An Application of the California Environmental Flows Framework to the Lower Cosumnes River

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Purpose and Summary

The Cosumnes River is the largest undammed river on the west side of the Sierra Nevada. Located between the American and Mokelumne River watersheds, the Cosumnes River flows from the Sierra Nevada mountains 80 miles westward to the San Francisco-Bay Delta via its confluence with the Mokelumne River in the Central Valley. The lower Cosumnes River in the Central Valley supports a Chinook salmon run, hundreds of species of migratory birds, diverse groundwater dependent ecosystems, as well as the largest remaining Central Valley riparian forest. In addition, the lower watershed supports thousands of acres of productive agricultural land and several local communities.

Decades of groundwater overdraft and uncoordinated diversions have contributed to diminished river flows in the lower Central Valley reaches, particularly in the summer and fall when some reaches periodically go dry. Agencies, agricultural entities, non-governmental organizations (NGOs), and other stakeholders are working to identify multi-benefit strategies to sustain water supply, ecosystems, and agriculture. Under the auspices of the Sustainable Groundwater Management Act (SGMA), work is currently underway to address groundwater basin aquifer sustainability, characterize surface-groundwater interactions, understand the related groundwater dependent ecosystems, and measure groundwater recharge and use. However, additional knowledge of surface water hydrology is needed in order to inform the development of instream flow targets supportive of anadromous fish, riparian habitat, and other ecological objectives.

To address this knowledge gap, the California Environmental Flows Framework (CEFF) was applied to determine ecological flow criteria based on a functional flows approach. This document details the results of this application.

Overview of the California Environmental Flows Framework

CEFF was developed by a technical team within the California Environmental Flows Working Group, a sub-group hosted by the California Water Quality Monitoring Council that includes scientists and managers from resource agencies, academia, and non-governmental organizations. CEFF establishes a technical process for developing environmental flow targets for rivers throughout the state. The framework is based upon **functional flows**, a scientific concept that emphasizes the biological, chemical, and physical functions of flowing water that sustain native aquatic species and riparian ecosystems. When coupled with the restoration of physical habitat, managing streams using functional flows represents a holistic approach for improving ecosystem health—one that delivers broad benefits for people and nature while also accommodating human demands on the system.

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The California Environmental Flows Framework (hereafter "Framework") was established to support resource managers tasked with defining ***ecological flow criteria***—quantifiable metrics that describe ranges of flow that must be maintained within a stream and its margins throughout the year to support healthy ecosystems—for California's river and streams. Developed by a collaborative team of agency personnel, academic researchers, and non-governmental organization scientists, the Framework aims to produce consistent, scientifically-supported ecological flow criteria that can be used to determine ***environmental flow recommendations*** that satisfy ecosystem water needs and other water management objectives. Environmental flow recommendations are expressed as a "rule set" of flow requirements that are informed by ecological flow criteria but also take human uses and other water management objectives into consideration.

The technical approach of the Framework rests upon the scientific concept of ***functional flows***—distinct aspects of a flow regime that sustain ecological, geomorphic, or biogeochemical functions, and support the specific life history and habitat needs of native aquatic species (Yarnell et al. 2015). Managing for functional flows preserves essential patterns of flow variability within and among seasons, but does not mandate the restoration of full natural flows nor maintenance of historical ecosystem conditions. In addition, the functional flows approach is not focused on the habitat needs of a particular species, but rather, focuses on preserving key ecosystem functions, such as sediment movement, water quality maintenance, and environmental cues for species migration and reproduction, that maintain ecosystem health and are broadly supportive of native freshwater plants and animals.

The Framework focuses on the following five basic functional flow components that represent significant drivers of ecological processes in California, and are defined in Yarnell et al. (2020) (Figure 1):

- **Fall pulse flow**, or the first major storm event following the dry season. These flows represent the transition from dry to wet season and serve important functions, such as moving nutrients downstream, improving streamflow water quality, and signaling aquatic species to migrate or spawn.
- **Wet-season baseflow**, which support native aquatic species that migrate through and overwinter in streams.
- **Wet-season peak flows**, which transport a significant portion of sediment load, inundate floodplains, and maintain and restructure river corridors.
- **Spring recession flow**, which represents the transition from high to low flows, provide reproductive and migratory cues for native aquatic species, and redistribute sediment.
- **Dry-season baseflow**, which support native aquatic species during the dry-season period when water quality and quantity limit habitat suitability.

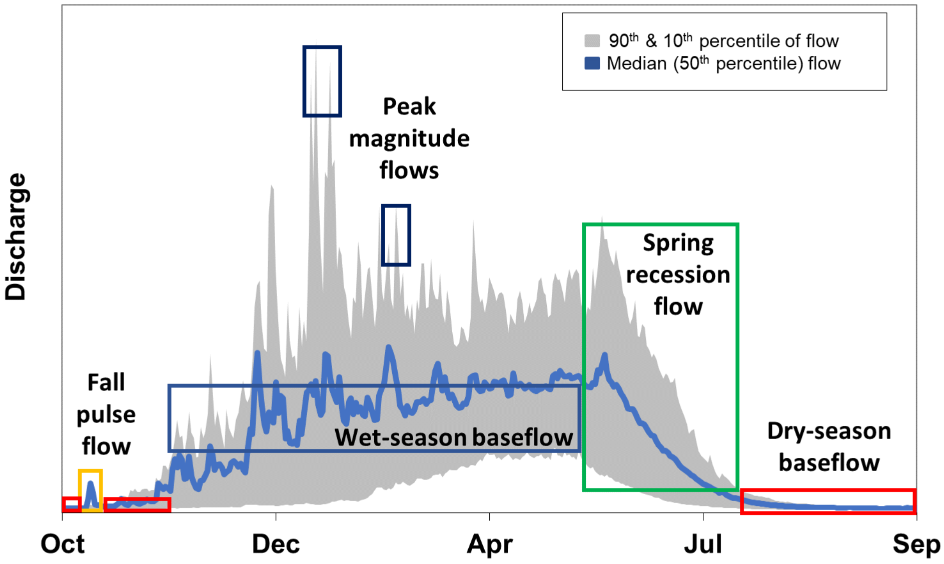

Figure 1. Functional flow components (colored boxes with labels) for California illustrated over a representative hydrograph (Figure from Yarnell et al. 2020). Blue line represents median (50th percentile) daily discharge. Gray shading represents 90th to 10th percentiles of daily discharge over the period of record.

The five functional flow components identified for California provide the basis for determining ecological flow criteria and assessing potential stream flow alteration in the Framework. Each functional flow component is quantified by several functional flow metrics that describe the magnitude, timing, frequency, duration, or rate of change of flows within the flow component. Together this suite of functional flow metrics can be used as ecological flow criteria for any stream location in the state (Yarnell et al. 2020).

The initial steps of the Framework provide guidance on setting broad ecological management goals and identifying specific location(s) of interest (LOI(s)) within the geographic region. The Framework then provides a set of ecological flow criteria that quantify the range of instream flow conditions at each LOI supportive of ecological processes under natural (i.e. non-altered) flow conditions. In instances where non-flow impairments, such as altered physical habitat or poor water quality, may limit the ability for the natural range of functional flow metrics to support desired ecological functions, the Framework provides further guidance for determining appropriate ecological flow criteria. In later steps of the Framework, the ecological flow criteria are then compared with current streamflow conditions at each LOI to assess potential flow alteration. Depending on management objectives, these ecological flow criteria can be translated into environmental flow recommendations or assessed in relation to anthropogenic water needs to determine environmental flow recommendations that balance ecological and non-ecological objectives. Further information about CEFF, including a CEFF application guidance document and FAQs, can be found at *ceff.ucdavis.edu*.

The remainder of this report is organized to follow and detail the steps outlined in the CEFF application document (Version 1.0, April, 2021) to determine ecological flow criteria and potential flow alteration at two locations on the lower Cosumnes River: Michigan Bar USGS gage and McConnell USGS gage.

Application of CEFF to the Lower Cosumnes River

Step 1: Define ecological management goals

Site Context

The geographic focus of this analysis was the lower Cosumnes River watershed (Figure 2).

This analysis focused on two locations of interest (LOIs) within the lower Cosumnes watershed: 1) the USGS gage at Michigan Bar (Gage ID 11335000, NHD COMID 20192498), located approximately two miles upstream of the Highway 16 crossing, and 2) the USGS McConnell gage (Gage ID 11336000, NHD COMID 3953273), located approximately 20 miles downstream of the Michigan Bar gage where the Cosumnes River crosses Highway 99 (Figure 3). These LOIs were selected due to the availability of flow data, including long-term daily flow monitoring records, modeled monthly unimpaired flow data, and stream morphology data from HEC-RAS modeling, as well as aquatic species data available in the adjacent stream reaches from USFWS. The McConnell gage has not measured flow data since 1982, a significant data gap since groundwater overdraft has intensified since that time. Gage installation and surface water-groundwater interaction analyses initiated in 2020 under SGMA will contribute to a more complete understanding of flows in the future.

Objective: To identify ecological management goals for the study area and the corresponding ecosystem functions that must be supported by ecological flow criteria to satisfy those goals

Outcome of Step 1:

- A well-defined study area accompanied by a written description and map with watershed boundaries, the stream network, and LOIs (stream reaches)
- A list of LOIs with a short description of why they were selected
- A list of ecological management goals
- A list of ecosystem functions (associated with each functional flow component) that must be supported by ecological flows to achieve ecological management goals

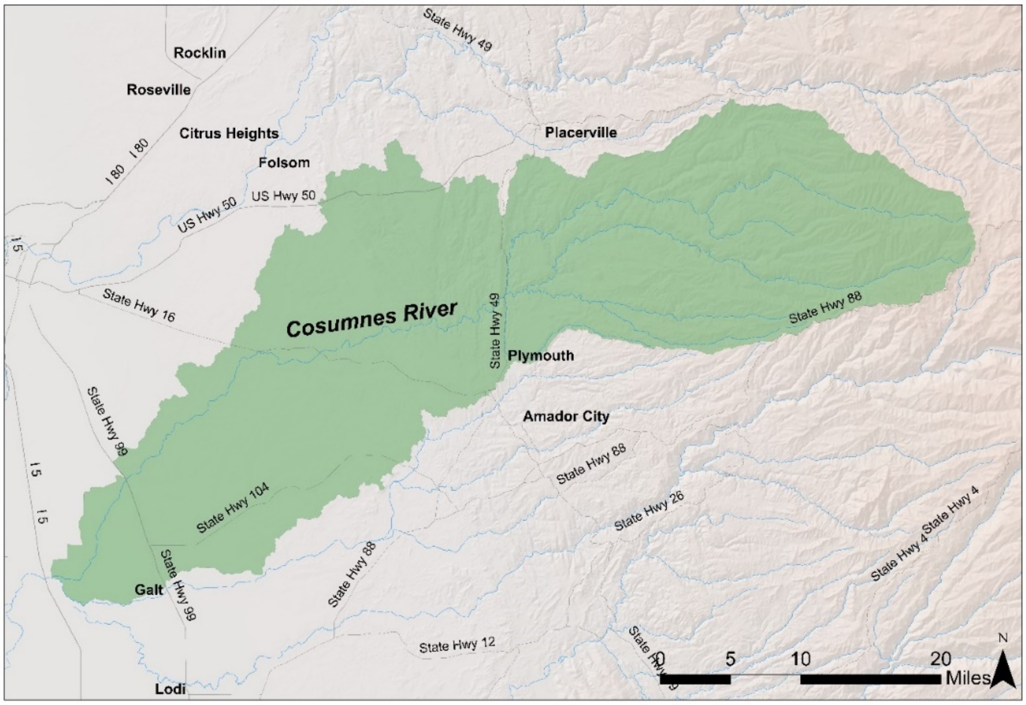

Figure 2. Geographic study region: the Cosumnes River watershed (green shading).

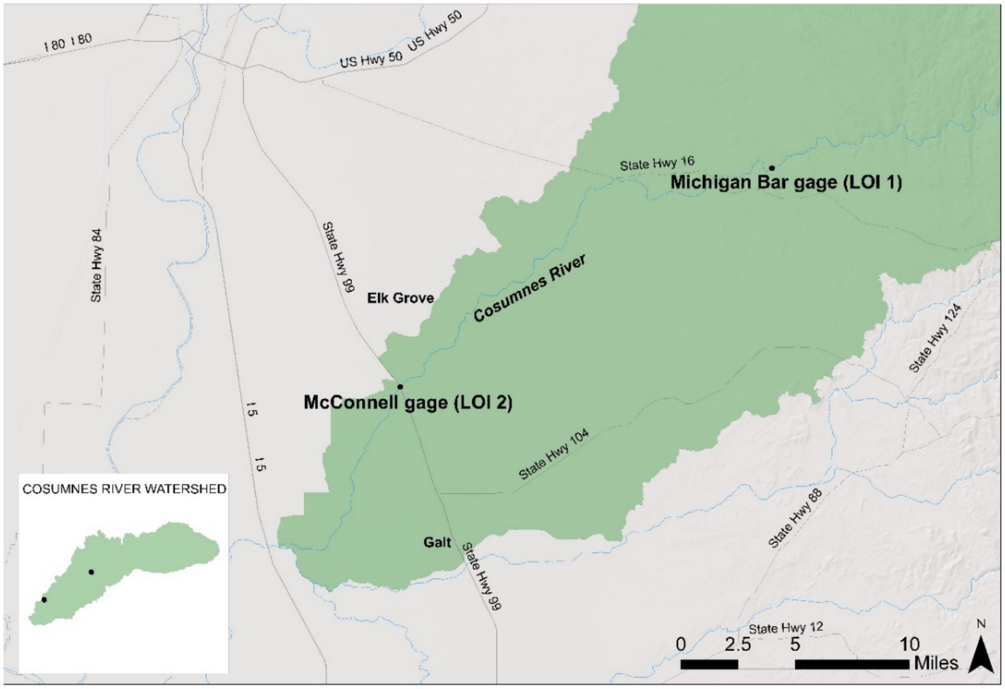

Figure 3. Locations of Interest (LOIs) for this analysis (Michigan Bar and McConnell USGS gages) on the lower mainstem Cosumnes River.

Ecological Management Goals

Establishing ***ecological management goals***, or the ecological or biological response that occurs due to a management action aimed at improving or maintaining overall stream health or conditions, allows for the critical evaluation of whether functional flow criteria at each LOI adequately address management needs.

We reviewed existing plans and studies associated with the Lower Cosumnes River in order to further understand watershed conditions, stakeholder values and concerns, and to develop desired ecological outcomes. Multiple existing reports and studies have identified enhancing and preserving stream flows for native fish species, particularly Fall-run Chinook salmon and Central Valley steelhead, as a key priority in the lower watershed (National Marine Fisheries Service 2014; Robertson-Bryan, Inc. 2006; Kleinschmidt Associates 2008; USFWS 2001). Fall-run chinook salmon (*Oncorhynchus tshawytscha*) require suitable flows in the channel for migration and spawning in fall and winter, while the inundated floodplain provides valuable rearing habitat for juvenile chinook salmon before emigration in spring. Steelhead (*Oncorhynchus mykiss*) have been known to opportunistically use the channel for migration in fall after flows increase sufficiently to allow passage and for rearing when flows are sufficient to maintain perenniality through the summer.

Improving floodplain access for native fishes during the spring has also been identified as a critical management goal (Robertson-Bryan, Inc. 2006; Kleinschmidt Associates 2008). The Sacramento splittail (*Pogonichthys macrolepidotus*) uses the inundated floodplain for spawning in early spring and the main channel for rearing after spring flows have receded and the floodplain disconnects. Although non-native fish inhabit the floodplain during high flows, they are not cued to leave the floodplain as flows decrease and often perish in the remnant disconnected pools (Jeffres et al. 2008).

Existing studies further identified the need to protect special-status terrestrial and riparian species in the lower Cosumnes watershed, including the greater sandhill crane, Swainson’s hawk, valley elderberry longhorn beetle, western pond turtle, CA tiger salamander, vernal pool fairy and tadpole shrimp, and giant garter snake (Klausmeyer et al. 2015; Robertson-Bryan, Inc. 2006; Kleinschmidt Associates 2008). While many of these species are not directly reliant on Cosumnes River in-channel streamflows, they are reliant on the Cosumnes River floodplain habitat and the annual winter overbank stream flows that maintain the floodplain habitat.

Unlike other Sierran watersheds, the Cosumnes River is not impacted by large dams that capture runoff and block fish passage. As such, the stream flow regime is largely intact, with possible exception of the summer baseflow in the lower watershed where once perennial flows now become intermittent in some reaches. The native species assemblages in the lower watershed are reliant on this largely natural flow regime that includes seasonally varying flows to support their life histories. Specifically, peak flood flows in winter inundate the floodplain scouring new channels, providing connectivity and access for native fish, and driving riparian and ecological successional processes (Yarnell et al. 2015). Spring recession flows provide critical spawning habitat and ecological cues for outmigration, while fall pulse flows kickstart biogeochemical processes and nutrient cycling as well as provide migration cues for the upcoming winter season. Sustained spring and early summer flows also support higher groundwater levels into the summer supporting riparian habitat and decreasing the duration of dry season low flows. Sufficient dry season baseflows maintain hydrological connectivity through the lower watershed and provide aquatic habitat for native species. These seasonal flows and associated functions are thus a high priority to preserve and maintain in the lower Cosumnes River.

Based on the above studies and reports, the following ecological management goals were identified at each LOI:

Ecological Management Goals for Michigan Bar (LOI 1):

- Increase available in-channel spawning habitat for Fall-run Chinook salmon and other native fish species.
- Preserve and maintain natural ranges of all functional flow components in order to support native species communities.

Ecological Management Goals for McConnell (LOI 2):

- Maintain or increase available native riparian and wetland habitat for special-status species.
- Increase access to floodplains for fish, including native Splittail and Fall-run Chinook salmon, during the winter and spring spawning and rearing season.
- Improve passage and migratory conditions for Fall-run Chinook salmon and Central Valley steelhead during fall months.
- Preserve and maintain natural ranges of all functional flow components in order to support native species communities.

Using Table 1.2 from the CEFF application document, a set of ecosystem functions needed to achieve the above ecological management goals was selected for each of the five functional flow components (Table 1).

Table 1. Ecosystem functions that must be supported by ecological flows to satisfy ecological management goals in the study area.

Functional Flow Component	**Ecosystem Function(s)**
Fall pulse flow	Flush fine sediment and organic material from substrate, increase longitudinal hydrologic connectivity, increase riparian soil moisture, increase nutrient cycling, reactivate exchanges with hyporheic zone, decrease water temperature and increase dissolved oxygen, cue native fish migration
Wet season baseflow	Maintain longitudinal hydrologic connectivity, support hyporheic exchange, support riparian habitat along channel margins, support fish migration and spawning
Wet season peak flows	Scour and deposit sediment and large wood in channel and floodplains, increase lateral hydrologic connectivity, recharge groundwater via floodplain inundation, increase nutrient cycling on floodplains, increase exchange of nutrients between floodplains and channel, support riparian vegetation diversity via disturbance, riparian succession, and extended inundation in floodplains, support fish spawning and rearing in floodplains, limit non-native species and in-channel vegetation encroachment through disturbance and displacement
Spring flow recession	Increase sorting of sediments via increased sediment transport and size selective deposition, recharge groundwater via floodplain inundation, increase lateral and longitudinal hydrologic connectivity, decrease water temperatures, increase export of nutrients and primary producers from

	floodplain to channel, provide hydrologic cues for native fish outmigration, support juvenile native fish rearing, increase hydraulic habitat diversity and habitat availability resulting in increased algal productivity, macroinvertebrate diversity, arthropod diversity, native fish diversity, and general biodiversity, provide hydrologic conditions for riparian species recruitment (e.g. cottonwood), limit riparian vegetation encroachment into channel
Dry season baseflow	maintain channel margin riparian soil moisture, limit lateral hydrologic connectivity to disconnect floodplains, maintain longitudinal hydrologic connectivity, maintain habitat availability for native aquatic species, support algal growth and primary producers

Step 2: Obtain natural ranges for functional flow metrics

Objective: To download natural functional flow metrics and characterize natural functional flow components at locations of interest.

Outcome of Step 2:

- A table of natural functional flow metric values associated with each functional flow component for each LOI, downloaded from the California Natural Flows Database (rivers.codefornature.org).

Statewide statistical models have been developed to predict natural functional flows for all stream reaches in California. The models rely on streamflow data from reference gages in California located on streams with minimal disturbance to natural hydrology and land cover (Falcone et al. 2010). Functional flow metrics were calculated at each reference gage from daily flow values, using algorithms described by Patterson et al. (2020). Separate models were then developed for each functional flow metric, using machine learning methods to relate functional flow metric values to watershed characteristics, following the approach described by Zimmerman et al. (2018). Additional details of the modeling approach, input data, and performance evaluation are provided in the CEFF guidance document.

Natural functional flow metrics can be viewed and downloaded at the California Natural Flows Database. Metrics are quantified as a range of values expected to occur at LOIs under natural conditions over a long-term period of record (10 or more years). The range of predicted metric values are defined by quantiles (the 10th, 25th, 50th, 75th, and 90th percentiles below which predicted values fall). In addition to reporting the expected range of values for each metric across all years, predictions are also provided for wet, moderate, and dry water year types.

Table 2 below contains the natural functional flow metrics for the Michigan Bar and McConnell gage locations.

In general, the natural functional flow metrics at the two gage sites were very similar with a few exceptions. Given that the McConnell gage is downstream of the Michigan Bar gage and drains a larger watershed area, the natural peak flow magnitudes, fall pulse magnitude, and spring recession flow duration and magnitude were all higher at the McConnell LOI than at the Michigan Bar LOI, as would be expected. Similarly, the natural wet season median flow magnitude was slightly higher at the McConnell LOI than at the Michigan Bar LOI. However, the natural dry season baseflow magnitude flow was slightly lower at the McConnell LOI than at the Michigan Bar LOI, perhaps reflecting the natural influence of locally lower stream gradient or geologic conditions that support transfer of surface flow to groundwater.

Table 2. Natural functional flow metrics for Michigan Bar gage (LOI 1) and McConnell gage (LOI 2). Values reflect medians and 10th – 90th percentiles in parentheses of functional flow metrics for all water year types combined.

Flow Component	Flow Metric	**Natural Functional Flow Metrics at LOI 1** median (10th - 90th percentile)	**Natural Functional Flow Metrics at LOI 2** median (10th - 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	212 (65-671)	239 (69-1046)
	Fall pulse timing (WY day)	27 (8-48)	28 (7-51)
	Fall pulse duration (days)	4 (2-9)	4 (2-9)
Wet-season baseflow	Wet-season baseflow (cfs)	183 (66-344)	160 (55-352)
	Wet-season median flow (cfs)	510 (290-937)	580 (253-1111)
	Wet-season timing (WY day)	77 (52-103)	80 (48-102)
	Wet-season duration (days)	121 (72-171)	115 (69-176)
Peak flows	2-year flood magnitude (cfs)	7158 (3998-13436)	9563 (4086-17746)
	2-year flood duration (days)	3 (1-16)	3 (1-16)
	2-year flood frequency (# per season)	2 (1-5)	2 (1-5)
	5-year flood magnitude (cfs)	13502 (8083-22216)	18313 (9684-30589)
	5-year flood duration (days)	1 (1-5)	1 (1-5)
	5-year flood frequency (# per season)	1 (1-3)	1 (1-3)
	10-year flood magnitude (cfs)	18815 (11110-28708)	27149 (11834-38892)
	10-year flood duration (days)	1 (1-3)	1 (1-3)
	10-year flood frequency (# per season)	1 (1-2)	1 (1-2)
Spring recession flows	Spring recession magnitude (cfs)	1954 (668-5719)	2515 (737-9612)
	Spring timing (WY day)	200 (168-228)	196 (162-227)
	Spring duration (days)	60 (33-115)	65 (31-128)
	Spring rate of change (percent)	0.07 (0.04-0.16)	0.07 (0.04-0.16)
Dry-season baseflow	Dry-season baseflow (cfs)	35 (7-127)	24 (1-107)
	Dry-season high baseflow (cfs)	100 (40-227)	80 (22-213)
	Dry-season timing (WY day)	267 (236-304)	265 (227-301)
	Dry-season duration (days)	161 (109-217)	160 (104-222)

Step 3: Evaluate whether the natural ranges of functional flow metrics will support functions needed to achieve ecological management goals

Objective: To perform an evaluation of factors that may limit the ability of the natural range of functional flow metrics to support essential ecosystem functions

Outcome of Step 3:

- Identification of functional flow components where there is evidence that their natural range of flow metrics will not be supportive of ecological management goals, and a list of associated limiting factors and potentially affected ecosystem function(s); these focal components will be subject to further investigation in Section B to develop their corresponding ecological flow criteria.

Maintaining functional flows within their natural range is hypothesized to support ecosystem functions and sustain healthy ecosystem conditions for native freshwater species (see CEFF guidance document). However, historical and ongoing land- and water-management activities have the potential to degrade the physical, chemical, and biological conditions of rivers and streams, such that the natural ranges of functional flow metrics may be less effective in supporting ecosystem functions.

Here, we evaluate factors that may limit the effectiveness of the natural range of functional flow metrics in supporting ecosystem functions within the lower Cosumnes River. We focus on the potential influence of ***non-flow*** aspects, including physical habitat, water quality, and biotic interactions (flow-related impacts such as diversions and groundwater pumping will be addressed in steps 8-12), on the relationship between natural functional flows and ecosystem functions, identified in Step 1, that are essential to achieving ecological management goals.

The Cosumnes watershed is less impacted than most Sierra Nevada watersheds in that it is free of large hydroelectric or water supply dams leaving natural geomorphic and hydrologic processes largely intact. However, once the river reaches the valley floor near LOI 1, the main channel is incised to varying degrees as it crosses the alluvial central valley. In particular, the stream reaches between highways 16 and 99 (between LOI 1 and LOI 2) are incised with levees on one or both sides of the river channel (Phil Williams and Associates, 1997; Robertson-Bryan, Inc. 2006). The potential lack of floodplain access due to channel incision between the two LOIs may impact the functionality of wet season peak flows, particularly for floodplain functions such as riparian recruitment and spawning habitat for native fish. Similarly, the channel incision may limit the effectiveness of natural spring recession flows to provide extended floodplain inundation and rearing habitat. Therefore, the potential impacts from channel incision on the functionality of wet season peak flows and spring recession flows should be evaluated further in steps 5 and 6. Additionally, sediment inputs from development at Ranch Murieta may impact the channel morphology near LOI 1 such that key ecosystem functions during the fall pulse flow such as fish passage may be limited. An evaluation of the channel morphology near LOI 1 with regard to the functionality of the fall pulse flow should also be evaluated further in steps 5 and 6.

A summary of known non-flow factors that may limit the ability of the natural functional flow components to support essential ecosystem functions is provided in Table 3. These factors are broadly identified based on review of existing studies, but further discussion with stakeholders may provide additional information regarding potentially limiting non-flow factors within the lower Cosumnes River.

Table 3. Potential ***non-flow*** limiting factors that may alter the relationship between the natural range of functional flow metrics and their intended functions for each functional flow component at locations of interest. Flow-related factors, such as diversions or groundwater pumping, are discussed in step 8.

Functional Flow Component	**Potential Non-flow Limiting Factor**	**Affected Ecosystem Function(s)**
Fall pulse flow	Channel incision; levees; sedimentation from Rancho Murieta and levee erosion	Limiting to riparian rewetting, hyphoreic reactivation, and fish passage
Wet season baseflow	None identified	None
Wet season peak flow	Channel incision; levees	Limiting to all floodplain functions
Spring flow recession	Channel incision; levees	Limiting to all floodplain functions
Dry season baseflow	None identified	None

Step 4: Select ecological flow criteria

Objective: To select ecological flow criteria for all functional flow components (unless it is determined in Step 3 that further assessment is required for one or more components) to support ecological management goals using natural functional flow metrics.

Outcome of Step 4:

- Ecological flow criteria values for functional flow components where the natural range of functional flow metrics are expected to support ecological management goals.

Ecological flow criteria are selected for all functional flow components for which the natural range of metrics is expected to support ecosystem functions. These ecological flow criteria are defined as the median (50th percentile) metric value and bounded by the 10th to 90th percentile range of metric values for each flow component. The median represents the long-term value around which annual values should center. The 10th to 90th percentile values represent the lower and upper bounds, respectively, in which annual values of the metric are expected to vary. Ecological flow criteria can be defined for all water years, or by water year type.

Following the assessment in Step 3, channel incision at both LOIs (and in the stream reaches between) may be a limiting factor for achieving floodplain functions associated with peak flow magnitudes and the spring recession magnitude in particular. Additionally, there may be impacts to channel morphology due to levee erosion and sediment inputs from development near LOI 1 that may affect the functionality of the fall pulse flow for fish passage. Therefore, the natural functional flow metrics are selected as ecological flow criteria for the wet season and dry season baseflow components for LOI 1 and LOI 2 as shown in Table 4. Ecological flow criteria for the other three functional flow components will be further evaluated in steps 5-6 to determine the degree to which alterations to physical habitat may affect the relationship between the natural range of functional flow metrics and their intended functions and whether alternate flow criteria may be needed.

Table 4. Ecological Flow Criteria for Michigan Bar gage (LOI 1) and McConnell gage (LOI 2) for those functional flow components where additional evaluation of non-flow factors is not needed. Values reflect medians and 10^{th} – 90^{th} percentiles in parentheses of functional flow criteria for all water year types combined.

Flow Component	**Flow Metric**	**Ecological Flow Criteria at LOI 1** median (10th - 90th percentile)	**Ecological Flow Criteria at LOI 2** median (10th - 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	To be determined	To be determined
	Fall pulse timing (WY day)	27 (8-48)	28 (7-51)
	Fall pulse duration (days)	4 (2-9)	4 (2-9)
Wet-season baseflow	Wet-season baseflow (cfs)	183 (66-344)	160 (55-352)
	Wet-season median flow (cfs)	510 (290-937)	580 (253-1111)
	Wet-season timing (WY day)	77 (52-103)	80 (48-102)
	Wet-season duration (days)	121 (72-171)	115 (69-176)
Peak flows	2-year flood magnitude (cfs)	To be determined	To be determined
	2-year flood duration (days)	3 (1-16)	3 (1-16)

	2-year flood frequency (# per season)	2 (1-5)	2 (1-5)
	5-year flood magnitude (cfs)	To be determined	To be determined
	5-year flood duration (days)	1 (1-5)	1 (1-5)
	5-year flood frequency (# per season)	1 (1-3)	1 (1-3)
	10-year flood magnitude (cfs)	To be determined	To be determined
	10-year flood duration (days)	1 (1-3)	1 (1-3)
	10-year flood frequency (# per season)	1 (1-2)	1 (1-2)
Spring recession flows	Spring recession magnitude (cfs)	To be determined	To be determined
	Spring timing (WY day)	200 (168-228)	196 (162-227)
	Spring duration (days)	60 (33-115)	65 (31-128)
	Spring rate of change (percent)	0.07 (0.04-0.16)	0.07 (0.04-0.16)
Dry-season baseflow	Dry-season baseflow (cfs)	35 (7-127)	24 (1-107)
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	Dry-season timing (WY day)	267 (236-304)	265 (227-301)
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Step 5: Develop detailed conceptual model relating focal flow components to ecological goals

Objective: To develop a conceptual model to visualize the relationship between functional flow components and the physical, chemical, and biological factors that influence ecological management goals

Outcome of Step 5:

- A detailed conceptual model for each LOI (or study area, if it includes multiple LOIs that can be addressed by the same conceptual model) that illustrates the flow-ecology relationships that influence ecological responses and management goals expressed as ecological performance measures.

A conceptual model that explicitly links a flow component with ecological management goals will help understanding and visualization of how physical habitat, water quality, or biological interactions could affect the relationships between flow and ecological response. The conceptual model also guides collection of the data required to verify and quantify these ecological response relationships (if needed) as described in Step 6. The structure of the conceptual model will have a significant influence on the quality and nature of the results, and as such, should be developed through an open, collaborative process informed by stakeholders.

Based on our analysis in step 3, there is concern that channel incision between the two LOIs will affect the functionality of the wet season peak flows as well as the spring recession flow with regard to the adjacent floodplain. For example, if the channel is greatly incised, the natural 2-year flood magnitude of 7158 cfs at Michigan Bar may not inundate the floodplain in most years as expected, but rather a higher magnitude flow would be needed to achieve floodplain inundation and the associated ecosystem functions. Figure 4 provides an example conceptual model detailing the relationships between the peak flows and spring recession, physical habitat in the floodplain, associated key ecosystem functions, and the related ecological management goals identified in step 1. To determine if channel incision is potentially limiting the functionality of flow, a hydraulic model relating channel morphology to flow magnitude would provide information on what flows are needed to inundate the floodplain. Similarly, a groundwater model would provide information on the relationship between floodplain inundation extent and groundwater recharge and groundwater elevations. Additional information on the habitat suitability requirements for juvenile salmon and riparian succession would link the physical floodplain conditions to ecological responses (Figure 4).

Discussions with stakeholders will be needed to more fully elucidate conceptual models for the Lower Cosumnes River that will be most helpful in assessing ecological flow needs and incorporating site specific study data.

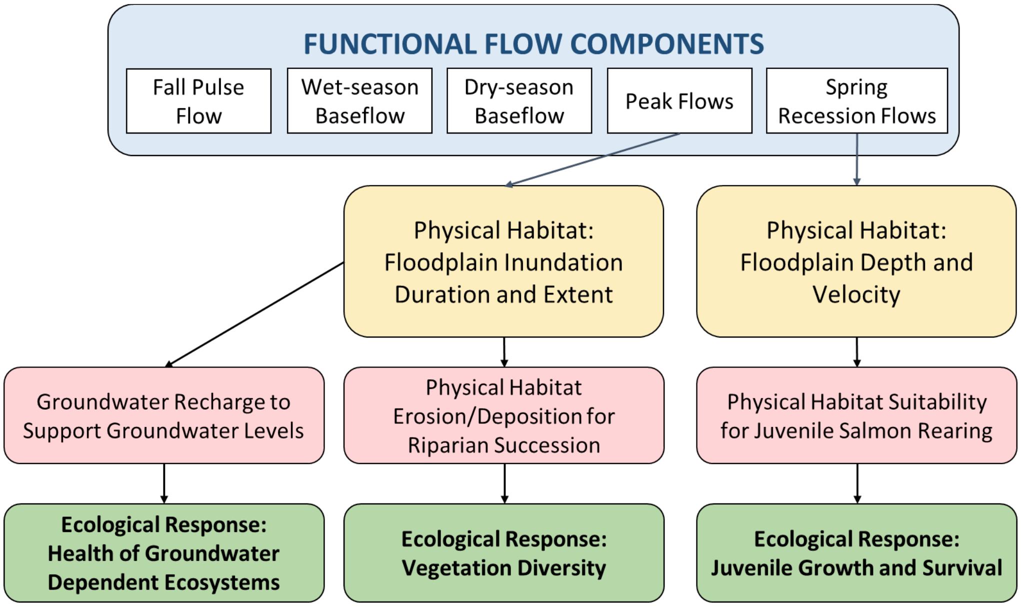


Figure 4. Example conceptual model linking peak flows and spring recession flows with physical habitat in the floodplain (channel incision was a limiting factor identified in table 3), key ecosystem functions (from table 1), and ecological management goals identified in step 1.

Step 6: Quantify flow-ecology relationships

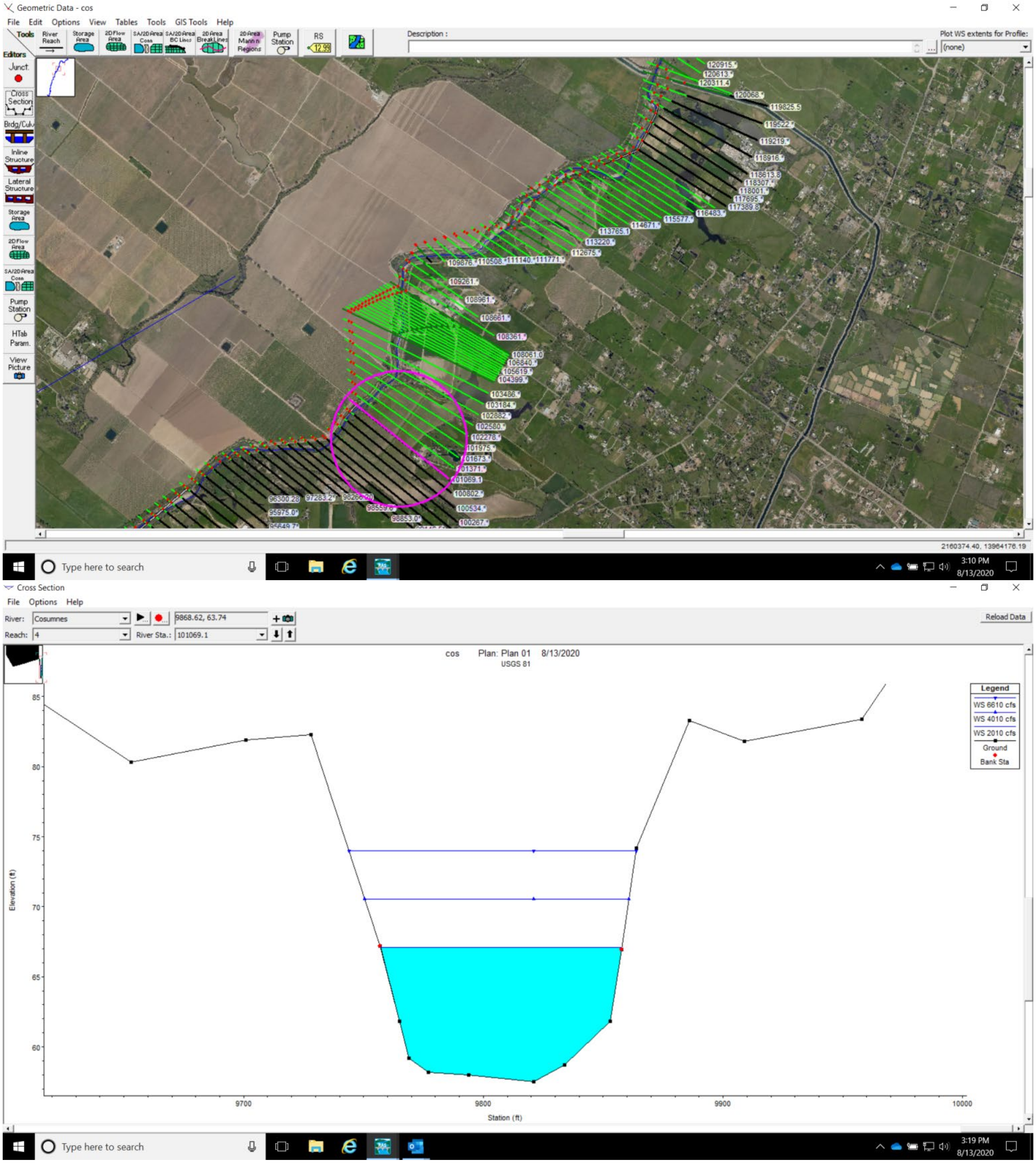
Objective: To quantify flow-ecology relationships in the conceptual model using provided guidance on data sources and methods for defining these relationships

Outcome of Step 6:

- Quantitative flow-ecology relationships that relate focal functional flow components to ecological responses.

There are a substantial number of previous studies that have been completed in the Lower Cosumnes River, many of which are summarized by the Cosumnes Research Group and in various available agency reports (see data summarized in step 1). Depending on the conceptual models developed for the Lower Cosumnes with stakeholders, many of these studies may be suitable for quantifying links between flow components (and flow metrics such as peak flow magnitude) and ecological management goals. For those links where existing data is inadequate, additional studies may be needed. Regarding the example conceptual model specific to floodplain inundation presented in Figure 4 above, some data created and compiled by CDFW can be used to initially explore the flow magnitude potentially needed to inundation the floodplain downstream of Michigan Bar.

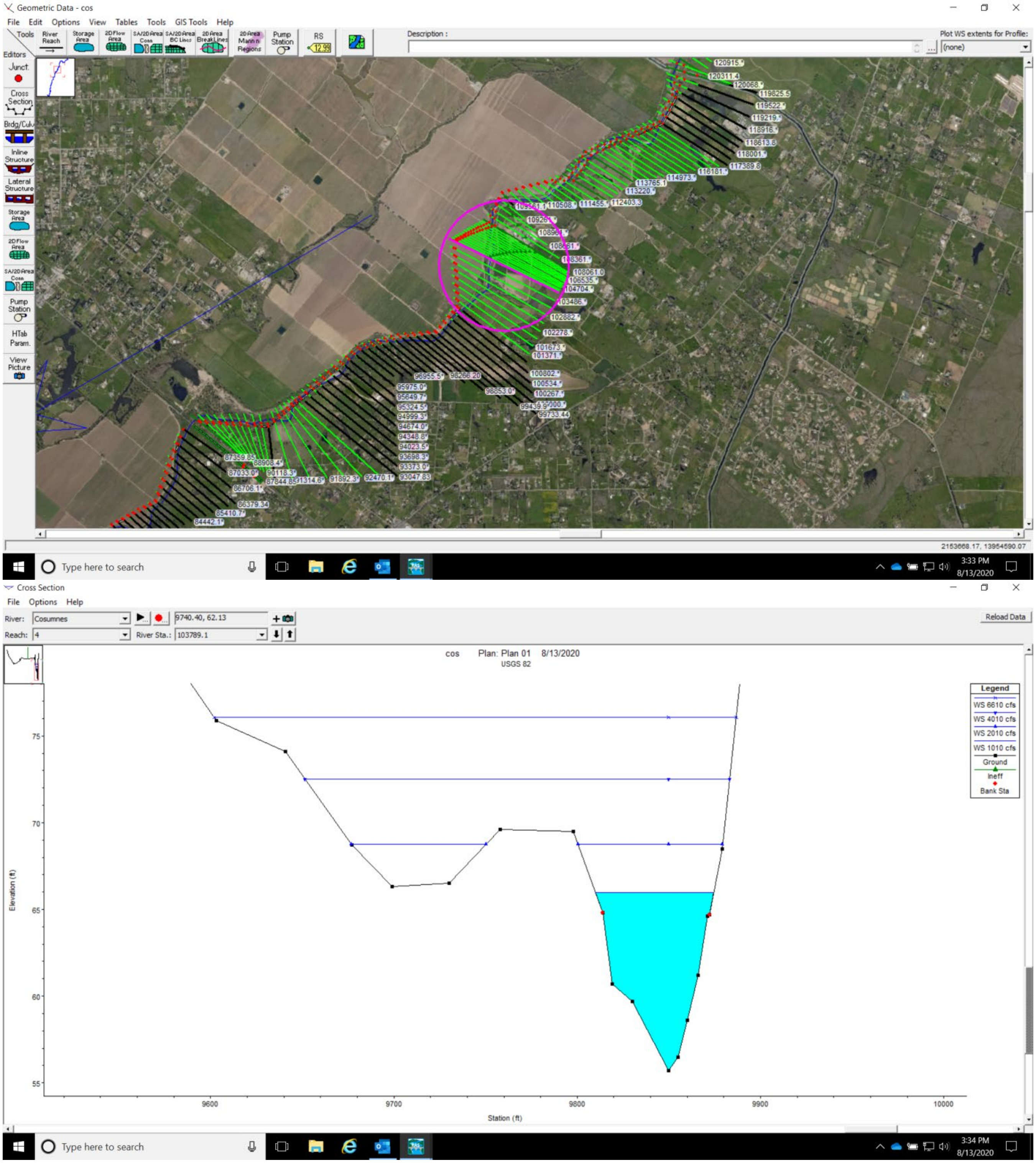
Using a HEC-RAS model developed by USFWS, the relationship between floodplain inundation area and flow can be quantified (results from this analysis, including methods, model calibration and validation can be found in USFWS (2001)). Two example figures from the model output are shown below to illustrate the degree of channel incision between Michigan Bar and McConnell and the various estimated stages of flow magnitudes needed to fill the channel and begin to inundate the floodplain. Figure 5 shows a typical representative cross-section located between Hwy 16 and Hwy 99 that is incised such that only flows greater than about 8000 cfs inundate the floodplain. In contrast, figure 6 shows one of the less incised cross-section locations that has an inset channel bar below the floodplain and where flows greater than about 6600 cfs inundate the floodplain. The natural median predicted 2-year peak flow is 7158 cfs (Table 2) at Michigan Bar, which suggests flows may only be accessing the floodplain in moderate-wet or wet years (approximately half the years). Under natural channel morphology conditions in an alluvial stream, we would expect the channel to be sized for approximately the 1.5-year flood recurrence interval flow, such that flows greater than the 1.5-year flood flow inundate the floodplain in about 2 out of 3 years. Given that the natural predicted wet season median flow is about 500-1000 cfs at Michigan Bar, we would expect flows between 1000 cfs (greater than the wet season median flow) and 7158 cfs (less than the 2-year flood flow) should at least partially inundate the floodplain in most years. Additional analysis of the channel morphology in relation to flow between the LOIs will further inform the degree of channel incision and potential locations for habitat restoration actions that may increase floodplain activation and inundation.


River: Cosumnes

Reach: 4

River Sta.: 101069.1

Figure 5. Cross-section located between Hwy 16 and 99 that is incised such that only flows greater than 6600 cfs inundate the floodplain. Upper panel shows cross-section location (pink line and circle). Lower panel shows cross-sectional profile where blue shading represents flow less than 2010 cfs and blue horizontal lines represent 4010 cfs and 6610 cfs.



Geometric Data - cos

Description:

Plot WS extents for Profile: (none)

2153668.17, 13954590.07

Cross Section

River: Cosumnes

Reach: 4

River Sta.: 103789.1

9740.40, 62.13

cos Plan: Plan 01 8/13/2020

USGS 82

Figure 6. Cross-section located between Hwy 16 and 99 that is not incised such that flows greater than 1000 cfs inundate the inset channel bar and flows greater than 6610 cfs inundate the floodplain. Upper panel shows cross-section location (pink line and circle). Lower panel shows cross-sectional profile where blue shading represents flow less than 1010 cfs and blue horizontal lines represent 2010 cfs, 4010 cfs, and 6610 cfs.

Although a conceptual model was not presented for the fall pulse flow, concerns regarding potential sedimentation impacts on channel morphology and fish passage near LOI1 could be illustrated in a similar manner to figure 4. Specifically, in-stream physical habitat conditions (depths, velocities) at different flows could be assessed with a hydraulic model, and depth suitability for passage could be assessed to determine the minimum flows required for Chinook migration to the upper watershed. USFWS has performed an initial passage analysis using the HEC-RAS model described above, and found that a minimum of 180 cfs at each LOI would be needed to allow salmonid passage in fall under current physical habitat conditions. This is comparable to the natural fall pulse flow median magnitude of 212 cfs (range 65-671 cfs) at LOI1 and 239 cfs (range 69-1046 cfs) at LOI2 (Table 2).

Additional discussions on available flow-ecology data and the need for additional analysis or study should be undertaken with stakeholders to ensure all ecosystem functions identified in step 3 (Table 3) are addressed per the conceptual models developed in step 5.

Step 7: Define ecological flow criteria for focal flow components

Based on the information gathered in steps 5 and 6, ecological flow criteria can be defined for each focal flow component. These new criteria are then combined with those defined in step 4 to develop a comprehensive set of criteria for all five functional flow components (and their associated functional flow metrics).

Objective: To select ecological flow criteria for each focal functional flow component that support the ecological management goals defined in Step 1

Outcome of Step 7:

- Ecological flow criteria for all flow components defined from Sections A and B.

Based on additional information discussed in steps 5 and 6 above, we suggest ecological flow criteria for the 2-year peak magnitude and fall pulse flow magnitude reflect the initial analysis completed by CDFW. Specifically, we suggest that the minimum magnitude for the fall pulse flow reflect the minimum salmonid passage flow of 180 cfs at Michigan Bar and McConnell, but the remainder of the fall pulse flow metrics (median magnitude, duration, etc.) reflect the natural functional flow metrics from Table 2. We also suggest that the 2-year peak flow magnitude should reflect the incised channel conditions such that a floodplain connection flow of greater than 8000 cfs occurs in at least half the years. The remainder of the ecological flow criteria should reflect the natural functional flow metrics from Table 2. All suggested ecological flow criteria are shown in Table 5. *However*, we also suggest that discussions with stakeholders regarding the ecological management goals, conceptual models, and flow-ecology criteria should occur, including whether additional analyses or studies may be needed. Following any such additional analysis, modification to the ecological flow criteria below may result.

Table 5. Ecological Flow Criteria for Michigan Bar gage (LOI 1) and McConnell gage (LOI 2). Values reflect medians and 10th – 90th percentiles in parentheses of functional flow criteria for all water year types combined. Values determined in steps 5 and 6 are bolded, while all other values were determined in step 2.

Flow Component	**Flow Metric**	**Ecological Flow Criteria at LOI 1** median (10th - 90th percentile)	**Ecological Flow Criteria at LOI 2** median (10th - 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	212 (**180**-671)	239 (**180**-1046)
	Fall pulse timing (WY day)	27 (8-48)	28 (7-51)
	Fall pulse duration (days)	4 (2-9)	4 (2-9)
Wet-season baseflow	Wet-season baseflow (cfs)	183 (66-344)	160 (55-352)
	Wet-season median flow (cfs)	510 (290-937)	580 (253-1111)
	Wet-season timing (WY day)	77 (52-103)	80 (48-102)
	Wet-season duration (days)	121 (72-171)	115 (69-176)
Peak flows	2-year flood magnitude (cfs)	**8000** (**8000**-13436)	9563 (4086-17746)
	2-year flood duration (days)	3 (1-16)	3 (1-16)
	2-year flood frequency (# per season)	2 (1-5)	2 (1-5)
	5-year flood magnitude (cfs)	13502 (8083-22216)	18313 (9684-30589)
	5-year flood duration (days)	1 (1-5)	1 (1-5)

	5-year flood frequency (# per season)	1 (1-3)	1 (1-3)
	10-year flood magnitude (cfs)	18815 (11110-28708)	27149 (11834-38892)
	10-year flood duration (days)	1 (1-3)	1 (1-3)
	10-year flood frequency (# per season)	1 (1-2)	1 (1-2)
Spring recession flows	Spring recession magnitude (cfs)	1954 (668-5719)	2515 (737-9612)
	Spring timing (WY day)	200 (168-228)	196 (162-227)
	Spring duration (days)	60 (33-115)	65 (31-128)
	Spring rate of change (percent)	0.07 (0.04-0.16)	0.07 (0.04-0.16)
Dry-season baseflow	Dry-season baseflow (cfs)	35 (7-127)	24 (1-107)
	Dry-season high baseflow (cfs)	100 (40-227)	80 (22-213)
	Dry-season timing (WY day)	267 (236-304)	265 (227-301)
	Dry-season duration (days)	161 (109-217)	160 (104-222)

Step 8: Identify management objectives

Objective: To identify the full set of management objectives that should be considered in determining environmental flow recommendations, including both ecological management goals (from Step 1) and non-ecological management goals, in addition to any regulatory requirements

Outcome of Step 8:

- A full set of management objectives, both ecological and non-ecological, and associated performance measures
- Relevant regulatory requirements necessary to evaluate objectives
- List of key stakeholders and a process for ongoing stakeholder engagement

The ecological flow criteria developed in Steps 1-7 represent the ecological objectives for the study area. Development of environmental flow recommendations also requires consideration of non-ecological objectives, which for the Cosumnes may include meeting municipal and agricultural water demands, flood management, and providing water for recreational purposes.

Based on prior studies and conversations with some stakeholders in the lower Cosumnes study area, there is a flow-related concern regarding agricultural wells and pumping that affect local groundwater levels. Specifically, studies have shown groundwater pumping reduces groundwater levels in the area and limits surface water-groundwater connections during the dry season (e.g. see studies completed by the Cosumnes Research Group, additional studies cited in the draft Groundwater Sustainability Plan for the Cosumnes sub-basin, and recent review of groundwater studies by Wiener (2021) for American River Conservancy). An in-depth analysis of surface water-groundwater connectivity in the basin is ongoing under the SGMA process. Additionally, new gaging stations are being established to better quantify low flows in the channel and in shallow groundwater wells near LOI 2. These gaging efforts will help to determine the relationship between groundwater levels and channel flows under current conditions near LOI2 where recent historical channel flow data (since 1983) is lacking.

Further study and discussions with stakeholders are needed to understand the potential impact of lowered groundwater levels on dry season baseflow in particular at each LOI. Stakeholders should be consulted to determine any desired non-ecological management objectives and any potential mitigation measures that might be needed to achieve the ecological management goals. Discussion of potential management actions related to groundwater conditions is provided in Step 10 below.

Step 9. Assess Flow Alteration

Objective: To evaluate whether flow conditions at the location(s) of interest (LOI) are likely unaltered, likely altered, or indeterminate by comparing present-day ranges of functional flow metrics for functional flow components to the ecological flow criteria defined in Step 7

Outcome of Step 9:

- Determination of which functional flow metrics and flow components are altered
- Comparison of current and reference annual hydrology using dimensionless hydrographs
- Identification of likely causes of hydrologic alteration

In order to determine whether observed flows at each LOI were likely altered, the observed functional flow metric ranges were compared to the ecological flow criteria ranges (Table 5) both quantitatively, via a set of rules, and qualitatively, by examining patterns in observed and natural hydrology.

When comparing natural predicted and observed flow conditions quantitatively, current conditions were considered *likely unaltered* if the median observed value fell within the 10th to 90th percentile range of the ecological flow criteria and greater than 50% of the observations fell inside of the 10th to 90th interpercentile flow range. Current conditions were considered *likely altered* if the median observed value fell outside the predicted 10th to 90th percentile range of the ecological flow criteria. Alteration was *indeterminate* if the median observed value fell within the 10th to 90th percentile range of the ecological flow criteria but less than 50% of the observations fell inside of the 10th to 90th interpercentile flow range. Further details on this evaluation are provided in CEFF Appendix J: Assessing Flow Alteration.

The observed functional flow metrics for the Michigan Bar (LOI 1) and McConnell (LOI 2) gages are shown in Table 6, and results of the alteration assessment for each LOI are provided in Tables 7-8. Results indicated that only the wet season median flow and timing may or may not (indeterminate) be altered at the Michigan Bar gage, while the dry season baseflow was likely altered at the McConnell gage. The wet season timing was also found to be indeterminate as to whether it was altered at the McConnell gage. The McConnell gage has not measured flow data since 1982, a significant data gap since groundwater overdraft has intensified since that time. Gage installation and surface water-groundwater interaction analyses initiated in 2020 under SGMA will contribute to a more complete understanding of observed flows in the future.

All other observed functional flow metrics were found to be likely unaltered at both gages. Figures 7 and 8 show a comparison of the observed functional flow metric ranges to the ecological flow criteria ranges for the a) dry season flow component and b) wet season flow component at the Michigan Bar and McConnell gages, respectively. At the Michigan Bar gage, observed wet season median flow and timing were determined to be within the 10th to 90th percentile range of the ecological flow criteria, but since less than 50% of the observations fell inside of the 10th to 90th interpercentile reference flow range, alteration was indeterminate (Figure 7b). At the McConnell gage, the observed dry season baseflow was determined to be lower than the ecological flow criteria and likely altered (Figure 8a).

Table 6. Observed functional flow metrics for Michigan Bar gage (LOI 1) and McConnell gage (LOI 2). Values reflect median and 10th – 90th percentiles of functional flow criteria. Observed flows at each LOI reflect the period of record for each gage: 1908-2020 at LOI1 and 1942-1982 at LOI2.

Flow Component	Flow Metric	Ecological Flow Criteria at LOI 1	Observed Metrics at LOI 1	Ecological Flow Criteria at LOI 2	Observed Metrics at LOI 2
		median (10th-90th percentile)	median (10th - 90th percentile)	median (10th - 90th percentile)	median (10th - 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	212 (65-671)	95 (36-464)	239 (69-1046)	129 (46-361)
	Fall pulse timing (WY day)	27 (8-48)	26 (7-52)	28 (7-51)	31 (11-50)
	Fall pulse duration (days)	4 (2-9)	4 (3-9)	4 (2-9)	4 (2-8)
Wet-season baseflow	Wet-season baseflow (cfs)	183 (66-344)	216 (61-652)	160 (55-352)	234 (79-553)
	Wet-season median flow (cfs)	510 (290-937)	786 (200-1696)	580 (253-1111)	859 (231-1763)
	Wet-season timing (WY day)	77 (52-103)	86 (40-125)	80 (48-102)	76 (34-119)
	Wet-season duration (days)	121 (72-171)	129 (77-186)	115 (69-176)	131 (81-194)
Peak flows	2-year flood magnitude (cfs)	7158 (3998-13436)	6300	9563 (4086-17746)	7120
	2-year flood duration (days)	3 (1-16)	3 (1-11)	3 (1-16)	4 (1-10)
	2-year flood frequency (# per season)	2 (1-5)	2 (1-5)	2 (1-5)	3 (1-4)
	5-year flood magnitude (cfs)	13502 (8083-22216)	14460	18313 (9684-30589)	17300
	5-year flood duration (days)	1 (1-5)	2 (1-4)	1 (1-5)	2 (1-3)
	5-year flood frequency (# per season)	1 (1-3)	1 (1-2)	1 (1-3)	1 (1-1)
	10-year flood magnitude (cfs)	18815 (11110-28708)	18960	27149 (11834-38892)	20900
	10-year flood duration (days)	1 (1-3)	1 (1-3)	1 (1-3)	1 (1-2)
	10-year flood frequency (# per season)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-1)

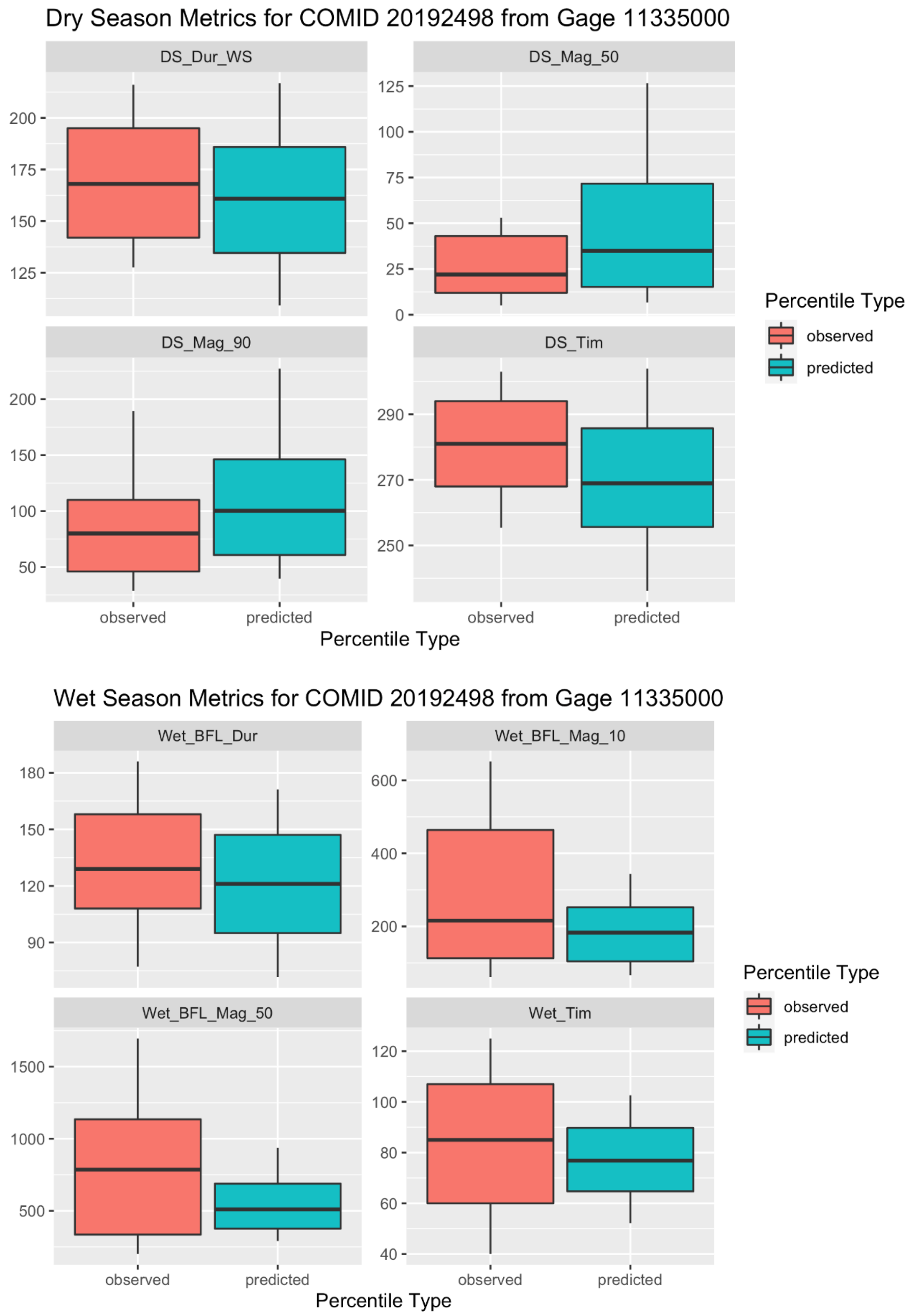
Spring recession flows	Spring recession magnitude (cfs)	1954 (668-5719)	1165 (274-4428)	2515 (737-9612)	1320 (413-6950)
	Spring timing (WY day)	200 (168-228)	220 (181-241)	196 (162-227)	213 (164-237)
	Spring duration (days)	60 (33-115)	64 (38-93)	65 (31-128)	58 (31-90)
	Spring rate of change (percent)	0.07 (0.04-0.17)	0.06 (0.05-0.10)	0.07 (0.04-0.16)	0.07 (0.05-0.10)
Dry-season baseflow	Dry-season baseflow (cfs)	35 (7-127)	22 (5-53)	24 (1-107)	0 (0-29)
	Dry-season high baseflow (cfs)	100 (40-227)	80 (29-189)	80 (22-213)	67 (6-255)
	Dry-season timing (WY day)	267 (236-304)	281 (255-303)	265 (227-301)	272 (246-300)
	Dry-season duration (days)	161 (109-217)	168 (127-217)	160 (104-222)	168 (124-228)

Table 7. Alteration assessment for Michigan Bar gage (LOI 1).

Metric Name	Metric Description	Status	Alteration Type
Dry season duration	Duration of the dry season (days)	Likely Unaltered	None Found
Dry season baseflow	Magnitude of dry season baseflow (50th percentile of daily flows within dry season) (cfs)	Likely Unaltered	None Found
Dry season high baseflow	Magnitude of dry season baseflow (90th percentile of daily flow within dry season) (cfs)	Likely Unaltered	None Found
Dry season timing	Dry season baseflow start timing (WY day)	Likely Unaltered	None Found
Fall pulse flow duration	Duration of fall pulse event (days)	Likely Unaltered	None Found
Fall pulse flow magnitude	Peak magnitude of fall pulse event (cfs) (maximum daily peak flow during event)	Likely Unaltered	None Found

Metric Name	Metric Description	Status	Alteration Type
Fall pulse flow timing	Water year day of fall pulse event	Likely Unaltered	None Found
Peak flow magnitude (10 year)	10-year recurrence interval peak flow (cfs)	Likely Unaltered	None Found
Peak flow magnitude (2 year)	2-year recurrence interval peak flow (cfs)	Likely Unaltered	None Found
Peak flow magnitude (5 year)	5-year recurrence interval peak flow (cfs)	Likely Unaltered	None Found
Peak flow duration (10 year)	Seasonal duration of 10-year recurrence interval peak flow (cumulative number of days in which this peak flow magnitude is exceeded)	Likely Unaltered	None Found
Peak flow duration (5 year)	Seasonal duration of 5-year recurrence interval peak flow (cumulative number of days in which this peak flow magnitude is exceeded)	Likely Unaltered	None Found
Peak flow duration (2 year)	Seasonal duration of 2-year recurrence interval peak flow (cumulative number of days in which this peak flow magnitude is exceeded)	Likely Unaltered	None Found
Peak flow frequency (10 year)	Frequency of 10-year recurrence interval peak flow events within a season	Likely Unaltered	None Found
Peak flow frequency (5 year)	Frequency of 5-year recurrence interval peak flow events within a season	Likely Unaltered	None Found
Peak flow frequency (2 year)	Frequency of 2-year recurrence interval peak flow events within a season	Likely Unaltered	None Found
Spring recession magnitude	Spring recession magnitude (daily flow on start date of spring-flow period, 4 days after last wet-season peak) (cfs)	Likely Unaltered	None Found

Metric Name	Metric Description	Status	Alteration Type
Spring recession rate of change	Spring flow recession rate (median daily rate of change of flow over decreasing periods during the recession) (percent)	Likely Unaltered	None Found
Spring recession timing	Start date of spring in water year days (WY day)	Likely Unaltered	None Found
Wet season duration	Wet season baseflow duration (# of days from start of wet-season to start of spring season)	Likely Unaltered	None Found
Wet season baseflow	Magnitude of wet season baseflow (10th percentile of daily flows within wet season, including peak flow events) (cfs)	Likely Unaltered	None Found
Wet season median flow	Magnitude of wet season flow (50th percentile of daily flows within wet season, including peak flow events) (cfs)	Indeterminate	High
Wet season timing	Start date of wet season in water year days (WY day)	Indeterminate	Unknown



a)

b)

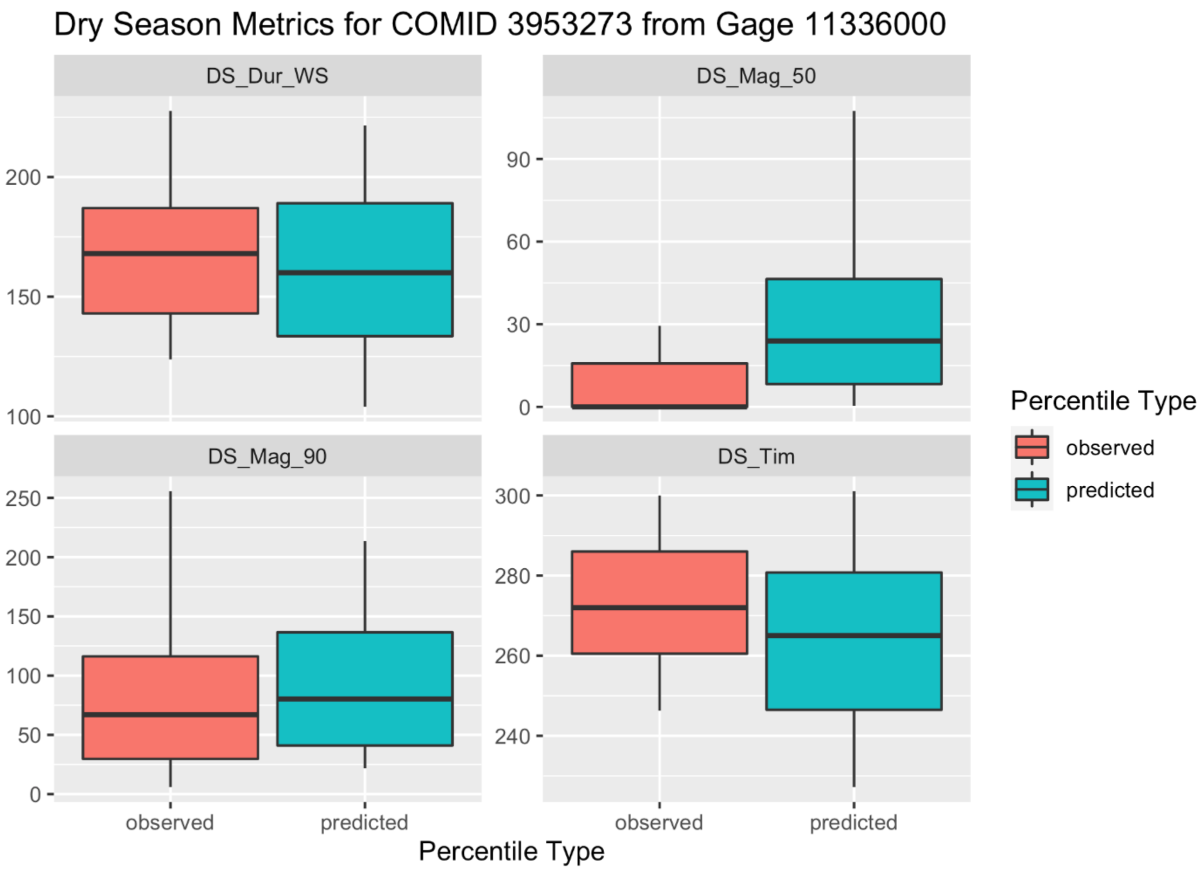
Figure 7. Boxplots showing the observed functional flow metric ranges compared to the ecological flow criteria (predicted natural functional flow metrics) ranges for the a) dry season flow component and b) wet season flow

component at the *Michigan Bar* gage. The observed wet season median flow magnitude (Wet_BFL_Mag_50) and timing (Wet_Tim) were determined to be within the 10th to 90th percentile range of the ecological flow criteria, but since less than 50% of the observations fell inside of the 10th to 90th interpercentile flow range, alteration was indeterminate.

Table 8. Alteration assessment for McConnell gage (LOI 2).

Metric Name	**Metric Description**	**Status**	**Alteration Type**
Dry season duration	**Duration of the dry season (days)**	Likely Unaltered	None Found
Dry season baseflow	Magnitude of dry season baseflow (50th percentile of daily flows within dry season) (cfs)	Likely Altered	Low
Dry season high baseflow	Magnitude of dry season baseflow (90th percentile of daily flow within dry season) (cfs)	Likely Unaltered	None Found
Dry season timing	Dry season baseflow start timing (WY day)	Likely Unaltered	None Found
Fall pulse flow duration	Duration of fall pulse event (days)	Likely Unaltered	None Found
Fall pulse flow magnitude	Peak magnitude of fall pulse event (cfs) (maximum daily peak flow during event)	Likely Unaltered	None Found
Fall pulse flow timing	Water year day of fall pulse event	Likely Unaltered	None Found
Peak flow magnitude (10 year)	10-year recurrence interval peak flow (cfs)	Likely Unaltered	None Found
Peak flow magnitude (2 year)	2-year recurrence interval peak flow (cfs)	Likely Unaltered	None Found
Peak flow magnitude (5 year)	5-year recurrence interval peak flow (cfs)	Likely Unaltered	None Found
Peak flow duration (10 year)	Seasonal duration of 10-year recurrence interval peak flow (cumulative number of days in which this peak flow magnitude is exceeded)	Likely Unaltered	None Found

Metric Name	Metric Description	Status	Alteration Type
Peak flow duration (5 year)	Seasonal duration of 5-year recurrence interval peak flow (cumulative number of days in which this peak flow magnitude is exceeded)	Likely Unaltered	None Found
Peak flow duration (2 year)	Seasonal duration of 2-year recurrence interval peak flow (cumulative number of days in which this peak flow magnitude is exceeded)	Likely Unaltered	None Found
Peak flow frequency (10 year)	Frequency of 10-year recurrence interval peak flow events within a season	Likely Unaltered	None Found
Peak flow frequency (5 year)	Frequency of 5-year recurrence interval peak flow events within a season	Likely Unaltered	None Found
Peak flow frequency (2 year)	Frequency of 2-year recurrence interval peak flow events within a season	Likely Unaltered	None Found
Spring recession magnitude	Spring recession magnitude (daily flow on start date of spring-flow period, 4 days after last wet-season peak) (cfs)	Likely Unaltered	None Found
Spring recession rate of change	Spring flow recession rate (median daily rate of change of flow over decreasing periods during the recession) (percent)	Likely Unaltered	None Found
Spring recession timing	Start date of spring in water year days (WY day)	Likely Unaltered	None Found
Wet season duration	Wet season baseflow duration (# of days from start of wet-season to start of spring season)	Likely Unaltered	None Found
Wet season baseflow	Magnitude of wet season baseflow (10th percentile of daily flows within wet season, including peak flow events) (cfs)	Likely Unaltered	None Found
Wet season median flow	Magnitude of wet season flow (50th percentile of daily flows within wet season, including peak flow events) (cfs)	Likely Unaltered	None Found
Wet season timing	Start date of wet season in water year days (WY day)	Indeterminate	Unknown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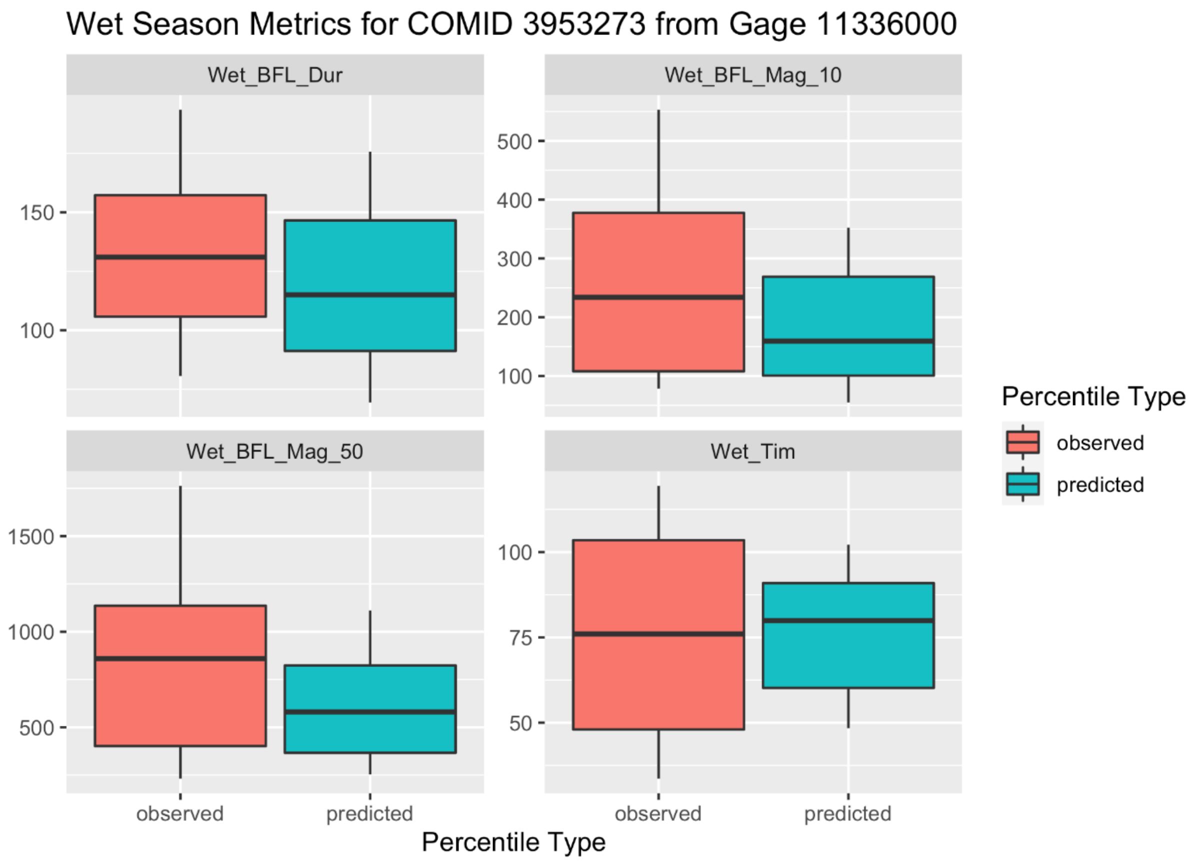
a)



b)

Figure 8. Boxplots showing the observed functional flow metric ranges compared to the ecological flow criteria (predicted natural functional flow metrics) ranges for the a) dry season flow component and b) wet season flow component at the *McConnell* gage. The observed dry season baseflow (DS_Mag_50) was determined to be lower than the ecological flow criteria and likely altered.

Additional analysis of observed functional flow metrics in comparison to natural functional flow metrics for each water year type was also completed. The results are shown in Appendix A. In general, similar patterns of flow alteration were reflected in each water year type. For all water year types (wet, moderate, and dry), flows were likely unaltered for all flow metrics at Michigan Bar. At McConnell, flows in all water year types were likely unaltered for all flow metrics except dry season baseflow, which was likely altered and low (depleted). While some metrics, such as the fall pulse flow magnitude in dry water years, appeared to be slightly depleted, they were determined to be likely unaltered due to the observed median value falling within the interquartile range of predicted values and less than 50% of observed values falling outside the predicted interquartile range. Note the McConnell gage only includes observed flows through 1982, so any further flow alteration in recent decades is not reflected.

Comparison with Reference Hydrology

Reference and observed hydrology were compared at both LOIs in order to further understand the observed potential alteration (wet season median flow at Michigan Bar gage and dry season baseflow at McConnell gage).

Both LOIs were located in the lower Cosumnes watershed where natural streamflow patterns were dominated by winter rain storms. The upper Cosumnes River received the influence of snowmelt in the spring, but the majority of the watershed occurred at mid-elevations where winter storm precipitation typically fell as rain. Thus in the lower Cosumnes river, a distinct snowmelt pulse in spring was typically observed in wetter colder years when the Sierra snowpack was more substantial, while more gradually decreasing spring flows were observed in other years. As a result, the lower Cosumnes river reaches fell within the rain and seasonal groundwater (RGW) stream class, as determined by Lane et al. 2017, which defined nine stream classes for California based on dominant watershed controls and distinct flow regime patterns. The dimensionless reference hydrograph (DRH) for the RGW stream class is shown in Figure 9 and illustrates the general hydrologic patterns over varying water year types in the absence of alteration for these types of streams.

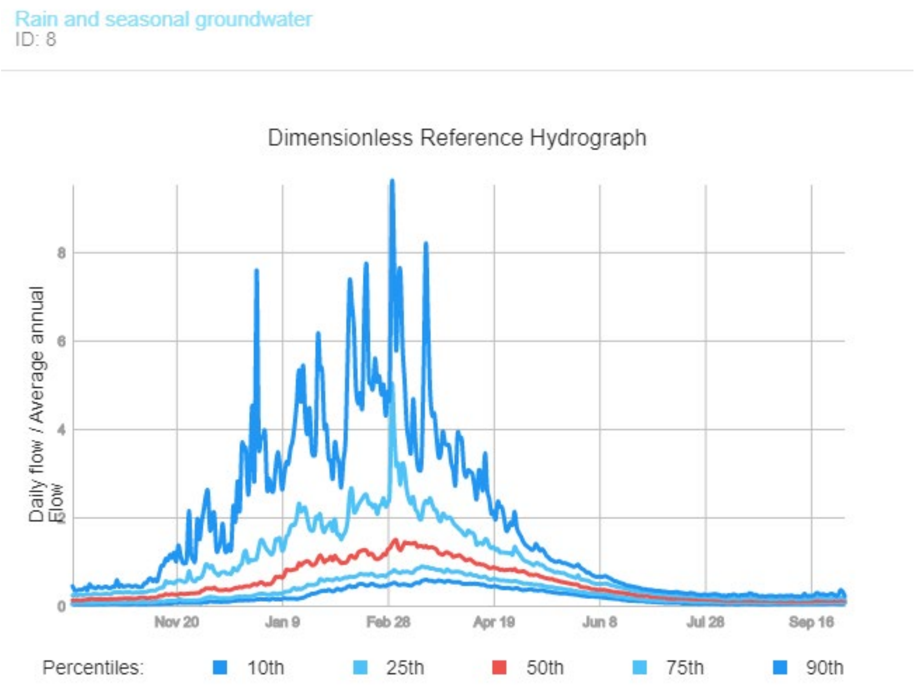


Figure 9. Dimensionless reference hydrograph (DRH) for rain and seasonal groundwater (RGW) stream class. Blue and red lines on hydrograph represent 10th – 90th percentile flows.

The DRH for the RGW stream class included data from 23 reference gages (as defined by Lane et al., 2017) across the state that had similar flow patterns. The closest of these reference gages to the LOIs was located on the South Fork Cosumnes River near River Pines, CA on the western edge of the watershed. The DRH for the SF Cosumnes reference gage is provided in Figure 10. In general, the timing of high flows occurred between December and March, with spring flows decreasing between April and June. Summer low flows extended from June into October, and were substantially smaller in magnitude than wet season baseflows. Additional reference hydrology data and calculated functional flow metrics for the SF Cosumnes gage location and the RGW stream class more generally can be found at eflows.ucdavis.edu.

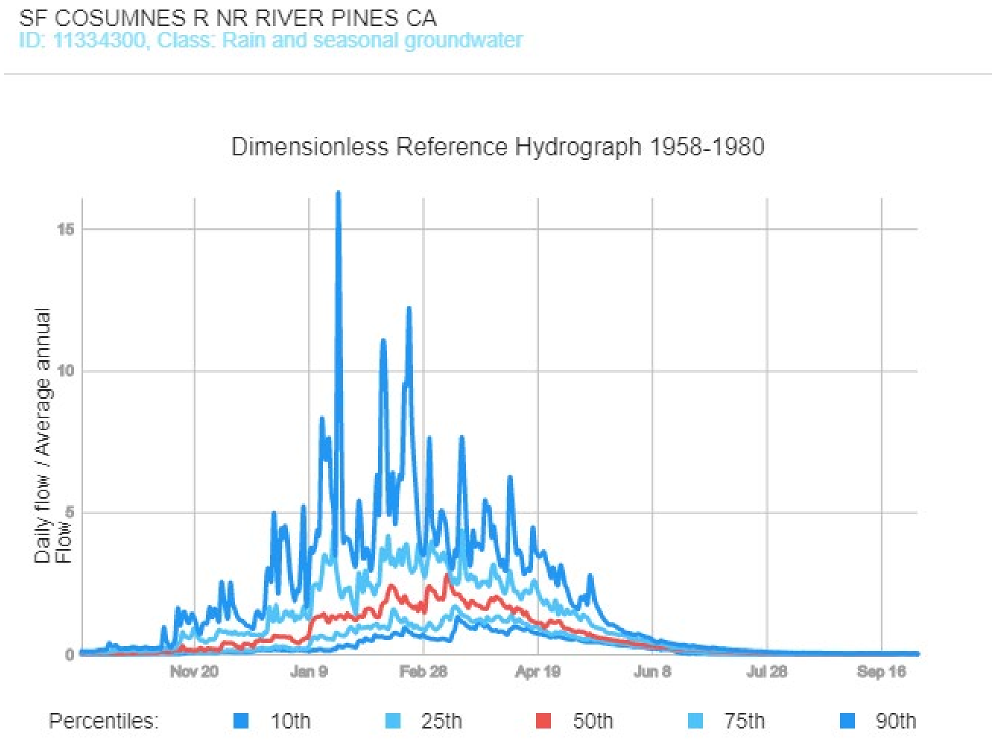


Figure 10. Dimensionless reference hydrograph (DRH) for nearest reference gage, the South Fork of the Cosumnes River near River Pines, California. Blue and red lines on hydrograph represent 10th – 90th percentile flows that have been non-dimensionalized by dividing the daily flow by the average annual flow.

When compared with the reference flows at the SF Cosumnes gage, the observed flows at the Michigan Bar and McConnell gages showed similar variability in flow patterns and seasonal timing (Figures 11-12). Peak flows occurred between January and March, while dry season baseflows typically extended to early November. The larger flows in the lower Cosumnes basin were reflected in longer duration wet season baseflow and lower variability in peak flow magnitudes. The observed transitions between wet and dry season were similar as well, with noticeable spring recessions that gradually decreased into summer baseflow and fall pulse flows that initiated the wet season. In general, the dimensionless observed hydrographs for each lower Cosumnes gage were similar to the dimensionless reference hydrograph at the SF Cosumnes, and the observed hydrographs did not show obvious flow alteration. These figures support the alteration assessment in tables 7-8, which indicated most functional flow components were likely unaltered with the exception of dry season baseflow at the McConnell gage.

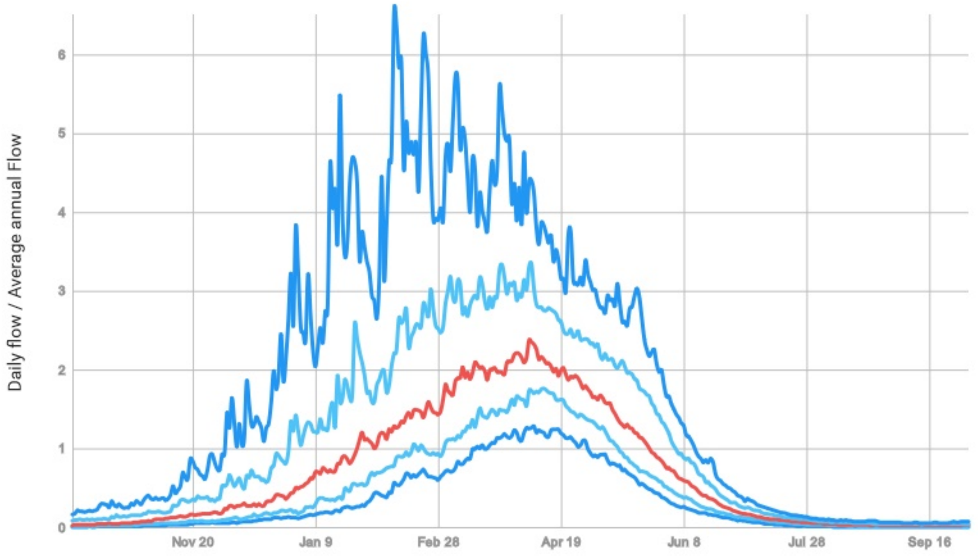


Figure 11. Dimensionless observed hydrograph for Cosumnes River at Michigan Bar gage based on USGS data from 1908-2020. Blue and red lines on hydrograph represent 10th – 90th percentile flows that have been non-dimensionalized by dividing the daily flow by the average annual flow.

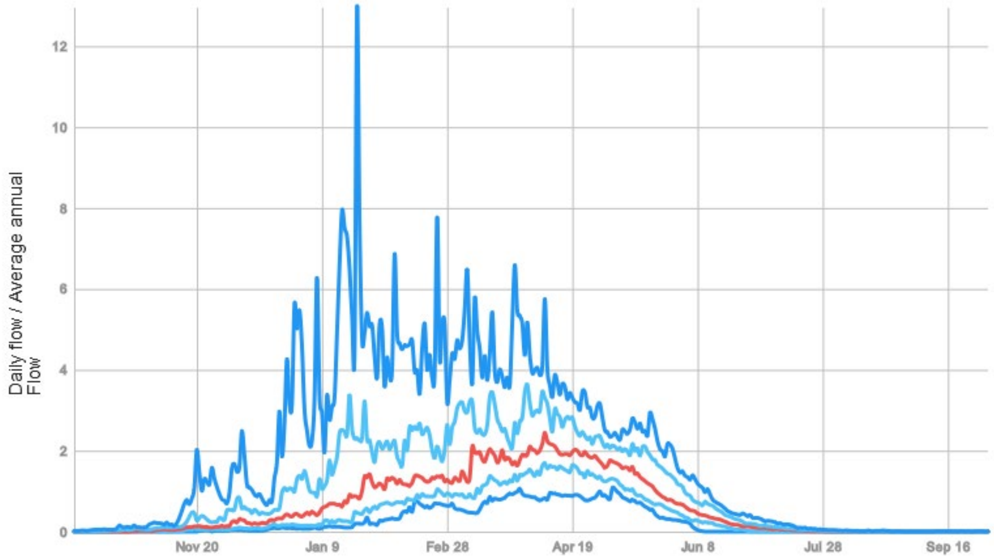


Figure 12. Dimensionless observed hydrograph for Cosumnes River at McConnell gage based on USGS data from 1942-1983. Blue and red lines on hydrograph represent 10th – 90th percentile flows that have been non-dimensionalized by dividing the daily flow by the average annual flow.

Discussion of Alteration Assessment

The alteration analysis indicated that all observed functional flow metrics were likely unaltered at the Michigan Bar gage LOI, with the exception of the wet season median flow and timing across all years, which was indeterminate (median flow may be slightly high). However, in the water year type analysis, the wet season median flow and timing were likely unaltered in all water years (Appendix A). Thus the indeterminate categorization across all years may reflect lower statistical variation in daily flows within the models used to predict natural functional flow metrics than was observed. Additional analysis of local gage or stage data within the upper watershed may help elucidate potential variations in winter flows.

The dry season baseflow across all years and for each water year type was likely altered (depleted) at the McConnell gage LOI, while all other functional flow metrics were likely unaltered. In dry water years, the fall pulse flow magnitude appeared to be slightly depleted, but was determined as likely unaltered due to the observed median of 75 cfs falling within the interquartile range of predicted values of 66-795 cfs. However, given that the McConnell gage reflects daily flows only through 1983, any additional flow alteration in the past 30 years, such as potential changes to the fall pulse magnitude or dry season duration, is not represented. Additional analysis of any available local stage data (e.g. from DWR gages) or newly established gages will help to quantify observed flows and potential alteration over time.

The depleted observed dry season baseflow at the McConnell gage likely reflects losses to groundwater due to underlying geologic conditions and decreased groundwater elevations associated with groundwater pumping. Several studies on subsurface stratigraphy, groundwater elevations, and surface water-groundwater connectivity link lowered groundwater elevations to disconnection of surface flows in the channel (e.g. Cosumnes Research Group; additional studies cited in the draft Groundwater Sustainability Plan for the Cosumnes sub-basin; studies reviewed by Wiener 2021). These and other related ongoing studies under SGMA will help quantify surface-groundwater connections and help inform the groundwater levels needed to support stream functionality in the dry season.

Additional exploration of the variance in modeled natural functional flow metrics for the dry season and wet season baseflows and how observed baseflows may be influenced by groundwater elevations and conjunctive use in the stream corridor will provide additional insights needed to develop environmental flow recommendations.

Steps 10-12 below will be completed in consultation with watershed stakeholders. They are included here for reference of the next steps in the Framework along with some comments and discussion regarding information provided in studies reviewed for this analysis. Additional details on these steps can be found in the CEFF application document at ceff.ucdavis.edu.

Step 10. Evaluate alternative management scenarios and address tradeoffs

Objective: To explore non-flow and flow-based strategies to satisfy ecological flow criteria, quantify the ecological consequences of failing to satisfy ecological flow criteria, and propose mitigation measures to offset impacts, if any.

Outcome of Step 10:

- Tradeoff analysis between ecological and non-ecological management objectives under alternative management scenarios
- Identification of preferred management alternative

Based on the information evaluated in steps 5 and 6, channel incision limits floodplain connection in many reaches of the lower Cosumnes basin, which affects the functionality of winter peak flows for supporting native riparian wetland habitat and rearing habitat for native fish (ecological goals identified in step 1). Further, limited floodplain connection reduces winter recharge to shallow groundwater exacerbating limited surface water and groundwater connectivity during the summer and fall seasons. The flow alteration analysis in step 9 indicated that while winter flow conditions were likely unaltered, summer dry season baseflow was likely altered (too low) in the downstream reaches of the lower Cosumnes basin in all years. Management actions that support increased floodplain functionality in winter and spring and promote higher stream flows in the summer should be considered by stakeholders in the basin.

In an effort to provide additional information for such stakeholder efforts, American River Conservancy conducted a literature review of groundwater recharge and surface-groundwater interaction studies within the basin (Wiener, 2021). The review provides a summary of hydrogeomorphic conditions within the basin, a synthesis of surface water and groundwater interactions and groundwater recharge processes in the lower basin, and an extensive annotated bibliography of key literature available. The results from this review are discussed in the context of potential management actions below.

Summary of groundwater conditions in the Lower Cosumnes

Historically, the lower Cosumnes river system was comprised of a series of shallow anastomosing fluvial channels grading into a complex of stream channels, seasonal marshes, and "lagunitas" or perennial floodplain lakes near the confluence with the SF-Bay Delta. Agricultural development in the late 1800s and early 1900s leveled the floodplains, leveed the main stream channel, and converted the river system into a deepened single channel corridor with little floodplain connectivity. Currently, the lower Cosumnes river can be described as three contiguous stream reaches with slightly differing conditions, constraints, and opportunities with regard to providing flow functionality and meeting ecological flow criteria.

The upper reach extends from the Michigan Bar gage (River Mile [RM] 36; LOI 1) to the Dillard Road crossing downstream (RM 28). Along this reach, levees and bank protection structures are less ubiquitous and not evenly spaced, providing opportunities for the river to adjust during high flows. The channel has widened in places due to bank failures, allowing for local in-channel deposition of sediments. Although still a single moderately incised channel, this reach may be transitioning to a state of aggradation that will provide more complexity in channel habitat at various flows. This upper reach has seasonally been connected to the primary underlying aquifer such that according to studies between 2001-2012, groundwater levels range from 0 ft to approximately 60 ft below ground surface (bgs) depending on the time of year and extent of river flow. More recent data between 2012-2019 suggests that seasonal groundwater levels have decreased to 100 ft bgs or more during late summer. Low groundwater levels in late summer and fall in particular contribute to drying of the stream channel in this losing reach such that when fall precipitation begins, elevated streamflows are often 'lost' to the underlying channel sediments until enough flow has saturated the subsurface and local groundwater levels have increased enough to limit seepage losses supporting higher sustained river flow.

In the middle reach from Dillard Road (RM 28) downstream to the Highway 99 crossing and the McConnell gage (RM 11; LOI 2), channel levees are frequent, and the river is deeply incised. Only large flood flows (>8000 cfs) are capable of inundating the floodplain in locations with levee setbacks, and in some locations where levees are highest, the floodplain is entirely disconnected. At the downstream end of this reach below the Wilton Road crossing (RM 17), the river is less confined and flood flows greater than 6000 cfs are able to access the floodplain and overbank areas. In this middle reach, surface flows are disconnected from the primary underlying aquifer, which is typically 40-100 feet bgs throughout the year. However, seepage from the channel during winter and spring flows that saturate the adjacent channel areas help to support riparian vegetation and may help recharge shallow perched aquifers throughout this reach. These shallow aquifers are prone to drying by mid-summer as surface flows diminish and connections to the deeper aquifer are limited. Similar to the upper reach, when fall precipitation begins, surface water runoff is lost to the underlying substrate until enough streamflow has saturated the subsurface and remains high enough in volume to overcome channel seepage rates.

The lower reach extends downstream of Highway 99 (RM 11) to the river confluence with the Delta (RM 0). The river is less incised in this reach with fewer levees that are set-back or breached from floodplain restoration projects to allow for more frequent floodplain inundation at flows as low as 900 cfs. The most downstream portion (RM 0 – RM 5) is comprised of multiple tidally-influenced channels that shift across the lower floodplain and support the most diverse aquatic and riparian habitat in the lower basin. Due to higher groundwater levels (<30 ft bgs) partially controlled by tidal backwater influences in the Delta, surface flows in this lower reach are seasonally connected to the primary underlying aquifer and support riparian and wetland vegetation throughout the floodplain. Frequent floodplain inundation during high flows contributes large volumes of water to groundwater recharge helping to maintain elevated groundwater levels and surface water-groundwater connectivity throughout much of the year.

Potential management objectives to improve functionality in each reach

Based on the varying hydrogeomorphic conditions in each reach, particularly with regard to seasonal connections between surface water and groundwater, several general management objectives could be delineated for each stream reach. In the upper reach, objectives include reducing channel incision, extending the seasonal connections between surface and groundwater further into the summer, promoting actions to wet the channel bed and saturate the adjacent channel areas prior to or during fall precipitation events, and limiting groundwater withdrawals to raise shallow groundwater levels to limit channel seepage losses and support fall pulse flows. In the middle reach, objectives include reducing channel incision, promoting deep aquifer recharge over the long-term, and extending or sustaining high groundwater levels in shallow perched aquifers to support riparian areas, groundwater-dependent ecosystems, and instream saturated hyporheic conditions. In the lower reach, objectives include promoting floodplain connections and extending the seasonal connections between surface and groundwater into the late summer. In all three reaches, any ensuing restoration actions should not limit or decrease the ecological functionality in other stream reaches or other locations that may be supplying water, and potential management actions should ensure coordination between all three reaches to create a contiguous stream and riparian habitat corridor through the lower basin.

Potential management actions and types of restoration projects

Mount et al. (2001) presented a three-part strategy to improving baseflow conditions that included: augmentation of surface flows, management of groundwater pumping, and restoration of natural flood regimes. Building on this still useful strategy for the lower Cosumnes basin, the following types of projects would improve ecological functionality, address the management objectives outlined above, and provide benefits to other stakeholder objectives:

- Managed recharge to both the primary and perched aquifers in the middle reach, benefitting surface water-groundwater connections and agricultural water supply
- Floodplain reconnection, levee relocation/set-backs, and habitat restoration projects to promote riparian and groundwater dependent habitats and improve flood management in the middle and lower reaches
- Channel widening to limit channel incision in the middle and upper reaches
- Short-term voluntary forbearance agreements on late season surface water diversions in the upper reach to augment streamflow in fall. If the channel is dry, then augmented flows could serve as 'pre-wetting' or channel saturating flows, or if the channel is wet, augmented flows could serve to increase flow volumes downstream. Such flows may also provide local groundwater recharge benefits.
- Relocation of shallow wells next to the river channel, particularly in perched aquifers in the middle reach, and use of alternative water sources such as recycled water in the middle and lower reaches to extend the duration of saturation in the channel.
- Preservation of agricultural and habitat lands along the river corridor, particularly those that can be used for groundwater recharge in the winter.
- Ensuring future water banking production wells are located far from the river corridor.
- Voluntary water use efficiency improvements

Regulatory Landscape

Stakeholder objectives in the lower Cosumnes basin also vary by reach. In the upper reach, large municipal and agricultural surface water diversions serve the Rancho Murieta community and irrigate pastures, row crops, orchards, and vineyards. This portion of the river is a key salmon spawning area and connects the alluvial habitat corridor to the cooler waters of the upper watershed. In the middle reach, groundwater pumping and riparian diversions support agriculture and the agricultural-residential communities of Wilton and Sheldon. The middle reach is also a riparian forest corridor for aquatic and terrestrial species movement in response to climate change that provides a barrier or opportunity for anadromous fish migration, depending on streamflow conditions. The lower reach includes agriculture supported by groundwater pumping and riparian diversions and has a large proportion of the landscape in conservation ownership at the Cosumnes Preserve. The lower reach offers opportunities for landscape-scale projects that build on earlier multi-benefit conservation and floodplain reconnection projects. Each reach is thus subject to a variety of regulatory compliances related to sensitive species, water diversions and use, and water quality conditions, depending on the location.

Of the various regulatory compliance programs, SGMA connects the Cosumnes Watershed stakeholders across the reaches with the mandate to manage groundwater sustainably. To accomplish this mandate, Groundwater Sustainability Agencies are gathering information on water use, suitability of geologic conditions for recharge, surface water flow conditions, relationships between surface flows and groundwater levels, and other factors related to water use and management. This information is invaluable for highlighting priority projects and implementing adaptive management strategies in the lower Cosumnes basin.

The California Water Resilience Portfolio (https://waterresilience.ca.gov/) highlights the following principles, which will guide State grant funding priorities for watershed restoration and water management projects:

- Prioritize multi-benefit approaches that meet multiple needs at once.
- Utilize natural infrastructure such as forests and floodplains.
- Embrace innovation and new technologies.
- Encourage regional approaches among water users sharing watersheds.
- Incorporate successful approaches from other parts of the world.
- Integrate investments, policies and programs across state government.
- Strengthen partnerships with local, federal and tribal governments, water agencies and irrigation districts, and other stakeholders.

Management actions and restoration projects that meet the various stakeholder objectives outlined above and align with the stated Water Resilience Portfolio principles, such as providing multiple benefits, are likely to be good candidates for State grant funding.

As discussion and evaluation of management actions by stakeholders in the basin continues, consideration of their potential effects on the ecological management goals identified in step 1 should be included. Additionally, further study and quantification of the ecological consequences of failing to satisfy the ecological flow criteria will help in evaluation of trade-offs inherent to meeting ecological and non-ecological management objectives.

Step 11. Define environmental flow recommendations

Once all analyses, studies, and discussions regarding ecological and non-ecological management objectives have been completed, stakeholders in the Cosumnes basin should establish their environmental flow recommendations and any associated non-flow management actions.

Objective: To select a preferred management alternative set of environmental flow recommendations in collaboration with stakeholders and agency partners based on the results from the previous 10 steps, and then to develop the final set of environmental flow recommendations

Outcome of Step 11:

- Final set of environmental flow recommendations
- List of measures to enhance the effectiveness of environmental flows or mitigate adverse effects (if final recommendations deviate from ecological flow criteria)

Step 12. Develop implementation plan

An adaptive management plan for the lower Cosumnes basin coordinated with an implementation plan for actions identified in step 11 will be key for future management considerations related to climate change impacts. Plans that allow for ongoing assessment and support of ecosystem functions will be essential for maintaining and increasing climate resilience within the Cosumnes River ecosystem.

Objective: To develop an implementation plan that includes an adaptive management plan and monitoring strategy that will guide implementation of environmental flow recommendations, including the associated mitigation measures

Outcome of Step 12:

- Implementation plan that includes mitigation measures and adaptive management
- Monitoring strategy that informs adaptive management

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Appendix A: Alteration Assessment by Water Year Type

Table A.1. **WET** years for LOI 1 (Michigan Bar) and LOI 2 (McConnell) (NA-natural flows model does not predict value)

Flow Component	**Flow Metric**	**Ecological Flow Criteria at LOI 1**	**Observed Metrics at LOI 1**	**Ecological Flow Criteria at LOI 2**	**Observed Metrics at LOI 2**
		median (10th-90th percentile)	median (10th - 90th percentile)	median (10th - 90th percentile)	median (10th - 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	254 (81-1004)	93 (39-800)	304 (85-1776)	151 (66-2385)
	Fall pulse timing (WY day)	23 (7-43)	20 (6-51)	25 (7-46)	23 (14-45)
	Fall pulse duration (days)	NA	5 (3-9)	NA	3 (2-6)
Wet-season baseflow	Wet-season baseflow (cfs)	360 (164-661)	539 (264-826)	368 (163-822)	356 (94-790)
	Wet-season median flow (cfs)	1080 (579-1840)	1195 (988-1954)	1240 (660-2290)	1170 (1015-2083)
	Wet-season timing (WY day)	69 (51-93)	79 (44-103)	68 (48-89)	75 (37-93)
	Wet-season duration (days)	137 (77-182)	130 (85-171)	134 (82-179)	130 (78-175)
Peak flows	2-year flood magnitude (cfs)	NA	6300	NA	7120
	2-year flood duration (days)	NA	6 (2-12)	NA	6 (3-11)
	2-year flood frequency (# per season)	NA	3 (1-5)	NA	3 (2-5)
	5-year flood magnitude (cfs)	NA	14460	NA	17300
	5-year flood duration (days)	NA	2 (1-4)	NA	2 (1-3)
	5-year flood frequency (# per season)	NA	1 (1-2)	NA	1 (1-1)
	10-year flood magnitude (cfs)	NA	18960	NA	20900
	10-year flood duration (days)	NA	1 (1-3)	NA	1 (1-2)

	10-year flood frequency (# per season)	NA	1 (1-2)	NA	1 (1-1)
Spring recession flows	Spring recession magnitude (cfs)	3524 (1237-11460)	2285 (945-11710)	4571 (1509-16060)	3470 (1875-16470)
	Spring timing (WY day)	200 (175-226)	212 (164-241)	196 (171-225)	202 (160-235)
	Spring duration (days)	58 (32-116)	69 (41-97)	62 (31-133)	72 (43-119)
	Spring rate of change (percent)	NA	0.05 (0.04-0.09)	NA	0.06 (0.05-0.07)
Dry-season baseflow	Dry-season baseflow (cfs)	77 (20-192)	45 (20-68)	60 (13-212)	14 (0-35)
	Dry-season high baseflow (cfs)	183 (83-348)	100 (63-265)	171 (76-422)	80 (36-315)
	Dry-season timing (WY day)	269 (235-303)	281 (263-304)	264 (227-300)	274 (254-300)
	Dry-season duration (days)	156 (111-214)	168 (130-227)	157 (105-221)	168 (130-209)

Table A.2. **MODERATE** years for LOI 1 (Michigan Bar) and LOI 2 (McConnell) (NA-natural flows model does not predict value)

Flow Component	**Flow Metric**	**Ecological Flow Criteria at LOI 1**	**Observed Metrics at LOI 1**	**Ecological Flow Criteria at LOI 2**	**Observed Metrics at LOI 2**
		median (10th-90th percentile)	median (10th - 90th percentile)	median (10th - 90th percentile)	median (10th - 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	227 (73-732)	98 (32-267)	226 (64-305)	133 (104-285)
	Fall pulse timing (WY day)	29 (9-47)	28 (14-46)	32 (8-51)	33 (20-54)
	Fall pulse duration (days)	NA	4 (3-9)	NA	3 (2-7)
	Wet-season baseflow (cfs)	181 (50-341)	251 (133-470)	157 (49-351)	244 (155-455)

Wet-season baseflow	Wet-season median flow (cfs)	510 (276-900)	786 (540-1145)	573 (253-1120)	788 (599-1107)
	Wet-season timing (WY day)	86 (53-110)	99 (40-144)	83 (49-113)	101 (44-135)
	Wet-season duration (days)	110 (69-162)	120 (71-188)	107 (70-166)	121 (79-189)
Peak flows	2-year flood magnitude (cfs)	NA	6300	NA	7120
	2-year flood duration (days)	NA	2 (1-3)	NA	2 (1-3)
	2-year flood frequency (# per season)	NA	1 (1-2)	NA	2 (1-2)
	5-year flood magnitude (cfs)	NA	14460	NA	17300
	5-year flood duration (days)	NA	1 (1-1)	NA	0
	5-year flood frequency (# per season)	NA	1 (1-1)	NA	0
	10-year flood magnitude (cfs)	NA	18960	NA	20900
	10-year flood duration (days)	NA	0	NA	0
	10-year flood frequency (# per season)	NA	0	NA	0
Spring recession flows	Spring recession magnitude (cfs)	2004 (653-5143)	1240 (797-3950)	2497 (737-8866)	1100 (839-1635)
	Spring timing (WY day)	200 (172-234)	227 (197-245)	198 (162-230)	231 (205-250)
	Spring duration (days)	61 (33-113)	60 (42-77)	65 (31-124)	50 (36-68)
	Spring rate of change (percent)	NA	0.06 (0.05-0.10)	NA	0.08 (0.05-0.09)
Dry-season baseflow	Dry-season baseflow (cfs)	35 (6-126)	20 (10-36)	24 (0-107)	1 (0-15)
	Dry-season high baseflow (cfs)	87 (35-228)	79 (40-122)	77 (25-219)	59 (9-121)
	Dry-season timing (WY day)	271 (239-305)	284 (255-302)	266 (64-1045)	282 (268-299)
	Dry-season duration (days)	161 (109-211)	174 (121-203)	160 (102-215)	158 (108-193)

Table A.3. **DRY** years for LOI 1 (Michigan Bar) and LOI 2 (McConnell) (NA-natural flows model does not predict value)

Flow Component	**Flow Metric**	**Ecological Flow Criteria at LOI 1**	**Observed Metrics at LOI 1**	**Ecological Flow Criteria at LOI 2**	**Observed Metrics at LOI 2**
		median (10th-90th percentile)	median (10th - 90th percentile)	median (10th - 90th percentile)	median (10th - 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	176 (62-560)	90 (34-222)	207 (66-795)	75 (14-180)
	Fall pulse timing (WY day)	31 (5-50)	27 (5-55)	29 (5-52)	41 (7-48)
	Fall pulse duration (days)	NA	4 (3-9)	NA	5 (4-9)
Wet-season baseflow	Wet-season baseflow (cfs)	93 (30-213)	87 (42-166)	95 (27-255)	101 (34-167)
	Wet-season median flow (cfs)	262 (92-566)	282 (92-491)	326 (103-699)	316 (93-517)
	Wet-season timing (WY day)	85 (54-116)	84 (37-125)	82 (49-117)	56 (31-112)
	Wet-season duration (days)	101 (64-156)	129 (76-180)	105 (54-177)	145 (105-204)
Peak flows	2-year flood magnitude (cfs)	NA	6300	NA	7080
	2-year flood duration (days)	NA	1 (1-1)	NA	0
	2-year flood frequency (# per season)	NA	1 (1-1)	NA	0
	5-year flood magnitude (cfs)	NA	14460	NA	16740
	5-year flood duration (days)	NA	0	NA	0
	5-year flood frequency (# per season)	NA	0	NA	0
	10-year flood magnitude (cfs)	NA	18960	NA	20770
	10-year flood duration (days)	NA	0	NA	0
	10-year flood frequency (# per season)	NA	0	NA	0

Spring recession flows	Spring recession magnitude (cfs)	871 (275-3503)	495 (174-1150)	1070 (223-5528)	631 (197-926)
	Spring timing (WY day)	197 (159-226)	216 (181-242)	193 (158-227)	213 (190-227)
	Spring duration (days)	61 (32-116)	66 (37-96)	64 (31-132)	45 (24-69)
	Spring rate of change (percent)	NA	0.06 (0.05-0.11)	NA	0.08 (0.06-0.13)
Dry-season baseflow	Dry-season baseflow (cfs)	12 (0-44)	12 (2-28)	6 (1-36)	0 (0-0)
	Dry-season high baseflow (cfs)	162 (109-220)	46 (20-179)	46 (9-149)	18 (0-174)
	Dry-season timing (WY day)	268 (237-304)	278 (254-302)	265 (225-300)	259 (240-281)
	Dry-season duration (days)	162 (109-220)	166 (127-212)	161 (106-223)	171 (150-231)

Review of Groundwater Recharge and Surface Water-Groundwater Interactions for the Lower Cosumnes River

Prepared by Jason Wiener for American River Conservancy

Purpose and Summary

The Cosumnes river watershed is unique among the large-scale river systems draining the west side of California's Northern Sierra Nevada range. Unlike other major Sierran systems, the river remains relatively unregulated as it is free of high-head dams and significant surface water impoundments. This freedom allows river flows to retain a signature similar to their natural unimpaired flow regime. The river, its associated floodplains, and groundwater recharge basin provide numerous societal and ecological benefits including a population of fall-run Chinook salmon and other native fish species, hundreds of species of migratory birds, diverse groundwater dependent ecosystems, the largest remaining Central Valley riparian forest, as well as thousands of acres of agricultural production and communities (Yarnell & Obester, 2020).

Recognition of the system's value but also its susceptibility to ongoing impairments from anthropogenic factors has resulted in decades of effort by agencies, agricultural entities, non-governmental organizations (NGOs), and other stakeholders to study the hydrology, hydrogeology, geomorphology, and ecology of the region and to identify and implement multi-benefit strategies to sustain water supply, ecosystems, and agriculture (Yarnell & Obester, 2020). Recently, Yarnell & Obester (2020) completed an analysis of ecological flow criteria for the Lower Cosumnes using the California Environmental Flows Framework (CEFF) to inform the development of instream flow targets supportive of anadromous fish, riparian habitat, and other ecological objectives (CEFF analysis). Results of the CEFF analysis provide flow recommendations at two locations (USGS gage at Michigan Bar [Gage ID 11335000, NHD COMID 20192498], located approximately two miles upstream of the Highway 16 crossing, and the USGS McConnell gage [Gage ID 11336000, NHD COMID 3953273], located approximately 20 miles downstream of the Michigan Bar gage (MHB) where the Cosumnes River crosses Highway 99) and highlight dap gaps and areas for further study.

One key conclusion of the CEFF analysis is the likely alteration of the magnitude of median dry season flows at the McConnell gage (MCC) as compared to reference conditions. These depletions were attributed to decreases in regional groundwater levels. While, a number of previous studies link lowered groundwater elevations to surface flow reductions in the channel, this issue was also identified in the CEFF analysis as a topic for ongoing study with the aim that better quantification of surface-groundwater connections and description of underlying hydrogeologic processes would lead to better understanding of potential impacts of lowered groundwater levels on dry season baseflow. Accurate quantification of such connections and improved process understanding is crucial to inform groundwater levels needed to support stream functionality in the dry season.

Contemporary groundwater management includes both approaches and requirements mindful of the coupling between the surface and sub-surface water systems. For example, conjunctive use actions, such as focused groundwater recharge, have become an increasingly promulgated and implemented method to improve shallow groundwater levels that may benefit surface water systems. The use of focused groundwater recharge to potentially mitigate dry season surface flow losses to infiltration was specifically referenced in the CEFF analysis as requiring further evaluation. Surface water-groundwater (SW-GW) interactions, managed aquifer recharge (MAR), as well as the influence of decades of groundwater overdraft on river flows have been the focus of numerous targeted studies in the Cosumnes region. Thus, the purpose of this study was to compile and review relevant research on Cosumnes groundwater recharge processes and how groundwater conditions interact with Cosumnes surface flow conditions.

The scope of this effort was generally limited to documents specifically related to the Cosumnes region as opposed to a more comprehensive review of the vast literature base on surface-water groundwater interactions and groundwater recharge, which are available by others (e.g. Barlow and Leake, 2002; Barthel & Banzhaf, 2016; Brunke & Gonser, 1997; Hayashi & Rosenberry, 2002; Levy et al., 2008; as well as references included in this review). Findings of this study are presented in narrative form, summarizing relevant background information on the basin and results on the focused research topics, as well as in the form of an annotated bibliography. The goal is to provide a concise synthesis of existing knowledge of SW-GW interactions and groundwater recharge for the Cosumnes region, as well as provide a comprehensive index of relevant research that can be used to supplement the CEFF analysis and aid in ongoing work to identify management actions to address flow and habitat alteration. These results will help inform the development of environmental flows along the Lower Cosumnes river.

The structure of the document is organized as follows:

- Section 1 – Descriptions of the study area and review of basin conditions including floodplain and channel morphology, dry-season hydrology, and groundwater conditions.
- Section 2 – Synthesis of current understanding of SW-GW interactions within the study area.
- Section 3 – Synthesis of current understanding of recharge processes in the basin.
- Section 4 – Key Data Gaps.
- Section 5 – Annotated bibliography of key literature on SW-GW interactions and recharge in the basin.
- Section 6 – Data dictionary of physical properties relevant for modeling SW-GW interactions and recharge in the basin.
- Section 7 – Additional References.

SGMA

It is important to acknowledge that concurrent with this study is the ongoing preparation of Groundwater Sustainability Plans (GSPs) for the two groundwater basins underlying the Cosumnes river. These plans are being prepared pursuant to the Sustainable Groundwater Management Act (SGMA). SGMA tasks Groundwater Sustainability Agencies (GSAs) with demonstrating how they will curtail historic groundwater overdraft and achieve a sustainable balance between water use and recharge within a 20-year implementation horizon. As part of sustainable management, SGMA identifies six types of undesirable results that GSAs must avoid, which include, “Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water.” GSP development will include detailed analysis of groundwater conditions including identification and characterization of SW-GW interactions and groundwater dependent ecosystems. While SGMA efforts overlap with the focus of this study and are intertwined with goals of the CEFF analysis, it is outside of the scope of this effort to incorporate SGMA materials at this time. However, it is plausible that findings from this study could inform current SGMA efforts and data gaps identified may be addressed by the GSPs. Ultimately, coordination between SGMA and CEFF stakeholders can help increase understanding of streamflow processes in the lower Cosumnes and aid in linking project and management actions completed for SGMA compliance with CEFF goals.

1. Setting and Background

Study Area

The Cosumnes river watershed[1] drains an area of approximately 949 mi^2 (2,460 km^2) ranging in elevation from 7,743 feet (2,360 m) in the headwaters to near sea level at the confluence with the Mokelumne river (Figure 1). This review focuses on the portion of the river from the USGS Michigan Bar gage (MHB) (River Mile [RM] 36) downstream to the confluence with the Mokelumne river (RM 0), and the associated underlying groundwater basins (Figure 2). The study area is located within the Sacramento and San Joaquin Valley groundwater basins of California's Central Valley, and the river serves as the boundary between the South American sub-basin (DWR Basin Number 5-21.65 [SASb]) to the north and the Cosumnes sub-basin (DWR Basin Number 5-22.16) to the south (Figure 1). The SASb is bound to the west by the Sacramento river, on the north by the American river, on the south by the Cosumnes and Mokelumne rivers, and on the east by the Sierra Nevada range. The SASb underlies the urban centers of Sacramento, Elk Grove, and Rancho Cordova. The Cosumnes sub-basin is bounded on the north and west by the Cosumnes river, on the south by Dry Creek and Mokelumne River, and on the east by consolidated bedrock of the Sierra Nevada mountains. The Cosumnes sub-basin underlies the cities of Galt and part of Rancho Murieta. Both sub-basins are pumped extensively for local agricultural and municipal uses.

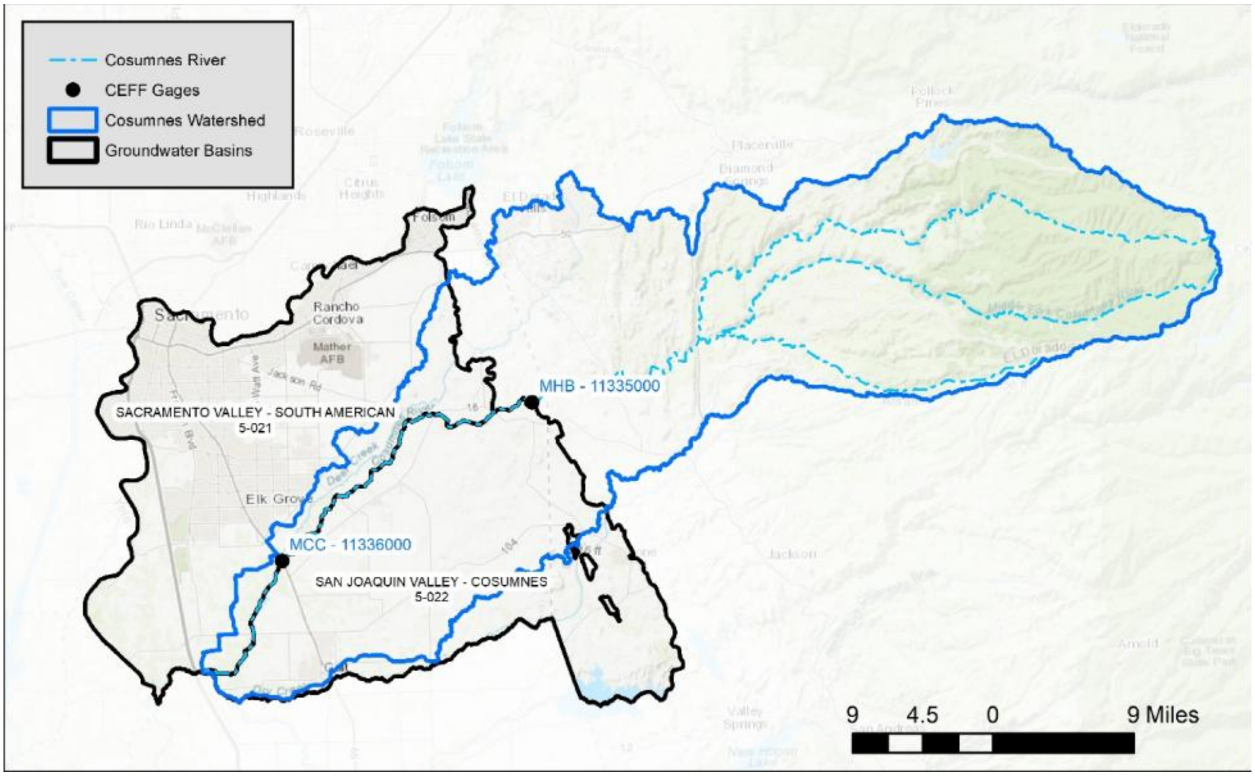

Figure 1. Cosumnes watershed and groundwater basins.

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[1] In general this report used "watershed" when referring to the surface drainage area of the Cosumnes and "basin" when referring to area of underlying alluvial materials that support groundwater production.

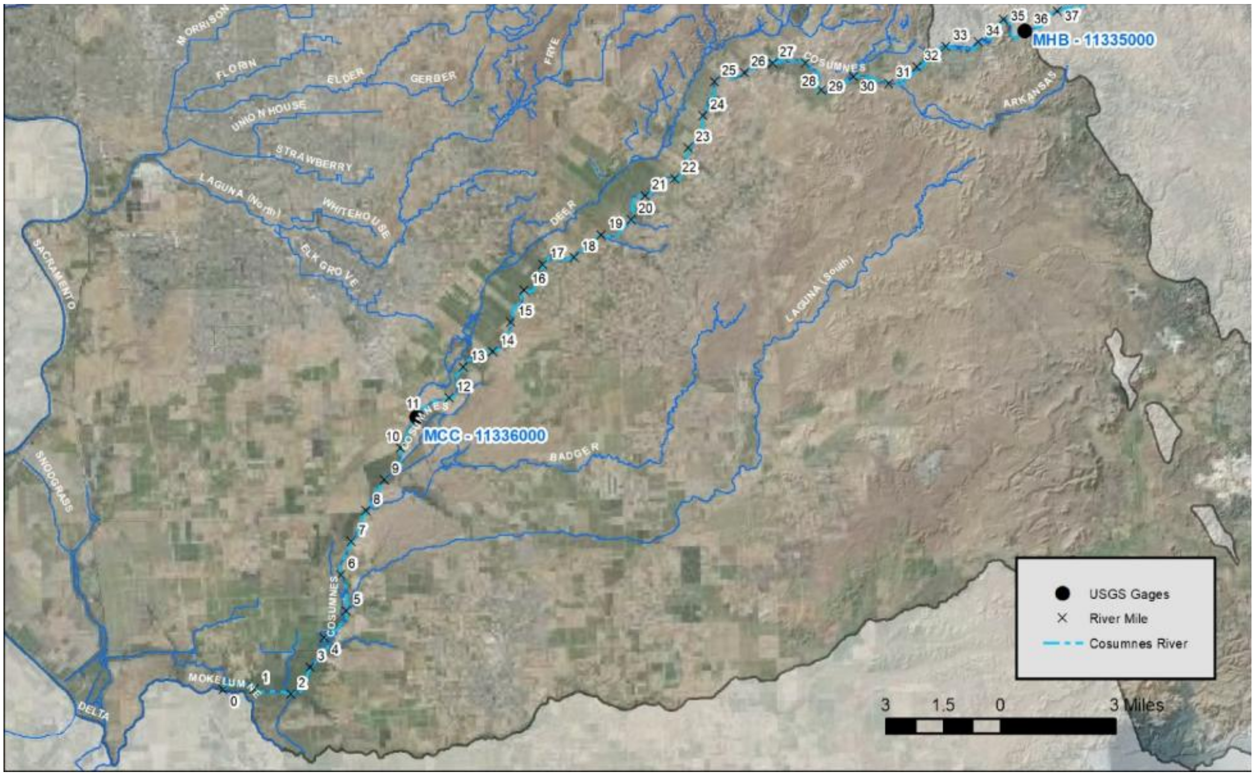

Figure 2. Study area and river miles.

Precipitation

Annual rainfall in the watershed typically ranges from 22 inches (559 mm) in the lower portions of the watershed along the valley floor to upwards of 60 inches (1,524 mm) in the headwater portion of the watershed. Nearly all precipitation occurs between October and April, typical of the regions Mediterranean climate. The vast majority of the watershed (~84%) lies below the Sierran snow-level elevation of ~5,000 feet (1,500 m), meaning intense winter rainfall events are the primary driver of system flooding (Florsheim & Mount, 2002; Robertson-Bryan Inc., 2006a; Booth et al., 2006). While snowmelt is not a large contributor to the annual streamflow volume, snowmelt and particularly rain-on-snow events influence flooding, the latter of which has been associated with peak flow events (Kleinschmidt Associates, 2008).

Floodplains and Geomorphology

The floodplains of the Cosumnes occupy a broad alluvial fan derived from aggradation of sediments from the Sierra Nevada block (Robertson-Bryan Inc., 2006a). Connection of the river with its floodplain influences several hydrologic, geomorphic, biogeochemical, and ecological processes that are vital to the life-histories of many aquatic and terrestrial species (e.g. Whipple et al., 2016). However, the hydrodynamics of flood events in the study area, such as the depth, duration, and area of flooding, have been significantly altered due to construction of intermittent levees, land use changes, and resultant changes in channel geomorphology (Florsheim & Mount, 2003). Detailed descriptions and locations of levees, natural and human-induced levee breaches, channel geomorphology, history of channel and floodplain modifications, as well as channel incision along the study area are documented in several studies (Florsheim & Mount, 1999, 2002, 2003; Constantine, 2001; Constantine et al., 2003; Robertson-Bryan Inc., 2006ab) (Figure 3).

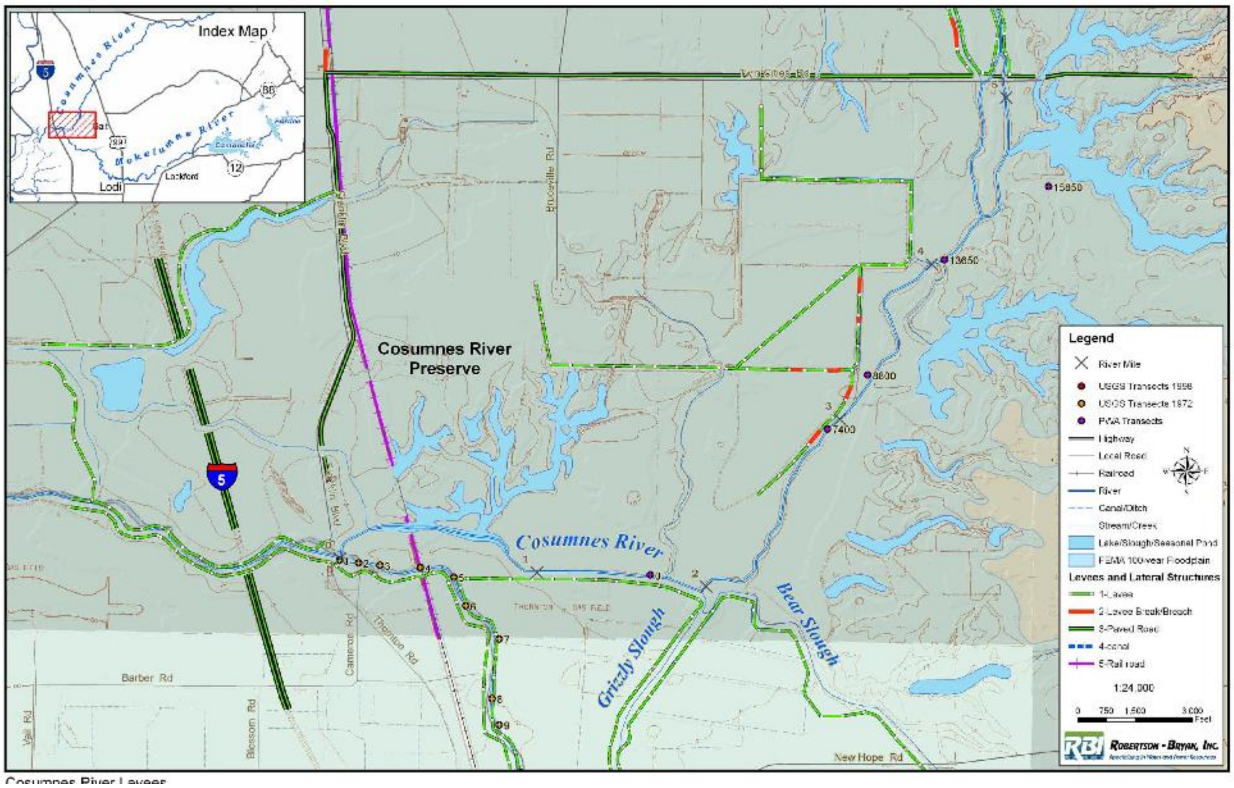

Figure 3. Example of map from Robertson-Bryan Inc., (2006a) showing levees and levee breach locations (Appendix C). River miles may differ slightly from those used in this review.

Flooding along the Cosumnes is major source of recharge to the regions aquifers, and thus is relevant to the intent of this study. Historic and current hydrogeomorphic conditions are summarized below focusing on factors that have influenced the rivers connection with its floodplain (e.g. incision and levees). Additional discussion, detailed statistical analysis (i.e. frequency, magnitude, duration) of Cosumnes flooding, and classification of flood typologies are reported by Robertson-Bryan Inc. (2006ab), Booth et al. (2006), and Whipple et al. (2017), respectively. Flood durations provided by Booth et al. (2006) and Whipple et al. (2017) are based on the timing that MHB gaged flows exceed specified thresholds and do not necessarily represent the duration over which the floodplain is inundated with water. Additional information on the extent, duration, and depth of floodplain inundation is available for the lower portion of the study area (~RM 2-9) based on unsteady hydrodynamic modeling completed by Whipple (2018) and Robertson-Bryan Inc., (2013)[2]. Such modeling is highly valuable toward understanding the floodplain-recharge dynamics of the system, especially when coupled with groundwater flow modeling (e.g. Lui, 2014).

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[2] This report was unavailable for review but was referenced by Lui, 2014.

In the period prior to European settlement, the portion of the Cosumnes river system downstream of Highway 16 (RM 32.5) was comprised of a series of shallow anastomosing channels (Florsheim & Mount, 2002). These sinuous 5 to 10 foot (1.5-2.5 m) deep channels were highly dynamic, experiencing frequent avulsions and overbank flooding during even moderate flow events (Constantine, 2001 and references therein). Floodplains downstream of Highway 99 (RM 11) contained complex channel networks, seasonal marshes, and ‘‘lagunitas,’’ or perennial floodplain lakes, while floodplains upstream of Highway 99 contained vegetated islands defined by the more stable anabranching channel network of the Cosumnes River-Deer Creek fluvial system (Florsheim & Mount, 1999).

Beginning in the 1850’s, intensified settlement of the region was accompanied by watershed-scale land use changes that included filling and leveling of floodplains and clearing of native vegetation, all of which disrupted the natural Cosumnes flow and sediment regimes. Landscape modifications continued, and in the early 1900’s construction of agricultural levees constrained the river to a single-threaded channel. Over the next three to five decades levee construction intensified, and by 1937 right-bank levees were present along the entire Dillard Road (RM 27.5) to Wilton Road (RM 17.3) reach. Increased sediment transport capacity and reduced potential for lateral migration of the modified channel resulted in rapid incision and lowering of the riverbed, often exposing the underlying duripan (hardened interglacial soil layers). From the 1950’s through the 1990’s, net incision in the study area was estimated to be between 1.64 and 9.84 feet (0.5 and 3.0 m) (Constantine, 2001 and references therein). Levees constructed on the nearby Sacramento river during the same timeframe impeded floodwaters and sediment from entering the Cosumnes floodplain, thereby further changing the hydrogeomorphology of the flood basin (Florsheim & Mount, 2003).

Currently, various structures including levees, bank protection, and agricultural diversion dams continue to influence study area morphodynamics. However, these structures are not evenly distributed, thus allowing portions of the river more adjustability and hydraulic connection with floodplains. For example, levees are discontinuous along the uppermost portion of the study area from MGH to Dillard Road (RM 27.5-36). Previous incision in this area has caused widening of the channel through bank failure, and evidence suggests the area is transitioning from a mode of degradation to aggradation.

From Dillard Road downstream to Highway 99 (RM 11-27.5), levees are frequent and the river is deeply incised, at times up to 10-15 feet (3-4.6 m) below the adjacent land surface. Structural bank protection and resistant duripan minimize the natural tendencies for channel widening and lateral migration. Incision and levee construction has increased bankfull flow capacity in this river reach such that flows typically exceeding 8,000 ft^3/s (227 m^3/s) are now required to inundate the floodplain (Yarnell & Obester, 2020). In certain locations between Dillard and Wilton Roads (RM 17.3-27.5), channel capacity may be as great as 30,000-40,000 ft^3/s (859-1,133 m^3/s) where levees are highest (Robertson-Bryan Inc., 2006a). Downstream of Wilton Road to Highway 99 (RM 11-17.3), the river is less confined and channel capacity is reduced to approximately 6,000 ft^3/s (170 m^3/s) (Robertson-Bryan Inc., 2006a).

Downstream of Highway 99 to Twin Cities Bridge (RM 5.5-11), the river is less incised and levees are less frequent or set-back thereby allowing more frequent overbank flooding. In the lowermost reaches of the study area (RM 0-5.5), the river system is still comprised of multiple, shifting, tidally-influenced channels in a broad floodplain upwards of 8 miles (12.9 km) wide. Here geomorphic diversity, levee breaches, and more frequent floodplain inundation support a mosaic of aquatic and terrestrial habitats (Moyle et al., 2003). Observations by Florsheim & Mount (2002) estimate connectivity of the floodplain at the Cosumnes River Preserve (~ RM 3) to occur when flows at MGH exceed 829-900 ft^3/s (23.5-25.5 m^3/s). Nichols and Viers (2017) studied the hydrologic and geomorphic response of two intentional levee breaches at RM 7 and RM 5.6 and reported post-breach floodplain connectivity when flows at MGH were 2,013 ft^3/s and 424 ft^3/s (57 m^3/s and 12 m^3/s), respectively (Figure 4). These flow magnitudes are a significant reduction from the pre-restoration connectivity threshold of 7,946 ft^3/s (225 m^3/s), which remains the threshold discharge for floodplain inundation upstream of the levee breach sites.

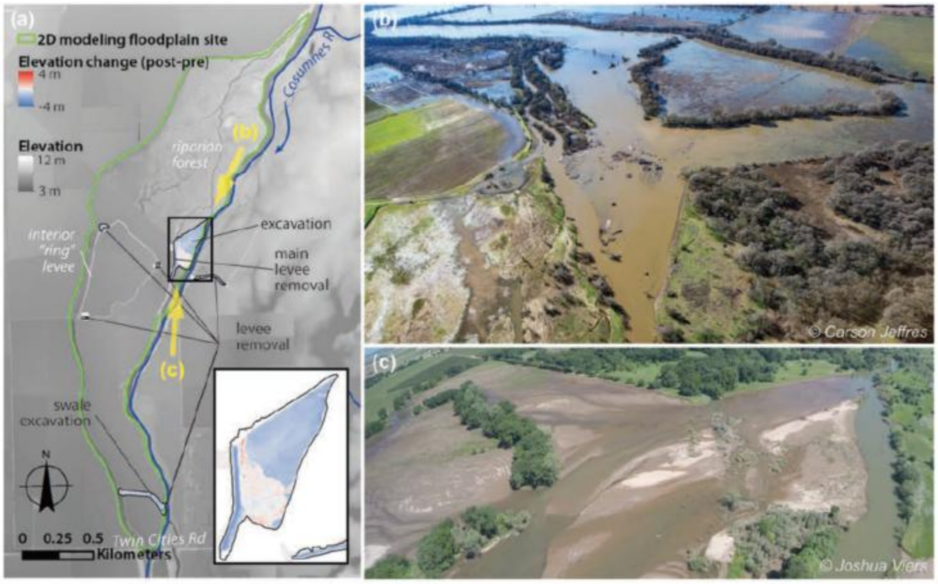

Figure 4. Cosumnes river levee breach floodplain restoration sites near RM 5.6 & RM 7 (Figure 4.3, Whipple, 2018).

Conceptually, historic Cosumnes flooding would have contributed large volumes of water to groundwater recharge. This recharge would have regulated and maintained elevated groundwater levels facilitating connection of the river with the underlying aquifer. Depending on hydraulic gradients, groundwater discharge to the river would have occurred. The spatial and temporal nature of this connection, as well as the magnitude of groundwater discharge, is unknown, but inference from numerical simulations and physical measurement do provide some estimates, which are discussed in Section 2 of this report.

Where overbank flows still occur, the multiple-benefits of flood processes can be realized. For example, natural and induced levee breaches have reconnected large portions of the river with its floodplain, especially in the reaches downstream of Highway 99 (RM 11) (Nichols & Viers, 2017; Robertson-Bryan Inc., 2006a; Yoder, 2018). Restoration of these more natural hydrogeomorphic processes likely plays a substantial role in contributing to groundwater recharge. Indeed, evidence shows that groundwater levels in this region remain elevated and facilitate intermittent to continuous hydraulic connection between surface water and groundwater; see Section 2 for more detail. Where the river is tidally influenced (RM 0-4.5-5) and does not run dry, the value of floodplain recharge in maintaining dry-season baseflows may be less critical than other benefits provided by floodplain restoration. However, the role this recharge plays in maintaining groundwater levels remains relevant to the overall basin and especially to river reaches immediately upstream where it helps ensure groundwater gradients are not increased, supports efforts to restore upstream hydraulic connections, and mitigates potential propagation of declining groundwater levels that could inhibit seasonal SW-GW connections of the river.

While there has been some effort to quantify recharge volumes associated with flooding and floodplain restoration projects (Mount et al., 2001; Lui, 2014; Yoder, 2018), see Section 3, data are still lacking. There is little information on the cumulative effect of these efforts on groundwater levels or how floodplain recharge influences dry-season and wet-season baseflows. Given the interest and beneficial possibilities of MAR in the basin, additional work to better understand the water balance of floodplain recharge would be highly useful (e.g. questions of interest include: under different flooding circumstances, what are magnitudes and variability of relative proportions of water that are lost to evapotranspiration (ET), that infiltrate into perched and shallow unconfined aquifers and eventually into the deeper semi-confined to confined aquifers, and what portion would be conveyed as shallow-subsurface flow back to the river system).

Notably, to the reviewer's knowledge, the impact of channel incision and levee construction on reduced floodplain recharge and associated declining groundwater levels have not been fully quantified. Stream channel incision has been documented elsewhere to lower water tables and dry-out streambanks (Schilling et al. 2004; Wang, 2015). The mechanisms behind these impacts are two-fold. First, incision decouples the stream from it floodplain, as discussed above. Second, incision increases the hydraulic gradient of the groundwater system toward the stream channel, which creates a temporary increase in discharge but ultimately reduces the capability for maintaining higher adjacent groundwater levels. The spatial range of this impact is not well constrained but is typically more localized to the stream corridor, which has consequences for riparian vegetation. The relative effects of channel incision and levees on groundwater dynamics compared to groundwater extraction represents a large data gap.

Dry-Season Stream Flows & Fish Passage

Detailed analysis of stream flows has been completed by several studies leveraging data from the MHB gage, which has daily discharge data from 1907 to the present, and the MCC gage, which has daily discharge data from 1941-1982 (e.g. Anderson et al., 2004; Fleckenstein et al., 2004; Mount et al., 2001; Robertson-Bryan Inc., 2006abc; Yarnell & Obester, 2020[3]). Of the river's natural flow regime, dry-season baseflows at MCC appear to be the most likely altered. This alteration has been

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[3] Note that information presented by Anderson et al. (2004), Mount et al. (2001), and Fleckenstein et al. (2004) is nearly identical in nature thus effort was made to reduce duplicate citations in the subsequent text.

attributed to changes in SW-GW interactions, and thus discussion of Cosumnes stream flow in this reivew is limited to dry season baseflows. Dry-season baseflows are also critical to upstream migration of fall-run Chinook salmon (*Oncorhynchus tshawytscha*) to their spawning grounds, and declines of Cosumnes salmon populations have been linked to changes in SW-GW interactions.

The CEFF analysis identified current dry-season median baseflows of 22 (5-52[4]) ft^3/s (0.62 [0.14-1.47] m^3/s) at MHB and 0 (0-28) ft^3/s (0 [0-0.79] m^3/s) at MCC. This is consistent with reports that flows at MHB are typically below 30 ft^3/s (0.85 m^3/s) between August and October. At this discharge, portions of the river from Highway 16 downstream to the tidal zone (RM 5-32.5) are generally dry due to seepage and evapotranspiration. This drying is more pronounced downstream of Wilton (RM 17.3), where the river runs dry nearly every year (Robertson-Bryan Inc., 2006c). At the MCC gage (RM 11), the river is dry nearly 60 percent of the time in fall months (Ascent, 2014). Detailed mapping of the wetting front and discharge measurements at several locations along the river were conducted by Robertson-Bryan Inc. (2006c) at various upstream flows as part of the October 2005 Cosumnes River Flow Augmentation Project (see also Niswonger et al., 2008 for measurements of the flow front). Historical analysis suggests discharge in the lower reaches of the river decreased steadily from 1942 to 1982, as indicated by a linear increase in the number of days per year with flows below 10 ft^3/s (0.28 m^3/s) at MCC (Mount et al., 2001). These decreases coincide with periods of increased groundwater extraction in the study area; see Section 2 for detailed discussion.

Fall-run chinook salmon typically complete their spawning migration between October and December. During this period, they require flows that create conditions suitable for passage and spawning[5]. The majority of spawning in the river occurs in the 16 mile reach between Latrobe Falls (RM 41.5) downstream to Meiss Road (RM 25.5) with some additional spawning occurring from Meiss to Wilton Roads (RM 25.5—17.3) (Robertson-Bryan Inc., 2006c). Historically, the Cosumnes supported large fall runs of Chinook salmon upwards of 17,000 fish. Over the past forty years, the fall run has declined to 0-5000 fish and is consistently less than 600 fish, with occasional higher returns in the last five years (USFWS, 1995; CDFW Grand Tab: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=84381&inline).

Several studies provide estimates of what flow conditions are necessary for upstream fish passage. Most recently, hydraulic modeling by US Fish and Wildlife Service (USFWS) as part of an initial passage analysis identified 180 ft^3/s (5.1 m^3/s) as the minimum bypass flow condition for both the MCC and MHB locations. This estimate does not account for river seepage, which under current conditions would necessitate a larger flow requirement at MBH (Figure 5). Seepage estimates vary along the riverbed (see Section 2 and Section 6) but are generally in the range of 1 to 3.5 ft^3/s/mile (0.03-0.10 m^3/s/mile), suggesting flows upward of 266 ft^3/s (7.5 m^3/s) at MBH would be required. The effect of stream diversions between MHB and MCC at the time of passage must also be

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[4] Flow given is the median of annual median values and numbers in parenthesis are the 10th and 90th percentiles of annual median values.

[5] Water depth and speed are common hydraulic factors considered though spawning success is influenced by many physical, chemical, and biological factors.

considered and added to recommended bypass flow requirements at MHB (see SWRCB, 2020 for example).

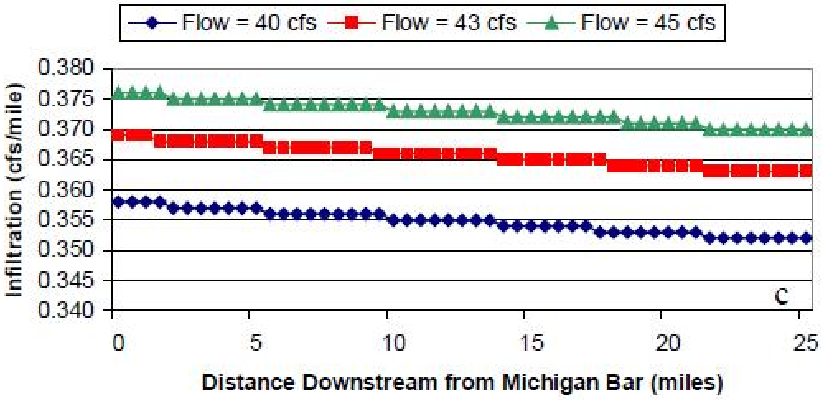

Figure 5. Example of simulated seepage profile from MHB to MCC (Figure 16(c), Mount et al., 2001).

The USFWS passage estimates are larger than previous passage estimates for flows at MHB by Anderson et al. (2004), Fleckenstein et al., (2004), and Mount et al. (2001) of 32.8 ft^3/s (0.93 m^3/s), 54.7 ft^3/s (1.55 m^3/s), and between 40-45 ft^3/s (1.13-1.27 m^3/s), respectively. These earlier predictions were each based on achieving a minimum flow depth of 0.6 feet (0.18 m) at MCC using 1-D hydraulic modeling and accounting for seepage losses[6]. Anderson et al. (2004) also concluded that higher initial flow conditions would be needed at MBH to achieve the desired passage depth at MCC when the river is dry (see also Niswonger et al., 2008). They estimated a flow pulse of 86.5 ft^3/s (2.45 m^3/s) for 23 hours would be required to wet the channel, at which point flows could return to the previously recommended 32.8 ft^3/s (0.93 m^3/s) to sustain passage. Similar observations have been made by the Fisheries Foundation of California (FFC), who note that fall (October-November) pulse flows on the order of 100 ft^3/s (2.8 m^3/s) are needed for a period of at least 10 days to provide and maintain passage conditions throughout the lower Cosumnes reach. FFC also report stranding or delays can occur for higher pulse events of 200-400 ft^3/s (5.7-11.3 m^3/s) when flows last for less than a week and are followed by extended dry periods (FFC, 2004).

Several factors may explain the wide range of reported flows needed for fish passage. For one, river conditions (e.g. hydraulic geometry, slope, and substrate) are constantly changing. This means conditions in the river 15-20 years ago associated with the flows recommended by Mount et al. (2001) and Anderson et al. (2004), which at that time met their passage criteria, would not result in the same hydraulic conditions in the contemporary river setting. Second, passage criteria also evolve over time as understanding of species biological requirement improves. While, the passage criteria and date of physical conditions (e.g. river topography/bathymetry) used by USFWS in their evaluation are unknown, it is presumed their analysis reflects both updated river conditions and

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[6] Slight variation in listed model parameters may explain differences in estimates.

species requirements compared to those employed by Mount et al. (2001) and Anderson et al. (2004). In this manner, the more recent USFWS passage recommendation of 180 ft^3/s (5.1 m^3/s) is considered to more likely account for current river conditions and species biological requirements. However, given the range of required passage flows additional study may still be warranted to better define necessary passage requirements. Further evaluation should also be conducted to understand constraints of the current flow regime relative to the recommended USFWS passage requirements. For example, Anderson et al. (2004), who recommended the lowest of all passage flows, found that from 1994 to 2004 only one year consistently had sufficient flow at MBH from October through December and that in three years there was no flow at MHB at some point during the migration period. October was revealed as the driest month with flows frequently below their identified threshold.

In addition to flow constraints, Cosumnes salmon must also navigate several in-stream structures during migration to their spawning grounds. These include a box culvert near RM 6.75, four low-head dams (RM 12.4, 16.25, 22.5, and 25), and two fish ladders at Granlees Dam (RM 34.5). All structures have been improved for fish passage in the last three decades, and current estimates by FFC suggest a minimum flow of 100 ft^3/s (2.83 m^3/s) is needed for fish navigability.

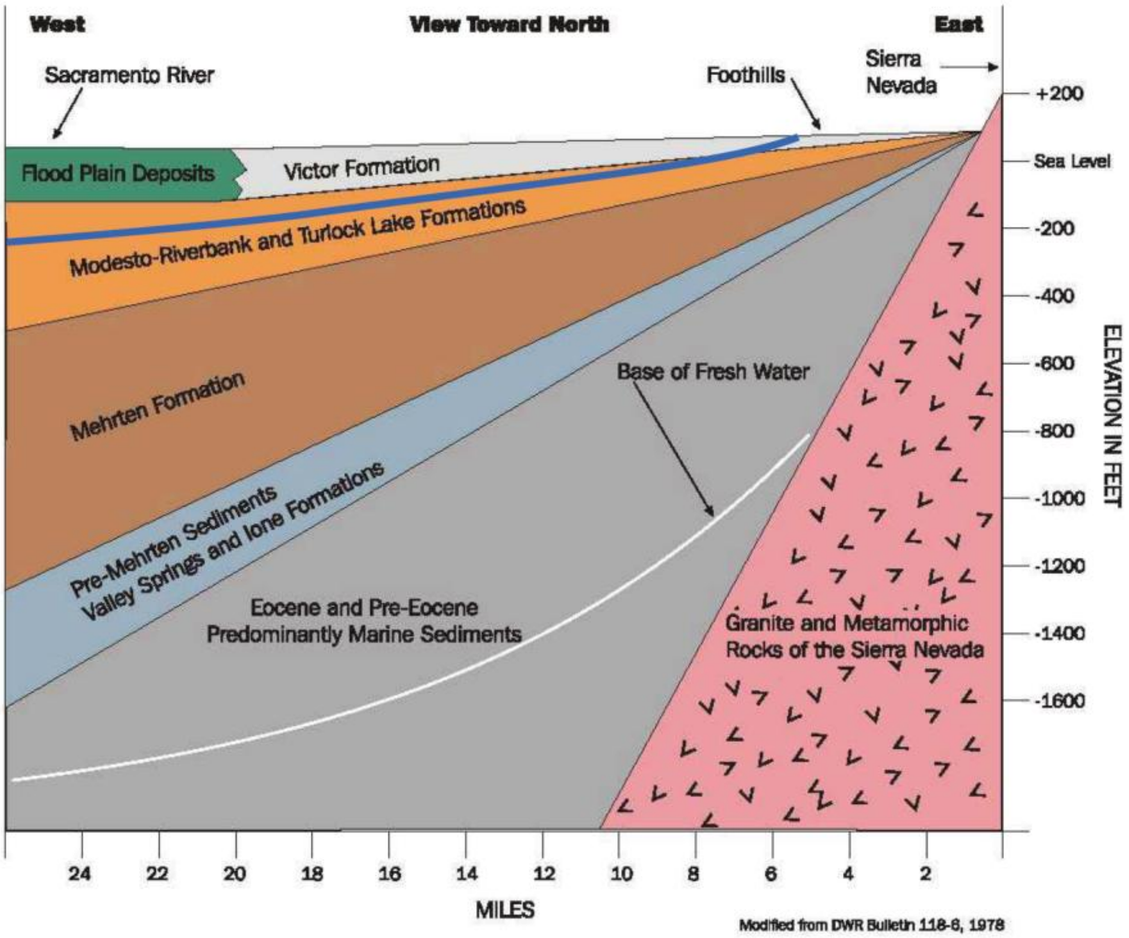
Groundwater Management and Conditions

The Cosumnes River is the boundary between the SASb and the Cosumnes Sub-basin (Figure 1). The Water Forum Agreement created in 2000 set the sustainable yield of the area roughly corresponding to the SASb at 273,000 acre-feet (ac-ft) per year and the Cosumnes Subbasin at 115,000 ac-ft per year.

Aquifers

The complex subsurface geology of the SASb and Cosumnes sub-basins results in a combination of unconfined, semi-confined, and confined aquifer conditions (DWR, 1978). Primary water bearing units in the study area include recent alluvial deposits near active stream channels and floodplains and consolidated rocks of the Laguna, Victor, and Mehrten Formations, with groundwater occurring in distinct shallow and deep aquifer zones (Figure 6). The shallow aquifer is 200–300 ft (61-91 m) thick extending about 200 ft (61 m) below means sea level and is separated from the deep aquifer by a discontinuous clay layer that acts as a semi-confining layer for the deep aquifer (MWH, 2006). The deep aquifer has an average thickness of 1,600 feet (488 m), but may produce lower quality water with higher TDS, iron, and manganese, especially at depth (Robertson-Bryan Inc., 2006b; GEI Consultants, 2016).

Groundwater levels have been monitored and modeled in the sub-basins with extensive reporting by several management agencies (e.g. MWH, 2006; GEI Consultants, 2016; RMC, 2015; Robertson-Bryan, Inc. & WRIME, 2011). A brief summary of groundwater conditions for each basin is provided below. Discussion of groundwater levels directly under the Cosumnes river is presented in Section 2. A series of groundwater level maps from the various sources reviewed as part of this effort are included as Appendix A.



Modified from DWR Bulletin 118-6, 1978

Figure 6. Simplified regional geologic cross-section (Figure 2-15 MWH, 2006). See EKI, 2019 for more detailed hydrogeologic cross sections.

South American Sub-basin

Groundwater production in the SASb began at the turn of the 20th century but drastically increased from the 1930's onward (Bryan, 1923; DWR, 1974). Groundwater levels in the sub-basin have been monitored since as early as the 1930's. In the SASb, groundwater levels were relative steady from 1930-1940. In the subsequent decades, regional groundwater levels declined on average by over 1 ft/yr (0.3 m/yr) decreasing 35 feet (11 m) from 1941-1970 (DWR, 1974). Declines around 1 ft/yr continued until 1980, at which point water levels recovered by about 10 feet (3 m) by 1987. During the 1987 drought however, water levels declined by roughly 15 feet (5 m) through 1995. From 1995 to 2000, levels once again recovered upwards of 20 feet (6 m) in certain locations, overcoming the declines that occurred during the 1987-1992 drought. This recovery is attributed to increased use of surface water and the fallowing of previously irrigated agricultural lands that transitioned into new urban development areas (MHW, 2006). Cumulatively, this amounts to a net average decline in groundwater level of 40 feet (12 m) from 1930-2000.

Groundwater declines are not spatially uniform across the sub-basin. For example, in 1968 a cone of depression had formed around the pumping center of Elk Grove with groundwater levels at 90 feet) below the ground surface (bgs). Cones of depression create strong hydraulic gradients for groundwater flow that can extend several miles and draw from recharge sources such as surface waters. For many decades, the Elk Grove depression attracted recharge flows from the Delta, as well as groundwater from the American river to the north and Deer creek and the Cosumnes river to the south. Since 1968, the Elk Grove depression has fluctuated from a low of -70 feet (-21 m) in 1996 to -40 feet (-12 m) in 2015 (elevations referenced to mean seal level [msl] and correspond to 100 feet [30m] to 70 feet [21 m] bgs). As of 2015, the depression had been partially removed, and although groundwater levels remain depressed compared to historic conditions, they appear to be more stable and no longer creating as strong of a hydraulic gradient (GEI Consultants, 2016).

Recent comparison of 2005 to 2015 groundwater levels suggests the SASb continues to experience spatially varying areas of groundwater decline and increase (GEI Consultants, 2016) (Figure 7). Areas of decline were found to occur along the eastern half and southern portions of the sub-basin, several of which are in close proximity to groundwater remediation programs. In contrast, stable and increasing levels occupied much of the central and north-western portion of the sub-basin, though it is important to note that there is uncertainty in how current groundwater levels compare to historic levels prior to groundwater development. Cumulatively, average annual storage loss across all declining areas was estimated to be 11,000 ac-ft per year. This was slightly counter-balanced by average annualized storage increases over recharge areas estimated at 7,000 ac-ft per year, indicating an average annual loss of storage from 2005-2015 of 4,000 ac-ft per year. GEI Consultants (2016) equate this volume to 4 to 5 large municipal wells and posit that it is representative of a basin in equilibrium (e.g. “natural recharge from deep percolation, hydraulically connected rivers, and boundary subsurface inflows is in long-term equilibrium with active pumping and changes in hydrology”). The 4,000 ac-ft per year deficit is smaller than the 6,200 ac-ft per year and 19,000 ac-ft per year deficits predicted by the Sacramento County Integrated Groundwater and Surface water Model (SacIGSM) and the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM), respectively. Work is currently underway (2021) to update the estimate of deficit or equilibrium in order to create the basin groundwater sustainability plan.

Recharge processes in the SASb were assessed by RMC (2015). Results from the Sacramento Area Integrated Water Resources Model (SacIWRM) found higher recharge southwest of Folsom, where soils were classified as coarser, and in regions with extensive application of agricultural applied water and near the Cosumnes River (e.g., south of Elk Grove and between Grant Line Road and the Cosumnes river). Lower recharge was concentrated in urban centers around Elk Grove and on relatively low permeability soils. From a water balance perspective, the majority of the simulated recharge came from rivers and the combination of rainfall and applied water, providing 41% and 43% of the overall recharge, respectively; the remaining 16% of recharge was from subsurface flow, predominantly from the Delta. Notably, 30% of the recharge was from the Cosumnes River, and only 8% was from the American River (Figure 8). Stable isotope sampling of wells and surface waters also indicated higher recharge near surface water features. Their isotope analysis corroborated water level measurements showing that groundwater flow directions from the foothills were predominately toward the southwest and flow directions within the valley floor were toward pumping depressions located in the center of the basin. Away from the basins major surface water bodies (i.e. Sacramento, American, and Cosumnes rivers), their sampling found large portions of the basin had groundwater that was isotopically similar to local rainfall, and therefore was considered to be recharged from infiltration of local rainfall and seepage of storm water run-off in Laguna creek and other similar water courses. Isotopic signatures north of the Cosumnes river identified a transition zone between river seepage and groundwater recharged by local rainfall.

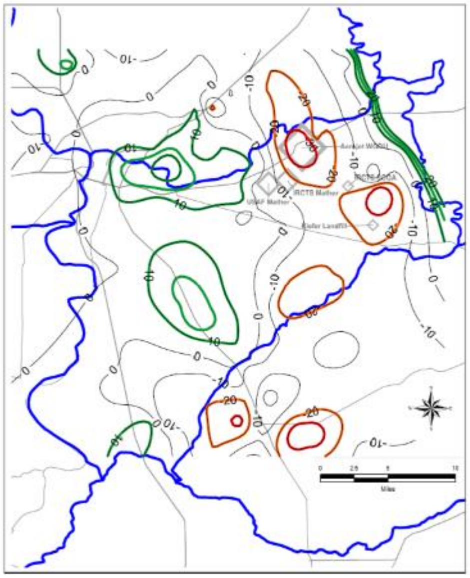


Figure 7. Difference in Fall 2005 to Fall 2015 groundwater level contours (Figure 2-26, GEI Consultants, 2016).

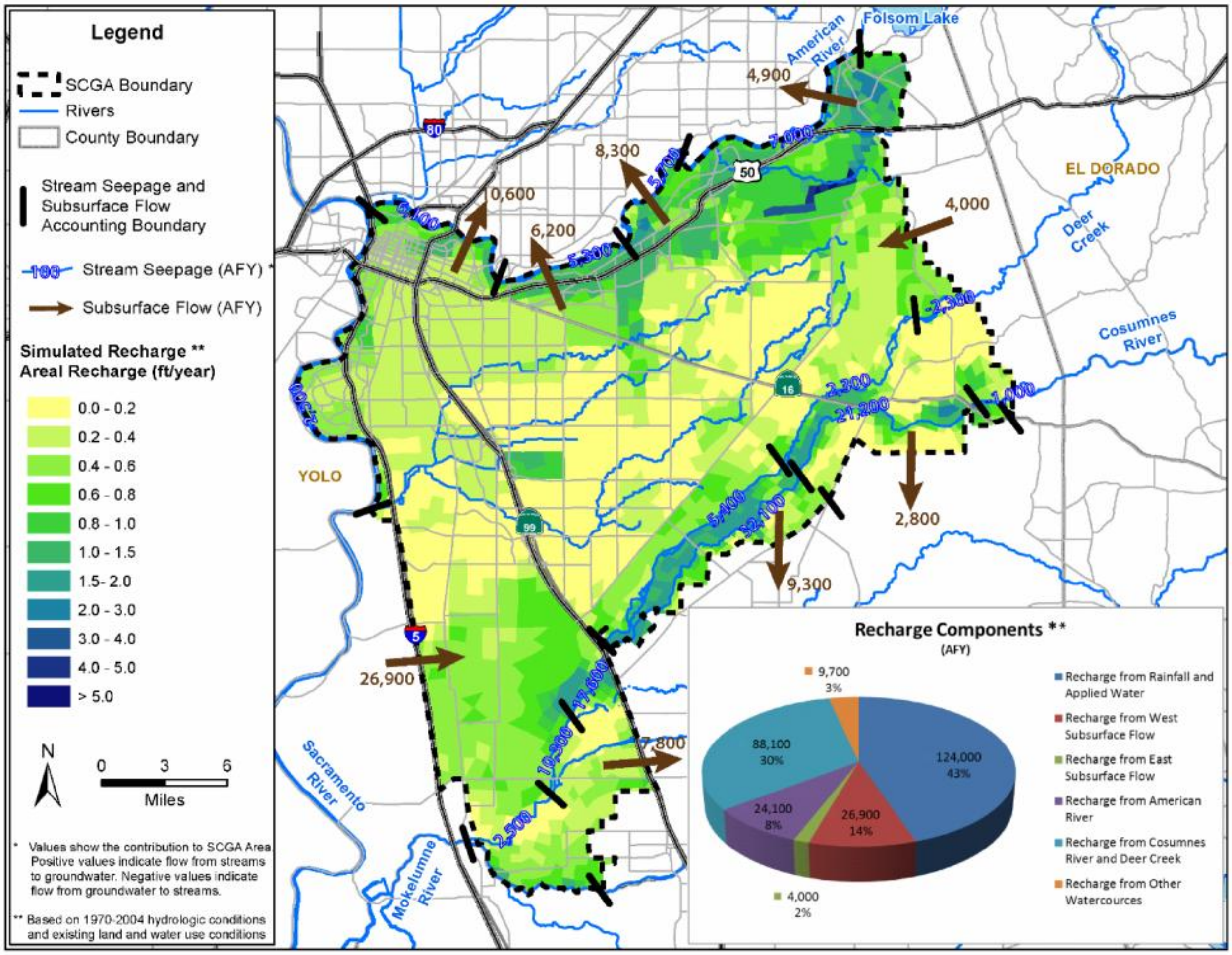


Figure 8. SASb recharge map (Figure 2, RMC, 2015).

Cosumnes Sub-basin

Monitoring of Cosumnes sub-basin groundwater levels trends shows fairly consistent spatial patterns have existed since the 1960's (Robertson-Bryan, Inc. & WRIME, 2011). Overall, wells near the Cosumnes river and the Delta show more stable groundwater levels, whereas wells away from the river are dominated by declining trends. The relative stability of wells near the river is considered to be due to the consistent source of surface water recharge (Robertson-Bryan, Inc. & WRIME, 2011). Outside the recharge influence of the Cosumnes river in the center of the valley floor, water levels have generally declined at long-term rates of 0.1-1.4 ft/yr (0.03-0.42 m/yr). Over the available period of monitoring, water levels in the valley floor declined 20 to 30 feet (6-9 m) from the mid- 1960's to about 1980 (~1 -2 ft/yr [0.3-0.6 m/yr]). During a wet period from 1980 to 1986, groundwater levels recovered 5 to 10 feet (1.5-3 m) but declined again by 10 to 15 feet (3-5 m) over the five-year 1987 drought. After the drought, much of the basin recovered on the order of 15 to 20 feet (5-6 m) by 2000 returning groundwater conditions to those observed in the mid-1980's. Groundwater levels declined again between 2000 and 2007, with an overall net decline between 10 and 50 feet (3 and 15 m) since 1960 in valley wells not influenced by Cosumnes river recharge. Water levels in the southeastern area have declined steadily from the beginning of their record in the mid-1980s to about 30 feet (9 m). As of fall 2018, depth to groundwater is highly variable across the basin ranging from less than 30 feet (9 m) bgs near the Delta influenced western boundary and in the highly variable eastern foothill region, to over 200 feet (61 m) bgs in the central portion of the valley floor (EKI, 2019) (Figure 9 and Figure 10).

Like Elk Grove, a cone of depression has persisted in the Cosumnes sub-basin near the city of Galt since the late 1960's. This depression acts as a hydraulic sink drawing recharge from the Cosumnes river and likely inter-basin flows from the SASb. Over time the depression has fluctuated and changed shape, and as of 2015 had elongated extending eastward with groundwater levels as deep as 90 feet (27 m) below msl (~160 ft [49 m] bgs).

Groundwater currently supports nearly 95 percent of all water demands in the Cosumnes sub-basin, which puts substantial pressure on the aquifer. (Robertson-Bryan, Inc. & WRIME, 2011). Despite the heavy reliance on groundwater, simulation using SacIGSM during different periods suggests annual storage changes are highly variable depending on hydrologic conditions. For example, the simulated 2000-2004 water balance showed a deficit of 11,900 ac-ft /year, whereas the water balance for 1980-2004 found annual groundwater storage increased 2,500 ac-ft /year, suggesting a degree of resiliency to hydrologic variability. Recent assessment by EKI (2019) comparing Fall 1999 and Fall 2018 groundwater levels found an average annual loss of storage of 10,200 ac-ft/year over this period, which is more consistent with the long-term measured declines in groundwater levels.

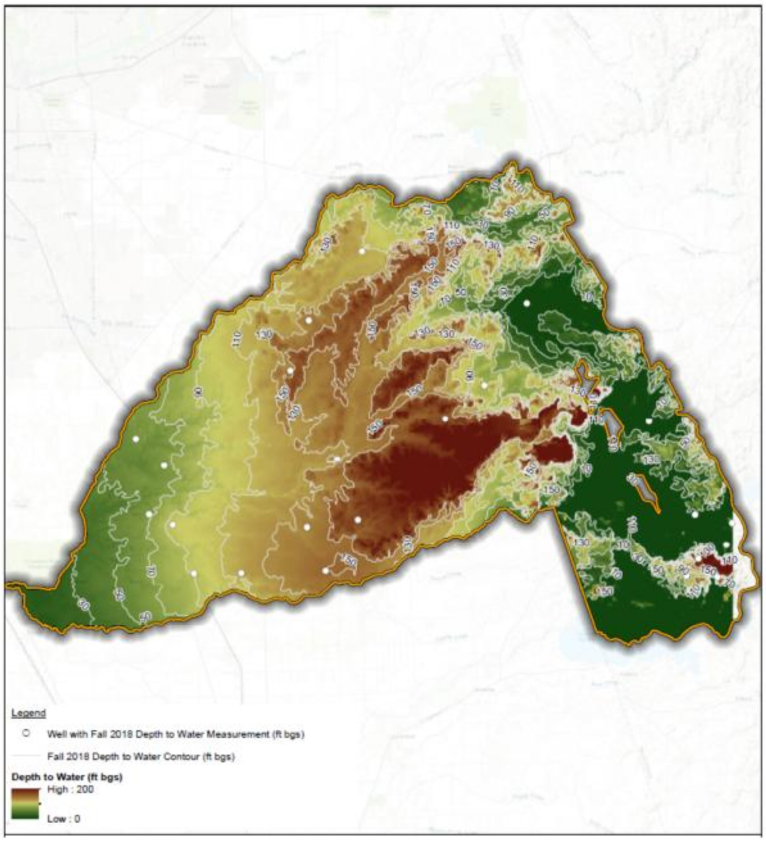


Figure 9. Cosumnes sub-basin 2018 depth to water (Figure GWC-4, EKI, 2019).

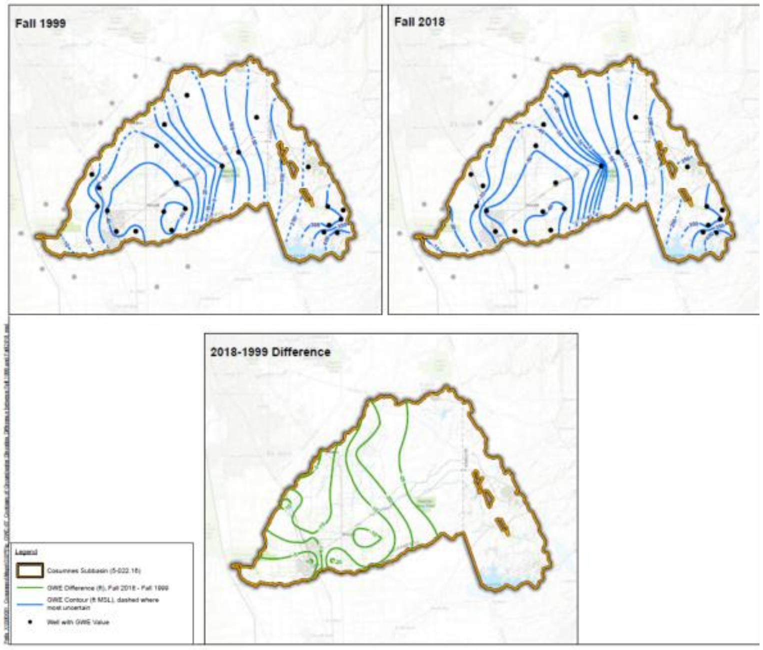


Figure 10. Difference in Fall 1999 to Fall 2018 groundwater level contours (Figure GWC-7, EKI, 2019).

Paleochannels

Cyclic Pleistocene aged glaciation in the American River drainage basin resulted in a series of migrations of the American river over large swaths of the valley floor (Meirovitz et al., 2017) (Figure 11). With each migration, a sequence of incision and deposition produced large incised-valley fill (IVF) deposits in the river's paleochannels that extend far into the Central Valley. These coarse-grained glacially derived sediments are an important source for groundwater flow conveyance. Several of the historic American River paleochannels were oriented southwest from Folsom toward the current position of the Cosumnes (Figure 12). Due to preferential flow along these pathways, hydraulic connections exist between the Cosumnes and regions far to the north and south that must be considered when managing groundwater in the study area (DWR, 1978; Meirovitz et al., 2017). The subsurface and cryptic nature of these deposits makes comprehensive mapping difficult.

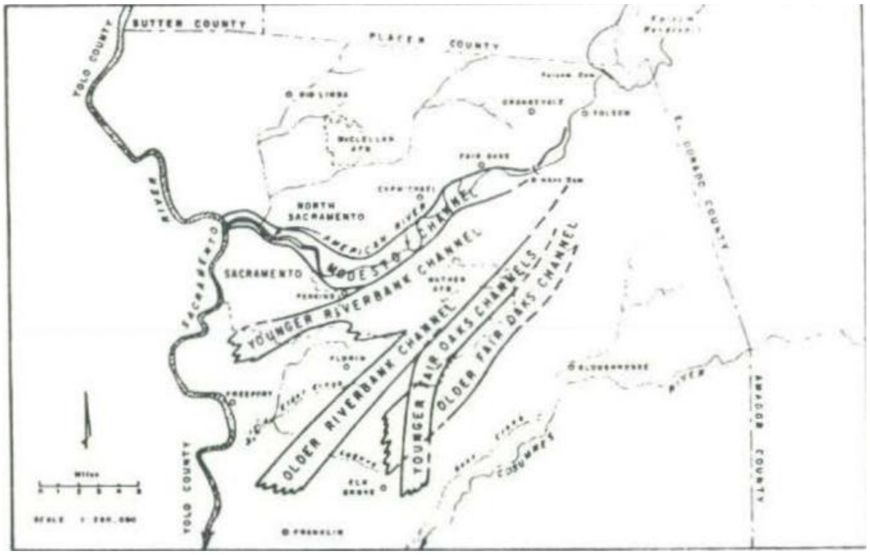


Figure 11. Pleistocene channel of the lower American river (Figure 2 Shlemon, 1974).

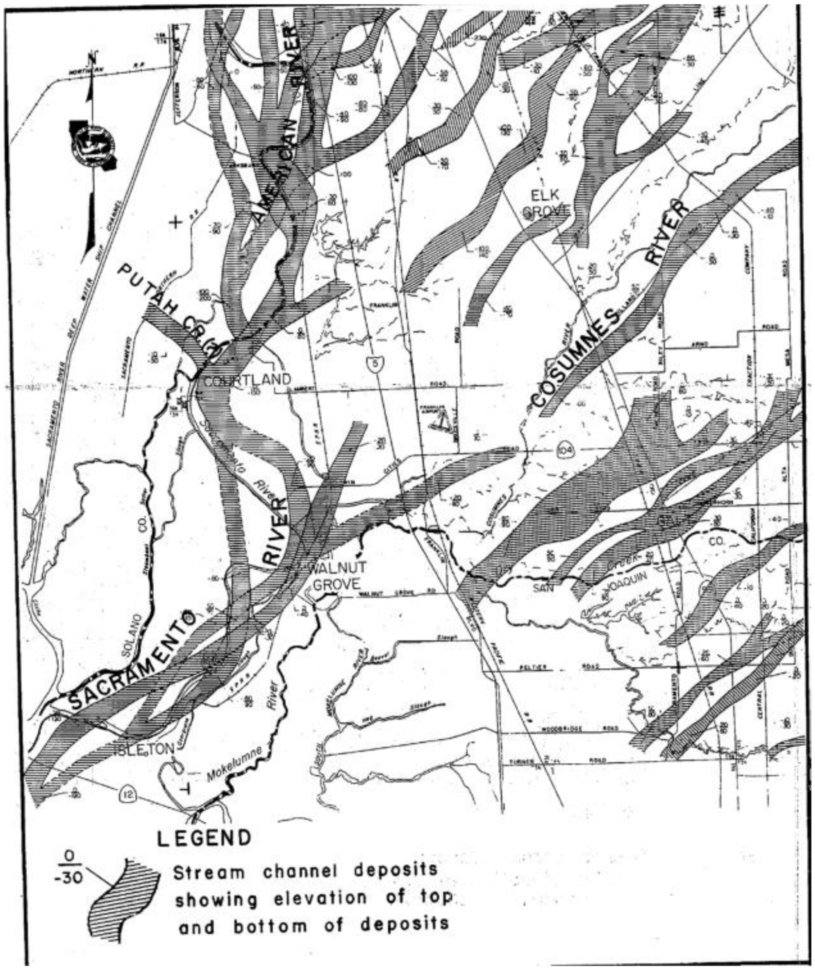


Figure 12. Areal distribution of superadjacent stream channel deposits (e.g. IVF) (Figure 3, Sheet 2 of 2, DWR, 1974).

Surface Water Use and Water Rights

Surface flows in the study area are affected by diversions and impoundments across the watershed. The State Water Resources Control Board (SWRCB) Water Rights Database lists 694 water rights holders for the Cosumnes Watershed. Some water rights are limited to certain times of the year, some are year-round.

Water rights include diversion rights and storage rights. Many storage water rights are "fill and spill". There is no diversion from the larger river; instead, the impoundment straddles a tributary and no flow reaches the river from that tributary until the impoundment is full. These impoundments can be small, such as one-half acre-foot, or large, such as Rancho Murieta's nearly 5600 ac-ft of storage.

In other cases, a water rights holder has both a diversion right and an impoundment right, with multiple rights on the same tributary. For example, El Dorado Irrigation District has diversion rights on Camp Creek at 600 ft^3/s, 43.8 ft^3/s, 24.2 ft^3/s, with 15000 and 9400 ac-ft of storage, and 27.1 ft^3/s and 30.7 ft^3/s on Sly Park Creek (Cosumnes tributaries) with 5400 and 7000 ac-ft storage.

The Cosumnes is considered a fully appropriated stream (FAS) from July 1st to October 31st. Similarly, the South Fork Cosumnes river is FAS from April 15th to October 31st, and Deer creek is FAS from May 1st to October 31st (SWRB Order WR 98-08).

Management of surface water diversion timing, efficiency improvements, conveyance evapotranspiration reduction, conjunctive use, and other strategies may offer opportunities to increase groundwater storage and improve base flows while still supporting municipal and agricultural beneficial uses.

2. SW-GW Interactions along the Lower Cosumnes River

Brief primer on SW-GW Interactions

In the most basic sense, the rate and direction of water movement from the channel bed to underlying porous media is controlled by the vertical hydraulic conductivity (K_v) of the riverbed, the geometry and thickness of the riverbed, and the hydraulic gradient (hydraulic head) between the river and the aquifer (Levy et al., 2018). In the case of a losing environment and all factors being equal, increases in K_v, a thinner channel bottom, and a stronger downward hydraulic gradient will intensify infiltration (seepage) into the aquifer. Alternately, when the head gradient is toward the stream, gaining conditions prevail and groundwater will discharge into the stream. Where the stream and groundwater are hydraulically disconnected (i.e. separated by an unsaturated zone), seepage is widely taken to not be influenced by the aquifer and becomes a function of streambed K_v, properties of the underlying aquifer materials, and water depth in the stream. The simplifying assumption that the underlying media is unsaturated is taken to be true in most cases due to more complicated flow dynamics under conditions of variably saturated flow (e.g. porous media is partially saturated and flow properties are highly non-linear) and that result from the presence of perched aquifers (Figure 13).

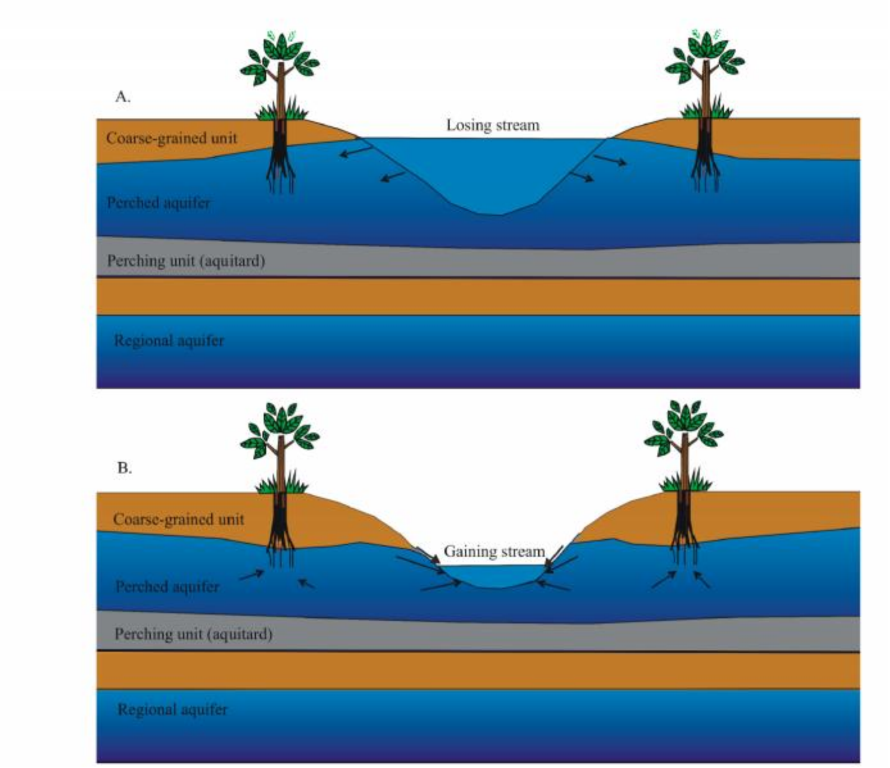


Figure 13. Stream/perched groundwater interaction under losing (a) and gaining (b) conditions (Figure 2.1 Niswonger, 2005).

Complexities in even the simplest SW-GW flow systems begin to arise due to several factors. For one, it is difficult to quantify streambed K_v as well as aquifer hydraulic conductivities, which can range in value over more than 12-13 orders of magnitude. Hydraulic conductivities are also highly spatially heterogeneous, and K_v values vary temporally as bed sediment composition evolves (e.g. low flow clogging, bio-clogging, siltation, and high flow scour) (Barlow & Leake, 2002; Levy et al., 2008). Aquifer properties will also evolve under conditions of variably saturated flow. Where layers or lenses of low-permeability sediments exist, the presence of perched saturated zones can form. Such perched zones can reduce seepage and even reverse gradients to promote water discharge to the river (Niswonger & Fogg, 2008). Alternately, preferential flow via connected pathways of highly permeable materials can rapidly transmit immense seepage losses over small portions of the riverbed (Fleckenstein et al., 2006). In addition to these factors, consideration and inclusion of evapotranspiration may be equally important when quantifying SW-GW fluxes (Min et al., 2020; Niswonger, 2005). Cumulatively, these dynamical and heterogeneous conditions at the river–aquifer interface contribute to high spatial and temporal variability in SW-GW fluxes (Fleckenstein et al., 2006; Frei et al., 2009).

As noted above, near river SW-GW interactions are strongly influenced by various scales of localized subsurface heterogeneity. Such heterogeneity is often described and stochastically represented by the arrangement of hydrofacies, which can be assigned variable conductivities amongst other physical properties. Spatial variability in hydrologic processes due to the organization of hydrofacies can result in localized mounding of GW or formation of perched water tables near the active channel bed and within the extent of paleochannels and associated floodplain surfaces (Niswonger & Fogg, 2008). These localized effects can serve to reduce or even reverse flow gradients between surface water and groundwater, and they have been documented to facilitate SW-GW interconnection in several Californian rivers thought to be disconnected from their regional GW tables, a list which includes the Cosumnes river (Fleckenstein et al., 2006; Niswonger 2005; Niswonger & Fogg, 2008).

The difficulty in representing the complex lithology of alluvial sediments along river channels means it is not uncommon for such conditions to be inaccurately quantified. For example, such connections could be missed by monitoring networks (e.g. wells) where observed GW levels instead measure heads of the deeper aquifer rather than water levels immediately below the river (Fleckenstein et al., 2006). Common groundwater or coupled surface-groundwater modeling strategies (e.g. those that use mean monthly flows, simplified river geometry, calibrated conductivities of bed, and uniform laterally extensive aquifers) have also been found to be inappropriate when considering the hydrogeologic and ecological dynamics of river-aquifer systems (Fleckenstein et al., 2006).

SW-GW Interactions along the Lower Cosumnes River

Study of SW-GW interactions along the Lower Cosumnes River has primarily been addressed in two ways: i) through data-driven approaches that include field measurement of streamflow, groundwater levels, seepage rates, sediment temperatures, soil moisture, and sedimentology; and ii) through numerical simulations. Numerical simulation approaches can be further distinguished based on whether simulations are designed to mimic field and background water management conditions with models calibrated to observed conditions or if simulations are more theoretical in nature using idealized study domains based on field conditions present in the study area.

Combining review of historical field measurements with a numerical groundwater-surface water model (IGSM), Mount et al. (2001) concluded that it was likely that the entire study area was connected to the primary aquifer (i.e. shallow unconfined aquifer) before the early 1940's. Under this condition, groundwater would discharge to the system at least during certain portions of the year (see also Fleckenstein et al., 2004). This finding was based on back extrapolation of historic well data and model simulation of baseline conditions with groundwater pumping set to zero (see No Pumping [S0] scenario Figure 14), thus representing a "quasi-pristine or natural pre-development groundwater condition". Both methods have uncertainty but provide a reasonable basis for the conclusion, especially in the absence of other historic records. Following the 1940's, the advent of increased groundwater production and extensive declines of regional groundwater levels (Section 1) brought about the process of decoupling of the river from the primary aquifer along much of the study area. Increased groundwater pumping in subsequent decades has exasperated this issue further, resulting in continued lowering of the regional water tables and increasing the aquifers disconnection from the river. These groundwater declines are suggested by Mount et al. (2001) and others to be responsible for declines in fall streamflows in the study area and the observed increase in low-flow and no-flow periods.

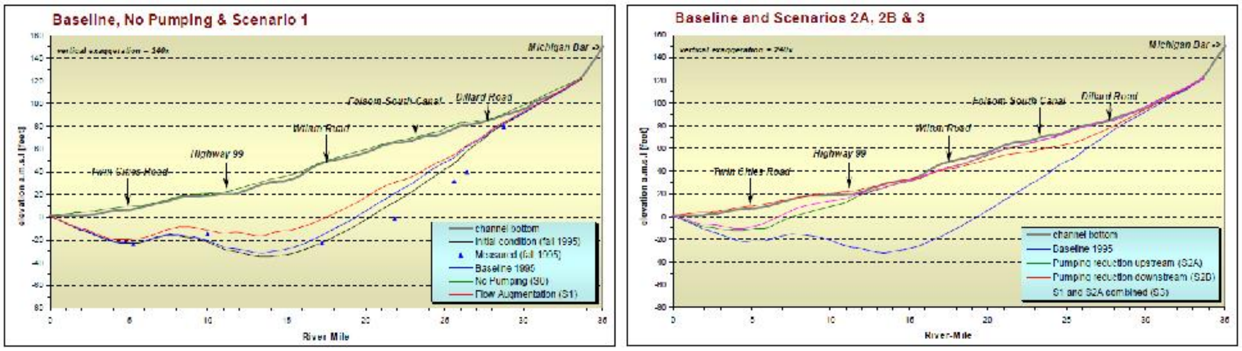


Figure 14. Measured, modeled, and simulated groundwater levels below river channel by Mount et al. (2001) (Figures 8 and 9). River miles may differ slightly from those used in this review.

Interestingly, in Mount's no-pumping simulation, 12-years were required for the MBH-MCC reach to transition to a net gaining reach, and even at the end of the simulation, the reach was net losing during the fall. This determination simply reflects the period required to raise water levels from the fall 1995 groundwater elevations that were used for the model's initial boundary condition. Over the 15-yr simulation period, the annualized water volumes necessary to overcome this deficit were estimated to be 166,000 ac-ft per year to partly reconnect the upper reaches of the river and ~250,000 ac-ft per year to reconnect the entire study area. These volumes are relatively close to the entire Water Forum sustainable yields for the SASb and Cosumnes sub-basin areas, respectively. Gaining conditions were achieved more rapidly (6-years) between MCC (RM 0) and Twin Cities Bridge (RM 5.5). While the no-pumping scenario reduced seepage and thus improved fall conditions, the fact the river was still losing during this period highlights the seasonal nature of potential groundwater discharge and the importance of accurate representation of seepage processes.

Comparisons of measured and modeled groundwater levels with streambed elevations have been another effective method for spatial characterization of SW-GW interactions in that study area and have shown varying levels of disconnection between the Cosumnes riverbed and underlying primary aquifer. Using well data from April 2000 to 2001, Mount et al. (2001) recorded groundwater to be 7-20 feet (2-6 m) below the channel near Dillard (RM 27.5), between 30-50 feet (9-15 m) below the channel from Meiss to Highway 99 (RM 11-25.5), and between 3-15 feet (1-5 m) below the channel from near Twin Cities Bridge (RM 5.5). Upstream of Dillard (RM 27.5-36), groundwater levels were within a few feet of the channel during the wet season, and levels were within 3-15 feet (1-5 m) of the channel downstream of Twin Cities Bridge (RM 5.5) (Figure 14). In contrast to the well comparison, shallow piezometers installed downstream of Twin Cities Bridge documented groundwater levels at or above the ground surface, thus reflecting the spatial heterogeneity of water levels and potential limitations of this kind of comparative analysis.

Ultimately, Mount et al. (2001) concluded that reaches upstream of Dillard (RM 27.5) and downstream of Twin Cities Bridge (RM 5.5) were hydraulically connected to the primary aquifer and likely received seasonal groundwater discharge. These locations were demarcated as “sensitive transition areas” where further lowering of groundwater levels could result in increased stream flow depletions. The mechanisms driving these connections were not explicitly addressed in the study, and better understanding of why connections still exist in these regions is a relevant topic for future study. Conjecturally, the relatively intact connection of the river with its floodplains could be a primary driver for these observations. Further, depth to the bottom of the basin is higher (~400 ft [122 m] bgs) along the upstream portions of the study area, and this area may receive higher relative quantities of mountain block recharge, which combined with connections to the floodplain could facilitate filling of the aquifer and thus more stable groundwater levels.

The analysis of Mount et al. (2001) is now nearly two decades old and groundwater elevations have recovered in certain portions of the basin. However, updated analyses of current disconnections and volumes needed to reconnect the river are generally lacking. Such information is likely to emerge as part of the ongoing SGMA process. For instance, EKI (2019) in assessing the presence of interconnected surface waters in the Cosumnes sub-basin as part of the Cosumnes GSP made a preliminary conclusion that none of the sub-basins surface waters were interconnected. This determination was partially based on comparison of stage measurement at the MBH and MCC gage sites with nearby groundwater wells showed groundwater levels were 100 feet (30 m) and 15-20 feet (5-6 m) below river stage, respectively. Comments from the Cosumnes Surface Water Advisory Group (SWAG) about the adequacy of EKIs analysis were provided in September 2019, and the SWAG are working with EKI and Cosumnes GSAs to improve the analysis. Preliminary analysis of interconnected surface waters in the SASb as part of SGMA is currently employing similar but more detailed approaches than Mount et al. (2001), whereby streambed profiles are being compared to a series of interpolated groundwater levels representing 2005-2019 conditions (personal communication LWA, 2021). Preliminary results using a threshold of groundwater to be within 30 feet (10 m) of the streambed (i.e. assumed depth of saturated zone that accounts for connection under losing conditions) suggest the river is at least seasonally interconnected from the confluence with the Mokelumne to just above the confluence with Deer Creek (RM 0-12).

As discussed in the "primer" section above, geologic complexity of the Cosumnes fluvial-riparian environment can induce high localized variability of groundwater conditions that may not be accurately represented with certain numerical models or groundwater measurements (such as those employed by Mount et al., 2001 and others [e.g. MHW, 2006; GEI Consultants, 2016]). Such uncertainty is exemplified when comparing the findings from these references with simulations that include higher resolution representations of aquifer heterogeneity (e.g. Fleckenstein et al. 2006; Niswonger, 2005[7]). For instance, conducting simulations with six different but equally likely geostatistical simulations of aquifer heterogeneity, Fleckenstein et al. (2006) identified spatially and temporally varying locations of local reconnection between the river bed and groundwater levels (Figure 15 and Figure 16). Whether these connections were with the primary aquifer or due to formation of shallow perched aquifers is unclear. While their simulated groundwater levels had large local variability between geologic realizations, most connections occurred during the wet season, whereas dry-season connections generally occurred in similar locations to those identified by Mount et al., (2001). In addition to the up- and- downstream ends of the study area, wet season connections were clustered between Twin Cities Bridge and Wilton (RM 5.5-17.3) and were conjectured to even promote gaining conditions. These findings have been corroborated by physical observations of shallow local saturated zones below the river channel (Niswonger, 2005). Given the time period of SW-GW connections identified by Fleckenstein et al. (2006), as well as those discussed by Mount et al. (2001), it is unclear if groundwater discharge could contribute to dry-season flows, which is generally not supported by observed low-flow conditions. However, identification and better understanding of these connected zones is relevant due to their potential to reduce seepage losses, contribute to wet-season and possibly dry-season baseflow, and provide benefits for riparian vegetation and groundwater dependent ecosystems.

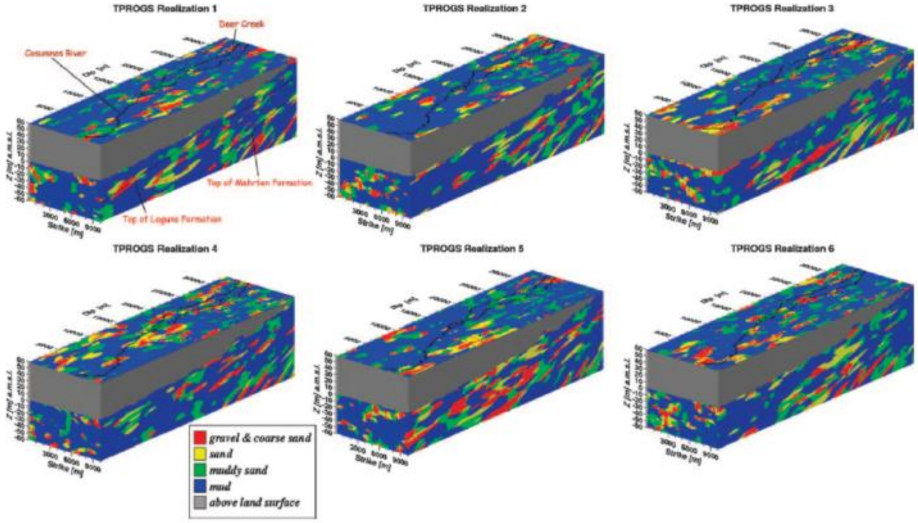


Figure 15. Geologic realizations from Fleckenstein et al. (2006) (Figure 3).

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[7] Note information presented by Niswonger (2005) is similar in nature to what is contained in Niswonger and Fogg (2008).

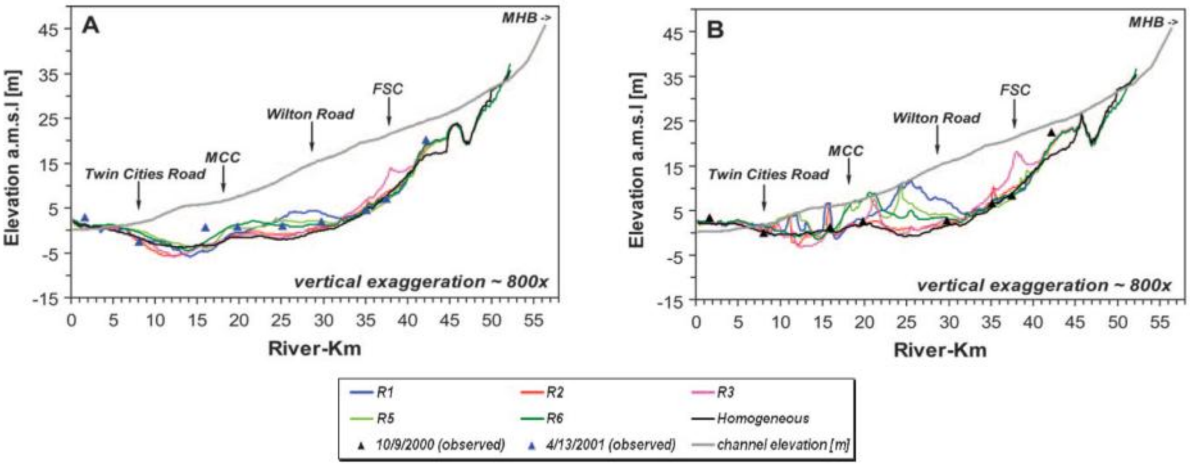


Figure 16. Simulated dry season (a) and wet season (b) groundwater levels of Fleckenstein et al., (2001) from different geologic realizations (Figure 11). River miles may differ slightly from those used in this review.

Another key finding of Fleckenstein et al. (2006) was recognition of the influence of geologic heterogeneity on spatial variability of river seepage. In creating different but all equally plausible geologic realizations, they showed that large proportions of total seepage were consistently conveyed within a few localized areas of high conductivity (i.e. 50% of total seepage was recharged by ~23% of the channel across geologic realizations) (Figure 17). Even more pronounced findings were obtained by Frei et al. (2009) when simulating an idealized river domain based on the Cosumnes using geologic properties obtained from Fleckenstein et al. (2006). In their study, 98% of total seepage was conveyed by “preferential flow zones” that occupied 50% of the channel. Awareness that seepage may be highly concentrated can have management implications. For instance, if it is possible to identify these high conductivity pathways, they could serve as locations for spatially focused recharge to increase local groundwater levels. Alternatively, such areas may wish to be avoided in favor of siting recharge where it is likely to promote formation of perched aquifer conditions, which could provide at least seasonal contributions to baseflows without restoring regional groundwater levels. Regardless, increased understanding and ability to quantify spatial and temporal variability of seepage losses in the study area is important when considering projects aimed at flow management.

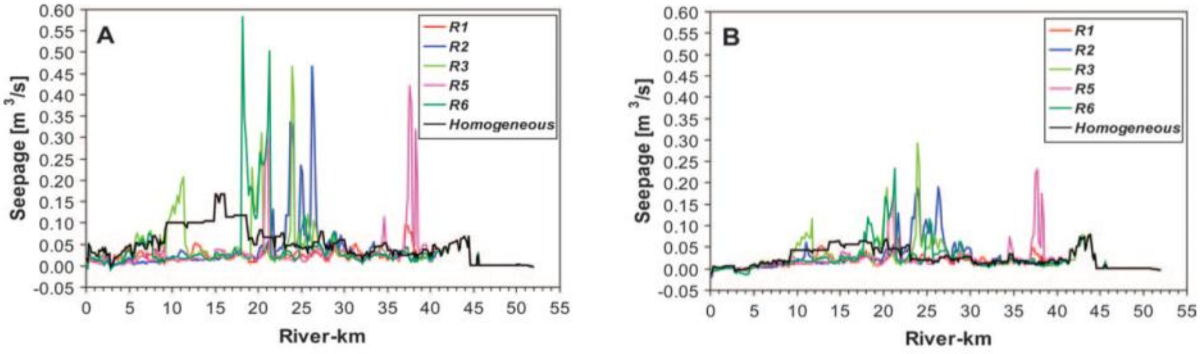


Figure 17. Simulated seepage rates of Fleckenstein et al., (2001) from February 28, 2000 and April 14, 2000 (Figure 10). River miles may differ slightly from those used in this review.

No discussion of Cosumnes SW-GW interactions is complete without considering the influence of perched aquifers, which are covered in depth by the collective works of Niswonger (Niswonger, 2005; Niswonger & Fogg, 2008). Perched aquifer conditions occur where low conductivity sediments underlie higher conductivity sediments, and as discussed in the primer section, perched aquifers can diminish seepage losses and support gaining stream conditions. Where perched layers extend laterally from the stream corridor, perched water may also be vital to maintaining saturation of the riparian root zone. Even in the absence of providing groundwater discharge to the stream, hyporheic flows from perched aquifers can provide aeration of spawning habitats and drive biogeochemical cycling.

Under idealized circumstances, values simulated or reported by Niswonger show discharge from perched aquifers to streams could be as large as 1.5 ft^3/s per mile (0.04 m^3/s per mile), which are roughly proportional to estimates of Cosumnes seepage rates. However, the magnitude and duration of perched groundwater contributions is sensitive to properties of the streambed and underlying unsaturated porous media as well as geologic structure. Niswonger's studies show that a threshold condition for the ratio between the hydraulic conductivity of coarse streambed sediments to that of fine underlying sediments of 200 is required to create perching conditions capable of producing baseflows. Simulations in an idealized 2000 m long stream segment based on the Cosumnes River near Highway 99 show that regardless of model parameters, dry-season perched groundwater discharges rapidly dissipate, often reducing to zero over a period of a few days to a few weeks. Larger baseflow contributions were found to be sustained for periods up to about 2-3 months after the cessation of bankfull-flows (e.g. mid-June) where, everything else being equal, coarse sediment hydraulic conductivity was higher. Even under these best-case scenarios, simulations show that discharges only on the order of 0.6 ft^3/s (<0.02 m^3/s) would be expected during the first month after high flows, with even smaller contributions thereafter (Figure 18). As shown by Niswonger and others, geologic heterogeneity strongly controls SW-GW interactions, such that perched aquifers and associated discharge in one region may seep into the subsurface downstream where perched layers are absent (Figure 19). Given the magnitude and spatially heterogeneous nature of these discharges, the total role of perched aquifer discharges in contributing to or potentially managing dry-season baseflows remains unclear. That said, perched aquifers undoubtedly provided benefits to the study areas through sustaining ephemeral pools, decreasing seepage losses, and contributing to wet-season baseflows.

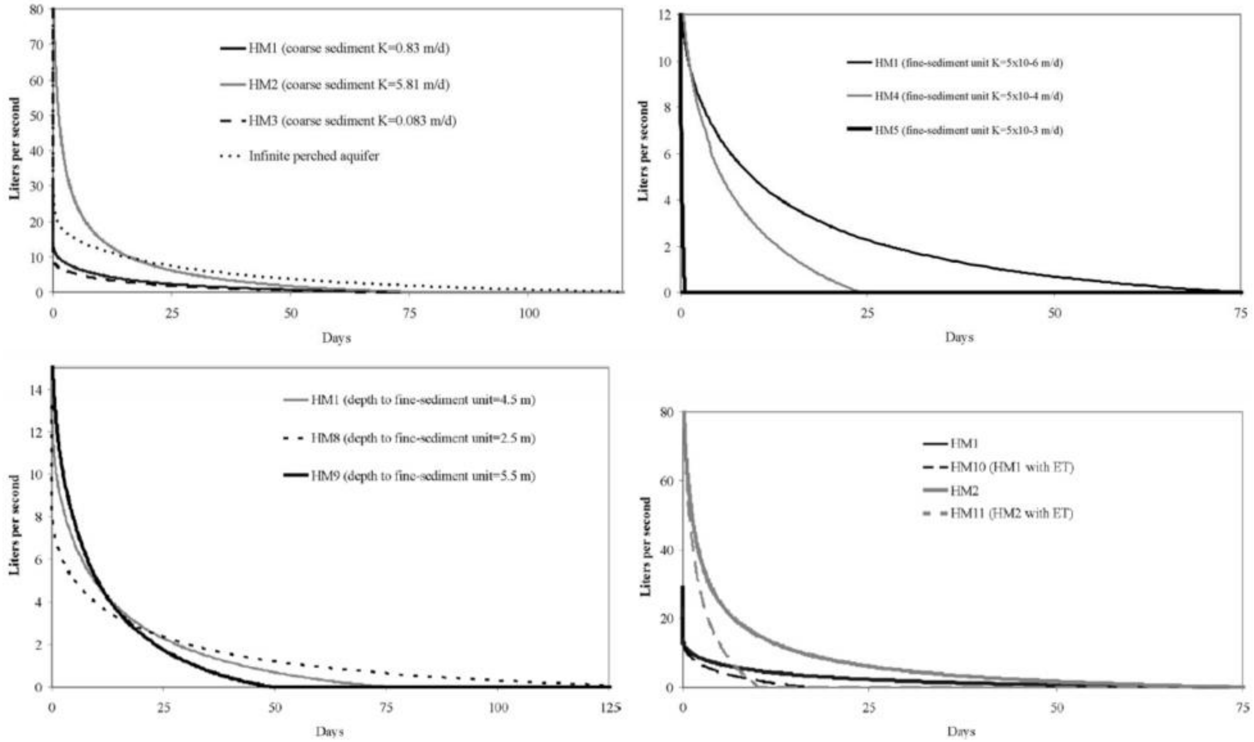
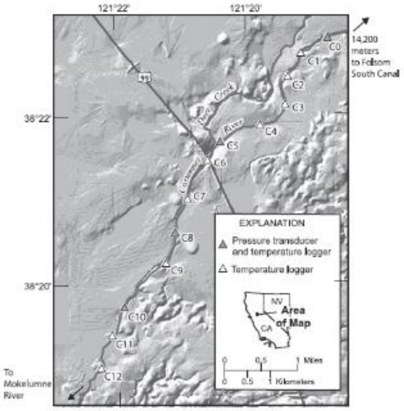


Figure 18. Perched-groundwater discharge to stream for various river and aquifer conditions (Figures 5, 6, 9, and 10 Niswonger and Fogg, 2008).



Base from U.S. Geological survey digital data, 1:100,000, 2006
Universal Transverse Mercator projection, zone 10
North American Datum of 1983
Shaded-relief base from 10-meter National Elevation Data, 2007,
sun-illumination from northwest at 30 degrees above horizon

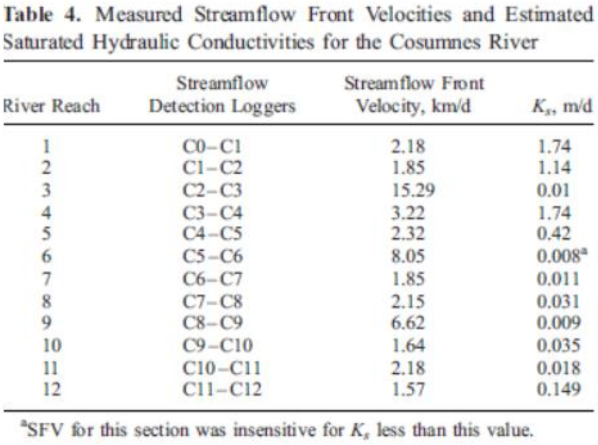


Table 4. Measured Streamflow Front Velocities and Estimated Saturated Hydraulic Conductivities for the Cosumnes River

River Reach	Streamflow Detection Loggers	Streamflow Front Velocity, km/d	K_s, m/d
1	C0–C1	2.18	1.74
2	C1–C2	1.85	1.14
3	C2–C3	15.29	0.01
4	C3–C4	3.22	1.74
5	C4–C5	2.32	0.42
6	C5–C6	8.05	0.008[a]
7	C6–C7	1.85	0.011
8	C7–C8	2.15	0.031
9	C8–C9	6.62	0.009
10	C9–C10	1.64	0.035
11	C10–C11	2.18	0.018
12	C11–C12	1.57	0.149

[a] SFV for this section was insensitive for K_s less than this value.

Figure 19. Spatial variation in streambed conductivity may create physical conditions that promote longitudinally discontinuous gaining and losing conditions (Figure 4 and Table 4 Niswonger et al., 2008).

Another key contribution from Niswonger's studies was inclusion of ET from riparian vegetation in groundwater-surface water model simulations, which showed ET could further reduce perched groundwater discharge by upwards of 30-60% under certain physical circumstances. Notably, in model domains that included channel incision, riparian ET did not affect perched aquifer discharge as the root zone was decoupled from the perched groundwater table. As discussed in Section 1 above, large portions of the Cosumnes river are deeply incised, creating a complex response with regard to streamflow-primary aquifer-perched aquifer-riparian ET dynamics, the interactions of which must be considered when managing flows (e.g. riparian ET may not play an additional role in downstream dry-season losses or diminish perched groundwater discharge, but due to the role of channel incision in overall lowering of groundwater tables, this vegetation could become increasingly stressed).

Lastly, various simulations have been conducted to understand the response of SW-GW interactions to different management scenarios in the study area (Anderson et al., 2004; GEI Consultants, 2016; Fleckenstein et al., 2004; MHW, 2006; Mount et al., 2001; Robertson-Bryan, Inc. & WRIME, 2011). A complete review of these simulations is outside the scope of this effort, but a few key takeaways form these efforts are listed. Mount et al. (2001) present a three-part strategy to improving baseflow conditions that includes: augmentation of surface flows, management of groundwater pumping, and restoration of natural flood regimes. A flow augmentation pilot project was conducted in the study area in fall of 2005 that successfully pre-wet the channel using imported water in anticipation of natural connection (Niswonger et al., 2008; Robertson-Bryan Inc., 2006c). Additional pre-wetting operations have been proposed by the Cosumnes GSAs as a potential SGMA project and management action.

3. Recharge Processes and Potential along the Lower Cosumnes River

Similar to SW-GW interactions, recharge along the lower Cosumnes river has also been studied using both data-driven and numerical simulation approaches.

The physical processes and theoretical potential for MAR in the study area are best addressed in the work of Maples et al. (2019, 2020), Sager (2012), and Lui (2014). Notably, these efforts do not necessarily relate to actual water volumes that might be available for recharge, and therefore are better utilized as proof-of-concepts to demonstrate the influence of geologic heterogeneity on MAR dynamics in hypothetical but physically realistic domains based on study area conditions. Moreover, these studies typically do not always consider several surface processes that influence real-world MAR feasibility and dynamics, including topographic site limitations, evaporative losses, and clogging effects (Maples et al. 2019).

Employing a numerical groundwater model to simulate variably-saturated water flow dynamics, Maples et al. (2019) found recharge potential to vary over nearly two orders of magnitude between five 'regional-scale' MAR sites cited in the study area (Figure 20). The observed variability was highly dependent on subsurface geologic architecture, whereby the occurrence of interconnected coarse texture recharge pathways were able to accommodate rapid high-volume MAR and propagate increases in hydraulic head over several miles through the semi-confined aquifer system. This finding supports siting MAR over locations with high conductance pathways such as those overlying IVF deposits that have a higher probability of increased recharge rates compared to the rest of the landscape. Maples et al. (2020), expanding on this concept, identified a geological proxy parameter (GPP) with potential to indicate relative MAR potential across the landscape. The identified GPP was the linear combination of K_{geom} and depth to groundwater, where K_{geom} is the up-scaled geometric medium of hydraulic conductivities of aquifer materials in a vertical column from the ground surface to the water table. Both studies also warn about the sole use of surface metrics (i.e. soil properties) in the absence of deeper subsurface geologic heterogeneity when inferring recharge potential. Results from Maples's work have been used to produce preliminary estimates of recharge rates for a large portion of the study area (Conservation Fund, unpublished). Coupling these data with other factors covered in this review (i.e. potential for perched aquifers, depth to current groundwater levels, riverbed seepage rates) and logistic and constructability considerations are recommended when planning MAR projects.

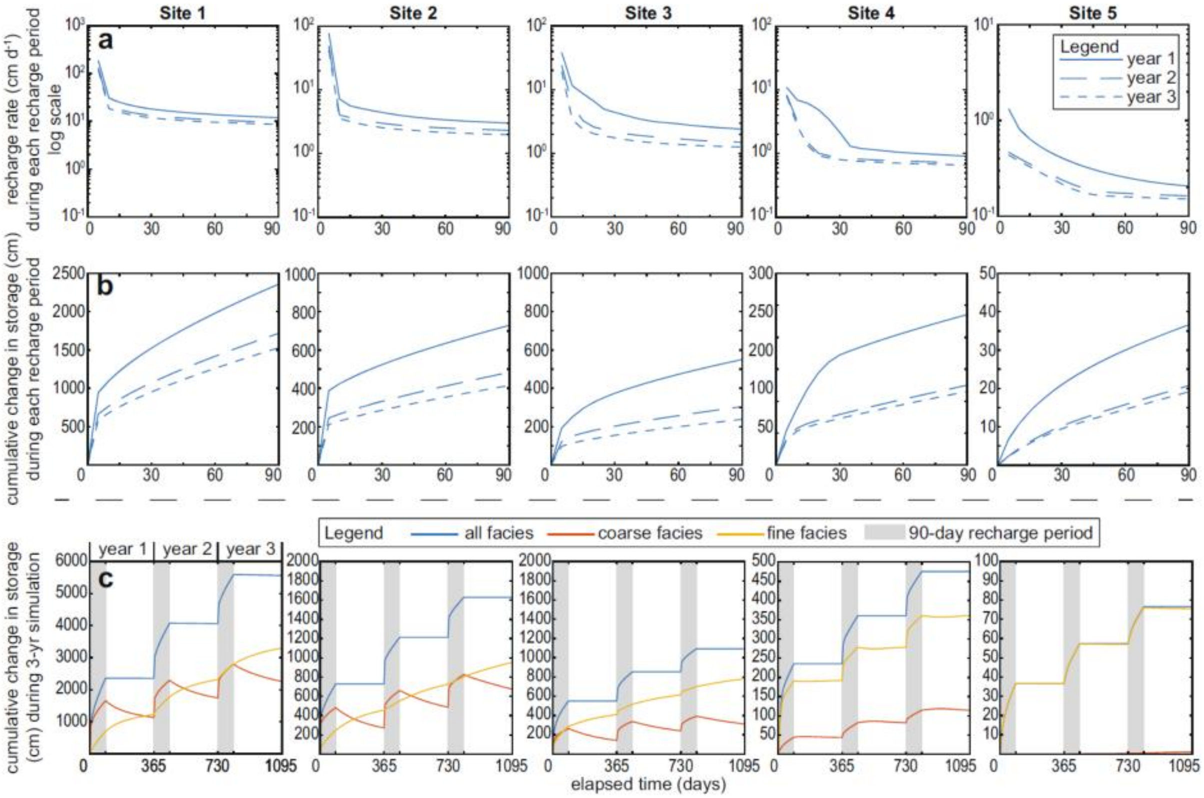


Figure 20. Simulated recharge rates (a), cumulative change-in-storage (b), and multi-year cumulative change in storage at five MAR sites (Figure 11 Maples et al. 2019).

MAR potential in the study area was also addressed by Sager (2012) using a numerical groundwater model in a hypothetic domain based on the Cosumnes river-aquifer system. The key outcome of their model simulations was the theoretically large volumes of water that could be recharged to the system. For example, they found the required volume of net annual recharge identified by Mount et al. (2001) to reconnect the system[8] could be recovered through flooding between 33,360-65,480 acres (135-265 km^2) with 3.2 feet (1 m) of water for 10 days per year[9]. Smaller areas were required for longer inundation durations or by targeting MAR in areas with connected high conductance recharge pathways (e.g. the minimum area identified was of 13,340 acres [54 km^2] with a 60 day inundation duration). For context, the area of the mapped FEMA 100-yr flood between MHB and MCC is approximately 21,600 acres (87 km^2) and is approximately 20,700 acres (84 km^2) from MCC to RM 2 with an approximate inundation duration of 42 days (Booth et al., 2006). Not accounting for depth of flooding, even this low-frequency event may not make-up the annual groundwater deficit according to recharge estimates by Sager (2012) (see

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[8] 166,000-250,000 ac-ft/yr

[9] To reconnect the river with the primary aquifer this would have to occur seven to fifteen years in a row.

Table 5 in Section 6). This conclusion is corroborated by the modeling efforts of Lui (2014), who used the extents, depths, and duration estimates for the 3.5, 10, and 100-year floods from previous 2D hydrodynamic floodplain modeling in a numerical groundwater model to simulate recharge for these events for the area downstream of Highway 99. Total simulated groundwater recharge from these events was 12,150 ac-ft, 19,440 ac-ft, and 25,110 ac-ft, respectively (7, 12, and 15% of the minimum required amount of Mount et al, [2001]). Thus, the feasibility of MAR to make up the annual recharge required to reconnect the river with the primary aquifer over the entire study area appears unrealistic in the short-term without significant pumping reductions and other management actions.

A different approach to assessing MAR potential in the study area is presented by Gailey et al. (2019). This study employs a hydroeconomic simulation-optimization scheme to evaluate the use of on-farm MAR and associated changes in groundwater storage and stream flow under different conditions of water availability and application. Model physics (groundwater and surface water flow) are based on a groundwater simulation model (C2VSIM) and include a number of simplifying assumptions. Water for MAR was assumed to be provided through reoperation of the Folsom Reservoir with delivery through Folsom South Canal and other local infrastructure (i.e. conveyance of available water to fields was not constrained). Folsom reservoir operations were studied extensively by Goharian et al. (2020) to understand the timing and volumes of water that might be available for MAR, taking into account the various water rights and environmental water requirements of the system. They concluded that over the 1922-2002 period between 307-706 thousand ac-ft (TAF) of water would be available annually during the extended winter period (November- March), which coincides with the recharge period using by Gailey. Accounting for Delta flow requirements, Goharian et al. (2020) report more general annual expected value for extended winter water availability of 308 TAF. Over the hydroeconomic simulation's 20-year period (1983-2003 conditions), Gailey et al. (2019) estimated that a maximum of 3,921 TAF of water could be recharged if all 140,000 acres of private cropland available in the their study site were used (average of 196 TAF/yr). This estimate was unconstrained by economic considerations, and notably only 62% went into groundwater storage with 18% exiting to surface waters and 20% leaving the study area (Figure 21). Inclusion of economic constraints (i.e. variable funding levels to rent private land for MAR) reduced total recharge volumes. At the minimum funding level of $500,000, total recharge was 937 TAF with similar partitioning to groundwater, surface water, and out-of-basin losses as above. At the maximum funding level of $120,000,000, the outputs were the same as the unconstrained version. Notably, results from the unconstrained model found recharge volumes were able to provide enough baseflow to the Cosumnes river to maintain flow throughout the 20-year simulation except during the 1987-1992 drought.

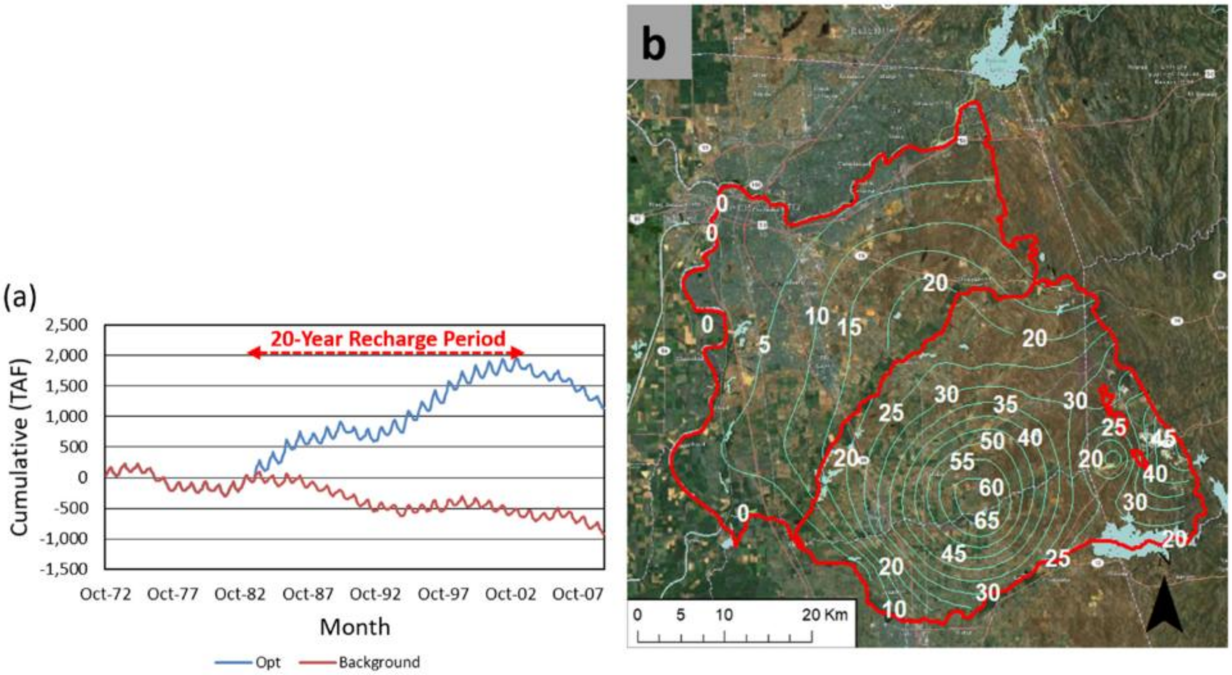

Figure 21. Simulated change in groundwater storage (a) and total change in groundwater levels at end of simulation period (b) using all available cropland for MAR (Figure 14 Gailey et al., 2019).

Beyond model simulations, Yoder (2018) estimated annual and event based recharge to the shallow groundwater aquifer underlying the Oneto–Denier site (RM 7) from 2013-2017 based on detailed measurements of shallow groundwater levels and applying a mass balance approach. Recharge was estimated both pre- and post-levee breach to understand the benefits of onsite levee breach restoration. Post-breach recharge volumes for the same upstream discharge were between 132-192% of pre-restoration volumes demonstrating the potential for levee removal to cause a significant upward shift in shallow aquifer recharge rates. Over the ~ 0.67 mi^2 (1.74 km^2) sampling area, a total depth of water between 0.79 and 3.4 ft (0.24-1.04 m) was recharged annually. This depth equated to total annual recharge volumes ranging between 316.2 (± 98.1) to 1,467.4 (± 458.9) acre-feet (ac-ft) with a tendency for higher recharge during wet years.

Recharge project feasibility is partly dependent on the rate water can percolate into the ground, as well as depth to groundwater (RMC, 2016). Where depth to water is large, the aquifer can support high volumes of water, otherwise storage may be limited. Percolation rates may also not be constant and are typically higher at the beginning of recharge season. Depending on recharge facilities, maintenance may be required to ensure continued recharge (e.g. recharge ponds require frequent cleaning) (RMC, 2016).

Groundwater Sustainability Agencies and their partners in both the SASb and Cosumnes sub-basin are contemplating a variety of recharge and demand side management strategies, including floodplain re-connection/between levee recharge, in lieu recharge using recycled water, water transfer to dry wells, agricultural field flooding, fallowing of annual crops, and so on.

For example, Omochumne-Hartnell Water District (OHWD) has constructed an off season irrigation project on vineyard land near RM 20. The project diverts winter flows that meet USFWS and CA Department of Fish and Wildlife diversion criteria in compliance with a State Waterboard Temporary Stormwater Diversion Permit (SWRCB, 2020). Leveraging existing studies, infiltration rates were estimated to be between 6-8 inch/day or more. Overall the project posits it will increase local groundwater levels 2-5 feet over the next 10 years with potential benefits to SW-GW interactions.

The proposed Sacramento Regional County Sanitation District (Regional San) Harvest Water Project involves conveying up to 50,000 ac-ft/yr of recycled water from the Sacramento Regional Wastewater Treatment Plant (SRWTP) to up to 16,000 acres of irrigated lands in the southwest portion of the SASb and 400 acres of managed wetlands within the South Stone Lake area of the NWR (RMC, 2016). Current groundwater levels at the proposed recharge site are approximately 10 to 30 feet below msl. Results of groundwater modeling using SacIWRM by RMC (2016) indicated that over the project's lifespan (20 years) the project will produce a net increase of groundwater storage between 379,000 and 533,000 ac-ft depending on which program elements are implemented. This is projected to increase groundwater levels by approximately 20 to 25 feet in the center of the proposed irrigation area (located directly northwest of Twin Cities Bridge), with commiserate increases in groundwater levels upwards of 10 to 15 feet along the lower portions of the study area (RM 5.5 – 11) (Figure 22). Recharge rates within the project area were also estimated at 6-8 inch/day.

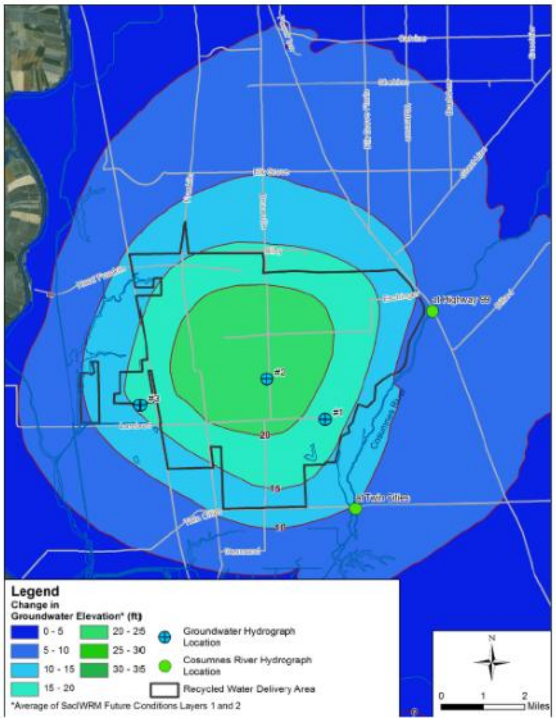

Figure 22. Simulated change in groundwater levels with Harvest Water Project (Figure 3.10-6 RMC, 2016).

4. Data Gaps

Data gaps and recommendations for further areas of research identified in this study are listed below:

- Given the wide range of estimates for fish passage, additional study may be warranted to better constrain necessary passage requirements. Further evaluation should also be conducted to better understand the constraints of the current flow regime relative to the range of passage requirements.
- Updated analysis on the spatial and temporal extent of SW-GW connections and current estimates of the volume of water required to re-establish connection of the river with the primary aquifer. This is expected to be completed as part of the SGMA process.
- Better understanding of the mechanism driving the relatively persistent SW-GW connections in the upstream and downstream portions of the study area. This may be completed as part of the SGMA process.
- Continued improvement to understanding the role of ET in dry-season flow losses.
- Spatially explicit mapping of the depth of the saturated zone below the river.
- Field confirmation of estimated and simulated floodplain recharge rates. This is expected as the proposed recharge projects go into operation.
- Continued field observation and numerical modeling to quantify the cumulative benefits of floodplain restoration and MAR, especially as it pertains to influencing dry-season and wet-season baseflows.
- Continued field observation and numerical modeling to better understand the water balance of floodplain recharge/MAR focused on quantifying the magnitude and variability of relative proportions of water lost to ET, that infiltrates into perched and shallow unconfined aquifers and eventually into the deeper semi-confined to confined aquifers, and that may be conveyed as shallow-subsurface flow back to the river system as well as the fate of such return flows.
- Better understanding of the impact of channel incision and levee construction on reduced floodplain recharge and associated declines in groundwater levels.
- Better understanding of methods to manage perched aquifers for ecological benefits.

5. Annotated Bibliography

This section provides brief annotations for the key literature reviewed as part of this study and is generally limited to resources specifically studying the Cosumnes river-aquifer system. Annotations generally focus on how resources relate to the goals of the study and CEFF objectives.

SW-GW Interactions

Anderson, M. L., Chen, Z. Q., and Kavvas, M. L. (2004). ‘‘Modeling low flows on the Cosumnes River.’’ J. Hydrol. Eng., 9(2), 126–134.

The authors employ numerical and analytical solutions for the one-dimensional diffusion wave equations coupled with a two seepage routing routines based on the Green and Ampt infiltration and a head-based seepage routine to simulate low flow conditions between MHB and MCC. Longitudinal seepage processes are explored with estimates on total seepage rates and minimum MHB flows required to provide conditions that facilitate fish passage at MCC based on 0.6 ft (0.18 m) depth requirement. Minimum pulse flows are also addressed and resultant requirements are compared to the historic flow record to characterize volumetric requirements to make up differences.

Bush, N.J. (2006). Natural water chemistry and vertical gradient in the hyporheic zone of the Cosumnes River near Sacramento, California, Masters thesis, 203 pp., California State University, Sacramento.

The author summarizes finding from a 2002-2003 field campaign just downstream of Highway 16 that included measuring vertical hydraulic gradients, seepage rates, and water chemistry. The potential for perched aquifers is discussed, and findings are related to spawning requirements. The main contribution is the record of physical measurements.

Fleckenstein J, Anderson M, Fogg G, Mount J, (2004). Managing Surface Water-Groundwater to Restore Fall Flows in the Cosumnes River. Journal of Water Resources Planning and Management 130(4): 301-310. doi: 10.1061/(ASCE)0733-9496(2004)130:4(301)

Similar materials to those presented by Mount et al. 2001 with only minor differences in values. Primary difference is level of detail and this resource having undergone peer-review.

Fleckenstein JH, Niswonger RG, Fogg GE, (2006). River-Aquifer Interactions, Geologic Heterogeneity, and Low Flow Management. Ground Water 44(6): 837-853. https://doi.org/10.1111/j.1745-6584.2006.00190.x

This critical study addresses the role of how textural heterogeneity of the Cosumnes river-aquifer system alluvial system influences river seepage and low flows. Conditional sequential indicator simulations (SIS) based on Markov chain models (geostatistical model) of transition probabilities of hydrofacies (geologic structure) were used to generate six different but equally probable geologic realizations that were incorporated into an existing regional groundwater model (i.e. the model used by Mount et al. 2004 and Fleckenstein et al. 2004). Through incorporating local geologic heterogeneity often ignored by regional groundwater models, the authors showcase the range of spatial and temporal variability in riverbed seepage and groundwater levels that when coupled identify previously missed SW-GW connections.

Frei, S., Fleckenstein J.H., Kollet, S.J., Maxwell, R.M. (2009). Patterns and dynamics of river–aquifer exchange with variably-saturated flow using a fully-coupled model. Journal of Hydrology: Volume 375(3-4): 383-393.

The authors employ the surface–subsurface model PARFLOW to simulate variably saturated flow conditions for 100 different geologic realizations of a hypothetic river domain based on the same Cosumnes river-aquifer system geostatistical models of Fleckenstein et al. 2006. Across all simulations preferential flow zones comprised of connected high conductivity hydrofacies conveyed disproportionately high volumes of water compared to low conductivity hydrofacies. Perched aquifers were able to form where laterally contiguous zones of low conductivity hydrofacies were present. The temporal evolution of seepage through the system was discussed.

Mount, JF., Fogg G., Kavvas L., Fleckenstein J., Anderson M., Chen Z Q., & Suzuki E. (2001). Linked Surface Water-Groundwater Model for the Cosumnes River Watershed: Hydrologic Evaluation of Management Options to Restore Fall Flows. U.S. Fish and Wildlife Service Anadromous Fish Restoration Program. http://watershed.ucdavis.edu/pdf/Mount-et-al-USFWS-2007.pdf

This is the quintessential study for Cosumnes River SW-GW interactions. This study has it all: historical data analysis, numerical groundwater-surface water modeling, surface water routing and infiltration modeling, watershed rainfall-runoff modeling, and field measurements. Key finding from the authors include the scale and scope of historic and current connection of the SW-GW system, volumetric requirements to reconnect the system and the influences of different management scenarios on SW-GW connections and river flows, and riverbed seepage rates.

Niswonger, R. G. (2006), The hydroecological significance of perched groundwater beneath streams, Ph.D. dissertation, 171 pp., Hydrol. Sci. Grad. Group, Univ. of Calif., Davis.

The author’s dissertation is a great treatise on perched aquifers and the importance of including the effect of riparian vegetation ET when modeling SW-GW interactions and recharge. New findings are presented around each corner breaking conventions of previous assumptions about what happens when the regional water table drops below and separates from the saturated zone associated with a streambed. Numerical modeling simulations of hypothetical river domains, partly based on a 2000 m of the Cosumnes river-aquifer system near Highway 99, provide insight into sedimentological conditions necessary to generate perched aquifers, provide an upward limit on flux from perched aquifers to support streamflows, describe the temporal evolution of flux from perched aquifers to stream, and provide first order estimates of the percent of perched discharge that may be lost to ET. Management considerations for perched aquifers are discussed but are more general in nature.

Niswonger, R. G., and G. E. Fogg (2008), Influence of perched groundwater on base flow, Water Resour. Res., 44, W03405, doi:10.1029/2007WR006160.

Similar materials to those presented by Niswonger, 2005 in chapter 3, with only minor differences in values. Primary difference is level of detail and this resource having undergone peer-review.

Niswonger, R. G., D. E. Prudic, G. E. Fogg, D. A. Stonestrom, and E. M. Buckland (2008), Method for estimating spatially variable seepage loss and hydraulic conductivity in intermittent and ephemeral streams, Water Resour. Res., 44, W05418, doi:10.1029/2007WR006626.

The authors couple a kinematic wave based streamflow routing model with an infiltration model (Philips equation) to estimated spatial variations in seepage losses and hydraulic conductivities along intermittent and ephemeral streams. The model is applied in a section of the Cosumnes river near Highway 99. Measurements of streamflow front velocities from the October 2005 Cosumnes Flow Augmentation Project were used to calibrate and asses model performance. Spatially varying estimates for seepage losses and hydraulic conductivities are provided for the modeled flow conditions and show a longitudinal trend for streambed hydraulic conductivities to decrease downstream owning to an observable decrease in sediment texture over the lower section of the river.

Recharge

Gailey, R.M., Fogg, G.E., Lund, J.R. et al. (2019). Maximizing on-farm groundwater recharge with surface reservoir releases: a planning approach and case study in California, USA. Hydrogeol J 27, 1183–1206. https://doi.org/10.1007/s10040-019-01936-x

The authors simulate agricultural MAR potential in the study area using water from Folsom reservoir. Simulations are based on a set of rules designed to maximize recharge while still accounting for physical and economic constraints of the system. Limitations of agricultural MAR are identified that include 1) temporal variability in recharge water availability, (2) variations in infiltration rate and few high-infiltration recharge sites in the study area, and (3) recharged water escaping from the study area groundwater system to surface water and adjacent sub-basins. Total volumes of recharge are reported for different economic scenarios all of which show the potential for larger volumes of water to be recharged into the system annually (937-5,400 TAF total recharge with ~ 60% going to groundwater, 20% leaving as streamflow, and 20% leaving the groundwater basins).

Goharian, E., Azizipour, M., Sandoval-Solis, S.,and Fogg, G. (2020). Surface Reservoir Re-Operation for Managed Aquifer Recharge: Folsom Reservoir System. J. Water Resources Planning and Management. American Society of Civil Engineers. 146(12): 04020095

FolSim, a new simulation tool is used to study reoperation of Folsom Reservoir to provide water for MAR while still accounting for required multi-purpose reservoir operations. While not explicitly included in the tool good-faith effort was made to account for larger California water management operations (SWP and CVP) and downstream Delta requirements. In theory reoperation could be done to provide substantial annual quantities of water for MAR, especially in wet and above normal years, with nonsignificant deficits and violations of old operation objectives.

Detailed estimates of available MAR water are provided for the 1922–2002 period and summarized by water year type.

Liu, Y. (2014) Modeling study of groundwater and surface water interaction using high resolution integrated model. MSc Thesis, University of California, Davis, CA.

Excellent modeling study estimating the dynamics and volumes of water recharged below Highway 99 during three realistic flood scenarios (3-yr, 5-yr, and 100-yr). Unlike other theoretical studies in the study are flood extents, depths, and durations are taken from previous flood modeling and used as boundary conditions for a numerical groundwater model. Resulting recharge volumes help contextualize recharge potential from natural flooding in this portion of the study area.

Maples, S.R., G.E. Fogg, R.M. Maxwell, (2019) Modeling Managed Aquifer Recharge Processes in a Highly-Heterogeneous, Semi-Confined Aquifer System Hydrogeology Journal doi:10.1007/s10040-019-02033-9

The authors simulate the variably-saturated water flow dynamics of MAR at five representative sites within the Cosumnes river-aquifer system. Results show that recharge potential is highly dependent on subsurface geologic architecture, with a nearly 2 order-of-magnitude range of recharge across the domain. Where interconnected coarse texture recharge pathways occur, results show that these features can (1) accommodate rapid, high-volume MAR and (2) propagate widespread and rapid pressure responses over multi-kilometer distances in the semi-confined aquifer system. An excellent conceptual model is presented of the temporal evolution of how recharged water is accommodated in the unsaturated vs saturated media of the aquifer system as well as the idea that while the benefit of physical change in storage occur locally, the increase in groundwater heads from MAR can be regionally beneficial. Reasonable bounds for initial as well as decaying recharge rates are also provided.

Maples, S. R., Foglia, L., Fogg, G. E., and Maxwell, R. M.. 2020. Sensitivity of hydrologic and geologic parameters on recharge processes in a highly heterogeneous, semi-confined aquifer system, Hydrol. Earth Syst. Sci., 24, 2437–2456, https://doi.org/10.5194/hess-24-2437-2020.

The authors conduct a sensitivity analysis to reveal factors relevant to MAR feasibility. A geological proxy parameter (GPP) that is the combination of K_{geom} and depth to groundwater was the best indicator for MAR potential and can be applied across the landscape where these two variables can be reasonably estimated. Details and limitations of the GPP are discussed and approaches to map and model the required parameters are covered.

Sager, J.C. (2012) Effects of subsurface heterogeneity on floodplain recharge and subsurface storage of water. MSc Thesis, University of California, Davis, CA.

Vast volumes of water are recharged in a hypothetical test domain based on the Cosumnes river-aquifer system. The volume of recharge depends on geologic structure, aquifer properties, the depth and duration of flooding, and the MAR strategy. The study involves similar methods and conclusions as Lui, 2014 and Maples et al. 2019.

Yoder, A. M. (2018). Effects of levee-breach restoration on groundwater recharge, cosumnes river floodplain, california (Order No. 13420847). Available from Dissertations & Theses @ University of California; ProQuest Dissertations & Theses A&I. (2191600268). Retrieved from https://search.proquest.com/dissertations-theses/effects-levee-breach-restoration-on-groundwater/docview/2191600268/se-2?accountid=14505

The author uses detailed measurements of shallow groundwater levels and a mass balance to track shallow groundwater levels and estimate recharge rates on the Oneto–Denier levee breach restoration site. Comparisons of pre- to post-restoration suggest of levee breach restoration provides benefits to increasing recharge. Assumptions and data limitations constrain some of the inference on recharge rates and processes.

Geomorphology and Hydrology

Booth, Eric, Jeffrey Mount, and Joshua Viers. Hydrologic Variability of the Cosumnes River Floodplain. San Francisco Estuary and Watershed Science. Vol. 4, Issue 2 [September 2006]. Article 2. http://repositories.cdlib.org/jmie/sfews/vol4/iss2/art2

10 different types are differentiated in the MHB flow record with unique durations and magnitudes.

Constantine, C.R. 2001. The effect of substrate variability and incision on the downstream-fining pattern in the Cosumnes River, Central Valley, California. Masters thesis, 132 pp., Geology, Univ. of Calif., Davis.

Changes in channel geomorphology, primarily incision, are linked to river bed sedimentology. An overall downstream fining in bed sediment is described that shows locally alternating patterns depending on channel confinement. The extensive field surveys provide a trove of sedimentological information and an excellent historic record.

Constantine, C.R., Mount, J.F., and Florsheim, J.L. 2003. The effects of longitudinal differences in gravel mobility on the downstream fining pattern in the Cosumnes River, California. The Journal of Geology: 111:2, 233-241.

Similar materials to those presented by Constantine, 2001, with only minor differences in values. Primary difference is level of detail and this resource having undergone peer-review.

Florsheim, J.L., Mount, J.F., 1999. Geomorphic and ecological response of the anastomosing lower Cosumnes River, California, to anthropogenic disturbances: implications for restoration. Geol. Soc. Am. Abstr. Prog. 31 (7), A-202.

See Florsheim and Mount, 2003.

Florsheim, J.L., Mount, J.F., 2002. Restoration of floodplain topography by sand splay complex formation in response to intentional levee breaches, lower Cosumnes River, California. Geomorphology 44 (1–2), 67–94.

See Florsheim and Mount, 2003.

Florsheim, J.L., Mount, J.F. 2003. Changes in lowland floodplain sedimentation processes: pre-disturbance to post-rehabilitation, Cosumnes River, CA. Geomorphology, Volume 56, Issues 3–4, Pages 305-323, https://doi.org/10.1016/S0169-555X(03)00158-2.

The cumulative works of these two authors include a trove of detail on the current and historic geologic and geomorphic context of the Cosumnes river-floodplain system. In Florsheim and Mount, 1999 the historic anastomosing river is revealed. Modern dynamics of levee breach restoration are relayed by Florsheim and Mount, 2002. Lastly, the entire history is summarized through geologic investigation.

Nichols, AL, Viers, JH. Not all breaks are equal: Variable hydrologic and geomorphic responses to intentional levee breaches along the lower Cosumnes River, California. River Res Applic. 2017; 33: 1143– 1155. https://doi.org/10.1002/rra.3159

Repeated topographic observations are employed by the authors at levee breaches along the lower Cosumnes River to illustrate how breach architecture influences floodplain and channel hydrogeomorphic process. Estimates are provided of pre- and post-breach flows that connect the river with the floodplain.

Whipple, AA, Viers, JH, Dahlke, HE. Flood regime typology for floodplain ecosystem management as applied to the unregulated Cosumnes River of California, United States. Ecohydrology. 2017; 10:e1817. https://doi.org/10.1002/eco.1817

Six types of flood are distinguished in the MHB record according to statistical differences in their timing, duration, and magnitude.

Groundwater

Collectively the following resources provide excellent reviews of the basin groundwater conditions.

DWR, 1974, Bulletin 118-3, Evaluation of Ground Water Resources: Sacramento County, 141 pp.

Environment & Water, Inc. (EKI). 2019. Draft Technical Memorandum #6 – Hydrogeological Conceptual Model and Groundwater Conditions Cosumnes Subbasin, Sacramento County, CA (EKI B80081.00). Available online at: http://cosumnes.waterforum.org/meetings

MWH. 2006. Central Sacramento County, Groundwater Management Plan. Prepared for Water Forum, and Sacramento County Water Agency, dated February 2006.

Robertson-Bryan, Inc. and WRIME, 2011, *South Basin Groundwater Management Plan.* Prepared for South Area Water Council, dated October 2011.

GEI Consultants, Inc. 2016. South American Subbasin Alternative Submittal, 2014 Sustainable Groundwater Management Act, dated December 2016.

Basin Setting

Collectively the following resources provide excellent reviews of the basin setting.

Kleinschmidt Associates. 2008. Cosumnes River Preserve Management Plan.

Robertson-Bryan, Inc. 2006b. Lower Cosumnes River Watershed Assessment.

Robertson-Bryan, Inc. 2006c. Cosumnes & Mokelumne Rivers Floodplain Integrated Resources Management Plan. *Floodplain Resources Characterization Report*. Prepared for Southeast Sacramento County Agricultural Water Authority.

6. Data dictionary

This section provides relevant physical parameters (i.e. seepage rates, streambed and aquifer hydraulic conductivities, river properties [slope, roughness], and aquifer properties [specific yield, porosity, specific storage], and recharge rates) taken from the reviewed documents that may be valuable for ongoing efforts to assess recharge, seepage, and SW-GW interactions in the study area.

Table 1. Average Seepage Rates

Rate (ft^3/s/mile)	Location[1]	Notes	Source
1.02-1.77	MBH-MCC	Based on comparison of stream gages	Mount et al., 2001
0.008-0.75	MBH-MCC	Extrapolated from point based seepage meter measurements	Mount et al., 2001
1.36	MBH-MCC	Average from numerical groundwater-surface water model simulations	Fleckenstein et al., 2004
0.42	MBH-MCC	Simulated seepage at 32.8 cfs	Anderson et al., 2004
0.9	near MHB	Simulated seepage from pulse of 86.5 cfs at MHB	Anderson et al., 2004
0.26	near MCC	Simulated seepage from pulse of 86.5 cfs at MHB	Anderson et al., 2004
1-3.5	unknown	field measured by Graham Fogg	SSCAWA, 2005
2.7	Hwy 99-Twin Cities	field measured by Graham Fogg	SSCAWA, 2005
8.90-18.9	MHB-MCC	High flow (7,134 cfs) simulations from multiple geologic realizations	Fleckenstein et al., 2006
6.36-9.61	MHB-MCC	Moderate flow (847 cfs) simulations from multiple geologic realizations	Fleckenstein et al., 2006
2.27-113.67	Hypothetical 5 km domain	Range from multiple geologic realizations	Frei et al., 2009

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[1] As noted in Section 2 local seepage rates are highly variable and may at times be reversed to discharge groundwater

Table 2. Streambed Hydraulic Conductivities

Rate (inch/hr)	Location	Notes	Source
0.015	MBH-MCC		Anderson et al., 2004
0.135	MBH-MCC		Mount et al., 2001
0.241-0.307	MBH-MCC	Arithmetic mean of vertical K values of river cells based on multiple geologic realizations	Fleckenstein et al., 2006
5.51E-05 - 0.030	Hwy 99	Average values from cores for fine-sediment and coarse-sediment	Niswonger and Fogg, 2008
0.136-9.53	NA	coarse sediment range from published values	Niswonger and Fogg, 2008
8.2E-06 - 0.008	NA	fine sediment range from published values	Niswonger and Fogg, 2008
0.013-2.85	RM 8-13	range of estimated values, see original article for reach-specific values	Niswonger et al., 2008

Table 3. Streambed properties from seepage studies

Property	Source			
	Anderson et al., 2004	Mount et al., 2001	Niswonger and Fogg, 2008	Niswonger et al., 2008
Streambed thickness (ft)	0.75	1.33	-	-
Aquifer hydraulic conductivity (in/hr)	0.15	0.252	-	-
Porosity (%)	35	30	36-41	
Channel slope (ft/ft)	0.001	0.001	-	0.00068
Manning's n	0.024	0.028	-	0.045

Table 4. Aquifer properties

Aquifer hydraulic conductivities (m/s)				
Geologic media	Frei et al., 2009; Sager, 2012	Fleckenstein et al., 2006	Lui, 2014; Maples et al., 2019, 2020	
Gravel, coarse sand	1.67E-04	4.00E-03	7.81E-04	
Sand	6.25E-05	1.50E-03	4.77E-04	
Muddy sand	1.04E-05	2.50E-04	2.31E-06	
Muddy sand	2.71E-07	6.50E-04	1.97E-08	
Deep aquifer	-	-	5.21E-04	
Specific storage (1/m)				
Description	Frei et al., 2009	Fleckenstein et al., 2006	Sager, 2012	Lui, 2014; Maples et al., 2019, 2020
Gravel, coarse sand	1.00E-04	2.00E-05	2.00E-05	4.00E-05
Sand	1.00E-04	8.00E-05	5.00E-05	8.00E-05

Muddy sand	1.00E-04	2.00E-04	1.00E-04	1.00E-04
Mud	1.00E-04	5.00E-04	1.00E-03	1.00E-03
Deep aquifer	-	-	-	4.80E-04
Specific Yield (-)				
Description	Fleckenstein et al., 2006			
Gravel, coarse sand	0.25			
Sand	0.20			
Muddy sand	0.15			
Mud	0.10			
Deep aquifer	-			
Porosity (-)				
Description	Sager, 2012 (Baseline); Lui, 2014; Maples et al., 2019, 2020			
Gravel, coarse sand	35			
Sand	35			
Muddy sand	40			
Mud	45			
Deep aquifer	35			

Table 5. Recharge Rates from Sager (2012) recharge simulations (m^3/m^2)[1]

Time (days)	Min of Realizations	Max of Realizations	Hi-K Targeting	Low-K Targeting
1	0.53	0.85	1.61	0.41
10	1.13	1.48	2.52	1.11
30	1.71	2.01	3.17	1.83
60	2.16	2.34	3.7	2.67

[1] Note annual rates from Yoder (2018) were between 0.24-1.04 m^3/m^2

Table 6. Average Monthly and Annual Recharge Rates from Maples et al., 2019 (cm/d)

Site	Month							Year		
	1	2	3	4	5	6	1 to 6	1	2	3
1	53.1	12	11.1	10.6	10.2	9.9	18.5	26.2	19.1	17
2	18.4	3	2.8	2.7	2.6	2.5	5.4	8.1	5.4	4.6
3	13	2.4	2.2	2	1.9	1.8	4	6.1	3.4	2.6
4	6	0.9	0.8	0.8	0.8	0.7	1.7	2.6	1.4	1.3
5	0.7	0.2	0.2	0.2	0.2	0.2	0.3	0.4	0.2	0.2

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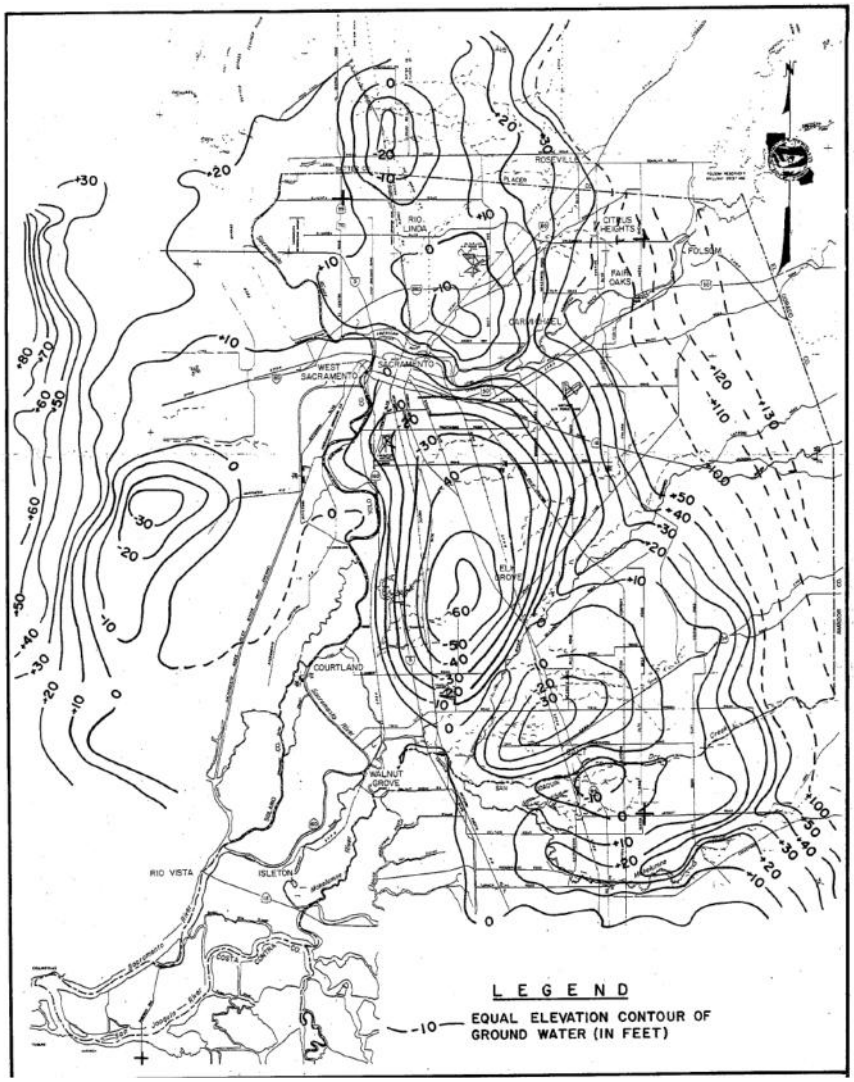
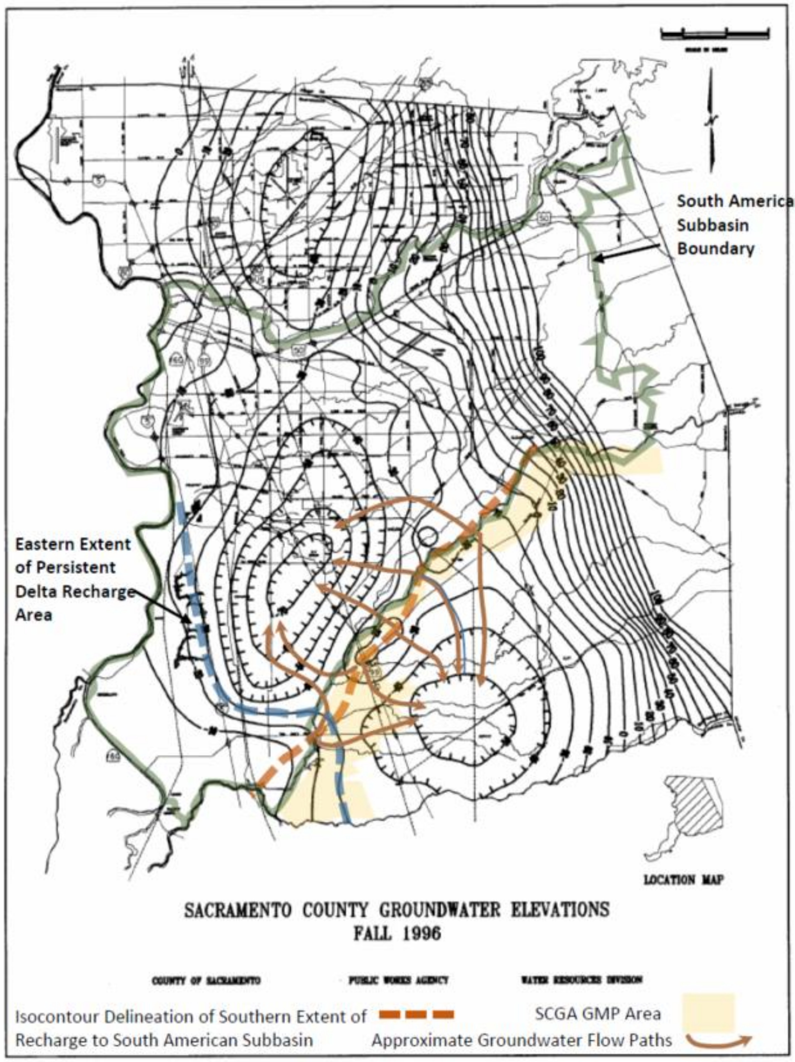
Appendix A - Selected Groundwater Level Maps

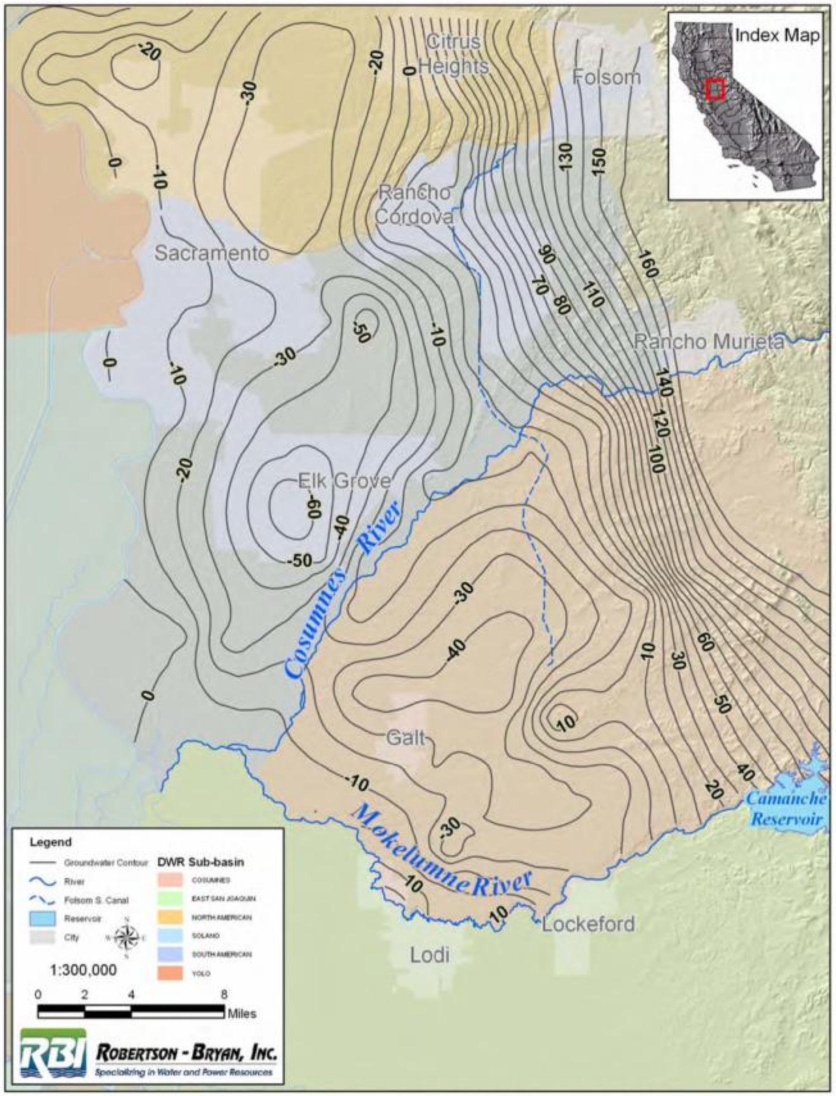


Spring 1968 (Figure 17 DWR, 1974)

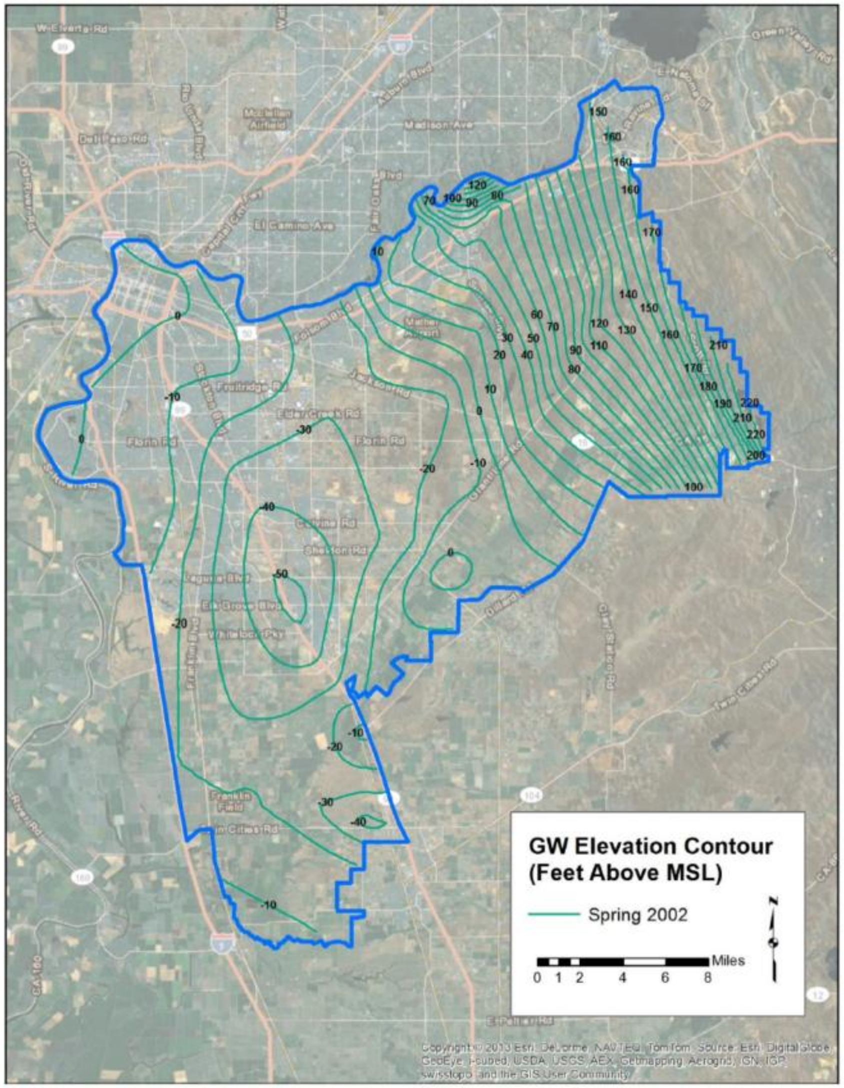
Spring 1991 (Figure 2-6)



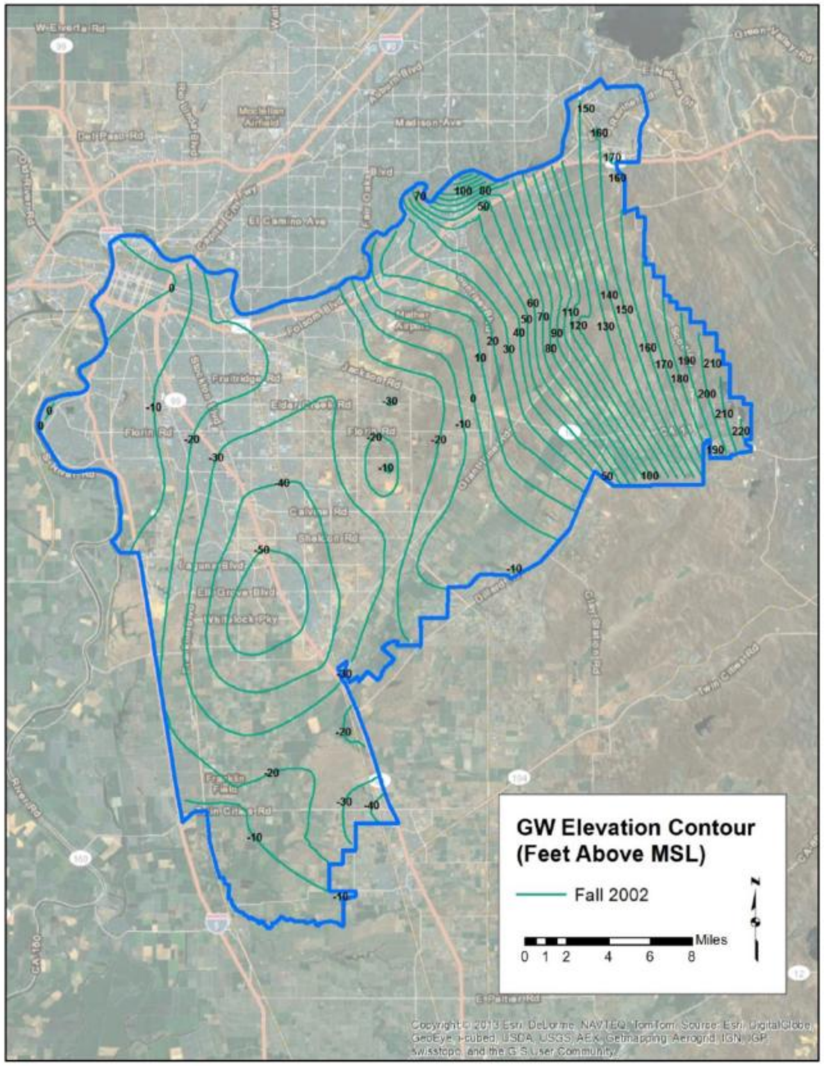
Fall 1996 (Figure 1-3 GEI, 2016)



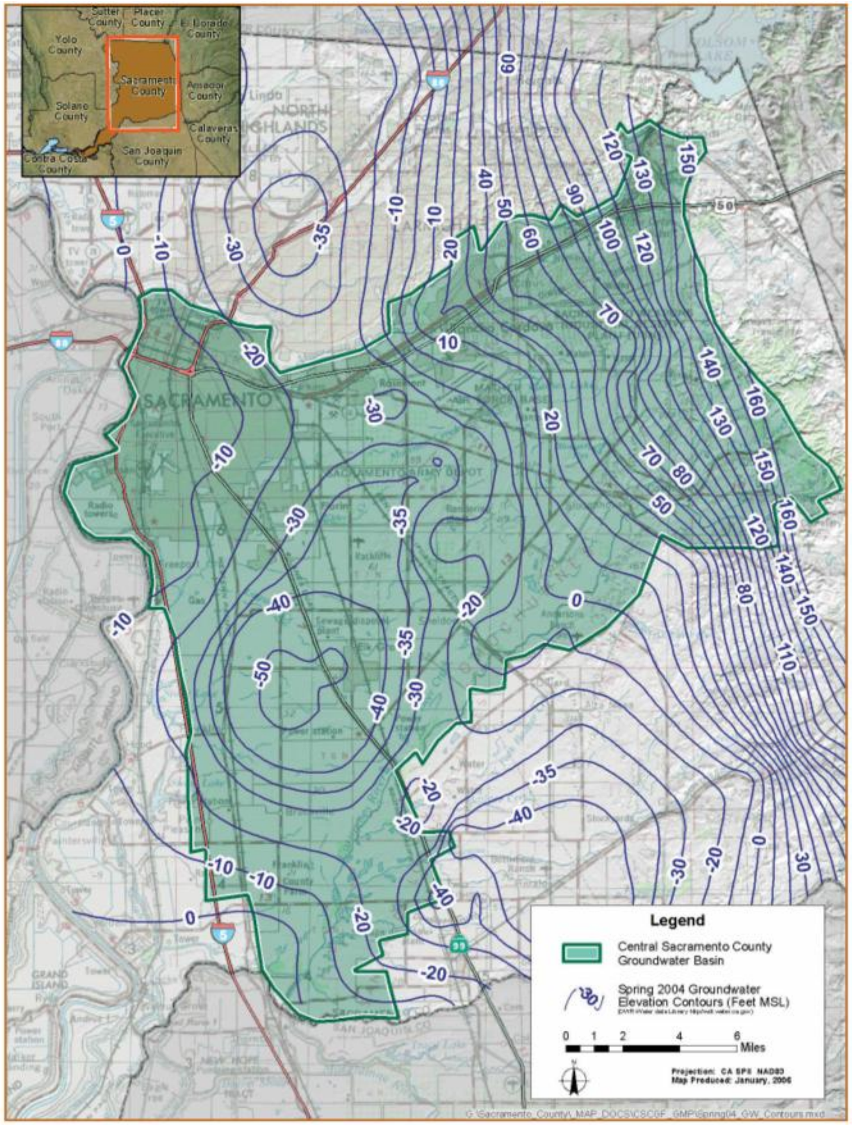
Fall 2000 (Figure 3-27 RBI, 2006a)



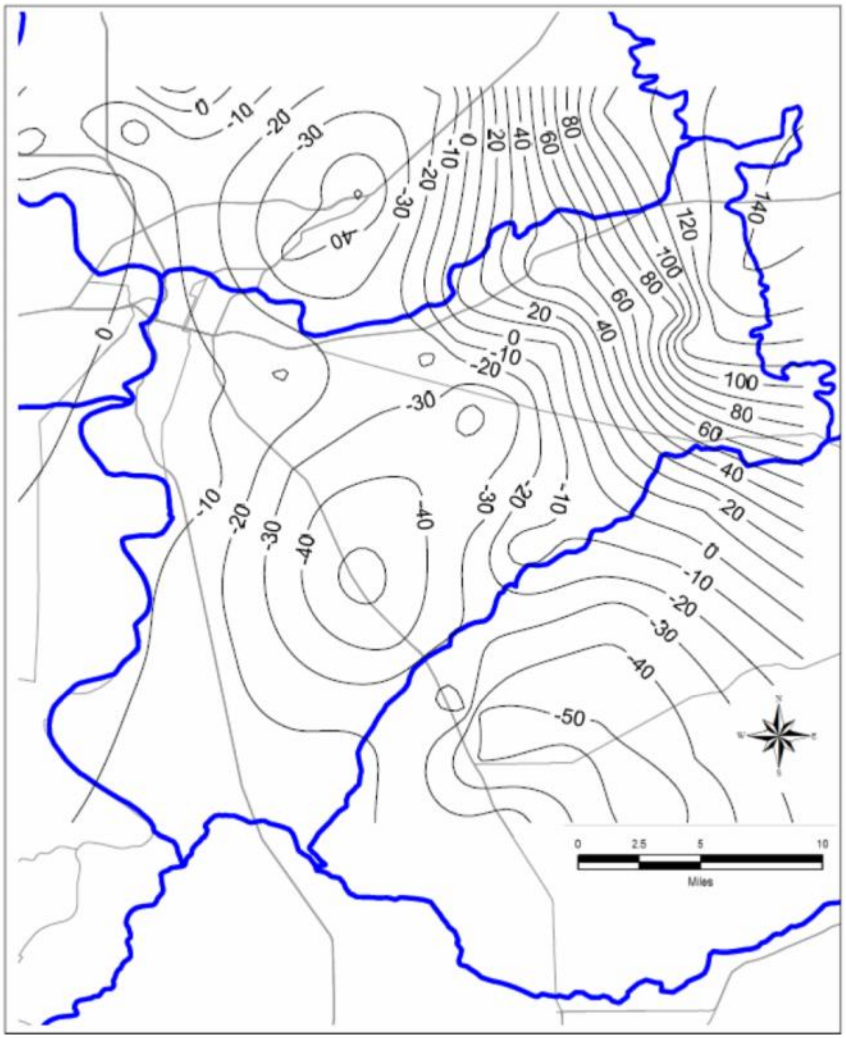
Spring 2002 (Figure 4 SCGA basin plan)



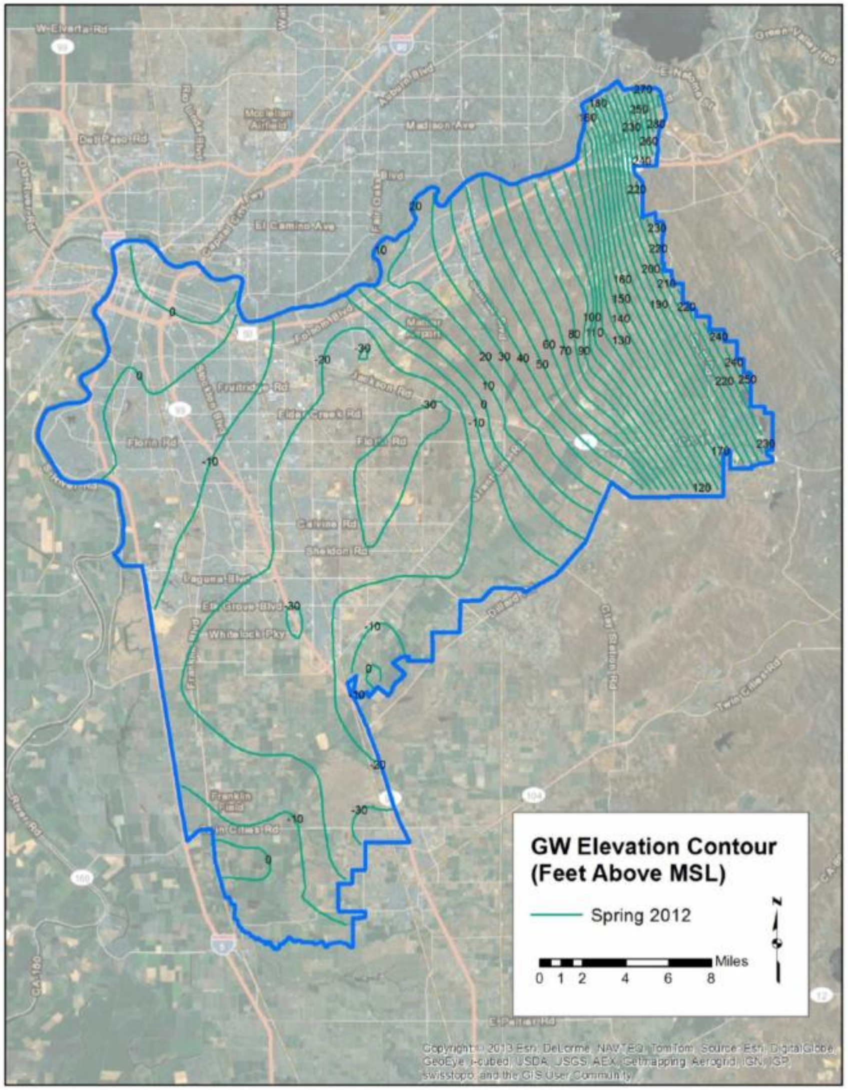
Fall 2002 (Figure 6 SCGA basin plan)



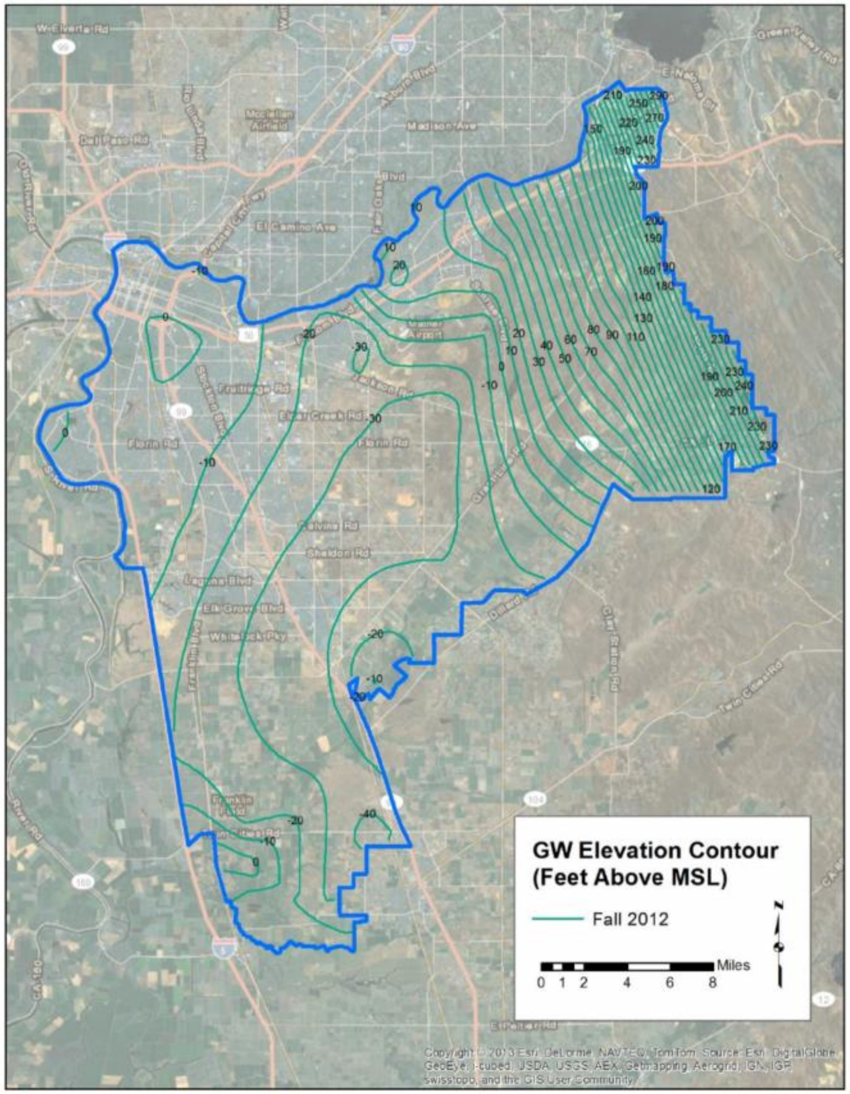
Spring 2004 (Figure ES-3 SSCAWA plan)



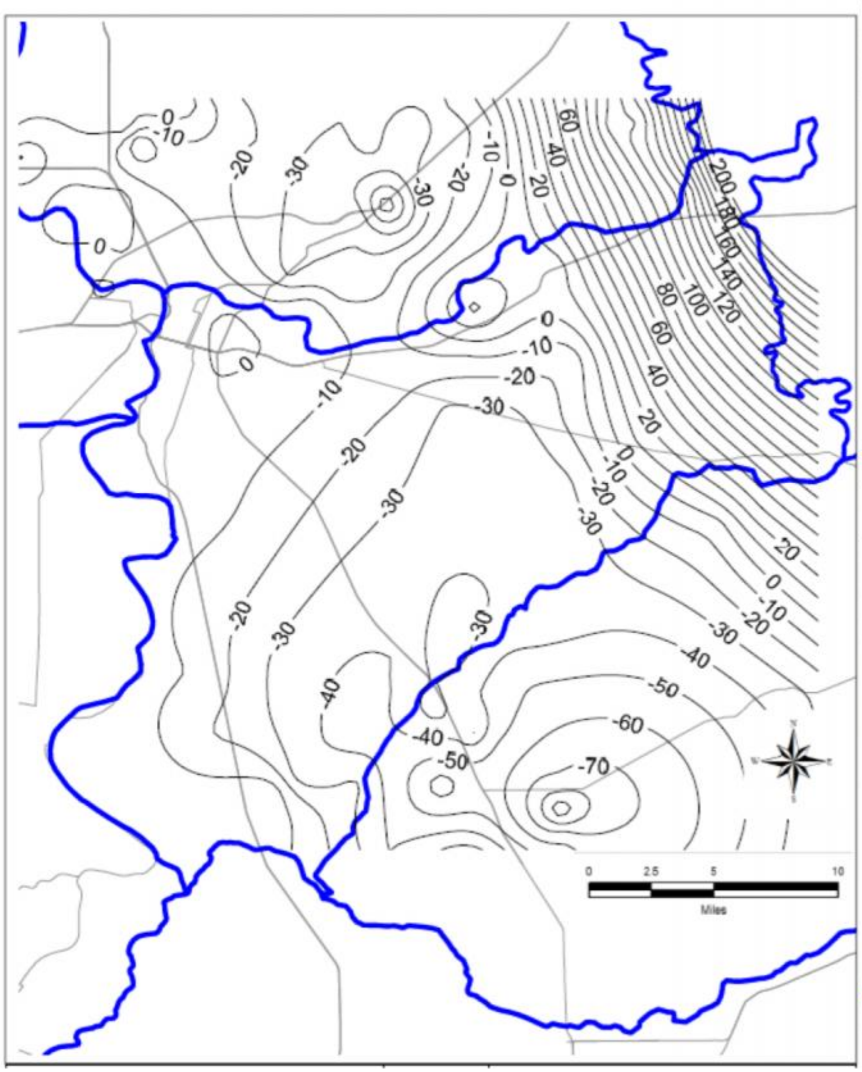
Fall 2005 (Figure 2-17 GEI, 2016)



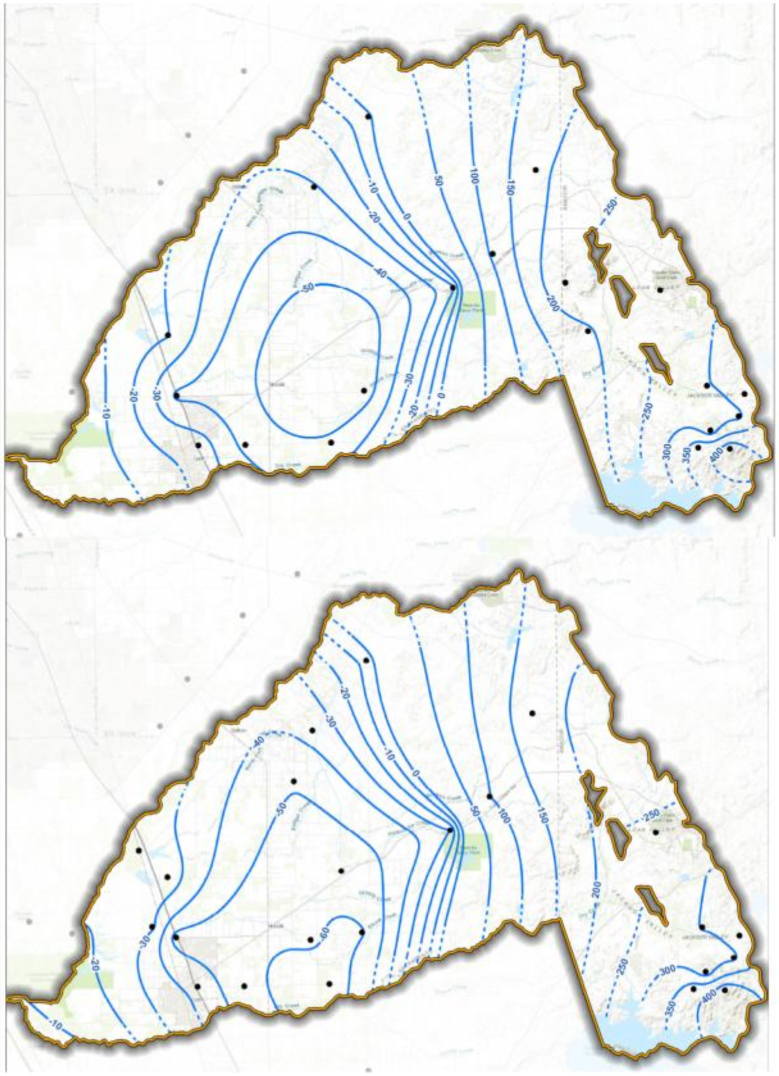
Spring 2012 (Figure 5 SCGA basin plan)



Fall 2012 (Figure 7 SCGA basin plan)



Fall 2015 (Figure 2-18 GEI, 2016)



Spring (Top) and Fall (Bottom) 2018 (Figure GWC-1 and GWC-2 EKI 2019)