Appendix 3-A

Interconnected Surface Water (ISW) in the South American Subbasin: Characterization of Historical and Present-day Conditions, and Approaches for Monitoring and Management (June 18, 2021)

Interconnected Surface Water (ISW) in the South American Subbasin: Characterization of Historical and Present-day Conditions, and Approaches for Monitoring and Management

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1. Introduction

The South American Subbasin (SASb) is a medium priority groundwater basin in California's Central Valley. Groundwater pumping in the SASb provides water for municipal, agricultural, and domestic beneficial users, but has lowered groundwater elevations over time and lead to depletions of interconnected surface water (ISW), defined as:

> 23 CCR § 351(o): "Interconnected surface water" refers to surface water that is hydraulically connected at any point by a continuous saturated zone to the underlying aquifer and the overlying surface water is not completely depleted.

The Sustainable Groundwater Management Act (SGMA) identifies "Depletions of Interconnected Surface Water" as an Undesirable Result (CWC § 10721(x)). Thus, ISW depletion requires the development of Sustainable Management Criteria (SMC) to quantify existing ISW depletion and plan for sustainable groundwater management that mitigates significant and unreasonable ISW depletion. Specifically, 23 CCR § 354.28. Minimum Thresholds states that the Minimum Threshold (MT) for Depletions of Interconnected Surface Water, "*shall be the rate or volume of surface water depletions caused by groundwater use that has adverse impacts on beneficial uses of the surface water and may lead to undesirable results*" and that developed MTs will be supported by:

A. The location, quantity, and timing of depletions of interconnected surface water.
B. A description of the groundwater and surface water model used to quantify surface water depletion.

Although numerous surface water bodies that support environmental flows and aquatic ecosystems are present in the SASb (i.e., Sacramento, American, and Cosumnes rivers, and minor creeks and streams in the basin's interior), seasonal and historical trends in the location and timing of ISW, as well as ISW volumetric depletion rates (quantity) remain poorly characterized. Herein, we report on long-term, recent groundwater level conditions (2005-2018) in the SASb, characterize the spatial location, timing, and quantity of ISW using output from the Cosana integrated hydrologic model, and recommend management actions that align ISW depletion with the mandates of SGMA.

Fundamentally, this memorandum shows that stream depletion is occurring in the SASb, and identifies ISW locations, timing, and quantity. Next, a management approach and sustainable management criteria (SMC) for groundwater level are recommended that arrest groundwater levels, which arrest hydraulic gradients, and finally, arrest streamflow depletion (Figure 1).

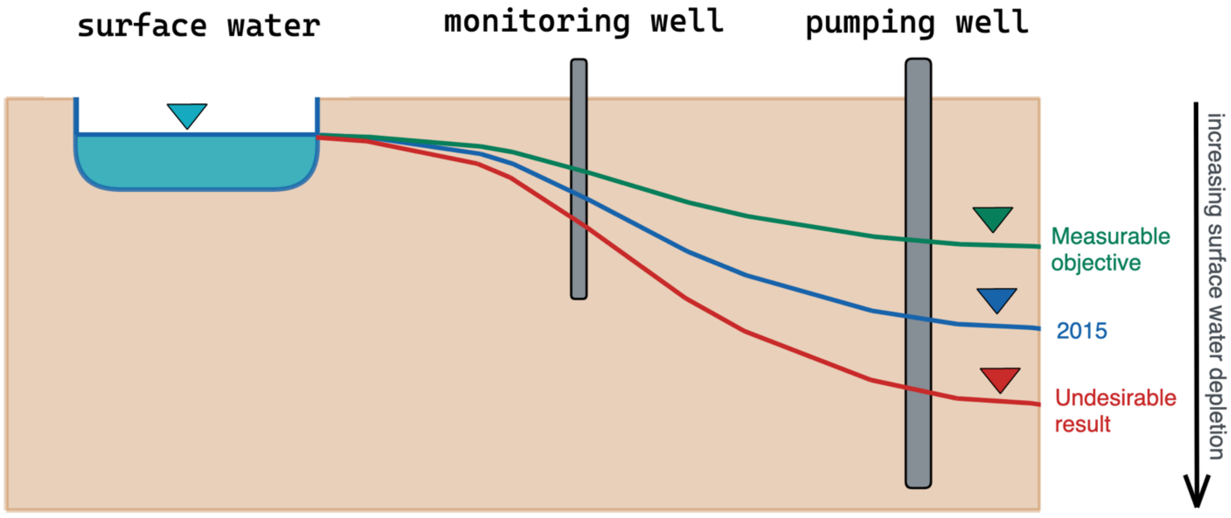

Figure 1: Surface water depletion can occur when adjacent groundwater elevation (green, blue, and red lines) falls below the stream stage elevation. As groundwater elevation declines, for example, due to groundwater pumping, the regional groundwater level falls, which steepens the gradient between surface and groundwater and increases the quantity of surface water depletion (black downwards-pointing arrow). In the figure above, the 2015 groundwater level is shown as a historic low groundwater elevation (blue line). Examples of an undesirable result (red line) and measurable objective (green line) are groundwater levels below and above this historic low, respectively.

This memorandum is outlined as follows. First, in Section 2, we briefly review study area and basin setting insofar as it is necessary to understand the subsequent material[1], then follow with an extensive review of major surface water features, special-status species, instream flow requirements, and surface and groundwater interactions in the SASb. Next, in Sections 3-4, we present the methods and results of analysis of historical and present-day groundwater level conditions. Groundwater level data and the numerical integrated surface and groundwater flow model Cosana are used to inform a characterization of ISW location, timing, and quantity in the SASb. We find persistently disconnected reaches, persistently connected reaches, and reaches that oscillate between connection and disconnection across seasons and water years. Gaining and losing reaches are identified and seepage values are quantified and discussed. Finally, in Sections 5-6 we discuss limitations of the study and propose management and monitoring actions.

Results inform a monitoring and management approach for ISW within the context of SGMA that arrests groundwater levels in ISW-adjacent representative groundwater monitoring wells. This ensures that hydraulic gradients are not increased beyond roughly present-day values plus reasonable hydrologic variability, which guarantees that ISW depletion remains within historic quantities, and that Undesirable Results to beneficial users and uses of ISW are avoided.

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[1] An extensive review of study area and basin setting beyond the scope of the memo, and this information is readily accessible in existing documents. The key focus of this memorandum is to address the knowledge gap surrounding characteristics of surface waters and interconnected surface water in the SASb, and to develop a management plan for ISW consistent with requirements defined by SGMA.

2. Study Area and Setting

The SASb Groundwater Sustainability Plan (GSP) area (Figure 2) consists of five Groundwater Sustainability Agencies (GSAs), and is bordered on nearly all sides by major surface waters, including the Sacramento, American, Cosumnes and Mokelumne Rivers, which drain into the Bay Delta region – a complex aquatic ecosystem with species of concern, and a major surface water transfer point for beneficial users with appropriative surface water rights. The SASb is contained within Sacramento County and bordered by two medium priority basins: the North American subbasin to the north and the Cosumnes subbasin to the south. Interbasin coordination between adjacent basins is critical to address potential ISW depletion of the shared surface water resources that delineate basin boundaries.

Surface water in the SASb maintains aquatic ecosystems, provides recreation, and is distributed as urban water supply. At the time of writing, significant projects and management actions are in various stages of development to conjunctively manage surface and groundwater, which will bolster drought resilience and promote stable and sustainable groundwater storage and levels.

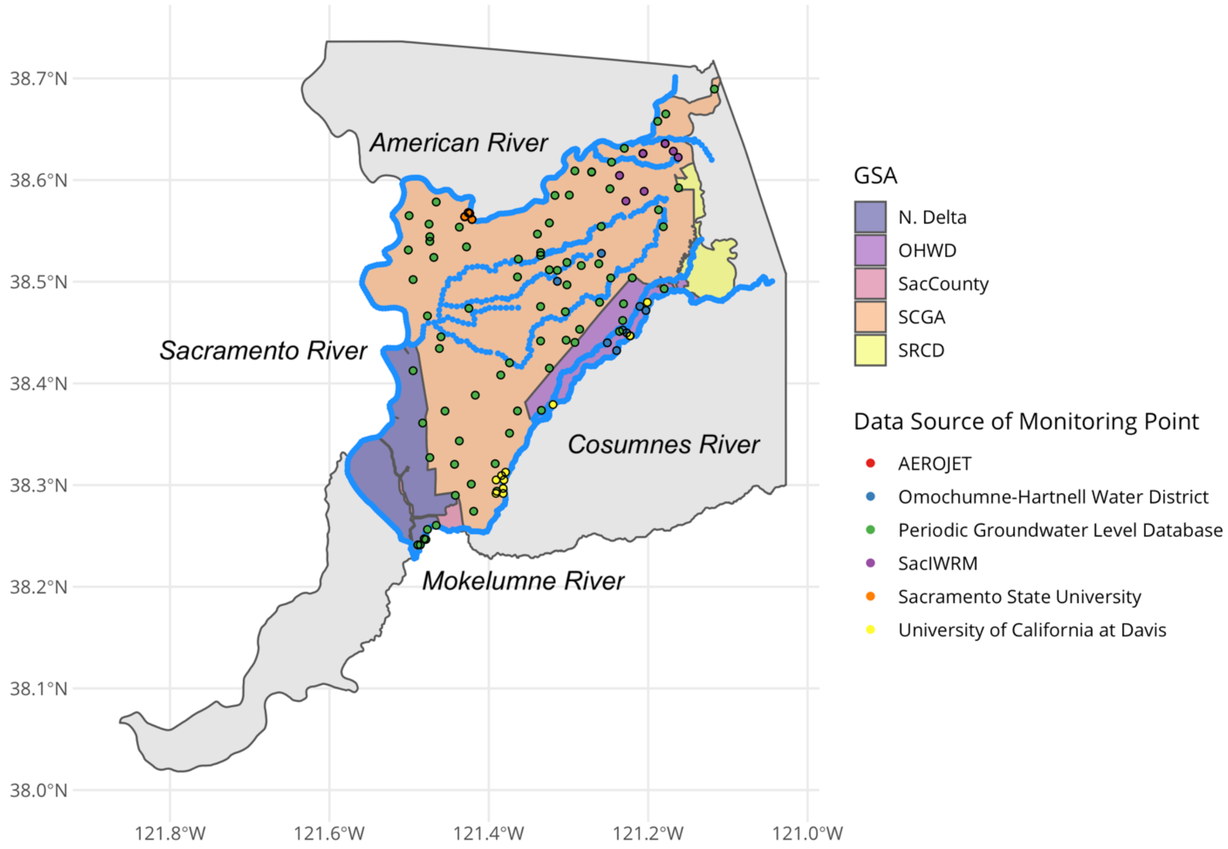

Figure 2. The South American Subbasin is an alluvial aquifer-aquitard system in California's Sacramento County (grey) housing 5 GSAs, and bordered by the American, Cosumnes, Mokelumne, and Sacramento Rivers on the north, east, south, and west boundaries respectively. Representation of these major surface water bodies in the Cosana integrated hydrologic model (including interior creeks) are shown in blue. Groundwater level monitoring

points are colored by the data source of the monitoring point. Monitoring points outside of the SASb which were used in the groundwater level interpolation are not shown.

The SASb subsurface geology is characterized by fluvial-alluvial clastic sedimentary deposits made of fines (silts and clays) and coarser, interconnecting aquifer material (sands and gavels). Long term water budgets in the SASb suggest generally stable groundwater storage conditions. The principal aquifer system primarily produces water for domestic, urban, and agricultural water supply, and interacts with major surface water bodies via baseflow and seepage[2].

Land use is characterized by the greater Sacramento urban area extending along the American and northern Sacramento Rivers. The Elk Grove urban area southeast of Sacramento is positioned at an urban-rural interface and reflects trends of urban expansion in the basin. Mixed agricultural-residential land is found along the Cosumnes River and extends north into the center of the basin. Northeastern foothills in the basin are contrasted by low-elevation wetlands in the southwest, which ultimately drain into the Sacramento-San Joaquin Delta.

It is in this diverse assemblage of GSAs in a basin bounded by surface waters and dependent on groundwater use that the sustainable management of ISW is to play out under SMGA. In the following subsections, we review characteristics of major surface waters, special-status species in these major surface waters, and instream flow requirements, and surface-groundwater interactions in the SASb.

2.1 Review of Major surface waters

Geographically, the SASb overlaps portions of the Sacramento river, American river, Cosumnes river, Mokelumne river, and San Joaquin Delta watersheds and supports a diverse assemblage of surface water bodies (Figure 3). The principal surface waters, the Sacramento, American, and Cosumnes rivers, define the basin's western, northern, and southern boundaries, respectively. The Cosumnes river flows into the Mokelumne river which serves as the southwestern boundary of the basin. The major surface water bodies in the SASb can be further subdivided into 21 reaches (Figure 4). In the subsections that follow, the lower Sacramento, lower American, Cosumnes, and Mokelumne rivers and relevant tributaries are described.

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[2] For more information on the hydrogeologic conceptual model and a detailed history of groundwater conditions, please refer to the SASb GSP, section 2, "Plan Area and Basin Setting".

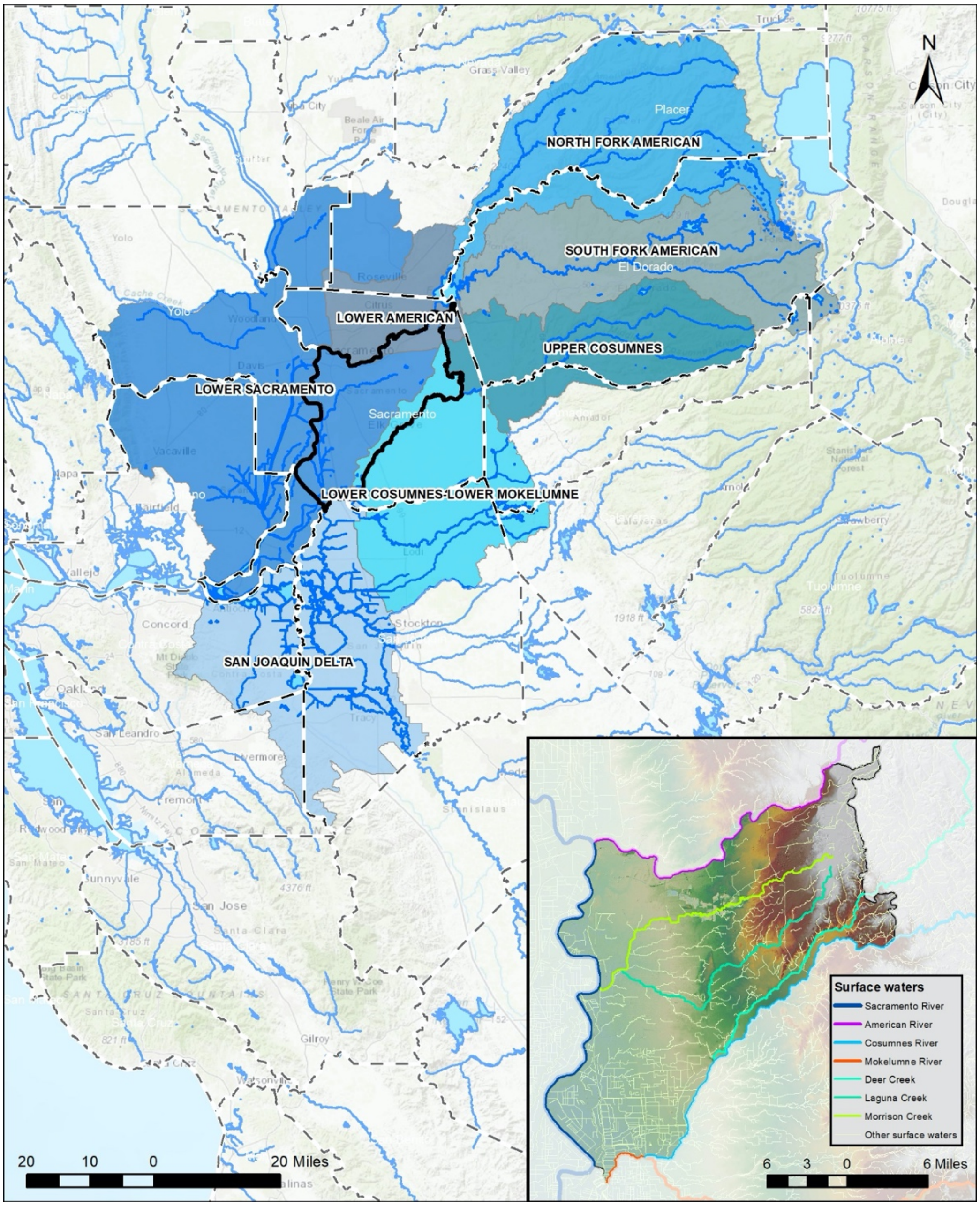

Figure 3. SASb watersheds and major surface water bodies.

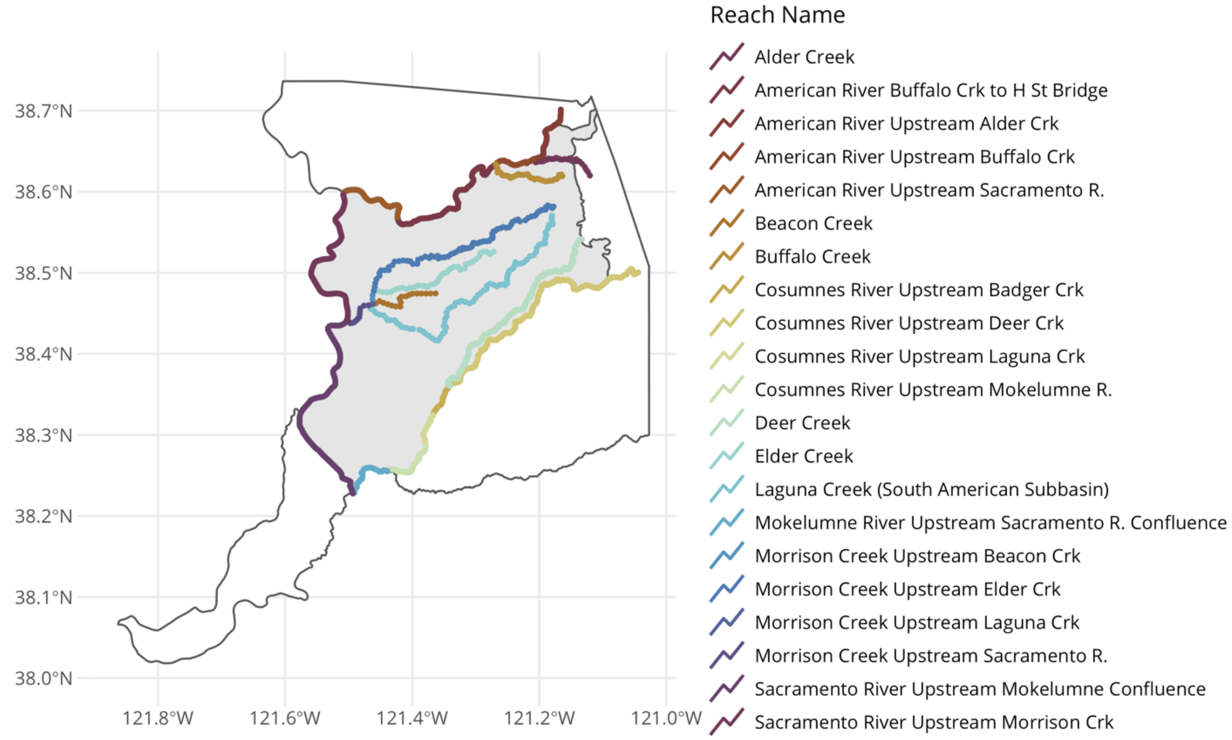

Figure 4. Major surface waters in the South American Subbasin are divided into 21 reaches, based on the surface water node representation in Cosana.

2.1.1 Lower Sacramento River

The Sacramento river watershed is the largest in the state, and drains a significant portion of Northern California. In the SASb the Sacramento river flows north-to-south along the basin’s western margin from an elevation of approximately 10 feet above sea level at the northern inlet to nearly sea level at its southern outlet where it discharges out to the Sacramento-San Joaquin Delta. This portion of river is heavily modified with a system of levees present along both banks. River flows here are substantially altered compared to their natural flow regime due to a system of complex water management operations that provide societal benefits in addition to meeting environmental flow requirements.

Based on classification by Lane et al., (2018) the Sacramento river in the SASb is characterized as a ‘High-Volume snowmelt and rain’ (HSR) hydrologic regime. Key components of this bi-modal snow-rain driven hydrograph include a spring snowmelt pulse, high seasonality with large winter storm contributions, and high summer baseflows. Comparing dimensionless hydrographs for the HRS regime and flows recorded at the USGS gaging station at Freeport (Gage ID 11447650) illustrates the homogenizing influence of water management on river flows. While measured flows retain elements of the HRS regime there is a clear decrease in seasonality and depression of the snowmelt pulse (Figure 5).

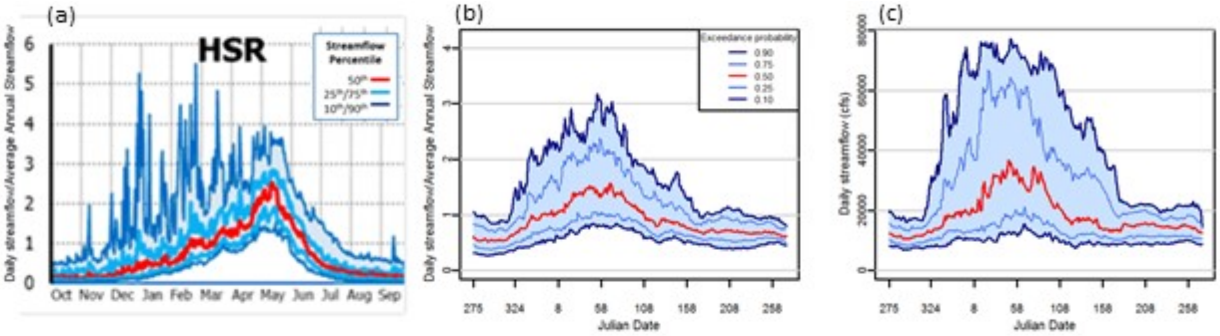

Figure 5. HSR non-dimensional hydrograph (a – modified from Figure 6 Lane et al., [2018]) and non-dimensional (b) and dimensional (c) hydrographs for Sacramento River at Freeport.

Average daily flow at the Freeport gage for the period of record between October 1, 1948 and September 30, 2015 was 22,923 cubic feet per second (cfs). Annual peak flows at Freeport over this same period ranged from 13,700 cfs in water year (WY) 1977 to 115,000 cfs in WY 1986. During high flow periods, a significant portion of flow from the Sacramento River Basin is diverted through the Yolo Bypass west of the Sacramento River and SASb. Notably, the entire SASb section of the Sacramento river is tidally influenced.

The Morrison creek watershed is the main system of tributaries that drain into the Sacramento river within the SASb. In addition to Morrison creek this system comprises a number of smaller creeks (e.g., Elder, Florin, and Stawberry creeks) which drain an approximately 192 square mile area of the central portion of the SASb. These drainages have been heavily modified, especially in the highly urbanized western portions of the basin near the City of Elk grove, and range in condition from semi-natural channels to concrete drainage canals. Morrison creek typically drains to the Sacramento River.

However, during high flow events, water may be directed to the Beach-Stone lakes basin including the Stone Lake National Wildlife Refuge and eventually to the Mokelumne River and Sacramento-San Joaquin Delta via Snodgrass Slough (Sacramento DWR, 2009). Hydrologically, flows in Morrison creek and its tributaries are driven by winter precipitation and stormwater runoff, but also receive discharge of treated groundwater. Daily average flows in Morrison creek were recorded from August 1, 1959 through November 27, 2017 at USGS gaging station ID # 11336580. These data show the flashy nature of the creek's response to storm events as well as prolonged periods of low flow (<5 cfs) during later spring and summer (e.g. May – October) (Figure 6). The average daily flow over this period was 21 cfs. Although measured flows at this location were rarely zero (< 0.1% of time) upstream portions of Morrison creek and associated tributaries have been described as intermittent or ephemeral and thus regularly do not flow in summer months (RWQCB, 2017; USFWS, 2007). While the flow records show the existence of interdecadal variability in average monthly flows, the lack of consistent monotypic trends between decades suggests flows have not experienced substantial statistical changes in bulk trends over the period of record. The peak discharge reported by the USGS gage over the period of record was 1,940 cfs during the winter of 1982.

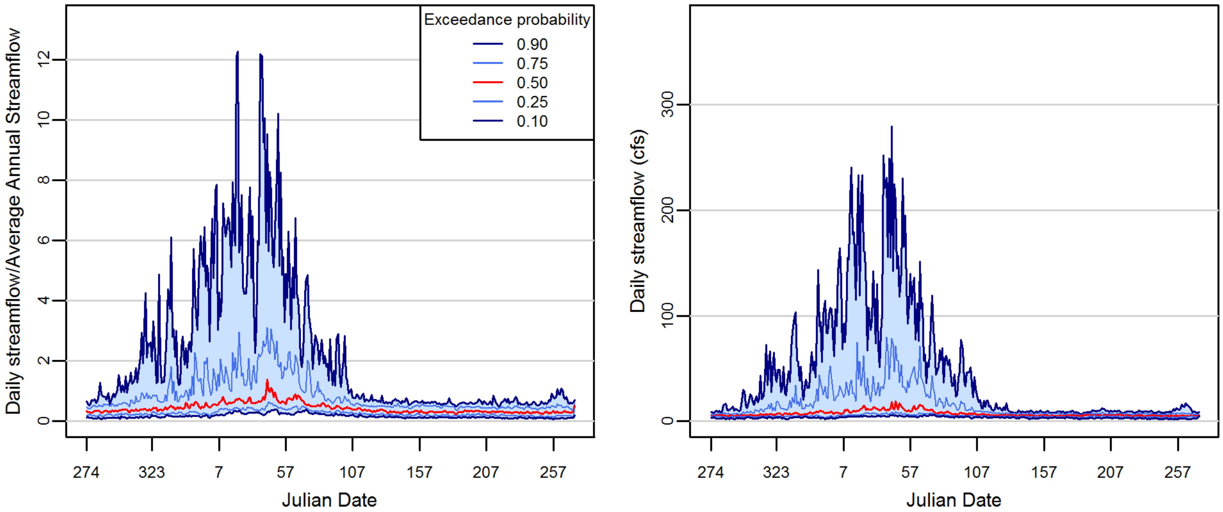

Figure 6. Non-dimensional and dimensional hydrographs for Morrison creek (USGS gage 11336580).

2.1.2 Lower American River

The American river watershed drains an area of approximately 2,155 mi^2 (5,581 km^2) ranging in elevation from over 10,000 feet in the headwaters in the Northern Sierra Nevada range to approximately 10 feet at the confluence with the Sacramento River. The lower American river defines the entirety of the northern boundary of the SASb. Like other basin surface waters the American river has been both physically modified (e.g., construction of levees, dams or other impoundments, and other in-channel infrastructure) and its flows are highly managed for water supply, flood control, and other societal and environmental benefits. Folsom reservoir, located just upstream outside of the SASb, is a critical component of the Central Valley Project (CVP) surface water storage and delivery system. The reservoir was established following completion of Folsom dam in 1955 and has a storage capacity of 976,000 acre-feet. Lake Natoma, located immediately downstream of Folsom reservoir on the northeast side of the SASb, serves as an afterbay that regulates Folsom flow releases to the American River.

Based on classification by Lane et al., (2018) the lower American river – like the lower Sacramento river – is characterized as a HSR hydrologic regime. Comparing lower American river flows recorded at the Fair Oaks USGS gaging station (Gage ID 11446500) with the HSR regime clearly reflects the influence of water management on river flows (Figure 7). This is exemplified by splitting the lower American river flow record to flows occurring prior to 1955 and those after (i.e., record split at October 1, 1954. For example, the pre-1995 hydrographs closely resemble the HSR regime, whereas post-1955 flows are much more homogenous. Average daily flows at the Fair Oaks gage for the periods between October 1, 1904 and September 30, 1954 and October 1, 1955 to March, 10 2021 were 3,752 and 3,686 cfs, respectively. Annual peak flows for the complete period of record ranged from 1,820 cfs in water year (WY) 1977 to 132,000 cfs in WY 1951, however flows as high as 318,000 cfs have been historically documented.

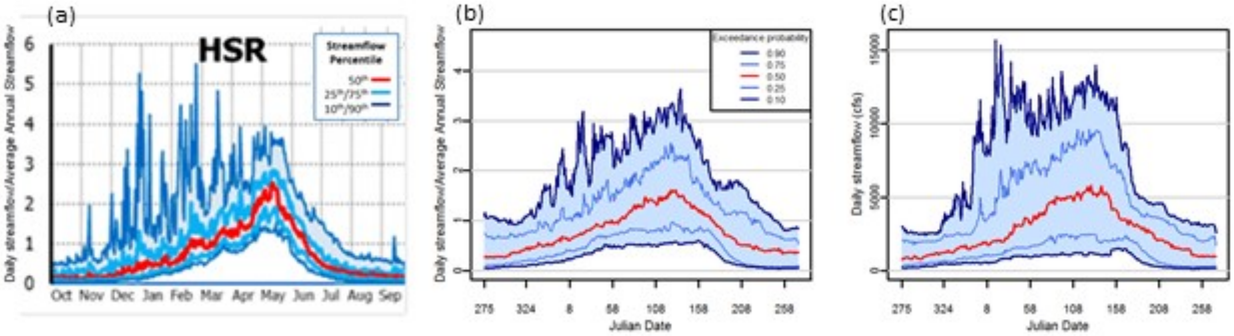

Figure 7. HSR non-dimensional hydrograph (a – modified from Figure 6 Lane et al., [2018]) and non-dimensional (b) and dimensional (c) hydrographs for American river at Fair Oaks.

2.1.3 Lower Cosumnes River

The Cosumnes river watershed drains an area of approximately 949 mi^2 ranging in elevation from 7,743 feet in the headwaters to near sea level at the confluence with the Mokelumne river. Annual rainfall in the watershed typically ranges from 22 inches in the lower portions of the watershed along the valley floor to upwards of 60 inches in the headwater portion of the watershed. Nearly all precipitation occurs between October and April, typical of the region's Mediterranean climate. The vast majority of the watershed (~84%) lies below the Sierran snow-level elevation of approximately 5,000 feet, meaning intense winter rainfall events primarily drive system flooding (Florsheim & Mount, 2002; Robertson-Bryan Inc., 2006a; Booth et al., 2006). Although 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).

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. Detailed analysis of stream flows has been completed by several studies using data from the USGS Michigan Bar gage (ID 11335000), located approximately two miles upstream of the Highway 16 crossing, and the USGS McConnell gage (MCC) (ID 11336000), located approximately 20 miles downstream of the Michigan Bar gage (MHB) where the Cosumnes River crosses Highway 99) (e.g. Anderson et al., 2004; Fleckenstein et al., 2004; Mount et al., 2001; Robertson-Bryan Inc., 2006abc).

Of the river's natural flow regime, dry-season (May-October) baseflows at MCC appear to be the most likely altered (S. Yarnell, personal communication, January 2021). This is consistent with reports that flows at MHB are typically below 30 cfs 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 (Figure 8). This drying is more pronounced downstream of Wilton road (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). 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 cfs at MCC (Mount et al., 2001). These decreases coincide with periods of increased groundwater extraction and have been attributed to changes in surface water-groundwater (SW-GW) interactions. Dry-season baseflows are 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.

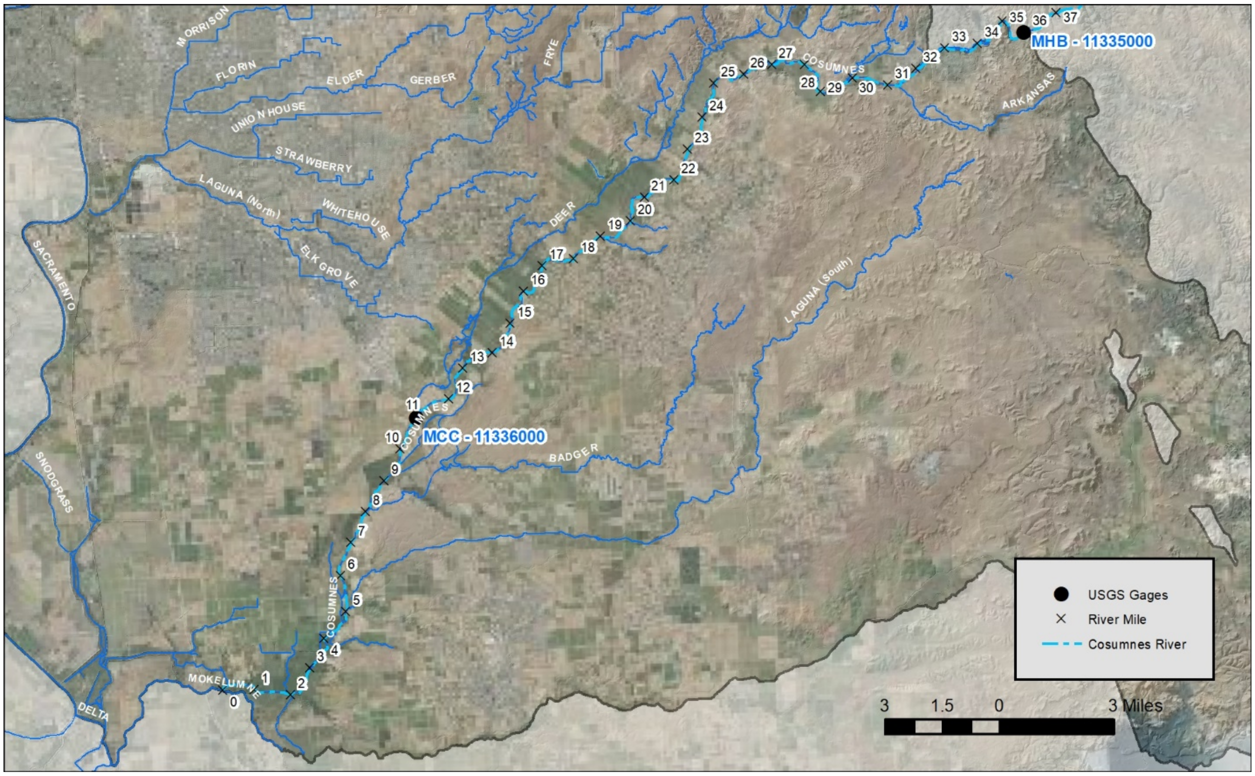

Figure 8. Lower Cosumnes river and river miles.

Based on classification by Lane et al., (2018) the Cosumnes river is mapped as having a 'Rain and seasonal groundwater' (RGW) hydrologic regime. This regime is characterized by winter storms and a low magnitude spring baseflow pulse. Waning snowmelt or groundwater contributions may result in ephemeral streamflow conditions. In general, flows at MHB and MCC coincide with the RGW regime (e.g., Figure 9). Average daily flow at the MHB for the period between October 1, 1907 and October 3, 2019 was 498 cfs, while average daily flow at MCC between October 1, 1941 and October 15, 1982 was 543 cfs. Annual peak flows at MHB for the complete period of record ranged from 134 cfs in water year (WY) 1977 to 61,600 cfs in WY 1997.

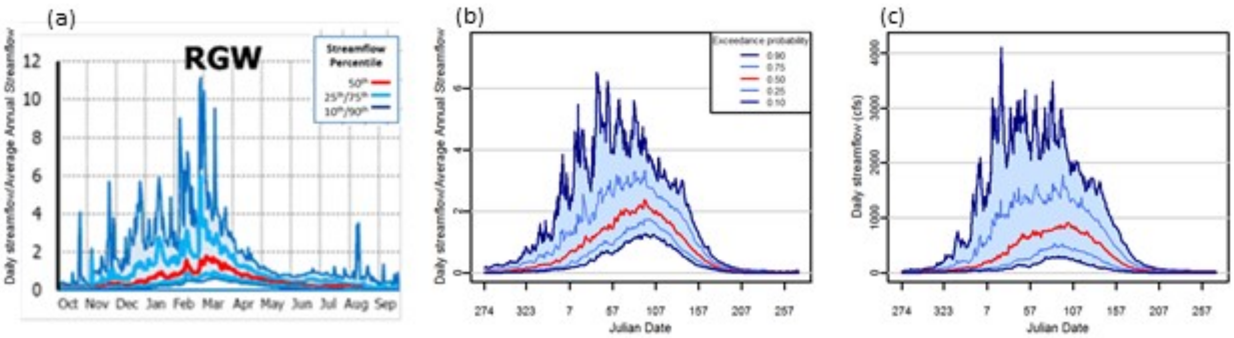

Figure 9. RGW non-dimensional hydrograph (a – modified from Figure 6 Lane et al., [2018]) and non-dimensional (b) and dimensional (c) hydrographs for Cosumnes River at Michigan bar.

The approximately 123 square mile Deer creek watershed is the main system of tributaries draining to the Cosumnes river in the SASb. Hydrologically, flows in Deer creek and its tributaries are driven by winter precipitation, stormwater runoff, irrigation runoff or return flows, and discharge of treated wastewater. Daily average flows in Deer creek were recorded from October 1, 1960 through September 29, 1977 at USGS gaging station ID # 11335700. These data show the flashy nature of the creeks response to storm events as well as prolonged periods of no or low flow (<5 cfs) during later spring and summer (e.g. May – October) (Figure 10). Overall, 45% of all days had zero flow, of which 100% of August and September measurement were zero. The average daily flow over this period was 25 cfs and the peak flow was 2,160 cfs.

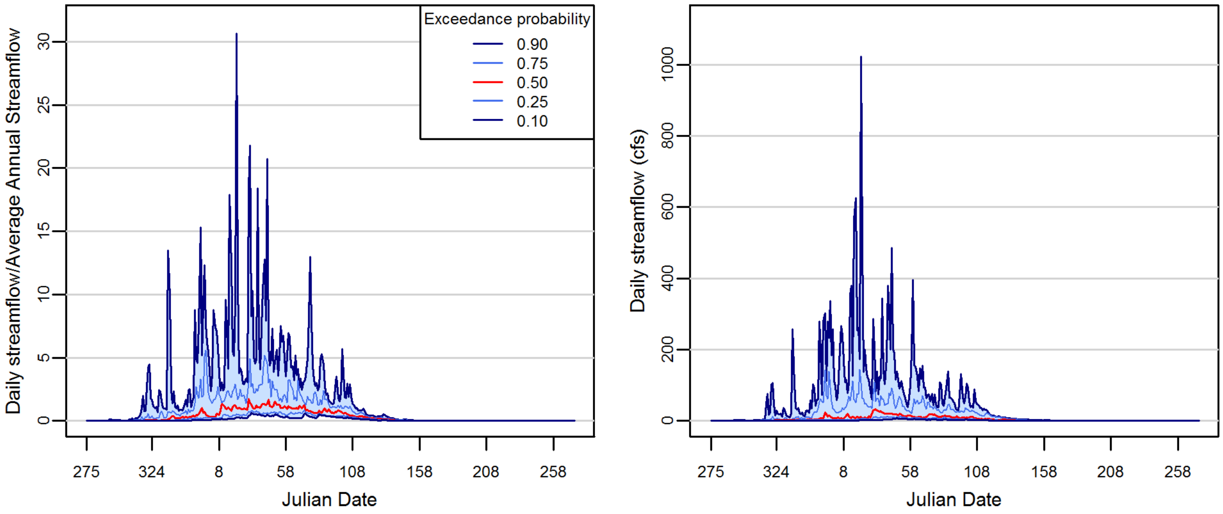

Figure 10. Non-dimensional and dimensional hydrographs for Deer creek (USGS gage 11335700).

2.1.4 Mokelumne River and Delta

The southwestern boundary of the SASb is defined by portions of the Delta cross-channel, Snodgrass slough, and the Mokelumne river. At the confluence with the Cosumnes the Mokelumne river watershed drains an area to the east of approximately 1085 mi^2 that overlaps with the Cosumnes subbasin. In addition to these areas the Mokelumne river also drains areas to the north that include Snodgrass slough, Stone Lakes National Wildlife refuge and Laguna Creek, which drains to the refuge system and Snodgrass slough via the lower portion of Morrison creek that does not discharge to the Sacramento River. Flows in Laguna creek and its tributaries are ephemeral.

Based on flow records at USGS gage 11336585 Laguna creek was dry 12% of the time from October 1, 1995 through October 21, 2018 and regularly experienced periods of zero or low flow throughout the year (USFWS, 2007). Downstream of Laguna creek water surface elevations in the Stone lakes system and Snodgrass slough depend on both flows from upstream and tidal influence from the delta but can be influenced by backwater from the Mokelumne River. These regions as well as the Sacramento river and the American river up to the I Street Bridge are all within the extent of the legal Delta established under the Delta Protection Act (Section 12220 of the Water Code) passed in 1959. The Delta consists of a mix of water from San Francisco Bay and tidally influenced fresh water from the Sacramento and San Joaquin River watersheds, with a land surface lower than the high river stage.

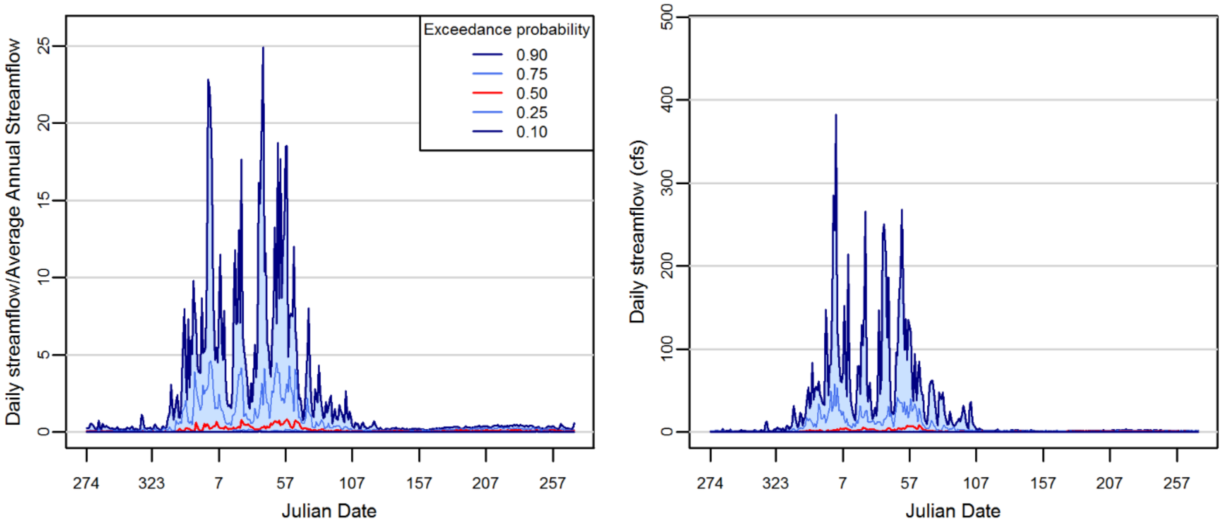

Figure 11. Non-dimensional and dimensional hydrographs for Laguna creek (USGS gage 11336585).

2.2 Special-status species

LWA conducted a review to identify potential sensitive biological features including target plant and wildlife species that have the potential to occur in the SASb. The review was initiated with a query of the most recent version of the CDFW California Natural Diversity Database (CNDDB) to identify reported occurrences of sensitive species within 1 mile of the SASb. In addition to the CNDDB query, USFWS species lists and critical habitat maps were reviewed. Existing environmental documents and reports were also reviewed to supplement these data sources (County of Sacremento et al., 2018; Moyle et al., 2015; Santos et al., 2014; SWRI, 2001; UC Davis, 1999). For the purposes of this report, special-status species are defined as follows:

- Plants and animals listed, proposed, or candidates for listing as threatened or endangered (including delisted species) under FESA.
- Plants and animals listed or proposed for listing by the State of California as threatened or endangered under CESA.
- Plants listed as rare under the California Native Plant Protection Act.
- Plants included in CNPS Ranks 1 and 2.
- California designated status:
    - Animal species that are fully protected in California; or,
    - Species of special concern (CSC) to the CDFW.

The list of special-status species was compiled and subset to only those species that occupy surface waters for at least part of their life-history. The final list includes 14 fish species and 2 reptile species (Table 1). Consideration of habitat requirements (e.g., physical and chemical conditions such as hydraulics [depth and velocity], substrate, and temperature) for these species often plays a large role in water management operations influencing SASb surface waters (Section 3).

Table 1. Special-status species occupying surface waters in the SASb

Scientific name	Common name	ESA status	CESA status	CDFW status	Principal Rivers[1]	Tributaries[2]
Acipenser medirostris	southern green sturgeon	Threatened	None	SSC	Sacramento is a migration corridor for adults and juveniles to and from upstream spawning grounds	low to no potential
Acipenser transmontanus	white sturgeon	None	None	SSC	Sacramento is a migration corridor for adults and juveniles to and from upstream spawning grounds	low to no potential
Archoplites interruptus	Sacramento perch	None	None	SSC	Transplanted populations in American and Sacramento and their tributaries	moderate potential
Cottus gulosus	riffle sculpin	None	None	SSC	Mokelumne, Sacramento, and Delta	low potential
Entosphenus tridentatus	pacific lamprey	None	None	SSC	All	low potential
Hypomesus transpacificus	delta smelt	Threatened	Endangered	SSC	Mokelumne, Sacramento, and Delta	no potential
Mylopharodon conocephalus	hardhead	None	None	SSC	Sacramento and American	moderate to high potential
Oncorhynchus mykiss irideus	steelhead - Central Valley DPS	Threatened	None		All life stages in American and Cosumnes; Sacramento is a migration corridor for adults and juveniles to and from upstream spawning grounds	low potential
Oncorhynchus tshawytscha	chinook salmon - Sacramento River winter-run ESU	Endangered	Threatened		Sacramento is a migration corridor for adults and juveniles to and from upstream spawning grounds	no potential

Scientific name	Common name	ESA status	CESA status	CDFW status	Principal Rivers[1]	Tributaries[2]
Oncorhynchus tshawytscha	chinook salmon - Central Valley spring-run ESU	Threatened	Threatened		Sacramento is a migration corridor for adults and juveniles to and from upstream spawning grounds	no potential
Oncorhynchus tshawytscha	chinook salmon - Central Valley fall & late fall-run ESU	None	None	SSC	All life stages in American and Cosumnes; Sacramento is a migration corridor for adults and juveniles to and from upstream spawning grounds	low to moderate potential
Pogonichthys macrolepidotus	Sacramento splittail	None	None	SSC	Delta	low potential
Spirinchus thaleichthys	longfin smelt	Candidate	Threatened	SSC	Sacramento and Delta	no potential
Emys marmorata	western pond turtle	None	None	SSC	moderate potential	moderate to high potential
Thamnophis gigas	giant garter snake	Threatened	Threatened		low potential	moderate to high potential

[1] Either brief description of occupancy within the SASb principal surface waters or potential for species to be present

[2] Potential for species to be present

2.3 Instream flow requirements

2.3.1 Lower Sacramento River

Many project-level and system-wide agreements or regulatory obligations dictate water management operations in the Sacramento river basin. Of the multitude of water management operation in the basin integrated operations of the CVP and State Water Project (SWP) aggregate to have the strongest influence on conditions downstream. A summary of several key CVP and SWP regulatory requirements are provided in Table 2 (see also reviews by NCWA, 2019; SWRI, 2001).

Table 2. Key CVP and SWP regulatory requirement

Regulatory agreement/obligation	Date(s)	Description
SWRCB Water Rights Order 90-05 & 91-01	1990 & 1991	Establishes water right requirements on the U.S. Bureau of Reclamation's (Reclamation) operations of Keswick Dam, Shasta Dam, the Spring Creek Power Plant and the Trinity River Division related to temperature control in the Upper Sacramento River for the protection of fishery resources and requires monitoring and reporting to evaluate compliance with those requirements.
SWRCB Revised Water Right Decision 1641 (Water Rights Order 2000-02)	2000	Amended the water right license and permits for the CVP and SWP requiring them to meet certain flow objectives in the Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary (1995 Bay-Delta Plan). Specifically, places responsibility on the Department of Water Resources and the U.S. Bureau of Reclamation for measures to ensure that specified water quality objectives are met.
NMFS Biological Opinion for the Reinitiation of Consultation on the Long-Term Operation of the Central Valley Project and State Water Project	2019	Contain numerous terms and conditions for CVP and SWP operations including minimum flow requirements, temperature requirements, water quality standards, and entrainment controls.

2.3.2 Lower American River

Flow and temperature conditions in the lower American river results from complex interactions between hydrologic conditions, water management operations, and other decision-making regarding protection of environmental resources (SWRI, 2001). Folsom and Nimbus dams are part of the CVP and thus subject to some of the same requirements listed above for the lower Sacramento river. In addition to these requirements the U.S. Bureau of Reclamation who owns and operates the CVP has adopted instream flow requirements proposed by the Water Forum as outlined in the "Modified Flow Management Standard Proposed Water-Right Terms and Conditions, November 2017" (ARWA, 2017). The Water Forum is comprised of local business and agricultural leaders, citizen groups, environmentalists, water managers and local governments in the Sacramento region. The stated goals for the modified standards include "protecting anadromous salmonids, preserving recreational and aesthetic values, avoiding catastrophic water shortages in the basin and contributing to the Delta's ecological health downstream".

2.3.3 Lower Cosumnes River

To the best of our knowledge, at the time of writing, no overarching agreement or regulatory obligation exists for defining minimum instream flow requirements for the lower Cosumnes river. However, requirements for individual projects, diversions, and/or water rights exist on an ad hoc basis (see SWRCB, 2020 for example). Generally, such agreements are based on meeting flow requirements necessary to satisfy existing water rights (i.e., the State Water Resources Control Board [SWRCB] designation of the Cosumnes river as a 'fully appropriated stream' [FAS] from July 1st to October 31st, the South Fork Cosumnes river as a FAS from April 15th to October 31st, and Deer creek as a FAS from May 1st to October 31st [see SWRCB Order WR 98-08]). However, some instream flow agreements are based on environmental factors such as habitat and/or passage requirements for chinook salmon.

Cosumnes 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[3]. 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 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, 2020[4]).

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 cfs as the minimum bypass flow condition for both the MCC and MHB locations. This estimate does not

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

[4] See CDFW Grand Tab: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=84381&inline.

account for river seepage, which under current conditions would necessitate a larger flow requirement at MBH. Seepage estimates vary along the river but are generally in the range of 1 to 3.5 cfs/mile, suggesting flows upward of 266 cfs at MBH would be required. The effect of stream diversions between MHB and MCC at the time of passage must also be considered and added to recommended bypass flow requirements at MHB (see SWRCB, 2020 for example).

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) which estimate flows of 32.8, 54.7, and between 40-45 cfs, respectively. These earlier predictions were each based on achieving a minimum flow depth of 0.6 feet at MCC using 1-D hydraulic modeling and accounting for seepage losses[5]. Observations by the Fisheries Foundation of California (FFC), note that fall (October-November) pulse flows on the order of 100 cfs may be required for a period of at least 10 days to provide and maintain passage conditions throughout the lower Cosumnes reach. FFC also report that stranding or delays can occur for higher pulse events of 200-400 cfs 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. Second, passage criteria also evolve over time as understanding of species biological requirement improves. Although 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 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 cfs is considered to more likely account for current river conditions and species biological requirements.

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.

2.4 Surface water and Groundwater 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)

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

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.

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 (Fleckenstein et al., 2006; Niswonger 2005; Niswonger & Fogg, 2008).

A review of existing studies on SW-GW interactions in the SASb principal surface water bodies are described in the sections below.

2.4.1 Lower Sacramento River

Explicit study of SW-GW interactions along the Lower Sacramento River in the SASb has not been extensively evaluated. Limited analysis of spatial and temporal SW-GW interactions were investigated by TNC (2014) using results from C2VSim-FG model[6] historical simulation (1922-2009). Based on simulated annual groundwater flows, the researchers found the portion of the Lower Sacramento River in the SASb (e.g., defined as Reach E in their analysis) to be net losing at the beginning of the simulation period in the 1920's and found the losing trend to increase through time. Variable, but generally gaining conditions were simulated in Sacramento river reaches outside of the SASb upstream of Fremont. This finding corroborates other reports stating that while the Sacramento river may be hydraulically connected with the regional groundwater system it is a losing stream (MHW, 2006). The spatial extent of this possible hydraulic connection is not well constrained but studies support that it does not extend far from the river (RMC, 2015). For example, groundwater in the nearby Beach/Stone Lakes basin has been reported to have little exchange with the river and thus be considered hydrologically independent (Carollo Engineers, 2000).

2.4.2 Lower American River

Surface water and groundwater hydrology of the lower American river have been the subject of extensive documentation but studies explicitly focused on SW-GW interactions remain limited with the exception of focused studies centered on the Aerojet Superfund Site. Additional focus on this topic emerged as part of SWRCB review of a petition by Southern California Water Company to revise the Declaration of Fully Appropriated Streams adopted by SWRCB Order WR 98-05 in order to appropriate treated groundwater that was being discharges to the lower American river (SWRCB, 2003). Expert testimony and extensive evidentiary materials presented as part of the petition supported that circa 1980s to 2000s groundwater levels were typically at or above the bottom of the riverbed from Lake Natoma to approximately 3,000 feet downstream of Nimbus Dam and were close to riverbed for an additional 3,000 feet downstream (e.g., 3,000 to 6,000 feet downstream of the dam). Beyond the 6,000 foot mark, westward declining groundwater levels resulted in an increasingly large unsaturated zone between the river and groundwater table. Review of historic groundwater contours presented from the 1950s onward corroborated these findings consistent with the view that downstream portions of the lower American River are a losing stream. Further review indicated that prior to 1958 stream losses appeared to be at relatively steady state (e.g., groundwater withdrawals were in balance with river recharge). However, subsequent changes in head due to lowered groundwater levels resulted in increased river losses as it recharged groundwater. Although the potential exists it is unclear if higher groundwater levels in the region below lake Natoma result in groundwater discharge to the river and if so, what the magnitude of such discharges are.

In addition to materials associated with the SWRCB petition, investigation by TNC (2014) (see above) found, on average, the lower American river was annually gaining

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[6] See TNC (2014) for details of the C2VSim-FG integrated hydrologic model.

during the period from 1922 to 1930 but subsequently transitioned to a losing reach after the 1960s.

2.4.3 Lower Cosumnes River

Previous study of SW-GW interactions along the Lower Cosumnes River has primarily been addressed in two ways: (1) through data-driven approaches that include field measurement of streamflow, groundwater levels, seepage rates, sediment temperatures, soil moisture, and sedimentology; and (2) through numerical simulation. 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 1940s. 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 12), 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 1940s, increased groundwater production and declines of regional groundwater levels decoupled the river from saturated groundwater along much of the river. Increased groundwater pumping in subsequent decades has exacerbated this issue, resulting in continued lowering of regional water tables and increasing the saturated groundwater disconnection from the river. These groundwater declines are suggested by Mount et al. (2001) and others to be responsible for declines in fall streamflows and observed increases in low-flow and no-flow periods.

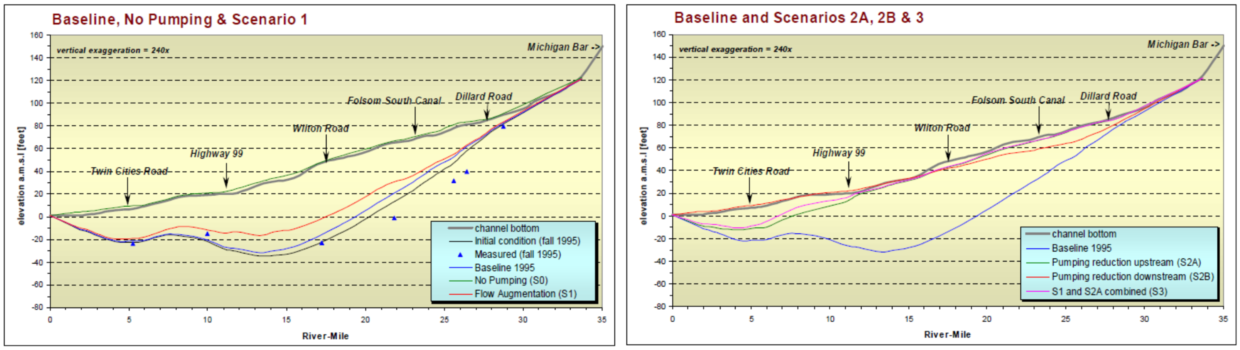

Figure 12. Measured, modeled, and simulated groundwater levels below river channel by Mount et al. (2001) (Figures 8 and 9). River miles may differ slightly from those used in this review.

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 acre-feet per year to partly reconnect the upper reaches of the river and ~250,000 acre-feet per year to reconnect the entire river. Gaining conditions were achieved more rapidly (6-years) between MCC (RM 0) and Twin Cities Bridge (RM 5.5).

Although the no-pumping scenario reduced seepage and thus improved fall conditions, that the river remained 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 and have shown varying levels of disconnection between the Cosumnes riverbed and underlying principal aquifer. Using well data from April 2000 to 2001, Mount et al. (2001) recorded groundwater to be 7-20 feet below the channel near Dillard (RM 27.5), between 30-50 feet below the channel from Meiss to Highway 99 (RM 11-25.5), and between 3-15 feet 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 of the channel downstream of Twin Cities Bridge (RM 5.5) (Figure 12). 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. 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 feet below ground surface [bgs]) along the upstream portions of the river, 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.

As discussed 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 13). Whether these connections were with the primary aquifer or due to formation of shallow perched aquifers is unclear. Although their simulated groundwater levels had large local variability between geologic realizations, most connections

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

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.

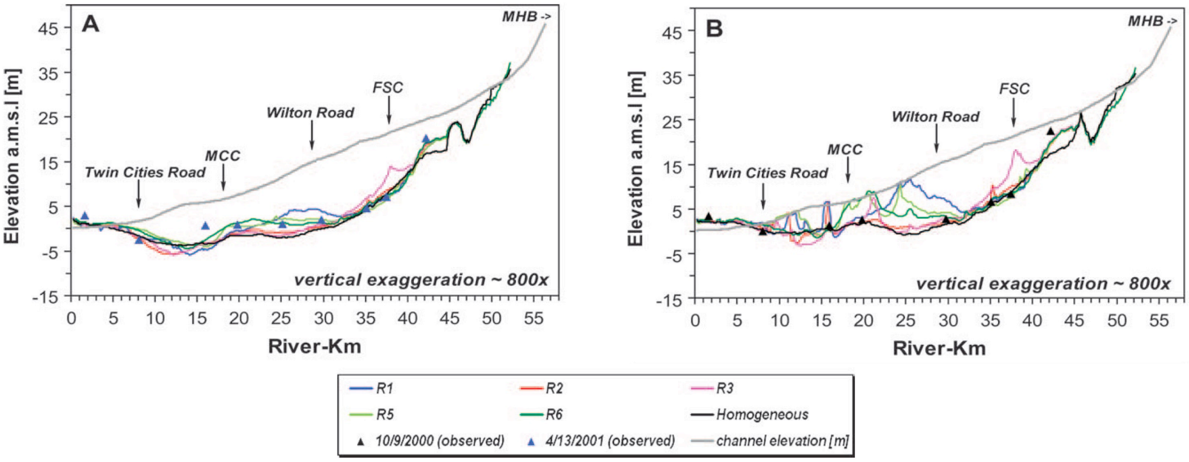

Figure 13. Simulated dry season (a) and wet season (b) groundwater levels of Fleckenstein et al., (2001) from different geologic realizations (Figure 11). River miles may differ slightly from those used in this review.

Lastly, 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 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 2,000 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.

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. 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.

3. Methods

In this section, we provide an overview of the data and models used in this study, the rationale behind groundwater flow simulation scenarios, and the classification system applied to ISW.

3.1 Data sources

3.1.1 Groundwater

Historic and present-day groundwater conditions were analyzed using all available data from six sources (Figure 2):

(1) California Department of Water Resources (DWR) Periodic Groundwater Level Database
(2) University of California at Davis (UCD) monitoring network
(3) Omochumne-Hartnell Water District (OHWD) monitoring network
(4) Sacramento State monitoring wells
(5) Aerojet
(6) Sac IWRM

Most groundwater level data is collected biannually in spring and fall and intended to capture seasonal variation – notably due to winter recharge and pumping and recharge during the dry growing season. In the South American Subbasin, periodic groundwater level data measurements peak in April and October (Figure 14) and suggest that future data collection should occur in these months to maximize data comparability across space and time.

Biannual seasonal groundwater level within the Sacramento Central Groundwater Authority (SCGA) jurisdictional boundary has been measured for decades; these measurements account for most of the spatial spread of groundwater level observations in the SASb and can be found in the DWR Periodic Groundwater Level Database [source (1) above]. Three additional networks, either established or maintained by UCD, OHWD, and Sacramento State all collect high-frequency, 15-minute interval groundwater elevation data. The UC Davis network (2) is situated on land owned by the Nature Conservancy and has collected data fall of 2012, the OHWD network (3) has collected data since fall of 2018, and the Sacramento State network (4) has collected data since spring of 2016. Aerojet monitoring wells (5) used in this study have been collecting data since 1982 and are actively monitored as part of on-site monitoring and remediation actions. Sac IWRM (6) is hydrologic model that includes the SASb and incorporates historic groundwater monitoring data; most of these data are included in (1). Duplicate measurements between data sources were reconciled by comparing monitoring site identification codes and position (latitude and longitude).

Modeled groundwater hydraulic head reflecting the transmissivity-weighted layer 2 and 3 (Laguna and Mehrten) heads from Cosana which represent average groundwater level in the production zone of the principal aquifer were compared against field-based monitoring groundwater level data[8].

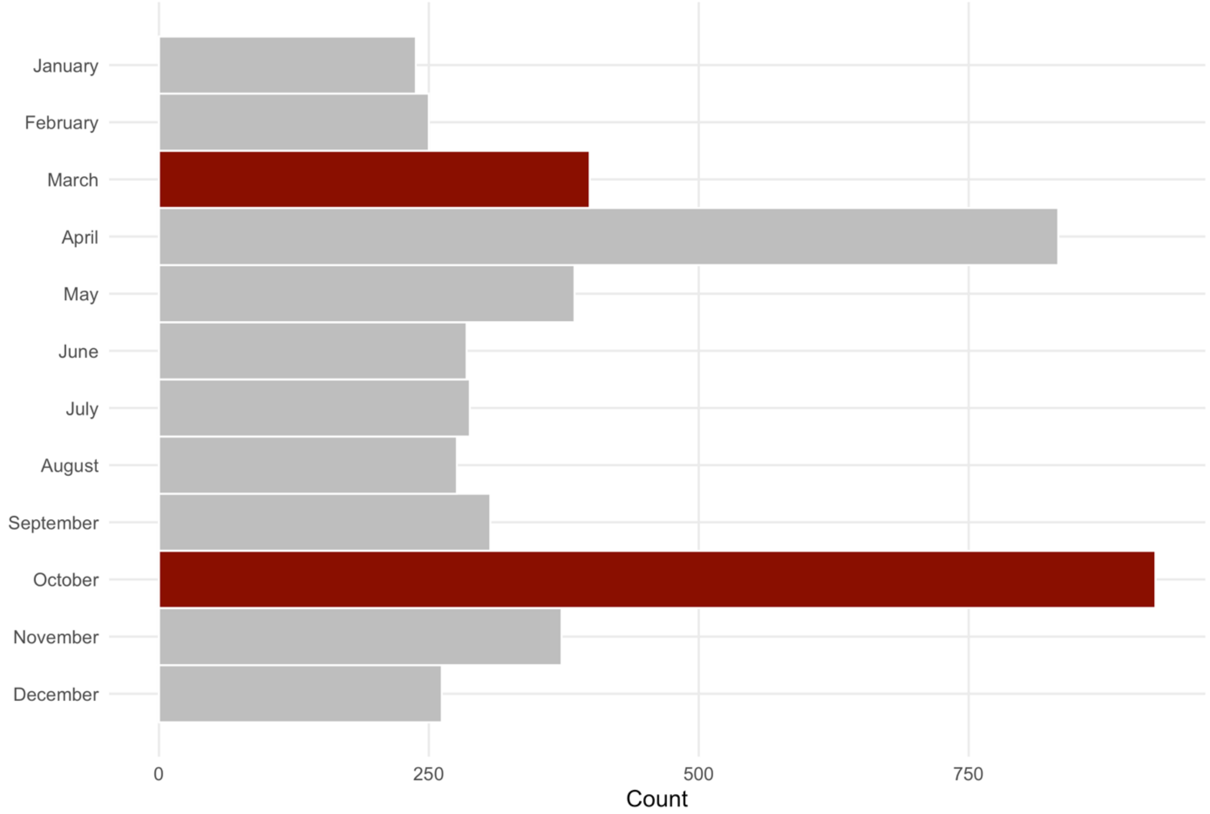

Figure 14: Periodic groundwater level measurements (2000-2021) reported by DWR in the South American Subbasin indicate peaks of seasonal data collection in April and October although DWR Best Management Practices indicate that monitoring wells should collect at least biannual measurements in spring (mid-March) and fall (mid-October) (CA-DWR, 2017). March and October are highlighted in the graph above, and roughly agree with historical data collection trends. It is especially important in dry years to monitor in mid-March, because pumping may begin as early as April; thus, a March measurement in a such a dry year provides a more accurate representation of ambient spring groundwater level. Consistent data collection in March and October ensures data comparability across years.

3.1.2 Surface Water

Surface water data considered in this analysis were designed to be consistent with the Cosana numerical groundwater flow model, and thus, the Cosana stream node representation (Figure 2 - *Figure 3*) was used. In particular, the vertical thalweg elevation, which represents the bottom of the streambed was used to ascertain the approximate vertical elevation at which various parts of streams may be reasonably connected to groundwater. This study uses 1,107 stream nodes. Soil thickness from the SSURGO soil database (Soil Survey Staff, NRCS, 2021) was taken to be a reasonable proxy for the clogging layer, a thin layer beneath streams, which is typically of lower conductivity than the surrounding sediment. Thus, at each stream node location, soil

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[8] As demonstrated in 3.2 Groundwater Level Interpolation, 99.4% of observations at wells occur within the Alluvium, Laguna, and Mehrten layers.

thickness[9] was extracted and subtracted from the thalweg elevation to define the elevation at which surface waters may be connected to groundwater.

Modeled nodal seepage at each of the Cosana stream nodes considered in this study were aggregated into reach-level (Figure 3) seasonal spring and fall seepages to assess historic variability in ISW depletion rates.

3.2 Groundwater Level Interpolation

Groundwater levels were assessed at biannual seasonal intervals during the period from spring 2005 to fall 2018 and encompass what can be considered "historic"[10] to approximately "present-day" seasonal conditions. This temporal range was selected because poor data density prior to spring 2005 and after fall 2018 prohibits meaningful analysis. "Spring" was defined as the months of March, April, and May and "fall" was defined as the months of August, September, and October.

At each monitoring location, the average groundwater level measured during spring and fall was computed by taking the grouped mean of observations in each spring and fall respectively. Next, to improve spatial data density and ascertain long-term regional trends, data were arranged in 4-year running seasonal means. For example, the 2005-2008 spring level is defined as the average spring groundwater elevation in 2005, 2006, 2007, and 2008. A four-year sliding window was applied to data from 2005 to 2018, resulting in 22 seasonally averaged groundwater elevation conditions (e.g., spring 2005-2009, fall 2005-2009, …, spring 2015-2018, fall 2015-2018). Windows of differing length (e.g., 1, 2, and 3-year long running means) were explored but resulted in larger groundwater level variance due to a lack of adequate spatial density, and hence, not used. By contrast, 4 year running means gave adequate regional spatial data density and were not so long in duration as to mute the impact of significant dry periods such as the 2012-2016 drought.

After data were grouped into seasonal 4-year windows, ordinary kriging[11] (Journel A.G. and Huijbregts, 1978) was applied to groundwater elevation measurements to generate groundwater level surfaces across the SASb at a 500 meter (0.31 mile) resolution. In order to minimize boundary effects, monitoring well data within a 20 kilometer (12.4 mile) buffer of the SASb were included, which effectively incorporates groundwater level data from the Cosumnes and North American subbasins, and Yolo county to the west of the Sacramento river (Figure *17*). Groundwater level measurements were screened to include data from wells shallower than 300 feet in total completed depth to reflect

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[9] According to SSURGO, soil thickness in the SASb ranges from 0 to about 170 centimeters.

[10] Importantly, this period contains the recent 2012-2016 drought.

[11] An exponential variogram model was used, and results did not appreciably differ from linear or spherical models. Stationarity across the unconfined to semiconfined aquifer is a reasonable assumption in the unconsolidated, alluvial aquifer-aquitard system that spans the South American subbasin and adjacent subbasins, which exhibit relatively continuous geology across borders. Data outliers were controlled by removing tails of the distribution above and below the 97.5th and 2.5th percentiles respectively. Groundwater elevations were approximately normal in distribution, thus log-transformation and exponentiation after kriging was not required.

conditions in the unconfined to semiconfined production aquifer, which are comparable to heads in layers 2-3 of Cosana. All monitoring points were further intersected with the Cosana model grid, and 99.4% of observations at wells occur within the Alluvium, Laguna, and Mehrten layers. 0.6% of observations occur in the Ione and Valley Springs.

3.3 Forward simulations of Projects and Management Actions and Climate Change

ISW depletions are characterized in terms of historical data and models of past hydrology (i.e., via Cosana), but also in terms of future, anticipated hydrology. Forward-simulated hydrologic conditions using the Cosana groundwater flow model were used to estimate the impact to ISW from:

- the combined effects of projected water use in the Basin;
- projects and management actions (PMA) already underway (Harvest Water, OHWD[12] recharge, and regional conjunctive use); and
- climate change.

Model outputs including future groundwater basin storage, groundwater level, seepage from streams, and streamflow were collectively used to analyze impacts to ISW.

In the presentation of results (Section 4), groundwater level conditions in the current conditions (baseline) are compared to groundwater level conditions in the scenarios evaluated. Five scenarios are compared:

- ***Baseline***: current conditions
- ***Projected***: projected groundwater use (i.e., business as usual with increased demand)
- ***Projected CC***: projected groundwater use with a median climate change warming scenario[13]
- ***Projected PMA***: projected groundwater use considering feasible, in-progress projects and management actions (Harvest Water, OHWD recharge, regional conjunctive use)
- ***Projected PMA CC***: projected groundwater use considering feasible, in-progress projects and management actions (Harvest Water, OHWD recharge, regional conjunctive use) and with a median climate change warming scenario

Differences in groundwater level, seepage, and streamflow between each of the scenarios and the “baseline” inform how ISW in the basin may respond to projected groundwater management. These differences are applied to observed data to translate model estimates of change to observed data. For example, to estimate the change in ISW location (and hence,

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[12] OHWD = Omochumne - Hartnell Water District

[13] Climate change (CC) scenarios are driven by changes in temperature and streamflow provided by the American River Basin Study (USBR, 2020) “central tendency” scenario, which reflect median temperature and precipitation outcomes.

change in ISW reach length) under each scenario, the groundwater level differences implied by each scenario at a Fall 2015 reference point were evaluated by the model, then this difference was applied to the measured and interpolated Fall 2015 level. Fall 2015 was chosen as a reference point because it represents a recent historical minimum in groundwater level across the basin.

3.4 Classification of ISW and Disconnected Surface Waters

The overarching goal of this analysis was to characterize the location, timing, and quantity of ISW in the SASb to inform the development of sustainable management criteria that avoid significant and unreasonable ISW depletion as defined by SGMA. Thus, it was important to classify all surface waters into "ISW" and "Disconnected" and explore how these classifications change over time. Groundwater and surface water data and modeled results were used to inform this classification.

As described in Section 2.4 Surface water and Groundwater Interactions, groundwater and surface water interact based on the relationship between the groundwater level and adjacent stream stage. Generally, if the groundwater level (also called the groundwater hydraulic head) exceeds the stream stage, a stream is interconnected and gaining. By contrast, if the stream stage exceeds the groundwater level, the stream is losing (Figure 15). However, a losing stream may still be ISW if the groundwater level intersects the clogging layer elevation; otherwise, if groundwater does not intersect the clogging layer, the stream can be considered disconnected. Importantly, a stream may be assessed along its entire reach to determine reaches characterized by connection and disconnection.

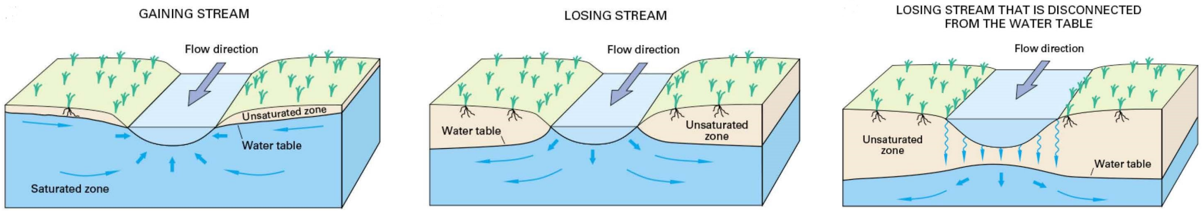

Figure 15: Surface water may be characterized as interconnected and gaining (left), interconnected and losing (center), or disconnected and losing (right). Figure modified from USGS.

This study uses a two-step system[14] to distinguish ***ISW*** and ***Disconnected*** surface water reaches described below and depicted in Figure 16. First, we determine interconnected and disconnected *stream nodes*:

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[14] Previous research has advanced similar classification schemes as the one put forward in this study. For instance, Brunner et al. (2009) devised a three-class surface water classification system (interconnected, transition, and disconnected), and defined the "transition" class based on a zone of capillary action between saturated groundwater and the streambed clogging layer which was determined via a 1D analytical model informed by geologic properties. In this study, we neglect the impacts of capillary action because the local-scale geologic information required to drive 1D modeling of capillary action are poorly constrained in the study site and difficult to obtain, but may represent a potential path for future scientific investigation.

- *Interconnected stream nodes*: groundwater elevation at the stream node in question is greater than or equal to the clogging layer elevation under the thalweg
- *Disconnected stream nodes*: groundwater elevation at the stream node in question is less than the clogging layer elevation under the thalweg

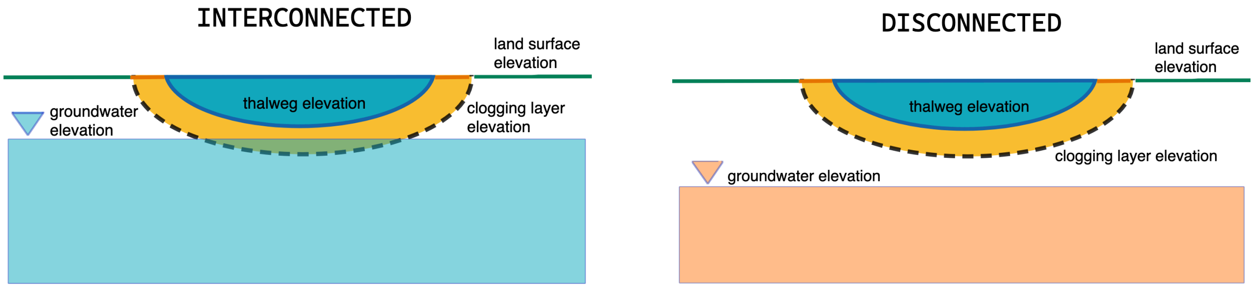

Figure 16: Classification of *Interconnected* Surface Water (ISW) and *Disconnected* stream nodes depends fundamentally on a comparison of the clogging layer elevation beneath the streambed and the groundwater elevation. If the groundwater elevation intersects the clogging layer, a stream node is considered ISW (right), otherwise, it is considered disconnected (left).

This classification is applied at each of the 1,107 stream nodes, and across the 22 seasonal groundwater level conditions from 2005-2018 (3.2 Groundwater Level Interpolation).

Second, looking across all reaches (Figure 4), we distinguish between *ISW and Disconnected* reaches (Figure 24).

- ***ISW:*** a majority of stream nodes are *Interconnected* for > 0% of all seasons evaluated in the historical period from 2005-2018.
- *Disconnected*: a majority of stream nodes are persistently *Disconnected* during all seasons from 2005-2018.

ISW and ***Disconnected*** categories thus represent reach- and seasonal-level summary statistics of *Probable ISW* and *Probable Disconnected* Cosana stream nodes, and are the final classifications used to inform GSP planning and SMC development. SMC and monitoring networks are developed for ***ISW*** reaches. Due to their persistent disconnection, ***Disconnected*** reaches are not considered within the requirements established by SGMA.

This classification is applied to historical groundwater level interpolations, and then across projected groundwater management in order to assess how expected groundwater use and climate change could affect ISW location.

3.5 Estimation of Depletion Volume at ISW Reaches

ISW depletion is extremely difficult to measure in the field, especially at the scale of an entire reach, and hence, numerical and analytical models are relied upon to estimate the magnitude and direction of stream-aquifer exchange. In accordance with SGMA, the Cosana groundwater flow model is used to estimate stream seepage along surface water reaches. The time period analyzed was 2005-2018 to maintain consistency with the previous groundwater level analysis. Cosana only runs through 2018.

Depletion volume is driven by the relative difference between aquifer and stream hydraulic head. Generally, if additional groundwater drawdown occurs adjacent to a connected, losing stream, increased surface water depletion is expected because the hydraulic gradient between the stream and aquifer also increases.

3.6 Location and Timing of Gaining and Losing Reaches

Gaining and losing reaches are defined by the direction of flow between surface and groundwater, which is itself controlled by the hydraulic gradient between these two systems. Gaining surface water reaches have a stage elevation lower than adjacent groundwater elevation; losing surface water reaches have a stage elevation higher than adjacent groundwater elevation (Figure 15). Gaining and losing conditions are examined by analysis of Cosana model results of stream-aquifer interaction captured by the seepage term. Positive seepage indicates gaining stream conditions, and negative seepage indicates losing stream conditions. Seepage was aggregated at the seasonal (spring and fall) and reach level for major surface water bodies (American, Sacramento, Mokelumne, and Cosumnes Rivers) in the SASb. Location and timing of gaining and losing reaches is examined by mapping and hydrogeologic interpretation of seepage timeseries.

3.7 Changes in ISW streamflow

A primary concern of projected groundwater management is the avoidance of groundwater pumping that causes significant decreases in groundwater baseflow to streams that reduces streamflow and causes damage to beneficial users of that streamflow. Thus, changes in streamflow along the American, Sacramento, and Cosumnes rivers resulting from projects and management actions and climate change were evaluated with Cosana and compared to best available estimates of streamflow requirements for fish migration (Section 2.3.3 Lower Cosumnes River). Flows are summarized by exceedance probability during October to December flows because this time frame aligns with salmonid spawning migration. Due to modeling constraints, flows are estimated at the downstream outlets of the Cosumnes and Sacramento Rivers in the model domain. American River flows are estimated at H Street Bridge.

3.8 Satellite Analysis of Wetting and Drying

Portions of the American Sacramento, and Mokelumne Rivers that border the SASb are perennial, but certain reaches along the Cosumnes River are ephemeral. High resolution remote sensing was assessed as a potential means to qualitatively describe important reaches along the Cosumnes River. “Drying” events along the Cosumnes River were assessed with 30-centimeter pan-sharpened resolution imagery provided by

Google Earth Pro in order to scope the feasibility of on-demand, reach-scale documentation of the timing location of “drying” events.

4. Results

4.1 Historic and Present-day Groundwater Conditions

4.1.1 Monitoring well hydrographs

Historic groundwater conditions were assessed via hydrographs at monitoring points in the SASb, and groundwater surfaces derived from these measurements (grouped by season over 4-year sliding windows as described in Section 3.2 Groundwater Level Interpolation). Monitoring well hydrographs[15] – depending on the temporal resolution available – can provide sub-seasonal insights into ambient groundwater level trends at specific monitoring locations and at particular screened interval depths. Taken together, the individual hydrographs in the SASb do not show one consistent trend, but rather, show decreasing, increasing, and stable groundwater elevations trends over time. This implies that groundwater pumping is localized and depth-dependent, a trend that is visible in the 120 hydrographs in *Appendix A: Hydrographs*, and the groundwater elevation surfaces discussed in the following section.

4.1.2 Groundwater elevation trends and flow direction

Groundwater elevation surfaces are statistical representations across the entire study area computed from monitoring well hydrographs. In this study, groundwater elevation surfaces were used to compare groundwater and surface water features over time to determine the location and timing of ISW.

Interpolation occurs at a larger spatial scale than the SASb to minimize boundary effects and allow for some interpretation of groundwater flow direction, thus interpolation results show Sacramento County-wide groundwater level estimates (Figure 17). Groundwater levels in the SASb (Figure 18) show oscillating seasonal trends, which are more easily visible when comparing the median and interquartile range of groundwater level across years and seasons (Figure 19). The difference between median fall and spring groundwater level in the SASb suggests a typical interannual fluctuation of around 3 to 10 feet. Moreover, median spring and fall groundwater levels show a consistent downwards trend from 2005 to the period ending in 2016, and an increasing trend thereafter. These regional groundwater level changes were caused by the historic 2012-2016 drought and demonstrate that prolonged drought conditions have an impact not only on fall lows, but also on the height of spring groundwater level recovery. Furthermore, trends in median groundwater levels also demonstrate that following drought, groundwater levels generally rebound to pre-drought levels. For instance, the

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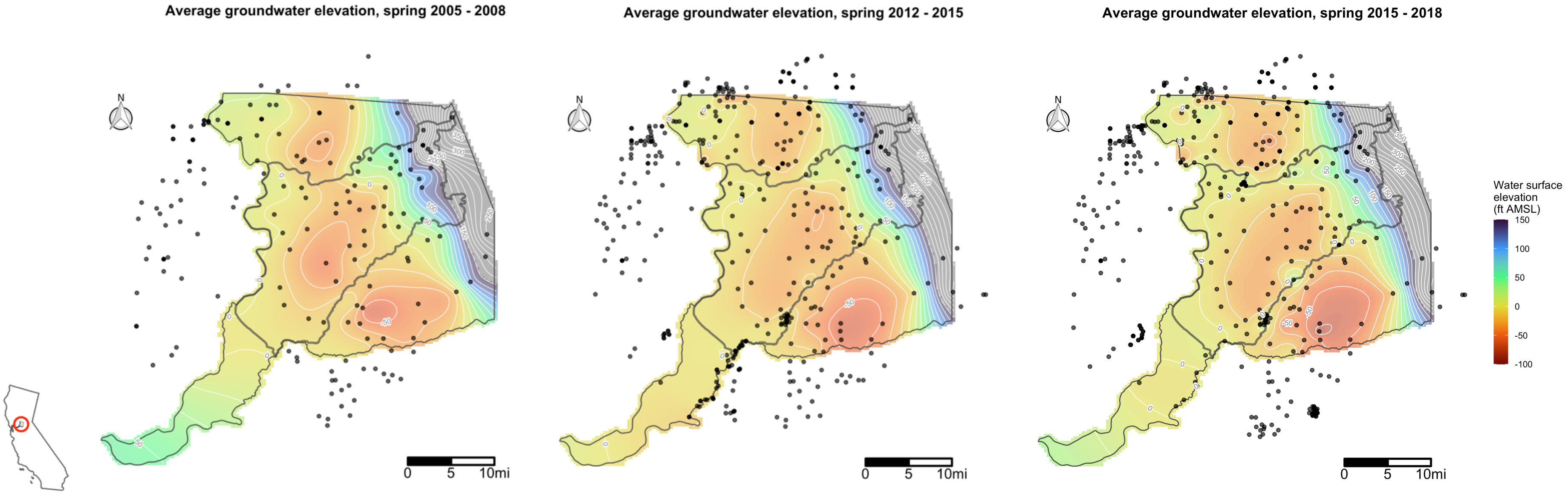
[15] The 120 hydrographs considered in this study are presented in *Appendix A: Hydrographs*, although not all data shown in these hydrographs were used in the groundwater level interpolation due to the time period assessed in this study (2005-2018).

2015-2018 spring and fall median groundwater levels are roughly equivalent to the pre-drought 2005-2008 spring and fall levels.

Groundwater flow direction can be interpreted from groundwater elevation maps (Figure *17*, Figure *18*) which define the approximate subsurface “topography” of saturated groundwater in the principal aquifer given our best available data. Groundwater flows laterally from high to low groundwater elevation, along the lateral hydraulic gradient. Groundwater elevation mapping in the SASb indicates groundwater flow inwards towards the central and eastern SASb, coincident agricultural and rural areas which may pump more groundwater than urban areas. Urban areas near Sacramento, Rancho Cordova, and Folsom generally exhibit higher and more stable groundwater elevation trends, apart from notable groundwater drawdown near the Elk Grove urban-rural fringe. Higher groundwater elevations along the Sacramento and American river channels result from substantial seepage into groundwater causes groundwater to flow inwards to lower groundwater elevation sites in the SASb. Notably, the Cosumnes River channel does not show consistently higher groundwater elevation than interior groundwater elevation, perhaps due to seasonal wetting and drying of the river, and its closer proximity to groundwater pumping compared to the Sacramento and American rivers. Hence, groundwater in some seasons flows away from the Cosumnes towards the interior of the SASb, and in other seasons appears not to flow. North to south flow from the interior of the SASb towards the Cosumnes does not appear common in the period of record analyzed, consistent with a characterization of the Cosumnes as a stream experiencing active depletion.

A rigorous assessment of interbasin flow was outside of the scope of this study but should be conducted with the CoSANA model, or groundwater level measurements in all available datasets across the Cosumnes, South American, and North American basins. Nevertheless, Periodic Groundwater Level Measurements from the Department of Water Resources (see Section 3.1 Data sources) in the North American and Cosumnes basins provide some insight into general patterns of interbasin flow directions. Across years and seasons, lower groundwater elevations in the interior of each of these basins compared to groundwater elevations near major surface water channels suggests the presence of losing streams and active surface water depletion. This depletion moves along a hydraulic gradient from high groundwater elevation (near stream) to low groundwater elevation (basin interior). Therefore, interbasin coordination measures that arrest groundwater level decline (or increase groundwater levels) within zones of pumping inside the SASb, North American, and Cosumnes basins are critical to maintain surface water flows and preventing loss of ISW locations in the basin.


Average groundwater elevation, spring 2005 - 2008

Average groundwater elevation, spring 2012 - 2015

Average groundwater elevation, spring 2015 - 2018

Figure 17: Spring groundwater elevation computed by ordinary kriging at three representative time steps (2005-2008, 2012-2015, and 2015-2018) demonstrate the presence of regional hydraulic gradients that contribute to inter-basin groundwater flow. Red indicates lower elevation and blue indicates higher elevation. Kriging is informed by groundwater level measurements taken at monitoring points (black dots), which are not constant across time steps. To best represent groundwater level in the SASb, monitoring points beyond the SASb boundary are incorporated into the analysis.

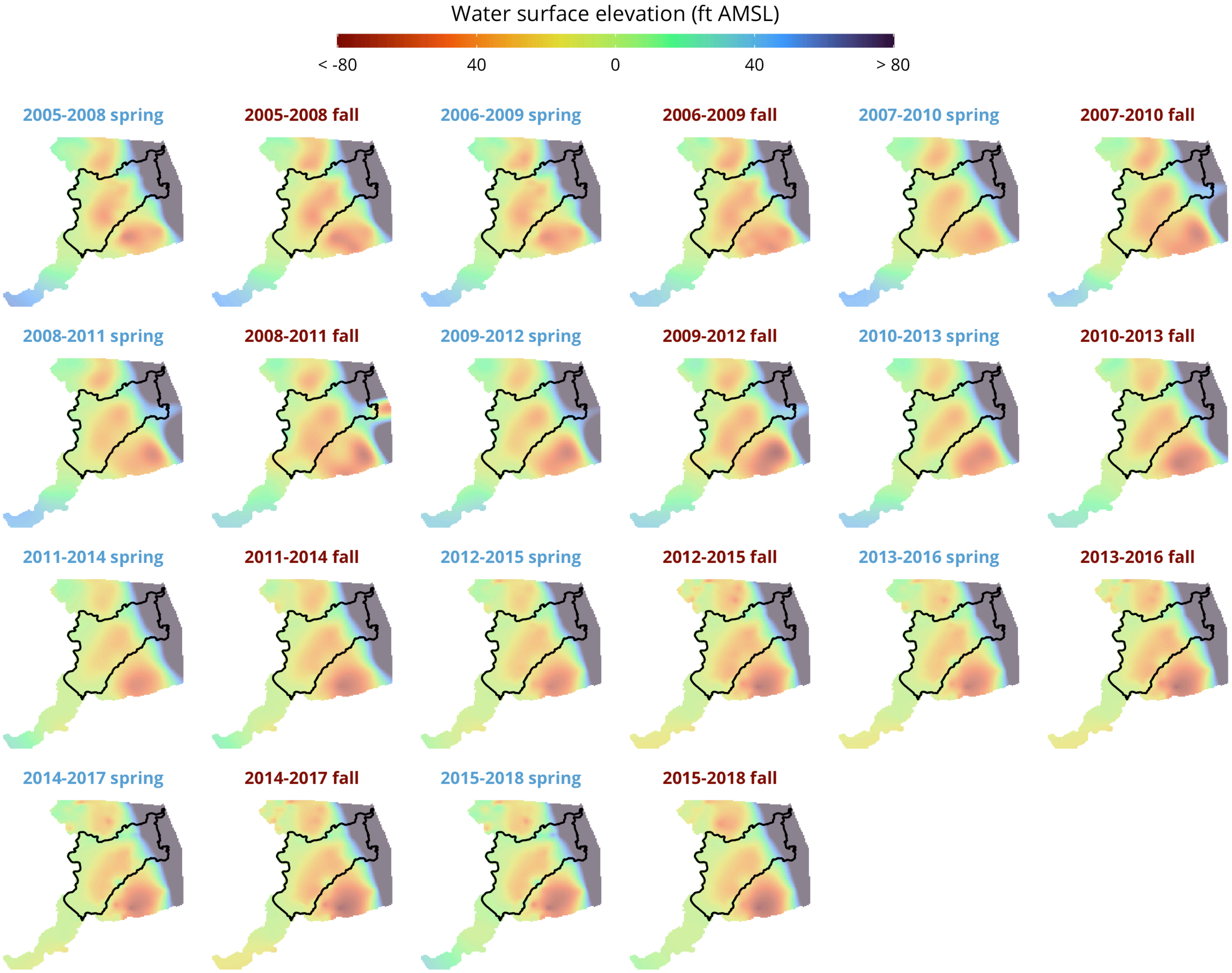


Figure 18: Seasonal, 4 year running mean interpolated groundwater elevations in the South American Subbasin from spring 2005 to fall 2018 show seasonal oscillation, with generally higher (blue) groundwater elevation in spring, and generally lower (red) groundwater elevation in the fall. Groundwater flows from areas of high (blue) to low (red) elevation groundwater elevation. Groundwater elevation mapping indicates groundwater flow inwards towards the center of the basin, coincident with areas of groundwater pumping.

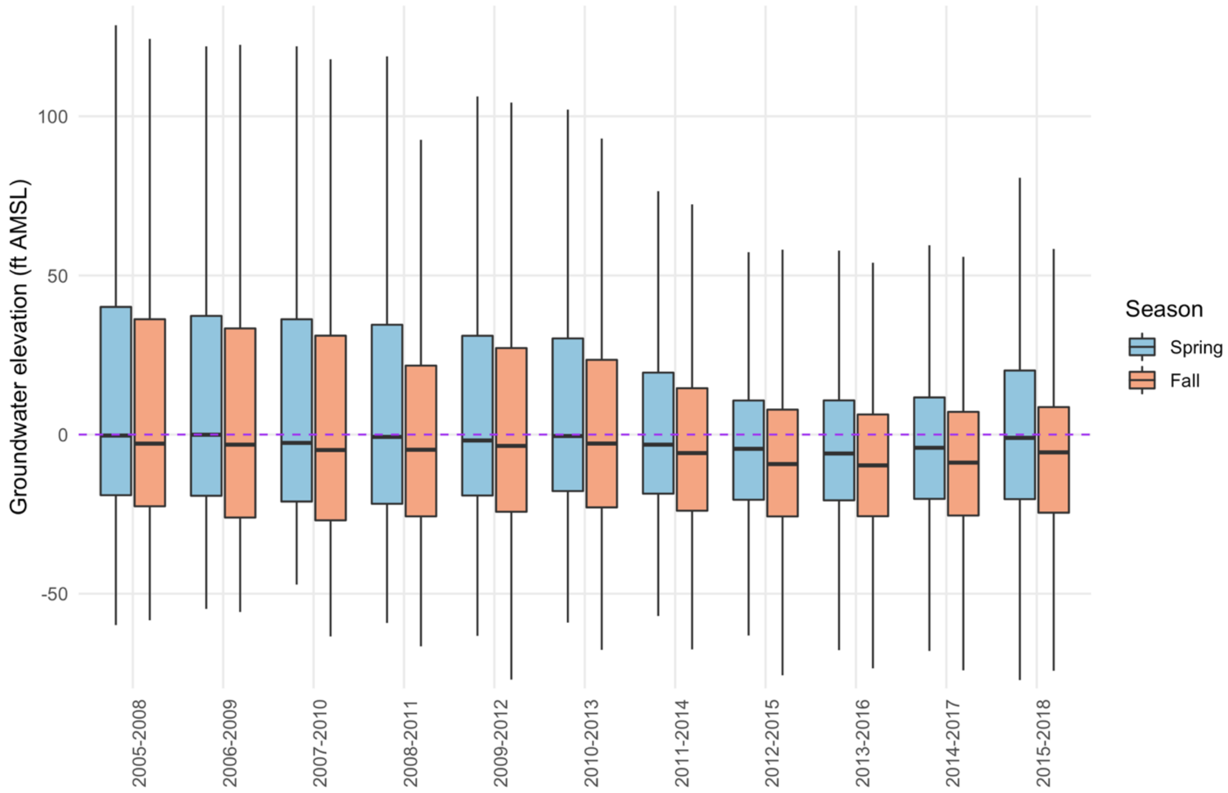


Figure 19: Seasonal summary of interpolated groundwater elevations in the SASb (Figure *18*) show oscillating seasonal medians, with consistently higher groundwater elevation in spring, and lower groundwater elevation in fall. Median fall groundwater elevation decreases over the period of record and reaches its lowest value during the average period of 2013-2016 due to the combined impact of 4 years of drought. After this minimum, spring and fall median groundwater levels trend upward. A purple, horizontal dashed line is shown at mean sea level elevation (0 feet) for reference.

4.1.3 Shallow groundwater locations

The depth to groundwater is calculated from seasonal groundwater elevations by subtracting the groundwater elevation from a digital elevation model. Estimated depth to groundwater (Figure 20) suggests that shallower groundwater is encountered moving from northeast to southwest in the SASb, from the foothills towards the Delta. Depths to groundwater are estimated at around 20-180 feet below land surface in the interior of the SASb[16], depending on the location considered. Areas of shallow groundwater occur along the southern Cosumnes River, along the American River above the Sacramento River confluence, along the Sacramento River, and within wetlands approaching the Delta. Moreover, relatively shallow depths to groundwater parallel the upper Cosumnes and American River channels, likely due to seepage from these major surface water bodies. Moving further away from these surface water channels, the depth to groundwater generally increases, which reflects the impact of groundwater pumping. Together, results suggest that ISW is more likely in regions with a shallower depth to

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[16] Poorly constrained data in the foothills (dark red eastern areas in Figure 20) prohibits meaningful estimates of groundwater elevation and hence, depth to groundwater. Thus, results in these areas should be interpreted with caution. Actual depths to groundwater are likely higher in the foothills. Incidentally, most groundwater pumping does not occur in these areas.

groundwater and are consistent with subsequent findings on the estimated location of ISW.

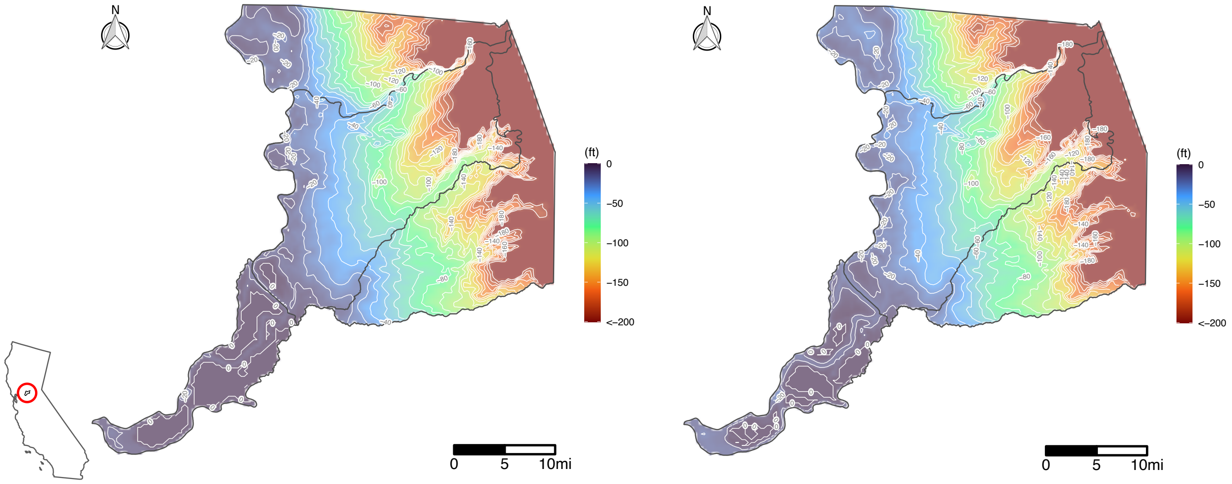

Figure 20: Depth to groundwater in the SASb for average spring (left) and fall (right) conditions across the entire period of record evaluated (2005-2018).

4.1.4 Projected groundwater levels

The impact of projected groundwater conditions including projects and management actions and climate change were evaluated with Cosana (see Section 3.3 Forward simulations of Projects and Management Actions and Climate Change).

Projected groundwater use assumes anticipated groundwater pumping on the part of water systems and GSAs across the SASb, the North American subbasin, and the Cosumnes subbasin. Results demonstrate that groundwater level declines around 15 to 20 feet or less are anticipated near Elk Grove and the Sacramento urban area respectively. Projects and management actions – including regional conjunctive use and recharge projects in Harvest Water and OHWD – lead to the mitigation of groundwater level declines near Elk Grove, and declines in the Sacramento region on the order of 15 feet or less. Groundwater level declines are estimated because of plans to exercise the basin, and declines are calculated between modeled scenarios and the current conditions baseline at the same time step (Fall 2015)[17].

Importantly, groundwater level decline in and of itself is not inherently harmful to beneficial users. Rather, declines must be evaluated with respect to beneficial users to anticipate potential significant and unreasonable impacts. The following subsections will detail the results of such analyses. In particular, we evaluate projected groundwater management and climate change impacts to ISW reach length, seepage at ISW reaches, and ISW streamflow.

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[17] In practice, another time step may be chosen as a benchmark (e.g., Spring 2018), however, groundwater level decline will be similar no matter what benchmark is chosen because groundwater levels in each scenario follow repeated hydrology as in the current conditions baseline scenario (see Figure 23).

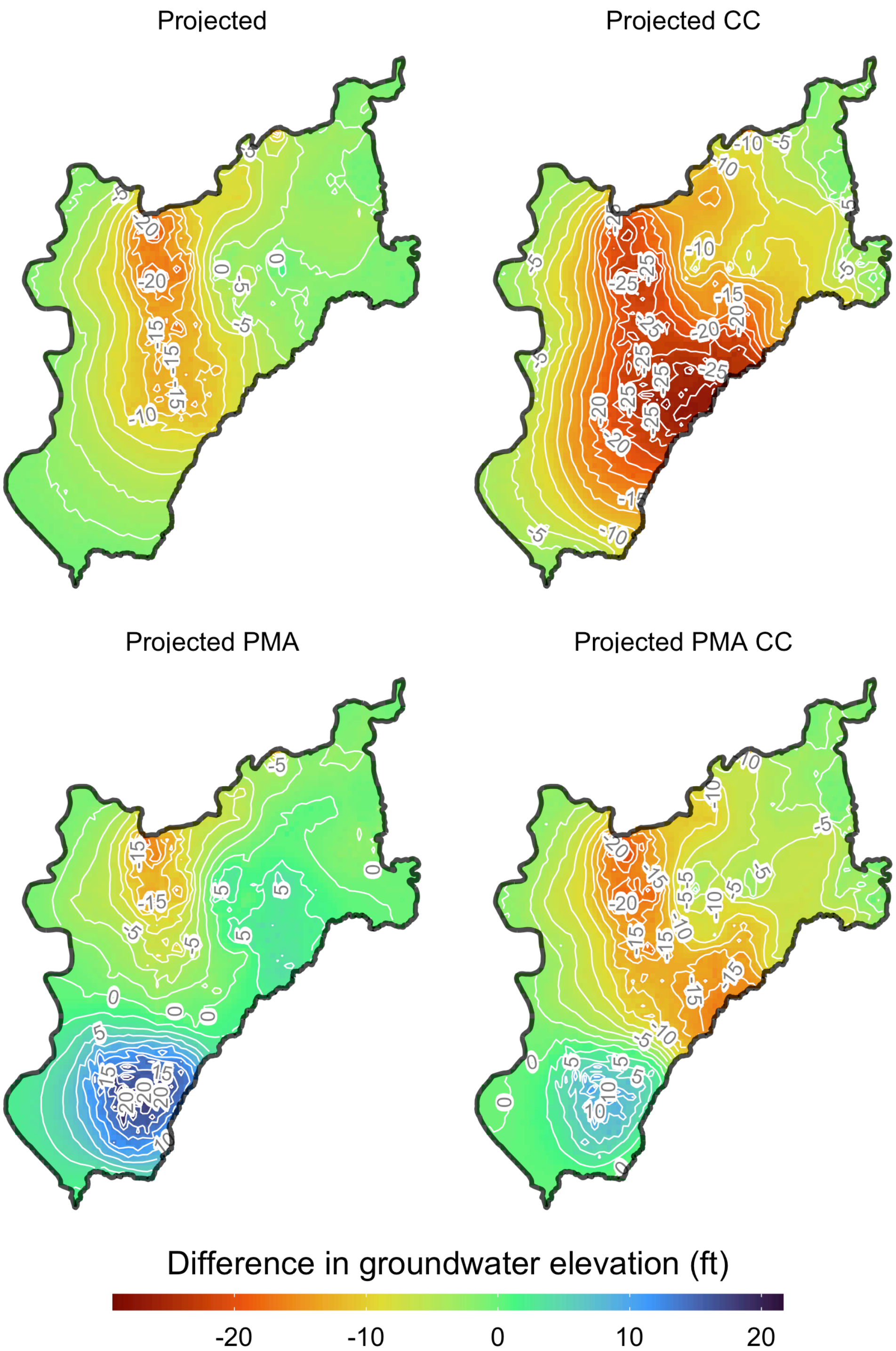


Figure 21: Modeled difference in groundwater level between each of the scenarios and the current conditions baseline at a Fall 2015 benchmark. PMA lead to substantial increases in groundwater level that reduce seepage (e.g., improve baseflow) and increase streamflow at ISW reaches. Climate change projections lead to groundwater level declines, but assume no corrective action or land use change. In reality, climate change would require specialized adaptive management to avoid significant and unreasonable impacts to beneficial users of groundwater and ISW.

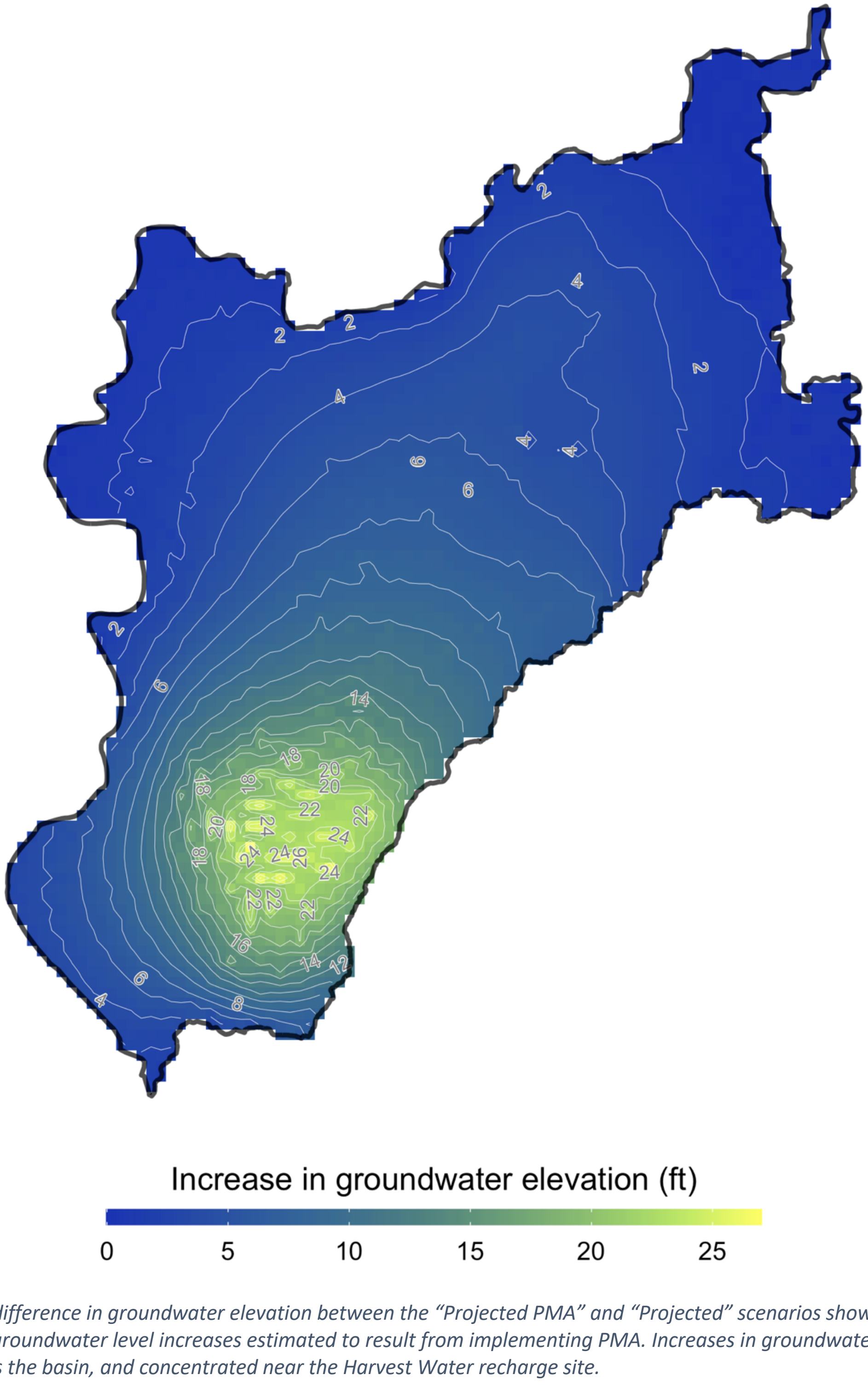


Figure 22: The difference in groundwater elevation between the "Projected PMA" and "Projected" scenarios shows the spatial distribution of groundwater level increases estimated to result from implementing PMA. Increases in groundwater level are observed across the basin, and concentrated near the Harvest Water recharge site.

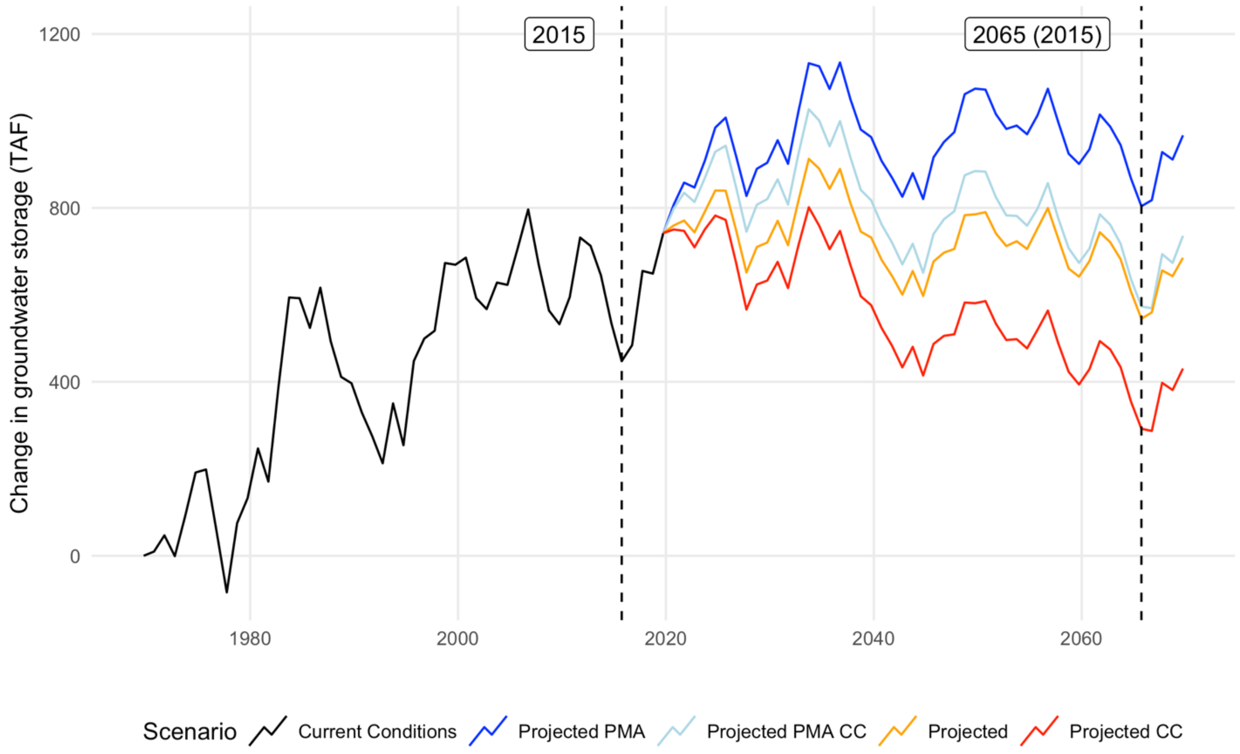


Figure 23: Cumulative change in groundwater storage under the current conditions baseline (black line), and the four scenarios (dark blue, light blue, orange, and red line). Importantly, projects and management actions (PMA) increase storage, and climate change (CC) reduces storage. A black dashed line shows where groundwater level differences are calculated between the projected scenarios and the current conditions baseline (Fall 2015) to maintain consistency.

4.2 Location and Timing of Interconnected Surface Waters

4.2.1 Historical data analysis

The location and timing of ISW was assessed by comparing each of the average seasonal groundwater level conditions presented above to the depth of the clogging layer of major surface water bodies (as described in 3.4 Classification of ISW and Disconnected Surface Waters). The proportion of seasons (across the 22 seasons evaluated in this study) that a stream node was classified as “Interconnected” to groundwater (3.4 Classification of ISW and Disconnected Surface Waters) was calculated at each stream node (Figure 24A), and used to inform a classification of “Interconnected” (ISW) and “Disconnected” stream nodes (Figure 24A) and reaches (Figure 24B).

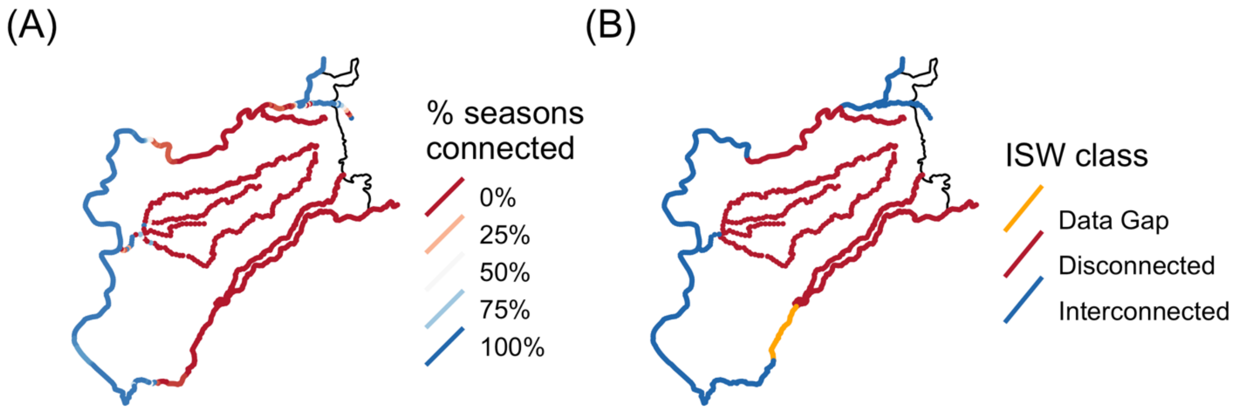


Figure 24: Interconnected and Disconnected stream nodes and reaches are defined by computing (A) the percentage of seasons evaluated from 2005 – 2018 where average groundwater elevation intersects the clogging layer of the streambed. (B) Disconnected stream reaches have a majority of stream nodes that are persistently disconnected from groundwater at all seasons evaluated, whereas Interconnected reaches are conservatively defined as having a majority of nodes connected for > 0% of all seasons evaluated. The Cosumnes River approximately between Deer Creek and Twin Cities Road is disconnected on a seasonal level, but some evidence of sub-seasonal connection exists, thus it is considered a data gap for planning purposes and more research is needed to understand stream-aquifer interactions in this region.

Final ISW classification results in a larger proportion of the Cosumnes River upstream of the Mokelumne River being classified as ISW. Due to relatively low groundwater levels in the basin's interior, most interior creeks are "Disconnected". ISW characterization is consistent with ISW characterization in The Nature Conservancy's ICONS web tool (TNC, 2021) and those in adjacent basins (North American and Cosumnes basins) that share boundaries with the South American Subbasin.

Results suggest that ISW locations over the period of record analyzed from 2005-2018 include:

- the entire Sacramento River;
- the American River upstream of the Sacramento River and downstream of the H Street Bridge;
- the American River upstream of Alder Creek and Buffalo Creek;
- Alder Creek and Morrison Creek upstream of the Sacramento River;
- the Mokelumne River; and
- the Cosumnes River upstream of the Mokelumne Confluence and downstream of the Laguna Creek confluence.

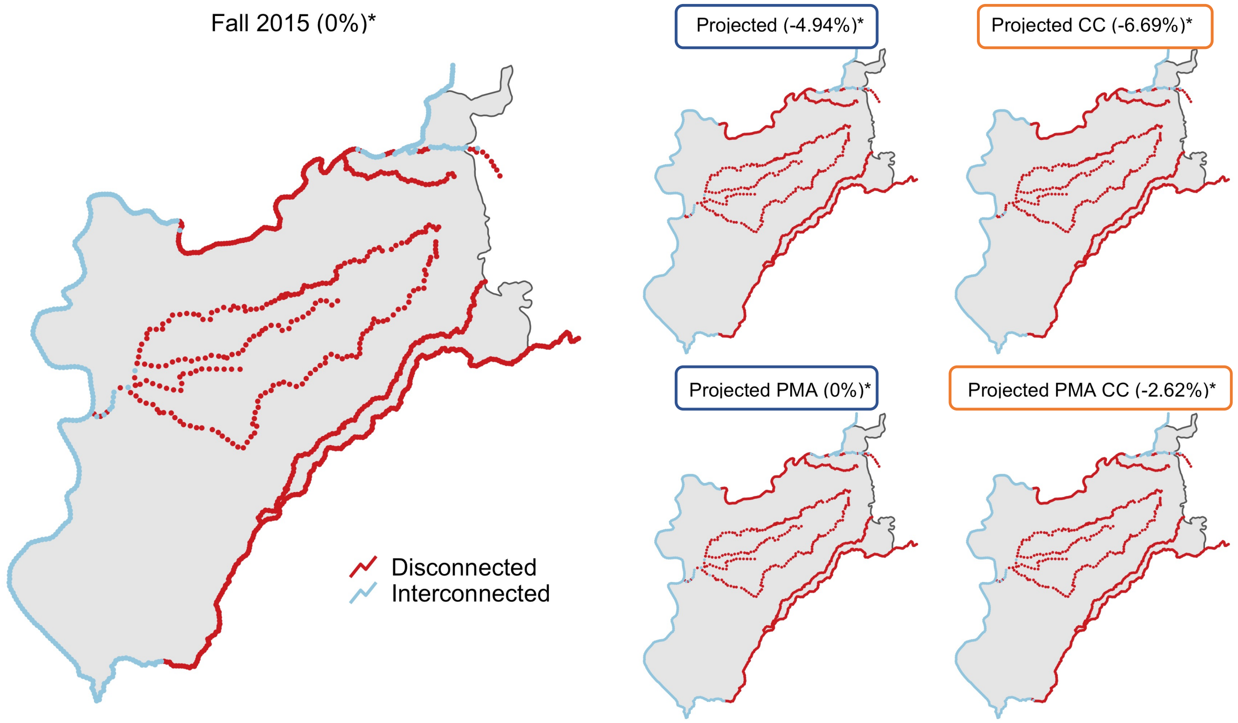
The actual location along the Cosumnes River where interconnection between surface and groundwater occurs should continue to be monitored and studied. Results suggest that seasonal average groundwater levels are not sufficiently high as to interconnect with streams, but some evidence of sub-seasonal connection exists, and this sub-seasonal connection may play a role in the maintenance of aquatic ecosystems. To better understand shorter-term interactions in this location, this region could be investigated with continuous groundwater and stream monitoring, which may improve understanding of sub-seasonal interconnection events and hydraulic gradients between surface and groundwater.

Figure 25: Probable ISW reaches by name, Disconnected reaches, and GSAs in the Basin. Monitoring points are assigned to nearby ISW reaches and are discussed in (SMC) *and Monitoring Approach*.

4.2.2 Impact of projected groundwater management on ISW reach length

The impact of projected groundwater conditions (including projects and management actions and climate change) on reach length were evaluated with Cosana (see Section 3.3 Forward simulations of Projects and Management Actions and Climate Change). Declines in the groundwater level may lead to disconnection events where previously interconnected stream nodes become disconnected, and conversely, increases in groundwater elevation may raise groundwater levels such that previously disconnected nodes become interconnected. Finally, the change in groundwater elevation may be such that connection or disconnection (relative to some historical benchmark) remains the same.

Results suggest that compared to a Fall 2015 baseline, projected conditions lead to a -4.94% decline in ISW reach length, and a 0% change if projects and management actions are implemented. The Harvest Water recharge project in the southern SASb substantially improves groundwater levels in and around the project area (Figure 22), resulting in a maintenance of ISW reach length. Decreases in reach length associated with climate change scenarios is attributable to increased temperatures and groundwater demand, but may be addressed with adaptative management.



*compared to the 'Fall 2015' scenario

Figure 26: Impact analysis of projected groundwater level scenarios (described in Section 3.3 Forward simulations of Projects and Management Actions and Climate Change) shows minimal impacts to ISW reach length across scenarios suggesting the avoidance of significant and unreasonable disconnection events. The “Projected” and “Projected PMA” scenarios (blue border) should be compared, and the “Projected CC” and “Projected PMA CC” scenarios (orange border) should be compared. In each pair of comparable scenarios, scenarios with PMA lead to a less than 5% reduction of ISW reach length compared to a 2015 baseline, and are generally more protective of ISW than scenarios without PMA.

4.3 Depletions of Interconnected Surface Waters

4.3.1 Comparison of current and projected seepage

Active ISW depletion is occurring in the SASb due to historical groundwater development and evidenced by the prevalence of disconnected surface water bodies and mostly losing stream reaches across the basin.

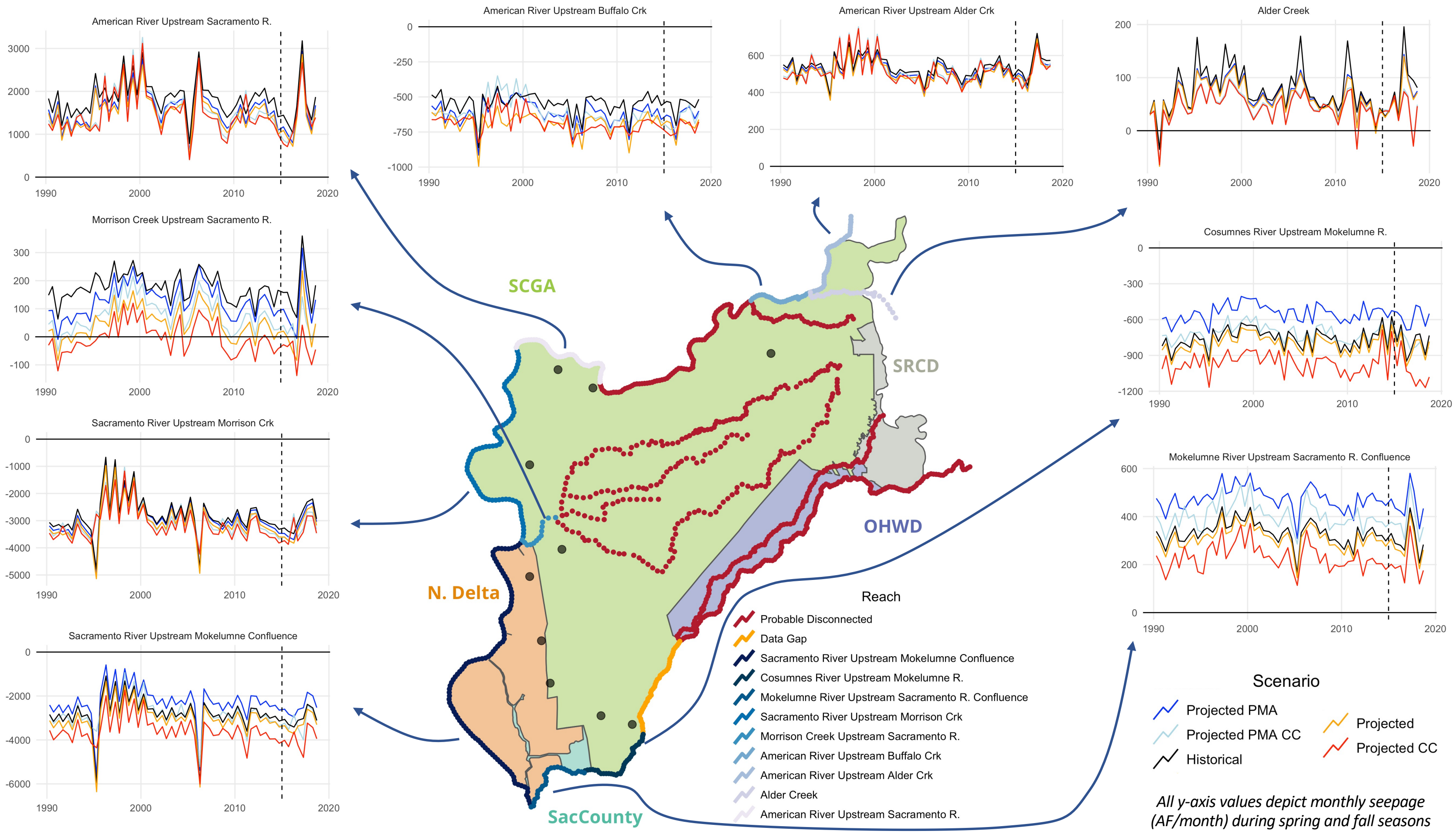
In practice, streamflow depletion is difficult to measure in the field, and varies considerably along a stream reach, thus it is almost always a modeled quantity. The

Cosana model simulates stream-aquifer exchange at stream nodes. The term that describes the flux of water between surface and groundwater bodies is called "Seepage". A negative seepage along a reach indicates losing stream conditions, and a positive seepage indicates gaining conditions (Figure 15). Cosana was used to simulate seepage under current conditions, as well as seepage under projected groundwater management and climate change (Figure 27) at ISW reaches identified above (Section 4.2 Location and Timing of Interconnected Surface Waters).

The primary driver of the direction and magnitude seepage is the relationship between groundwater elevation and the stream stage elevation. Generally speaking, water flows from areas of higher elevation to lower elevation as a result of potential energy and gravity, and thus changes in groundwater elevation (e.g., from pumping or recharge) and stream stage (e.g., from diversions or floods) change the relationship between groundwater and surface water elevations (Figure 1), and hence, the seepage. Overall, surface waters in the SASb exhibit seasonally and interannually variable stream depletion that results from the relationship between groundwater elevation and stream stage.

The magnitude of ISW depletion at interconnected stream reaches (Figure 27) is greatest along the Sacramento River due to its relatively larger stream geometry and larger volumetric flow compared to the American, Cosumnes, and Mokelumne Rivers. The American River is heavily managed and thus flows that are held back in Folsom reservoir generally decrease the magnitude of seepage along this river compared to what they may be in unmanaged conditions.

Projects and management actions generally reduce loss from losing streams and increase baseflow to gaining streams. Across all ISW reaches, all gaining and losing reaches remaining predominately gaining or losing reaches under all scenarios. A notable exception is Morrison Creek upstream of the Sacramento River, which is predominately losing assuming climate change and no PMA. Overall, projected management and PMA tend to either improve or maintain current conditions (Figure 27).



All y-axis values depict monthly seepage (AF/month) during spring and fall seasons

Figure 27: Seasonally averaged ISW depletion estimated by CoSANA at ISW designated reaches over the current conditions baseline model simulation is relatively constant. Negative numbers indicate losing stream conditions (stream loss to groundwater) and positive number indicate gaining stream conditions (stream gain from groundwater). Spring (February - April) and fall (August - October) depletion rates are averaged per month in each 3-month seasonal window. A black vertical dashed line at 2015-01-01 is drawn for reference, and a black solid horizontal line at y = 0 indicates the transition from gaining to losing conditions. Most scenarios have little impact on seepage. The Cosumnes and Mokelumne gain more under projected conditions, even with climate change. Morrison Creek loses more in all scenarios.

4.3.2 Dependence of seepage on water year type

Dry years tend to encourage groundwater pumping – this lowers groundwater level adjacent to streams, and hence, steepens the gradient between surface and groundwater bodies. A steeper hydraulic gradient between surface and groundwater[18], particularly in the losing streams found in the SASb, intensifies and increases depletion volumes.

Wet years sometimes lead to increased seepage from losing streams to groundwater due to excess water in stream channels that increases the hydraulic gradient. Increased seepage to groundwater during these wet years should not be interpreted as damaging aquatic habitats or ecosystem functions, but rather, as the result of floods and increased hydraulic head in rivers[19]. If the elevation of adjacent groundwater is relatively high and wet years have the effect of increasing groundwater level, the opposite effect can occur, and increased groundwater levels contribute to streamflow, observed in positive spikes in the seepage timeseries of the Mokelumne River upstream of the Sacramento River confluence.

Many factors influence seepage. Within the context of SGMA, it is important for management plans to evaluate how groundwater management may alter stream-aquifer interactions that lead to undesirable results for ISW or beneficial users of ISW. Measurable quantities that may be used in management plans include alterations to the reach length of identified ISW, changes in ISW seepage, and changes in critical flows for fish passage.

4.4 Location and Timing of Gaining and Losing Reaches

Although not directly managed by SGMA, an understanding of location and timing of gaining and losing streams is critical to anticipate how depletions of ISW may change under different water management scenarios. Importantly, a conceptual understanding of gaining and losing stream conditions may help identify *losing connected* and *gaining* reaches that should be maintained, to prevent the transition of ISW to losing disconnected reaches (Figure 15). Gaining and losing reaches according to Cosana are presented.

Seepage calculated by Cosana can be positive (stream gains from groundwater) or negative (stream loses to groundwater). The seasonal gaining and losing conditions for each reach (Figure 29) demonstrate consistent and mostly losing conditions (red) over

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[18] Hence, arresting the steepness of the hydraulic gradient between surface and groundwater is the management approach proposed in this memo, consistent with recommendations by Hall, Babbit, Saracino, and Leake (2018).

[19] Increased depletion during wet years along losing reaches that result from higher hydraulic head in streams (i.e., flood conditions) motivates sustainable management criteria based on groundwater levels rather than estimated depletion volume, because groundwater levels adjacent to streams represent the impact of groundwater management decisions that ultimately impact streams. Thus, SMC based on groundwater elevation more accurately target groundwater management.

time, apart from gaining reaches (blue) along the upper and lower American river, and the Mokelumne river. The average reach-level seepage across the period of record from 2005-2018 (Figure 28) does not appreciably differ between spring and fall.

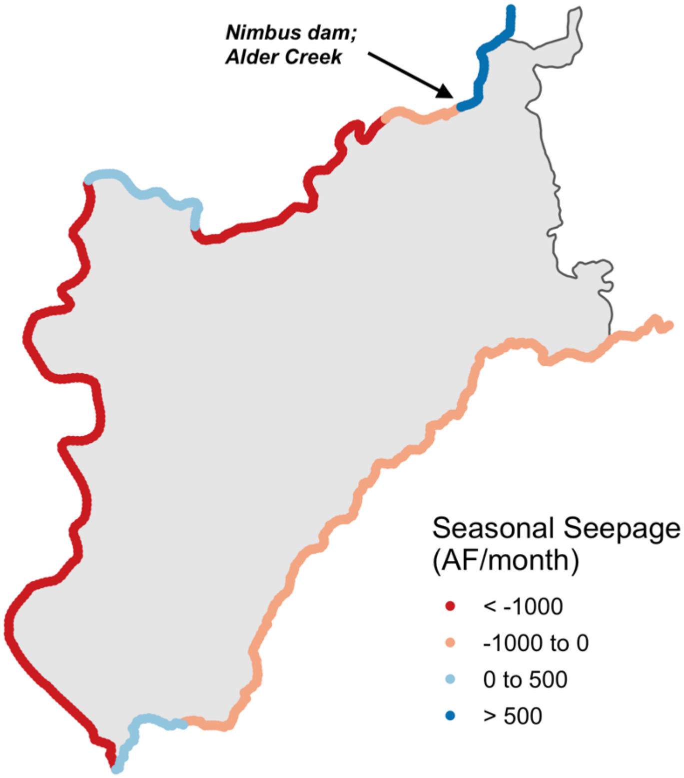

Figure 28: Average reach-level seasonal seepage from 2005-2018 computed by Cosana show gaining sections along the Mokelumne River, the lower American River downstream of the H Street bridge, and the American River upstream of Alder Creek (Nimbus dam), otherwise known as Lake Natoma. In this figure, spring and fall seasons are averaged because they do not appreciably differ.

Gaining and losing reach characterization is important insofar as it informs the hydrogeologic conceptual model of stream-aquifer interactions in the basin and provides a benchmark against which projected changes can be compared to. Future groundwater management planning should consider how projected groundwater use may impact gaining and losing systems. In particular, gaining and losing ISW that depend on minimum flows for fish migration may be sensitive to changes in seepage that deplete surface waters.

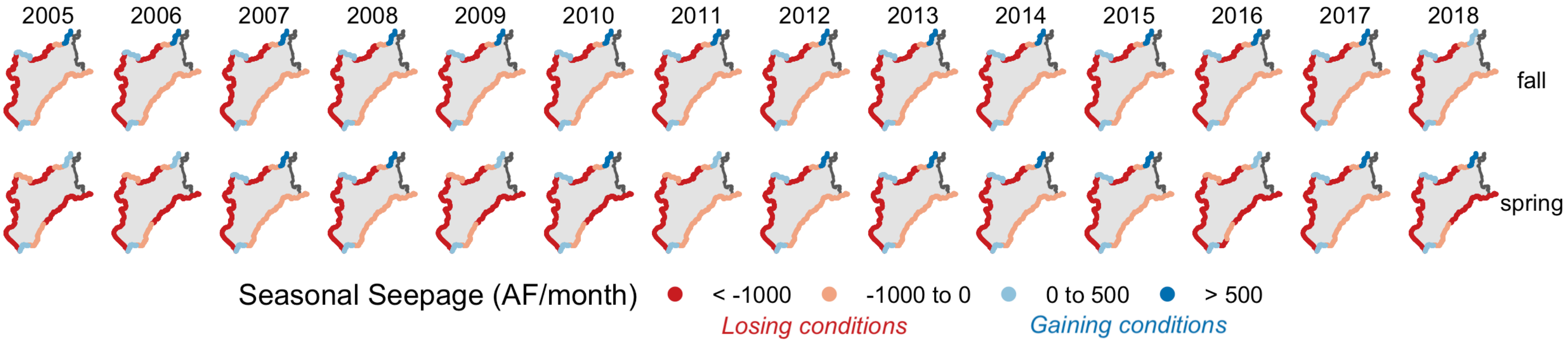

Figure 29: Major gaining and losing stream reaches from 2005-2018 in fall and spring according to the current conditions baseline. Average seasonal seepages show mostly losing (red) reaches.

4.5 Impacts to Streamflow

As in previous subsections, Cosana was used to compare the current conditions baseline scenario to projected management and climate change scenarios (3.3 Forward simulations of Projects and Management Actions and Climate Change). Streamflow exceedance probability at the outlets of the American, Cosumnes, and Sacramento rivers was compared across all scenarios. Exceedance probability represents the probability that a certain flow will be met or exceeded based on the hydrology observed during a period of record. The periods of record considered in this study are equivalent in length and based on monthly average streamflow values calculated by Cosana from 1990-2018 (and based on that hydrology). “Projected” and “Projected PMA” scenarios show increases in streamflow in the Sacramento and Cosumnes Rivers between 1-16%, and a negligible -1% decrease in the American River. Increases in flow, particularly in the Cosumnes River are attributable to increased groundwater elevations from the Harvest Water project and other regional conjunctive use projects (Figure 22), which increase local groundwater conditions upwards of 25 feet, thus reducing seepage from streams to groundwater along the losing Cosumnes River, and increasing baseflow to the gaining Mokelumne River (Figure 27).

Climate change scenarios cause outsized direct reduction in streamflow unrelated to groundwater management. Comparison of “Projected CC” and “Projected PMA CC” shows that across all ISW in the SASb, PMA dampen the impact of climate change on streamflow.

Table 3: October-December simulated streamflow for the American, Cosumnes, and Sacramento rivers under current conditions (Baseline), and projected scenarios (also see Figure 30)

River	Scenario	10th percentile (cfs)	25th percentile (cfs)	50th percentile (cfs)	75th percentile (cfs)	90th percentile (cfs)	% Difference in 50th percentile exceedance compared to Baseline
American	Baseline	4037	2714	2025.29	1283	914	0%
American	Projected PMA	4019	2699	2004.91	1266	892	-1%
American	Projected PMA CC	2346	2181	701.37	584	507	-65%
American	Projected	4020	2692	2000.04	1261	888	-1%
American	Projected CC	2337	2177	693.52	579	503	-66%
Cosumnes	Baseline	1662	523	153.77	47	35	0%
Cosumnes	Projected PMA	1695	564	177.93	59	45	16%
Cosumnes	Projected PMA CC	1752	462	142.91	52	37	-7%
Cosumnes	Projected	1679	537	163.59	52	40	6%
Cosumnes	Projected CC	1742	443	134.42	48	34	-13%
Sacramento	Baseline	36150	19323	13857.07	11294	8554	0%
Sacramento	Projected PMA	36441	19537	13969.06	11424	8672	1%
Sacramento	Projected PMA CC	24794	14612	11300.27	8206	6822	-18%
Sacramento	Projected	36421	19514	13943.24	11401	8648	1%
Sacramento	Projected CC	24763	14585	11270.08	8181	6797	-19%

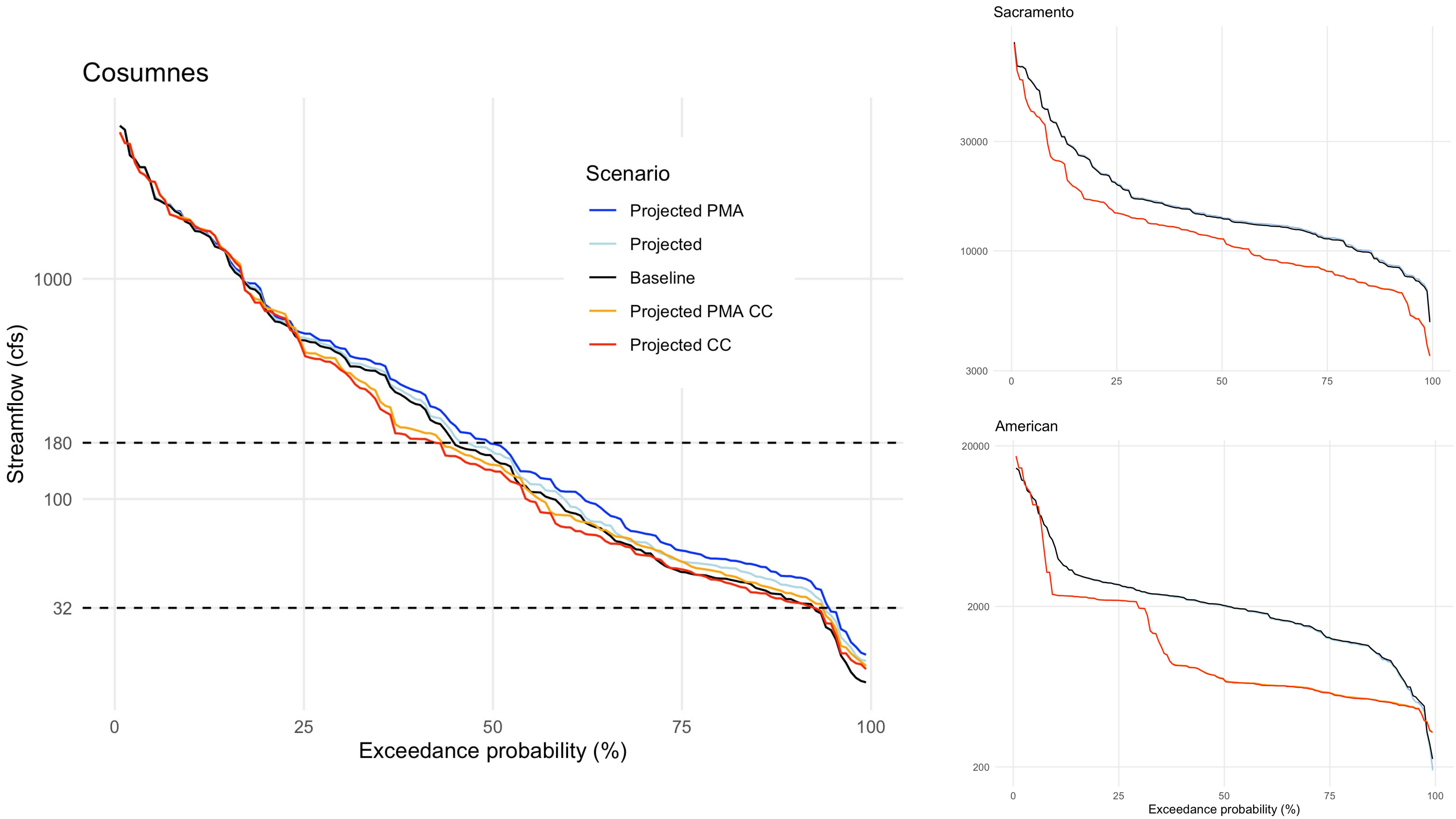

Figure 30: All projected scenarios show minimal impacts to October-December streamflow exceedance (Table 3) at ISW locations along the Cosumnes, Sacramento, and American rivers when compared to current conditions baseline flows (black solid line). American and Sacramento flows are only impacted by climate change and the absence of PMA (overlapping red and orange lines). In the Cosumnes, PMA introduction improves flow conditions, and projected management does not differ from current conditions. Black dashed horizonal lines on the leftmost plot indicate the envelope of flow target values reported by literature to support fish passage during low-flow October-December spawning months. The lower bound of this envelope (32 cfs) has a 90% exceedance probability across all scenarios which implies fish passage during spawning months. Due to modeling constraints, flows are estimated at the downstream outlets of the Cosumnes and Sacramento Rivers in the model domain. American River flows are estimated at H Street Bridge. Note the log-scale y-axis.

4.6 Satellite Analysis of Wetting and Drying

High spatial resolution, pan-sharpened, 30-centimeter satellite imagery from Google Earth Pro was used to qualitatively assess “drying” events along the ephemeral Cosumnes River. Results demonstrate the feasibility of commercial, on-demand imagery (e.g., Planet 50-centimeter satellite imagery) to assess drying events (Figure 31). True color composite images taken in the visible spectrum of light (380-750 nanometers) work best in cloud-free environments. Dry summer months when the Cosumnes is most likely to experience “drying” events co-occur with relatively cloud-free days with low atmospheric moisture, and thus the feasibility of using high resolution remote sensing to broadly assess ISW monitoring is promising.

Figure 31: Selected dates of 30-centimeter pan-sharpened true color images of a selected location along the Cosumnes River qualitatively demonstrate the effectiveness high-resolution satellite imagery in determining drying events.

Aerial images can only indicate if reaches have dried out or stranded some sections of river which may serve as critical fish passage and habitat. These images cannot, however, indicate if surface and groundwater become disconnected, and are thus not practical approaches for measurable strategies for sustainable groundwater management. Sustainable management criteria for groundwater based on the observation of dry streams in satellite imagery is thus misguided: ephemeral stream reaches are likely to dry out from upstream conditions (i.e., dry and critical years with little rainfall), which are completely unrelated to the impact of groundwater management (e.g., pumping). Thus, developed SMC in this memorandum rely on in-situ groundwater level observations to identify changes in groundwater level that would lead to increased ISW depletion. Nevertheless, remote sensing of the Cosumnes River presented in this study demonstrate the utility of remote sensing analysis towards improving regional understanding of drying events on surface water bodies.

Finally, coarser resolution, publicly accessible imagery from the Sentinel II satellite (10-meter spatial resolution) were assessed as a potential low-cost alternative to high resolution imagery, but it was determined that the features of interest are too coarse at

10-meter scale (Figure 32, Figure 33). This was unsurprising as some stream channels along the Cosumnes River can fit within less than one grid cell to a few grid cells.

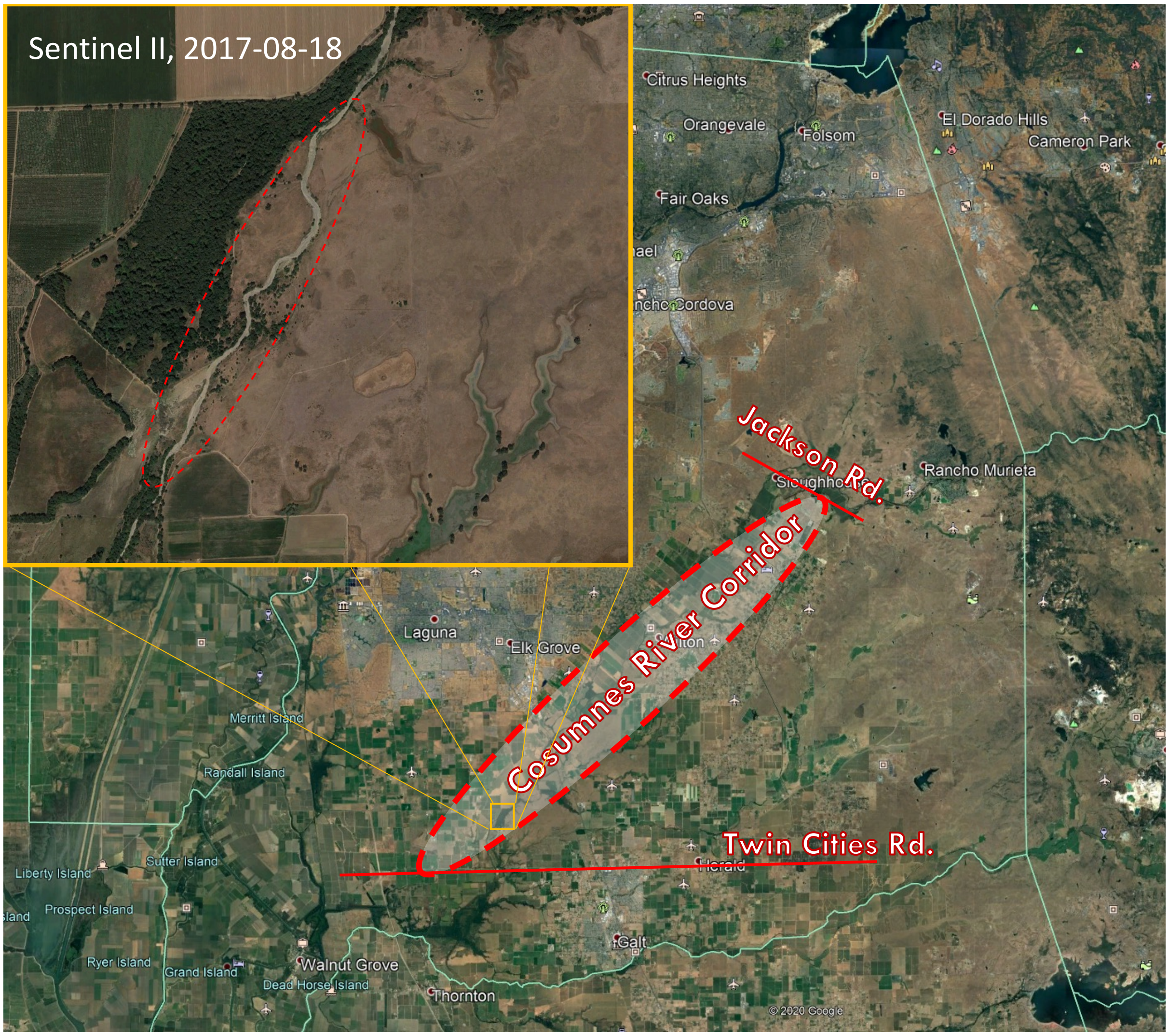

Figure 32: Sentinel II, which offers 10-meter resolution in the visible spectrum and regular flyovers of the SASb was investigated but did not offer appropriate spatial resolution for the task of qualitatively determining drying events.

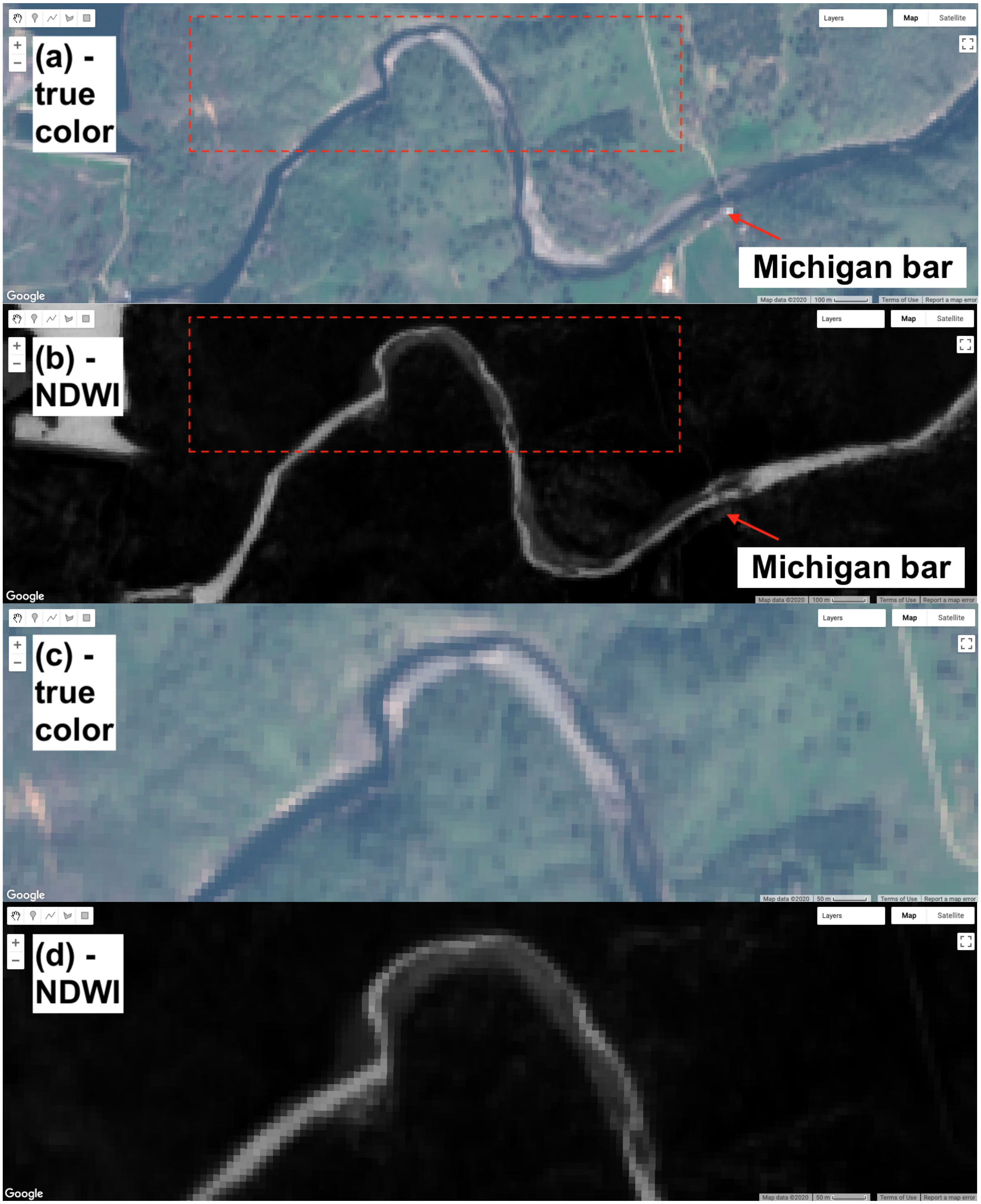

*Figure 33: Sentinel-2 true color and NDWI near Michigan Bar on the Cosumnes River for the period from 2018-02-01 to 2018-03-3. Lower right scale bar is 100m in **(a-b)**, and 50m in **(c-d)**. Dotted region in **(a-b)** is zoomed into in **(c-d)**.*

5. Limitations

Average regional, seasonal groundwater level cannot capture shorter-term connections between groundwater and surface water, or the impact of perched zones. Some studies suggest that on sub-monthly timescales, groundwater adjacent to streams may demonstrate higher hydraulic head than in the stream, consistent with gaining stream conditions. However, these trends often dissipate when looking at average conditions across the season. Therefore, the ISW mapping resulting from this study should be interpreted as regional and seasonal average conditions.

We ignore capillary action due to poorly constrained local-scale geologic data for the sediment underlying the streambed, but incorporation of these processes may allow in some cases for surface water to interconnect over a few more feet. To compensate for this effect, we conservatively consider an entire reach as connected if the majority of stream nodes within a reach are interconnected. This causes ISW classification to trend further upstream than what best available data suggest.

ISW connection estimates depend strongly on groundwater elevation data and thalweg elevation data, both of which always have room for improvement. Groundwater elevation data near streams is particularly important to refine ISW location estimates. Higher resolution thalweg elevation data may be obtained from local surveys and remote sensing (e.g., drones using LiDAR to acquire stream bathymetry data). The cost of these expeditions should be weighed against their ability to improve upon existing data, and the period of which the acquired data may become invalid (e.g., in the case of a large flood which scours channel geometry and changes the thalweg elevation).

6. Conclusion and Management Recommendations

In this section we summarize the main findings of the study and then advance management recommendations that pertain to SMC as defined by SGMA for the avoidance of Undesirable Results to beneficial users and users of ISW.
Data-driven analyses and modeling presented in this study show the location of ISW along the American, Sacramento, Mokelumne, and Cosumnes Rivers where ISW are located based on a historical (2005-2018)[20] analysis of seasonal groundwater elevation, thalweg elevation, and reach-level seepage. Modeled projected management and projects and management actions (PMA) generally improve ISW conditions compared to equivalent scenarios without PMA. Climate change has negative impacts of ISW streamflow, but these impacts are isolated from groundwater management actions.

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[20] Groundwater level analyses with data run from 2005-2018, and analyses of Cosana-calculated seepage runs from 2005-2018 because 2018 is the final year in which output is available at the time of writing.

Management actions should emphasize maintenance of ISW within reasonable margins, such that undesirable results to ISW are strictly defined. The strong dependence of threatened and endangered species on streamflow also suggests that SMC should emphasize similar quantitative criteria at which undesirable results are experienced. For example, the identification of undesirable results due to ISW depletion may include significant and unreasonable:

- percent decline in an ISW reach length
- percent decline in median exceedance probability at ISW reaches

Importantly, these metrics should be easy to measure over time to inform GSP implementation. Furthermore, the GSP should clearly link groundwater level declines to the above measurable outcomes so that groundwater level may be used as a proxy for ISW depletion.

6.1 Sustainable Management Criteria (SMC) and Monitoring Approach

SMC are monitored at representative monitoring points (RMPs), and it is critical that these RMPs are strategically sited to best represent changes in hydraulic gradient that indicate ISW depletion (Figure 34).

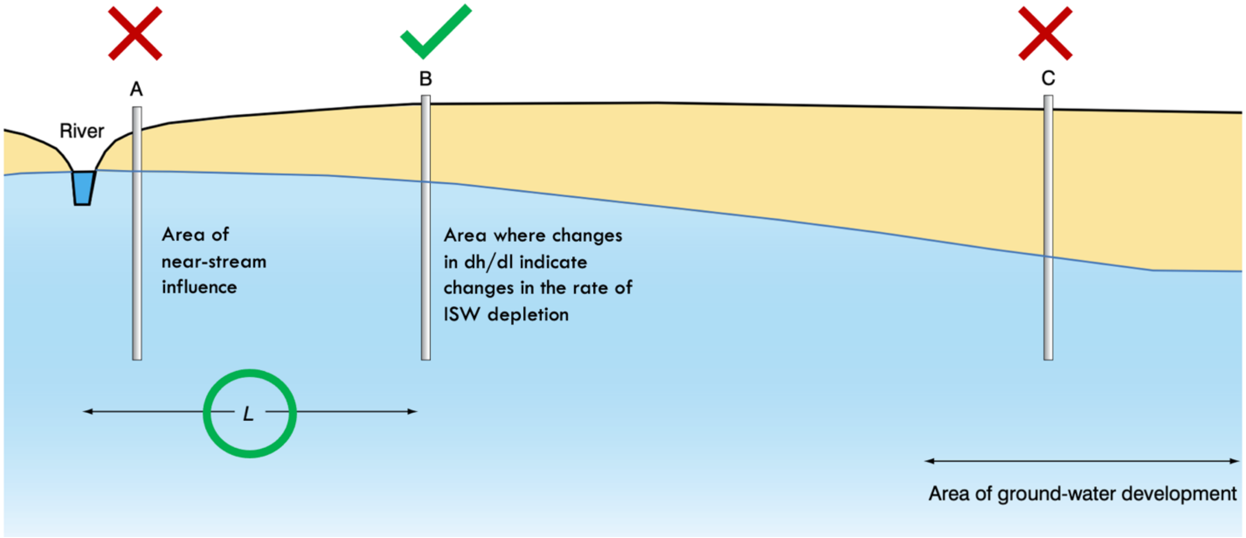

Figure 34: Monitoring wells for ISW depletion should be selected at a distance away from ISW such that areas of near-stream influence (A) and groundwater pumping (C) are avoided. Rather, groundwater levels should reflect the zone in which a propagating cone of depression has yet to reach the stream (B). In this way, monitoring reflects ambient groundwater conditions that may be impacted by overextraction, and anticipates ISW depletion. Modified from (EDF, 2018).

Analysis of hydraulic gradients along transects perpendicular to ISW demonstrated a buffer between 3000 and 9000 feet from ISW with relatively flat hydraulic gradients that appear to be unimpacted by near-stream influences or groundwater pumping. It is in this buffer that shallow monitoring wells were selected (Figure *27*). Whenever possible and appropriate, selected monitoring wells were drawn from the existing groundwater level network to minimize monitoring.

UC Davis and Sacramento State monitoring wells are situated in key locations and harbor valuable historical data, but the likelihood of these institutions supporting measurements over the GSP implementation timescale should not be taken for granted. It is recommended that the GSP monitoring effort coordinate with these entities to secure long-term monitoring, at least on a biannual basis.

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Appendix A: Hydrographs