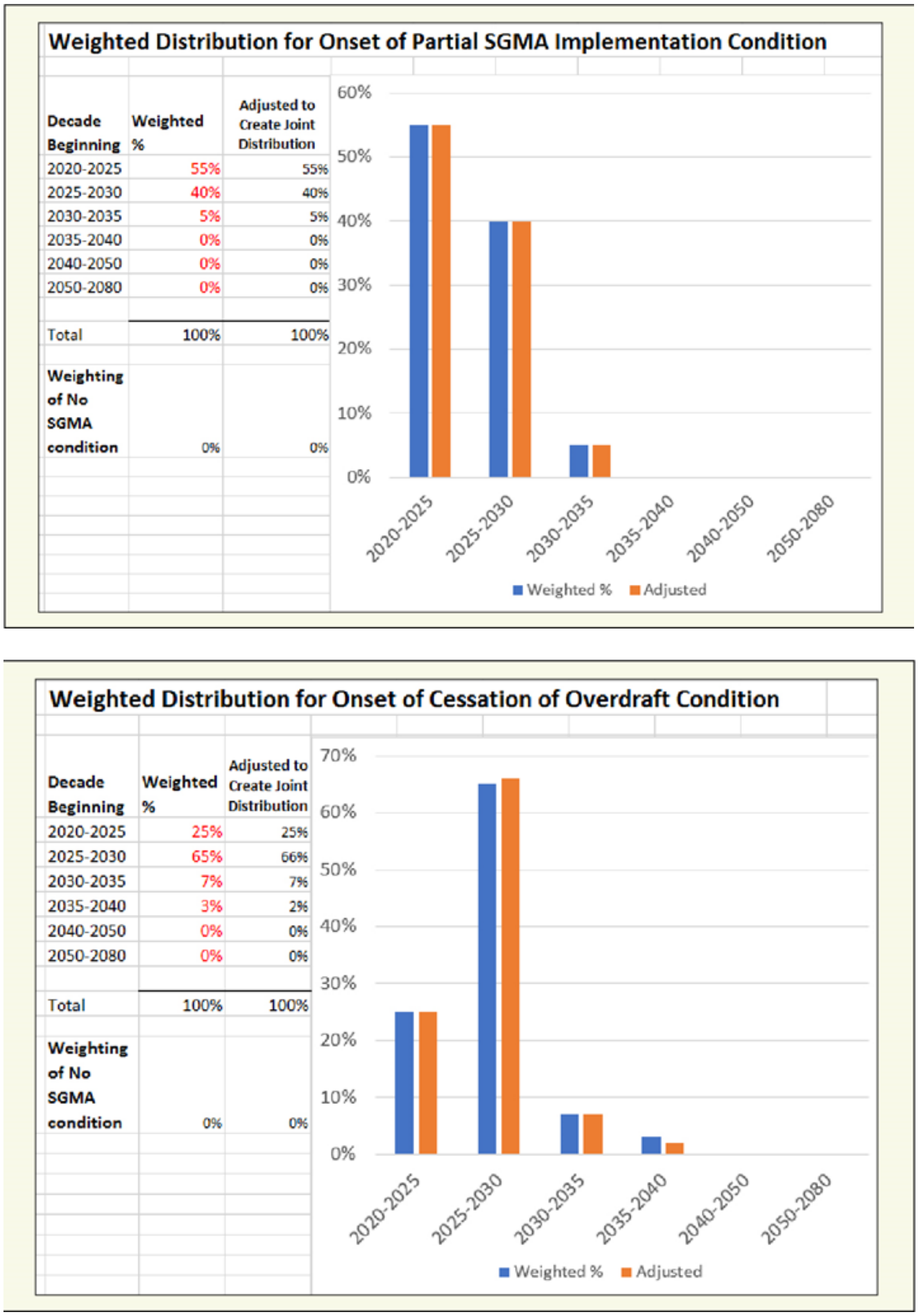
During SSHAC meeting 7, the TI Group also considered developing separate distributions for Ttp and Tno specific to the Westside basin. The TI Group noted that reaches of the Aqueduct in the SLFD that are significantly impacted by subsidence are entirely within the Westlands water district (Luhdorff and Scalmanini, 2018) and will be potentially affected by management actions described in the 2020 draft Westside GSP. Specifically, the draft Westside GSP (Luhdorff and Scalmanini, 2020) proposes a ramp-down schedule for groundwater pumping that is envisioned to bring the entire sub-basin into sustainability by 2040. The draft GSP further provides a schedule for meeting its sustainability targets, with groundwater elevations being the key measurable objectives. The draft Westside GSP sets objectives for groundwater elevations in the deep aquifer proximal to the Aqueduct to steadily increase above 2015 elevations over the next 20 years. If implemented, this will result in Transitional Pumping near the Aqueduct effectively beginning by 2025. According to the draft GSP, groundwater elevations near the Aqueduct will progressively increase between about 15-47 ft above 2015 levels between 2025 and 2040. In terms of the anticipated physical response of the deep aquifer, the planned rise of water elevations would likely result in a relatively rapid transition to a Cessation of Overdraft condition proximal to the Aqueduct.

The TI Group discussed and adopted consensus marginal distributions for Ttp and Tno that assume the management actions described in the Westside GSP are fully and successfully implemented. For convenience, these distributions are referred to as the "Westside scenario", to be distinguished from the distributions for the "Basin-wide scenario" described in Section 5.3.1. Consensus marginal distributions for the Westside scenario are presented in Figure 5-9. The Westside distributions are represented by five-year bins instead of the 10-year bins for the basin-wide scenario in Figures 5-7 and 5-8 because the Westside GSP presents measurable objectives at five-year benchmarks. Key points in the TI Group discussion included:

6) The TI Group placed a total of 95% weight on transitional pumping (Ttp) beginning by 2030. Although the management actions described in the draft GSP suggest that transitional pumping will begin almost immediately (i.e., on or before 2025), the TI Group assigned 40% weight to transitional pumping beginning between 2025-2030, and 5% weight to 2030-2035, to reflect its uncertainty in how rapidly the plan will be implemented and whether it will be delayed by the dry 2021 water year, possible infrastructure failures, or management actions taken by neighboring GSAs.

7) The TI Group assigned a total of 90% weight to Cessation of Overdraft beginning by 2030 to reflect its belief that induced subsidence will rapidly cease if water levels are allowed to rise over the next decade as stated in the GSP. The TI Group assigned majority weight (65%) to 2025-2030, with a total of 10% assigned to the 2030-2040 decade to reflect uncertainty about future conditions that could delay full implementation of the GSP, including unknown effects of planned groundwater elevation reductions elsewhere within the sub-basin between now and about 2035. For example, the draft Westside GSP (2020) states that proprietary groundwater modeling indicates the maximum lateral extent of subsidence from pumping at a point is about one mile; however, as discussed in SSHAC meeting 3, InSAR data show that the 2012-2016 subsidence anomaly at MP 163 has a maximum diameter of about 3.25 miles. The TI Group concluded that there is significant uncertainty in the dimensions of the proximate zone of pumping influence.

Figure 5-9. Consensus marginal distributions of Ttp and Tno for the Westside-specific model



Weighted Distribution for Onset of Partial SGMA Implementation Condition

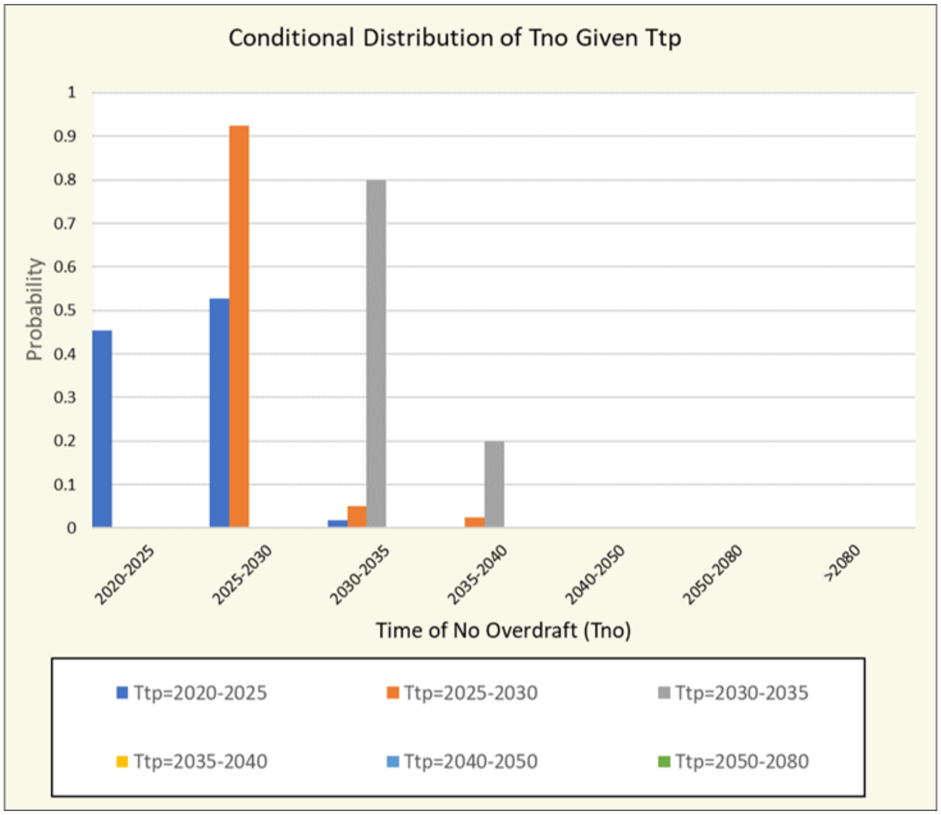
Decade Beginning	Weighted %	Adjusted to Create Joint Distribution
2020-2025	55%	55%
2025-2030	40%	40%
2030-2035	5%	5%
2035-2040	0%	0%
2040-2050	0%	0%
2050-2080	0%	0%
Total	100%	100%
Weighting of No SGMA condition	0%	0%

Weighted Distribution for Onset of Cessation of Overdraft Condition

Decade Beginning	Weighted %	Adjusted to Create Joint Distribution
2020-2025	25%	25%
2025-2030	65%	66%
2030-2035	7%	7%
2035-2040	3%	2%
2040-2050	0%	0%
2050-2080	0%	0%
Total	100%	100%
Weighting of No SGMA condition	0%	0%

Following the same approach for developing the Basin-wide distributions of Ttp and Tno (Figures 5-7 and 5-8), the marginal Westside distributions for Ttp and Tno were used by the TI Group to construct joint and conditional distributions, as required for the model simulations. Again, the marginal distribution of Ttp (blue bars, Figure 5-9) was unchanged and the marginal distribution of Tno was changed slightly (orange bars, Figure 5-9). Final conditional distributions (Tno given Ttp) for the Westside-specific scenario are presented in Figure 5-10.

Figure 5-10. Conditional distributions for Tno given Ttp, Westside-specific scenario



In addition, the TI Group decided during SSHAC meeting 15 that the 20 percent weight for the No-SGMA condition should apply to both the Basin-Wide and Westside-specific scenarios. The rationale for this decision is the same one employed for the Basin-Wide scenario. This 20 percent No-SGMA condition is represented at a high-level (SGMA/No SGMA) branching in the logic tree of Section 5.5.

5.3.3 Model for the Decline in Subsidence Rate During Partial SGMA Implementation

Subsidence is assumed to decline from historical rates, as represented by the No SGMA condition stochastic model, to the natural geological rate during the period from time between Ttp and Tno. This is achieved in the probabilistic modeling by applying a linear taper to the two mean annual subsidence rates and to the standard deviation. The TI Group considered other forms of tapering (with faster or slower tapering in the first years), but their effects on the results were nearly identical to those of the linear taper. This is not surprising, considering that the mean duration of the partial SGMA implementation period (i.e., the difference between the means of the two distributions in Figures 5-7 and 5-9) is only 4.7 and 2.5 years, respectively, for the Basin-wide and Westside-specific scenarios.

5.4 No Overdraft Condition

Upon cessation of overdraft, the subsidence rate is expected to return to the natural or background geologic rate. This rate has been estimated from long-term average subsidence of the Corcoran clay, and it is on the order of low tenths of mm/yr (DWR, 2019; Section 3.1.1), which the TI Group assessed to be of no engineering significance. The TI Group used a mean value of 0 ft/yr as the subsidence rate for the No Overdraft condition, but it did allow for potential elastic variations (both positive and negative) to occur in the simulations. The standard deviation associated with elastic variations was estimated by examining the standard deviations in Figure 5-3 (bottom) for those locations with very low subsidence rates (absolute value of non-drought subsidence rates of 0.005 ft/yr or less) during 1986-2009, obtaining a σ value of 0.034 ft/yr. The TI Group adopted these parameter values, together with the random walk model, to model uncertainty in land surface elevation due to elastic variations during the No Overdraft condition.

5.5 Logic Tree Branches and Weights

Logic trees are a convenient graphical and computational approach to represent epistemic uncertainties in the probabilistic analysis of an engineering system. Each successive level of the tree (from left to right) represents the possible values of one parameter or modeling assumption. Each parameter value or assumption has an associated weight, which may have been derived by evaluating expert opinion, or by a formal statistical analysis. The sum of weights of all branches attached to any node is unity. When there is dependence between parameters, the weights at a particular level may depend on the branch to the left. Parameters usually take a discrete number of values (which may be the result of discretizing a continuous distribution). Each end branch at the right end of the tree represents one unique set of values for the epistemic uncertainties required for a probabilistic analysis; its associated weight is the product of all the weights of branches followed from the root node to the end branch. The ensemble of results from all end branches, together with the associated weights, represents the distribution of all possible epistemic uncertainties.

Figure 5-11 shows the logic tree for the main quantities with epistemic uncertainty in the CASP subsidence model, as described in Section 5.3. The 20 percent weight assigned to the No SGMA branch that was selected in SSHAC meeting 15 is taken to apply to both the Basin-wide and Westside-specific distributions of Ttp and Tno, and to all locations. Also, note that Westside-specific distribution applies only to the SLFD, so that the logic trees are different for the SLFD and SJFD. The vertical bar in the logic tree indicates different cases that are part of the model, rather than alternatives.

The branches associated with alternative values of Ttp and Tno in the logic tree are shown only in a schematic manner in Figure 5-11 for the sake of clarity. Figures 5-12 and 5-13 illustrate those branches for the Basin-wide and Westside distributions in more detail, but do not show all possible end branches. In Figure 5-12, the probabilities for Ttp are the probabilities appearing in Figure 5-7, after revising them by excluding the 20-percent No SGMA branch (which is represented separately at a high level in the logic tree; Figure 5-11) and normalizing the remaining branch probabilities, so they add to unity. The conditional probabilities shown for Tno given that Ttp=2020-2030 are the corresponding probabilities shown in Figure 5-8. The conditional probabilities for other values of Ttp are not shown for the sake of clarity; their values are shown in Figure 5-8.

Figure 5-11. High-level structure of the logic tree, highlighting major epistemic uncertainties represented in the subsidence forecast model

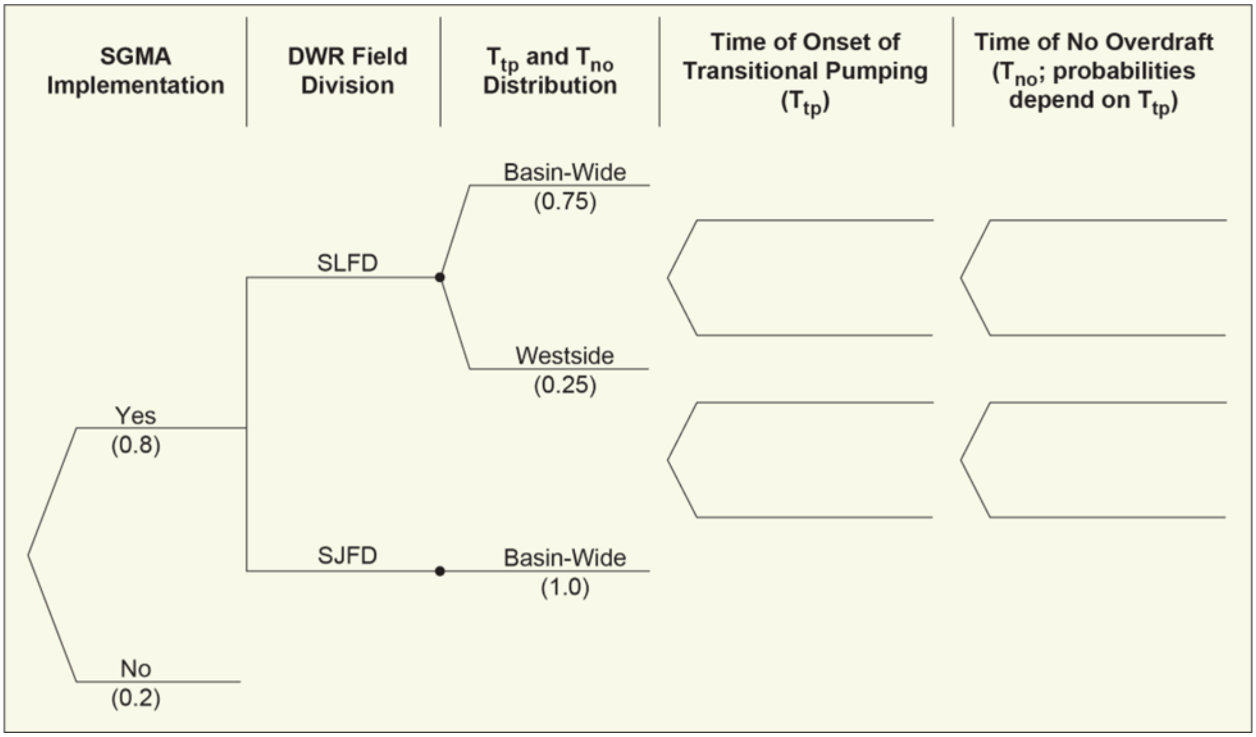


Figure 5-12. Branches and weights for Ttp and Tno, Basin-Wide scenario

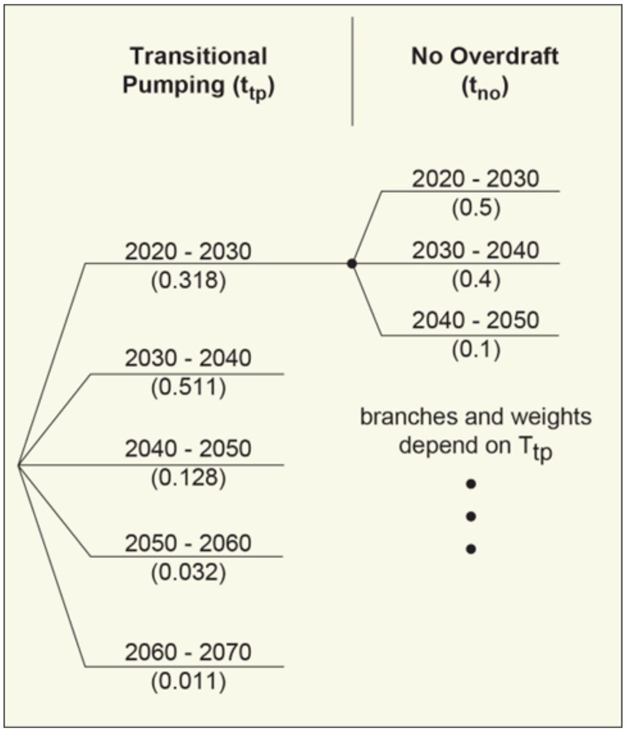
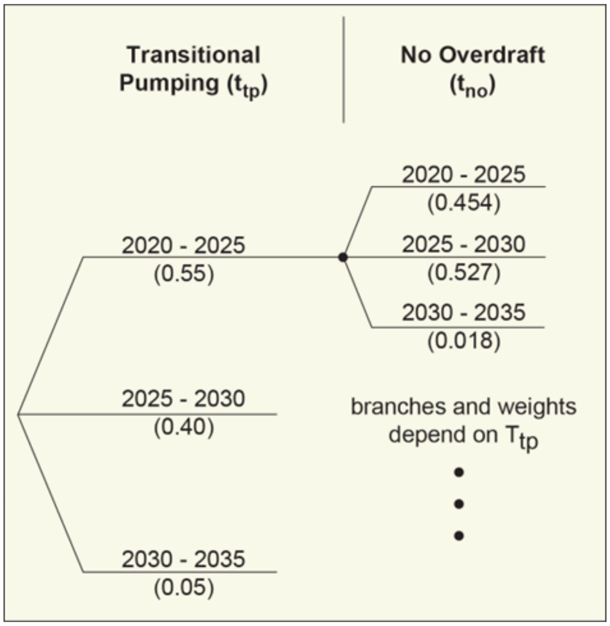


Figure 5-13. Branches and weights for Ttp and Tno, Basin-Wide scenario



Not all epistemic uncertainties are accounted for in the logic tree. Some of the less important ones are accounted for as part of the simulations. Table 5-1 indicates where all epistemic uncertainties are accounted for. Although a strict separation of epistemic and aleatory uncertainties is preferable, it is not essential, especially for the less important contributors to the total epistemic uncertainty.

Table 5-1. Treatment of all epistemic quantities in the probabilistic subsidence model

Epistemic Uncertainty	Treatment
SGMA implementation	Logic tree
Time of onset of transitional pumping (T_{tp})	Time intervals (or bins) are accounted for in logic tree. The time within the bin is accounted for in the simulations (see Figure 5-15)
Time of onset of no overdraft (T_{no})	Time intervals (or bins) are accounted for in logic tree. The time within the bin is accounted for in the simulations (see Figure 5-15)
Mean annual subsidence rate (m, different for drought and non-drought years)	Statistical uncertainty in m accounted for in simulations
Standard deviation of annual subsidence rate (σ)	Statistical uncertainty in σ accounted for in simulations

Figure 5-14 shows a flow chart associated with the epistemic uncertainties in the logic tree. In addition to the uncertainties represented in the logic tree of Figures 5-11 through 5-13, there is uncertainty about the exact years of Tno and Ttp, given that they fall in certain specific time bins or intervals. These uncertainties are considered in the simulations by drawing uniformly distributed values of Ttp and Tno at random from within each corresponding bin, taking care that Ttp≤Tno, even when both quantities fall in the same time bin. The flow chart in Figure 5-15 illustrates this step and all other steps in the simulation of one subsidence history. Figure 5-15 differs from 5-6 in that it includes the simulation of Ttp and Tno described above, and that the parameters of the random walk model vary through the stages of SGMA implementation.

As indicated in Figure 5-14, the number of simulations is 5,000 for each branch of the logic tree. This number is more than enough to obtain stable estimates of percentiles and sensitivity results, considering that the highest percentile of interest is 99%.

Figure 5-14. Flow chart associated with the epistemic uncertainties in the logic tree

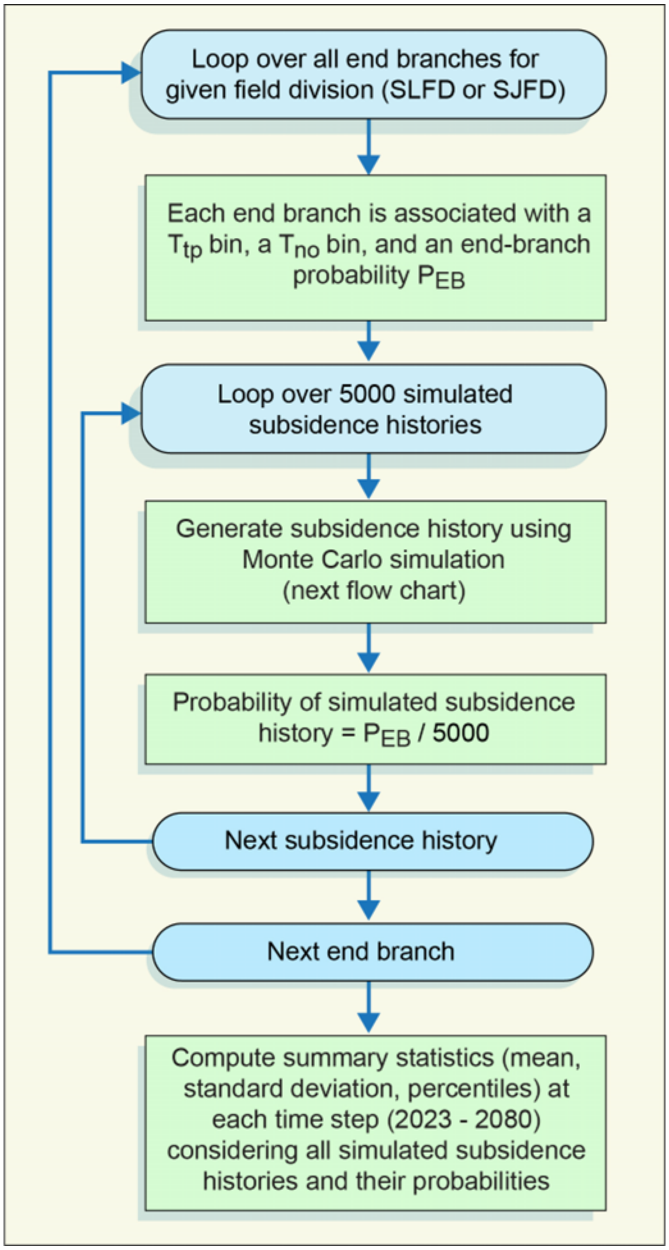
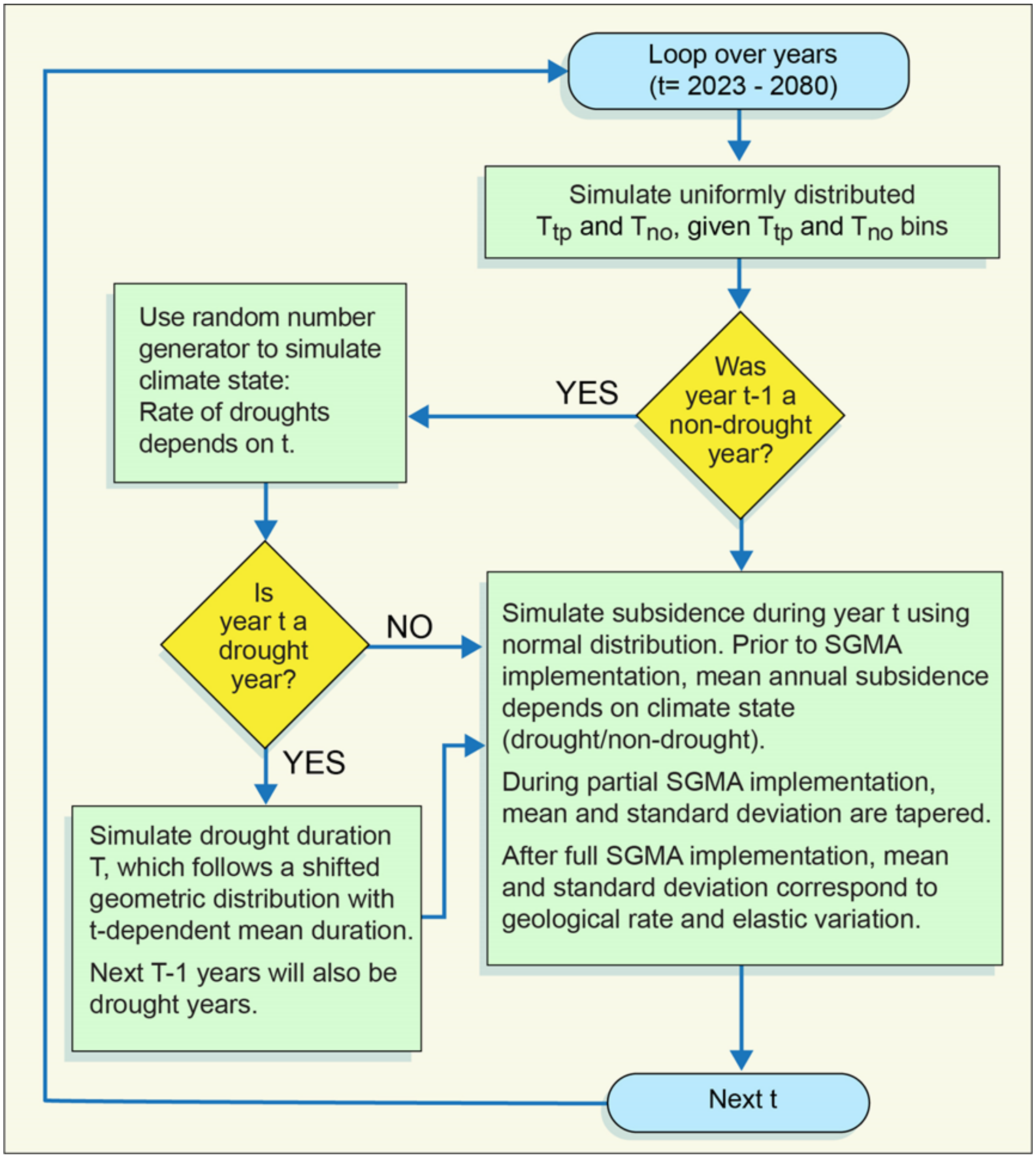


Figure 5-15. Flow chart associated with the epistemic uncertainties in the logic tree



5.6 Chapter References

Akaike, H., 1974, A New Look at the Statistical Model Identification: IEEE Trans. Auton. Contr., 19, p. 716-723.

Department of Water Resources, 2019, *California Aqueduct Subsidence Study: Supplemental Report.*

Luhdorff & Scalmanini, 2018, *Hydrologic Conceptualization Report, Westside Basin*: report prepared for Westlands Water District, 57 p. plus appendices.

Luhdorff & Scalmanini, 2020, *Westside Subbasin Groundwater Sustainability Plan:* report prepared for Westlands Water District.

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6.0 Model Output and Sensitivity

6.1 Subsidence Distributions at Representative Mileposts

Figures 6-1 and 6-2 illustrate the model output (in the form of subsidence percentiles vs. time) at two mileposts, namely MP 160.45 (in the SLFD Los Gatos Bowl) and MP 270 (in the SJFD Pleito Bowl) (see Figure 3-1 for locations of subsidence bowls). These mileposts have some of the highest observed subsidence in the past. These results capture the TI Group's intent in constructing and parameterizing the model. The mean and median curves are initially steep as the past and current practice of pumping groundwater during severe drought years to supplement limited or no distributions from the SWP and CVP continues (i.e., modeling the No SGMA condition). The curves subsequently tend to flatten during partial SGMA implementation. The shape of the higher-percentile curves in the first ten years is controlled by the steepening mentioned earlier and by the $\sqrt{time}$ dependence of the standard deviation of the cumulative subsidence in the random-walk model; later portions of the higher-percentile curves are controlled by the "no SGMA" branch of the logic tree, as will be seen later in the sensitivity results.

Another way to visualize the distribution of subsidence is by plotting the Probability Density Function (or PDF) of subsidence at a specific milepost and a specific year. In contrast to the percentiles shown in Figures 6-1 and 6-2, which show the subsidence associated with a certain non-exceedance probability, the area under the PDF within a certain range of subsidence values shows the probability content within that range. Figures 6-3 and 6-4 show the PDF of subsidence at mileposts 160.45 and 270 (the same mileposts considered in Figures 6-1 and 6-2) and for years 2040, 2060, and 2080. These figures show that the tail of the distribution of subsidence becomes longer at later times, meaning a low but non-zero potential for greater subsidence; however, much of the probability mass remains roughly unchanged and associated with lower subsidence values. This is consistent with Figures 6-1 and 6-2, where the 10th through 70th percentile curves are roughly horizontal, while higher percentile curves have a significant downward slope.

It should be noted that, although the distributions of subsidence were generated using logic trees with discrete branches, the resulting PDF's are essentially unimodal (i.e., they don't have multiple distinct peaks). The reason for this is that the random-walk model and the randomly arriving drought periods introduce significant aleatory uncertainty in the magnitude of subsidence for a given logic-tree branch, which blurs the differences between logic-tree branches.

6.2 Subsidence Forecast Profiles

The main outputs of the CASP subsidence forecast model are longitudinal profiles of additional subsidence (since 2022) at various non-exceedance percentiles along the Aqueduct in the San

Joaquin Valley for specific years. These percentiles account for both aleatory variability (represented by the random climate and the random walk model) and epistemic uncertainties (represented by the logic tree). Additional subsidence profiles are calculated for every year through 2080 and are reported for years 2025, 2030, …, 2075, 2080, and for non-exceedance percentiles of 1, 2, 3, 4, 5, 10, 15, …, 90, 95, 96, 97, 98, 99. Consistent with common engineering practice, the higher percentiles are associated with more severe conditions (i.e., greater subsidence). Means and standard deviations are also reported.

Figures 6-5 through 6-11 show selected forecast percentile subsidence profiles for selected years between 2030 and 2080. These figures show large differences between the central values of the forecast distribution (i.e., mean and 50th percentile) and the upper tails (e.g., 90th percentile), and also reveal significant skewness (i.e., the difference between the 90th and 50th percentiles is greater than the difference between the 50th and 10% percentiles). The skewness is largely caused by the logic tree, and also by droughts. The high-percentile subsidence profiles also show a strong variation along the aqueduct, with the greatest projected future subsidence occurring in the bowls of greatest past subsidence (i.e., the Panoche and Los Gatos bowls in the SLFD; and Kern, Maricopa, and Pleito bowls in the SJFD; see Figures 3-1 and 5-3). The greatest subsidence is projected at the southern portion of the Los Gatos bowl, at milepost 163.69.

Figures 6-12 through 6-14 present the same results, but showing the increases in mean, 50th and 90th percentiles over time.

Figure 6-1. Sample output of the model for MP160.45 in the San Luis Field Division

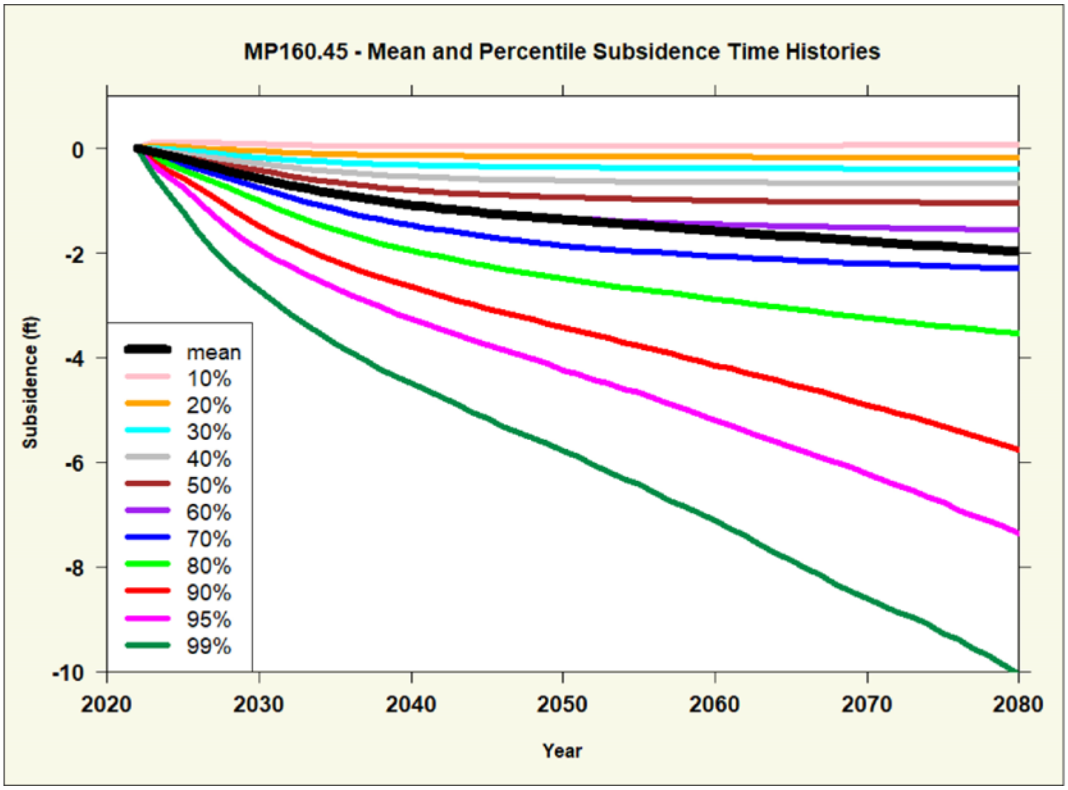


Figure 6-2. Sample output of the model for MP160.45 in the San Luis Field Division

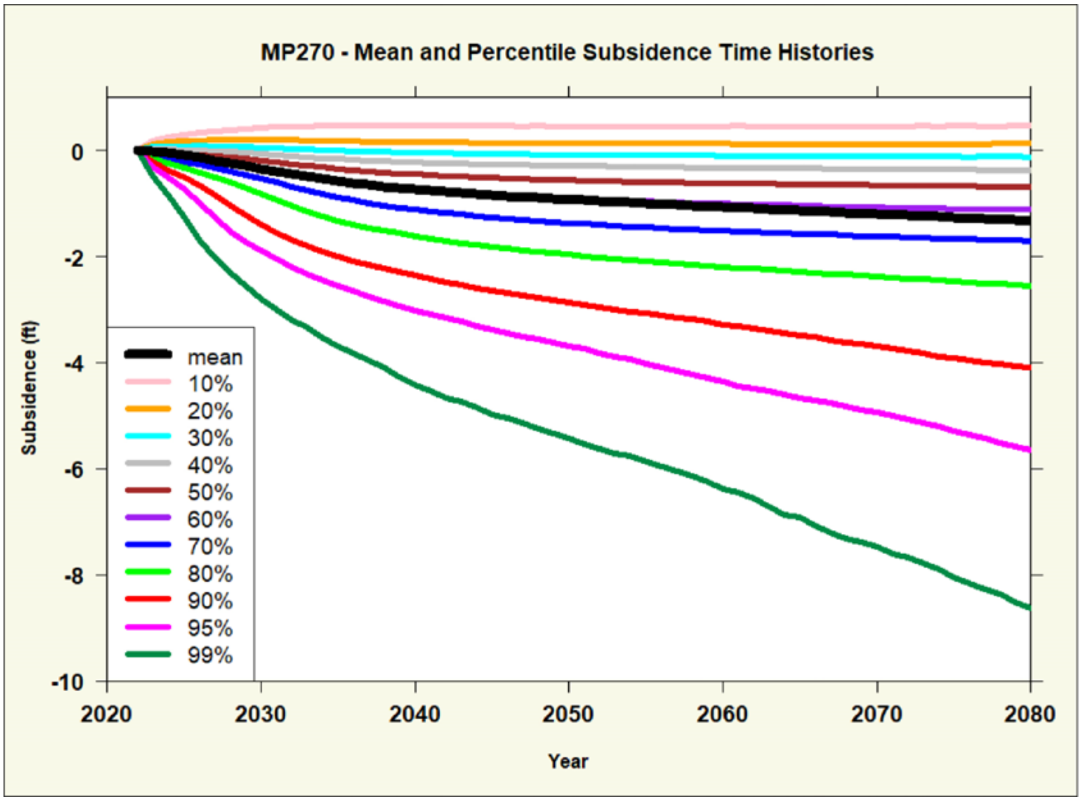


Figure 6-3. Probability density functions of subsidence for MP160.45 in the San Luis Field Division at three different times

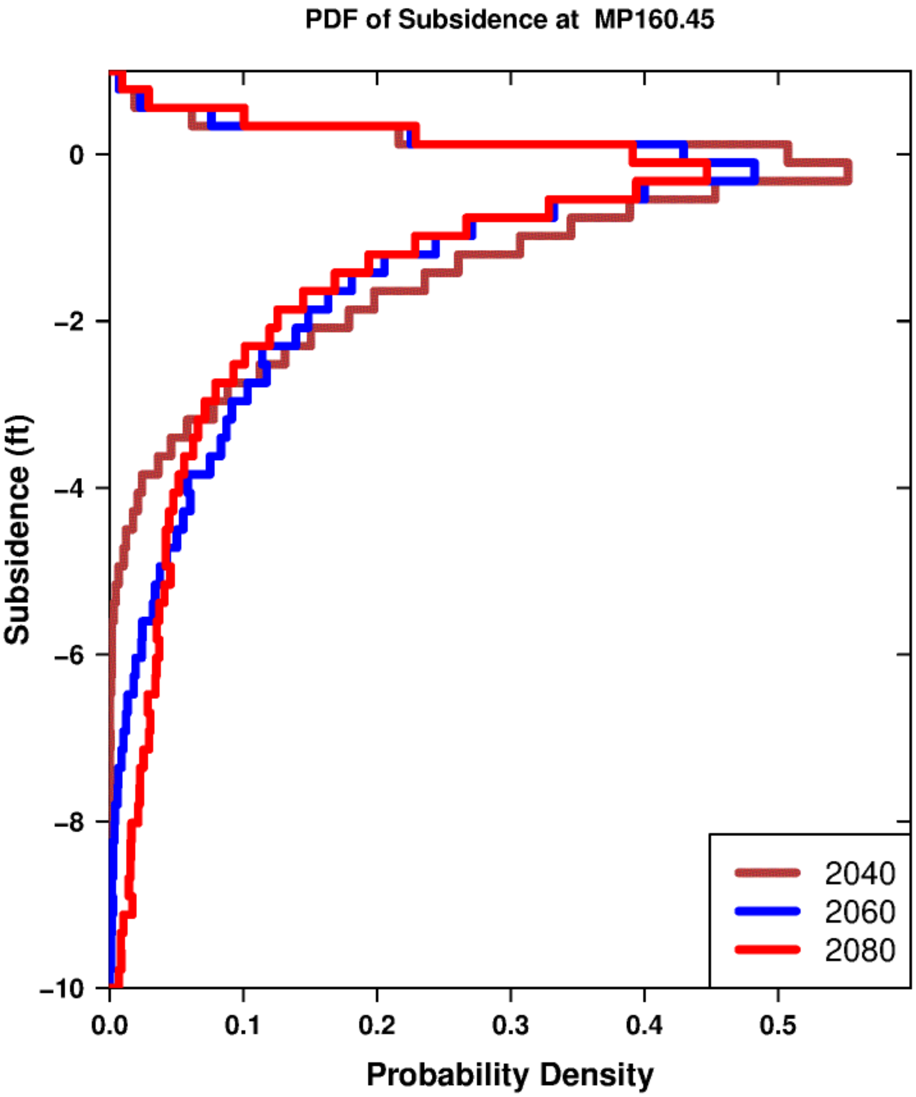


Figure 6-4. Probability density functions of subsidence for MP270 in the San Joaquin Field Division at three different times

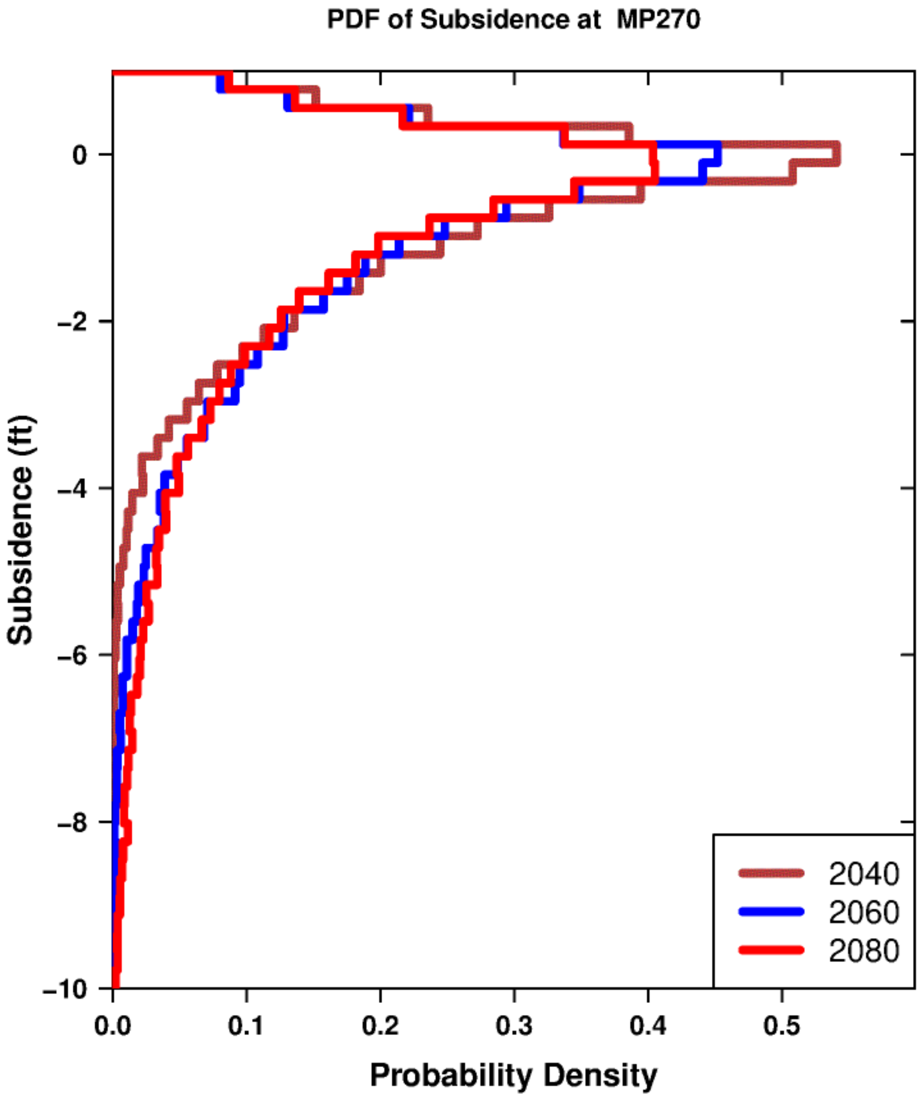


Figure 6-5. Forecast mean and percentile subsidence profiles for 2025

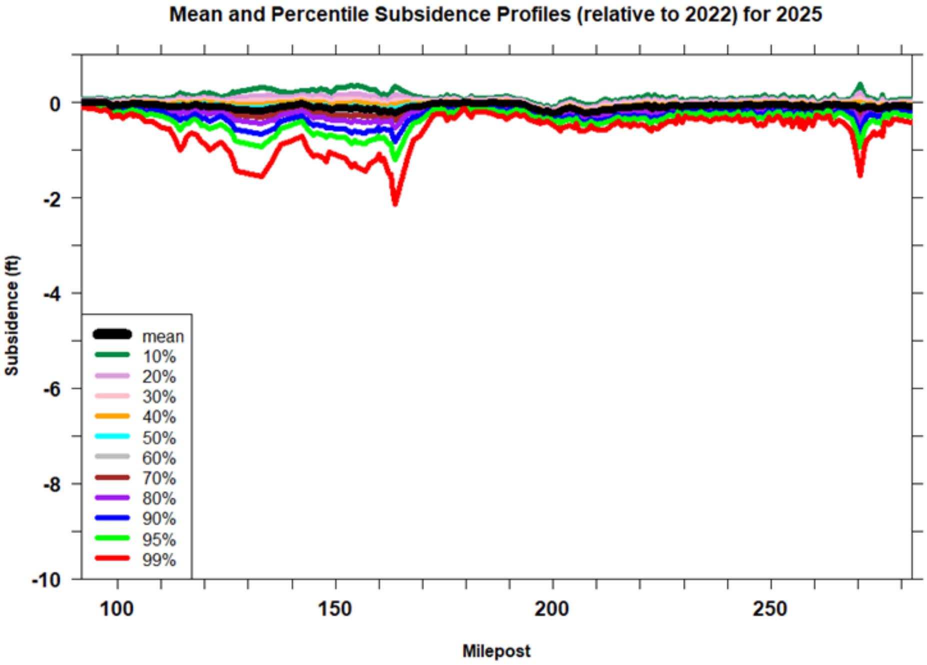


Figure 6-6. Forecast mean and percentile subsidence profiles for 2030

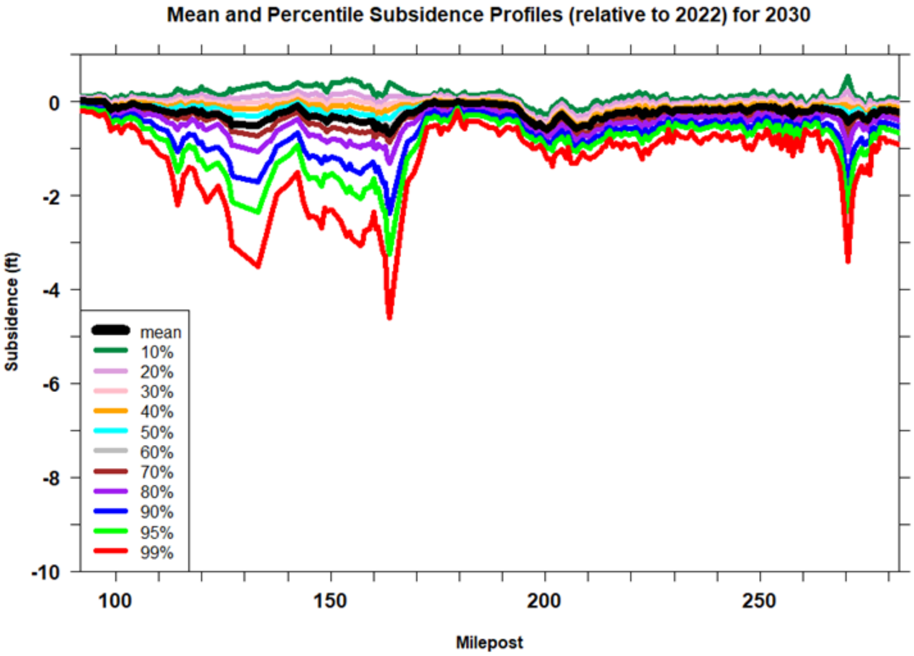


Figure 6-7. Forecast mean and percentile subsidence profiles for 2040

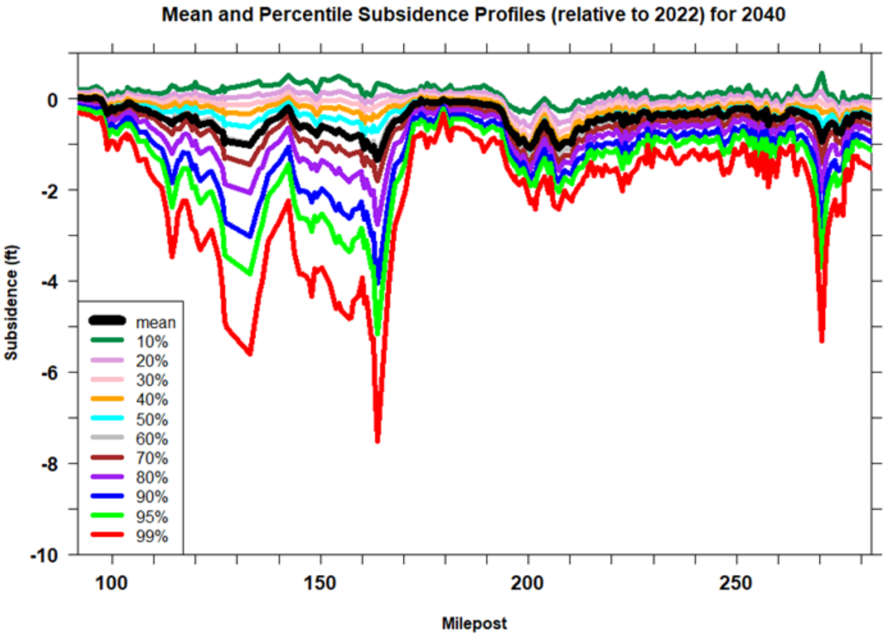


Figure 6-8. Forecast mean and percentile subsidence profiles for 2050

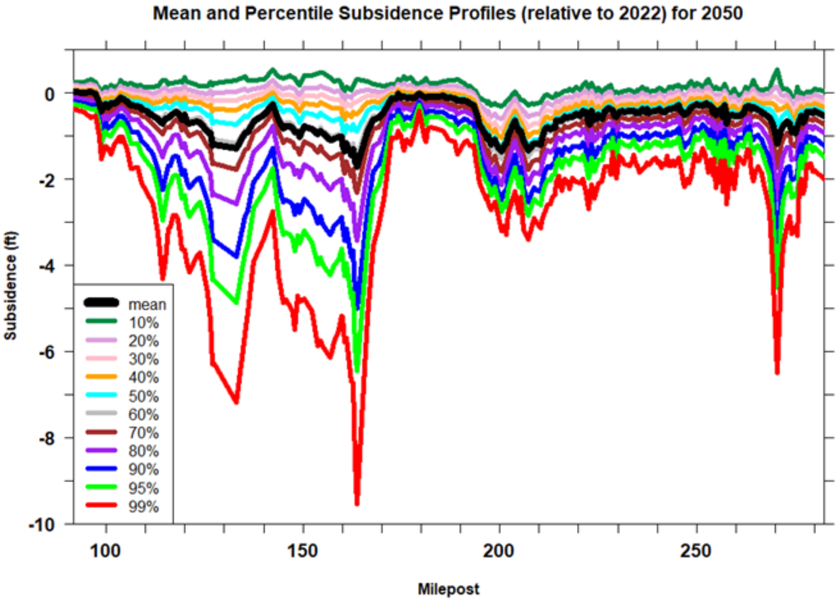


Figure 6-9. Forecast mean and percentile subsidence profiles for 2060

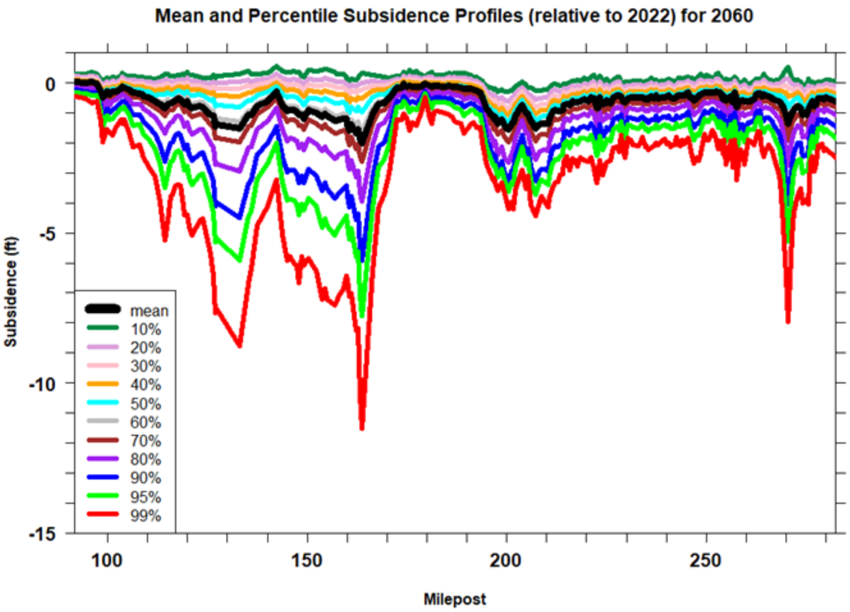


Figure 6-10. Forecast mean and percentile subsidence profiles for 2070

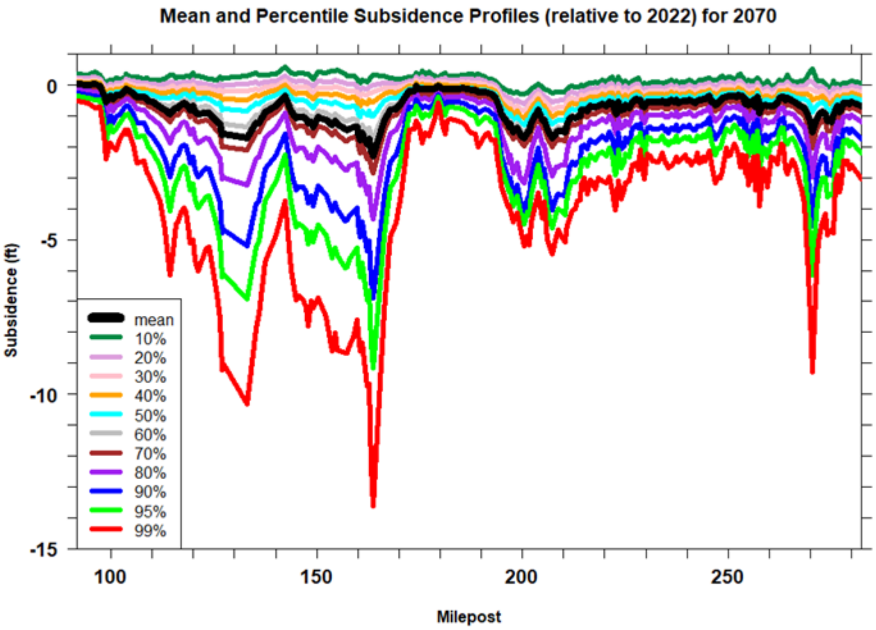


Figure 6-11. Forecast mean and percentile subsidence profiles for 2080

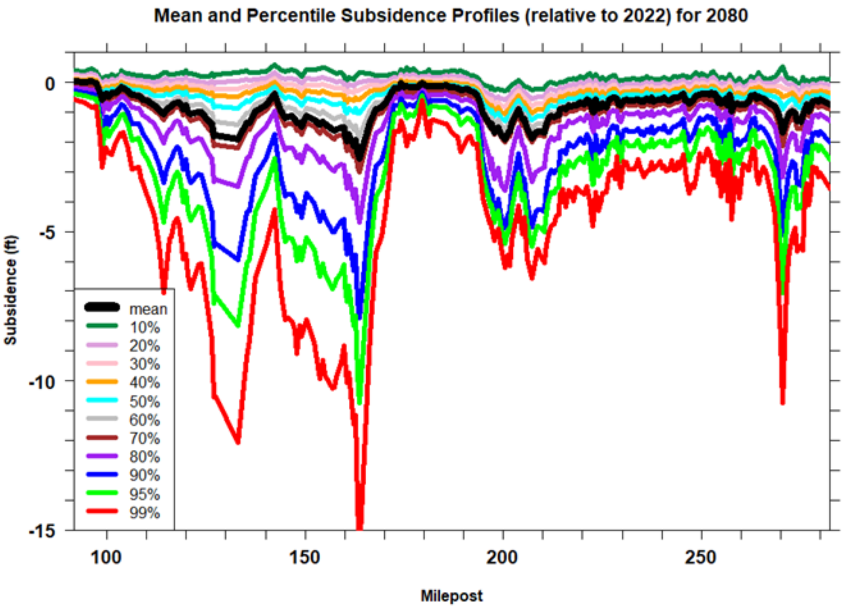


Figure 6-12. Forecast mean subsidence profiles for 2030-2080 decades

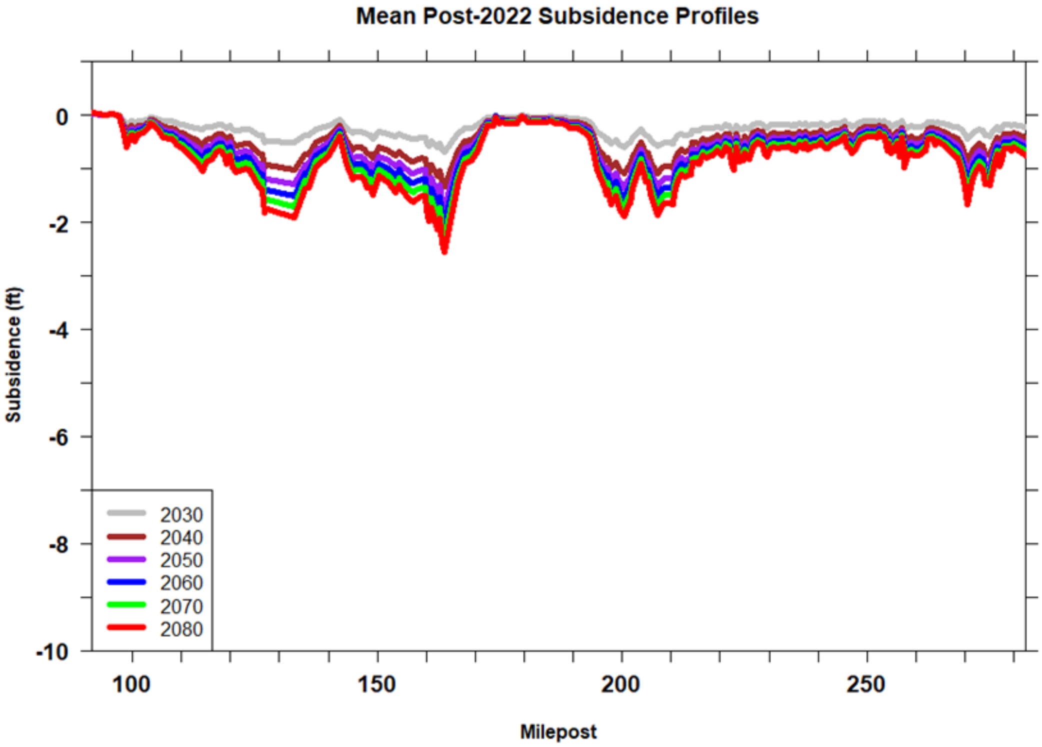


Figure 6-13. Forecast 50th percentile subsidence profiles for 2030-2080 decades

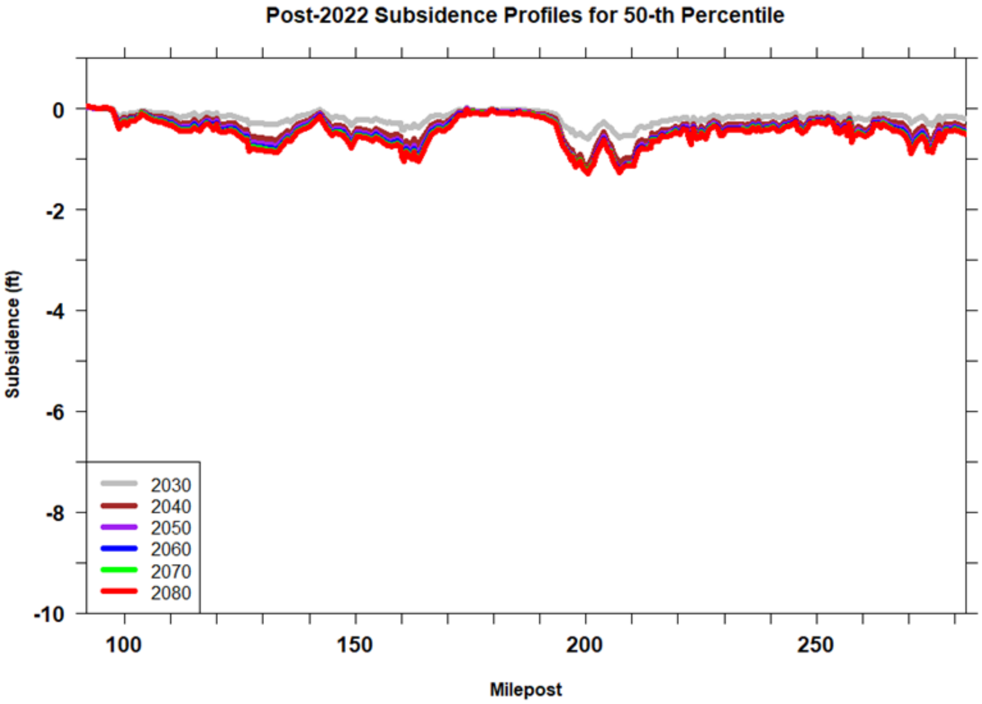
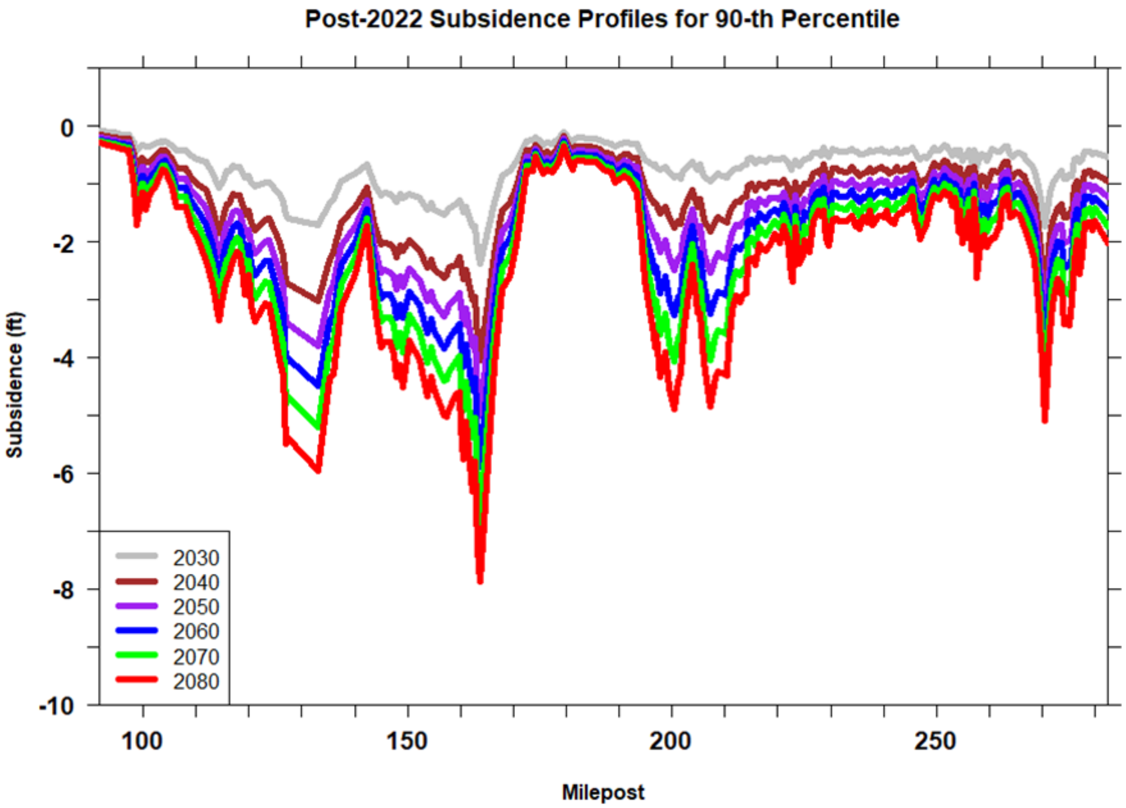


Figure 6-14. Forecast 90th percentile subsidence profiles for 2030-2080 decades



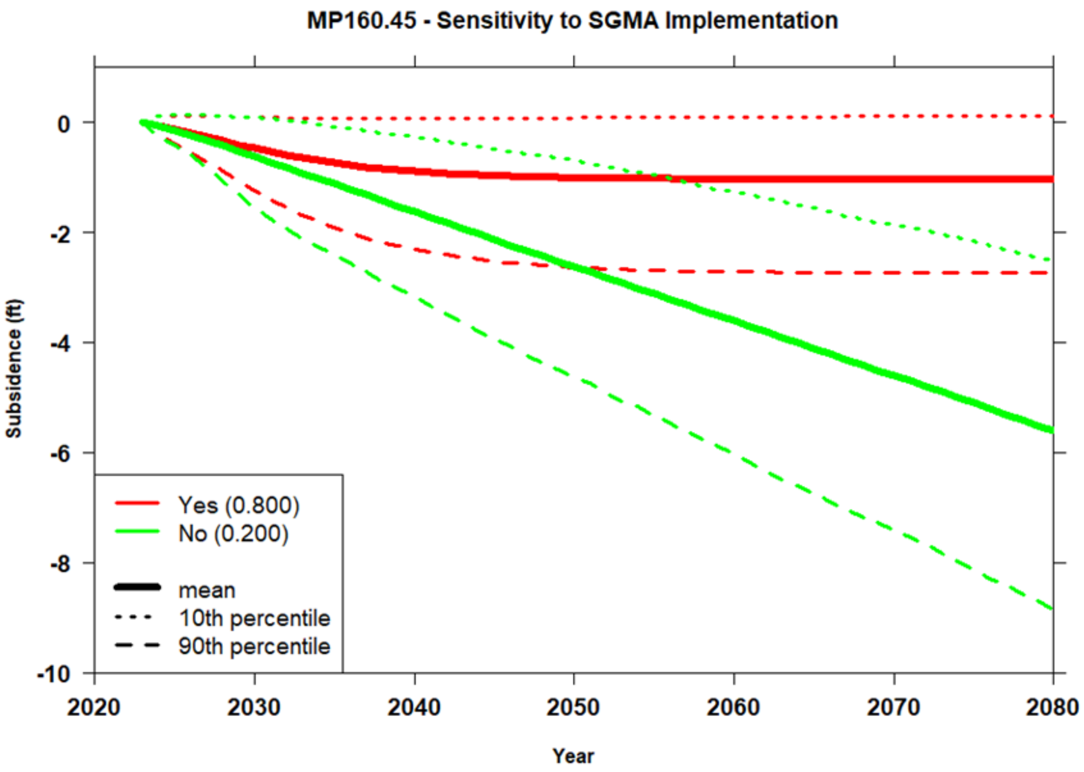
6.3 Model Sensitivity

This section examines the results obtained for various branches of the logic tree presented in Figures 5-11 through 5-13, by calculating and comparing the 10th percentile, mean, and 90th percentile for each individual branch at a specific level of the logic tree. We could have used the median (or 50th percentile) instead of the mean; generally, the mean is more sensitive to the distribution tails. The purpose of these sensitivity analyses is to isolate the effects of the various levels and branches of the logic tree, to investigate their relative importance and possible differences in their temporal evolution. Results are presented first for MP 160.45 (SLFD) and then for MP 270 (SJFD).

6.3.1 Sensitivity to SGMA Implementation for SLFD

Figure 6-15 shows the sensitivity (relative effect on modeled outcomes) to whether SMGA is implemented, which is represented in the first level in the logic tree (Figure 5-11). The modeled future subsidence values vary significantly between these two potential conditions. The mean and percentile curves for future subsidence with SGMA implementation (red) flatten around 2050, while the curves for future subsidence with No SGMA implementation (green) continue with a downward slope. The flattening of the red curve is consistent with the expectation of most of the experts and stakeholders interviewed for this study that "glide path" implementation of SGMA will result in a gradual reduction in subsidence rate and a cessation of subsidence at or around 2040. Note the large separation between the 10-th and 90-th percentile curves, which indicates a broad uncertainty within each of these branches. This uncertainty is due to subsequent branches, as well as the within-bin variation in Ttp and Tno, climate variability, and the observed historical variability modeled by the random-walk, as described in Chapter 5. The latter three effects are modeled in the flow-chart in Figure 5-15.

Figure 6-15. Sensitivity of forecast to weight assigned to SGMA Implementation



6.3.2 Sensitivity to Distributions of Ttp and Tno for SLFD

Figure 6-16 shows the sensitivity of forecasted subsidence to the different distributions of Ttp and Tno included within the Basin-wide and Westside scenarios considered for the SLFD. Note that the broader Basin-wide scenario distributions for Ttp and Tno produce a delayed flattening of the curves and a broader uncertainty range than the Westside distributions.

6.3.3 Sensitivity to Values of Ttp and Tno for SLFD

Figure 6-17 shows the sensitivity of forecast subsidence to Ttp, the onset time of transitional pumping, for the Basin-wide scenario. Note the broad uncertainty ranges for all branches. The later branches have broader uncertainty ranges due to contributions of variability in climate and the No SGMA random walk model accumulating over a longer time, before subsidence is arrested with partial SGMA implementation. Figure 6-18 shows the sensitivity to Tno, the time of no overdraft. For the sake of clarity, this figure shows only the mean curves for each branch. Subsequent sensitivities to Ttp or Tno will show only branch means, but it is important to keep in mind that each logic-tree branch is associated with a broad range of possible future subsidence histories, and that uncertainty ranges generally increase as Ttp and Tno occur at later dates.

To investigate the effect of different values of Tno (time at which overdraft no longer occurs) alone, Figure 6-19 shows the sensitivity to Tno, given that Ttp (the onset of transitional pumping) is equal to 2030-2040 (the most likely Ttp bin). Comparison to Figure 6-17 suggests that the effect of Ttp on the subsidence forecast is stronger than the effect of Tno, but this may be a consequence of which distribution was specified first in the logic tree (note that the two distributions have roughly the same standard deviation in Figure 5-7).

Figure 6-16. Sensitivity of forecasted subsidence to timing of SGMA Implementation (Ttp and Tno) for the alternative Basin-wide and Westside scenarios in the SLFD

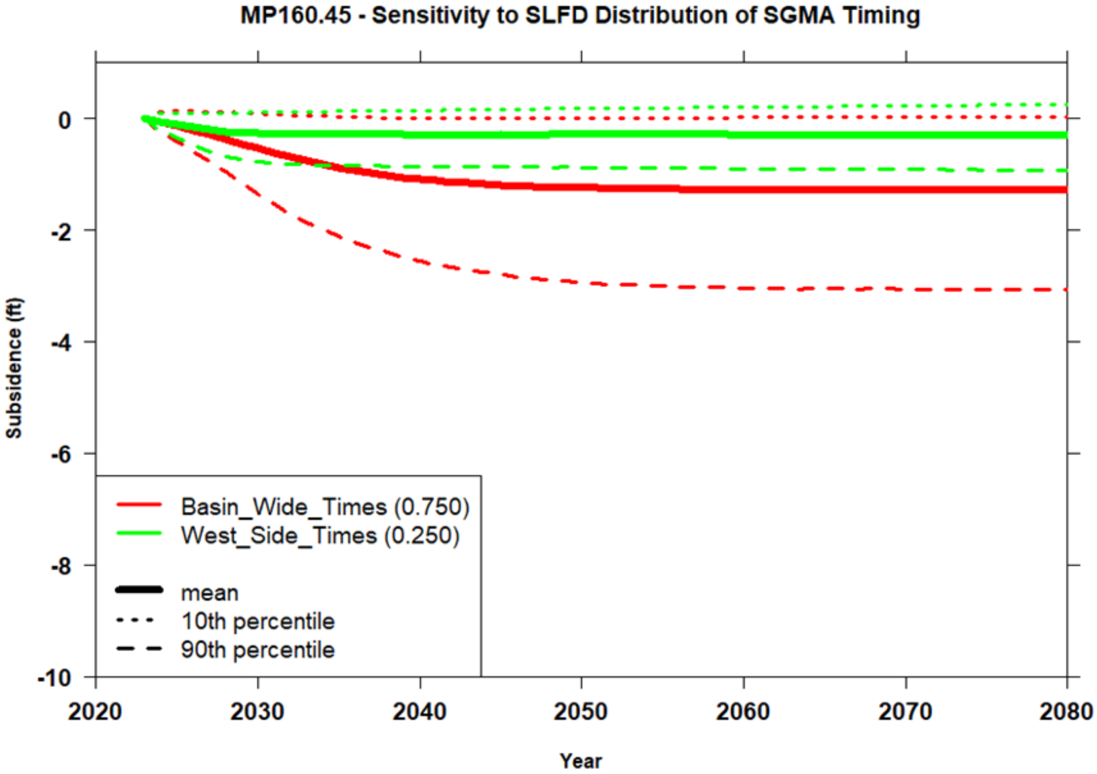


Figure 6-17. Sensitivity of forecast to onset time of Partial SGMA Implementation (Ttp), Basin-wide scenario

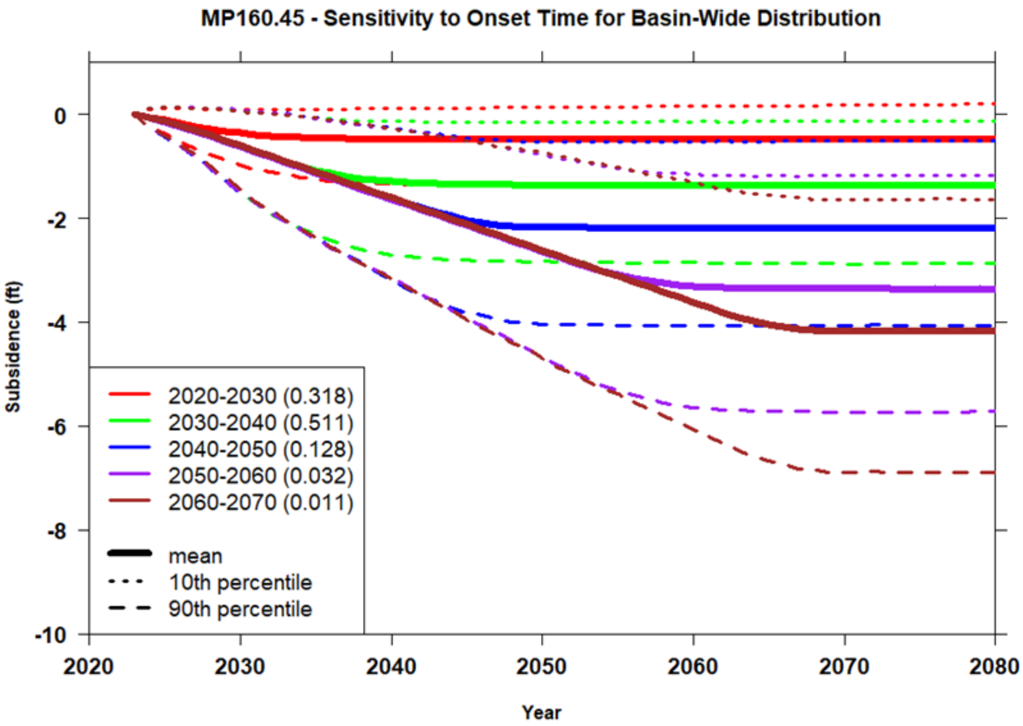


Figure 6-18. Sensitivity of forecasted subsidence to time of Cessation of Overdraft (Tno), Basin-wide scenario

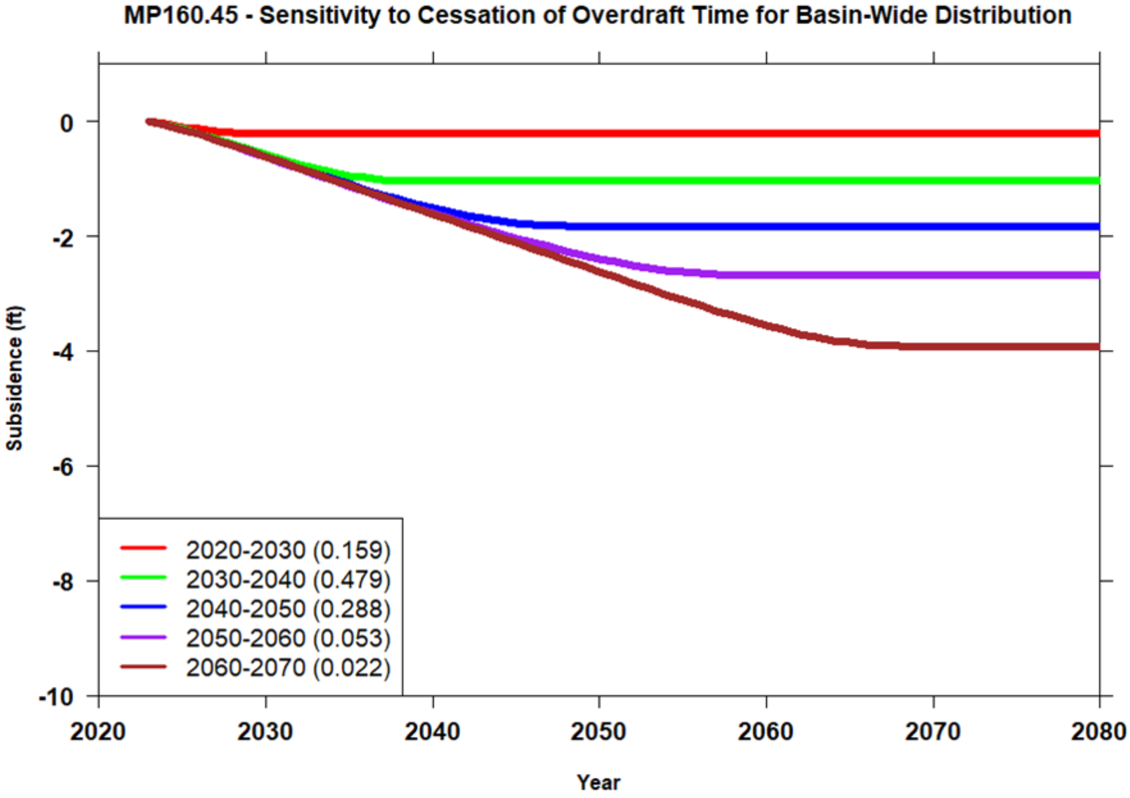
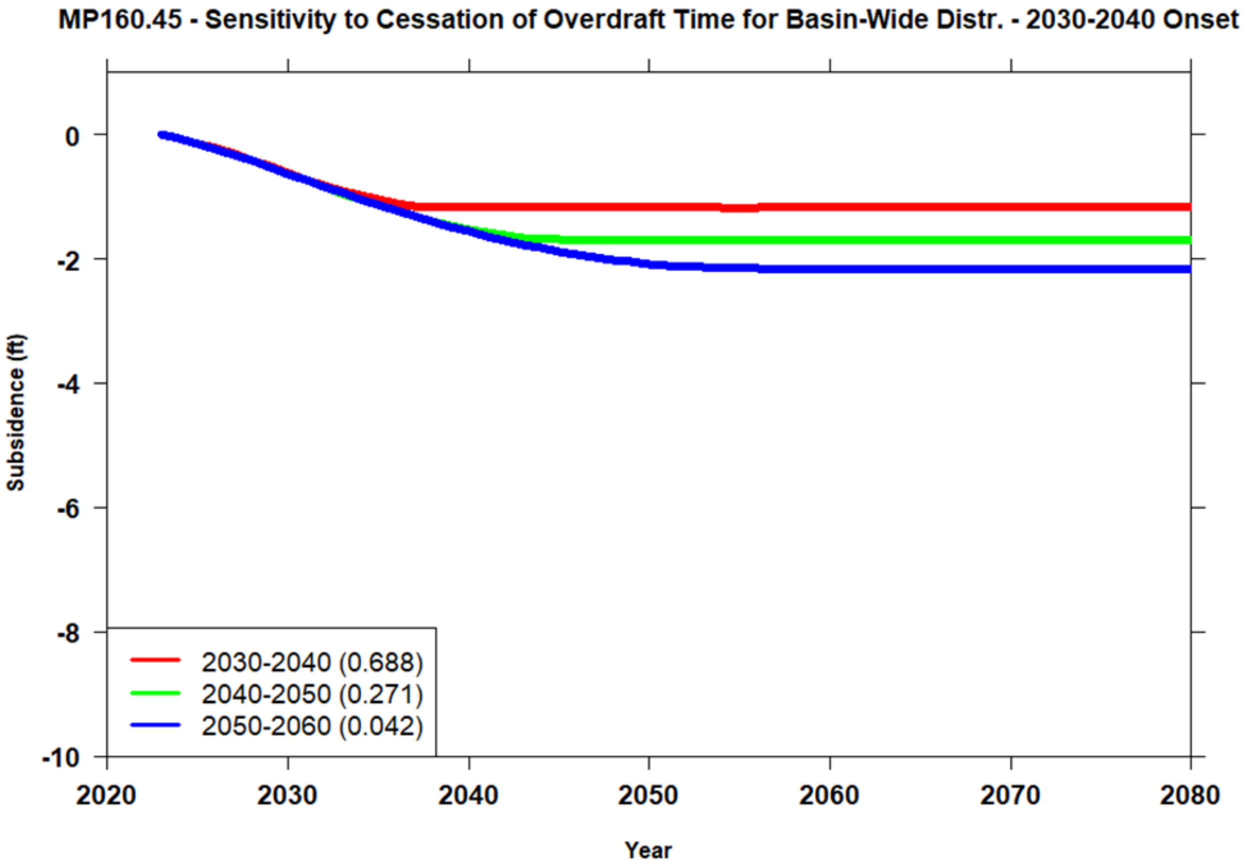


Figure 6-19. Sensitivity of forecast to time of Cessation of Overdraft (Tno), given onset of Partial SGMA Implementation in the 2030-2040 decade, Basin-wide scenario



Figures 6-20 and 6-21 show the sensitivity to Ttp and Tno for the Westside scenario. As anticipated, the effects are smaller because these distributions are much tighter than observed in Figures 6-17 and 6-18 for the Basin-wide scenario.

Figure 6-20. Sensitivity of forecast to onset of Partial SGMA Implementation (Ttp), Westside scenario

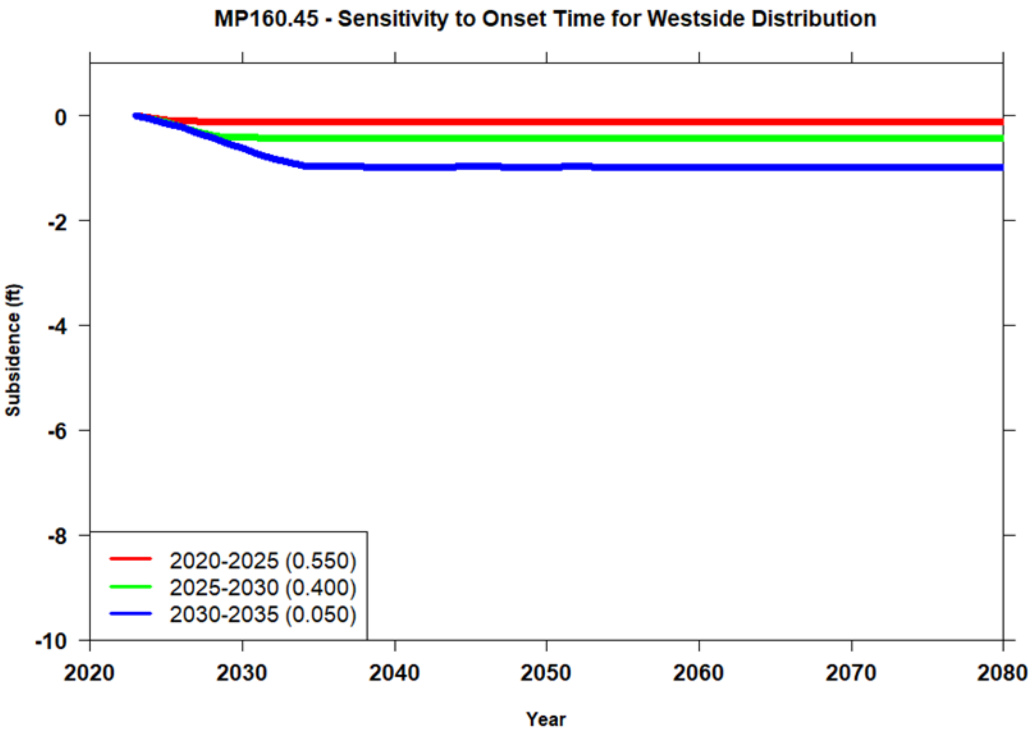
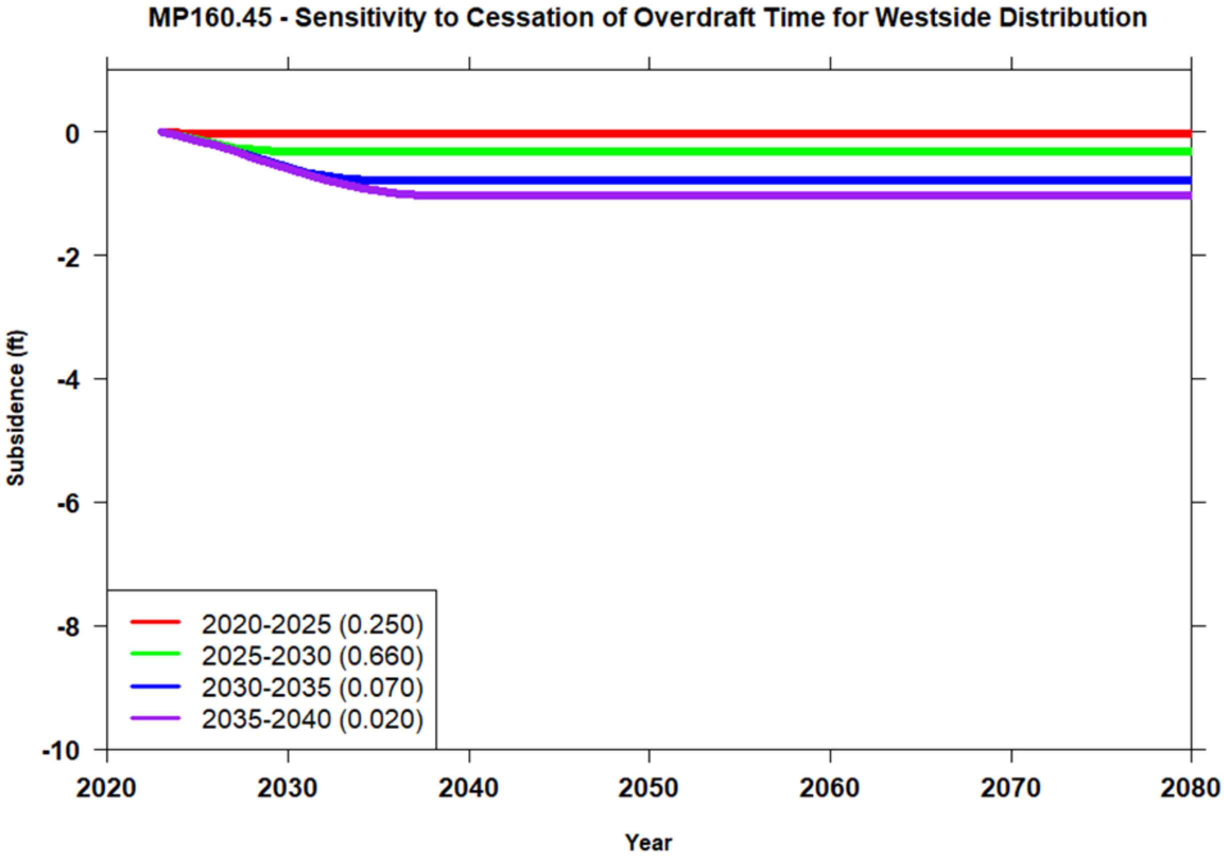


Figure 6-21. Sensitivity of forecast to time of Cessation of Overdraft (Tno), Westside scenario



6.3.4 Sensitivity to SGMA Implementation and Values of Ttp and Tno for SJFD

Figures 6-22 through 6-24 show results for MP 270 in the SJFD. The forecast trends are similar to those observed for MP 160.45 in SLFD. The mean trend for the No SGMA branch is steeper in Figure 6-15 than in Figure 6-22 because the mean severe-drought subsidence rate in the random-walk model is higher for MP 270 than for MP 160.45 (see Figure 5-3). Similarly, the 10-90 percent range for the No SGMA branch is somewhat broader in Figure 6-15 than in Figure 6-22 because the annual standard deviation is slightly higher for MP 160.45 than for MP 270 (see Figure 5-3).

Figure 6-22. Sensitivity of forecast to SGMA Implementation under the Basin-wide scenario (red) vs. No SGMA implementation (green), MP 270

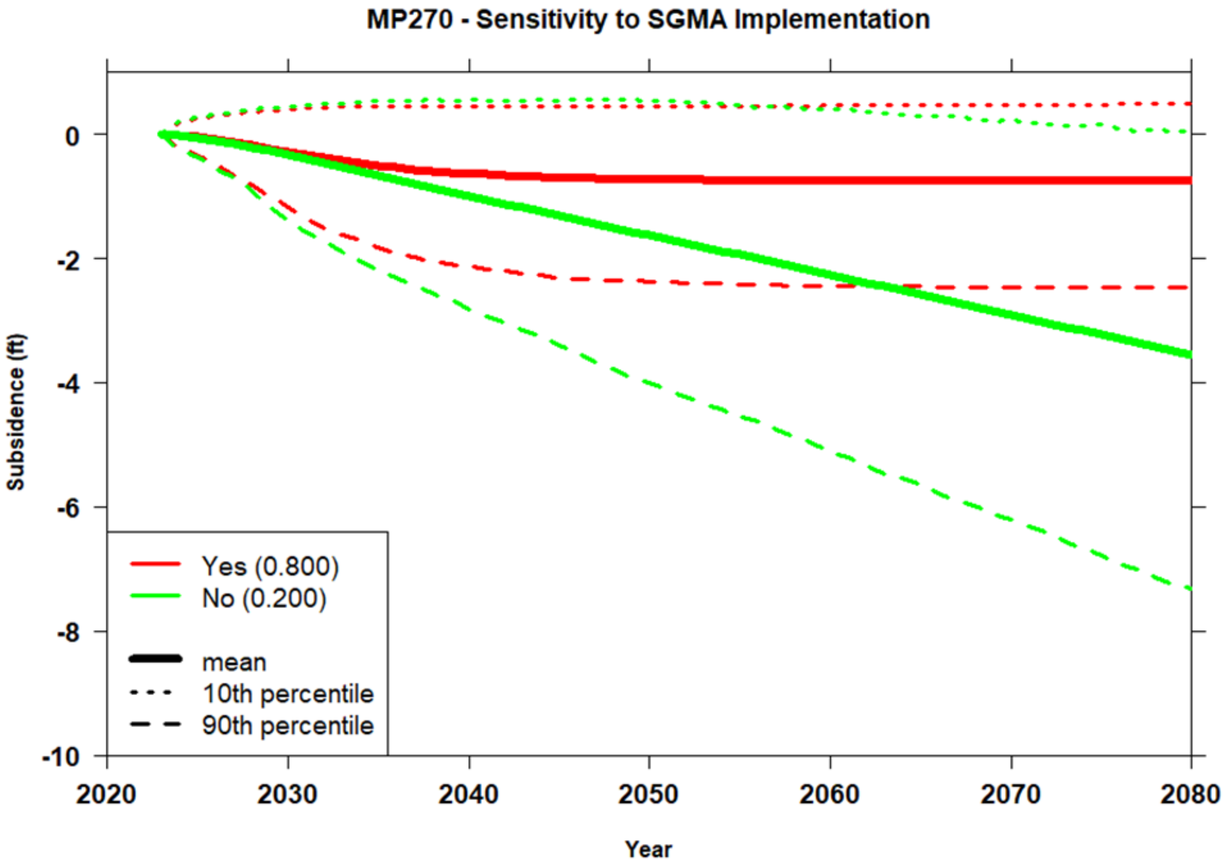


Figure 6-23. Sensitivity of forecast to time of onset of Partial SGMA Implementation (Ttp), Basin-wide scenario, MP 270

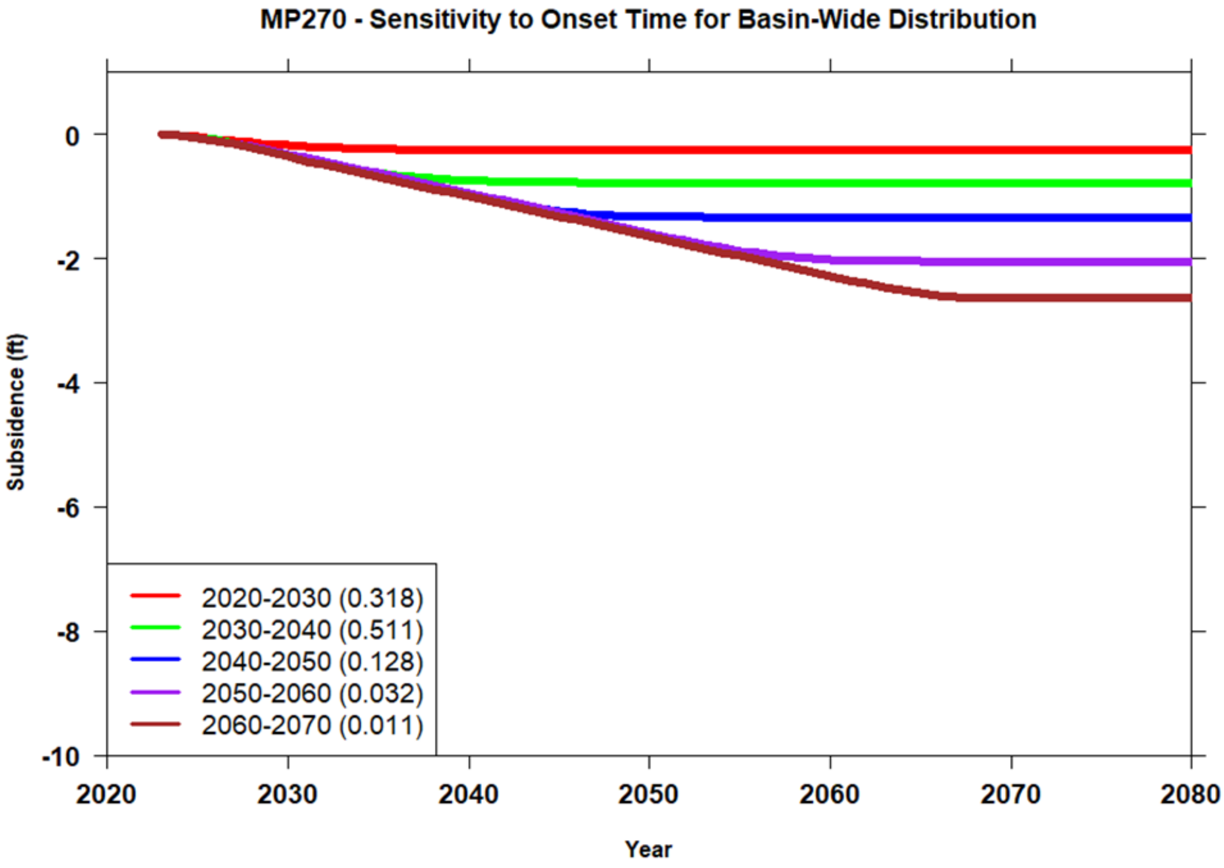
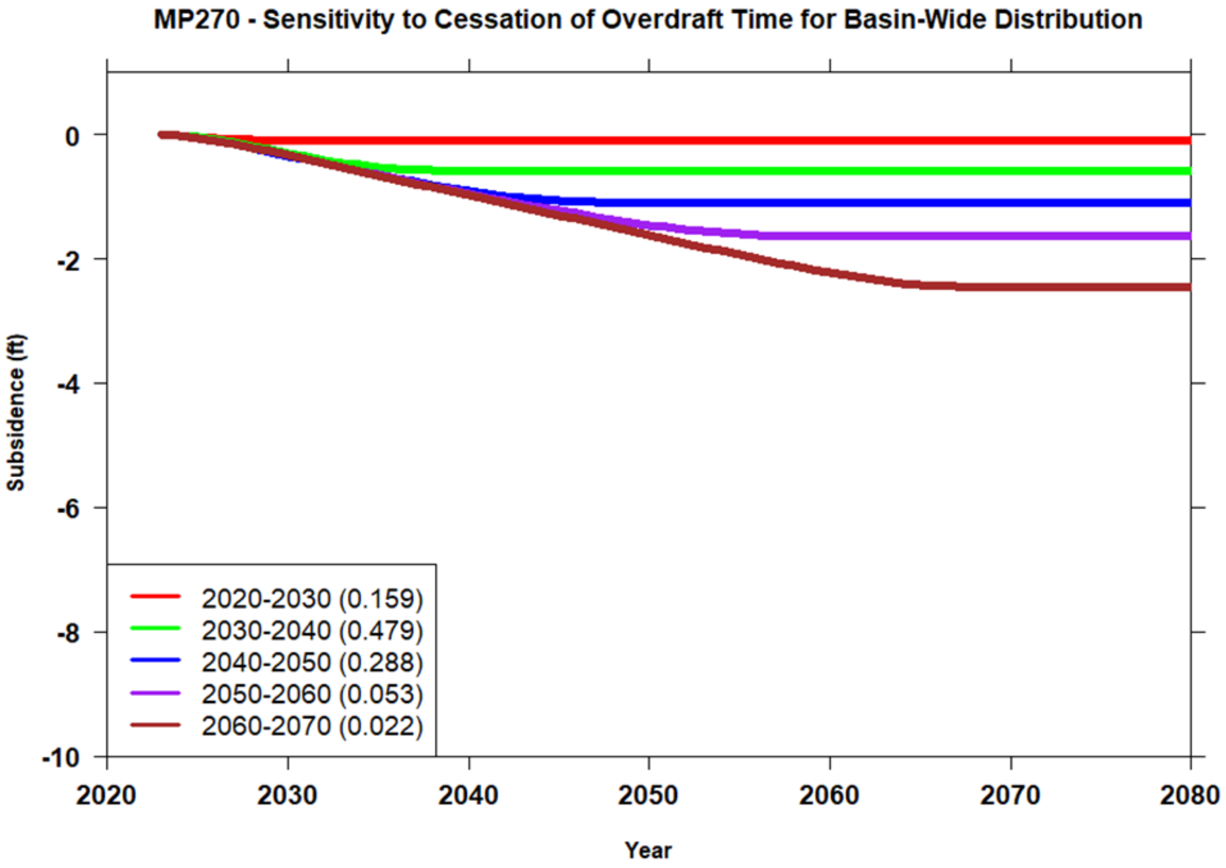


Figure 6-24. Sensitivity of forecast to time of Cessation of Overdraft (Tno), Basin-wide scenario, MP 270



6.4 Comparison of Forecast Model Predictions with Regression Analysis

The TI Group reviewed some initial comparisons of the probabilistic model forecasts with predictions based on a linear regression of 1986-2021 survey data for MP 157.97 (Table 6-1, below). The mean forecasted subsidence estimate from the probabilistic model is influenced by SGMA implementation, whereas the regression model is based on a continuation of historical subsidence (i.e., a No SGMA condition), and it incorporated no distinction between drought and non-drought periods. As expected, the mean forecasted subsidence of the probabilistic model for 2040 and 2060 is lower than the mean forecast from the regression model for the same years. In contrast, the 10% exceedance value of subsidence (i.e., the 90th percentile) from the probabilistic model is greater than the comparable percentile from the regression approach. The difference between these results illustrates the greater range of uncertainty reflected in the probabilistic model, and most likely results from the effect of increased frequency and duration of severe droughts with time in the No SGMA model (which is not accounted for the in the regression model).

Table 6-1. Comparison of Mean and 90th Percentile Subsidence Predictions from the Probabilistic Forecast Model and Regression Analysis of Survey Data, MP 157.97

Forecast Date	Mean Prediction Regression	Mean Prediction, Subsidence Forecast Model	90th Percentile, Regression	90th Percentile, Subsidence Forecast Model
2040	~1.5 ft	~1.3 ft	~2.1 ft	~3.5 ft
2060	~2.9 ft	~2 ft	~3.8 ft	~4.7 ft

7.0 Summary and Conclusions

The probabilistic model developed for this study incorporates the observed historical variability in subsidence during severe drought and other years, the anticipated future increase in severe drought frequency and duration caused by climate change, and uncertainty about future conditions that control pumping behavior, to forecast future subsidence in the absence of CASP mitigation projects. Compared to earlier trend extrapolations (*i.e.,* regression analysis), the present model better represents the structure of uncertainties underlying forecasts of subsidence and allows a better understanding of how those uncertainties affect future subsidence. The forecast model considers three conditions that determine the rate of subsidence, beginning with the No SGMA condition, during which the behavior of subsidence is represented by a statistical model based on historical patterns, followed by Partial SGMA Implementation, during which the parameters of the statistical model are tapered down, and a Cessation of Overdraft condition, during which only the natural geologic and background subsidence rate and elastic fluctuations are represented.

The forecast model uses probability distributions to represent uncertainty in the timing of the transitions between the modeled conditions. These distributions were developed in conformance with SSHAC guidance to represent the “center, body and range” of informed expert and stakeholder opinion regarding SGMA implementation. In a manner consistent with the SSHAC guidance, the TI Group presented the model and results at different stages of development to the PPRP, and it received timely feedback from the latter.

The output from the probabilistic forecast model provides the distribution of forecast subsidence magnitudes for any year of interest through the 2080 CASP planning horizon. The model generates projections of future land subsidence that incorporate the range of expert opinions on SGMA implementation in combination with future climate change. It is considered appropriate for use in a planning study of potential preventative and corrective actions to address the consequences of subsidence on the Aqueduct in the San Joaquin Valley.

State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES

PROBABILISTIC SUBSIDENCE FORECAST MODEL FOR THE CALIFORNIA AQUEDUCT SUBSIDENCE PROGRAM SAN JOAQUIN VALLEY, CALIFORNIA

DESIGN REPORT

APPENDIX A
References Evaluated

August 18, 2023

Reference	Date	Full Citation	Comments	Cited in SSHAC Report ? (Y/N)
Akaike 1974	1974	Akaike, H. (1974). "A New Look at the Statistical Model Identification." IEEE Trans. Auton. Contr., 19, 716-723.	Reference for use of AIC criterion to evaluate trade-off between goodness of fit and model complexity	**Y**
Ake et al. 2018	2018	Ake, J., Munson, C., Stamatakos, J., Juckett, M., Coppersmith, K., and Bommer, J., 2018, Updated implementation guidelines for SSHAC hazard studies: NUREG-2213, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington D.C.	SSHAC implementation guidance	**Y**
Arax 2019	2019	Arax, M., 2019, The Dreamt Land, Chasing Water and Dust Across California: Vintage Books, a Division of Penguin Random House LLC, New York, 562 p.	History of water development and agriculture in California, with emphasis on the San Joaquin Valley. Discussion of development of the SWP and CVP, and establishment of Westlands water district. Written by a journalist who covered water and land use issues for the Los Angeles Times	**N**
Armenti 2017	2017	Armenti, T., 2017, Land rebound and preconsolidation head in the Houston Ship Channel area: M.S. thesis, University of Houston, 109 p.	M.S. thesis on determining preconsolidation head in areas of past subsidence near Houston TX. Relevant to understanding management of groundwater levels to avoid inducing new subsidence	**Y**
Arvin- Edison 2019	2019	Arvin-Edison Water Storage District, 2019, Executive Summary, Management Area Plan, Kern Sub- Basin, 14 p., available from https://aewsd.org/wp-content/uploads/AEWSD-GSP-FINAL-executive-summary-only.pdf (last accessed 1/10/22).	Includes discussion of "glide path" scenario for implementation of SGMA	**Y**
Babbitt and Hall	2018	Babbitt, C. and Hall, M., 2018, Groundwater Pumping Allocations Under California's Sustainable Groundwater Management Act-Considerations for Groundwater Sustainability Agencies: prepared by Environmental Defense Fund in collaboration with New Current Water and Land, LLC, 13 p., available from https://www.edf.org/sites/default/files/documents/edf_california_sgma_allocations.pdf (last accessed 12/18/20).	Discusses potential groundwater allocation schemes consistent with common law principals for GSAs to consider in implementing SGMA	**N**
Batres et al. 2019	2019	Batres, M., Brand, E., Cameron, D., Crane, L., Leslie, E., and Wu, G., 2019, Power of Place: Land Conservation and Clean Energy Pathways for California—Executive Summary: Nature Conservancy, available from https://www.scienceforconservation.org/products/power-of-place(last accessed 12/18/20).	Analysis and policy recommendations regarding feasibility of achieving zero-carbon electricity supplies by 2050. Specifically discusses expansion of solar energy capacity in the SJV	**N**
Bruno and Bovberg	1992	Bruno, M.S., and Bovberg, C.A., 1992, Reservoir compaction and surface subsidence above Lost Hills field, California, in Tillerson, J.R. and Wawersik, W.R. eds, Rock Mechanics, Proceedings of the 33rd U.S. Symposium: 3-5 June 1992, Sweeney Convention Center, Sante Fe, New Mexico: A.A. Balkema, Rotterdam, p. 263-272.	Cited in CASS Supplemental Report (2019)	**N**

Reference	Date	Full Citation	Comments	Cited in SSHAC Report ? (Y/N)
Budnitz et al. 1997	1997	Budnitz, R.J., Apostolakis, G., Boore, D.M., Cluff, L.S., Coppersmith, K.J., Cornell, C.A., and Morris, P.A., 1997. Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts: Washington, D.C., US Nuclear Regulatory Commission, NUREG/CR-6372, p. 278	SSHAC implementation guidance	**Y**
Department of the Interior, 1981	1981	U.S. Department of the Interior, 1981, Ground Water Manual: U.S. Government Printing Office, Denver, 480 p.	Technical manual published by USDOI Water and Power Resources Service on groundwater hydrology (second reprint)	**N**
DOGGR 1998	1998	Division of Oil, Gas and Geothermal Resources (DOGGR), 1998, North Lost Hills Oil Field: Volume 1-Central California Oil and Gas Fields, Fourth Edition, California Department of Conservation Publication No. TR11.	Cited in CASS Supplemental Report (2019)	**N**
DWR 1965	1965	California Department of Water Resources, April 1965, Specification No. 65-28, Canal – STA. 845+30 to STA. 2580+90 Avenal Gap to 7th Standard Road Mile 187.1 to Mile 220.1 As-Built Drawings, South San Joaquin Division, California.	Cited in CASS (2017)	**N**
DWR 1965	1965	California Department of Water Resources, September 1965, Specification No. 66-03, Canal – STA.192+00 to STA. 845+30 Kettleman City to Avenal Gap Mile 174.8 to Mile 187.1 As-Built Drawings, South San Joaquin Division, California.	Cited in CASS (2017)	**N**
DWR 1965	1965	California Department of Water Resources, October 1965, “Selection of Methods Used for Computing the Head Loss in the Open Canals of the California Aqueduct, Technical Memorandum #18”, California	Cited in CASS (2017)	**N**
DWR 1965	1965	California Department of Water Resources, February 1965, “Aqueduct Design Criteria”, Division of Design and Construction, Aqueduct Branch, California	Cited in CASS (2017)	**N**
DWR 1966	1966	California Department of Water Resources, November 1966, Specification No. 67-06, Canal – STA. 2580+90 to STA. 3575+00 7th Standard Road to Tupman Road Mile 220.1 to Mile 239.0 As- Built Drawings, South San Joaquin Division, California.	Cited in CASS (2017)	**N**
DWR 1967	1967	California Department of Water Resources, January 1967, “Plan of Operations for the Facilities from the Delta to Buena Vista Pumping Plant”, California	Cited in CASS (2017)	**N**
DWR 1967	1967	California Department of Water Resources, April 1967, Specification No. 67-37, Canal – STA. 3575+00 to STA. 4250+00 Tupman Road to Buena Vista Pumping Plant Intake Channel Mile 239.0 to Mile 251.8 As-Built Drawings, South San Joaquin Division, California.	Cited in CASS (2017)	**N**
DWR 1967	1967	California Department of Water Resources, September 1967, Specification No. 67-69, Canal – STA. “N” 4250+00 to STA. “B” 1507+53 Buena Vista Pumping Plant to Wheeler Ridge Pumping Plant Mile 251.8 to Mile 280.0 As-Built Drawings, South San Joaquin Division, California.	Cited in CASS (2017)	**N**
DWR 1967	1967	California Department of Water Resources, December 1967, Specification No. 68-07, Canal – STA. “W” 5+57 to STA. “T” 670+61-Wheeler Ridge Pumping Plant to Tehachapi Pumping Plant Mile 280.8 to Mile 295.8 As-Built Drawings, South San Joaquin Division, California.	Cited in CASS (2017)	**N**

Reference	Date	Full Citation	Comments	Cited in SSHAC Report ? (Y/N)
DWR 1968	1968	California Department of Water Resources, October 1968, “Transient Control in the California Aqueduct, Technical Memorandum # 40,” Computer System Branch, Sacramento California.	Cited in CASS (2017)	**N**
DWR 1974	1974	California Department of Water Resources, November 1974, “Bulletin No. 200 California State Water Project, Volume II: Conveyance Facilities,” California State Water Project, Sacramento, California.	Cited in CASS (2017)	**N**
DWR 1979	1979	California Department of Water Resources, February 1979, “Water Operations Manual OP-450R,” Division of Operations and Maintenance, Sacramento, California.	Cited in CASS (2017)	**N**
DWR 1979	1979	California Department of Water Resources, June 1979, “Milepost at Structure Sites San Luis Canal,” Division of Operations and Maintenance.	Cited in CASS (2017)	**N**
DWR 1979	1979	California Department of Water Resources, August 1979, “San Luis Canal Report on Subsidence,” Division of Operations and Maintenance.	Cited in CASS (2017)	**N**
DWR 1979		California Department of Water Resources, February 1979, “Water Operations Manual OP-450R,” Division of Operations and Maintenance, Sacramento, California.	Cited in CASS Supplemental Report (2019)	**N**
DWR 1979	1979	California Department of Water Resources, June 1979, “Milepost at Structure Sites San Luis Canal,” Division of Operations and Maintenance.	Cited in CASS Supplemental Report (2019)	**N**
DWR 1989	1989	California Department of Water Resources, March 1989, Specification No. 89-26, Aqueduct Modification Mile 182.4 to Mile 184.8 and Mile 194.9 to Mile 197.0 Drawings, South San Joaquin Division, California.	Cited in CASS (2017)	**N**
DWR 1989	1989	California Department of Water Resources, June 1989, “Water Operations Manual OP-350R,” Division of Operations and Maintenance, Sacramento, California.	Cited in CASS (2017)	**N**
DWR 1989	1989	California Department of Water Resources, June 1989, “Water Operations Manual OP-350R,” Division of Operations and Maintenance, Sacramento, California.	Cited in CASS Supplemental Report (2019)	**N**
DWR 1996	1996	California Department of Water Resources, July 1996, Specification No. 96-19, Aqueduct Modification Mile 206.10 to Mile 207.94 Drawings, South San Joaquin Division, California.	Cited in CASS (2017)	**N**
DWR 2009	2009	California Department of Water Resources, 2009, “Data Handbook State Water Project,” Division of Operations and Maintenance.	Cited in CASS Supplemental Report (2019)	**N**
DWR 2012	2012	California Department of Water Resources, September 2012, “California Aqueduct Strip Maps by Field Division,” Division of Operations and Maintenance, Sacramento, California.	Cited in CASS (2017)	**N**
DWR 2012	2012	California Department of Water Resources, September 2012, “California Aqueduct Strip Maps by Field Division,” Division of Operations and Maintenance, Sacramento, California.	Cited in CASS Supplemental Report (2019)	**N**
DWR 2013	2013	California Department of Water Resources, July 2013, “Standing Operating Order PC 600.22,” Division of Operations and Maintenance.	Cited in CASS Supplemental Report (2019)	**N**
DWR 2014	2014	California Department of Water Resources, October 2014, “Aqueduct Liner Inspection Report (MP106.6L, MP125.48L, MP125.6L, MP126.02R, And MP126.55R), October 1-3, 2014”, San Luis Field Division, Gustine, California	Cited in CASS (2017)	**N**
DWR 2016	2016	California Department of Water Resources, 2016, Precise Survey Data, Division of Operations and Maintenance.	Cited in CASS Supplemental Report (2019)	**N**
DWR 2016	2016	California Department of Water Resources, 2016, LiDAR Data, Division of Engineering.	Cited in CASS Supplemental Report (2019)	**N**
DWR 2017	2017	California Department of Water Resources, June 2017, “California Aqueduct Subsidence Study,” Division of Engineering.	Cited in CASS Supplemental Report (2019). This is the CASS 2017 report.	**Y**

Reference	Date	Full Citation	Comments	Cited in SSHAC Report ? (Y/N)
DWR 1968	1968	California Department of Water Resources, October 1968, “Transient Control in the California Aqueduct, Technical Memorandum # 40,” Computer System Branch, Sacramento California.	Cited in CASS (2017)	**N**
DWR 2017	2017	California Department of Water Resources, 2017, Precise Survey Data, Division of Operations and Maintenance.	Cited in CASS Supplemental Report (2019)	**N**
DWR 2018	2018	California Department of Water Resources, 2018, Flood-MAR: using flood water for managed aquifer recharge to support sustainable water resources: DWR White Paper, 54 p.	Overview of flood-MAR approaches to facilitate aquifer recharge. Recommendations for additional work to implement a comprehensive flood-MAR program	**N**
DWR 2019	2019	California Department of Water Resources, 2019, Flood-MAR research and data development plan: Flood-MAR Research Advisory Committee, 79 p.	Plan outlining key information needed by those making management decisions about capturing available flood water to replenish California’s depleted aquifers.	**N**
DWR 2019	2019	Department of Water Resources, 2019, California Aqueduct Subsidence Study: Supplemental Report.	This is the CASS Supplemental Report.	**Y**
DWR 2020	2020	California Department of Water Resources, 2020, Proposal for the assessment of climate change driven risks to California Aqueduct subsidence: memo from DWR Climate Change Program to James Lopes, May 2020, 10 p., plus table of statistical parameters provided by email to James Lopes on 18 June 2020.	Description of an approach to model the anticipated future frequency and duration of 2012-2106-type droughts.. The DWR Climate Change Group developed and provided statistical parameters for use in a "method of increments" approach to model subsidence beyond 2040 under a scenario in which SGMA is not implemented.	**N**
Escriva-Bou 2019	2019	Escriva-Bou, A., 2019, Technical Appendix A: Updated Assessment of San Joaquin Valley's Water Balance, in Hanak, E., et al., Water and the future of the San Joaquin Valley: Public Policy Institute of California, available from https://www.ppic.org/wp-content/uploads/0219ehr-appendix-a.pdf (last accessed 1/5/21).	Water-balance calculations to estimate groundwater overdraft and changes in storage between 1968-2017, San Joaquin Valley	**Y**
Escriva-Bou et al. 2020	2020	Escriva-Bou, A., Hui, R., Maples, S., Medellin-Azuara, J., Harter, T., and Lund, J.R., 2020, Planning for groundwater sustainabiity accounting for uncertainty and costs: an application of California's Central Valley: Journal of Environmental Management, v. 264, 15 June 2020, 110426, 13 p.	Evaluates uncertainty in water balance estimates by comparing/contrasting C2VSim and CVHM model results. Paper also examines trade-offs between economic losses and probability of achieving GW sustainability within the SGMA implementation period, assuming different groundwater level buffering scenarios.	**N**
Farr et al. 2016	2016	Farr, T.G., Jones, C.E., Zhen, L., 2016, Progress Report: Subsidence in California: report submitted to the California Department of Water Resources from Jet Propulsion Laboratory, California Institute of Technology, 37 p.	Use of multiple SAR technologies to map subsidence in the San Joaquin Valley, Santa Clara Valley and and southern California coastal areas.	**N**
Faunt et al. 2010	2010	Faunt, C.C., Belitz, K., and Hanson, R.T., 2010, Development of a three-dimensional model of sedimentary texture in valley-fill deposits Central Valley, California: Hydrogeology Journal, v. 18, p. 625-649.	Cited in CASS Supplemental Report (2019)	**N**
Faunt et al. 2016	2016	Faunt, C.C., Sneed, M., Traum, J., and Brandt, J.T., 2016, Water Availability and land subsidence in the Central Valley, California, USA: Hydrogeology Journal, v. 24, no. 3, p. 675-684.	Cited in CASS Supplemental Report (2019)	**N**
Fielding et al. 1998	1998	Fielding, E.J, Blom, R.G., and Goldstein, R.M., 1998, Rapid subsidence over oil fields measured by SAR interferometry: Geophysical Research Letters, v. 25, no. 17, p. 3215-3218.	Cited in CASS Supplemental Report (2019)	**N**

Reference	**Date**	**Full Citation**	**Comments**	**Cited in SSHAC Report ? (Y/N)**
Fresno County 1994	1994	Fresno County, 1994, Fresno County Annual Crop and Livestock Report: Department of Agriculture, 20 p.; available at http://www.co.fresno.ca.us/Home/ShowDocument?id=16886 (last accessed 9/7/17).	Cited in CASS Supplemental Report (2019)	**N**
Frink and Kues 1954	1954	Frink, J.W., and Kues, H.A., 1954, Corcoran Clay—a Pleistocene lacustrine deposit in the San Joaquin Valley, California: American Association of Petroleum Geologists Bulletin, v. 38, no. 11, p. 2353-2371.	Cited in CASS Supplemental Report (2019)	**N**
Galloway and Burbey 2011	2011	Galloway, D.L., and Burbey, T.J., 2011, Review: regional land subsidence accompanying groundwater extraction: Hydrogeology Journal, v. 19, p. 1459-1486.	Good summary of the aquitard drainage model, with abundant citations of previous references	**N**
Galloway and Riley	1999	Galloway, D.L., and Riley, F.S., 1999, San Joaquin Valley, California: largest human alteration of the Earth's surface, in Galloway, D.L., Jones, D.R., and Ingebritsen, S.E., eds., Land subsidence in the United States: United States Geological Survey Circular 1182, p. 23–34.	Cited in CASS Supplemental Report (2019)	**N**
Galloway et al. 1999	1999	Galloway, D.L., Jones, D.R., and Ingebritsen, S.E., 1999, Land subsidence in the United States: United States Geological Survey Circular 1182, 177 p..	Chapters in volume discuss physical processes of aquifer compaction due to groundwater withdrawal; historic land subsidence in the San Joaquin Valley associated with agricultural land use	**Y**
Hanak et al. 2017	2017	Hanak, E., and 12 co-authors, 2017, Water Stress and a Changing San Joaquin Valley: Public Policy Institute of California, 50 p., available at http://www.ppic.org/content/pubs/report/R_0317EHR.pdf (last accessed 1/15/18).	Cited in CASS Supplemental Report (2019)	**N**
Hanak et al. 2019	2019	Hanak, E., and 9 co-authors, 2019, Water and the future of the San Joaquin Valley: Public Policy Institute of California, 100 p. plus technical appendices and overview, available from https://www.ppic.org/publication/water-and-the-future-of-the-san-joaquin-valley/ (last accessed 1/4/21).	Multi-disciplinary analysis of land-management challenges associated with surface water scarcity in the SJV and implementation of SGMA. Identifies priorities for balancing water supplies and demands.	**Y**
Hanak et. 2018	2018	Hanak, E., Jezdimirovic, J., Green, S., and Escriva-Bou, A., 2018, Replenishing groundwater in the San Joaquin Valley: Public Policy Institute of California, 38 p., available from https://www.ppic.org/wp-content/uploads/r-0417ehr.pdf (last accessed 1/4/2021).	Survey of groundwater recharge efforts by water districts in the SJV. Policy recommendations to improve future recharge opportunities	**N**
Hanemann and Dyckman 2009	2009	Hanemann, M., and Dyckman, C., 2009, The San Francisco Bay-Delta: a failure of decision-making capacity: Environmental Science and Policy, v. 12, p. 710-725.	Summary of legislative, policy and legal issues regarding California water use and impacts on the Bay-Delta system	**Y**
Ireland et al. 1980	1980	Ireland, R.L., Poland, J.F., and Riley, F.S., 1980, Land subsidence in the San Joaquin Valley, California, as of 1980: United States Geological Survey Professional Paper 437-I, 93 p.	Cited in CASS Supplemental Report (2019)	**Y**
Johnson and Cody 2015	2015	Johnson, R., and Cody, B.A., 2015, California Water Production and Irrigated Water Use: Congressional Research Service, CRS Report R44093, 25 p., submitted 30 June 2015; archived at https://www.everycrsreport.com/files/20150630_R44093_126291b87754c75f5965cae138b0363371948f61.pdf (last accessed 14 Nov 2017).	Cited in CASS Supplemental Report (2019)	**N**
Kern County 1998	1998	Kern County, 1998, Crop Report: Department of Agriculture, Kern County, California, 18 p.; available at http://www.kernag.com/caap/crop-reports/crop90_99/crop1998.pdf (last accessed 12/8/17).	Cited in CASS Supplemental Report (2019)	**N**
Kern County 2015	2015	Kern County, 2015, Kern County Agricultural Report: prepared by the Department of Agriculture and Measurement Standards, Kern County, California, 15 p.; available at http://www.kernag.com/caap/crop-reports/crop10_19/crop2015.pdf (last accessed 9/7/17).	Cited in CASS Supplemental Report (2019)	**N**
Kings County 1996	1996	Kings County, 1996, Agricultural Crop Report: prepared by the Agricultural Commissioner, Sealer of Weights and Measures, 14 p; available at https://www.countyofkings.com/home/showdocument?id=2786 (last accessed 12/8/17).	Cited in CASS Supplemental Report (2019)	**N**
Kings County 2016	2016	Kings County, 2016, Annual Agricultural Crop Report: prepared by Department of Agriculture, Measurement Standards, 23 p; available at https://www.countyofkings.com/home/showdocument?id=16141 (last accessed 9/7/17).	Cited in CASS Supplemental Report (2019)	**N**
Kooi and de Vries 1998	1998	Kooi, H. and de Vries, J.J., 1998, Land subsidence and hydrodynamic compaction of sedimentary basins: Hydrology and Earth System Sciences, v.2, no. 2-3, p. 159-171.	Cited in CASS Supplemental Report (2019)	**Y**

Reference	**Date**	**Full Citation**	**Comments**	**Cited in SSHAC Report ? (Y/N)**
Kourakos et al. 2019	2019	Kourakos, G., Dahlke, H.E., and Harter, T., 2019, Increasing groundwater availability and seasonal base flow through agriculatural managed acquifer recharge in an irrigated basin: Water Resources Research, v. 55, p. 7464-7492.	Analysis of of Managed Aquifer Recharge (MAR) principals applied to agricultural practices (Ag-MAR) in the northern Sacramento Valley. Modeling is used to evaluate short-term and long-term changes in groundwater storage and regional baseflow	**N**
Land 1984	1984	Land, P.E., 1984, Lost Hills Oil Field: Publication no. TR32, California Department of Conservation, Division of Oil and Gas, p. 1-16.	Cited in CASS Supplemental Report (2019)	**N**
Land IQ 2017	2017	Land IQ, 2017, Draft Report, 2014 Statewide Land Use Mapping: report prepared for the California Department of Water Resources, 17 p.	Cited in CASS Supplemental Report (2019)	**N**
Lettis 1982	1982	Lettis, W.R., 1982, Late Cenozoic stratigraphy and structure of the western margin of the central San Joaquin Valley, California: Ph.D. dissertation, University of California, Berkeley, 202 p. plus plates.	Cited in CASS Supplemental Report (2019)	**N**
Lofgren 1968	1968	Lofgren, B. E., 1968, Analysis of stresses causing land subsidence, in U.S. Geological Survey Research 1968: U.S. Geological Survey Professional Paper 600-B, p. 219-225.	Quantitative comparison of head changes to aquifer compaction near Pixley, CA. Includes discussion of effective stress changes in the confined aquifer	**N**
Lofgren 1975	1975	Lofgren, B. E., 1975, Land subsidence due to ground-water withdrawal, Arvin-Maricopa area, California: U.S. Geological Survey Professional Paper 437-D, 55 p.	Study to derive empirical relationships between head decline and land subsidence in the Arvin-Maricopa area	**N**
Lofgren and Klausing 1969	1969	Lofgren, B. E., and Klausing, R. L., 1969, Land subsidence due to ground-water withdrawal, Tulare- Wasco area, California: U.S. Geological Survey Professional Paper 437-B, 103 p.	Study to derive empirical relationships between head decline and land subsidence in the Tulare-Wasco area	**N**
Lucas and James 1976	1976	Lucas, Clifford V., and James, Lauren B., December 1976, “Land Subsidence and the California State Water Project,” Publication No. 121 of the International Association of Hydrological Sciences Proceedings of the Anaheim Symposium, California Department of Water Resources, Sacramento, California.	Cited in CASS (2017)	**N**
Luhdorff & Scalamini 2020	2020	Luhdorff & Scalamini Consulting Engineers, 2020, Westside Subbasin Grounwater Sustainability Plan	GSP for Westside Subbasin (Westlands Water District), encompassing much of SLFD and major subsidence bowls affecting the Aqueduct	**Y**
Luhdorff & Scalmanini 2018	2018	Luhdorff & Scalmanini, 2018, Hydrologic Conceptualization Report, Westside Basin: report prepared for Westlands Water District, 57 p. plus appendices.	Characterization of general hydrologic conditions in the Westside sub-basin	**Y**
Mall and Herman 2019	2019	Mall, N.K. and Herman, J.D., 2019, Water shortage risks from perennial crop expansion in California's Central Valley: Environmental Research Letters, v. 14. Available from https://iopscience.iop.org/article/10.1088/1748-9326/ab4035/pdf (last accessed 12/18/20)	Discusses expansion of permanent crop acreage in the SJV due to market forces. Estimates economic losses due to future water shortages for permanent crops in the SJV.	**N**

Reference	**Date**	**Full Citation**	**Comments**	**Cited in SSHAC Report ? (Y/N)**
Medwedeff 1989	1989	Medwedeff, D.E., 1989, Growth fault-bend folding at southeast Lost Hills, San Joaquin Valley, California: American Association of Petroleum Geologists Bulletin, v. 73, no. 1, p. 54-67.	Cited in CASS Supplemental Report (2019)	**N**
Merced County 2004	2004	Merced County, 2004, Annual Report of Agriculture: Merced County Department of Agriculture, 15 p.; available at https://www.co.merced.ca.us/ArchiveCenter/ViewFile/Item/243 (last accessed 12/8/17).	Cited in CASS Supplemental Report (2019)	**N**
Merced County 2015	2015	Merced County, 2015, Annual Report on Agriculture: Merced County Department of Agriculture, 13 p.; available at https://www.co.merced.ca.us/ArchiveCenter/ViewFile/Item/521 (last accessed 9/7/17).	Cited in CASS Supplemental Report (2019)	**N**
Miller et al. 1971	1971	Miller, R.E., Green, J.H., and Davis, G.H., 1971, Geology of the compacting deposits in the Los Banos-Kettleman City subsidence area, California: United States Geological Survey Professional Paper 497- E, 43 p.	Cited in CASS Supplemental Report (2019)	**N**
Morgan 2014	2014	Morgan, M.G., 2014, Use (and abuse) of expert elicitation in support of decision making for public policy: PNAS, v. 111, no. 20, p. 7176-7184.	Review of approaches for eliciting and incorporating expert opinion in decision making and engineering evaluation	**Y**
Mount et al. 2018	2018	Mount, J., and 30 co-authors, 2018, Managing drought in a changing climate: Four essential reforms: Public Policy Institute of California, 30 p., available from https://www.ppic.org/wp-content/uploads/managing-drought-in-a-changing-climate-four-essential-reforms-september-2018.pdf (last accessed 12/18/20)	Policy recommendations for managing future 2012-2016 type droughts.	**N**
Neely et al. 2021	2021	Neely, W. R., Borsa, A. A., Burney, J.A., Levy, M. C., Silverii, F., and Sneed, M., 2021, Characterization of groundwater recharge and flow in California's San Joaquin Valley from InSAR-observed surface deformation: Water Resources Research, v. 57, e2020WR028451. https://doi.org/10.1029/2020WR028451 (last accessed 4/10/21)	Use of InSAR data to map vertical displacement of the land surface in the San Joaquin Valley during and immediately after the 2012-2016 drought, and infer groundwater flow patterns	**N**
NRC 2012	2012	Nuclear Regulatory Commission, 2012, Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies: Washington D.C., US Nuclear Regulatory Commission, NUREG 2117, Revision 1.	SSHAC implementation guidance	**Y**
O'Hagan et al. 2006	2006	O'Hagan, A., Buck, C.E., Daneshkhah, A., Eiser, J.R., Garthwaite, P.H., Jenkinson, J.E., Oakley, J.E., and Rakow, T., 2006, Uncertain Judgements: Eliciting Experts' Opinions: John Wiley & Sons Ltd, England, 321 p.	Survey paper on methods for eliciting and incorporating expert opinion for engineering design	**N**
Pauloo et al. 2020	2020	Pauloo, R.A., Escriva-Bou, A., Dahlke, H., Fencl, A., Guillon, H., and Fog, G.E., 2020, Domestic well vulnerability to drought duration and unsustainable groundwater management in the California's Central Valley: Environmental Research Letters, v. 15, 044010, 14 p. Available from https://iopscience.iop.org/article/10.1088/1748-9326/ab6f10 (last accessed 1/4/2021).	Numerical model for domestic groundwater well failures during droughts due to falling groundwater levels. Model is tested against well failure data during the 2012-2016 drought, and is used to evaluate potentially longer future droughts.	**N**
Phillips and Tadayon 2006	2006	Phillips, J.V., and Tadayon, S., 2006, Selection of Manning's roughness coefficient for natural and constructed vegetated and non-vegetated channels and vegetation maintenance plan guidelines for vegetated channels in central Arizona: U.S. Geological Survey Scientific Investigations Report 2006-5108, 41 p.	Cited in CASS (2017)	**N**

Reference	Date	Full Citation	Comments	Cited in SSHAC Report ? (Y/N)
Pierce et al. 2018	2018	Pierce, D.W., Kalahnsky, J.F., Cayan, D.R., (Scripps Institution of Oceanography), 2018, Climate, drought, and sea level rise scenarios: report prepared for California's Fourth Climate Change Assessment, supported by California Energy Commission Agreement No. 500-14-005, publication number CNRA-CEC-2018-006, 71 p.	Forecasts of California future temperature and precipitation trends, and sea level rise.	**N**
Prokopovic h 1963	1963	Prokopovich, Nikola P., November 1963, Ultimate Amounts of Deep Subsidence — San Luis Canal, Reaches 3 to 4 – San Luis Unit – Central Valley Project, California", U.S. Bureau of Reclamation.	Cited in CASS (2017)	**N**
Prokopovic h 1969	1969	Prokopovich, N., 1969, "Prediction of Future Subsidence along Delta- Mendota and San Luis Canals, Western San Joaquin Valley, California," U.S. Bureau of Reclamation, Sacramento, California.	Cited in CASS (2017)	**Y**
Prokopovic h 1972	1972	Prokopovich, Nikola P., October 1972, "Land Subsidence Along San Luis Canal 1972 Progress Report," U.S. Bureau of Reclamation, Division of Design and Construction Geology Branch, Central Valley Project, San Luis Unit, Sacramento, California.	Cited in CASS (2017)	**N**
Prokopovic h 1976	1976	Prokopovich, Nikola P., December 1976, "Quality of Predictions of Land Subsidence Along Delta- Mendota and San Luis Canals in California, USA," Publication No. 121 of the International Association of Hydrological Sciences Proceedings of the Anaheim Symposium, Sacramento, California.	Cited in CASS (2017)	**N**
Rentschler and Bloch 1988	1988	Rentschler, M.S., and Bloch, R.B., 1988, Flexural subsidence modeling of the San Joaquin basin, California, in Graham, S.A., and Olson, H.C., eds., Studies of the Geology of the San Joaquin Basin: Society of Economic Paleontologists and Mineralogists, Pacific Section Field Trip Guidebook, v. 60, p. 29-57.	Cited in CASS Supplemental Report (2019)	**N**
Sarna-Wojcicki et al. 1984	1984	Sarna-Wojcicki, A.M., Bowman, H.R., Meyer, C.E., Russell, P.C., Woodward, M.J., McCoy, G., Rowe, J.J., Jr., Baedecker, P.A., Asaro, F., and Michael, H., 1984, Chemical analyses, correlations, and ages of Upper Pliocene and Pleistocene ash layers of east-central and southern California: United States Geological Survey Professional Paper 1293, 40 p.	Cited in CASS Supplemental Report (2019)	**N**
Smith et al. 2017	2017	Smith, R.G., Knight, R., Chen, J., Reeves, J.A., Zebker, H.A., Farr, T., and Liu, Z., 2017, Estimating the permanent loss of groundwater storage in the southern San Joaquin Valley, California: Water Resources Research, v. 53, p. 2133–2148; doi:10.1002/2016WR019861.	Technical summary of preconsoldiation stress and the relationship between head changes and subsidence; use of SAR data to estimate GW storage loss	**Y**
Sneed and Galloway 2000	2000	Sneed, M., and Galloway, D. L., 2000, Aquifer-System Compaction and Land Subsidence: Measurements, Analyses, and Simulations-the Holly Site, Edwards Air Force Base, Antelope Valley, California (No. 2000-4015): United States Geological Survey Water Resources Investigation Report 00-4015.	Technical summary of preconsoldiation stress and the relationship between head changes and subsidence	**Y**
Sunding and Roland- Holst 2020	2020	Sunding, D. and Roland-Holst, D., 2020, Blueprint economic impact analysis: Phase One results: 17 p., available from https://static1.squarespace.com/static/5e56f3cdb4c0de1f3af59166/t/5ebd753c879bb66cc1b0c74e/1589474628077/Blueprint.EIA.PhaseOne.2.28-v4+%281%29.pdf (last accessed 12/18/20)	Analysis by UC Berkeley economists of impact of SGMA implementation on SJV agricultural industry. Estimates that up to 1M acres of land will need to be fallowed, with $7.2B in annual farm revenue loss.	**N**
Swain et al. 2014	2014	Swain, D.L., Tsiang, M., Haugen, M., Singh, D., Charland, A., Rajaratnam, B., and Diffenbaugh, N.S., 2014, The extraordinary California drought of 2013/2014: character, context and the role of climate change: Bulletin of the American Meteorological Society, v. 95, no. 9, p. S3-S7	Cited in CASS Supplemental Report (2019)	**N**
Swain et al. 2018	2018	Swain, D.L., Langenbrunner, B., Neelin, J.D., and Hall, A., 2018, Increasing precipitation volatility in twenty-first century California: Nature Climate Change, https://doi.org/10.1038/s41558-018-0140-y, 10 p. plus supplementary material	Examines increasing precipitation volatitlity in California and potential changes in frequency of future extreme dry-to-wet precipitation events.	**N**

Reference	Date	Full Citation	Comments	Cited in SSHAC Report ? (Y/N)
USBR 1962	1962	U.S. Bureau of Reclamation, January 1962, Specification No. DC-5900, San Luis Canal Station 37+50 to Station 870+00 Plan and Profile As-Built Drawings.	Cited in CASS (2017)	**N**
USBR 1962	1962	U.S. Bureau of Reclamation, September 1962, Specification No. DC-5977, San Luis Canal Station 900+00 to Station 2050+00 Plan and Profile As-Built Drawings.	Cited in CASS (2017)	**N**
USBR 1963	1963	U.S. Bureau of Reclamation, March 1963, Specification No. DC-6148, San Luis Canal Station 2053+00 to Station 3907+00 Plan and Profile As-Built Drawings.	Cited in CASS (2017)	**N**
USBR 1964	1964	U.S. Bureau of Reclamation, February 1964, Specification No. DC-6280, San Luis Canal Station 3907+00 to Station 4404+00 Plan and Profile As-Built Drawings.	Cited in CASS (2017)	**N**
USBR 1964	1964	U.S. Bureau of Reclamation, August 1964, Specification No. DC-6344, San Luis Canal Station 4404+00 to Station 5449+00 Plan and Profile As-Built Drawings.	Cited in CASS (2017)	**N**
USBR 1969	1969	U.S. Bureau of Reclamation, March 1969, Specification No. 200C-752, “San Luis Canal Lining Modifications Station 3315+00 to Station 3355+90,” Central Valley Project, San Luis Unit, California.	Cited in CASS (2017)	**N**
USBR 1970	1970	U.S. Bureau of Reclamation, January 1970, “Deep Subsidence – Review and Progress Report San Luis Canal,” Project Development Division Geology Branch, Central Valley Project, San Luis Unit, Sacramento, California.	Cited in CASS (2017)	**N**
USBR 1970	1970	U.S. Bureau of Reclamation, May 1970, Specification No. DC-6859, “San Luis Canal Station 3134+00 to Station 3570+00 Canal Bank and Lining Modifications,” Central Valley Project, West San Joaquin Division, San Luis Unit, California.	Cited in CASS (2017)	**N**
USBR 1970	1970	U.S. Bureau of Reclamation, July 1970, “Designer’s Operating Criteria, San Luis Canal, San Luis Unit”, West San Joaquin Division, Central Valley Project, California, U.S. Bureau of Reclamation.	Cited in CASS (2017)	**N**
USBR 1974	1974	U.S. Bureau of Reclamation, December 1974, “Technical Record of Design and Construction Report, Volume 1: History, General Description and Geology,” Central Valley Project, West San Joaquin Division, San Luis Unit, California.	Cited in CASS (2017)	**N**
USBR 1974	1974	U.S. Bureau of Reclamation, October 1974, “Technical Record of Design and Construction, Volume VI: Design Water Ways and Detention Dams”, Central Valley Project, West San Joaquin Division, San Luis Canal Unit, California.	Cited in CASS (2017)	**N**
USBR 1982	1982	U.S. Bureau of Reclamation, February 1982, Specification No. 20-C0144, “San Luis Canal Lining Raise MP 87 to MP 172,” Central Valley Project, San Luis Unit, California.	Cited in CASS (2017)	**N**
USBR 2004	2004	U.S. Bureau of Reclamation, June 2004, Long-term Central Valley Project Operations and Plan, CV-OACP:Mid-Pacific Region, Sacramento, California. Available at https://www.usbr.gov/mp/cvo/OCAP/OCAP_6_30_04.pdf (last accessed 1/23/21)	Description of how CVP shortages are allocated among agricultural, municipal, and industrial contractors	**N**
USBR 2008	2008	U.S. Bureau of Reclamation, May 2008, Central Valley Project and State Water Project Operations Criteria and Plan Biological Assessment: Mid-Pacific Region, Sacramento, California. Available at https://www.usbr.gov/mp/cvo/OCAP/docs/OCAP_BA_2008.pdf (last accessed 1/23/21)	Description of how SWP shortages are allocated per 1994 Monterey Agreement	**N**
USGS 1984	1984	U.S. Geological Survey; Ireland, R.L.; Poland, J.F.; Riley, F.S., 1984, “Land Subsidence in the San Joaquin Valley, California, as of 1980,” USGS Professional Paper 437-I, 93 p.	Cited in CASS (2017)	**N**

State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES

PROBABILISTIC SUBSIDENCE FORECAST MODEL FOR THE CALIFORNIA AQUEDUCT SUBSIDENCE PROGRAM SAN JOAQUIN VALLEY, CALIFORNIA

DESIGN REPORT

APPENDIX B
Summary of Expert Interviews

August 18, 2023

1.0 Introduction and Narrative Summary

This document summarizes a series of interviews to elicit information and expert opinion relevant to forecasting future land subsidence. The document includes three sections:

1) A narrative summary (this section) of the interview responses
2) A digest of key responses to individual questions from the interviewees (Section 2)
3) Notes of all the interviews (Section 3)

The interviews were conducted in person and by phone over a six-month period in 2020. A total of 14 experts from academia, non-governmental organizations, journalism, the agricultural industry, and private consulting firms agreed to be interviewed. Experts included:

Fluvial geomorphologist and policy expert, Public Policy Institute of California (PPIC)
Consulting engineer with expertise in California water policy and implementation
Groundwater hydrologist, UC Davis, Land, Air and Water Resources (LAWR)
Engineer with expertise in environmental resources management, PPIC and UC Davis
Watershed and groundwater hydrologist, UC Davis, LAWR
Groundwater hydrologist, UC Davis, LAWR
California water development and resource management expert, PPIC
Engineer and systems optimization expert, UC Davis, LAWR
Environmental engineer and hydro-economic analyst, UC Merced
Grower, Sacramento Valley
Environmental policy and planning expert, Environmental Defense Fund
Journalist and author specializing in the California agricultural industry
Consultant specializing in water resources development and program implementation
California water policy expert, PPIC
Grower, San Joaquin Valley

Each expert was asked the same set of prepared questions regarding the implementation of the Sustainable Groundwater Management Act (SGMA), agricultural land use in the San Joaquin Valley, future climate and hydrologic uncertainty, and related issues. Following is a narrative summary of the questions and responses:

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

Full implementation of SGMA is here defined to be effective management of groundwater resources to eliminate overdraft and associated negative consequences, including subsidence. The 2020-2040 period is the time frame in which implementation is mandated to occur; GSAs are expected to comply with SGMA by 2040. Many experts believe there is a significant possibility (about 20-30%, or higher) that some GSAs will not be in full compliance by 2040. Although many of the experts expressed optimism that the law will eventually be fully implemented, in part because they believe the San Joaquin Valley farming community recognizes that current groundwater overdraft is unsustainable, several noted that the necessary water use reductions will require significant land fallowing and changes to the local economy. Given the magnitude of changes required, many of the experts interviewed do not believe that all currently over-drafted basins will be operating sustainably within 20 years (i.e., SGMA compliant). Several experts specifically identified the Kern and Tulare basins as most likely to be the last to come into balance and full compliance with the law.

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for implementation of SGMA?

The consensus of the experts interviewed is that progress toward sustainability initially will be slow and "noisy", with likely delays of 10 to 15 years before significant reductions in GWO that reduce the average subsidence rate are achieved. The experts generally believe the most critically over-drafted basins (e.g., Kern and Tulare basins) will be the last to show progress toward meeting SGMA sustainability goals. As evidence for likely slow progress in reducing GWO, some experts noted that most initial draft GSPs submitted for review in 2020 focus primarily on "supply side" remedies to supplement groundwater for irrigation and do not address the "demand side" of the GWO problem. One expert observed that most initial GSPs do not propose a "ramp-down schedule" for reducing groundwater withdrawals to meet a sustainable yield by 2040, and another did not expect GSPs to address this issue until the 2025 update at the earliest. Other expert assessments are that some water users will not make any progress toward implementing SGMA until forced to by the state and/or courts, and that at best groundwater overdraft may only be reduced by 50% over the next 20 years. Several experts noted that a recurrence of a 2012-2016 drought in the next 20 years will significantly reduce the likelihood of basins coming into balance by 2040.

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

The majority of experts believe that GWO in the SJV will probably end at or around 2040. Some experts believe there will be "substantial" but incomplete compliance with SGMA by 2040, with full compliance (i.e., basins in groundwater balance) taking an additional 5-10 years after the legislative deadline (i.e. around 2050). A minority of experts believes there is a substantial likelihood (20%-50%) that the status quo in groundwater pumping will continue until at least 2040, and possibly beyond.

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If delayed, by how many years?

Among the experts who answered this question, opinion ranges from "0% likelihood" to "90% certainty" that SGMA will be challenged in the courts. Some experts observed that agricultural interests may view litigation as a business strategy to maintain the status quo in groundwater use for as long as possible. One expert with strong ties to the Central Valley farming community believes the likelihood of litigation will depend on how the State approaches implementation and enforcement of SGMA. Other experts noted that although lawsuits probably will be filed, California water rights law is complex and that it will not be easy to stop statewide implementation of SGMA through the courts. One expert who is currently working with GSAs to develop implementation approaches said that growers so far are not "rattling the litigation saber".

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

Opinions ranged from "0% likelihood" to about a "30-50% chance" that a future legislature and governor may weaken or overturn SGMA. Some experts noted that a repeat of the 2012-2016 drought could mobilize agricultural interests to seek political relief from compliance with the law. One expert noted that even without another drought the required reductions in pumping will be "extreme" and possibly prompt challenges to the law. Another expert observed that the law could be weakened or softened by lack of funding for state oversight and regulatory compliance, rather than repealed outright. Several experts noted that if California continues to be a liberal ("blue") state, then there is "zero" to "very low probability" that the law will be overturned. One expert pointed out that SGMA was originally passed without a single vote of support from legislators representing the Central Valley, implying that survival of the law will probably not depend on whether it is supported or opposed by the farming community.

Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

Expert opinion on this question is mixed. Several experts declined to answer this as speculative. Some observed that there is an emerging belief or consensus in the ag community that sustainable groundwater management is in its best interest, and that "groundwater mining" is a "fringe sentiment". Others noted that there is a strong possibility that some farmers will refuse to implement SGMA, perhaps making a "business decision" to continue overdraft pumping until forced to stop. A couple of experts observed that groundwater "mining" by individual growers could have negative consequences for achieving sustainable yields within a basin, and thus GSAs will have an incentive for self-policing to control "bad actors". One expert noted that DWR is a key stakeholder in subsidence issues, and that the State has the option to "play hardball" and sue specific water users if their pumping is damaging public infrastructure.

What does the "post-SGMA" agricultural economy in the SJV look like?

Experts believe that major changes to San Joaquin Valley agriculture arising from full implementation of SGMA will include significant land fallowing and changes in cropping due to a reduction in available irrigation water. The experts do not believe it will be possible to fully replace the current annual groundwater overdraft of about 2.5 Maf (Escriva-Bou, 2019) with "new" surface water captured as runoff in the San Joaquin Valley or exported from the Delta. If anything, experts believe there will most likely be reductions in future exports from the Delta to mitigate the effects of rising sea level and salt-water intrusion. The experts generally believe that meeting the SGMA sustainability goals will require taking at least 10% (0.5 million acres) of current agricultural land out of production, and perhaps as many as 1.0 to 1.5 million acres will ultimately need to be fallowed. Most of this fallowing will be concentrated in the southern San Joaquin Valley. The experts predict that farmers will adapt to reductions in irrigation water by shifting crop types and trading water to minimize changes in overall agricultural productivity. Other changes may include operational and land consolidation as better capitalized farmers buy smaller farms; and expansion of solar energy operations onto land that goes out of agricultural production. In general, however, experts believe that farmers will adapt to new conditions, and that SGMA implementation will not significantly change the character of the San Joaquin Valley.

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future?

Most experts expect continued expansion of high-value permanent crops (orchards and vineyards) for at least the next decade. The main driver of this expansion is market forces (e.g., foreign demand for California almonds). One expert estimated that permanent crops may ultimately increase from about 30% of current agricultural land use in the San Joaquin Valley to 40% to 60%. Another expert estimated that acreage in permanent crops will continue to expand for the next 5-10 years, but at a progressively lower rate until some plateau is reached dictated by water availability and commodity prices.

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change the amount of precipitation that is currently captured and stored as surface water?

The consensus of the experts is that increasing global temperatures will translate into reduced snowpack in the Sierra Nevada, resulting in more winter runoff and less storage as snow. One expert noted that California has already moved into a winter climate where the mean temperature in the mountains is above freezing. California's reservoirs and water infrastructure were built to optimally manage spring snowmelt, not winter runoff. Higher average temperatures will also result in longer growing seasons, longer dry seasons, and increased evapotranspiration, all of which will strain available surface water supplies for agriculture.

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

Opinions on this question were split between recommendations to include both options in a probabilistic model, or preference for using the 1998-2017 overdraft rate to predict future subsidence in the next 20 years.

Note: Largely since the expert interviews were conducted, the DWR climate change group has provided CASP with statistical parameters for the modeled frequency and duration of future "design droughts", similar to the 2012-2016 drought. These parameters more directly model anticipated future hydrologic uncertainty than selectively sampling the historical subsidence rate record to represent future conditions.

How much of the current GWO can be replaced by expanded GW recharge?

Most experts who felt qualified to answer this question cited research by the Public Policy Institute of California (PPIC, 2019) that estimates approximately 0.5 Maf per year of surface runoff may be available to support expanded groundwater recharge ("managed aquifer recharge", or "Flood-MAR"). According to PPIC (2019) studies, the maximum runoff that is potentially available for Flood-MAR could be about 1.0 Maf per year; however, much of this water would be difficult and expensive to capture, and one expert noted that there are existing environmental benefits that will be lost if all this water is diverted to groundwater recharge. Although experts observed that expanded recharge and improved management of groundwater could do much to mitigate groundwater overdraft, they don't believe it will be sufficient to replace the average 2.5 Maf of annual overdraft in the SJV since 1998.

How will climate variability (wet/dry) change in the next 20 years? Next 50 years?

There is general agreement among the experts interviewed that climate variability (i.e., intensity and periodicity of alternating very wet and very dry periods) will likely increase in the coming decades (see Swain et al., 2018). Although the average annual precipitation may not change, the wet season is anticipated to shorten and intensity of rainfall during the wet months may increase. Several experts pointed to the 2012-2016 drought followed immediately by the very wet winter of 2017 as evidence that climate variability associated with global warming is "already here" and has "shown its hand." As one expert characterized it, California will receive more and "flashier" winter runoff, with the state's existing water storage and conveyance system needing to manage "water through a firehose".

Should we assume that another 2012-2016 drought could happen in the next 20 years? Next 50 years?

The experts who chose to answer this question believe there is a strong likelihood of a repeat of the 2012-2016 drought in the next 50 years, and a less probable but still very significant possibility of a repeat in the next 20 years.

Note: These views are captured by using statistical parameters provided by the DWR Climate Group for the frequency and duration of future "design droughts".

Speculatively, do you think there could be something we are not currently considering (an "unknown unknown") that could contribute to reducing GWO?

The intent of this question was to elicit thoughts and speculation about factors other than water availability and land use that could affect groundwater pumping and potential overdraft in the future. Responses included the following:

--Future changes in global markets and global demand for agricultural products may reduce the value of permanent crops relative to annual crops, reducing "demand hardening" for irrigation water
--A "paradigm shift" in groundwater management may re-orient priorities toward storage, as well as integrated management of ground water and surface water (to support habitat?)
--Political conflict may develop if overdraft significantly impacts the drinking wells of low-income communities, with unknown political and legal outcomes
--Depending on the length and severity of the coronavirus crisis, the availability of ag labor may be affected
--Future labor and immigration laws may affect the availability and costs of farm labor
--Will the state water board be willing to take greater political risks in managing water use? Many (currently unknown) physical realities will come up. SGMA implementation issues will arise.
--What approach will DWR take regarding implementation of SGMA? How will it be received by the ag community?
--What will create the best value for lands coming out of production?

2.0 Digest of CASP Expert Elicitation Responses

Experts Interviewed:

A = Fluvial geomorphologist and public policy expert, PPIC
B = Consulting engineer with expertise in California water policy and implementation
C = Groundwater hydrologist, UC Davis, LAWR
D = Engineer with expertise in environmental resources management, PPIC and UC Davis
E = Watershed and groundwater hydrologist, UC Davis, LAWR
F = Groundwater hydrologist, UC Davis, LAWR
G = California water development and resource management expert, PPIC
H = Engineer and systems optimization expert, UC Davis, LAWR
I = Environmental engineer and hydro-economic analyst, UC Merced
J = Grower, Central Valley
K = Environmental policy and planning expert, Environmental Defense Fund
L = Journalist and author specializing in the California agricultural industry
M = Consultant specializing in water resources development and program implementation
N = California water policy expert, PPIC
O = Grower, San Joaquin Valley

Note: Blank entries below indicate that an expert declined to comment on a particular question or issue

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

A: “SGMA will be implemented”. Farm community in SJV privately acknowledges the need for SGMA and sees implementation in its long-term interest
B: Don’t think SGMA will be fully implemented in 2040; estimate 20% probability that status quo will prevail through 2040
C: Greater than 75% likelihood that SGMA will be implemented by 2040; if SGMA can get a foothold, it will work
D: Going in the right direction. Don’t know what the future will bring. Will need to deal with hydrologic variability
E: 70-80% likely that SGMA will be fully implemented. "Full implementation” will not occur everywhere in the San Joaquin Valley
F: “80% likelihood that SGMA will be implemented”. Optimistic that most basins will be in balance by 2040. (20% estimate that SGMA will not be implemented primarily applies to uncertainty about Tulare basin)
G: In general, there will be “substantial compliance” with SGMA by 2040

H: SGMA will be “partly implemented” by 2040. Fully implemented in some basins; politics, difficulty in getting people organized will delay implementation elsewhere
I: Overall, optimistic. 80% likelihood SGMA will be implemented. Implementation failures will more likely be local (individual farmers and GSAs) than regional/basin-wide
J: SGMA will be difficult to implement. Anticipate a lot of opposition; lawsuits and legal issues. 50% chance SGMA won’t be implemented by 2040
K: Cautiously optimistic law will work. Recognize that it puts a lot on locals to figure it out
L: “Hope it will be implemented, but I have doubts too”. 60% likelihood that SGMA will be implemented by 2040. Not sure if DWR has staff to follow through with implementation
M: SGMA will be implemented. Give 80-90% probability that GSA’s will be sustainable by 2040.
N: “I hope so!”. Mitigation of “undesirable results” is a big gray area. A lot of leeway in how that is implemented/satisfied. May not resolve subsidence problems (by 2040)
O: “I don’t believe that SGMA will be fully implemented by 2040.”

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for implementation of SGMA?

A: “Noisy, slow” transition to sustainability. Can make “fair assessment” that ag users will continue to draw down groundwater levels for the next 10-15 years, but overdraft will end at or around 2040
B: GW overdraft not likely to be fully contained by 2040. May be able to cut current overdraft by 50% by 2040. Some GSA’s will wait for state to enforce the law before doing anything. Probably won’t see significant reduction in overdraft until 2035.
C: Regulations require GSP’s submit periodic progress reports; up to DWR to evaluate progress and take action. If DWR and state government are serious, then non-compliant GSAs will be flagged and state water board will act
D: Likely to have “undesirable results” between now and 2040. Some areas of the valley have more challenges in implementing SGMA Can others
E: No significant improvement in overdraft for minimum of 5-10 years; longer if we have another serious drought. May start to see positive effects in 15 years. GSA’s "haven’t yet achieved a complete change in mindset”
F: It will take 5-10 years to see real reductions in most basins. For most heavily over-drafted basins, will take the full 20 years to come into balance (e.g., Tulare basin)
G: Although another drought could affect implementation, will start seeing over-drafted basins come into balance within 10 years, or by 10 years. Some GSA’s won’t do anything to comply until forced to.
H: Expect to see beginning of compliance in 10 years (2030). Unless we see a string of wet years, don’t expect sudden outbreak of early compliance.
I: Probably take 10 years to see significant reductions in GWO. There will probably an acceleration in compliance before 2040.

J: Expect implementation of SGMA to be "very bumpy". Many districts open to implementation of SGMA, but success will depend on how cooperative DWR is with farmers
K: Expect to start seeing reductions in GWO in 5 years
L: (Timing of implementation) will depend on where farmers are (in the SJV); also, drought/future weather
M: GSAs need to come to understand that there's not enough water available to forego pump restrictions. Status quo through 2025; can expect a steepening curve of GW use reduction between 2030-2040
N: Starting to see beginning of management of GWO now (in some GSPs). GSA's are currently focused on supply side; not yet focusing on managing demand, which will be contentious and difficult. Implementation will be uneven
O: "I do think that some GSA's will be able to manage ground water before 2040 and reduce overdraft, but not very soon."

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

A: Overdraft will end at or around 2040
B: GW overdraft not likely to be fully contained by 2040. Estimate 20% probability that status quo will prevail through 2040.
C: After 2040, subsidence will be effectively reduced to zero. Probably not before 2040, however
D: SGMA is a "good path". Early adoption of sustainability desirable for long-term benefits.
E: In the long term (2040-2050 and beyond), SGMA goals likely achievable
F: Should be enough time between now and 2040 to plan and adjust for SGMA compliance
G: There will be "substantial compliance" with SGMA by 2040
H: SGMA will eventually eliminate GWO and subsidence after 2040.
I: Yes, by 2040
J: If implemented, expect SGMA will be successful in eliminating GWO by 2040. If by nothing else, through fallowing of land (1.0-1.5 M acres)
K: SGMA will be 75% effective in eliminating GWO by 2040 (75% of basins can "get there" (balance) by 2040). For the 25% not in compliance by 2040, estimate it will take an additional 10-15 years to reach balance
L: Cynical response is "No, because the state won't do what's necessary". Hopeful response: "Optimistic we'll see some (positive) change". Currently, this expert is "60% hopeful" (and 40% cynical)
M: It's all contingent on how hard DWR comes back (on GSAs) in reviews (of GSPs)
N: By 2040, we may be somewhat stabilized with respect to subsidence. SGMA says "measurable progress" is required. It will be important for DWR as a regulator to seriously hold GSAs feet to the fire
O: "I'm not sure if [SGMA] will ultimately be successful. I do believe that the glide path scenario is the best method for managing ground water overdraft"

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If delayed, by how many years?

A: Some ag landowners may conclude it is in their “business interest” to pump GW in spite of SGMA; may lead to court challenges to law
B:
C: (No basis for an informed answer)
D: Definitely possible. Likelihood is less than 50%, greater than 15%
E: 0% likelihood of SGMA being delayed by litigation or repealed by future legislature
F: “I don’t know” whether SGMA will be litigated or overturned by a future legislature/governor.
G: Greater probability of delay due to politics than litigation
H: “90% certainty” that SGMA will be challenged in court. Will probably result in a 5-20 year delay of full implementation of SGMA
I: Don’t think hostile litigation is likely. More likely to see GSAs suing each other than the state
J: Pretty confident there will be resistance. There are billions of dollars at stake, and SJV farmers have a lot of “get mad” money available for litigation if implementation is “crammed down” on them by DWR. SGMA could be tied up in courts for 30 years.
K: Estimate 10% likelihood that SGMA will be delayed by litigation
L: 80-90% possibility of litigation, unless the state comes up with creative ways to retire land. Don’t know if litigation can ultimately stop the law (SGMA), however.
M: Want to believe that GSAs will find adopting SGMA more desirable than litigation. Haven’t heard a lot of people “rattling the litigation saber”, but know some attorneys who think litigation is “inevitable”. Adjudication is a 10-15 year process
N: Can’t imagine this happening statewide. Lawsuits per se won’t stop implementation of the law. Water rights law is complex. In practice, (challenges to law) will be specific to a local area
O: “I do believe that litigation will play a major role in the slow completion of SGMA.”

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

A: Gives 25% probability to scenario that SGMA will be weakened or repealed
B: If we get another 2012-16 drought, legislature could step in to relax/exempt compliance
C: Those with interest in implementing SGMA will support and defend the law against attempts to weaken or eliminate it. No guarantee against the future, however
D: Repeat of 2012-2016 drought after 2030 could lead to political pressure to overturn law
E: 0% likelihood of SGMA being delayed by litigation or repealed by future legislature
F: Necessary reduction in GW pumping will be extreme; much land will need to go out of production. Consequently, wouldn’t be surprised if law is challenged.
G: Don’t think SGMA will be repealed outright, but could be softened/weakened by lack of funding and political will
H: Estimate 30-50% chance that SGMA is overturned legislatively. Law more likely to be weakened than completely overturned

I: Legislative intervention is possible; most likely to address access issues of “white areas vs gray areas” in SJV
J: Because stakes are very high, CA may see “fight of century” in the legislature over survival of SGMA. Implementation issues need to be solved by cooperation between agriculture and the state to avoid legislative fights
K: “Zero percent” likelihood that SGMA will be overturned by a future legislature
L: Don’t think that California will turn “red” and support wholesale repeal of SGMA
M: Very low probability of SGMA being repealed. “Repeal” would be an admission that the GW resource will be mismanaged until it is unusable
N: Cannot imagine repeal in California
O:

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the “post-SGMA” agricultural economy in the SJV look like?

A: (recommends reviewing PPIC studies on impacts of implementing SGMA on SJV ag)
B: Implementation of SGMA will have significant effect on ag land use (i.e., reduction in irrigated acreage). Only way to come into balance and eliminate GW overdraft. Shift in crop types to make profit with less water, but shift won’t affect trees (i.e., reduce permanent crops).
C: SGMA will not change the character of the SJV. More orchards, less field crops. More fallowing. Transition to solar energy production in some areas
D: Future SJV will look very similar to today. Maybe 10% of land will go out of production (approx. 500,000 acres). Probably won’t see a big change in overall productivity. It will be important to have mix of crops, including annual crops, to accommodate variable future hydrology
E: Future ag land use under SGMA will be an “optimization problem”. Diversification may be driven by market forces. Development of water markets has already begun
F: A lot less ag water use. Different crop types, different percentages than we have now
G: Anticipate consolidation of land as better-capitalized farmers buy smaller farms. Will lead to operational consolidation. Possible that bigger farmers take longer view in making cropping decisions
H: Bottom line: 0.5-1.0 million fewer acres of irrigated land. In addition to GWO, future ag will have to deal with salt balance problems in Tulare and Westside basins
I: Will see land fallowing, “concentration in value”. Reduction in grain production. More focus on fruits and nuts. Some shrinkage in livestock and dairy sectors. Some field crops will be more difficult to justify. Will see increased consolidation of farming operations; small farmers may be at a disadvantage to compete for water
J: Land fallowing will occur. Transition of a lot of current cropland to “dry land pasture or tumbleweeds”. Skeptical about local water markets being very effective at minimizing economic losses due to land fallowing and cropping changes
K: Anticipate a diversified post-SGMA ag economy

L: Ag will be “smarter, leaner, and more nimble”, focused on growing highest value crops (less alfalfa, no more mega-dairies)
M: Retirements will favor (i.e., relatively increase) permanent crops. Reductions will occur in marginal land and annual crops
N:
O: “I believe that GW pumping will be extremely limited in the future and as a result most farming will be converted to permanent plantings that can survive severe drought growing conditions. The only areas that will be able to continue to grow row crops will be in irrigation Districts that don’t rely on federal water.”

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co’s for the foreseeable future? Is there a foreseeable “peak” or plateau in conversion to permanent crops? If so, when?

A:
B: Next 10-15 years will continue to see transition of ag land to permanent crops. Less acreage in pasture. Demand for nuts is driving land use change
C: There will be additional orchards as crops traded in exchange for water rights
D: There will be continued expansion of permanent crops
E: Don’t believe the rapid transition to permanent crops (O/V) is likely to continue
F:
G: Don’t think that the trend of the last several decades towards more permanent crops will change significantly in near term
H: Permanent crops will increase from current 30% of ag land use to 40-60%. Market forces will lead to future mix of permanent and annual crops
I: Yes, with “concentration in value”
J: Yes
K: Likely see continued expansion of permanent crops.
L: Yes, there will be more expansion of permanent crops; at some point, could lead to a “nut glut”
M: More permanent crops for the next 5-10 years. Don’t expect to see almond expansion continuing at the same rate. Likely plateau. Commodity prices and water supply will determine ultimate acreage
N:
O: “Planting of permanent crops will continue for several more years and then will most likely stop.”

Agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance? If so, where will fallowing be concentrated?

A: Yes (endorses PPIC analyses)
B: Yes. Only way to get to SGMA compliance is to cut water use
C: PPIC study suggests 10% fallowing will be required. Fallowing will be focused in Kings, Tulare, Fresno and Kern counties (southern SJV)

D:
E: Yes; southern SJV
F: Not familiar with PPIC analysis, but believes necessary reduction in GW pumping will be extreme; much land will need to go out of production. Fallowing will be concentrated in southern SJV
G: Agree with PPIC analysis. Significant fallowing will have to occur for basins to come into compliance with SGMA
H: (Agree with PPIC analysis. See responses above)
I: (Agree with PPIC analysis)
J: Expect 1.0-1.5 million acres will have to go out of production. Most in the SJV
K: Possible that 750k-1.5M acres may go out of production. Fallowing will be concentrated in the Kern, Tulare regions of the southern SJV
L: Believe that the PPIC estimates of post-SGMA fallowing are too low; about 1 M acres will need to be retired
M: Agree with PPIC estimate of land retirement: approx. 700k acres will go out of production. Kern and Tulare basins will suffer larger than proportionate share of land retirement due to limited surface water availability
N:
O: “The first lands to be fallowed will be those in the white areas. Next will be those with lower grade soil.”

3) Impacts of climate change on surface water availability and use (specifically for the SWP)

Will increases in temperature and “precipitation volatility” (per Swain et al. 2018) significantly change the amount of precipitation currently captured and stored as surface water? If so, then how?

A: (recommends contacting experts at UCD LAWR for comment)
B: Agree with assessment of Mount et al. (2018) that less water will be available due to increased crop demands for water with rising air temps and longer dry seasons. Less snowpack means less water availability. Won’t be able to capture as much water in Sierra Nevada watersheds. Higher temperatures and more evapotranspiration mean less production for same amount of water.
C: With increasing temperatures: smaller snowpacks, increased growing seasons, increased evapotranspiration. Need to rethink how groundwater recharge can be a key piece to managing variable precipitation intensity and variable snowpack
D:
E: California has already moved into a winter climate with mean temperature above freezing in the mountains. Means more runoff and less storage as snow. Reservoirs/infrastructure not built to manage winter runoff. Don’t know how biology management will affect future water deliveries/exports from Delta
F: Warmer climate with less snowpack
G: Warmer winters will impact water supply and availability. Change in winter runoff patterns will have legal impacts. Increasing temperatures will have impact on when/where crops will

grow. Some crops require certain number of "cool days"; may not be viable. Will also impact investment strategies. Could make floodwater recharge more attractive
H: Sea level rise will require more outflow through the Delta to maintain water quality, reducing water available to export. Wetter, warmer winters will mean less storage as snow; less snowmelt
I: Impacts of SGMA implementation will be greater than those associated with climate change. Sea level rise is "the real threat"; will force changes in water management to prevent salt water from entering Delta pumps. There will be more intense droughts and floods
J:
K: Agree with Swain et al. analysis (shorter, more intense wet seasons; more extreme variability between drought/wet years). Need to maximize flood capture. Use groundwater as a bank; additional storage
L: Climate change <u>is</u> California. State does not need to make the case to farmers that climate change is already here
M: Don't have the infrastructure to manage significant changes in rainfall and snowpack. Probably won't make investment in SJV surface water reservoir
N:
O: "Climate change is increasing the volatility of our water supply and will continue. Without substantial increase in surface water storage we will be riding a roller coaster indefinitely."

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

A: "Business interest" on the part of some ag landowners to pump GW in spite of SGMA; may lead to court challenges to law
B: Much more likely that the state will threaten to sue specific water users to stop overdraft/subsidence. State will need to take direct action
C: (No basis for an informed answer)
D
E: There is a risk of some farmers/landowners not using groundwater sustainably. Most valley farmers are vested in long-term (sustainable) ag land use
F:
G:
H: "There is a 100% certainty that some farmers will refuse to embrace SGMA"
I: Potential for groundwater "mining" hopefully mitigated by requirements in SGMA for 5-year reporting
J: Farmers believe GW beneath the land is theirs to use. California water rights law is in their favor. "Every well that <u>can</u> be put in, <u>will</u> be put in between now and 2040"
K: Believe that "cultural shift" will lead to GSA's self-policing bad actors
L: Agree that this is a widespread sentiment among farmers. Farmers are going to pump until someone puts a lock on their pumps, or gives them a plan to help idle land
M: Fringe sentiment. Majority (of growers) believe sustainable GW management is a good thing

N: DWR is a key stakeholder on subsidence issues. Downstream water users will want DWR to act in its interest to prevent further loss of capacity in the CA Aqueduct. There are ways the state can play hardball, if the state wants to do it
O: "I do believe that some farmers will resist any regulations for pumping ground water. Farmers are generally very independent and resist any government intervention."

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

A:
B:
C:
D: Not necessarily. 1985-1998 one of wettest series of years in CA history. Need to be captured in range of possibility. 2005-2020 may be representative of next 10-20 years
E: Yes.
F: Overdraft estimates come out of models and the models need calibration. Probably accurate within 20-30%
G: Last 20 years more indicative of future than last 30 years
H: Would include both options in a subsidence hazard model, but weight the higher rate more conservatively for planning. Believes review of data justifies weighting both options equally in a logic tree
I: Last 20 years of GWO history is more relevant to predicting the next 20 years
J:
K: Believe that the last 20 years is more representative of the future (next 30 years)
L: The expansion of permanent crops over the past 20 years makes the average of the last 20 years of data more relevant than the average of the last 30 years
M: Gut says that the 1998-2017 data overly influenced by 2012-17 drought. The 1988-2017 period is probably more representative of a 50-year time frame.
N:
O: "GWO varies greatly from one basin to the next. Groundwater recharge will help the problem but everyone is planning to use the same flood water at this point. we will not be able to adequately recharge as quickly as will be necessary."

Are you aware of any other estimates of total GW overdraft in the SJV?

A: (Referred to data and analyses in 2019 PPIC study)
B:
C:
D
E: No

F:
G:
H:
J:
K: No
L:
M: Friant Water Authority has estimated GWO for the “Blueprint for The SJV”
N:
O:

How much of the current GWO can be replaced by expanded GW recharge?

A:
B:
C: (Recommends reviewing 2019 DWR report on Flood-MAR approach)
D: Approximately 0.5 Maf possibly available to support GW recharge. Approximately 1.0 Maf is the maximum available, but it would be difficult to capture (and not economically feasible). There is some environmental value in not capturing all surface water for GW recharge (refer to 2018 PPIC report for more info)
E: Some groundwater recharge is happening from Sierra Nevada mountain block to east; however, magnitude is uncertain and there is a lag time between big rainfall/snow years like 2019 and effects on GW elevations. Capturing runoff for groundwater recharge “won’t save us”
F: Flood-MAR in multiple basins, plus management, could mitigate GW overdraft. Shift of water storage from surface reservoirs to GW storage will involve legal challenges
G:
H: PPIC estimates are “pretty robust” (see Escriva-Bou et al.)
I: About 0.5 Maf/yr (refers to PPIC analysis)
J:
K:
L:
M: PPIC’s estimate of 900k af/yr replacement of GWO by new GW storage is likely too high, and DWR’s estimate is probably too low. Gut feeling is that 500k-600k of new GW storage in southern SJV can be affordably developed
N:
O:

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

A: Consultants hired by independent water agencies and ag businesses
B: Possibly Mojave Water Agency, SCVWD, MWD
C: Don’t know of anyone else doing this type of modeling
D
E:
F: No one

G: (suggests asking Jay Lund, UCD LAWR)
H: Local water districts may be doing independent modeling
I: Large GSA’s likely do their own modeling
J:
K: Likely private consultants working for GSAs
L:
M: Sub-basin models available; built on platforms of USGS and DWR models
N:
O: **“**I don’t know.”

7) Future climate variability?

How will climate variability (wet/dry) change in the next 20 years? Next 50 years? i.e., has climate change “already happened”, such That The past 20-30 years is indicative of the next 20-30 years?

A: “Climate change” is already here; i.e., 2012-2016 is what droughts are going to look like going forward
B: (decline to comment; recommend talking to climate experts)
C:
D: Potential effects of climate change on groundwater availability not well characterized
E: Climate changes are going to continue to intensify
F: Winter runoff will replace snowpack
G: Climate change in California has “revealed its hand”.
H: Average temperature will increase. Sea level will increase. Crop water demand will go up. There will be less water available from The Delta
I: "Climate change is a slow process” (so may not see significant changes in next 30-50 years relative to previous 30 years); Believes last 20-30 years is a good predictor of next 20-30 years
J:
K:
L: Drought is a specter. Farmers talking about using more groundwater banking (as hedge against drought/climate variability)
M:
N:
O: “I don’t think that future climate variability will change that much in the next 20 years. I do believe that extreme events will increase making capturing moisture when available even more paramount. I have no doubt that we will see extreme drought years in the next 20 years.”

Do you agree with Swain et al. (2018) model with predicted increase in frequency of extreme wet/extreme dry events?

A: It’s now the conventional wisdom (i.e., Swain et al. model)
B: (decline to comment; recommend talking to climate experts)
C:

D: Yes
E: Yes
F: More and "flashier" winter runoff; we will get "water through a firehose"
G: Variability is going to get worse/increase in magnitude
H:
I:
J:
K: Believe that 2012-2016 droughts will become more frequent in the next 50 years
L: Might start to see more partnerships between "almond guys" and "rice guys" for trading water
M:
N:

Should we assume that another 2012-2016 drought could happen in the next 20 years? Next 50 years?

A: (Recommends papers by Swain et al)
B: (decline to comment; recommend talking to climate experts)
C: "Very likely" to see another 2012-2016 drought in the next 20 years
D: Yes
E: Yes
F:
G:
H: There will "almost certainly be a repeat of the 2012-2016 drought within the next 50 years"
I:
J:
K:
L:
M:
N:

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

A:
B:
C: No "unknown unknowns". With respect to GWO, no sequence of buried issues; fairly straightforward water mass balance. Lawsuits may be source of delays (for SGMA implementation)
D: Future global markets? Future changes in demand for SJV ag products? Responses to future trade agreements? Future labor availability? (i.e., future immigration and labor laws) Potential for litigation
E: There are several basins that don't use surface water ("white areas"); rely on GW pumping only. Some GSA's planning to keep all water flowing into their boundaries. If so, "land-locked"

GSA’s won’t be able to supplement GW use with surface water. Can’t come into compliance with SGMA. State water board has taken fairly “hands off” approach to managing water use; need for state board to take more risks (political risks?) to address these issues
F: “Not impossible” that there could be a paradigm shift in GW management. Reorient priorities toward storing GW? Potential shift to “total” (integrated?) GW + surface water management.
G: Politics is big variable. Coronavirus may have long-term impact on ag labor availability. Future immigration policies could impact farmers’ crop selection. Overdraft will impact drinking wells of low-oncome communities; political conflict possible.
H: There is a 100% certainty of a significant future “unknown unknown”. Nothing will alter the fundamental mass balance of available water vs. use beyond 10-20% at the margin. DWR should prepare for multiple contingencies (e.g., not recovering 100% of design capacity of CA Aqueduct)
I: Many (currently unknown) physical realities will come up. SGMA implementation issues will arise. Seawater desalinization may become cheaper. Bottom line: 15% of ag water that comes from GWO is unlikely to be replaced from other sources
J: Big unknown is the culture within DWR. Is DWR open to cooperation? “Open hand” approach can lead to a lot of success. Farmers are very independent and don’t like being coerced. DWR needs an “ambassador”, a trusted partner to work with farmers. Looking for cooperation to help ag community survive.
K: Manage groundwater and surface water as an integrated system. Need to look at this problem holistically. Possible long-term impacts on food demand from COVID?
L: Don’t know if we can accurately forecast future of water trading; could be very important
M: Create deliberate habitat regions versus blind retirement of land?
N: How do we create value for lands coming out of production? Deploy solar and wind? Solar could occupy 9-10% of land coming out of production
O: “We should be bringing more water through the Delta by using subsurface drains.”

3.0 Notes of Individual Expert Interviews

Expert A, PPIC, CASS Risk Interview, 23 Jan 2020

Expert A is a senior fellow at the PPIC Water Policy Center. He is an emeritus professor of earth and planetary sciences and founding director of the Center for Watershed Sciences at the University of California, Davis. A geomorphologist who specializes in the study of rivers, streams, and wetlands, his research focuses on integrated water resource management, flood management, and improving aquatic ecosystem health. He has served on many state and federal boards and commissions that address water resource management issues in the West. He has published more than a hundred articles, books, and other publications, including the seminal book *California Rivers and Streams* (UC Press). He holds a PhD and MS in earth sciences from the University of California, Santa Cruz.

1) What do you think is the most likely outcome of SGMA?

--Thinks SGMA "will be implemented"
--Farm community in SJV privately acknowledges the need for SGMA; sees implementation in long-term interest
--Can make "fair assessment" that ag users will continue to draw down groundwater levels for the next 10-15 years, but that overdraft will end at or around 2040
--"Noisy, slow" transition to sustainability
--Fundamental issue for ag in future is "demand management"
--Beware of "black swan" drought events (e.g., 2012-2016) that will require pumping and cause overdrafting that can't be accommodated/recovered by GW management in subsequent years
--Gives 25% probability to scenario that SGMA will be weakened or repealed

2) What is the forecast for future expansion of orchards/vineyards in the SJV?

--Recommends reviewing 2019 PPIC study and appendices for modeling of GW supply vs. ag needs
--Also, PPIC analyses of economic tradeoffs between high-value perennial crops and cost of extracting deep GW
--Recommends contacting Ellen Hanak, Alvar Escriva-Bou and Josue' Medellin-Azuara from PPIC

3) What research has been or is being done on the impacts of climate change on surface water availability (specifically for the SWP)?

--"conventional wisdom" is that the future will be characterized by increased extremes in wet and dry periods
--"Climate change" is already here; i.e., 2012-2016 is what droughts are going to look like going forward
--Recommends papers by Swain et al.
--Recommends contacting Graham Fogg, Helen Dahlke and Thomas Harter at UCD LAWR for insights on numerical models of future GW use scenarios

4) What future developments (e.g., changes in land use; creation of new offstream storage; water-trading among GMAs; Chinese boycott of US almonds; etc.) could reduce pressure on farmers to pump groundwater?

--New offstream storage being proposed south of Delta is "marginal" and will not solve "big problem"

5) Anecdotal accounts from SJV indicate some (many?) farmers along the aqueduct are considering a strategy of freely pumping GW up until 2040, then letting the State condemn their land and taking a cash payout rather than accept permanent GW management/use restrictions. Comment?

--As noted above, believes SGMA will likely be implemented
--However, acknowledges the "business interest" on the part of some ag landowners to pump GW in spite of SGMA law; may lead to court challenges to law

6) What models of future SWP deliveries should be reviewed to assess incentives to pump GW?

--Referred to data and analyses in 2019 PPIC study
--Does not believe additional water will come through the Delta; if anything, could see 200k to 300k af annual reduction in Delta supply to CVP/SWP

7) Are you aware of any estimates of total GW withdrawal to mitigate deficits in SWP/CVP allocations?

-
-Referred to data and analyses in 2019 PPIC study

8) In addition to USGS, who is modeling response of SJV aquifer to GW pumping?

--DWR has a model ("it isn't very good"); also, "every consultant in the SJV with MODFLOW" is doing GW modeling

Expert B, CASS Risk Interview, 2 March 2020

Expert B is a consultant who works with water, flood, and other natural resources managers and stakeholders to help them become more effective at addressing complex challenges within their watersheds and groundwater basins.

1) What do you think will be the most likely outcome of SGMA?

--Don't think SGMA will be fully implemented in 2040
--Estimate 20% possibility that SGMA will be overturned
    Higher likelihood if Trump stays in office for second term
    As long as farmers have sympathetic ear, will try to overturn law
    If law is overturned, it will be "business as usual" (status quo)

--If SGMA stays in place, 60-70% probability the law will not be fully effective
    GW overdraft not likely to be fully contained by 2040
    Practically speaking, draft GSP's to reduce overdraft are not sufficient
        Early GSP drafts "entirely unrealistic" re: plans to curtail overdraft
        May be able to cut current 0.5 maf/yr overdraft by 50% by 2040
    Some GSA's will wait for state to enforce the law before doing anything
    Probably won't see significant reduction in overdraft until 2035

--If we get another 2012-16 drought, legislature could step in to relax/exempt compliance
What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If it is delayed, then by how many years?

--Estimate 20% probability that status quo will prevail through 2040

--Would place highest weight on late implementation (> 2035)

--Assign very low likelihood that SGMO will agree to a non-zero "manageable" subsidence rate
    DWR will have to insist on "zero subsidence" as a reviewer
    GSP's cannot allow for continued subsidence

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

--Implementation of SGMA will have significant effect on ag land use
    "Only way to come into balance" (i.e., no GW overdraft)

--Next 10-15 years will continue to see transition of ag land to permanent crops
    Less acreage in pasture

Demand for nuts driving land use change

--Probably see more water trading

Orchards/vineyards will buy water previously used for lower-value crops

-- Shift in crop types to make profit with less water, but shift won't effect trees

--Water trading will reduce effects of SGMA on ag economy, but it will not create "new water" to reduce the current overdraft

--Local politics will likely work against SGMA implementation. GSA reps are "local electeds". In the position of effectively cutting their neighbors' water use.

Politics are "cutthroat" in Kern Co.

Powerful local influencers for status quo.

--Recommend contacting Lester Snow for additional input

3) What are the most likely impacts of climate change on surface water availability for the SJV (specifically for the SWP)?

--Agree with assessment of Mount et al. (2018) that less water will be available due to increased crop demands for water with rising air temps and longer dry seasons

Less snowpack means less water availability

Won't be able to capture as much water in SN watersheds

--Higher T°'s and more evapotranspiration mean less production for same amount of water

--Most likely new infrastructure is Sites and enlarged Los Vaqueros

New storage will only contribute at margin, not significantly reduce 0.5 maf overdraft

--Optimistically, groundwater recharge will only replace about 20% of overdraft

4) What are the most likely future developments (e.g., changes in land use; creation of new offstream storage; water-trading among GMAs; "re-operation" of surface water supplies; groundwater recharge; Chinese boycott of US almonds; etc.) that could reduce need to pump groundwater?

--Only way to get to SGMA compliance is to cut water use

5) Anecdotal accounts from SJV indicate some (many?) farmers are considering a strategy of freely pumping GW up until 2040, then letting the State condemn their land and taking a cash payout rather than accept permanent GW management restrictions. Comment?

--Much more likely that the state will threaten to sue specific water users to stop subsidence
    State will need to take direct action

--State could offer to assist farmers in moving wells to areas outside of influence on aqueduct
    Could proceed via trade: provide new turnout in exchange for moving wells
    Need to develop data/models establishing zone of GW overdraft
    Locals could negotiate settlement with state within 5 years
    Non-structural solution, much better chance of direct influence on water use
    Some GSA's see this as an opportunity to barter
        "perpetrator and victim"

6) Evaluation of historic GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

Are you aware of any other estimates of total GW overdraft?

7) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

--Mojave Water Agency may be modeling subsidence
--Santa Clara Valley Water District also may have done subsidence modeling
--MWD may be doing subsidence modeling

8) Assume that DWR sets an "acceptable" or "manageable" rate of subsidence as the target for post-SGMA GW management. Also assume that GMAs accept and buy off on this rate. Given this scenario, what are your expectations about compliance and enforcement?

(see answers to previous questions)

9) Future climate variability?

(decline to comment; recommend talking to climate experts)

10) What are realistic options for recharging the deep aquifer below the Corcoran clay?

(see answers to previous questions)

Expert C, CASS Risk Interview, 25 March 2020

Expert C conducts groundwater and vadose zone research with emphasis on numerical modeling, stochastic analysis, and field characterization of soil and groundwater flow and contaminant transport, application of research efforts to groundwater quality, non-point source pollution, and groundwater resources problems in the State of California.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--Greater than 75% likelihood that SGMA will be implemented by 2040
--Framework for implementation of SGMA is in place and set up correctly
--Political will is currently "there" for implementing SGMA (may change, however)
    AZ had similar program, but political support and funding failed
--If SGMA can get a foothold, it will work

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?

--Regulations require GSP's submit periodic progress reports; up to DWR to evaluate progress and take action
--If DWR and state government are serious, then non-compliant GSAs will be flagged and state water board will act

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a "glide path" implementation of SGMA?

--After 2040, subsidence will be effectively reduced to zero. Probably not before 2040, however
--"Glide path" implementation most likely
    Question for DWR: what is "zero" after 2040? What is an acceptable/manageable rate?
--How much do we (CA public) want the state to assist growers in implementation vs. just setting boundaries/rules? Don't know where CA is going to go on this
    Will state support people getting through this with minimum effects on their lives?
--Think we can do this (SGMA). CA is not so water-poor that we can't do this
--GWO can be addressed. People in affected areas know that they are living on borrowed time
--Not an insurmountable problem

What likelihood do you assign to a scenario where DWR and water contractors jointly agree to tolerate and pay for (respectively) a non-zero "manageable" subsidence rate?

--Depends on balancing costs vs. value of crops

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If it is delayed, then by how many years?

--(No basis for an informed answer)

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--Those with interest in implementing SGMA will support and defend the law against attempts to weaken or eliminate it.
No guarantee against the future, however

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" ag economy in the SJV look like?

--PPIC report shapes (his) thinking
--SGMA will not change the character of the SJV
--More orchards, less field crops
--More fallowing
--Transition to solar energy production in some areas

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--Additional orchards as crops traded in exchange for water rights
--Don't have to trade water across geographic boundaries, just trade crops

Agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance?
If so, where will fallowing be concentrated? Kern basin area?

--PPIC study suggests 10% fallowing will be required
--Fallowing focused in Kings, Tulare, Fresno and Kern counties (southern SJV)

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change amount of precipitation that is currently captured and stored as surface water? If so, then how?

--with increasing temperatures: smaller snowpacks, increased growing seasons, increased evapotranspiration
--resilience to 2012-2016 event will be higher in future
--Need to rethink how groundwater recharge can be a key piece to managing variable precipitation intensity and variable snowpack

How much additional applied ag water will be required due to higher temperatures and increased evapotranspiration?

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

--(No basis for an informed answer)

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

Are you aware of any other estimates of total GW overdraft in the SJV?

There is a decent correlation between rate of GWO (per PPIC analysis) and the rate of subsidence measured by repeated precise surveys along the Aqueduct. Do you think anticipated future GWO would a good proxy for predicting subsidence?

How much of the current GWO can be replaced by expanded GW recharge?

--(Recommends reviewing 2019 DWR report on Flood-MAR approach)
--incentives and needs of growers will drive recharge
--Impediments?
    Existing water rights
    Water quality issues
    Natural water quality
    Constraints on recharge due to crop type
    Management of "agronomic impacts"

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

--Don’t know of anyone else doing this type of modeling

7) Future climate variability?

How will climate variability (wet/dry) change in the next 20 years? Next 50 years?
i.e., has climate change “already happened”, such that the past 20-30 years is indicative of the next 20-30 years?

Do you agree with Swain et al. (2018) model with predicted increase in frequency of extreme wet/extreme dry events?

Should we assume that another 2012-2016 drought could happen in the next 50 years?
--2012-2016 drought very similar to drought in 1920’s-30’s; “not an isolated event”
--Just looking at a graph, 2012-2016 drought could happen again
--“Very likely” to see another 2012-2016 drought in the next 20 years

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--No “unknown unknowns”
--With respect to GWO, no sequence of buried issues; fairly straightforward water mass balance
--Lawsuits may be source of delays

Expert D, CASS Risk Interview, 26 March 2020

Expert D is a research fellow at the PPIC Water Policy Center. His research explores integrated water, energy, and environmental resources management, including systems approaches, simulation and optimization of economic-engineering models, and climate change analysis. Previously, he worked as a civil engineer, managing and developing large infrastructure projects for local and regional governments and consulting firms in Spain. He holds a PhD and MS in water and environmental engineering and a BS in civil engineering from the Polytechnic University of Valencia in Spain, as well as an MS in agricultural and resource economics from the University of California, Davis.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--Going in the right direction
--Implementation by 2040 is a “static scenario”; don’t know what the future will bring
    Will need to deal with hydrologic variability
--Many potential pathways to sustainability
--GSPs represent a “first good step”; recognition of the problem

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a “glide path” implementation of SGMA?

--Likely to have “undesirable results” between now and 2040
--GSA’s are dominated by ag interests
--“Glide path” may be actions taken to avoid economic disruptions
    Externalities not fully incorporated in GSP’s
--Some areas of the valley have more challenges in implementing SGMA than others

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--SGMA is a “good path”
--More GWO mitigated early in the process will provide protection against exceeding 2015 levels during next drought
--Early adoption of sustainability desirable for long-term benefits

What likelihood do you assign to a scenario where DWR and water contractors jointly agree to tolerate and pay for (respectively) a non-zero “manageable” subsidence rate?

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If it is delayed, then by how many years?
What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--Definitely possible
Likelihood is less than 50%, greater than 15%
--Repeat of 2012-2016 drought after 2030 could lead to political pressure to overturn law

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" ag economy in the SJV look like?

--Likely that some land will go out of production
--Not a lot of water available to meet overdraft
--Maybe 10% of land will go out of production (approx. 500,000 acres)
--Large potential to adapt by shifting to high-value crops; could limit reduction in crop revenue to 5%
--Future SJV will look very similar to today
--Over the past several decades Fresno County has decreased acreage in ag land (due to urbanization and increased soil salinity), but production has gone up
--Probability won't see a big change in overall productivity
--Example: see alfalfa going out of production because it can be shipped into areas where it is needed
--It will be important to have mix of crops, including annual crops, to accommodate variable future hydrology

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--There will be continued expansion of permanent crops

Agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance?
If so, where will fallowing be concentrated? Kern basin area?

How long would it take at current or higher GWO rates before GW becomes too expensive to pump relative to value of crops?

Are there other experts in this area we should reach out to?

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change amount of precipitation that is currently captured and stored as surface water? If so, then how?

How much additional applied ag water will be required due to higher temperatures and increased evapotranspiration?

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

--Not necessarily. 1985-1998 one of wettest series of years in CA history. Need to be captured in range of possibility
--2005-2020 may be representative of next 10-20 years

There is a decent correlation between rate of GWO (per PPIC analysis) and the rate of subsidence measured by repeated precise surveys along the Aqueduct. Do you think anticipated future GWO would a good proxy for predicting subsidence?

--Yes

How much of the current GWO can be replaced by expanded GW recharge?

--Approximately 0.5 Maf possibly available to support GW recharge
--Approximately 1.0 Maf is the maximum available, but it would be difficult to capture (and not econ feasible)
--There is some environmental value in not capturing all surface water for GW recharge
--see 2018 PPIC report for details

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

7) Future climate variability?

How will climate variability (wet/dry) change in the next 20 years? Next 50 years?
i.e., has climate change "already happened", such that the past 20-30 years is indicative of the next 20-30 years?

--Potential effects of climate change on groundwater availability not well characterized
--Good studies of how climate change will effect runoff in Colorado River watershed

Should we assume that another 2012-2016 drought could happen in the next 50 years?

--Yes

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--Future global markets?
--Future changes in demand for SJV ag products?
--Responses to future trade agreements?
--Future labor availability? (i.e., future immigration and labor laws)
--Potential for litigation

Expert E, CASS Risk Interview, 27 March 2020

Expert E is an academic research hydrologist.
Statement of Expert E: "The research interests of my lab center around the science of catchment hydrology, experimental hydrology and hydrology-climate interactions in both nearly pristine and human-impacted landscapes. A primary goal of our research is to contribute to a better mechanistic understanding of hydrological processes and their links to climate and biogeochemical cycling. For our research we draw on a diverse suite of methods and techniques including (i) manual and automated field instrumentation and monitoring, (ii) multivariate/geo/spatial statistics, (iii) geographic information systems (GIS) and web-based GIS, (iv) stochastic hydrology and time series analysis, and (v) distributed watershed modeling and model development. This methodological approach and research has led to the discovery of tipping points and threshold behavior (e.g. in runoff generation) in hydrologic systems and the importance of changes in boundary conditions or system states (e.g., changes in antecedent moisture conditions, snow cover extent on glaciers) as underlying controls."

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--70-80% likely that SGMA will be fully implemented
--"Full implementation" will not occur everywhere in the San Joaquin Valley
    Less likely in critically overdrafted basins
--Subsidence and drivers comprise "dynamic system"; climate is "pushing against us"

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a "glide path" implementation of SGMA?

--Time of implementation depends on outreach
--No significant improvement in overdraft for minimum of 5-10 years; longer if we have another serious drought
--May start to see positive effects in 15 years
--Haven't read draft GSPs, but doubt if they anticipate a repeat of 2012-2016 drought
--GSA's "Haven't yet achieved a complete change in mindset"

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--In the long term (2040-2050 and beyond), SGMA goals likely achievable

What likelihood do you assign to a scenario where DWR and water contractors jointly agree to tolerate and pay for (respectively) a non-zero "manageable" subsidence rate?

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If it is delayed, then by how many years?
What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--0% likelihood of SGMA being delayed by litigation or repealed by future legislature

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" ag economy in the SJV look like?

--"Don't disagree" with PPIC assessment of potential land fallowing
--Farmers have always adapted
    Big companies will adapt and shift
    Will have to see what small farmers do to survive
--Future ag land use under SGMA will be an "optimization problem"
--Diversification may be driven by market forces
--Development of water markets has already begun
--Water trading not significantly limited by infrastructure at present
    Accounting within basins is important
--Future reliability of infrastructure is a concern
    State and fed facilities not getting any younger
    Long time for Delta Conveyance and other new facilities to come on line
    Without new investment in infrastructure, can't move more water thru system

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--Don't believe the rapid transition to permanent crops (O/V) likely to continue

Agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance?
If so, where will fallowing be concentrated? Kern basin area?

--Yes; southern SJV

How long would it take at current or higher GWO rates before GW becomes too expensive to pump relative to value of crops?

Are there other experts in this area we should reach out to?

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change amount of precipitation that is currently captured and stored as surface water? If so, then how?

--California has already moved into a winter climate with mean T° above freezing in the mountains
    Means more runoff and less storage as snow
    Reservoirs/infrastructure not built to manage winter runoff
--Don't know how biology management will affect water deliveries/exports from Delta
--Less than 50% probability for net increases in water delivery to southern SJV from Delta

How much additional applied ag water will be required due to higher temperatures and increased evapotranspiration?

--Hotter climate will affect GW recharge. Higher T°'s means higher ET; less recharge, because recharge only occurs after soil is saturated

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

--There is a risk of some farmers/landowners not using groundwater sustainably
--Most valley farmers are vested in long-term ag land use
--Very unfortunate if "black sheep" threaten compliance within a basin

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

--Yes

Are you aware of any other estimates of total GW overdraft in the SJV?

--No

There is a decent correlation between rate of GWO (per PPIC analysis) and the rate of subsidence measured by repeated precise surveys along the Aqueduct. Do you think anticipated future GWO would a good proxy for predicting subsidence?

--Yes
--Don't have good estimates of actual GW storage in SJV
--Water levels are indirect measurements of current processes

How much of the current GWO can be replaced by expanded GW recharge?

--Much GW recharge in SJV is from ag irrigation. Practices to optimize irrigation have reduced infiltration
--Some recharge is happening from Sierra Nevada mountain block to east; however, magnitude is uncertain and there is a lag time between big rainfall/snow years like 2019 and effects on GW elevations
--Also: there is a lag time in the response of the regional aquifer system to overdraft during 2012-2016 drought. System hasn't yet fully recovered from the drought
--Capturing runoff for groundwater recharge "won't save us"

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

7) Future climate variability?

How will climate variability (wet/dry) change in the next 20 years? Next 50 years?
i.e., has climate change "already happened", such that the past 20-30 years is indicative of the next 20-30 years?

--Feb 2020 was driest Feb on record in past 150 years
--Sac River flows are low
--Climate changes are going to continue to intensify
--As a country, we are not taking any action to curb global warming

Do you agree with Swain et al. (2018) model with predicted increase in frequency of extreme wet/extreme dry events?

--Yes

Should we assume that another 2012-2016 drought could happen in the next 50 years?

--Yes

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--There are 21 critically over-drafted basins
--There are several basins that don’t use surface water (“white areas”); GW pumping only
    Some GSA’s planning to keep all water flowing into their boundaries
    If so, “land-locked” GSA’s won’t be able to supplement GW use with surface water
    Can’t come into compliance with SGMA
--GSA’s “making run for high surface flows to recharge”
--Some water rights should be given to “white areas”
    Base water rights on need rather than who comes first
--State water board has taken fairly “hands off” approach to managing water use; need for state board to take more risks (political risks?)

Expert F, CASS Risk Interview, 1 April 2020

Expert F conducts research in groundwater contaminant transport; groundwater basin characterization and management; geologic/geostatistical characterization of subsurface heterogeneity for improved pollutant transport modeling; numerical modeling of groundwater flow and contaminant transport; role of molecular diffusion in contaminant transport and remediation; long-term sustainability of regional groundwater quality; vulnerability of aquifers to non-point-source groundwater contaminants.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--Optimistic most basins will be in balance by 2040
--Should be enough time between now and 2040 to plan and adjust for SGMA compliance
--"80% likelihood that SGMA will be implemented"
--(assumes law holds together and political will for implementation continues)

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a "glide path" implementation of SGMA?

--It will take 5-10 years to see real reductions in most basins
--For most heavily overdrafted basins, will take the full 20 years to come into balance (e.g. Tulare basin)
--20% likelihood that law not implemented (see above) primarily relates to Tulare basin

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If it is delayed, then by how many years?
What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--"I don't know" whether SGMA will be litigated or overturned by a future legislature/governor
--Hard to argue that the law is not in everyone's best interest
--Necessary reduction in GW pumping will be extreme; much land will need to go out of production. Consequently, wouldn't be surprised if law is challenged

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" ag economy in the SJV look like?

--Lot less ag water use
--Different crop types, different percentages than we have now

Agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance?
If so, where will fallowing be concentrated? Kern basin area?

--Not familiar with details of PPIC study
--Necessary reduction in GW pumping will be extreme; much land will need to go out of production
--Fallowing in southern SJV

--It is possible that groundwater will "salt up" before we reach max overdraft limits
--Salt is accumulating in aquifers because the San Joaquin Valley is a "closed' basin
--Lateral flow of GW to streams to ocean used to remove salt
--Currently not enough surface water in southern SJV to recharge GW and mitigate salt build up without importing more water from the Delta

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change amount of precipitation that is currently captured and stored as surface water? If so, then how?

--Warmer climate
--Less snowpack

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

--OD estimates come out of models and the models need calibration
--Probably accurate within 20-30%

--PPIC used C2VSim
--USGS and DWR haven't reconciled their models
--"C2VSim generally better"

Are you aware of any other estimates of total GW overdraft in the SJV?

--Other than DWR and USGS, no

There is a decent correlation between rate of GWO (per PPIC analysis) and the rate of subsidence measured by repeated precise surveys along the Aqueduct. Do you think anticipated future GWO would a good proxy for predicting subsidence?

How much of the current GWO can be replaced by expanded GW recharge?

--Flood-MAR in multiple basins, plus management, could mitigate GW overdraft
--Flood-MAR makes sense, but not as simple as building a dam
--Shift of water storage from surface reservoirs to GW storage will involve legal challenges
--A lot of water is available hydrologically
--Converting to GW storage is an "extra step"
--information/data is the first step toward regulation of GW
--GW data will have to be at least partially public (vs proprietary); show what's going on
--Reporting every 1-2 years "pitifully inadequate"

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

--No one

7) Future climate variability?

How will climate variability (wet/dry) change in the next 20 years? Next 50 years?
i.e., has climate change "already happened", such that the past 20-30 years is indicative of the next 20-30 years?

--Winter runoff will replace snowpack

Do you agree with Swain et al. (2018) model with predicted increase in frequency of extreme wet/extreme dry events?

--More and "flashier" winter runoff; "water through a firehose"

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--"Not impossible" that there could be a paradigm shift in GW management

--Reorient priorities toward storing GW?; repurpose GW storage
--“reimagine”, “rethink” GW
--Treat GW storage like a surface reservoir; storage potential unlimited
--Cost competitive with surface storage
--To date there has been no management of GW resources
--GW management requires monitoring. Current effects of GW use on storage is “massive but invisible”
    Specifics of state of GW system are poor
--Strong hunch that lack of GW management is related to lack of monitoring
    Spread of wireless networks will help
--Potential shift to “total” (integrated?) GW + surface water management
    Orange Co. has done this
    “Conjunctive use on steroids”
    Do-able

Expert G, CASS Risk Interview, 2 April 2020

Expert G is a consultant providing strategic counsel on programs, projects, and initiatives. His career has focused on innovation, collaboration and results while working on complex natural resource management matters. In 2016 he was appointed to the board of directors for the Klamath River Renewal Corporation, which will oversee various aspects of the dam decommissioning project on the Klamath. Prior to the Water Foundation, he served as Secretary of the California Natural Resources Agency and chief advisor on issues related to the state's natural, historic, and cultural resources. He also directed the California Department of Water Resources, including operation of the California State Water Project. He has also served as executive director of CALFED, regional director for the Bureau of Reclamation, and general manager of the San Diego County Water Authority. He spent six years with the Arizona Department of Water Resources implementing Arizona's first comprehensive groundwater management efforts. He holds a master's degree in water resources administration from the University of Arizona and a bachelor's degree from Pennsylvania State University, where he majored in in earth sciences.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--Unknown variable: how COVID-19 may affect decision making
    Some GSAs may use COVID crisis as an opportunity to delay SGMA implementation
May start to hear arguments to this affect by end of the year (2020)
--In general, believe there will be "substantial compliance" with SGMA by 2040
--DWR and State Water Board starting to think about enforcement if required

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a "glide path" implementation of SGMA?

--Although another drought could affect implementation, will start seeing over-drafted basins come into balance within 10 years, or by 10 years
    Some GSA's won't do anything to comply until forced to
    Biggest variable is future water supplies
    If 2020 is the first year of a 5-yr drought, likely to see continued overdraft

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--("substantial compliance" response above)
--Subsidence is not instantaneous or linear (i.e., direct response to changes in OD)

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If it is delayed, then by how many years?

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--Greater probability of delay due to politics than litigation
--Political pressures are most important
--Don't think SGMA will be repealed outright, but could be softened/weakened by lack of funding and political will

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" ag economy in the SJV look like?

--Talked to a lot of farmers
--Anticipate consolidation of land as better capitalized farmers buy smaller farms
    Will lead to operational consolidation
    Bigger farmers take longer view in making cropping decisions?

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--Don't think that the trend of the last several decades towards more permanent crops will change significantly in near term
    Permanent crops guarantee need to buy "pretty damn expensive water" at some point

Agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance? If so, where will fallowing be concentrated? Kern basin area?

--Agree with PPIC analysis. Significant fallowing will have to occur for basins to come into compliance with SGMA

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change amount of precipitation that is currently captured and stored as surface water? If so, then how?

--Warmer winters will impact water supply and availability

--Also impact investment strategies
--Could make floodwater recharge more attractive
--The idea of “re-operation” of reservoirs to facilitate GW banking has been around for a long time
    More tangible reasons now
    SGMA allows for a logical way to manage a GW basin

--Definitely need infrastructure improvement to facilitate maximum efficiency
    Fix Friant-Kern canal
    Build E-W “Mid-Valley” canal
    Concern about how state board will process permits/allocate GW

--Needs the governor’s personal attention
--Change in winter runoff patterns will have legal impacts
--Increasing temperatures will have impact on when/where crops will grow. Some crops require certain number of “cool days”; may not be viable

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

--Last 20 years more indicative of future than last 30 years
--Expect increase in pumping in 2020 due to dry winter

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

--Ask Jay Lund

7) Future climate variability?

How will climate variability (wet/dry) change in the next 20 years? Next 50 years?
i.e., has climate change “already happened”, such that the past 20-30 years is indicative of the next 20-30 years?

--Climate change in California has “revealed its hand”
--Variability is going to get worse/increase in magnitude

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--Politics is big variable
--Coronavirus may have long-term impact on ag labor availability
--Future immigration policies could impact farmers' crop selection
--Overdraft will impact drinking wells of low-oncome communities; political conflict possible

Expert H, CASS Risk Interview, 9 April 2020

Expert H is an academic research scientist specializing in integrated engineering of regional, utility, and household water resource and environmental systems using ideas from economics and operations research. Member: Civil and Environmental Engineering, Geography, Hydrologic Science, Environmental Policy and Management, Biological Systems Engineering, and International Agricultural Development graduate programs.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--SGMA will be "partly implemented" by 2040
    Fully implemented in some basins
    Politics, difficulty in getting people organized will delay implementation elsewhere
    Successful implementation depends on climate and drought
    "String of dry years" between now and 2040 will make it difficult to get to zero overdraft

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a "glide path" implementation of SGMA?

--Expect to see beginning of compliance in 10 years (2030)
--2020 has been a dry year. People will be pumping more GW this year, not less
--Unless we see a string of wet years, don't expect sudden outbreak of early compliance
--Recommends banishing the term "glide path"
    "Completely misleading"
    Compliance will require "a very steep climb"
    Sugar coating a very bitter pill

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--SGMA will eventually eliminate GWO and subsidence <u>after 2040</u>
--DWR needs to "rattle the litigation saber"

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If it is delayed, then by how many years?

--"90% certainty" that SGMA will be challenged in court
--Delay translates into money for a lot of people
--Even a futile litigation effort will result in delay and continuation of status quo

--Decision to sue will be strictly a business decision
--Will probably result in a 5-20 year delay of full implementation of SGMA

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?
--Estimate 30-50% chance that SGMA is overturned legislatively
--Law more likely to be weakened than completely overturned
--Depends on timing. Future governor seeking re-election and needing ag support may be willing to overturn law

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" ag economy in the SJV look like?

--Bottom line: 0.5-1.0 million fewer acres of irrigated land
--In addition to GWO, future ag will have to deal with salt balance problems in Tulare and westside basins
    Addressing salt problems will require a drain, political consensus and money
    Salt problems might spread slowly
--Farmers may consider easement near Aqueduct

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--Permanent crops will increase from current 30% of ag land use to 40-60%
--Market forces will lead to future mix of permanent and annual crops
--Farmers would like to see expanded water trading market
    Don't necessarily need new conveyance infrastructure to make this happen

Agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance? If so, where will fallowing be concentrated? Kern basin area?

--(Agree with PPIC analysis. See above)

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change amount of precipitation that is currently captured and stored as surface water? If so, then how?

--Sea level rise will require more outflow through the Delta to maintain water quality, reducing water available to export

--Wetter, warmer winters will mean less storage as snow; less snowmelt
    Re-operation of reservoirs can mitigate some of that
--There will be more variability and extremes in wet/dry; "less average"
--Farmers trying to capture more floodwater
    May mitigate 10-15% of GWO vis capturing flood flows
    "Still leaves 80% of the problem"
--Major problem with Flood-MAR is hydrology: water "comes at the wrong time and in the wrong place"
    "Probabilities are against you" for mitigating significant GWO
--recommends reviewing DWR (2018) report, papers by PPIC and Dahlke

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

--"There is a 100% certainty that some farmers will refuse to embrace SGMA"

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

--Would include both options in a subsidence hazard model, but weight the higher rate more conservatively for planning
--Believes review of data justifies weighting both options equally in a logic tree
--PPIC estimates "pretty robust"

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

--Local water districts may be doing independent modeling
--USGS and DWR models are different, but both are good and useful

7) Future climate variability?

How will climate variability (wet/dry) change in the next 20 years? Next 50 years?
i.e., has climate change "already happened", such that the past 20-30 years is indicative of the next 20-30 years?

--Average temperature will increase
--Sea level will increase
--Crop water demand will go up
--There will be less water available from the Delta

  Cost of marginal water supplies will adversely affect ag more than cities

--There will “almost certainly be a repeat of the 2012-2016 drought within the next 50 years”

  Look back on historical record: no 50-year span without a drought
  Statistically, droughts repeat every 15-20 years
  Prudent planning to assume 10-year recurrence of droughts
  In Jay’s career, there have been two serious droughts separated by about 30 years

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--There is a 100% certainty of a significant future “unknown unknown”
--Seawater desalinization isn’t practical; won’t ever be cheaper
--Nothing will alter the fundamental mass balance of available water vs. use beyond 10-20%; at the margin
--Forget increasing forest runoff; too expensive
--DWR should prepare for multiple contingencies

  e.g., Not recovering 100% of design capacity of CA Aqueduct

Expert I, CASS Risk Interview, 14 April 2020

Expert I is an adjunct fellow at the PPIC Water Policy Center, an associate professor of environmental engineering at the University of California, Merced, and an affiliate of the UC Davis Center for Watershed Sciences. His research and expertise include the economics of agricultural, environmental and urban water uses; the development of large-scale economic models for water supply; adaptation to climate change, and integrated water management. He has consulted for government agencies, NGOs, industry, and academia, including the Natural Heritage Institute, the Stockholm Environment Institute, the World Bank, the Catholic University of Chile and the University of Rio Grande do Sul in Brazil. He has served as an official for the California Water and Environmental Modeling Forum since 2013. He was the 2017 Steyer-Taylor Fellow at the Water Policy Center. He holds a PhD in ecology from the University of California, Davis. He also has degrees in engineering, business, and economics.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--Overall: optimistic
--Will be implemented for the most part
--Legislation leaves a lot of latitude for “local reality”
--Allows GSAs to be creative
--Likely that some areas will be deficient (in implementation)
--“Good time frame” in law for implementation
--Believe there is 80% likelihood the law will be implemented
    Of the 20% likelihood the law won’t be implemented:
        10% that it will be poorly implemented
        10% that 60% or less of farmers won’t implement law

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a “glide path” implementation of SGMA?

--Probably take 10 years to begin to see significant reduction in GWO
    However, possible to see some improvement by 2025
--Don’t expect much change in the first 5-10 years
--There will probably be an acceleration in the 10-15 years before 2040

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--Yes
--By 2040

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If it is delayed, then by how many years?

--Don't think hostile litigation is likely
--Litigation may happen in some basins
--Litigation may be initiated by conflict between "white and gray areas" over access to surface runoff
Accounts for most of J M-A's 20% estimate for implementation failure (see above)
Note: this is GSA's suing each other rather than the state of CA
--Most GSA's will do their part
What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--Legislative intervention is possible; most likely to address access issues of white areas
--Not an expert on litigation aspect

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" ag economy in the SJV look like?

--It will be more expensive to obtain water
--Land fallowing will occur
--"Concentration of value" will occur
    Reduction in grain production
    More focus on fruits and nuts
Some shrinkage in livestock and dairy sectors
    Some field crops will be more difficult to justify
--Will see increased consolidation of farming operations
    Small farmers may be at a disadvantage to compete for water

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--More permanent crops with concentration in value

Agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance? If so, where will fallowing be concentrated? Kern basin area?

--(Agree with PPIC analysis. See above)

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change amount of precipitation that is currently captured and stored as surface water? If so, then how?

--Impacts of SGMA implementation will be greater than those associated with climate change
--Sea level rise will force changes in water management to prevent salt water from entering Delta pumps
    Sea level rise is "the real threat"
--There will be more intense droughts and floods
--Don't know the impact on water availability; don't know if there is an consensus on this issue
--Farmers and planners will have to deal with more variability
--Increased temperature and precipitation variability will possibly affect crop yields and the types of crops grown

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

--Potential for groundwater "mining" hopefully mitigated by requirements in SGMA for 5-year reporting
--Believes some kind of "glide path" to sustainability is most likely

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

--Last 20 years of GWO history is more relevant to predicting the next 20 years

How much of the current GWO can be replaced by expanded GW recharge?

--About 0.5 Maf/yr (see PPIC analysis)

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

--Large GSA's likely do their own modeling
--USGS model more generic

7) Future climate variability?

How will climate variability (wet/dry) change in the next 20 years? Next 50 years?
i.e., has climate change "already happened", such that the past 20-30 years is indicative of the next 20-30 years?

--"Climate change is a slow process" (so may not see significant changes in next 30-50 years relative to previous 30 years)
--Historical evidence for century-long droughts
--Reductions in emissions may slow climate change
--Unlike GWO, efforts to mitigate climate change going much more slowly
--Believes last 20-30 years is a good predictor of next 20-30 years

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--Many (currently unknown) physical realities will come up
--SGMA implementation issues will arise
--Seawater desalinization may become cheaper
--Bottom line: 15% of ag water that comes from GWO is unlikely to be replaced from other sources

Expert J, CASS Risk Interview, 28 April 2020

Expert J is a Central Valley grower.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--SGMA will be difficult to implement
--Anticipate a lot of opposition; lawsuits and legal issues
--"Don't underestimate determination of folks south of the Delta to assert and defend their water rights"
--Will require cooperation on both sides
--Dictation or confrontation by DWR will delay implementation
--50% chance SGMA won't be implemented by 2040
  Possibility for the law not to be implemented in Sac Valley as well as SJV
  Billions of dollars will be lost with land fallowing

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a "glide path" implementation of SGMA?

--Many districts open to implementation of SGMA
--Implementation will depend on how cooperative DWR is with farmers
--Expect implementation of SGMA to be "very bumpy"

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--If implemented, expect SGMA will be successful in eliminating GWO by 2040
--Fallowing of land under SGMA will reduce GWO by brute force

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If it is delayed, then by how many years?

--Pretty confident there will be resistance
--Under current law, farmers own the groundwater beneath their land; don't accept idea that GW is just passing through their property like water in a river
--Billions of dollars at stake
--Most farmers are over-pumping in order to survive
--SJV farmers have a lot of "get mad" money available for litigation
--Litigation will be rampant if implementation "crammed down" by DWR

--Could spend 30 years in courts
--Non-antagonistic approach from DWR will be welcome

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--Because stakes are very high, CA may see "fight of century" in the legislature over survival of SGMA
--Implementation issues need to be solved by cooperation between agriculture and the state to avoid legislative fights

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" ag economy in the SJV look like?

--Land fallowing will occur. Transition of a lot of current cropland to "dry land pasture or tumbleweeds"
--Westlands will have to fallow a lot of land
--Agriculture community does not expect agencies to move any additional water to SJV
--Already using very efficient watering systems that have reduced aquifer recharge
--Land fallowing is not what farmers want to do. Want to grow things.
--Skeptical about local water markets being very effective at minimizing economic losses due to land fallowing and cropping changes

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--Yes

Agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance? If so, where will fallowing be concentrated? Kern basin area?

--Expect 1.0-1.5 million acres will have to go out of production. Most in the SJV

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

--(Didn't ask as part of interview)

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

--Farmers believe GW beneath the land is theirs to use. Water rights law in their favor
--Every well that can be put in will be put in between now and 2040

5) GW overdraft

--(Didn't ask as part of interview)

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

--(Didn't ask as part of interview)

7) Future climate variability?

--(Didn't ask as part of interview)

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--Big unknown is the culture within DWR
--High turnover through years means DWR staffed with a lot of people who don't know valley farmers
--"It's all about people"
--Is DWR open to cooperation?
"Open Hand" approach can lead to a lot of success
Cooperation and outreach most important
--Farmers are very independent and don't like being coerced
--DWR needs an "ambassador", a trusted partner to work with farmers
--Cooperation to help ag community survive

Expert K, CASS Risk Interview, 5 May 2020

Expert K is the Vice-Chair of the San Francisco Estuary Institute Board and sits on both the California Roundtable for Agriculture and Environment and the California Roundtable for Water and Food Supply. She previously sat on the Steering Committee for the Bay-Delta Conservation Plan which sought to improve urban and agricultural water supply reliability and restore the San Francisco Bay-Delta estuary. **Expert K** holds a Masters degree from the Bren School of Environmental Science & Management at U.C. Santa Barbara, and a B.S. degree in Marine Biology from U.C. Santa Cruz.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--Assume it will be; mandated by legislation
--EDF is doing everything it can to make it as easy and cost effective as possible to implement
--Implementation will be hard
--There are innovative ways of bringing groundwater basins into balance
--Successful efforts will provide models
--A lot of things currently in play; EDF focused on making the law work
--Policy tweaks may be required; e.g., capture more flood flows
--May need enabling policies
--Cautiously optimistic law will work. Recognize that it puts a lot on locals to figure it out
--EDF providing tools to make the law work

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a "glide path" implementation of SGMA?

--The most critically over-drafted basins/GSA's need to specify their "ramp down schedule" [to reduce GWO]
--Expect to start seeing reductions in GWO in 5 years
--Westlands has included a ramp-down schedule in their GSP
--DWR needs to be "really strong" in its response to GSA's
    Water users are not a monolith
DWR should not come out "guns ablazing"
DWR needs to provide specific guidance to GSAs
Strong role for DWR to play
--Helpful if some GSAs are able to model successful implementation of GSPs

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--SGMA will be 75% effective in eliminating GWO by 2040 (75% of basins can "get there" (balance) by 2040)
--For the 25% not in compliance by 2040, estimate it will take an additional 10-15 years to reach balance
--Feeling optimistic about reversing GWO
--Subsidence will continue as SGMA is progressively implemented

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If delayed, by how many years?

--Estimate 10% likelihood that SGMA will be delayed by litigation
--Still early in the process
--Believe that a "cultural shift" is in progress, re: ag water use
--There are water districts and growers who "get it"
--See momentum in ag sector; shift over the past 2-3 years;
--From one-on-one conversations with growers, initial negative reactions have been replaced by recognition that GWO is a threat to business and communities
--Pilot program in Kern Co is attracting attention
--Land conversion is becoming accepted as an option for reducing GWO
--Still pockets of resistance; smaller percentage in denial
    "SJV Blueprint" being discussed; generally negative on SGMA
    Focused on more Delta water and building more surface storage
--More productive conversations starting to emerge

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--"Zero percent" likelihood that SGMA will be overturned by a future legislature

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" agricultural economy in the SJV look like?

--Anticipate a diversified post-SGMA ag economy
--Possible that 750k-1.5M acres may go out of production, per some estimates
--Nobody wants to see land go out of production
--Give farmers and GSA's guidance for land conversion
--Develop "market" for land conversion; provide credits for habitat preservation
--Anticipate mosaic of different land uses
    "Wildlife-friendly" GW recharge

--Expect farmers to fallow least productive lands
--Need to consider full suite of options, including payments to landowners (to abandon/fallow ag land)

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--Likely see continued expansion of permanent crops
--Continue to lose flexibility to fallow in dry years
--Only so much water to go around, but not at tipping point yet (i.e., decline in perm crops)
--Perhaps see tipping point in next 10 years. Probably see more ag land go out of production by 2030-2035
--Kaweah sub-basin wants to get out ahead of this; create new opportunities
--Anticipate that water trading programs will reduce acreage that goes out of production

Do you agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance? If so, where will fallowing be concentrated?

--Yes. Fallowing will be concentrated in the Kern, Tulare regions of the southern SJV

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change amount of precipitation that is currently captured and stored as surface water? If so, then how?

--Agree with Swain et al. analysis (shorter, more intense wet seasons; more extreme variability between drought/wet years)
--Believe that climate change will demonstrate need to eliminate GWO, get basins in balance
--Extended droughts have bigger impact on system
--Need to maximize flood capture
--Use GW as a bank; additional storage
--Need to build more conveyance to recharge basins
--Need to account for GW storage; i.e., measure/monitor GW elevations
--GSAs can develop allocation schemes to preserve landowner GW rights

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

--Believe that "cultural shift" will lead to GSA's self-policing bad actors
--People will "daylight" farmers involved in GW mining
    Realize real consequences to abuse of shared resource and responsibility

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

--Believe that the last 20 years is more representative of the future (next 30 years)
Are you aware of any other estimates of total GW overdraft in the SJV?

--No

How much of the current GWO can be replaced by expanded GW recharge?

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

--Likely private consultants working for GSAs
--Use "Open ET" software to come up with average GW pumping info?

7) Future climate variability?

How will climate variability (wet/dry) change in the next 20 years? Next 50 years?
i.e., has climate change "already happened", such that the past 20-30 years is indicative of the next 20-30 years?

Do you agree with Swain et al. (2018) model with predicted increase in frequency of extreme wet/extreme dry events?

--Believe that 2012-2016 droughts will become more frequent in the next 50 years.

Should we assume that another 2012-2016 drought could happen in the next 20 years? Next 50 years?

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--Manage groundwater and surface water as an integrated system
--Need to look at this problem holistically
--Also need to look at water quality in addition to supply
--COVID Impacts?

--It is possible that growers could petition the government to change water exports “to ensure food supply”
--Could have longer term disruption than is currently apparent
    --Foreign food exports could be affected by COVID as well

Expert L, CASS Risk Interview, 26 May 2020

Expert L is an author and journalist whose writings on California and the West have received numerous awards for literary nonfiction. A former staffer at the *Los Angeles Times*, his work has appeared in the *New York Times* and *California Sunday Magazine*.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--Hope it will be implemented, but have doubts too
--Not sure DWR has staff to follow through with implementation
--Will require reversing a century and half of bad land-use decisions
--Ag went into “white areas” on map when it shouldn’t have
--Ag footprint expanded 25% more than it should have
--A lot of money invested (in current ag footprint)
--Ag practices currently not sustainable
--SGMA is already a reality in the ag community/culture
    --Farmers see it as necessary
--However, “these guys [farmers] aren’t going to go down quietly”
--State will have to hold firm [on SGMA implementation/requirements]
--Some farmers taking it seriously, some are fighting it/think it’s bullshit
--Farmers know that groundwater pumps have saved them in the past
--60% likelihood that SGMA will be implemented by 2040

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?

--(Timing of implementation) will depend on where farmers are (in the SJV)
--Westlands has different challenges than Kern
    -Kern Co has a water bank; wet years gives them a hedge
    -No county overdrafting more than Kern, but water bank helps
    -Westlands pumped 700k af during drought years
    -No choice but to go to GW pumping during drought
    -Westlands also bought GW pumped from Tulare during drought
--Fight going on in Westlands
-One group: “Let’s reduce irrigated land from 500k to 300k acres and make sure we’re getting enough water for remaining crops on best land”
-DWR may find partners within Westlands

--(Timing of implementation) also depends on drought/future weather
    -It will be hard to hold farmers to limited amount of GW if we have a new drought
    -Another drought will likely produce a “race to the bottom”

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--Cynical response is "No, because the state won't do what's necessary"
--Hopeful response: "Optimistic we'll see some (positive) change"
--Currently, Expert L is "60% hopeful" (40% cynical)
--Individual SJV farmers have personally acknowledged to Expert L that "we know that a third of the farmland has got to go"
--However, farmers are "relentless" about pursuing their interests

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If delayed, by how many years?

--80-90% possibility of litigation, unless the state comes up with creative ways to retire land
--Litigation may come primarily from farmers in "white areas" on map
--Don't know if litigation can ultimately stop the law (SGMA), however
--State needs to be firm; farmers will take advantage of any equivocation

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--Don't think that California will turn "red" and support wholesale repeal of SGMA

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" agricultural economy in the SJV look like?

--Ag will be "smarter, leaner, and more nimble", focused on growing highest value crops
--Less alfalfa (no more mega-dairies)
--Farmers will have the economic power to say "no" to land developers
--Believe that SGMA will turn out to be a fine thing for SJV

--Pricing water will impose its own constraints on ag land use
    e.g., water too valuable for use in CA mega-dairies
--Water market or markets may direct water to urban/suburban uses, away from ag
    --Should only allow trading of ag water for ag water
--CA is not the nation's "breadbasket"; should focus on high-value fruits and nuts
--Worried that high speed rail will facilitate development in the SJV
--Suburban growth from post-COVID work at home?
--"Last thing I want to see is the SJV being paved over"
--Replace some ag land with solar? DWR underwrite solar farms to help retire ag land?

--Big believer in the farmer planting what he/she wants
    -Combination of free enterprise and state-set guidelines
    -Want water to go to high-value crops
--Try to get back to a 70/30 split on ag vs. streamflow use
--Some kind of regulation will be required. State needs to get involved.

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--Yes, there will be more expansion of permanent crops
    -At some point could lead to a "nut glut"
    -Almonds starting to slow; pistachios hardier and more drought tolerant
-There will always be a place for annual crops

Do you agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance? If so, where will fallowing be concentrated?

--Believe that the PPIC estimates of post-SGMA fallowing are too low; about 1 M acres will need to be retired
--"Old timers recognize that a lot of land should not have been planted"

--"Water Blueprint for the San Joaquin Valley" (SJV ag interest group) supported May 2020 report by UCB economists (Sunding and Roland-Holst, 2020). Report concludes 1 M acres will be fallowed and SJV will take $7.2B economic blow. Report also predicts >42k jobs lost due to SGMA; however, this is likely an overestimate because study didn't account for existing high unemployment in SJV, or fact that increased mechanization is contributing to future ag job losses anyway.

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

--State does not need to make the case to farmers that climate change is already here
--Climate change <u>is</u> California
--Farmers know drought patterns from past experiences
--Silly/not productive to approach farmers about "climate change"; rather, talk about dry weather, frequency of droughts
--Farmers know that drought is a frequent visitor, may get worse in the future

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW ("mining") up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

--Agree that this is a widespread sentiment among farmers
--Farmers are going to pump until someone puts a lock on their pumps, or gives them a plan to help idle land
--Farmers put nut trees in the ground at $20k/acre. Drought comes along, and there is no CVP/SWP water. They're going to pump. Also, past experience is that state and feds stepped in to help.
--Farmers: "If the government saved my ass last time, then it will probably step in and save it again"

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual GW overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

--The expansion of permanent crops over the past 20 years makes the average of the last 20 years of data more relevant than the average of the last 30 years

6) In addition to USGS and DWR, who is modeling response of SJV aquifer to GW pumping?

7) Future climate variability?

--Farmers talking about using more groundwater banking (as hedge against drought/climate variability)
    --Need infrastructure to capture more flood flows
--Farmers understand that no more "upstream storage" is coming
--Drought is a specter

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--COVID pandemic may prompt new thinking
    --Less commuting?
--New focus on food security?
    --Farmers putting in backyard gardens and chicken coops for own food
--Might start to see more partnerships between "almond guys" and "rice guys" for trading water
--"Can't see anything preventing us from needing to make big changes to make SGMA work"
(Note: MA apparently understood the question to be about whether there is going to be a future innovation or new technology that would allow the status quo to continue indefinitely)

--“See a real middle ground between the farmers and the enviros”

Expert M, CASS Risk Interview, 4 June 2020

Expert M has more than 30 years of experience in public administration, fiscal management, and water resources policy development and implementation spanning federal, state and local levels. **Expert M** is recognized for his collaborative leadership and approach to solving complex issues. He has successfully developed and implemented large capital projects and programs, and he has participated in complex contract and settlement negotiations. Previously, **Expert M** served as general manager of Kings River Conservation District, a regional water resource management agency involved in power generation, flood management and integrated water resource planning, and as general manager and director of finance of Westlands Water District, the nation's largest federal irrigation contractor located on the westside of the San Joaquin Valley. **Expert M** is a member of the California Water Commission.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--SGMA will be implemented
--Will be very close to sustainable management by 2040, unless there is legislative delay
--GSA's required to ramp down to sustainable pumping by 2040
--Give 80-90% probability that GSA's will be sustainable by 2040

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a "glide path" implementation of SGMA?

--Right now, there are 46 GSPs in front of DWR, most from SJV.
    --Approx. 40 of those plans are relevant to the California Aqueduct
--Only 10 or so propose ramp down schedules
--Ramp down schedule will begin for some GSAs in 2022
--Westlands looking at transitional pumping schedule in 2023
--Assume 2025-2030 window for GSAs that haven't proposed ramp down
--GSAs need to come to understand that there's not enough water available to forego pump restrictions
--Some GSAs looking at 5+ years of study before starting to ramp down
--What "equitable considerations" must be made?
--Monitoring required for ramp down, including installation of equipment
--3 years since GSAs formed (2017) and less than 25% have faced this issue directly
--e.g. Tulare: their plan to reach safe yield is to look for "voluntary reductions". This is denial, not a plan
--DWR may need to come back hard (on inadequate GSPs) during review

--Westlands has a ramp down plan. Also, has identified a "management area" most impactful to the Calif. Aqueduct

--Can expect a steepening curve of GW use reduction between 2030-2040
    --Status quo through 2025
    --GSAs will hold off as long as possible
    --Hope for a "linear slope" to sustainability in 2040

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--It's all contingent on how hard DWR comes back (on GSAs) in reviews (of GSPs)
--Still seeing farmers investing in permanent crops in water-poor areas
    --DWR can change that in a heartbeat by requiring GSPs include ramp-down schedules
--Most GSAs with ramp downs assume a rolling average
--Climate variability (i.e. drought) has more significant impact on uncertainty (in subsidence/GWO) than when ramp down begins

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If delayed, by how many years?

--Want to believe that GSAs will find adopting SGMA more desirable than litigation
--Haven't heard a lot of people "rattling the litigation saber"
--Know some attorneys who think litigation is "inevitable"
--Adjudication is a 10-15 year process

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--Very low probability of SGMA being repealed
--"Repeal" would be an admission that the GW resource will be mismanaged until it is unusable

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

What does the "post-SGMA" agricultural economy in the SJV look like?

--Agree with PPIC estimate of land retirement: approx. 700k acres will go out of production
--Question is what commodities will be favored? Not going to retire almonds for garlic or alfalfa
--Retirements will favor (i.e., relatively increase) permanent crops
--Reductions will occur in marginal land and annual crops
--Don't see GW transfer occurring freely across sub-basin boundaries

Do you foresee continued expansion of permanent crops in western Merced, Fresno and Kern Co's for the foreseeable future? Is there a foreseeable "peak" or plateau in conversion to permanent crops? If so, when?

--More permanent crops for the next 5-10 years
--Don't expect to see almond expansion continuing at the same rate. Likely plateau
--Probably see increases in perm. crops in the Sac Valley
--Commodity prices and water supply will determine ultimate acreage

Do you agree with Hanak et al. (2019) that significant land fallowing will occur as a result of SGMA compliance? If so, where will fallowing be concentrated?

--Agree with PPIC estimate of land retirement
--Most retirement will occur in the southern SJV
--Some basins more out of balance than others
--Kern and Tulare basins will suffer larger than proportionate share of land retirement due to limited surface water availability

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Will increases in temperature and "precipitation volatility" (per Swain et al. 2018) significantly change amount of precipitation that is currently captured and stored as surface water? If so, then how?

--Don't have the infrastructure to manage significant changes in rainfall and snowpack
--GSAs need to get creative in capturing and storing groundwater
    --GSPs calling for significant increase in GW recharge
    --However, currently limited ability to control and convey flood flows
--Probably won't make investment in SJV surface water reservoir
--Most growers and GSAs will deal with changes to get as much water into GW storage as possible

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

--We (NCW&L) represent 300k acres of production and have not heard this
--Fringe sentiment
--Probably significant amount of peer pressure to prevent "insurmountable damage" (from GW mining) that affects everyone
--Think courts would uphold right of GSAs to restrict individual landowner pumping
    --Hope that such lawsuits are minimal
--Majority (of growers) believe sustainable GW management is a good thing

5) GW overdraft

PPIC analysis (Escriva-Bou, 2019) shows about 1.46 Maf average annual groundwater overdraft 1988-2017, and about 2.45 Maf from 1998-2017. For planning purposes, do you think the higher 1998-2017 rate should be assumed for future (unmitigated) overdraft rates between 2020-2040?

--The 1998-2017 time period has some asterisks around it; may overstate problem (i.e. LTA GWO rate)
--However, 1988-2017 history may understate the problem
--Probably give more deference to the longer hydrological period number
--Gut says that the 98-2017 data overly influenced by 2012-17 drought
--The 1988-2017 period is probably more representative of a 50-year time frame.

Are you aware of any other estimates of total GW overdraft in the SJV?

--Friant Water Authority has estimated GWO for the "Blueprint for the SJV"
--Reach out to Friant or Blueprint for work they've done

How much of the current GWO can be replaced by expanded GW recharge?

--PPIC's estimate of 900k af replacement of GWO by new GW storage is likely too high, and DWR's estimate is probably too low
--Gut feeling is that 500k-600k af of new GW storage in southern SJV can be affordably developed
--GSA's are assuming 2.4-2.5 Maf will be available

6) In addition to USGS and DWR, who is modeling response of the SJV aquifer to GW pumping?

--Sub-basin models available; built on platforms of USGS and DWR models

7) Future climate variability?

(declined detailed answer)
--Tend not to get too excited by probability estimates of future climate
--Climate is going to be what it's going to be

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--Don't know if we can accurately forecast future of water trading; could be very important

--What do we expect future surface water supplies to be?
--Regarding Delta exports, a change of +/- 500k af would be very significant to SJV

--Create deliberate habitat regions versus blind retirement of land?
    --Exercise: overlay preferred habitat maps over recharge areas
--Calculate “water to wildlife” benefit; could impact locus/loci of future pumping
    --Identify land retirements based on multiple use considerations?
    --Create alternative use for properties most impactful to subsidence

Expert N, CASS Risk Interview, 8 June 2020

Expert N is vice president and director of the PPIC Water Policy Center and a senior fellow at the Public Policy Institute of California, where she holds a Chair in Water Policy. Her other areas of expertise include climate change and infrastructure finance. Previously, she served as research director at PPIC. Before joining PPIC, she held positions with the French agricultural research system, the President's Council of Economic Advisers, and the World Bank. She holds a PhD in economics from the University of Maryland.

1) Most likely outcome of SGMA?

Do you think SGMA will be fully implemented in 2040, as currently envisioned?

--I hope so!
--Mitigation of "undesirable results" is a big gray area. A lot of leeway in how that is implemented/satisfied
--May not resolve subsidence (by 2040)

Do you think Groundwater Sustainability Agencies (GSAs) will begin managing groundwater resources in advance of 2040 and significantly reduce groundwater overdraft (GWO) and observed subsidence rates? If so, how soon?
--How much do you think GWO rates can be cut between now and 2040?
--Related: What is the most likely scenario for a "glide path" implementation of SGMA?

--Starting to see beginning of management of GWO now (in some GSPs)
--GSA's currently focused on supply side; not yet focusing on managing demand
--Managing demand will be contentious and difficult
--It will be uneven
--Models of doing this with adjudicated basins
--External pressure from DWR, USBR will be important (for meeting SGMA goals re: subsidence)

--Expect to start seeing some demand management by 5 years
    --First 5-year period in GSP process for "sorting things out"
    --Don't expect to see allocations before 2025

Do you think SGMA will eventually be successful in eliminating GWO and undesirable land subsidence? If so, when?

--Won't happen without DWR and the state water contractors weighing in
--May see hard pressure applied (by DWR) to stop subsidence hot spots in near term
--DWR was reluctant to use threat of litigation to stop pumping during the drought. DWR needs to get over hesitation (to employ litigation)
--SGMA says "measurable progress" is required. It will be important on DWR as a regulator to seriously hold GSAs feet to the fire

--Another 2012-16 drought will increase pressure to pump

--By 2040, we may be somewhat stabilized with respect to subsidence
--Some value in allowing flexibility to address issues locally

What likelihood do you assign to the scenario that implementation of SGMA will be significantly delayed by litigation? If delayed, by how many years?

--Can't imagine this happening statewide
--Lawsuits per se won't stop implementation of the law
--Water rights law is complex
    --In practice, (challenges to law) will be specific to a local area
--Already seeing lawsuits over issues important to implementation of SGMA
--Going to need court-sanctioned allocations to move forward
    --Adjudication process streamlined by follow-up legislation
--Court can be a help; facilitate allocation schemes for GSAs
--There will probably be future lawsuits over "undesirable results"

What likelihood do you assign to the scenario that SGMA will be repealed by the legislature and never implemented?

--Cannot imagine repeal in California
--SGMA was passed without a single vote from SJV reps
    --That said, it behooves politicians to care about how this plays out in the SJV

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

Limited time for interview. Did not discuss this issue.

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

Limited time for interview. Did not discuss this issue.

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

--There are ways the state can play hardball, if the state wants to do it
--DWR is a key stakeholder on subsidence issues
--Downstream water users will want DWR to act in its interest to prevent further loss of capacity in the CA Aqueduct

5) GW overdraft

Limited time for interview. Did not discuss this issue.

6) In addition to USGS and DWR, who is modeling response of the SJV aquifer to GW pumping?

Limited time for interview. Did not discuss this issue.

7) Future climate variability?

Limited time for interview. Did not discuss this issue.

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

--How do you make demand questions tractable?
--How do we create value for lands coming out of production?
    --Deploy solar and wind?
    --Solar could occupy 9-10% of land coming out of production
    --Future unknown is energy markets and policy
--(recommends “Power of Place” report by Nature Conservancy on topic)

Expert O, CASS Risk Interview, 1 February 2021

Expert O is a grower in the San Joaquin Valley operating in the Fresno area. Expert O provided the written responses below to the CASS interview questions via email.

1) Most likely outcome of SGMA?

"I don't believe that SGMA will be fully implemented by 2040. I do think that some GSA's Will be able to manage ground water before 2040 and reduce overdraft, but not very soon. I do believe that the glide path scenario is the best method for managing ground water overdraft. I'm not sure if GWO will ultimately be successful. I do believe that litigation will play a major role in the slow completion of SGMA."

2) What is your assessment of future ag land use in the SJV, and direct/indirect effects on GW pumping?

"I believe that GW pumping will be extremely limited in the future and as a result most farming will be converted to permanent plantings that can survive severe drought growing conditions. The only areas that will be able to continue to grow row crops will be in irrigation Districts that don't rely on federal water. Planting of permanent crops will continue for several more years and then will most likely stop. The first lands to be fallowed will be those in the white areas. Next will be those with lower grade soil."

3) Impacts of climate change on surface water availability and use (specifically for the SWP)?

"Climate change is increasing the volatility of our water supply and will continue. Without substantial increase in surface water storage we will be riding a roller coaster indefinitely."

4) Anecdotal accounts from SJV indicate some farmers are considering a strategy of freely pumping GW up until 2040, then letting the State take them to court and force them to stop rather than accept permanent GW management restrictions per SGMA. Comment?

"I do believe that some farmers will resist any regulations for pumping ground water. Farmers are generally very independent and resist any government intervention."

5) GW overdraft

"GWO varies greatly from one basin to the next. Groundwater recharge will help the problem but everyone is planning to use the same flood water at this point. we will not be able to adequately recharge as quickly as will be necessary."

6) In addition to USGS and DWR, who is modeling response of the SJV aquifer to GW pumping?

“I don’t know.”

7) Future climate variability?

“I don’t think that future climate variability will change that much in the next 20 years. I do believe that extreme events will increase making capturing moisture when available even more paramount. I have no doubt that we will see extreme drought years in the next 20 years.”

8) Speculatively, do you think there could be something we are not currently considering (an unknown unknown) that could contribute to reducing GWO?

“We should be bringing more water through the delta by using subsurface drains.”

State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES

PROBABILISTIC SUBSIDENCE FORECAST MODEL FOR THE CALIFORNIA AQUEDUCT SUBSIDENCE PROGRAM SAN JOAQUIN VALLEY, CALIFORNIA

DESIGN REPORT

APPENDIX C
PPRP Closure Letter

August 18, 2023

Participatory Peer Review Panel
Probabilistic Subsidence Forecast Model
California Aqueduct Subsidence Program
August 16, 2023

Jeffrey R. Unruh, PhD CEG PG
Senior Principal Geologist
Lettis Consultants International Inc.
1000 Burnett Avenue, Suite 350
Concord, CA 94520

RE: Participatory Peer Review Panel (PPRP) letter review

Dear Jeff,

It is our pleasure as the participatory peer review panel to provide this closure review letter for the report, *Probabilistic Subsidence Forecast Model for the California Aqueduct Subsidence Program, San Joaquin Valley, California*, dated **Error! Use the Home tab to apply LCI_CoverDate to the text that you want to appear here.**August 1, 2023.

History. The role of a Participatory Peer Review Panel has been to review and provide commentary on methodology, assumptions, data, and results developed for the *Probabilistic Subsidence Forecast Model* project. The Panel included expertise in geology, geotechnical engineering, and risk analysis to provide a range of perspectives. The panel also evaluated the transparency, completeness, and accuracy of the analysis.

Review process. The project used the SSHAC method to gather information and perform review. This is a structured process for incorporating engineering and scientific opinion in probabilistic models of natural hazards. It was originally developed by the Nuclear Regulatory Commission for seismic hazard analysis but is now widely used. Its application to the present project is appropriate. The PPRP reviewed the initial draft-final report dated March 27, 2023 and a subsequent updated version dated August 1, 2023.

Conclusion. The analysis and corresponding model are competently executed and based on reasonable assumptions. The report is well-written and its conclusions are clear. The comments made in the marked original comprise the principal responses and recommendations of the Panel. None of these was thought a serious obstacle to finalizing the report. The PPRP has reviewed the responses to those comments and accepted them all. We have no further comments on or objections to the report.

It has been our pleasure to support the California Aqueduct Subsidence Program, the Department of Water Resources, and Lettis Consultants International, Inc. We congratulate the team on a job well done.

Very truly yours,

GBaecher Claudia C. Faunt Raymond Costa

Gregory B. Baecher Claudia C. Faunt Raymond Costa

Attachment 3 2023 California Aqueduct Hydraulic Conveyance Capacity Report

State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES

CALIFORNIA AQUEDUCT HYDRAULIC CONVEYANCE CAPACITY

December 2023

Cover photo by Renato Espinoza Torres P.E. CFM.
Aqueduct profile with limited lined freeboard.
November 14, 2017.

State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES
Division of Engineering
California Aqueduct Subsidence Program

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By *:

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*This report is the culmination of the work of a much larger team of individuals both within the Department and those consulting for the Department. From each of the authors listed above, thank you to all those that contributed to the success of this project and your assistance in preparing this report.

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State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES
Division of Engineering

California Aqueduct Subsidence Program
California Aqueduct Hydraulic Conveyance Capacity

ENGINEERING CERTIFICATION

This report has been prepared under my direction as the professional engineer in direct responsible charge of the work, in accordance with the provisions of the Professional Engineers Act of the State of California.

RENATO ESPINOZA TORRES
C 83215
Exp. 3/31/25

Renato Espinoza Torres P.E. CFM
CASP Hydraulics Lead
Professional Civil Engineer No. C83215

Exp. March 31, 2025

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ABBREVIATIONS AND ACRONYMS

af	acre-feet
Aqueduct	California Aqueduct
BV	Buena Vista
CASP	California Aqueduct Subsidence Program
CASS	California Aqueduct Subsidence Study
cfs	cubic feet per second
DA	Dos Amigos
DOE	Division of Engineering
DWR	California Department of Water Resources
ft/s	feet per second
HCC	hydraulic conveyance capacity
HDR	HDR Engineering
HEC	Hydrologic Engineering Center
HEC-RAS	Hydrologic Engineering Center-River Analysis System
in	inch
LiDAR	light detection and ranging
Max	maximum
Min	minimum
MP	milepost
NAD 27	North American Datum of 1927
NAVD 88	North American Vertical Datum of 1988
NGVD 29	National Geodetic Vertical Datum of 1929
Reclamation	US Bureau of Reclamation
SLFD	San Luis Field Division
SJFD	San Joaquin Field Division
SOO	Standing Operating Order
SWP	State Water Project
WSE	water surface elevation

1.0 Introduction

1.1 Purpose and Scope

The purpose of this report is to present the hydraulic conveyance capacity (HCC) of the California Aqueduct (Aqueduct), including the San Luis Canal, in its current (2023) subsided condition and as currently operated. The calculated value of the HCC depends on many factors, including the analytical method used to calculate HCC, the physical conditions represented in the hydraulic model used, and the operating criteria applied.

HCC is the calculated, long-term, sustainable, maximum steady flow rate at which water can be conveyed through an Aqueduct pool or section (such as a check), given a specified physical condition of the Aqueduct and a specified set of operational criteria. HCC is typically represented in cubic feet per second (cfs). When calculated for a pool in this report, the HCC represents the flow rate at the upstream end of the given pool.

The HCC has been calculated for two analytical scenarios:

1. Scenario 1: 2020 SOO with Coalinga Canal Special Condition
    a. Physical geometry reflecting the Aqueduct's 2023 subsided condition.
    b. Standing Operating Order (SOO) 600.22 dated May 20, 2020 (hereinafter, SOO 2020) operating criteria, with water surface elevations corrected for 2018-2023 subsidence.
    c. Special conditions implemented to manage the operational impacts of subsidence.
    d. Special condition at check 18 to service the Coalinga Canal.
2. Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions
    a. Physical geometry reflecting the Aqueduct's 2023 subsided condition.
    b. SOO 2020 operating criteria, with water surface elevations corrected for 2018-2023 subsidence.
    c. Special conditions implemented to manage the operational impacts of subsidence.
    d. Special condition at check 18 to service the Coalinga Canal.
    e. Special condition at check 22 to service the Coastal Branch.

The HCC estimates provided in this report were calculated using a detailed hydraulic model of the Aqueduct that represents its current physical features, including recent changes caused by subsidence. Details about this model, along with technical modeling approach considerations, are documented in the California Aqueduct Hydraulic Model Development Report (DWR, 2023).

Prior to any use of the results presented herein, readers must have a thorough understanding of the results, consider their specific analytical needs and assumptions, and identify criteria that are appropriate for their specific application. Typical considerations include necessary corrections to published Aqueduct water surface elevations, timescale of a given scenario, freeboard objectives, velocity limits, gate operations, turnout loading, and special conditions. The selection of appropriate operating criteria and modeling assumptions depends on the purpose of the analysis and is critical to the applicability of the results presented herein.

It is important to note that the 2020 SOO criteria were developed using a model which reflected 2018 subsided conditions in the Aqueduct. Therefore, the HCC calculations in this report are based on water surface elevation criteria derived from the 2020 SOO normal operating range, but corrected for subsidence that has occurred since the normal operating range listed in the 2020 SOO was calculated with the 2018 conditions model. The 2020 SOO normal operating range is presented in Appendix A**.** (in National Geodetic Vertical Datum of 1929 [NGVD 29]). Appendix B shows the corrections made at the checks for 2018-2023 subsidence, the conversion factors from NGVD 29 to North American Vertical Datum of 1988 (NAVD 88) by milepost (MP), and the corrected normal operating range elevations in NAVD 88.

The estimated capacities presented in this report do not provide a basis for evaluating the feasibility of long-term actions to address subsidence because they represent a limited set of HCC estimates computed only for specific analytical scenarios representing the current (2023) subsided condition of the Aqueduct.

1.2 Background

The Aqueduct is a key feature of the State Water Project (SWP). It is owned and operated by the California Department of Water Resources (DWR), with the exception of a federally owned portion that extends for 102 miles from the O'Neill Forebay to the federal terminus at Kettleman City. This federally owned portion—the San Luis Canal—was designed and constructed by the US Bureau of Reclamation (Reclamation); however, it is operated and maintained by DWR's San Luis Field Division (SLFD).

The Aqueduct is made up of segments, referred to as pools, bounded by either pump stations or check structures. Water travels through the pools by gravity until it is lifted by pumping plants and then continues its journey south by gravity until the next pumping plant. Relying on gravity to move the water requires that water surface profile maintain a downstream slope, while maintaining a minimum amount of lined freeboard, vertically between the water surface elevation and the top of concrete liner.

Since initiation of operations in the mid-1960s, subsidence in California's San Joaquin Valley has caused differential changes in elevation along the profile of the Aqueduct. Subsidence has degraded the elevations of the Aqueduct's embankments, canal invert, checks, and the top of concrete channel liner (top of liner). Consequently, the elevation profiles of the Aqueduct have become irregular and uneven, instead of a constant downstream slope, and certain segments even have negative slope (locations where the downstream end of a segment or pool has higher elevation than the upstream end).

Five distinct subsidence “bowls” have been identified along the alignment of the Aqueduct in the San Joaquin Valley (DWR, 2017). Figure 1-1 shows these subsidence bowls in relation to the Aqueduct extents within DWR’s SLFD, which coincides with the San Luis Canal, and within DWR’s San Joaquin Field Division (SJFD), which extends from pool 21 to the Edmonston Pumping Plant (pool 40).

The irregular Aqueduct profile of affected pools inhibits the ability of SWP operators to convey water as originally intended (DWR, 2017). Certain severely subsided areas within these subsidence bowls have resulted in “choke points” along the Aqueduct, i.e., points where subsidence has lowered the elevation of the top of liner so much that the top of liner now encroaches into the operable water surface elevation profile creating obstacles to normal operations.

In response to subsidence and other operational challenges, including water surface elevation requirements for specific turnouts or bifurcations, the operational criteria for the Aqueduct have been updated multiple times since original construction, including in 1998, 2013, and 2020. The most recent updates to the operational water surface elevation criteria are documented in the 2020 SOO.

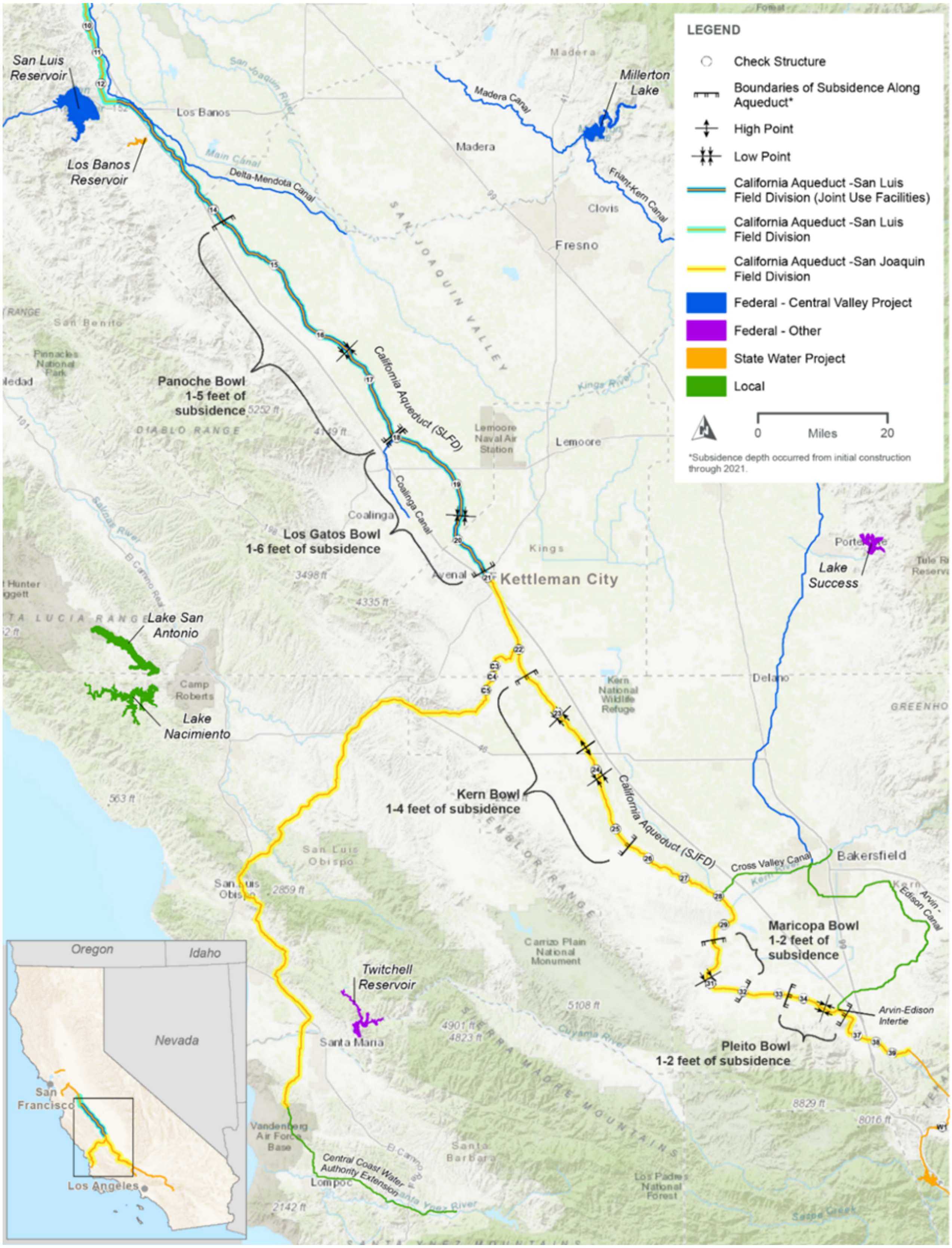


Figure 1-1. Locations of subsidence along the California Aqueduct

Periodically, DWR reevaluates the Aqueduct’s ability to convey water and make deliveries within the SLFD and SJFD. The HCC estimates previously reported by DWR in the California Aqueduct Subsidence Study (2017 CASS Report) (DWR, 2017) and the California Aqueduct Subsidence Study, Supplemental Report (2019 CASS Supplemental Report) (DWR, 2019) were based on operations, subsided conditions, and calculation methods in place at the time of those reports.

The 2017 CASS Report and 2019 CASS Supplemental Report presented HCC estimates that were derived from a steady-state, “pool-by-pool” analysis which is useful to show subsidence-related effects on individual pools independent of the performance of upstream or downstream pools. The pool-by-pool methodology (described in Appendix C) is representative of limited scenarios and does not consider conservation of mass across pools. The pool-by-pool analysis includes instantaneous flow rate changes across check structures (i.e., flow rate discontinuities between pools), which is a useful mathematical modeling approach, but cannot occur in real-world operations.

Furthermore, the HCC estimates presented in the 2017 CASS Report and 2019 CASS Supplemental Report were based on a criterion of maintaining 6 inches of freeboard from top of liner, which is not consistent with either the 2020 SOO or the freeboard incorporated in the original design for the original operating criteria. Since 2019, DWR has refined the California Aqueduct Hydraulic Model and modeling methods to include greater detail about the physical condition of the Aqueduct and more precise representations of operational adjustments.

Consequently, although the estimates presented in the 2017 CASS Report and 2019 CASS Supplemental Report are informative, the following caveats are important to consider:

- The 2017 and 2019 HCC values do not represent the current (2023) operation of the subsided Aqueduct.
- The 2017 and 2019 HCC values do not provide a representative base condition for evaluating and selecting potential corrective actions to address subsidence over the long term.
- Direct comparisons cannot be made between the 2017 and 2019 results and the results herein.

2.0 Original Design Capacity, Freeboard, and Normal Operating Range

2.1 Chapter Overview

Understanding how the Aqueduct was originally design and operated, including how elevation criteria were established and implemented, is helpful in formulating credible methods to estimate the HCC of a subsided Aqueduct. This chapter discusses the Aqueduct's original design capacity, freeboard considerations, and the normal operating range, all in the context of estimating the Aqueduct's current HCC. Additional details about the original design process are provided in Appendix D.

2.2 Original Design Capacity by Pool

This report introduces the term "original design capacity" to specify the Aqueduct's original HCC when it was first built according to its design criteria and operated according to its original operating criteria. In this report, original design capacity is equal in value to the "design discharge" in the 1965 Aqueduct Design Criteria (DWR, 1965) and in the SWP Data Handbook (DWR, 2018).

Table 2-1 shows the original design capacity for pools 14-40. The original design capacity was used, by the original Aqueduct designers, to size the concrete-lined and earth embankment sections of each pool.

Table 2-1. Original design capacity by pool

Pool	Original design capacity (cfs)
15	13,100
17	11,800
19	9,350
21	8,350
23	7,300
25	7,150/6,350
27	5,950
28	5,950
29	5,350
30	5,350/5,050
31	5,050
32	4,900
33	4,900
34	4,900
35	4,600
36	4,400
37	4,400
38	4,400
39	4,400
40	4,400

Source: DWR Data Handbook 2018

2.3 Calculation of Original Freeboard

This section provides an overview of considerations made as part of the original design when calculating the appropriate Aqueduct freeboard. It also discusses factors related to freeboard that are important to consider when calculating HCC under current or future subsided conditions of the Aqueduct.

The Aqueduct has two primary types of freeboard: lined and unlined. Lined freeboard is the vertical distance from the water surface elevation profile to the top of concrete liner. It guards against damage to the Aqueduct that could occur through erosion or through seepage from normal wave conditions, which are dictated by the top width of the water surface or by operational fluctuations (DWR, 1965).

Unlined freeboard is the vertical distance from the water surface to the top of the canal embankment (i.e., the sum of lined and unlined embankment above the water surface).[1] Referred to as “berm freeboard” in the Aqueduct Design Criteria (DWR, 1965), unlined freeboard provides additional protection (a factor of safety) during unplanned surges in water levels that may be caused by sudden gate closures, pumping plant failures, and/or large unplanned inflows. The design of Aqueduct freeboard depths was based on the size of the canal, expected flow rates, expected velocities in the canal, forecasted subsidence, and other expected operations such as flood flows.

The original SLFD design included a minimum lined freeboard of 3.0 ft above the original design water surface elevation, and the minimum unlined freeboard in the original design was approximately 5.5 ft in the SLFD. The original SJFD design included a minimum lined freeboard of 2.5 ft above the original design water surface elevation, and the minimum unlined freeboard in the original design was approximately 5.0 in the SJFD.

Some reaches of the Aqueduct included additional lined and/or unlined freeboard to accommodate expected subsidence (DWR, 1965). For the original Aqueduct design, the total canal depth was sized to be equal to the normal depth[2], plus the calculated appropriate lined and unlined freeboard, plus an additional height of lined and/or unlined embankment to account for the anticipated subsidence.

For a more complete description of the freeboard considerations made during the original design, refer to Appendix D and/or the Aqueduct Design Criteria (DWR, 1965).

---

[1] Unlined freeboard is sometimes defined from the top of the concrete liner to the top of embankment. In this report, it is defined from the top of the water surface to the top of the embankment.

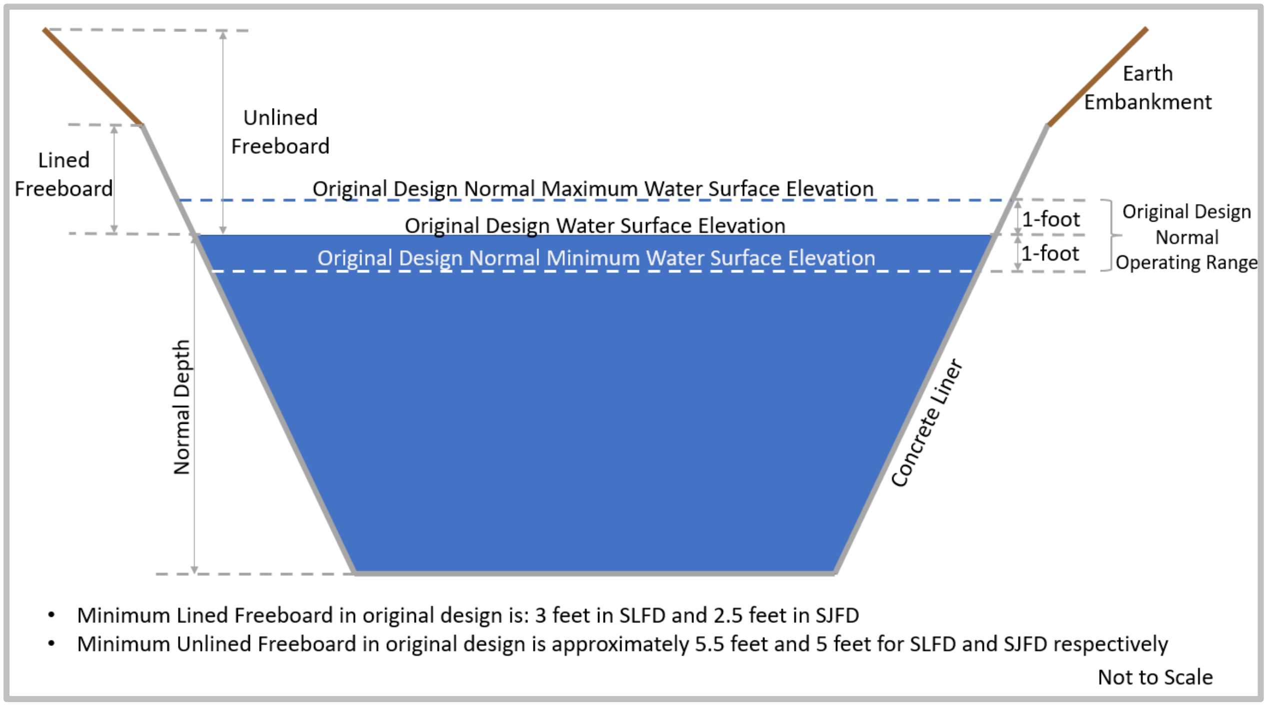
[2] Normal depth is known in hydraulics as the depth at which uniform flow will occur in an open channel. For the Aqueduct, normal depth also represents the distance from the canal invert to the original design water surface elevation needed to convey the original design capacity in the original design of the Aqueduct.

2.4 Original Design Normal Operating Range

After determining the required normal depth to convey the original design capacity, a normal operating range was established for each pool. The design normal operating range was set as the original design normal water surface elevation (hereinafter, original design water surface elevation), plus and minus 1 ft. Hence the original range of operating water surface elevations had a normal vertical variability of 2 ft, from 1 ft below to 1 ft above the original design water surface elevation. This range provided operators flexibility to initiate and accommodate flow changes. To summarize:

- The design normal maximum water surface elevation refers to the water surface elevation 1 ft above the original design water surface elevation.
- The design normal minimum water surface elevation refers to the water surface elevation 1 ft below the original design water surface elevation.

Figure 2-1 provides an illustration showing the relationship between freeboard, the normal operating range, and various elevations critical to operations and hydraulic conveyance capacity.



- Minimum Lined Freeboard in original design is: 3 feet in SLFD and 2.5 feet in SJFD
- Minimum Unlined Freeboard in original design is approximately 5.5 feet and 5 feet for SLFD and SJFD respectively

Not to Scale

Figure 2-1. Canal cross section with water surface elevations and operating criteria

3.0 California Aqueduct Hydraulic Model Overview

3.1 Chapter Overview

This chapter provides an overview of the California Aqueduct Hydraulic Model, the HEC-RAS hydraulic model that was used to simulate the analytical scenarios described in Chapter 5.0. The overview in this chapter is limited to information that is useful in understanding the application of the model to calculate the HCC values presented herein. Please refer to the California Aqueduct Hydraulic Model Development Report (DWR, 2023) for more information about the model and detailed descriptions of the model development.

3.2 Model Version and Specifications

The California Aqueduct Hydraulic Model L21PS23-V6.2-01 was used to compute the HCC estimates presented in this report. The L21PS23 label in the model's name indicates that the model elevations are based on 2021 LiDAR updated with 2023 Precise Survey; V6.2 indicates that the model was executed using HEC-RAS software Version 6.2; and 01 indicates this is the first model version with this combination of data.

The California Aqueduct Hydraulic Model was first developed as part of the 2017 CASS Report. Since that time, DWR has performed multiple iterations of geometry and gate algorithm refinements, as well as annual elevation updates using the latest available elevation data from the Precise Survey, which is conducted by a surveying unit with DWR's Division of Operations and Maintenance. The elevation dataset is also commonly referred to as the Precise Survey dataset.

3.3 Model Parameters

3.3.1 Model Extents

The California Aqueduct Hydraulic Model extends from Dos Amigos Pumping Plant to Edmonston Pumping Plant (Figure 3-1), i.e., pools 14 through 40. The model linework is projected using the North American Datum of 1927 (NAD 27), State Plane – California IV.

3.3.2 Model Elevation Data

The California Aqueduct elevations were first put into the hydraulics model using design plan sheets and details. Since then, the model has gone through several rounds of elevation updates. The elevations of the model used for the hydraulic analysis presented herein reflect adjustments made to the model using 2021 LiDAR to represent the subsided terrain trends and slopes more accurately. Model elevations were further adjusted by the difference between the 2023 and 2021 Precise Survey datasets to account for subsidence that happened between 2021 and 2023. Linear interpolation was used between points to adjust the model features located where Precise Survey points are not available.

The California Aqueduct Hydraulic Model elevations reference the North American Vertical Datum of 1988 (NAVD 1988).

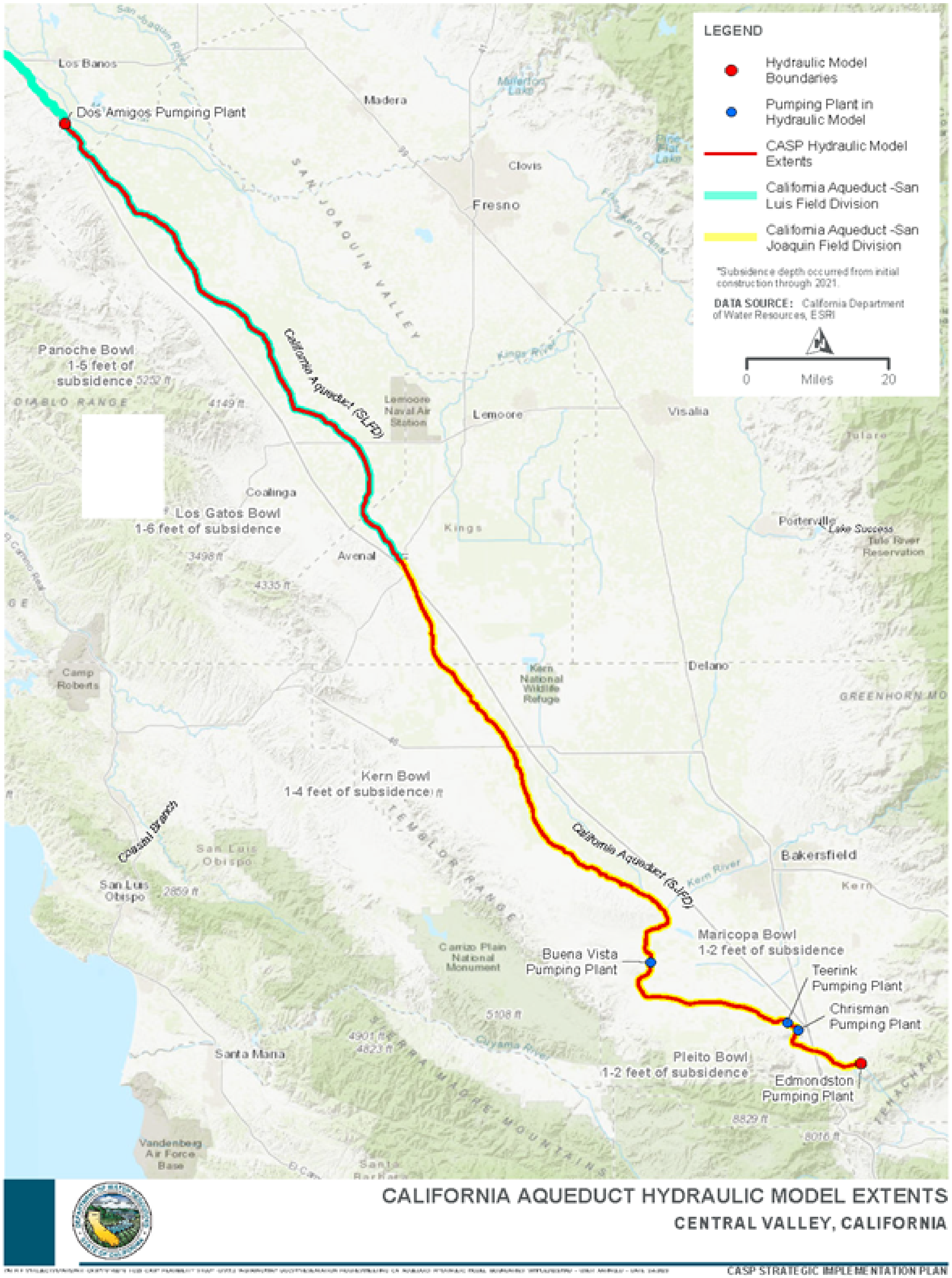


Figure 3-1. California Aqueduct Hydraulic Model extents

3.3.3 Model Cross Sections

Approximately 1,130 cross sections were used to model the Aqueduct channel. Cross sections are placed to capture variations in the channel such as widening, narrowing, bends, and changes in slope, roughness, or depth. The Aqueduct is a generally uniform channel, which allows for large distances between cross sections. Cross sectional spacing in the California Aqueduct Hydraulic Model varies from tens of feet to over a mile, with an average distance of 980 ft. Most cross sections represent the trapezoidal channel of the Aqueduct; a smaller subset of these represents the rectangular channel approach at check structures, siphons, or pump stations. Where the bottoms of overchutes are known to become submerged, the overchutes impact the upstream water surface by backing up water behind the overchute structure.

The Aqueduct is designed to be operated with water surface elevations below the top of liner; thus, the model was originally developed to represent the main channel and not overbank areas (e.g., outside of the bank stations). The cross-section bank stations were set at the concrete top of liner.

Channel base widths, side slopes, and depths (vertical distance between the base and the top of liner) for Aqueduct typical sections were developed in the model using design plan drawings. Cross-sections have been adjusted to include all the liner raises constructed as of the date of this report, including relatively recent liner raises (constructed between 2020-2021) in the vicinity of check 24 and check 25. Table 3-1 summarizes the Aqueduct segments that have been updated to account for concrete liner raises.

Table 3-1. Concrete liner raises in California Aqueduct Hydraulic Model

"Set" of Raises	Year	Spec no.	Start MP	End MP	Pool	Max Raise[3] (in)
Post Construction	1969	200C-752	132.19	132.95	17	24
	1970	200C-752	128.76	132.19	17	36
	1970	200C-752	132.19	132.95	17	24
	1970	200C-752	132.95	137.02	18	36
1982 Raises	1982	20-C0144	87.02	91.1	14	56
	1982	20-C0144	99.39	103.18	15	24
	1982	20-C0144	104.29	105.24	15	40
	1982	20-C0144	124.69	130.05	17	58
	1982	20-C0144	137	138.65	18	33
	1982	20-C0144	164.74	166.76	21	36
	1982	20-C0144	170.09	172.19	21	27
1989 Raises	1989	89-26	182.39	184.82	22	30
	1989	89-26	194.94	197.05	23	39
1996 Raises	1996	96-19	206.1	207.94	24	30
2018 Raises	2018	17-27	130.81	131.19	17	23
	2018	17-27	160.28	160.84	20	27
2021 Raises	2021	20-15	199.71	200.01	24	24
	2021	20-15	207.94	208.11	25	31
	2021	20-15	209.17	210.31	25	24

3.3.4 Effects of Subsidence

In several sections of the Aqueduct, subsidence has lowered the top of liner beyond what was originally anticipated: in some locations the resulting top of liner profile is below the original design freeboard elevation profile and, in some places, approaches the original intended operating water surface elevation profile, as shown in Figure 3-2. Figure 3-3 shows a section of the Aqueduct with very little freeboard during high flows.

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[3] "Max Raise" in Table 3-1 refers to the greatest vertical distance of the liner raise in that reach.

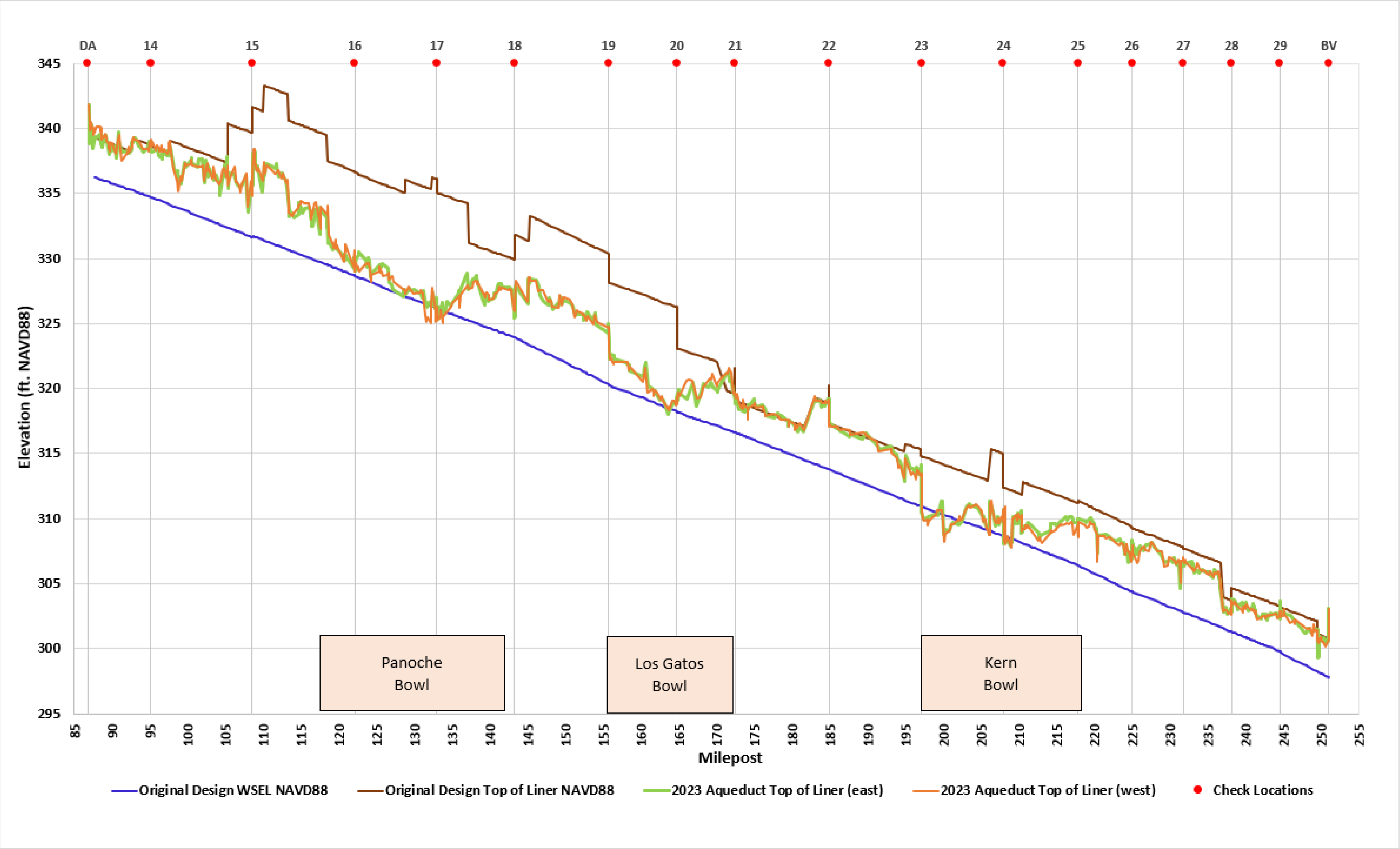

Figure 3-2. 2023 Top of liner compared to original design water service elevation (WSE) and original design top of liner

Figure 3-3. Section of the Aqueduct with reduced freeboard at high flows

3.3.5 Manning's Roughness Coefficient

In the California Aqueduct Hydraulic Model, Manning's n roughness coefficients for the main channel were set to a value of 0.02. This is consistent with recommendations made by the DWR Division of Engineering for current Aqueduct conditions (DWR, June 2017). It is also consistent with the analyses performed during the original design of the Aqueduct, which found that the roughness coefficient in Manning's equation must be increased to match the results generated by the Colebrook-White equation (for more details see Appendix D). Manning's roughness coefficients for concrete lined channels typically range from 0.011 to 0.027 depending on the smoothness of the finish (USACE, February 2016). During the original design of the San Luis Canal, a value of 0.016 was used (for more details see Appendix D). However, various calibration efforts indicated that 0.02 was more appropriate for the HEC-RAS hydraulic model of the Aqueduct (HDR, July 2018).

3.3.6 Modeled Structures

Several types of structures are represented in the California Aqueduct Hydraulic Model, as described below.

3.3.6.1 Check Structures (Inline Structures)

A total of 23 check structures (14-29, 31-34, and 37-39) are included in the California Aqueduct Hydraulic Model. Check structures are modeled as HEC-RAS inline structures with radial gate openings. Gate parameters including trunnion exponents, gate opening exponents, and head exponents were set to typical values of 0.16, 0.72 and 0.62, respectively. Radial discharge and orifice coefficient values were set to 0.7 and 0.8, respectively. These typical values are outlined in the HEC-RAS River Analysis System Hydraulic Reference Manual (USACE, February 2016).

3.3.6.2 Siphons (Lidded Cross Sections)

A total of thirteen siphons are included in the California Aqueduct Hydraulic Model, including Panoche Creek and Avenal Gap. Lidded cross sections were used to capture changes in elevation, height, and/or width of the siphons.

3.3.6.3 Pumping Plants (Pump Stations)

Four pumping plants are modeled as part of the California Aqueduct Hydraulic Model using the HEC-RAS pump station functions. The pumping plants modeled explicitly include Dos Amigos Pumping Plant (upstream end of pool 14), Buena Vista Pumping (downstream end of pool 30) Plant, Teerink Pump Plant (down stream end of pool 35), and Chrisman Pumping Plant (downstream end of pool 36). Edmonston Pumping Plant was modeled implicitly as the downstream boundary conditions for the model (downstream end of pool 40).

3.3.6.4 Lateral Structures

Lateral structures are included in the model to allow simulation of turnouts. The profile (weir elevations) of the lateral structures are not intended to be used for overtopping, so they do not accurately capture the top of embankment. Turnouts are simulated as gates. However, the gates are not modeled using weir or orifice equations. The model uses turnout gate rules and known turnout capacity to tell the model how much flow can be taken out of the system at that location.

3.3.6.5 Overcrossings

Overcrossings include overchutes, bridges, and pipelines. Hundreds of overcrossings exist between Dos Amigos Pumping Plant and Edmonston Pumping Plant. Because of subsidence, the low chord of some of these overcrossings is now encroaching below the originally intended operational water surface profile for some flow conditions. If partially submerged, these overcrossings can potentially experience uplift from buoyancy effects, can cause flow restrictions, or cause backwater effects. Twelve critical overcrossings that were deemed likely to be partially submerged during high flows (DWR, 2019) are included in the California Aqueduct Hydraulic Model using the HEC-RAS bridge modeling tool. These overcrossings are listed in Table 3-2.

Table 3-2. Modeled overcrossing

Overcrossing Type	MP	Pool
Check 17 Trunnion	132.95	17/18
Overchute	179.5	22
Overchute	196.58	23
Overchute	197.84	24
Overchute	207.18	24
Overchute	208.11	25
Overchute	209.36	25
Overchute	224.18	26
Overchute	225.05	27
Overchute	232.96	28
Pipeline	240.07	29
Overchute	246.51	30

3.4 Model Flow Data

The boundary conditions for HCC computations, including flow, downstream stages, and gate operations, are intrinsically tied to the modeling approach and objective of the simulations. The purpose of the HCC analyses described in this report is to estimate the maximum steady-state flow rate that can be achieved at specific Aqueduct locations (typically in each pool just below the upstream bounding check) while meeting a set of defined operating criteria. The process that is implemented to arrive at the various flow rates involves manipulation of downstream stages through gate settings.

The HCC results for each analytical scenario used in this report are described in Chapter 5.0.

3.5 Model Calibration and Validation

Model geometry settings such as the Manning's n roughness coefficients and gate orifice coefficients were calibrated as part of the base model refinement during 2018. Hourly stage and flow data for the SJFD and SLFD reaches of the Aqueduct were compiled for a period of 16 days extending from September 20, 2017, to October 5, 2017. Modeled results matched observed values with an average percent error ranging from 0.96 percent at check 18 to 4.22 percent at check 21 (where the maximum error occurred). The calibration process and results are presented in the 2019 CASS Supplemental Report.

An exercise was conducted in 2019 to validate a previous version of the California Aqueduct Hydraulic Model. At that time, the model elevations reflected 2018 conditions. Simulations were executed to estimate the HCC of the Aqueduct considering a 0.5-foot freeboard criterion. Using the flows derived from the simulations, an on-the-ground flow test was performed by the SLFD and SJFD. Results from these simulations were used to make predictions about the pools and mileposts where water surface elevations were expected to exceed the target freeboard amounts. DWR and HDR personnel then made on-sight field observations to scrutinize the model predictions. The flow test was performed from July 26, 2019, to July 31, 2019.

During the validation exercise, flow percent error values were calculated at locations where observed flow data were recorded, including check structures 18 – 22 and 25. Flow percent error is defined as the difference between observed and modeled flow rates divided by the observed flow rates. Flow percent error values ranged from 0.64 percent at check 18 to 5.18 percent at check 25. The flow percent error generally increased in the downstream direction. This is due to a lack of complimentary data including lateral outflow time series values and gate opening values which would allow modeled outputs to be more refined and mimic observed data. Stage data were recorded at checks 14 – 29. Water depth percent error values were calculated at these check structures. The water depth percent error was defined as the difference between observed and modeled depth relative to observed depth. The depth percent error values ranged from 0.7 percent at check 16 to 4.9 percent at check 25. The depth percent error ranged from 0.18 ft at check 29 to 1.28 ft at check 25. Observed water surface elevations at check 25 were consistently under the pool absolute minimum elevation of 304.9 ft NGVD 29 (307.9 ft in NAVD 88). However, this is acceptable because the model objective is to keep stages, i.e., depths, within a normal operating range, not at a specific target depth, similar to normal Aqueduct operations.

In general, the calibration and validation exercises have shown that the model produces reasonable results. These exercises were performed in 2018 and 2019, respectively, and since that time, subsidence has continued to alter Aqueduct elevations and modeling methods have been further refined, as described in Chapter 5.0.

4.0 Approach for Calculating Hydraulic Conveyance Capacity

4.1 Chapter Overview

This chapter provides an overview of the approach used to calculate HCC. It describes what an analytical scenario is, and the procedural steps that were used to estimate HCC.

4.2 Role of Operating Criteria in Analytical Scenarios

The appropriate modeling approach depends on the modeling objective. Here, the objective is to provide HCC estimates for specific analytical scenarios.

An analytical scenario is a combination of:

- Physical condition/geometry of the pool(s), including the subsidence effects on the Aqueduct's elevations. For the HCC estimates reported herein, the Aqueduct is modeled to represent its 2023 subsided condition.
- Operating criteria, including freeboard requirements, velocity restrictions, special conditions, the normal operating range.

In all the scenarios investigated herein, the physical condition of the Aqueduct (the 2023 subsided condition) is held constant. The scenarios vary in the operating criteria applied:

- Scenario 1: 2020 SOO with Coalinga Special Condition includes these conditions:
    - Physical condition/geometry: The Aqueduct's current subsided condition, as of 2023.
    - Operations criteria:
        - SOO 2020 operating criteria, with water surface elevations corrected for 2018-2023 subsidence.
        - General special conditions implemented to manage the operational impacts of subsidence.
        - Special Condition at check 18 to service the Coalinga Canal.
- Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions includes these conditions:

- Physical condition/geometry: The Aqueduct's current subsided condition, as of 2023.
- Operations criteria:
    - SOO 2020 operating criteria, with water surface elevations corrected for 2018-2023 subsidence.
    - General special conditions implemented to manage the operational impacts of subsidence.
    - Special Condition at check 18 to service the Coalinga Canal.
    - Special Condition at check 22 to service the Coastal Branch.

The operating criteria used to perform a simulation are fundamental elements of the HCC analyses. They help define the various analytical scenarios and are inextricably tied to the results. Given the subsided condition of the Aqueduct and the complex relationship between various facilities (e.g., pools, checks, turnouts, pumping plants), it is important to define the analytical scenario explicitly, including its operating criteria, as well as the modeling objective, before selecting the approach for estimating the HCC of a pool.

Thus, the intended use of the estimated HCC informs the operating criteria to be specified, which will, in turn, have a strong influence on the results and how the results may be interpreted and applied. Operating criteria include parameters such as:

- Lined freeboard constraints.
- Unlined freeboard constraints.
- Freeboard constraints at overcrossings such as checks, bridges, overchutes, and pipes.
- Velocity constraints.
- Special Conditions.
- Normal operating range.

Given the subsided condition of the Aqueduct, criteria such as the normal operating range may be difficult to define or may require modifications. Also, analysis of future scenarios and scenarios with greater freeboard requirements have shown that, at times, conflicts occur between criteria. If a conflict occurs between two criteria (for example freeboard and minimum water surface elevation), a decision must be made about which criterion to prioritize during the model simulation while trying to find a feasible solution; the appropriate decision will depend on the intended use of the modeling results.

4.3 Hydraulic Conveyance Capacity Computation Procedure

4.3.1 Model Simulation Process

A systematic approach for evaluating the HCC of Aqueduct pools was developed using HEC-RAS hydraulic structure rules capability algorithms; this approach allows for consideration of the Aqueduct as an interconnected system. The rules control the model gates (checks), lateral structures (turnouts), and pump stations (pumping plants). The modeling process consists of a long duration unsteady simulation during which algorithms evaluate the results at every timestep based on defined operational criteria.

Typically, the goal of each simulation is to maximize the flow in each pool. Criteria are set to meet specified lined freeboard at each pool and to operate within the normal operating range[4]. To maximize the HCC, target water surface elevations are set near the normal minimum water surface elevation at the downstream end of each pool. Based on the results of a simulation, the model automatically and systematically adjusts gate openings, turnout flow rates, and/or pumping plant flow rates to arrive at a solution.

The model implements the following process:

1. At the start of the simulation, the downstream boundary of each reach (i.e., each segment of the Aqueduct between two pumping plants) is set to specified water surface elevations (typically the average between the normal max and normal min water surface elevations per the 2020 SOO corrected for 2018-2023 subsidence), all check structure gates are open, and all turnouts are off.

2. The Dos Amigos Pumping Plant at the upstream end of the model supplies a flow rate of 13,100 cfs (original design capacity of pool 14) into the system at pool 14. Intermediate pumping plants (Buena Vista, Teerink, and Chrisman) convey flow at the end of their relative upstream reaches to the next reach downstream. For instance, the Buena Vista Pumping Plant transfers the flow from pool 30 to pool 31.

3. After the initial time-step, and each subsequent time-step, the model checks water surface elevations at every cross section (in all pools). The large flow rate at the beginning of the simulation will start to exceed the targeted operational criteria in pools as it moves downstream.

4. To meet the intended operational criteria, the model first attempts to adjust the flow rates in the system by engaging turnouts. Turnouts are turned on and ramped up in pools that have a simulated freeboard deficiency (less than the user-defined freeboard criteria). Turnouts are engaged starting with the most downstream turnout in a pool, sequentially moving upstream as necessary. As turnouts divert flow, the

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[4] The range of water surface elevations between the normal maximum water surface elevation and normal minimum water surface elevation

modeled flow reaching downstream pools will decrease. The reduced flow rate will result in a reduction in water surface elevations.

5. If all the turnouts in a freeboard-deficient pool have been engaged at maximum capacity and freeboard deficiencies still exist in that pool, the algorithm begins to turn on turnouts in pools upstream of the freeboard-deficient pool. Turnouts in the pools above the freeboard-deficient pool are also engaged sequentially, from downstream to upstream.
6. If water surface elevations cannot be regulated to meet the preset freeboard criteria with turnouts alone, then the algorithm begins to decrease the upstream flow rate at Dos Amigos Pumping Plant.
7. In some locations of the Aqueduct, water surface elevations need to be adjusted upward to meet minimum water surface elevation criteria. Choke points can limit the system's ability to convey the flow rates needed through downstream pools to sustain water surface elevations within the normal operating range. In these pools, gates are used to check up water levels and maintain water surface elevations at or above the preset minimum water surface elevation criteria.
8. The model evaluates the results of every timestep. If necessary, based on the preset criteria, the model adjusts check gate openings, turnout flows, and finally, the pumping plant flow (if needed) until conditions that meet the preset criteria are met. Eventually, when the modeled hydraulic conditions within all the pools satisfy the specified criteria, equilibrium is achieved.

If a conflict occurs between two criteria (for example freeboard and minimum water surface elevation), a decision must be made about which criterion to prioritize during the model simulation. Criteria prioritization will depend on the intended use or application of the analyses. This was not the case in any of the scenarios presented in this report. Although additional subsidence may lead to such scenarios in the future.

It is important to note that estimates of HCC can vary depending on the turnout loading[5]. A particular pool (e.g., pool X1) can have a limited HCC when looking at the system as a whole. However, in scenarios where large amounts of flow (in the range of 20 percent to 40 percent of the total flow) are being diverted from the pool directly downstream (e.g., pool X2), the HCC of pool X1 can experience significant increases in capacity (in the range of 10 percent to 40 percent more flow) while still meeting freeboard criteria. This happens because the additional flow diverted from pool X2 helps produce a lower water surface elevation profile, which ultimately leads to less backwater

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[5] Turnout loading refers to the configuration of engaged turnouts (i.e., the number of flowing turnouts, their location along a pool, and their flow rate). When calculating HCC, variations in the configuration of engaged turnouts can lead to differences in HCC estimates for a particular pool.

resistance for flows through pool X1. This phenomenon particularly affects significantly subsided pools, such as pool 20 and pool 24 under the 2023 conditions.

4.3.2 Normal Operating Range Subsidence Adjustments

During the first iteration of calculating the HCC for this report, the normal operating range elevations listed in the 2020 SOO were used to define the modeled target water surface elevations upstream of check structures. The 2020 SOO lists a normal minimum water surface elevation above check 24, approximately at MP 207.93, as 303.9 ft (NGVD 29) (306.9 ft in NAVD 88). However, the lowest point in the pool 24 liner has an elevation of 305.25 ft (NGVD 29) (308.25 in NAVD 88), approximately at MP 200.02. Maintaining 1 ft of freeboard from the top of liner yields a flat slope in pool 24 (approximately 1.4 x 10-5), which, in turn, results in an HCC of less than 2,000 cfs. Inquiries into the flow rates being conveyed through pool 24 during the summer of 2023 showed that the HCC of pool 24 is closer to 4,000 cfs.

Further investigation showed that check operations were not actually based on the elevations listed in the 2020 SOO, but rather on the relative depths these elevations produced at the time they were set in 2018. At the time the 2020 SOO normal operating range elevations were calculated, they produced a specific depth at the stilling wells above the check structures, including check 24. Stilling wells calculate water surface elevations using pressure based on depth. However, because subsidence has continued since the analyses in 2018 to establish the 2020 SOO elevations, and the stilling wells have subsided with the local conditions and their elevations have not been adjusted for subsidence, operators are actually operating at the same relative depth as when the 2020 SOO analysis was performed, rather than at the published elevations listed in the 2020 SOO.

Therefore, the normal operating range elevations actually being used to operate the Aqueduct are equal to the 2020 SOO elevations minus the subsidence that has occurred at each stilling well between 2018 and 2023; this subtraction is referred to in this report as “corrections” to the 2020 SOO. The normal operating range elevations corrected for 2018-2023 subsidence are presented in Appendix B (in NGVD 29).

Note that, whereas the 2020 SOO refers to NGVD 29, the California Aqueduct Hydraulics Model water surface elevations refer to NAVD 88. The conversion factors used to convert water surface elevations from NGVD 29 to NAVD 88 are shown in Appendix B. The normal operating range elevations shown in Appendix B were used to calculate all the HCCs presented in this report.

4.3.3 Modeling and Operation Constraints

Scenario simulations include a modeling constraint that gates must have a minimum opening of 1 ft. This minimum opening constraint prevents check structure gates from closing all the way, which can create simulation instabilities.

The simulations also honor an operational constraint that requires gates to remain submerged by at least 1 ft. This is a field practice to help measure flow through checks and to prevent the wind from potentially damaging the gates. The model limits the gate opening and closing rates to 1 ft per minute, consistent with the actual speed of gates at check structures. Check 17 is an exception; there has been so much subsidence at this check structure that its gates are no longer operated as originally intended–DWR keeps the gates at check 17 fully open year-round. Therefore, check 17 gates were modeled fully open for all scenarios analyzed herein.

4.3.4 Special Conditions

When applicable, scenarios must also include constraints in consideration of special conditions. Special conditions are field constraints (i.e., orders) operators must abide by to help with the functionality of a particular facility or to give operators additional flexibility in a constrained part of the Aqueduct.

There are special conditions in several locations along the Aqueduct. Each special condition is set for a unique reason. Typically, special conditions are requirements for water surface elevations to be maintained above or below a specific value. Their purpose is typically to maintain service to a specific turnout or for structural safety reasons.

One example is the special condition currently implemented at the Coalinga Canal diversion at approximately check 18. The water surface elevation at milepost (MP) 146.13 must be kept at least 2.5 ft higher than the 2020 SOO normal min water surface elevation [above elevation 320.5 ft (NGVD 29) (323.4 in NAVD 88] to prevent the pumps in the Pleasant Valley Pumping Plant from losing suction. A similar special condition is defined for the Coastal Branch. Many other special conditions have been established along the SLFD and SJFD. When calculating the HCC, one must check whether the appropriate special conditions are being applied for the given scenario.

5.0 Hydraulic Conveyance Capacities for 2023 Conditions

5.1 Chapter Overview

This chapter presents the estimated HCC, reported by pool, for two scenarios. These HCC estimates were computed as if the Aqueduct were operated in steady state under 2023 conditions. The two scenarios are:

1. Scenario 1: 2020 SOO with Coalinga Canal Special Condition
    a. Physical geometry reflecting the Aqueduct's 2023 subsided condition.
    b. SOO 2020 operating criteria, with water surface elevations corrected for 2018-2023 subsidence.
    c. General special conditions implemented to manage the operational impacts of subsidence.
    d. Special Condition at check 18 to service the Coalinga Canal.
2. Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions
    a. Physical geometry reflecting the Aqueduct's 2023 subsided condition.
    b. SOO 2020 operating criteria, with water surface elevations corrected for 2018-2023 subsidence.
    c. General special conditions implemented to manage the operational impacts of subsidence.
    d. Special Condition at check 18 to service the Coalinga Canal.
    e. Special Condition at check 22 to service the Coastal Branch.

Additional information is provided about the special conditions in Section 5.2.2.

5.2 Analytical Criteria Used for Hydraulic Conveyance Capacity Scenarios

5.2.1 Operating Criteria Common to Both Scenarios

The general operating criteria common to both analytical scenarios — Scenario 1: 2020 SOO with Coalinga Canal Special Condition and Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions — are summarized in Table 5-1.

Table 5-1. Operating criteria used in both scenarios to calculate HCC

Operating Criterion	Original Design Value	Scenario 1	Scenario 2
Lined freeboard	SLFD: 3.0 ft SJFD: 2.5 ft	1 ft	1 ft
Unlined freeboard	SLFD: 5.5 ft SJFD: 5.0 ft	N/C	N/C
Freeboard at checks	0.3 ft	N/C	N/C
Freeboard at overcrossings	Varies	N/C	N/C
Max velocity in the unreinforced concrete liner trapezoidal sections of the canal	8 ft per second	8 ft per second	8 ft per second
Target WSE at downstream end of pools, above checks and at pumping plant forebays	Original Normal Operating Range	2020 SOO Normal Operating Range*, except for special condition in pool 18	2020 SOO Normal Operating Range*, except for special conditions in pools 18 and 22

* Adjusted for subsidence as described in Section 4.3.2

5.2.2 Special Conditions and Constraints

The special conditions and constraints used in Scenario 1: 2020 SOO with Coalinga Canal Special Condition and Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions are summarized in Table 5-2.

Table 5-2. Summary of special conditions and constraints

No.	Description	Type	In Scenario 1	In Scenario 2
1	Max 3.8-ft submergence of check 17 trunnion deck	special condition	yes	yes
2	Max 2-ft overcrossing submergence	special condition	yes	yes
3	Max 0.75-ft submergence overchute at MP 197.84	special condition	yes	yes
4	Max 1.3-ft submergence overchute at MP 208.11	special condition	yes	yes
5	Check 17 locked at 24 ft opening	special condition	yes	yes
6	1 ft gate submergence	constraint	yes	yes
7	1 ft min gate opening	constraint	yes	yes
8	320.5 ft* (323.4 ft in NAVD 88) min water surface elevation upstream of check 18 to allow flow into the Coalinga Canal and prevent the pumps in the Pleasant Valley Pumping Plant from losing suction; this condition is implemented year-round	special condition	yes	yes
9	311.9 ft** (314.9 in NAVD 88) min water surface elevation upstream of check 22 to allow flow into the Coastal Branch and facilitate algae and weed management; this condition is generally implemented from spring through fall each year	special condition	no	yes

* 320.5 ft (NGVD 29) is water surface elevation not corrected for 2018-2023 subsidence; when corrected, the water surface elevation value is 319.98 ft (NGVD 29) (322.88 ft in NAVD 88).

** 311.9 ft (NGVD 29) is water surface elevation not corrected for 2018-2023 subsidence; when corrected, the water surface elevation value is 311.97 (NGVD 29) (314.97 in NAVD 88).

5.2.3 Description of Scenario 1: 2020 SOO with Coalinga Canal Special Condition

Scenario 1: 2020 SOO with Coalinga Canal Special Condition provides HCC estimates while implementing the operating criteria described in the 2020 SOO (adjusted for subsidence), with exception for special conditions. This scenario is representative of

Aqueduct year-round conditions, except when seasonal or temporary special conditions are in place.

Some special conditions are applied in the field to mitigate for the subsidence impacts to HCC. The special conditions included in this scenario to mitigate for the subsidence impacts to HCC are presented in Table 5-2 (items 1-5). These special conditions are in place year-round, with no exceptions.

This scenario also includes general constraints, as listed in Table 5-2 (items 6 & 7), that apply to all operating checks. Check 17 is the exception because it has been rendered inoperable by subsidence. The 1 ft gate submergence rule is a field constrained that is implemented to measure flows and protect gates from wind gusts. The 1 ft min gate opening rule is a modeling constrain that is implemented for model stability. This rule doesn’t impact the modeling results because the gates generally need to be mostly open to increase the HCC.

The Coalinga Canal Special Condition at check 18, listed in Table 5-2 (item 8), keeps the water surface above a specified elevation to allow flow into the Coalinga Canal and to prevent the pumps in the Pleasant Valley Pumping Plant from losing suction and/or starting to cavitate. The SJFD indicated that the Coalinga Canal Special Condition is in place year-round. To apply the Coalinga Canal special condition, the model uses the check 18 gates to prop the minimum water surface elevation just upstream of check 18 to an elevation of 322.88 ft (NAVD 88); approximately 2.4 ft higher than the 2020 SOO normal minimum water surface elevation. More information about the water surface elevations for special conditions used in Scenario 1 is provided in Table 5-3.

Table 5-3. Water surface elevation (WSE) values for special conditions used to compute hydraulic conveyance capacity for Scenario 1

Location	Referenced to 2020 SOO WSE	Corrected for 2018-2023 subsidence
Check 18 w/ Coalinga Canal Special Condition WSE, ft NAVD 88 (NGVD 29)	323.4 (320.5)	322.88 (319.98)
Check 22 normal min WSE, ft NAVD 88 (NGVD 29)	313.8 (310.8)	313.87 (310.87)

5.2.4 Description of Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions

Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions is like Scenario 1, but it includes an additional special condition. The additional special condition is implemented to help with functionality when operating the Coastal Branch of the Aqueduct near check 22.

As noted in Section 5.2.3, the Coalinga Canal special condition is set year-round to prevent the Pleasant Valley Pumping Plant from losing suction and causing the pumps to cavitate. The Coastal Branch special condition, however, is seasonal and it is set to help with algae and weed management at certain times of year. The Coastal Branch special condition typically becomes effective each year sometime in the April to June timeframe; and stays in place typically through sometime in the September to November timeframe.

The modeled Coalinga Canal and Coastal Branch Special Conditions force a higher water surface elevation at check 18 (same as Scenario 2) but also, force a water surface elevation at check 22 that is 1.1 ft higher than the 2020 SOO normal minimum water surface elevation. (Note: Check 22 has had a 0.07-foot bounce back since 2018.) The water surface elevations for special conditions used in Scenario 2 are provided in Table 5-4.

Table 5-4. Water surface elevation (WSE) values for special conditions used to compute hydraulic conveyance capacity for Scenario 2

Location	Referenced to 2020 SOO WSE	Corrected for 2018-2023 subsidence
Check 18 Coalinga Canal Special Condition min WSE, ft NAVD 88 (NGVD 29)	323.4 (320.5)	322.88 (319.98)
Check 22 Coastal Branch Special Condition min WSE, ft NAVD 88 (NGVD 29)	314.9 (311.9)	314.97 (311.97)

5.3 Simulation Results for Scenario 1: 2020 SOO with Coalinga Canal Special Condition

For Scenario 1: 2020 SOO with Coalinga Canal Special Condition, model simulations show three distinct choke points: check 17, pool 20, and pool 24. Check 17 flow is restricted at the trunnion deck. Pool 20 and pool 24 are restricted by the top of concrete liner. The check 17 restriction propagates all the way upstream to pool 14. The pool 20 restriction propagates all the way upstream to pool 18. The restricted pools above check 17 and pool 20 must make releases (or convey less flow) to accommodate the low capacity of each choke point. The low capacity in pool 20 also propagates downstream to pools 21, 22, and 23. The pool 24 restriction propagates downstream, limiting the amount of flow that can reach all the way down to pool 40.

Figure 5-1 shows the Scenario 1: 2020 SOO with Coalinga Canal Special Condition steady state HCC profile compared to the original design capacity. Note that the Model Output HCC shows the magnitude and locations of turnout flows (turnout loading) that are needed to accommodate the calculated steady state HCC at the upstream end of each pool. This indicates that more than 5,000 cfs would have to be delivered between pool 14 and pool 18 to get such high HCCs in the SJFD pools. The results presented herein are approximations limited by assumptions applied due to data gaps and variability in field conditions.

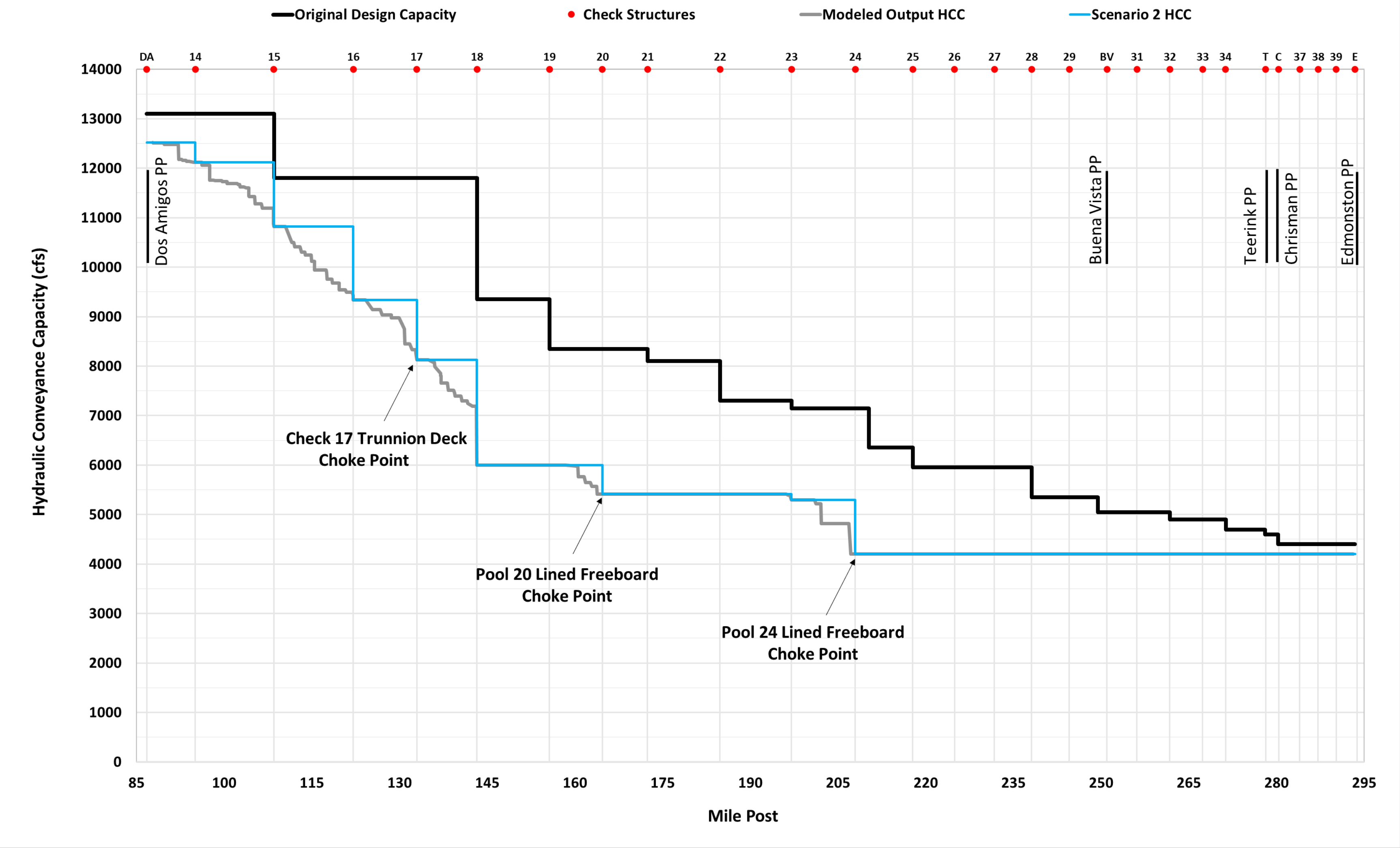

Figure 5-1. 2023 HCC profile for Scenario 1: 2020 SOO with Coalinga Canal Special Condition

5.4 Simulation Results for Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions

For Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions, model simulations show three distinct choke points: check 17, pool 20, and pool 24. check 17 flow is restricted at the trunnion deck. Pool 20 and pool 24 are restricted by the top of concrete liner. The check 17 restriction propagates all the way upstream to pool 14. The pool 20 restriction propagates upstream to pool 18. The restricted pools above check 17 and pool 20 must make releases (or convey less flow) to accommodate the low capacity of each choke point. The low capacity in pool 20, which is exacerbated by the Coastal Branch special condition, also propagates downstream to pools 21, 22, and 23. The pool 24 restriction propagates downstream, limiting the amount of flow that can reach pool 36.

Capacities downstream of pool 23 are greater than in Scenario 1: 2020 SOO with Coalinga Canal Special Condition because flows through pool 20 significantly less in Scenario 2. Therefore, flows can stay higher through pool 24 without creating a backwater effect that would lead to a freeboard violation in pool 20. Inversely, the flows can be increased through pool 24 for Scenario 1, but that would lead to reduced flows through pool 20. Figure 5-2 shows the Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions HCC profile compared to the original design capacity. As for Scenario 1, the Model Output HCC shows the magnitude and locations of turnout flows (turnout loading) that are needed to accommodate the calculated steady state HCC at the upstream end of each pool. This indicates that more than 5,000 cfs would have to be delivered between pool 14 and pool 18 to get such high HCCs in the SJFD pools. The results presented herein are approximations limited by assumptions applied due to data gaps and variability in field conditions.

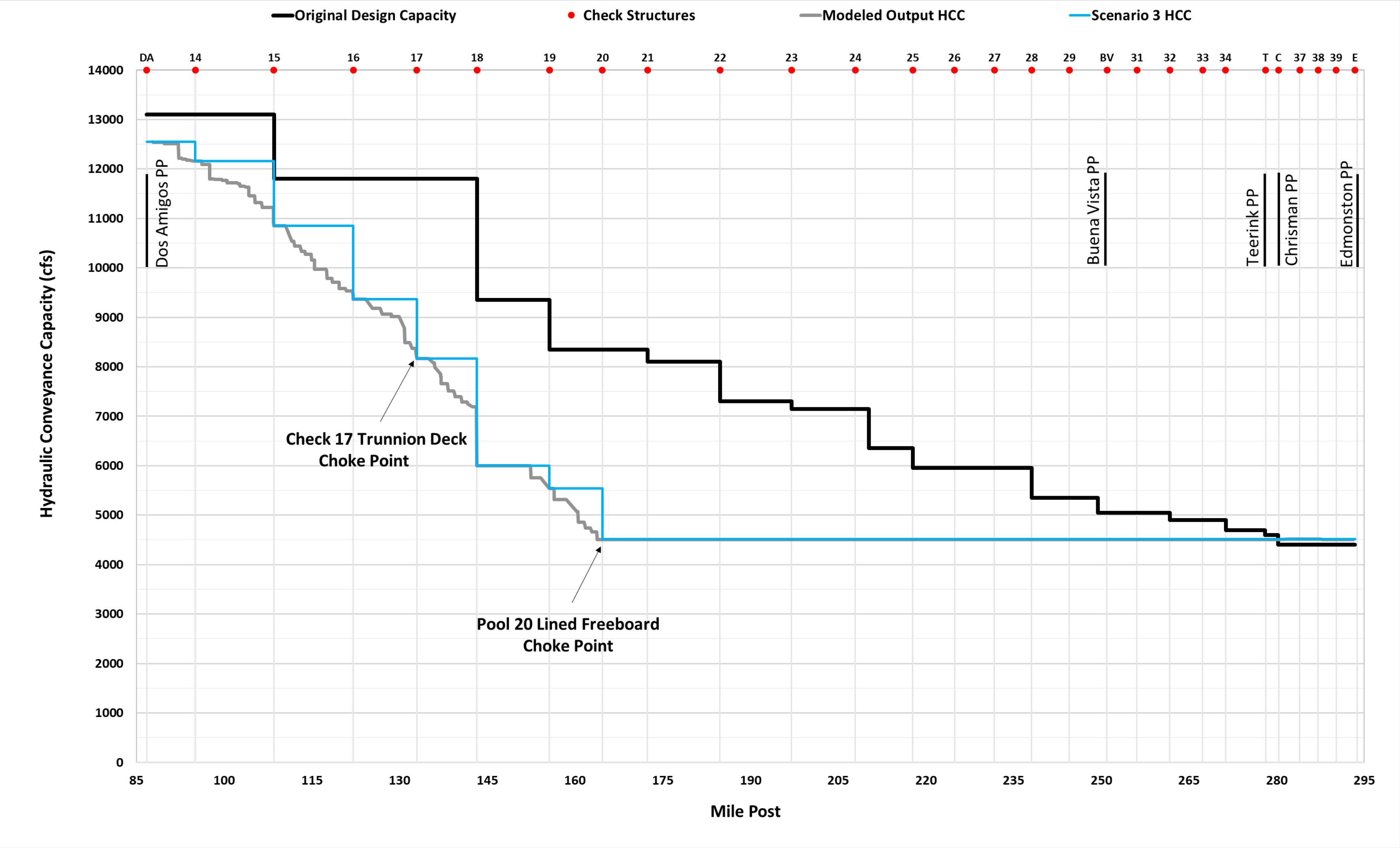

Figure 5-2. 2023 HCC Profile for Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions

Compiling the results of both analytical scenarios, Table 5-5 provides a summary of the estimated HCC for pools 14-40 for Scenarios 1 & 2. Scenario 1 likely represents the 2023 HCC between the months of November and May. Scenario 2 likely represents the 2023 HCC from late spring through fall, depending on algae and weed conditions.

The Aqueduct is a complex system that can be operated in many ways, including creating conditions which are favorable to specific pools. For example, by lowering the water surface elevations in a downstream pool, and “stacking” the water surface elevations in an upstream pool, this can create a short pulse (usually in a timescale of hours) of higher flows to increase the HCC through a specific pool. However, these conditions do not allow for a long-term, sustainable, flow rate. And averaged over a timeframe in the scale of a month, these short-term flow rates would be significantly lower. Therefore, they may not be useful in long-term planning.

The values presented in Table 5-5 represent current estimates of the maximum steady flow rates that may be sustained long-term (days or weeks) given adequate pumping and turnout loading. The results presented herein are approximations limited by assumptions applied due to data gaps and variability in field conditions.

Table 5-5. Hydraulic conveyance capacity estimates for pools 14-40 under both analytical scenarios

Pool	Original Design Capacity (cfs)	Scenario 1: 2020 SOO with Coalinga Canal Special Condition (cfs)	Scenario 2: 2020 SOO with Coalinga Canal and Coastal Branch Special Conditions (cfs)
14	13,100	12,520	12,550
15	13,100	12,120	12,160
16	11,800	10,820	10,860
17	11,800	9,340	9,370
18	11,800	8,130	8,160
19	9,350	6,000	6,000
20	8,350	6,000	5,540
21	8,350	5,410	4,510
22	8,100	5,410	4,510
23	7,300	5,410	4,510
24	7,150	5,300	4,510
25	6,350	4,200	4,510
26	5,950	4,200	4,510
27	5,950	4,200	4,510
28	5,950	4,200	4,510
29	5,350	4,200	4,510
30	5,050	4,200	4,510
31	5,050	4,200	4,510
32	5,050	4,200	4,510
33	4,900	4,200	4,510
34	4,900	4,200	4,510
35	4,700	4,200	4,510
36	4,600	4,200	4,510
37	4,400	4,200	4,510
38	4,400	4,200	4,510
39	4,400	4,200	4,510
40	4,400	4,200	4,510

6.0 References

California Department of Water Resources (DWR). 1965. Aqueduct Design Criteria.

California Department of Water Resources (DWR). 2017. California Aqueduct Subsidence Study (CASS). June 2017.

California Department of Water Resources (DWR). 2019. California Aqueduct Subsidence Study, Supplemental Report. March 2019.

California Department of Water Resources (DWR). 2018. Data Handbook, State Water Project.

HDR Engineering, Inc. (HDR). 2018. Hydraulic Analyses Report, DWR Task Order 47-CASS-02. July 2018.

US Army Corps of Engineers (USACE). 2016. HEC-RAS River Analysis System Hydraulic Reference Manual. February 2016.

7.0 Definitions

TERM	DEFINITION
California Aqueduct (Aqueduct)	A system of canals, pumping plants, tunnels, and pipelines that conveys water collected from the Sierra Nevada Mountains and valleys of Northern and Central California over 400 miles to Central and Southern California; the Aqueduct is a key feature of the State Water Project (SWP). It is owned and operated by the California Department of Water Resources (DWR), with the excep. on of a federally owned portion that extends for 102 miles from the O'Neill Forebay to the federal terminus at Kettleman City (pool 21 of the Aqueduct). This federally owned portion—the San Luis Canal—was designed and constructed by the US Bureau of Reclamation (Reclamation); however, it is operated and maintained by DWR's San Luis Field Division (SLFD).
California Aqueduct Hydraulic Model	A detailed hydraulic (HEC-RAS) model of the Aqueduct that represents its current physical features and their current condition, including recent elevational changes caused by subsidence.
Design normal maximum water surface elevation	The water surface elevation 1 ft above the original design water surface elevation.
Design normal minimum water surface elevation	The water surface elevation 1 ft below the original design water surface elevation.
Freeboard	The Aqueduct has two primary types of freeboard: lined and unlined. Lined freeboard is the vertical distance from the water surface to the top of the concrete liner. In this report, unlined freeboard is the vertical distance from the water surface to the top of the canal embankment (i.e., the sum of lined and unlined embankment above the water surface). This vertical distance above the water surface provides a factor of safety.
Hydraulic conveyance capacity (HCC)	The maximum steady flow rate at which water can be conveyed through an Aqueduct pool or section (such as a check), under specific physical conditions and operating criteria. In this report, the HCC value given for a pool represents the flow rate at the upstream end of the pool.
Maximum steady flowrate	The maximum flow rate that a particular Aqueduct feature, such as a pool or a check structure, can sustain for long periods. Typically, in a timescale of days and up to a month.

TERM	DEFINITION
Model reach	Various stretches of the Aqueduct between pumping plants represented in the California Aqueduct Hydraulic Model. For example, the model has a "model reach" between Dos Amigos Pumping Plant and Buena Vista Pumping Plant, which includes pool 14 through pool 30.
Normal depth	In hydraulics, the depth at which uniform flow will occur in an open channel. For the Aqueduct, normal depth also represents the original design water surface elevation needed convey the original design capacity in the original design of the Aqueduct.
Normal operating range	The range of water surface elevations between the normal maximum water surface elevation and normal minimum water surface elevation. Water surface elevations under normal operating conditions are typically within this range. (See Standing Operating Order (SOO) 600.22 dated May 20, 2020, for additional information about the normal operating range in the Aqueduct.)
Original design capacity	The Aqueduct's HCC when it was first built according to original design criteria and operated consistent with the original operating criteria. The original design HCC was defined for each pool in cfs.
Original design	A generic term referring to the condition resulting from the integration of the original layout and design of the physical features and geometry of the Aqueduct, the subsidence forecast at the time of design, and the intended operation criteria. The Aqueduct Design Criteria (DWR, 1965) defined the original design criteria for the State-owned portions of the Aqueduct. The 1961 Joint Use Facilities Operations and Maintenance Agreement defined the original design criteria for the San Luis Canal.
Original design water surface elevation	The water surface elevation needed to convey the original design capacity in the original design of the Aqueduct.
Pool	A distinct segment of the Aqueduct bounded by either pump stations or check structures. Each pool has a defined original design conveyance capacity, storage capacity, and water surface elevations. The sequential numbering of the Aqueduct pools is coincident with the check structure number at the downstream end of a pool.
Pool service demand	The sum of deliveries measured at turnouts within a pool, plus the deliveries conveyed downstream measured at the check structure, plus any losses of water within the pool for a given time period.

TERM	DEFINITION
Precise Survey	An annual topographic survey performed by DWR that measures elevations at established monuments along the Aqueduct. Elevations are measured at several types of locations including top of concrete liner, check structures, bridges, turnouts, and other Aqueduct facilities.
Special conditions	Field constraints (i.e., orders) operators must abide by to help with the functionality of a particular facility or to give operators additional flexibility in a constrained part of the Aqueduct.
Steady state	A condition of the Aqueduct during which hydraulics are not changing. Flows through pools, turnouts, and checks are constant and water surface levels are not changing.
Stilling well	Aqueduct facilities used to monitor water surface elevations. They are located upstream and downstream of every check structure. They measure the water depth using a pressure transducer. The depth is converted and reported as water surface elevation.
Turnout loading	The configuration of engaged turnouts (i.e., the number of flowing turnouts, their location along a pool, and their flow rate). When calculating HCC, variations in the configuration of engaged turnouts can lead to differences in HCC estimates for a particular pool.

Appendix A. 2020 SOO Water Surface Elevation Operating Range

The Absolute Maximum, Absolute Minimum, Normal Maximum, and Normal Minimum water surface elevation values presented in Table A-1 references the 2020 SOO 600.22 (with no water surface elevation adjustments for 2018-2023 subsidence). The values in this table are reported in NGVD 29 as presented in the 2020 SOO 600.22.

Table A-1. 2020 SOO water surface elevation operating range (NGVD 29)

Check No.	MP Pool Limits	Measurement Type Measurement Limits	Absolute Maximum (ft)	Absolute Minimum (ft)	Normal Maximum (ft)	Normal Minimum (ft)
DA	70.90-86.73	Stilling/encoder 225.0-215.0	225.0	213.3	224.0	217.0
CK 14	86.96-95.06	Stilling/encoder 335.5-325.5	333	328	331	329
CK 15	95.11-109.5	332.5-322.5	330.4	326	329	327
CK 16	108.56-122.07	Stilling/encoder 329.5-319.5	326	322.1	323.4	322.5
CK 17	122.13-132.95	Stilling/encoder 326.0-316.0	322.2	320.4	321.6	320.6
CK 18	133.0-143.23	Stilling/encoder 324.5-314.5	320.8	317.5	319	318
CK 19	143.29-155.64	Stilling/encoder 321.0-311.0	316.4	314.6	316.1	315.1
CK 20	155.70-164.69	Stilling/encoder 319.0-309.0	315.1	313.4	314.7	314
CK 21	164.74-172.40	Pressure transducer 317.0-307.0	314.5	311	313.7	311.3
CK 22	172.44-184.82	Pressure transducer 314.5-304.5	312.6	310.5	311.8	310.8
CK 23	184.84-197.05	Pressure transducer 311.5-301.5	309.1	305.6	306.7	306.2

Check No.	MP Pool Limits	Measurement Type Measurement Limits	Absolute Maximum (ft)	Absolute Minimum (ft)	Normal Maximum (ft)	Normal Minimum (ft)
CK 24	197.07-207.94	Pressure transducer 309.0-299.0	305.5	303.4	304.9	303.9
CK 25	207.96-217.79	Pressure transducer 307.0-297.0	303.8	301.9	303.4	302.4
CK 26	217.81-224.92	Pressure transducer 305.0-295.0	303.7	300	301.4	300.4
CK 27	224.94-231.73	Pressure transducer 303.5-293.5	302.8	298.6	299.9	298.9
CK 28	231.75-238.11	Pressure transducer 302.0-292.0	298.6	295.6	297.7	296.7
CK 29	238.13-244.54	Pressure transducer 300.5-290.5	297.8	295.2	296.7	296
BV	244.56-250.99	Pressure transducer 299.0-289.0	296.2	293.1	294.6	293.6
CK 31	251.01-256.14	Pressure transducer 502.0-492.0	500.3	498.8	*	*
CK 32	256.18-261.72	Pressure transducer 502.0-492.0	499.5	497.5	499.3	497.8
CK 33	261.77-267.36	Pressure transducer 498.0-488.0	497.7	495.2	497.2	495.7
CK 34	267.43-271.27	Pressure transducer 496.5-486.5	495.9	493.4	495.4	493.9
WR	271.33-278.13	Pressure transducer 494.5-484.5	494.5	492.0	494.0	492.5
WG	278.13-280.36	Pressure transducer 729.0-719.0	726.5	722.0	725.3	722.5
CK 37	280.37-283.95	Pressure transducer 1244.5-1234.5	1243.5	1241.4	1242.9	*
CK 38	284.01-287.09	Pressure transducer 1243.5-1233.5	1241.0	1240.5	*	*

Check No.	MP Pool Limits	Measurement Type Measurement Limits	Absolute Maximum (ft)	Absolute Minimum (ft)	Normal Maximum (ft)	Normal Minimum (ft)
CK 39	287.14-290.21	Pressure transducer 1242.5-1232.5	1239.0	1238.9	*	*
ED	290.23-293.45	Pressure transducer 1241.5-1231.5	1239.5	1237.5	*	*
DA	70.90-86.73	Stilling/encoder 225.0-215.0	225.0	213.3	224.0	217.0

* Buena Vista (BV); Check (CK); Dos Amigos (DA)

Appendix B. Subsidence corrections and vertical datums conversions for 2020 SOO WSE operating range

Table B-1 shows the corrections made to the 2020 SOO 600.22 water surface elevations at each check to account for 2018-2023 subsidence. Table B- also shows the conversions made from the NGVD 29 Datum to the NAVD 88 Datum.

Table B-1. Corrections made to the 2020 SOO water surface elevation operating range (NAVD 88)

Check No.	MP Pool Limits	2020 SOO Normal Minimum (NGVD 29)	2020 SOO Normal Maximum (NGVD 29)	2018 - 2023 Correction for Subsidence	2020 SOO Normal Minimum (NGVD 29) Corrected for Subsidence between 2018 - 2023	2020 SOO Normal Maximum (NGVD 29) Corrected for Subsidence between 2018 - 2023	Vertical Datum Conversion Factor (NGVD 29 to NAVD 88)	2020 SOO Normal Minimum (NAVD 88) Corrected for Subsidence between 2018 - 2023	2020 SOO Normal Maximum (NAVD 88) Corrected for Subsidence between 2018 - 2023
DA	70.90-86.73	217	224				2.8		
14	86.96-95.06	329	331	0.14	329.14	331.14	2.9	332.04	334.04
15	95.11-109.5	327	329	0.06	327.06	329.06	2.8	329.86	331.86
16	108.56-122.07	322.5	323.4	-0.6	321.9	322.8	2.9	324.8	325.7
17	122.13-132.95	320.6	321.6	-0.78	319.82	320.82	2.8	322.62	323.62
18	133.0-143.23	318	319	-0.52	317.48	318.48	2.9	320.38	321.38
19	143.29-155.64	315.1	316.1	-0.46	314.64	315.64	2.9	317.54	318.54
20	155.70-164.69	314	314.7	-0.93	313.07	313.77	2.9	315.97	316.67
21	164.74-172.40	311.3	313.7	0.17	311.47	313.87	3	314.47	316.87
22	172.44-184.82	310.8	311.8	0.07	310.87	311.87	3	313.87	314.87
23	184.84-197.05	306.2	306.7	-0.46	305.74	306.24	3	308.74	309.24
24	197.07-207.94	303.9	304.9	-0.56	303.34	304.34	3	306.34	307.34
25	207.96-217.79	302.4	303.4	-0.4	302	303	3	305	306
26	217.81-224.92	300.4	301.4	-0.47	299.93	300.93	3	302.93	303.93
27	224.94-231.73	298.9	299.9	-0.28	298.62	299.62	3	301.62	302.62
28	231.75-238.11	296.7	297.7	-0.17	296.53	297.53	3	299.53	300.53
29	238.13-244.54	296	296.7	-0.02	295.98	296.68	3	298.98	299.68
BV	244.56-250.99	293.6	294.6		293.6	294.6	3	296.6	297.6
31	251.01-256.14	498.8	500.3	-0.12	498.68	500.18	3	501.68	503.18
32	256.18-261.72	497.8	499.3	-0.12	497.68	499.18	3	500.68	502.18
33	261.77-267.36	495.7	497.2	-0.31	495.39	496.89	3	498.39	499.89
34	267.43-271.27	493.9	495.4	-0.43	493.47	494.97	3	496.47	497.97
WR	271.33-278.13	492.5	494		492.5	494	3	495.5	497
WG	278.13-280.36	722.5	725.3		722.5	725.3	3	725.5	728.3
37	280.37-283.95	1241.4	1242.9	0.01	1241.41	1242.91	3	1244.41	1245.91
38	284.01-287.09	1240.5	1241	0.03	1240.53	1241.03	3	1243.53	1244.03
39	287.14-290.21	1238.9	1239	0.04	1238.94	1239.04	3	1241.94	1242.04
ED	290.23-293.45	1237.5	1239.5		1237.5	1239.5	3	1240.5	1242.5

* Buena Vista (BV); Dos Amigos (DA)

Appendix C. Pool-by-Pool Method for Calculating Hydraulic Conveyance Capacity

The pool-by-pool method was used to calculate the hydraulic conveyance capacity (HCC) estimates presented in the 2017 CASS Report and the 2019 CASS Supplemental Report. The pool-by-pool method has limitations that prevent it from fully capturing an actual systemwide scenario, because it does not observe conservation of mass. Large flow changes are assumed within the modeling between some of the pools that are physically infeasible.

Regardless of its simplifying assumptions and limitations, the pool-by-pool method of evaluating HCC can be useful for estimating the localized pool capacities (although it has limitations when considering the impacts from downstream pools). This information can be useful when evaluating some localized operations such as water transfers and for evaluating CalSim operations. The analysis requires an iterative process by which steady-state HEC-RAS simulations are executed until one converges on a solution that satisfies all of the intended criteria. Each iteration follows the following procedure:

1. Set an elevation boundary condition at the most downstream end of each model reach.[6] If the elevations of the concrete liner permit, this will typically be the average between the SOO normal minimum and normal maximum water surface elevations.
2. Run the HEC-RAS model with flowrates set at the most upstream cross section of each pool equal to the original design capacity for that pool. For modeling purposes, as part of the pool-by-pool analysis, gates remain fully open and flow changes between pools occur instantaneously at the most upstream cross section of each pool.
3. Check the model results for operational criteria violations. Typically, this consists of checking whether the model exceeds specified lined freeboard criteria. During this step, the resulting water surface elevation profile is compared against the top of liner elevations and locations are noted where the calculated water surface elevation does not match the desired freeboard criteria.
4. Adjust flow inputs to the model and rerun simulations until all intended operating criteria are satisfied, starting with the most downstream location where target criteria are not satisfied, by reducing flow in the most downstream pool at which the unsatisfied criteria had occurred. Iteratively reduce the flow in the pool by trial and error and re-run the model until the intended criteria are satisfied.

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[6] In this context, “model reaches” refers to the various stretches of the Aqueduct between pumping plants. For example, the “model reach” between Dos Amigos Pumping Plant and Buena Vista Pumping Plant, which includes Pool 14 through Pool 30.

5. Progressively move upstream to the next location where criteria were not satisfied and adjust inputs and rerun simulations until all criteria are satisfied by repeating step 4. Once all criteria have been satisfied, the flowrate is noted for each pool.

If a particular pool has limited capacity (less than original design capacity), that limited capacity will typically be transferred to downstream pools when performing a pool-by-pool HCC assessment. This is because there is generally no way to introduce significant amounts of additional flow downstream of the limited capacity pool. This is referred to as the effective HCC, which is the HCC of a pool that is limited indirectly by the capacity of other system elements, such as upstream or downstream pools, rather than only by the concrete liner profile within the pool.

For example, pool 20 conveys water to pool 21. If pool 20 has a limited capacity of 5,600 cfs (and an original design capacity of 8,350 cfs), the limited capacity is carried downstream. Therefore, even if pool 21 has a greater standalone capacity of 7,000 cfs, the effective HCC of pool 21 (when analyzed using the pool-by-pool method) would be reported as 5,600 cfs. These results show that the capacity of upstream pools limit downstream pools and assumes there would be no other way to get water to the lower pool.

An alternative way to calculate pool-by-pool capacities is to assume that additional water could be delivered to downstream pools. Some turnouts also function as turn-ins, so there could be alternative ways to get water to downstream pools. To evaluate the discrete HCC of these pools—the HCC of a pool calculated without the indirect impacts from upstream or downstream pool conveyance limitations—the alternative “non-linear pool-by-pool analysis” assumes that pool capacities are not limited by the capacity of upstream pools. However, the non-linear pool-by-pool analyses, when performed with a model in series, often results in lower capacities for subsided pools. This is because flowrates in pools downstream of pools compromised by subsidence are increased (assuming downstream pools can have higher flowrates than upstream pools), which raises downstream pool water surface elevations and creates greater backwater resistance for upstream pool flows.

Another way to perform this evaluation and avoid impacts from downstream pools is to isolate the geometry and evaluate each pool separately. This analysis can help define the capacity of individual pools without the impacts from the rest of the system. However, it neglects the potential impacts from stages in downstream pools.

The pool-by-pool method may produce misleading results for a few pools. For example, the pool-by-pool analysis tends to overestimate the operable HCC of pool 19 because it does not directly take into consideration the limitations of pool 20 and the turnouts in pool 19 which lead to a lower effective HCC.

Other factors indirectly related to subsidence, besides lined freeboard, also can impact the hydraulic conveyance capacity of a pool. For example, as noted above, the capacity of an upstream pool can influence the effective hydraulic conveyance capacity of a downstream pool. Analyses showed that the capacity of a downstream pool can also limit the capacity of an upstream pool. Thus, more comprehensive approach for estimating hydraulic conveyance capacity is needed to reflect field operations and systemwide hydraulic constraints more closely.

Appendix D. Overview of Original Aqueduct Design

This appendix provides an overview of the approach the original designers of the Aqueduct took to establish the original intended flow rate ("original design capacity" described below), how that flow rate was used to size the canal pools, and how an additional factor of safety was incorporated through the addition of lined and unlined freeboard. This information provides additional context that may be useful in understanding how to calculate the long-term, sustainable, maximum steady flow rate HCC; as opposed to an instantaneous peak flow rate that cannot be sustained "long-term" (i.e., more than a few hours). As described below, the Aqueduct's original design capacity considers demand at a monthly timescale and includes flexibility in the form of a peaking factor.

Original Design Capacity Calculation

Original design capacity, as used herein, refers to the Aqueduct's original hydraulic conveyance capacity when it was first built according to design criteria and operated according to original operating criteria. The 1965 Aqueduct Design Criteria (DWR, 1965) indicate that the flow rate used to size the canal comprised two inputs: the Area Service Demand and a Peaking Factor. Area Service Demand refers to the water demanded from a specific Aqueduct facility, including deliveries and losses. The largest portion of an Area Service Demand is the net delivery volume.

To compute original design capacity by pool, an analogous pool-specific variable, pool service demand, is needed. For any given pool for a given time period, the pool service demand is the sum of the deliveries measured at turnouts within that pool, the deliveries conveyed downstream measured at the check structure, and any losses of water within the pool.

A monthly Peaking Factor (as defined in DWR, 1965) is added to the pool service demand to account for variable demand patterns through the year. The following Equation 1 for original design capacity was developed while evaluating the 2023 HCC based on the description provided in Section 2.1.1.6 of the Aqueduct Design Criteria (DWR, 1965).

Equation 1: Original Design Capacity

$$Q_D = Q_{max} + PF$$

Where:

Q_D = Original design capacity (cfs)

Q_{max} = The flow rate required for the month with the most demand if the demand was met with continuous flow during that month (cfs)

PF = Peaking Factor defined as $PF = 0.2\ (Q_{max} - Q_{avg})$

Q_{avg} = The flow rate required if the entire annual demand was delivered with continuous flow divided evenly throughout the year (cfs)

For example, consider a hypothetical pool with a pool service demand of 3 million acre-feet (af) per year. If distributed evenly over 12 months, this results in an average of 250,000 af per month, or an average continuous flow rate of approximately 4,200 cfs. Suppose that the month with the highest demand along this pool requires 20 percent of the total annual delivery. This is equal to 600,000 af or a required flow rate of approximately 10,083 cfs. Using Equation 1, the original design capacity for this hypothetical canal pool is 11,260 cfs.

$$QD = 10{,}083 \text{ cfs} + 0.2\ (10{,}083 \text{ cfs} – 4{,}200 \text{ cfs}) = 11{,}260 \text{ cfs}$$

Sizing the Original Canal Sections

After determining the original design capacity, Aqueduct designers established the depth, width, and side slopes of the canal trapezoidal sections necessary to provide the intended flow rate under the intended original operating criteria. A portion of the analyses focused on identifying the ideal, most hydraulically efficient canal depth-to-width ratio for a trapezoidal channel to convey the original design capacity. Based on these analyses, a range of depth-to-width ratios between 0.6 and 0.9 was recommended, varying based on the side slopes of the trapezoidal channel. Subsequently, the geotechnical properties of the foundation soil were used to determine the final channel cross section dimensions. Different approaches were used for the hydraulic design of the canal for the SLFD (Reclamation design) and SJFD (DWR design).

Numerous tests by Reclamation in the Delta-Mendota and Friant-Kern canals informed the selection of a hydraulic design approach for the San Luis Canal. Based on information discovered during these tests, Reclamation decided to design the San Luis Canal using Manning’s equation. When applying Manning’s equation, Reclamation designers used a roughness coefficient of $n = 0.016$ for the canal, and additional provisions were included to account for energy losses at bridges.

In the design of SJFD facilities, DWR used the Colebrook-White equation to design the Aqueduct (DWR, 1965). Tests performed prior to the design of the Aqueduct indicated that for larger channels, such as the Aqueduct, the roughness coefficient in Manning's equation must be increased to match the results generated by the Colebrook-White equation. This does not mean that the actual roughness of the canal increases, but rather that, according to these tests, a roughness higher than the typical value or range corresponding to the liner material is needed to match test results (DWR, 1965).

Once the Aqueduct slope and cross section dimension (bottom width and side slopes) were established, Equation 2 and/or Equation 3 were used to determine the normal water surface elevation. This normal water surface elevation is referred to herein as the original design water surface elevation.

Equation 2: Manning's Equation

$$V = \frac{1.486}{n} \mathrm{R}^{2/3} \text{ - } \mathrm{S}^{1/2}$$

Where:
V = velocity (ft/s)
n = Manning's roughness coefficient [0.016 in the original design of the San Luis Canal]
R = hydraulic radius (ft)
S = canal slope (ft/ft)

Equation 3: Colebrook-White Equation

$$V = -\sqrt{32gRS} * log\left[\frac{k}{14.8R} + \frac{1.255\upsilon}{R\sqrt{32gRS}}\right]$$

Where:
V = velocity (ft/s)
g = gravitational constant (32.2 ft/s^2)
R = hydraulic radius (ft)
S = canal slope (ft/ft)
k = equivalent sand-grain roughness [0.005 in the original design of the SJFD Aqueduct]
υ = kinematic viscosity (ft^2/s)

The elevations calculated using these equations are only a portion of the total canal depth (DWR, 1965). A subsequent assessment was implemented to calculate the height of the appropriate lined and unlined freeboard.

Original Design Freeboard

The chart shown in Figure D-1 was used as part of the original design to calculate the minimum appropriate freeboard. The source equations or analyses used to derive these relationships are not presented in the Aqueduct Design Criteria (DWR, 1965). However, the document does include some additional context.

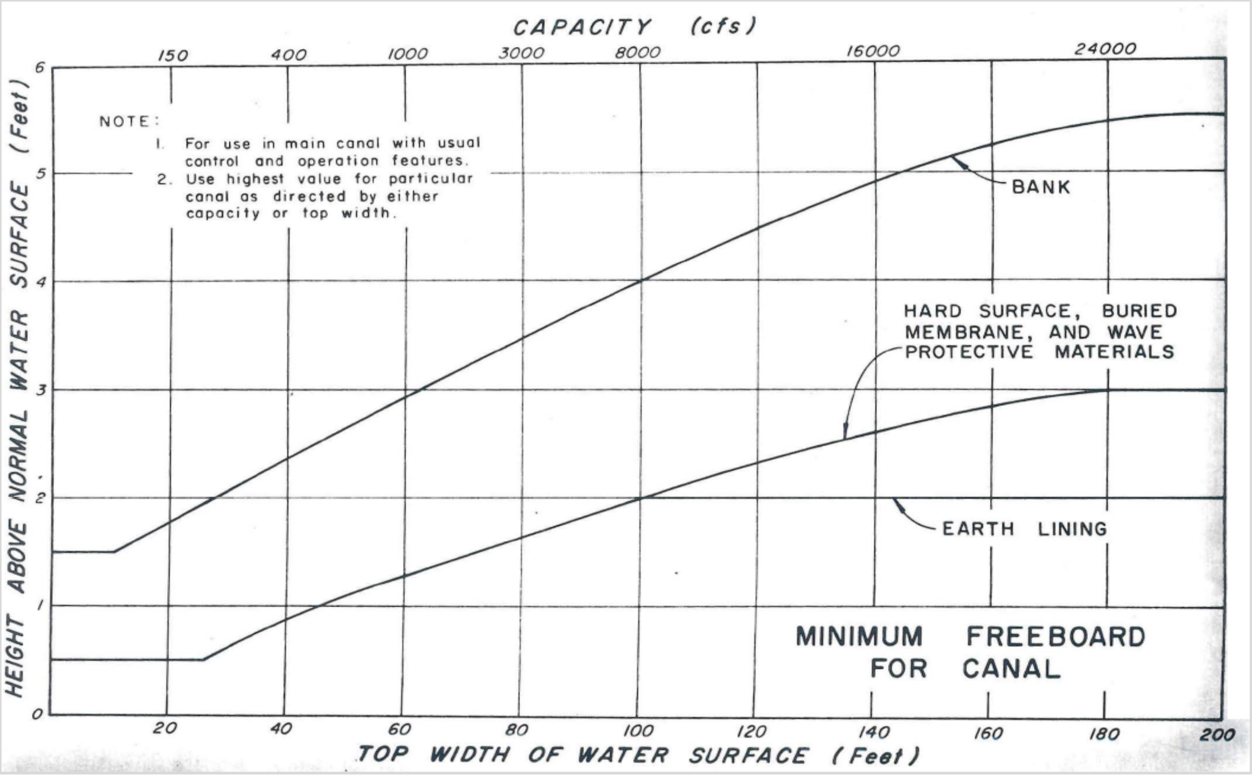

Figure D-1. Minimum freeboard value for Aqueduct canal with normal control and operation features

Source: DWR, Aqueduct Design Criteria, Figure 2.3-3