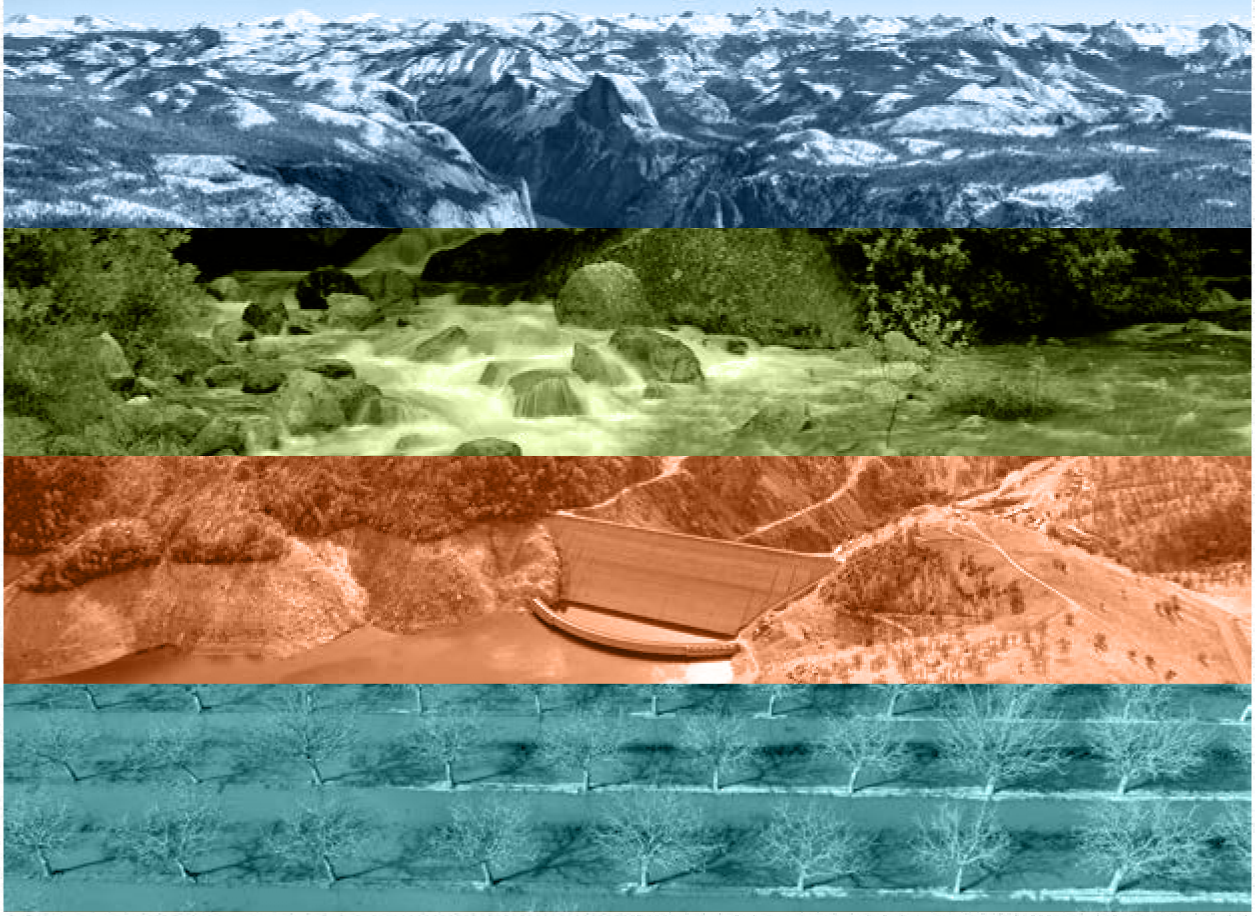
Merced River Watershed Flood-MAR Reconnaissance Study

STUDY REPORT

March 2024

Statewide Infrastructure Investigations Branch
CALIFORNIA DEPARTMENT OF WATER RESOURCES



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ON THE COVER – Top: Yosemite Valley and Half Dome in Yosemite National Park, February 5, 2014. Second: Along the Merced River in Yosemite National Park, June 22, 1993. Third: Exchequer Dam at Lake McClure, California, February 5, 2014. Bottom: Groundwater recharge project with floodwater diverted from the Kings River in an orchard at Terranova Ranch, March 13, 2023.

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MERCED RIVER WATERSHED FLOOD-MAR RECONNAISSANCE STUDY

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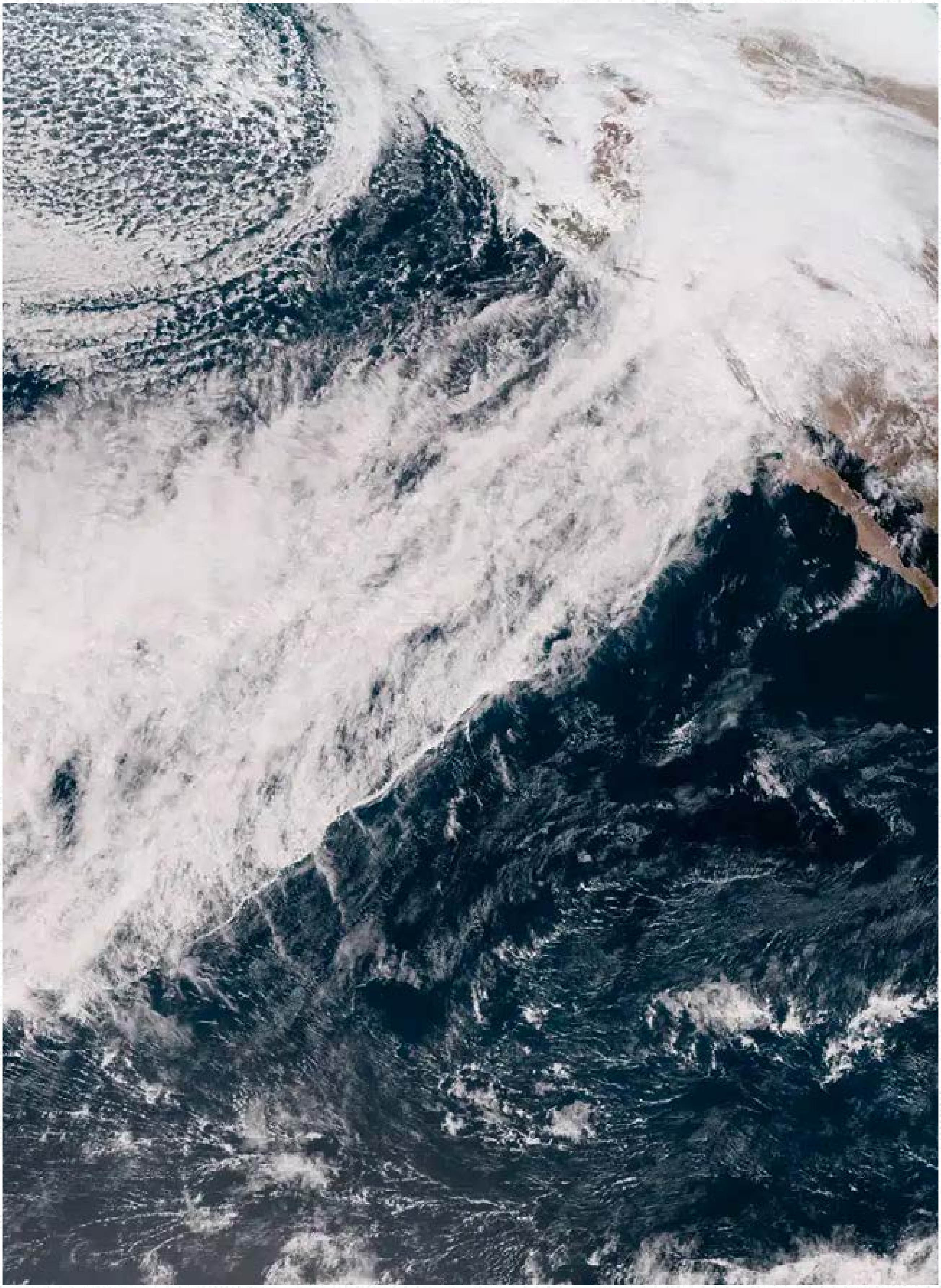
Acronyms and Abbreviations

cfs	cubic feet per second
DAC	disadvantaged community
DWR	California Department of Water Resources
FIRO-MAR	forecast-informed reservoir operations with managed aquifer recharge
Flood-MAR	flood-managed aquifer recharge
GDE	groundwater-dependent ecosystem
MAR	managed aquifer recharge
Merced watershed	Merced River watershed
MID	Merced Irrigation District
PH	planning horizon
Recharge-MAR	recharge pool reoperation concept that vacates additional flood control space by releasing water for managed aquifer recharge using agricultural land
study	Merced River Watershed Flood-MAR Reconnaissance Study
taf	thousand acre-feet
State Water Board	California Water Resources Control Board
TIR	technical information record
watershed studies	San Joaquin Basin Flood-MAR watershed studies
°C	degrees Celsius



California Department of Water Resources, Statewide Infrastructure Investigations Branch

Executive Summary

Climate change is profoundly altering California's water resources, leading to greater variability in weather and hydrology. Extended droughts are punctuated by strengthening deluges, snowpack and snowmelt are decreasing, and seasonal runoff patterns are shifting. All sectors of water management face increased risks from climate change. In the San Joaquin Valley, chronic water management challenges are intensifying with climate change. In just the last decade, water and flood managers have experienced both extremes — two record-setting wet years and the driest three- and four-year droughts on record. The occurrence and severity of droughts and floods likely will increase as the climate continues to warm. The Merced River watershed (Merced watershed) already faces chronic water management challenges even under current climate conditions, including groundwater overdraft that are exacerbated by climate change. Planning and analytical approaches that are siloed, focusing on a single water management sector, are insufficient for addressing 21st century water management challenges in California, the San Joaquin Valley, and for purpose of this study, the Merced watershed. Addressing these challenges demands flexible, multi-benefit, collaborative solutions that can improve flood, water supply, and ecosystem resilience.

Innovative infrastructure and multi-benefit water solutions are needed, implemented with multi-sector co-management, to reduce flood risk, replenish depleted aquifers, and restore terrestrial and aquatic habitats. To that end, a novel analytical toolset was developed for the Merced River Flood-MAR Reconnaissance Study (study) to integrate water system performance across these three sectors, enabling a shared understanding of climate vulnerability that motivates multi-benefit solutions using floodwaters for managed aquifer recharge (Flood-MAR).

To better understand climate vulnerabilities and how to address them, the California Department of Water Resources (DWR) conducted a three-year Merced study in partnership with Merced Irrigation District (MID) as a proof of concept to explore the effectiveness of Flood-MAR to concurrently reduce flood risk, improve water supply, and enhance ecosystems in the Merced River watershed, a tributary to the San Joaquin River. The Merced study is an exploratory watershed-scale analysis to develop and test analytical methods and models, assess climate change vulnerability, and evaluate adaptation strategies meeting multiple benefits that achieve these shared objectives:

Previous page: An atmospheric river drenches California in this image captured by a NOAA satellite. Photo by NOAA Satellites.

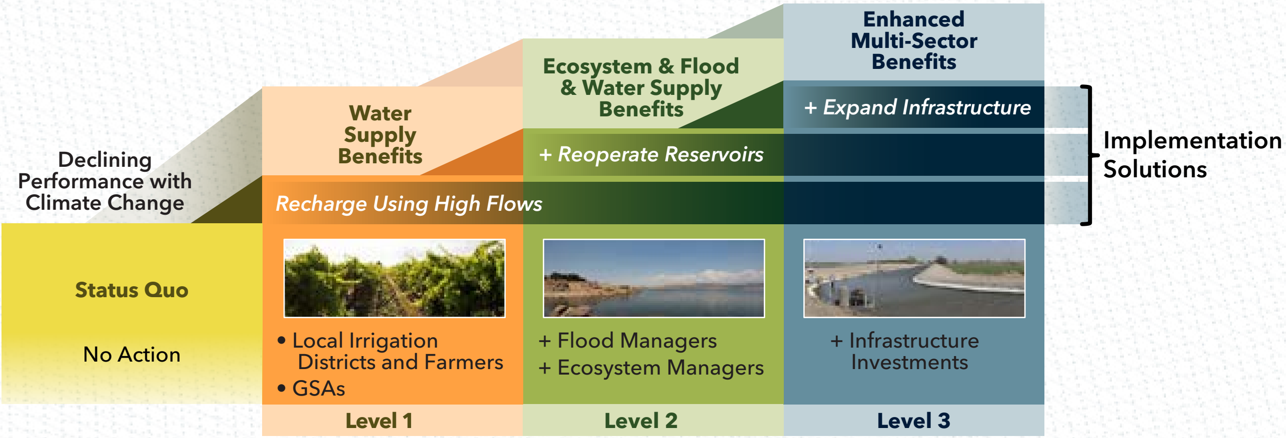
1. Assess watershed vulnerability to climate change for flood protection, water supply, and ecosystems.
2. Develop Flood-MAR strategies reflecting a range of operational complexity and infrastructure improvements.
3. Quantitatively evaluate the performance of Flood-MAR strategies in providing multi-sector benefits and climate resilience.

This approach acknowledges the value of watersheds as vital infrastructure and nature-based solutions. Using a climate risk-informed analytical approach known as decision scaling, the Merced watershed's hydrology and water system was stress-tested across a wide range of wetter, drier, and warmer climates that could occur under the 2040 and 2070 planning horizons. Use of the 2040 and 2070 planning horizons indicate that climate change effects will likely become greater over time. Combined with the estimated likelihood of these changes based on projections of global climate models, the Merced study shows the risk of worsening conditions for each water management sector:

- Under projected 2040 climate conditions, there is an 80-percent probability that increased runoff from winter storm events would cause an emergency spillway release at New Exchequer Dam resulting in a peak flow that would exceed the downstream flooding threshold identified by Merced Irrigation District.
- In the absence of actions to achieve groundwater sustainability, increased reliance on groundwater from higher agricultural demands (driven by higher temperatures) and reduced surface water availability in dry years would result in a 98-percent probability of increased groundwater overdraft under projected 2040 climate conditions.
- Species and habitats would suffer as well, because of declining groundwater levels (81-percent probability of impacts to groundwater-dependent ecosystem [GDE] habitat) and decreasing occurrence of flows that support instream spawning salmonid habitat (85-percent probability).

Multiple Flood-MAR strategies were explored in the Merced study, reflecting opportunities for increased adaptation and collaboration across sectors over time. As shown in Figure ES-1, Flood-MAR strategies were conceived and evaluated as a step-wise implementation pathway (i.e., Level 1, then Level 2, followed by Level 3) comprised of increasing multi-sector implementation actions.

Figure ES-1 Increased Levels of Flood-MAR Implementation through Multi-Sector Solutions and Partnerships



Level 1 Flood-MAR strategies are based upon diversions when flows exceed a defined threshold (using existing reservoir flood and water delivery operations). Level 2 Flood-MAR strategies build on Level 1 by introducing forecast-informed reservoir operations with managed aquifer recharge (FIRO-MAR) and a recharge pool reoperation concept that vacates additional flood control space by releasing water for managed aquifer recharge (Recharge Pool-MAR). Concepts that represent major changes to currently prescribed reservoir operations would require significant time and resources to reach implementation stage. Level 3 strategies build on Level 2 by incorporating infrastructure investments that increase recharge area and efficiency and targeted benefits of recharge management.

A closer look at Merced study results illustrates the significant multi-sector vulnerabilities resulting from climate change (previously highlighted in terms of risk) and the compelling performance of Flood-MAR strategies. Tables ES-1, ES-2, and ES-3 highlight a key result for each water management sector, comparing performance under the existing condition and with climate change (baseline) with the Level 1, 2, and 3 Flood-MAR strategies.

Table ES-1 **Flood Risk is Vulnerable to Climate Change and Flood-MAR with Reservoir Reoperation Builds Resilience**

Merced River 100-Year Peak Flow[1] (cfs)	Current	2040	2070
Baseline	6,000	15,680	29,330
Level 1: Recharge	6,000	15,670	29,310
Level 2: Reoperation + Recharge	7,040[2]	9,250	18,510
Level 3: Infrastructure + Reoperation + Recharge	6,020[2]	8,390	14,770

Note: [1]Simulated outflow downstream of Lake McClure reservoir at Crocker Huffman Diversion Dam. cfs = cubic feet per second.

[2]Release above the 6,000 cfs in Level 2 and Level 3 under current conditions is a modeling artifact and not an expected performance. This is due to a mismatch between the release decision and the available recharge capacity. To limit model iterations, any unused water available for recharge was routed downstream. However, there was enough capacity in the reservoir to safely withhold the releases above 6,000 cfs in storage and release it over the following days."

Warming temperatures and the potential for an overall wetter climate will significantly heighten the risk of 100-year peak flows beyond 7,300 cubic feet per second (cfs) in Merced River, the threshold of significant flooding downstream of the dam, which increases by more than 160 percent and 380 percent under 2040 and 2070 climate conditions, respectively. Although Flood-MAR Level 1 provides insignificant flood peak reduction, Level 2 reservoir reoperation combined with managed aquifer recharge (MAR) significantly reduces flood risk and is robust to more extreme climate change conditions.

Table ES-2 Water Supply is Vulnerable to Climate Change and All Flood-MAR Strategies Build Resilience

Groundwater Overdraft[1] (taf per year)	**Current**	**2040**	**2070**
Baseline	50	79	101
Level 1: Recharge	44	72	93
Level 2: Reoperation + Recharge	31	57	77
Level 3: Infrastructure + Reoperation + Recharge	19	46	66

Note: [1]Groundwater conditions assume that no actions or projects are implemented in Merced or neighboring subbasins to comply with the Sustainable Groundwater Management Act;
taf = thousand acre-feet.

Increased groundwater overdraft is expected under climate change conditions (a 58- and 102-percent increase under 2040 and 2070 climate conditions, respectively) because of significantly greater stresses on the groundwater system to meet higher irrigation demands and to make up for the reductions in surface water supply in drier years. Although all Flood-MAR strategies provide water supply resilience, Level 3 Flood-MAR, which achieves the largest volumes of applied recharge, could eliminate the increase in water supply vulnerabilty associated with 2040 climate conditions. Flood-MAR strategies to bolster water supply are robust, as shown by their continued effectiveness even under more extreme climate change conditions at 2070.

Table ES-3 Salmonid Habitat is Vulnerable to Climate Change and Flood-MAR with Reservoir Reoperation Builds Resilience

Merced River Instream Salmonid Spawning Habitat (thousand acre-days)	**Current**	**2040**	**2070**
Baseline	531	509	492
Level 1: Recharge	531	509	492
Level 2: Reoperation + Recharge	671	647	659
Level 3: Infrastructure + Reoperation + Recharge	638	616	625

Salmonid spawning habitat is also vulnerable to climate change, indicated by a reduction in usable area for spawning of 4 to 7 percent under 2040 and 2070, respectively. Level 1 Flood-MAR provides no improvement, but Levels 2 and 3 with reservoir reoperation and recharge, which also incorporates active management of flows to increase salmonid habitat, provides improvements (up to 34 percent), well beyond even the baseline condition.

The Merced study also evaluated the performance of potential off-channel salmonid rearing habitat, groundwater dependent ecosystems, and shorebird habitat under a range of climate conditions and Flood-MAR strategies. GDE and shorebird habitat exhibit increased vulnerability to climate change over time and benefit from the recharge operations under Levels 1, 2, and 3.

The potential off-channel salmonid rearing habitat relies on high flows above the over-bank inundation threshold. This habitat is considered potential since Merced River has limited suitability for salmonid rearing because of lack of structure, cover, and vegetation, all of which are important for rearing success. The inundation of this potential habitat is expected to improve with climate change. The diversion of high flows for recharge will reduce potential off-channel salmonid rearing habitat. However, the analysis also demonstrated that the Flood-MAR operations can be configured to lessen the impact to the potential off-channel habitat caused by recharge operations, while maintaining the flood and water supply, and other diversified ecosystem benefits.

Collectively, all Flood-MAR strategies explored in the Merced study provide some level of resilience to climate change in the Merced watershed. Specifically, Level 1 Flood-MAR provides some improvements for groundwater overdraft, but no resilience for flood peaks or salmonid spawning habitat. Levels 2 and 3 Flood-MAR, which incorporate significant changes to currently prescribed reservoir operations, enable additional groundwater overdraft reduction, as well as major benefits for flood and ecosystems.

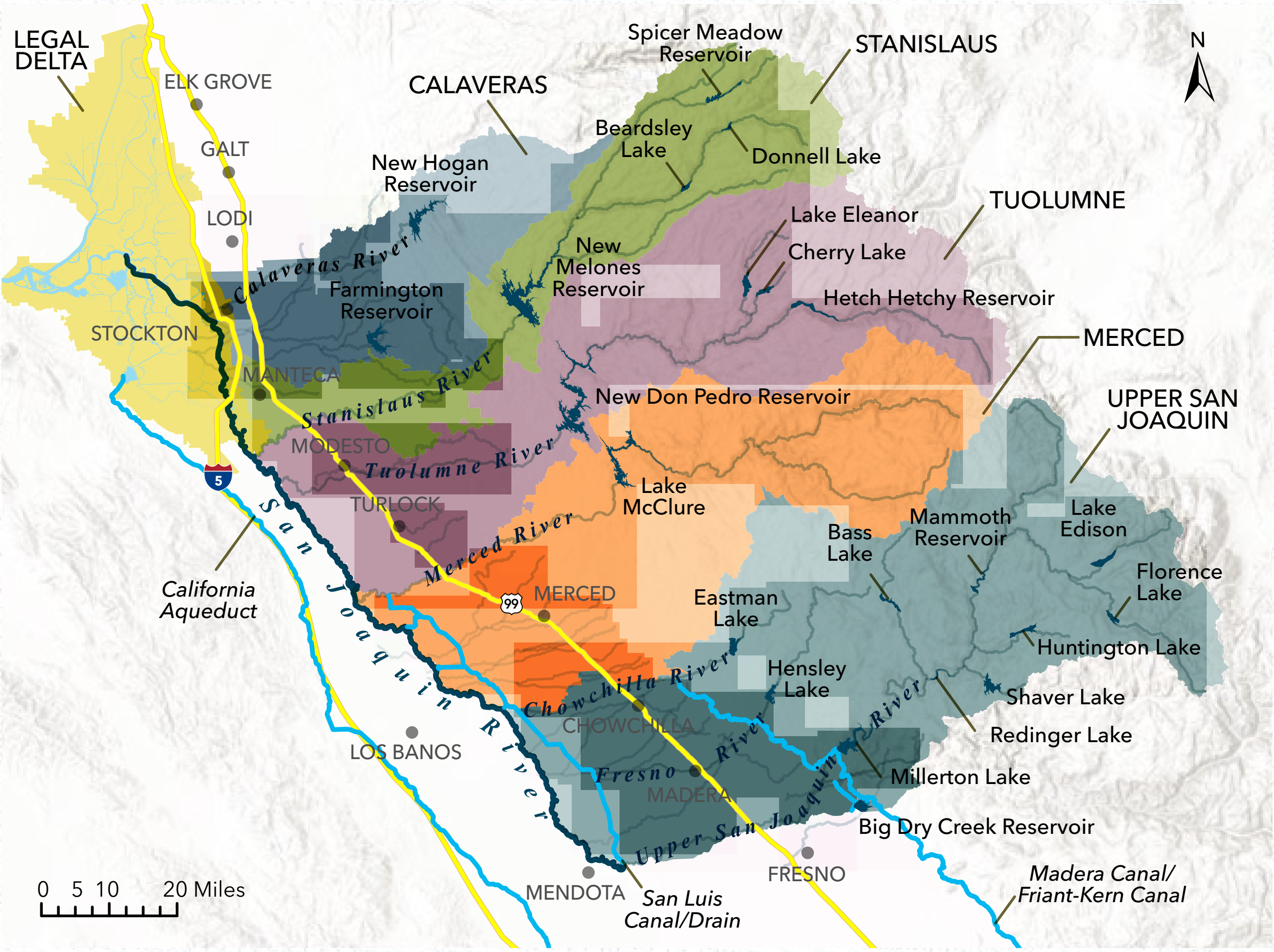
Infrastructure investments considered in Level 3 Flood-MAR, such as increased turnout capacity for fields and removal of conveyance bottlenecks, vastly reduces (more than 35 percent) the on-farm acreage needed for recharge applications. These types of infrastructure investment can be used to improve recharge efficiency that reduces the land area needed for onfarm recharge operations, increases total recharge, and enhances benefits of at-scale recharge operations with willing landowners in the watershed.

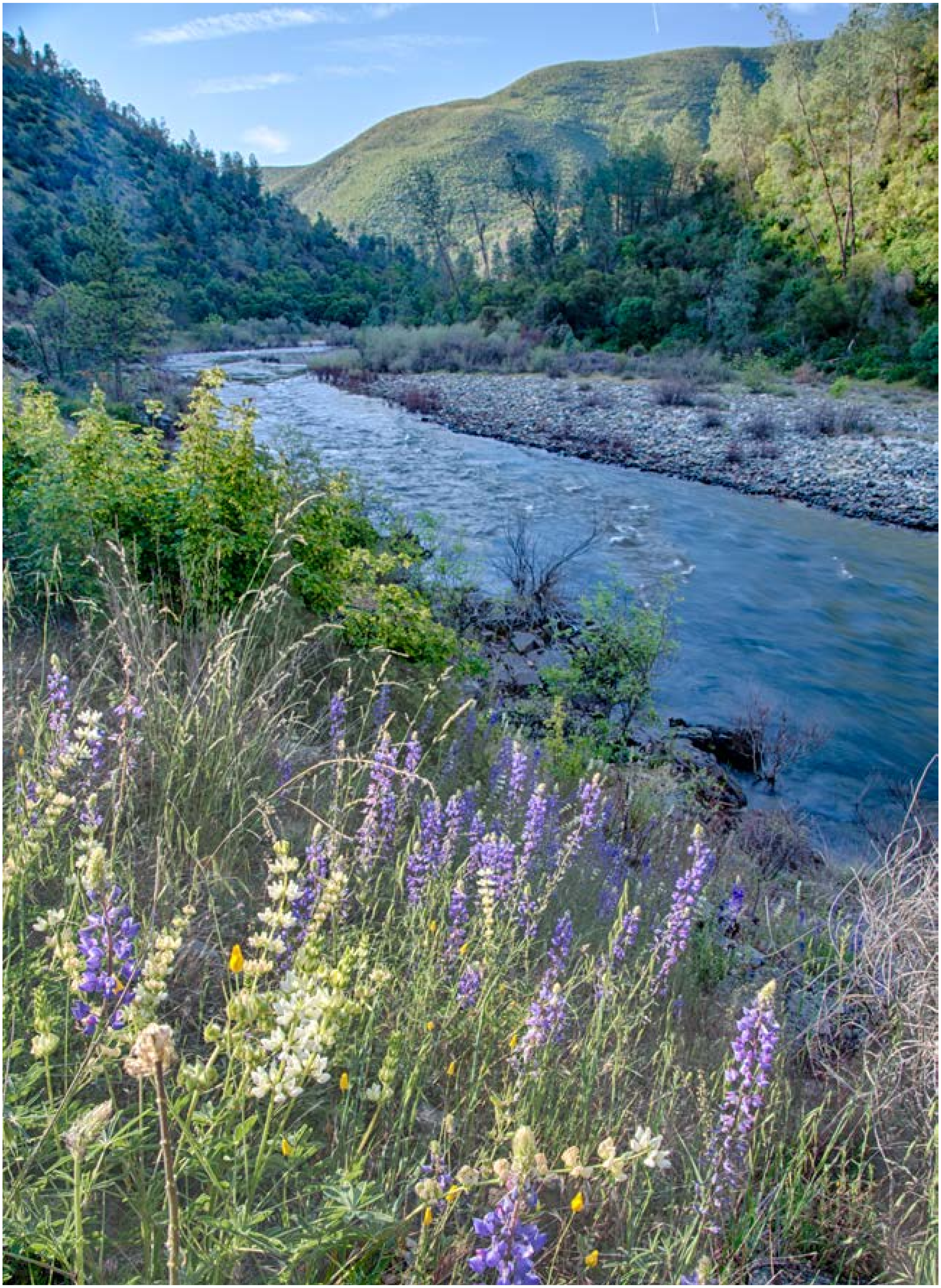
These highlighted outcomes were further extended by using recharge management areas to illustrate the potential for directed recharge outcomes. Specifically, the Merced study shows that subsidence mitigation, GDEs, shorebird and pollinator habitats, and reliability for underserved communities can all be improved by emphasizing recharge at specific locations. With these outcomes that are described in greater detail in technical information record (TIR) 4, the Merced study shows that where recharge occurs matters.

Flood-MAR strategies, especially those incorporating reservoir reoperation such as FIRO, can significantly reduce flood risk, improve water supply through conjunctive use, and enhance conditions for aquatic and terrestrial species. Flood-MAR provides a flexible framework for greater collaboration and integration across water management sectors.

In the Merced study, both the climate change vulnerability assessments and the performance of Flood-MAR strategies are compelling. This outcome demonstrates that Flood-MAR can play an important role in adapting water management in California and illustrates the value of project planning and implementation at the watershed scale. Next steps include applying the lessons learned from the Merced study analysis and outcomes to other watersheds to support the design and implementation of local on-the-ground pilot projects. DWR, with local and regional partners (including federal) is now conducting San Joaquin Basin Flood-MAR watershed studies (watershed studies) for all five tributaries of the San Joaquin River, including a refined Merced study to have consistent, comparable, and integrated results (see Figure ES-2). As part of these watershed studies, DWR and its study partners are evaluating opportunities to facilitate implementation of the multi-sector watershed-scale solutions. Flood-MAR and FIRO-MAR strategies are promising, and their implementation will require open dialogue, meaningful engagement, and a shared vision to implement at scale to realize multi-sector benefits.

Figure ES-2 DWR, with Local and Regional Partners, is Conducting San Joaquin Basin Flood-MAR Watershed Studies and Assessing Climate Vulnerability and Flood-MAR Adaptation Performance





Chapter 1. Purpose and Need

Over the last 10 years, California has seen increasingly extreme weather events, including the driest two (2021–2022) and four (2012–2015) consecutive years of statewide precipitation in the historical record interspersed with the second and third wettest years on record (2017 and 2023). These extreme events reflect the effects of climate change and are significantly stressing the state's natural and built water infrastructure systems. Climate change is profoundly altering California's water resources, leading to greater variability in weather and hydrology. Extended droughts are punctuated by strengthening deluges, snowpack and snowmelt are decreasing, and seasonal runoff patterns are shifting. All sectors of water management face increased risks from climate change. The occurrence and severity of droughts and floods will likely increase as the climate continues to warm. Many of California's water management challenges are clearly manifest in the San Joaquin Valley — flood risk is among the highest in the nation, water supplies are unreliable with groundwater managed unsustainably in many locations, and ecosystem habitats and species are in decline. In the San Joaquin Valley, chronic water management challenges are intensifying with climate change, including challenges associated with multi-year droughts and flood risk as noted above. The Merced River watershed (Merced watershed), tributary to the San Joaquin River, faces these chronic water management challenges even under current climate conditions, and these challenges are exacerbated by climate change. The increasing climate risk will be intractable, if not insurmountable, when addressed narrowly by individual water management sectors.

This Merced study highlights an improved understanding of climate change, including quantitative effects, as well as creative solutions and adaptation opportunities.

1.1 Flood Managed Aquifer Recharge

In 2018, the California Department of Water Resources (DWR) released a draft white paper, *Flood-MAR: Using Flood Water for Managed Aquifer Recharge to Support Sustainable Water Resources* (California Department of Water Resources 2018), to explore opportunities to use floodwater for managed aquifer recharge (Flood-MAR). Flood-MAR is an integrated and voluntary resource management strategy that can be used to address the risks of a changed climate condition to multiple sectors of water management including flood risk, water supply, and ecosystems. This study and other documents and forums continue to explore barriers and challenges associated with Flood-MAR implementation. This study highlights and assesses potential larger or watershed-scale Flood-MAR solutions.

Previous page: From its source on the south side of Mount Lyell at 13,114 feet, the Merced River flows to Lake McClure Reservoir through a glacially carved canyon. Photo by Bob Wick, BLM.

The *California Water Resilience Portfolio* (California Department of Water Resources 2020) prioritized key actions to secure California's water future, including opportunities to recharge and watershed-scale climate vulnerability and adaptation assessments. *California's Water Supply Strategy* (California Department of Water Resources 2022) again emphasized the opportunities associated with intentional groundwater recharge (i.e., managed aquifer recharge (MAR)) to harness the bounty of wet years to cope with dry years.

In winter 2023, Governor Newsom's Executive Orders N-4-23 and N-6-23 facilitated streamlined flood diversions and recharge in response to intense storms, record snowpack, and spring runoff. Although encouraging, these emergency and limited Flood-MAR actions will provide marginal improvements to the San Joaquin Valley's over-drafted aquifers and vulnerable flood management system. The State now has an opportunity to prepare for larger scale actions during the next wet season and beyond.

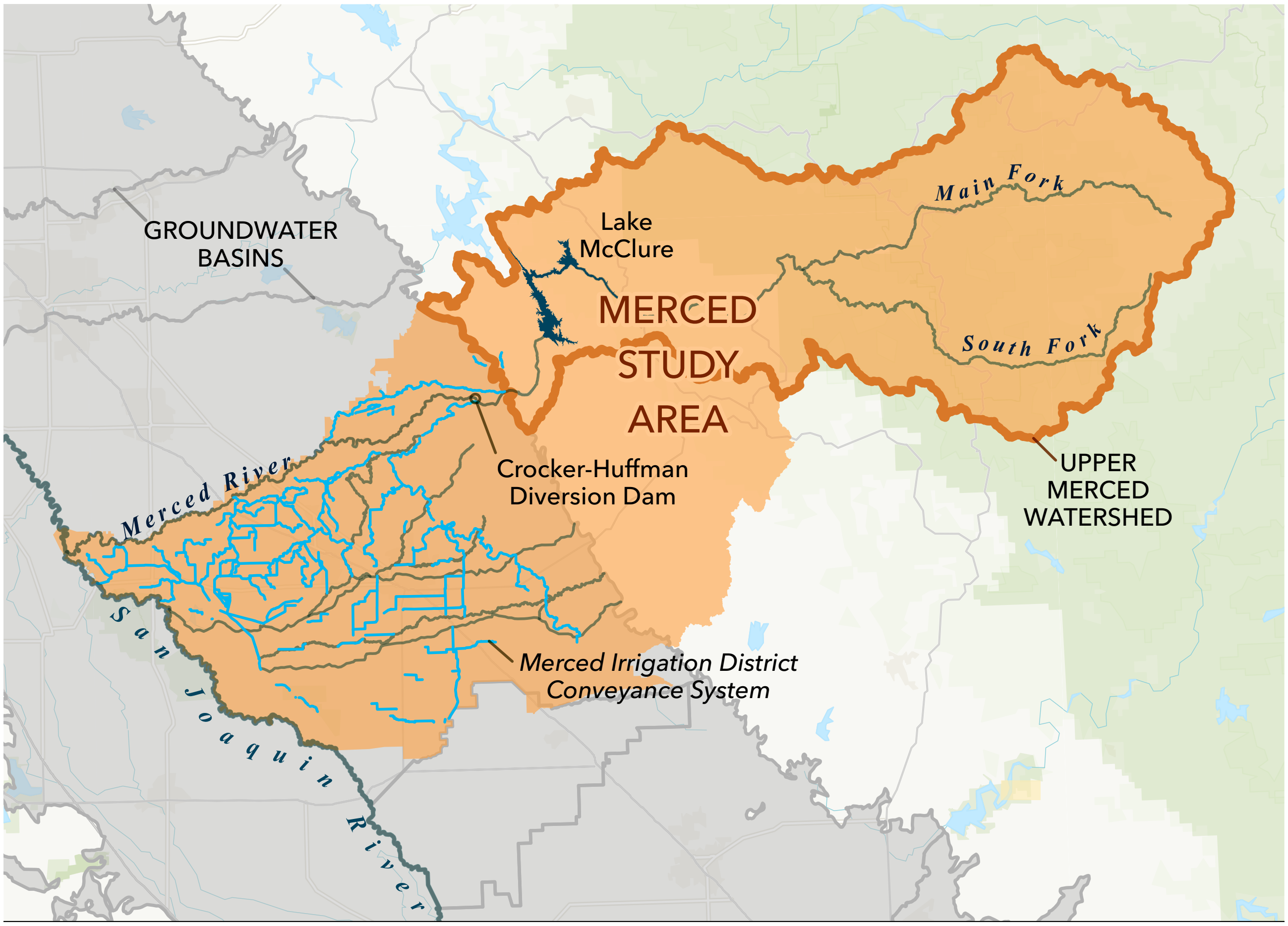
In partnership with the Merced Irrigation District (MID), DWR has conducted this three-year Merced River Watershed Flood-MAR Reconnaissance Study (Merced study) as a proof of concept to explore the effectiveness of Flood-MAR to concurrently reduce flood risk, improve water supply, and enhance ecosystems in the Merced watershed. The Merced study demonstrates that greater levels of multi-sector implementation of Flood-MAR strategies at scale-yield benefits to all three sectors, particularly under emerging water management challenges and opportunities associated with a changing climate. It also demonstrates that large-scale implementation of Flood-MAR can fundamentally and beneficially change how flood and groundwater management are integrated. Figure 1-1 shows the Merced River watershed, including the upper watershed, Lake McClure, Crocker-Huffman Diversion Dam, MID conveyance system, Merced River, creeks, and groundwater basins.

At these larger scales, Flood-MAR can achieve its full potential and value for California by integrating into the broader water management system. This exploratory study and the San Joaquin Flood-MAR watershed studies formulate and assess planned, comprehensive multi-sector Flood-MAR solutions. This report provides an overview of the Merced study's approach, methods, and key findings, identifying next steps and efforts to expand and accelerate Flood-MAR implementation at the watershed scale. The report is organized around the following topics that are more fully described in supporting technical information record (TIR) documents:

- Plan of Study – TIR 1
- Analytical Tools Integration – TIR 2
- Baseline Performance and Climate Change Vulnerability – TIR 3
- Adaptation Strategy Performance – TIR 4

As discussed in Chapter 5, to further demonstrate the need for and effectiveness of applying Flood-MAR and related watershed-scale solutions to address current and future water management risks, DWR is leveraging the toolset and lessons learned from the completion of this study to four additional San Joaquin Basin Flood-MAR watershed studies (watershed studies). In partnership with local, State, and federal agencies, DWR is evaluating the effectiveness of watershed-scale Flood-MAR solutions.

Figure 1-1 Merced River Watershed



1.2 Plan of Study

The plan of study described in TIR 1 lays out the approach for investigating Flood-MAR opportunities within the Merced watershed. As an exploratory study, some aspects of the study plan changed as the study progressed. The study has generally met its stated goals to:

- Assess the current conditions of the Merced watershed and the vulnerability of watershed management characteristics to a range of potential climate change futures.
- Determine the potential, feasibility, and effectiveness of Flood-MAR concepts, testing theories and assessing strategies in overcoming barriers and challenges to project planning and implementation. Quantify a range of benefits that Flood-MAR can provide in or adjacent to the Merced watershed, considering an extensive and multi-level menu of Flood-MAR strategies that range in their sectoral engagement and system complexity.
- Engage MID and other interested parties to scope and share the analysis and consider potential Flood-MAR actions. Engage and share study results with other State, federal, Tribal, and local entities; academia; and landowners to build on the knowledge and lessons from past and ongoing studies and programs, and to identify strategies to expand the integration of flood and groundwater management within the Merced River Basin.

Note: In this study, water available for recharge is determined as the volume of water physically remaining in the watershed after meeting the in-basin needs, downstream environmental and applied water demands, and filling the conservation storage space. Although this study evaluates if water is physically available, it does not explicitly consider the water rights needed to divert that water. Recognizing this simplification, the methodology used here will not meet requirements of a water right application, permit, or change to an existing water right permit. However, the streamlined permitting approach is employed analytically in the Level 1 Initial strategy described in this report.

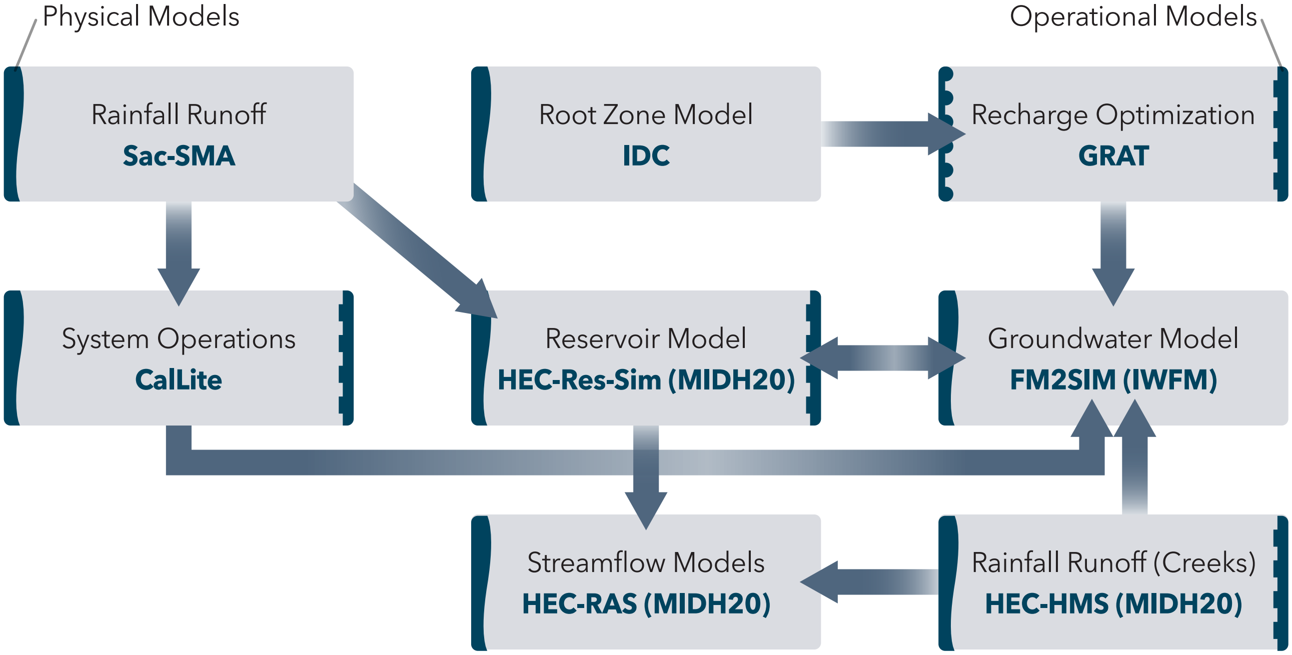
1.3 Analytical Tools Integration

Several models and innovative tools were developed for the analysis of climate vulnerability and Flood-MAR at the watershed scale. The resulting headwaters to groundwater toolset represents a state-of-the-art approach intended to provide information to multiple water management sectors for a shared understanding across those sectors of climate vulnerability and Flood-MAR adaptation performance. TIR 2 describes the analytical approach and integration of these models and tools. Three characteristics of the integrated toolset include:

- Analytics are performed across multiple water management sectors, including flood, surface water, groundwater, and ecosystems.
- All tools in the toolset use a shared continuous sequence of hydrology, thus mitigating the effect of water management sectors working in siloes.
- The toolset generates a shared understanding of vulnerabilities and Flood-MAR benefits across multiple water management sectors to motivate collective action and multi-sector solutions.

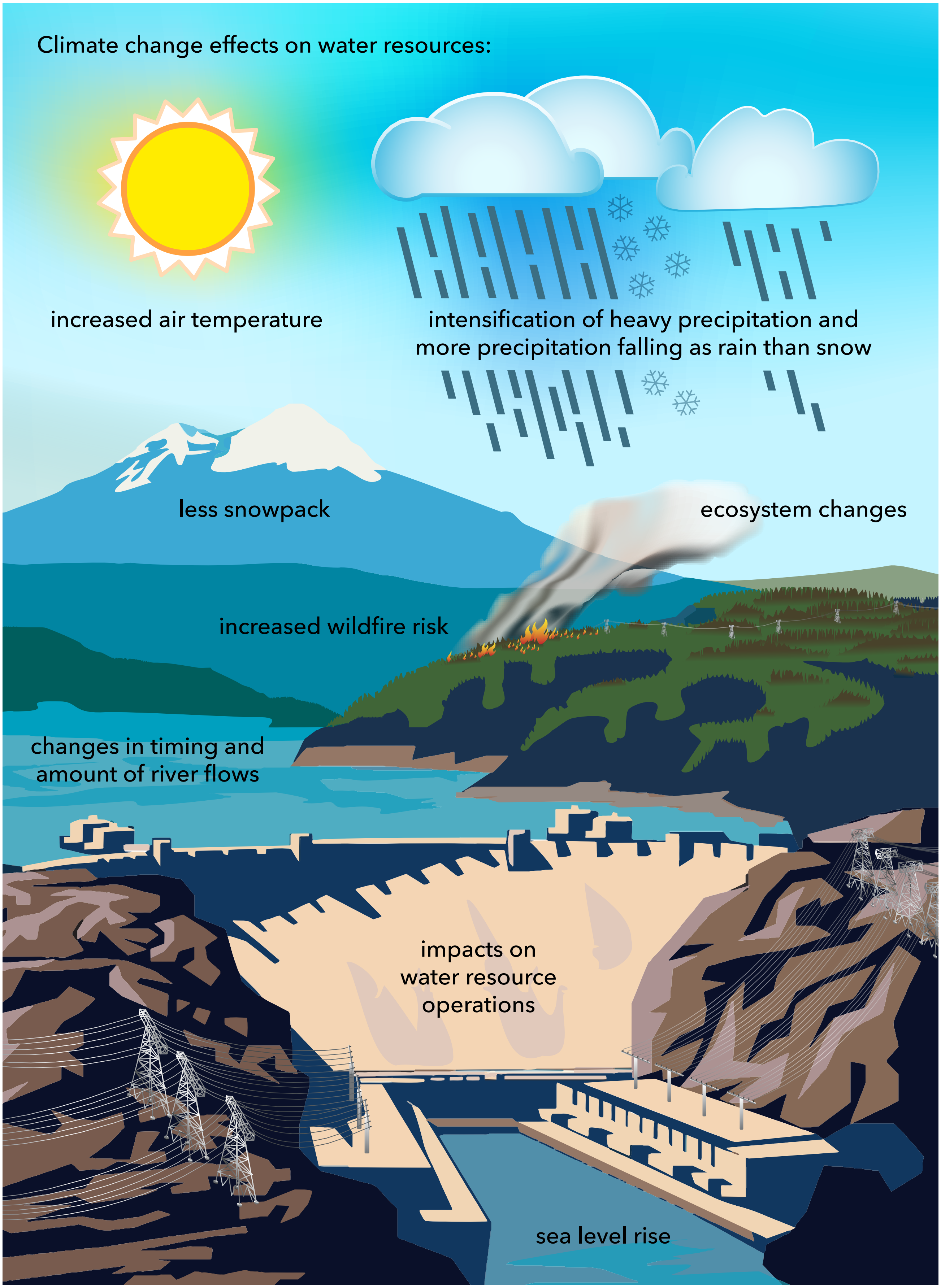
Figure 1-2 illustrates the communication and flow of information among the various models used in the Merced study. Some models were iteratively coupled given the strong dependency of model decisions on subsequent processes represented in another model (e.g., reservoir and groundwater operations), while other models were integrated in a single direction, given the lack of feedback between the two processes. When grouped together, these models can simulate the comprehensive headwater-to-groundwater response for watershed-based water management solutions.

Figure 1-2 Flood-MAR Models Integration



Notes: FMSJSim = Flood-MAR San Joaquin Simulation Model; GRAT = Groundwater Recharge Assessment Tool; HEC-HMS = Hydrologic Engineering Center – Hydrologic Modeling System; HEC-RAS = Hydrologic Engineering Center – River Analysis System; HEC-ResSim = Hydrologic Engineering Center – Reservoir System Simulation; IDC = Integrated Water Flow Model Demand Calculator; IWFM = Integrated Water Flow Model; SAC-SMA = Sacramento Soil MoistureAccounting.

Importantly, the integrated toolset was developed with close engagement of subject matter experts of each model domain (water sector) and through outreach and engagement with MID and interested parties. Each model seeks to faithfully represent and incorporate local knowledge and the operational assumptions of water managers in the watershed. The entire integrated toolset will be transferred to local partners to enable further analysis and support their eligibility for future funding of watershed-scale Flood-MAR activities.



California Department of Water Resources, Statewide Infrastructure Investigations Branch

Chapter 2. Baseline Performance and Climate Change Vulnerability

The study establishes a baseline condition of the Merced watershed and groundwater subbasin to evaluate performance across multiple water management sectors. The baseline condition reflects a constant level of development for land use and water demands indexed to the 2015 baseline year and includes existing reservoir and conveyance infrastructure and operations; however, the baseline does not incorporate potential projects and management actions by local groundwater sustainability agencies to meet requirements of the Sustainable Groundwater Management Act.

Climate change is incorporated using a "decision scaling" approach, which stress tests the Merced watershed, reservoir, and aquifers under a wide range of temperature and precipitation changes. In addition, application of conditional and relative likelihood of future climate changes enables interpretation of risk and decision-making (i.e., "scaling" the information to the decision-maker), facilitating a broader understanding of the uncertain climate future and actions that can be implemented over time.

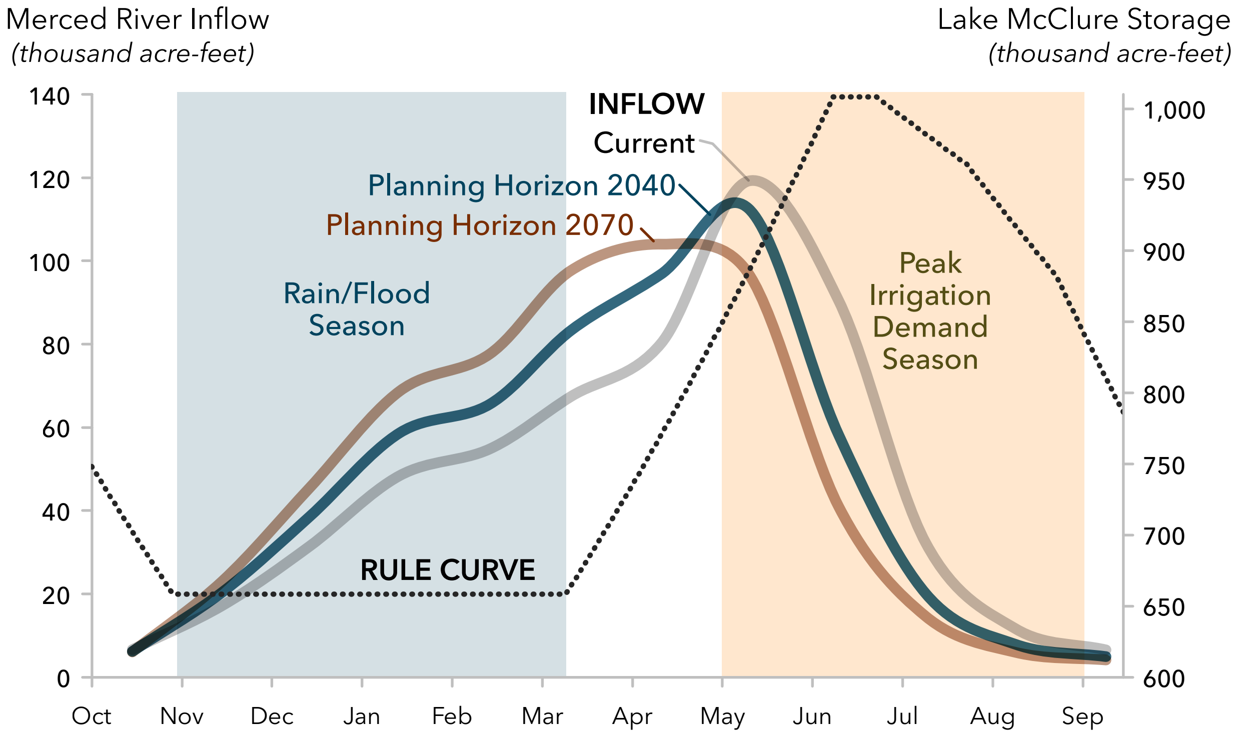
2.1 Watershed Conditions

The range of temperature and precipitation changes explored shows that climate change can alter the fundamental hydrology of the watershed system. As shown in Figure 2-1, changes in temperature and precipitation have a pronounced effect on total watershed runoff. Increases in temperature primarily drive changes in the timing of runoff, including inflow to Lake McClure, resulting in increased inflow from November through March and less inflow between April and October. Increased temperatures also stimulate the evaporative demand of the atmosphere, leading to reductions in total average runoff and increased agricultural applied water demand.

The change in inflow timing has major implications for the management of water supply, flood, and ecosystem. As shown in Figure 2-1, where the shift in timing of average monthly inflow is overlaid with the reservoir storage rule curve, Lake McClure's ability to store water while mitigating flood risk during the rain/flood season will be increasingly challenged as more inflow occurs during rain-flood season and less inflow is available during the peak irrigation demand season.

Previous page: Climate change is having a profound impact on California's water resources, as evidenced by higher temperatures, reduced snowpack, changes in the timing of river flows, and higher sea levels. Higher temperatures can drive longer periods of drought, longer and more destructive wildfire season, intensification of heavy precipitation events, and more precipitation falling as rain than snow. These changes create multiple water sector vulnerabilities and impact the performance of water resource system operations. Figure adapted from the DWR Climate Change Factsheet (2022). Learn more at https://water.ca.gov/Water-Basics/Climate-Change-Basics.

Figure 2-1 Climate Change Alters the Fundamental Hydrology of the Merced River and Causes Reservoir Management Challenges



Notes: Lines show average monthly Merced watershed simulated inflow under current climate conditions and future climate change conditions for the 2040 and 2070 planning horizons. Also shown is the rule curve for Lake McClure, with dotted line, that provides the guidance for flood and conservation (water supply and instream) operations of the reservoir; PH = planning horizon.

2.2 Multi-Sector Performance Metrics

A shared multi-sector understanding of flood risk, water supply, and ecosystems was developed by identifying multiple indicators for the Merced watershed and groundwater subbasin. Fourteen indicators are listed in Table 2-1. These indicators, or metrics, are selected based on relevance to the water managers for the respective sectors, broad understanding among the water management community, and are evaluated at an appropriate resolution that can be reasonably supported using the integrated modeling toolset. The indicators are used to illustrate a connected description of water management vulnerability and adaptation performance. For a broader description of these metrics, see TIR 3.

Table 2-1 Multi-Sector System Performance Indicators

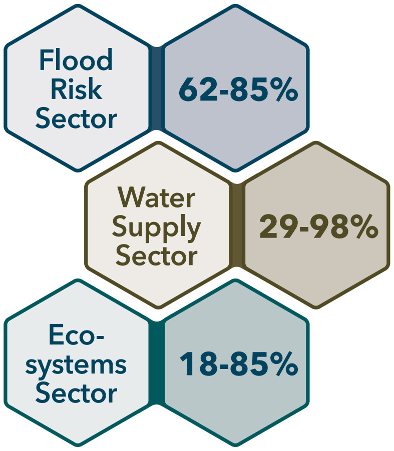
Sector	Indicator
Flood Risk	Maximum encroachment at Lake McClure (November 1–March 15)
	Merced River 100-year maximum simulated peak flow (November 1–June 30)
	Total number of years Merced River at Crocker Huffman Diversion Dam is above 7,300 cfs (November 1–June 30)
	Bear Creek 100-year maximum simulated outflow
Water Supply (Groundwater)	Basinwide average annual change in groundwater storage
	Average annual change in groundwater levels in subsidence prone region
	Average annual change in groundwater levels in aquifer underlying DACs east of Corcoran Clay layer
	Average annual total groundwater pumping to meet agricultural uses in the Merced watershed
Water Supply (Surface Water)	Average annual total surface water deliveries to agricultural users in the Merced watershed
	Number of years MID's surface water availability at or below 80 percent
	Average annual Lake McClure storage at the end of the irrigation season (October 31)
Ecosystem	Proportion of months with depth to groundwater less than 30 feet
	Merced River instream salmonid spawning habitat (September–April)
	Potential Merced River off-channel juvenile rearing habitat during qualified events (December–May)

Notes: cfs = cubic feet per minute; DAC = disadvantaged communities; MID = Merced Irrigation District.

2.3 Multi-Sector Risks to Climate Change

Figure 2-2 shows the risk of future performance becoming worse than the baseline performance threshold for the selected multi-sector metrics. All sectors have at least one metric that indicates a decline in future performance with a probability of 80 percent or higher, with some metrics showing up to 98-percent probability (e.g., water supply sector) by the 2040 planning horizon. These results are useful for understanding and spurring the actions needed to mitigate climate risks, showing that even with the wide range of possible climate outcomes 20 years from today (some beneficial and some hazardous for a given sector), the relative likelihood of these outcomes suggests an overall higher risk and vulnerability for all water management sectors.

Figure 2-2 Climate Change Makes All Water Management Sectors More Vulnerable

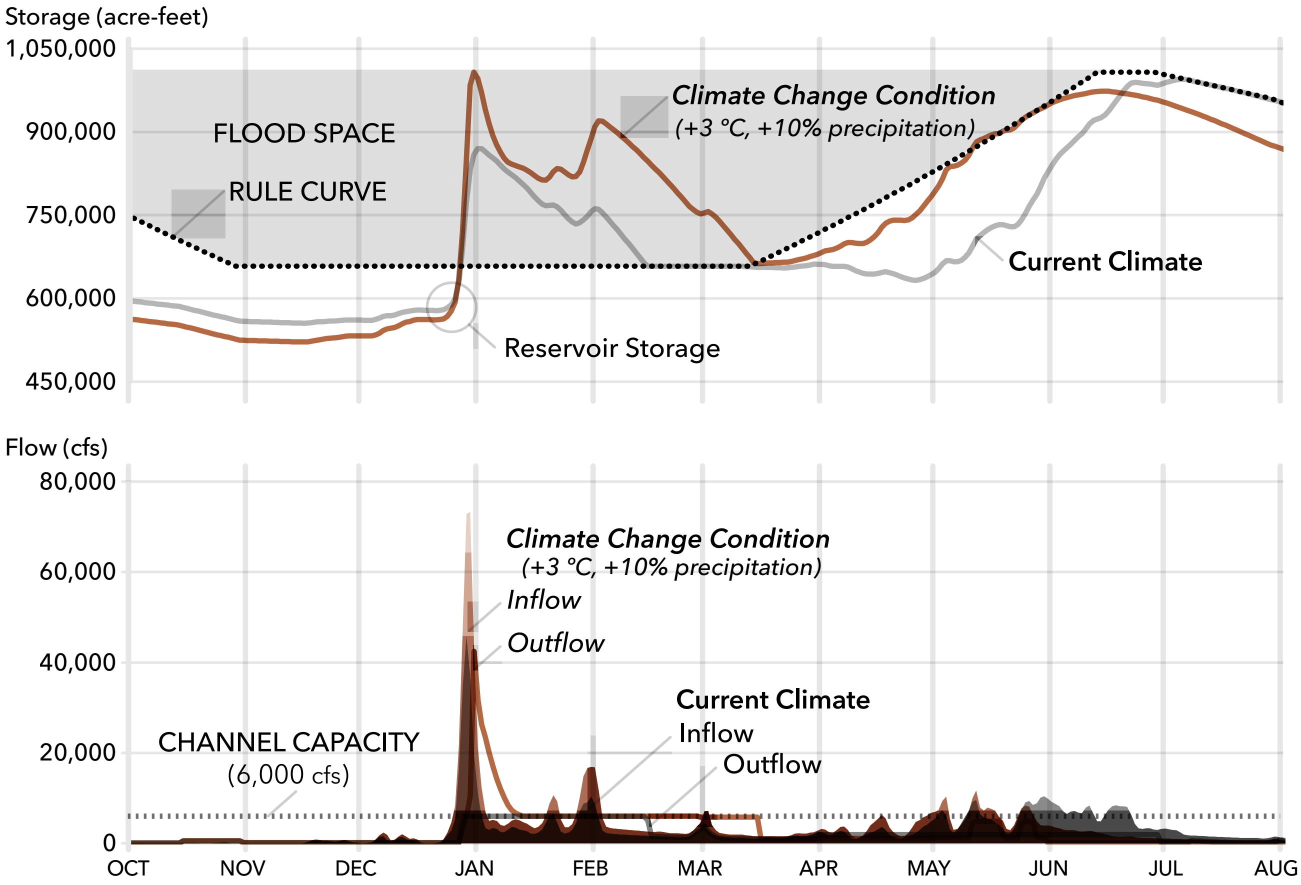


Note: Percentages indicate the probability of future performance becoming worse than current performance, given the range of projected climate changes at a 2040 planning horizon. The range of probabilities shown represents the range across the metrics for each sector.

2.4 Drivers of Flood Risk

An increase in upper watershed runoff associated with future climate conditions produces higher winter peak inflows to Lake McClure. As shown for a flood event in Figure 2-3, higher inflow volume simulated under a potential climate of 3 degrees Celsius (°C) warmer and 10 percent more precipitation pushes reservoir storage higher and more rapidly into the flood space compared to current climate conditions. As a result, storage reaches the top of flood pool and forces the reservoir into emergency operations. Under emergency operations, the reservoir release exceeds the channel capacity in the Merced River, consequentially producing flood conditions downstream of the reservoir. In this more extreme modeled climate condition (3 °C warmer and 10-percent precipitation increase), reservoir releases are 600 percent higher than channel capacity.

Figure 2-3 A Wetter-Warmer Future Climate Causes Substantial Increases in Flood Risk



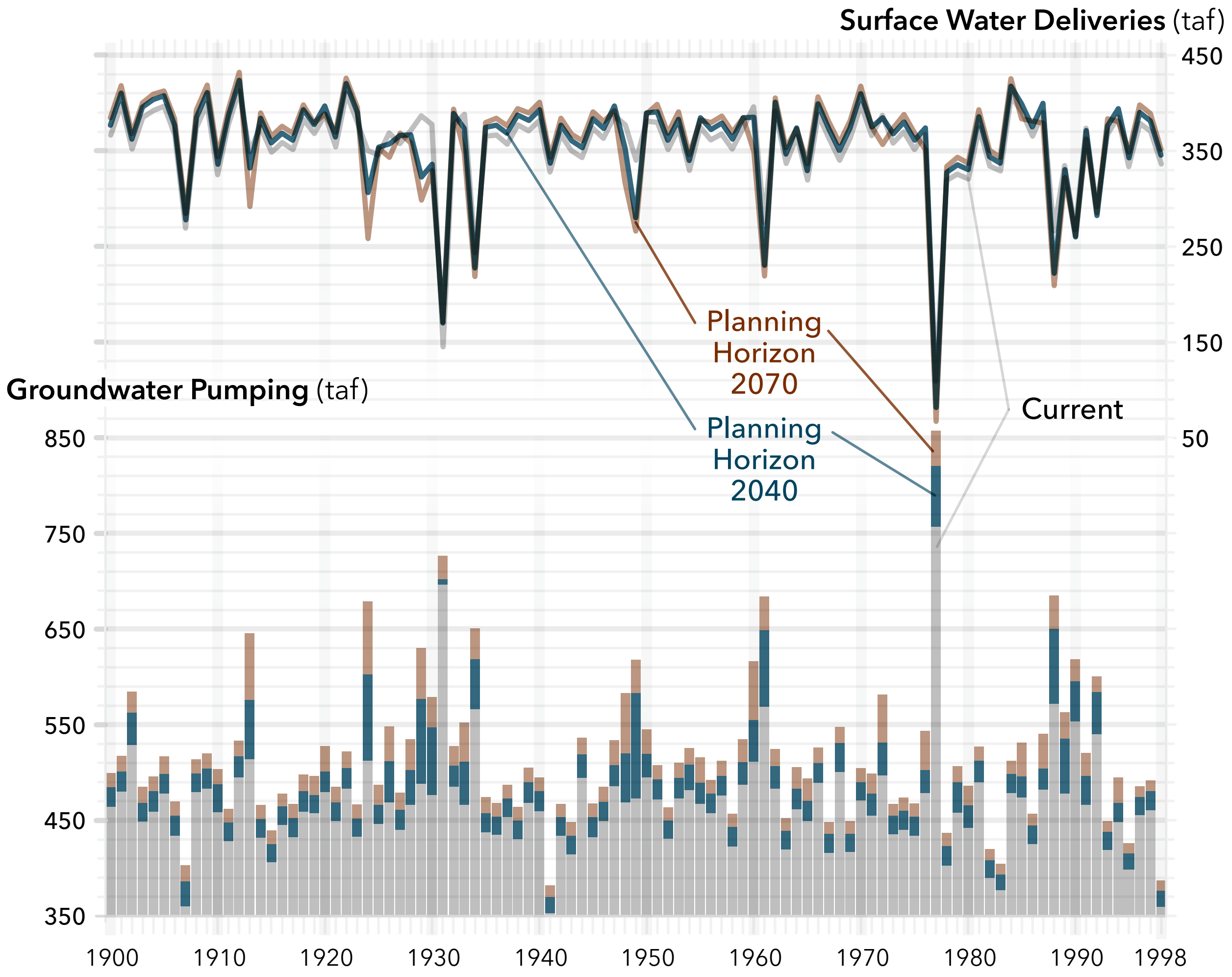
Notes: Modeling results shown for Lake McClure storage (top figure) and Merced River inflow to and outflow from Lake McClure (bottom figure). The climate change condition is 3 °C warmer and has 10 percent more precipitation than current climate; cfs = cubic feet per second; °C = degrees Celsius.

2.5 Drivers of Water Supply Risk

The risks to water supply in the Merced watershed caused by climate change are related to changes in evapotranspiration and inflow runoff timing, followed by subsequent reservoir operations and groundwater management response. Increases in temperature result in greater evapotranspiration from crops, thus raising applied water demand. This higher applied water demand, combined with the shift in the seasonal runoff to earlier in the spring, diminishes the refill potential during the irrigation season and ultimately yields a lower carryover storage by the end of the irrigation season. Because no demand management actions are assumed in the study, demand for applied water is fully met through a combination of surface water delivery and groundwater pumping. Consequently, this results in increased groundwater pumping to meet the higher applied water demand in all years and, in drier years, additional pumping to “cover” the reduction in surface supply resulting from lower carryover storage from prior years. This is evident in Figure 2-4 by the more pronounced increases in groundwater pumping during certain years of the simulation with significantly reduced surface water supply compared to current climate conditions (e.g., 1913, 1924, 1930, 1948–1949, 1960–1961, 1977, and 1988).

Based upon these assumptions, and for purposes of describing water supply for this study, including climate change vulnerability and adaptation performance, effects to groundwater overdraft provide a summary indicator for water supply. An increase in overdraft resulting from climate change is an increase in vulnerability to climate change for water supply. Similarly, a reduction in overdraft from a Flood-MAR strategy is an improvement in water supply.

Figure 2-4 **Climate Change Leads to Increased Groundwater Pumping Especially in Years with Reduced Surface Water Deliveries**



Notes: Modeling results for total annual surface water deliveries (top, lines) and groundwater pumping (bottom, bars) within the Merced groundwater subbasin under current climate and climate change for the 2040 and 2070 planning horizons. PH = planning horizon; taf = thousand acre-feet

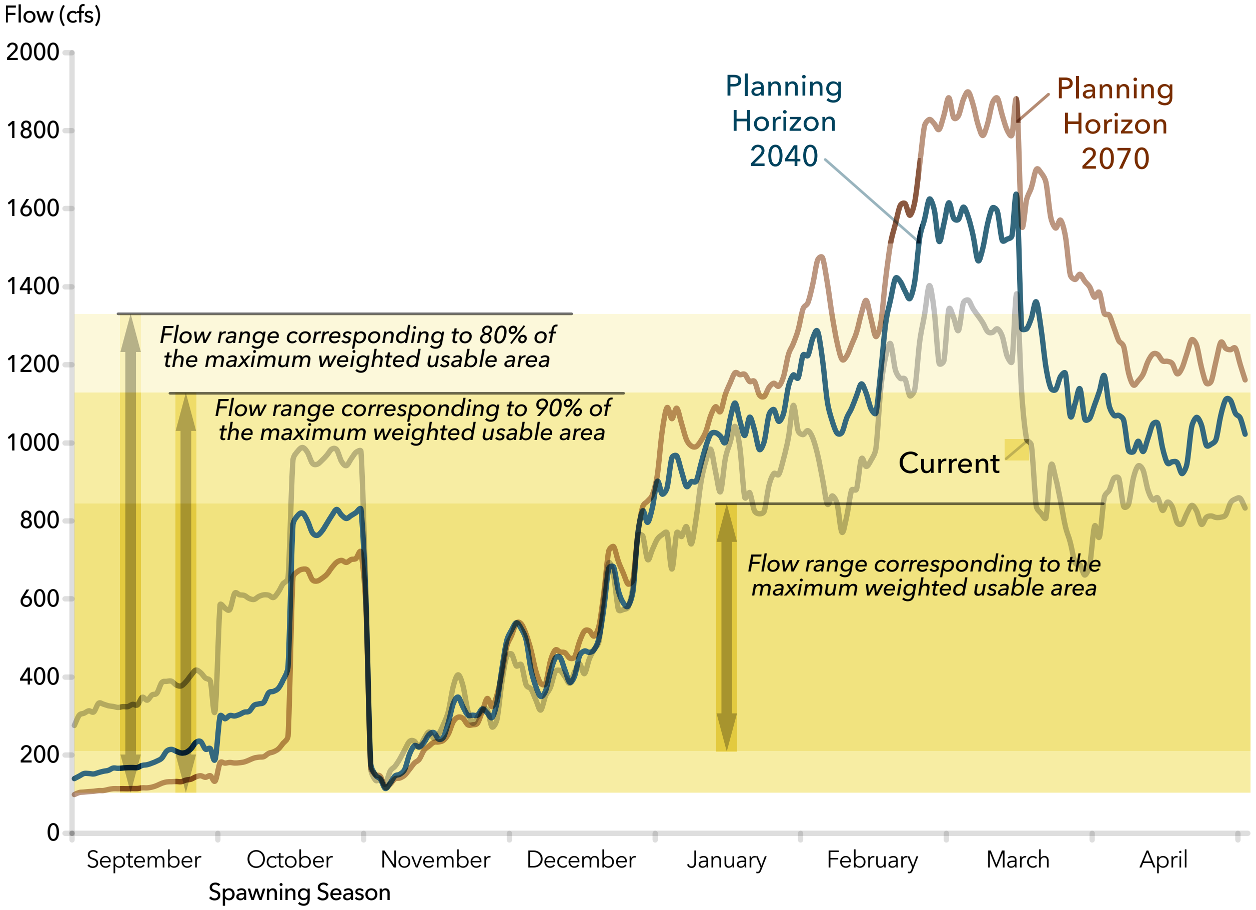
2.6 Drivers of Ecosystem Risk

Groundwater-dependent ecosystem (GDE) habitat availability closely tracks with groundwater conditions. As a result, GDEs likely will experience a decrease in groundwater availability under climate change as groundwater levels decline because of increased pumping, which likely will affect GDE sustainability.

Instream habitat for spawning salmonids is expected to decrease slightly between current and climate change conditions. The shift in runoff timing, along with the lower carryover storage resulting from increased evapotranspiration demands under future climate conditions, are expected to reduce flows during the fall months and increase flow during the late winter and early spring months, as shown in Figure 2-5. The net effect of the changes in flow is expected to reduce the frequency of time that flows are in the preferred flow range for salmonid spawning. These reductions in the habitat alone likely do not represent biologically relevant changes in spawning habitat for these species. However, the inclusion of water temperature data is expected to show greater vulnerability of salmonids to climate change than modeled by habitat quantity alone.

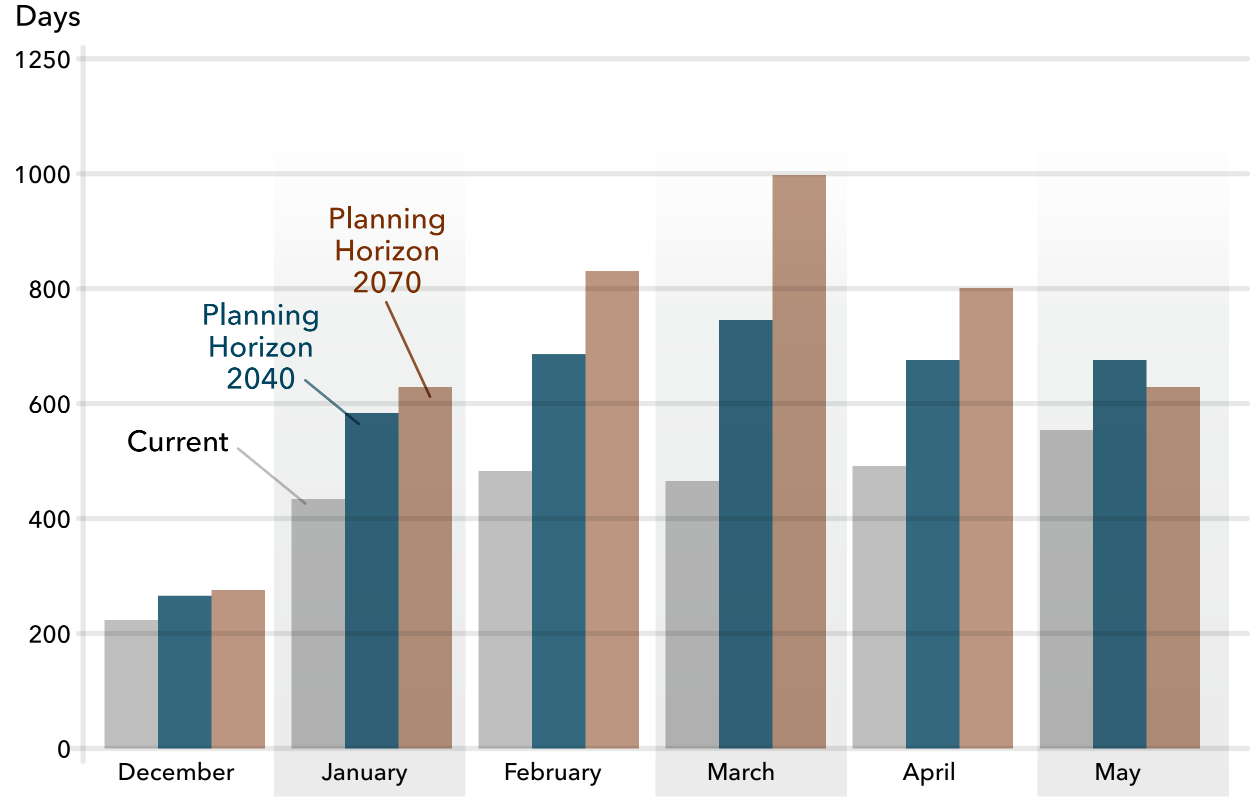
Potential off-channel habitat inundation for salmonids is predicted to increase for both 2040 and 2070 planning horizons. The primary driver behind the potential off-channel habitat improvement is the frequency of the Merced River flow at Crocker Huffman Diversion Dam above the 1,800 cubic feet per minute (cfs) over-bank inundation threshold between December and May. Climate change is expected to shift the runoff timing to earlier in the spring. This results in increased magnitude and frequency of off-channel inundation flows, as shown in Figure 2-6. Even though the off-channel inundation increases under future climate conditions, the current off-channel habitat on the Merced River has limited suitability for salmonid rearing because of the lack of structure, cover, and vegetation, all of which are important for rearing success. Hence, for this study, the inundated areas are considered potential habitat.

Figure 2-5 Climate Change Leads to Reductions in the Frequency of Flows in the Preferred Range for Salmonid Spawning



Notes: Simulated average daily Merced River flow at Crocker Hoffman between September 1 and April 30 under the current and the 2040 and 2070 planning horizons. The shaded area shows the approximate preferred flow range for achieving 80, 90, and 100 percent of the maximum instream salmonid spawning habitat based on the weighted usable area curves developed for the Merced River (Merced Irrigation District 2013). cfs = cubic feet per second.

Figure 2-6 Climate Change Leads to Increases in the Number of Days Flow Exceeds the Over-Bank Inundation During the Salmonid Rearing Season



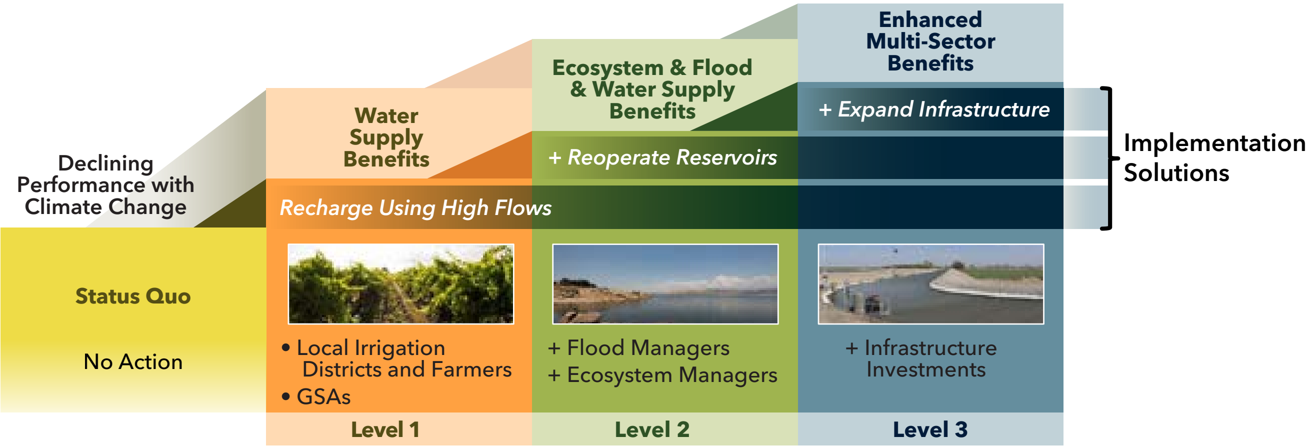
Notes: Total number of days simulated Merced River daily flow at Crocker Hoffman between December 1 and May 31 exceeds 1,800 cubic feet per second, the over-bank inundation threshold, under the current and the 2040 and 2070 planning horizons. PH = planning horizon.

Chapter 3. Flood-MAR Performance in a Changing Climate

This Merced study shows that the expected changes in the hydrology of the Merced watershed resulting from climate change also increase the potential for Flood-MAR opportunities. In addition to increased climate vulnerability across the water management sectors as described in Chapter 2, opportunities for Flood-MAR actions increase as well. Flood-MAR strategies take advantage of wetter periods to store water in groundwater subbasins to provide resilience during increasingly dry cycles. The multiple levels of Flood-MAR analyzed in the study demonstrate the strategies are scalable and flexible, both spatially and temporally.

Flood-MAR strategies developed for this study demonstrate the potential to create multi-sector benefits from headwaters to groundwater in the Merced watershed and Merced groundwater subbasin. Although the Flood-MAR strategies target specific water management objectives, the strategies are not optimized for any single management objective. Water supply, flood risk, and ecosystem sectors were evaluated across a range of Flood-MAR strategies and potential future climate conditions. Figure 3-1 illustrates the expanding footprint and complexity of each additional level of Flood-MAR implementation that progressively delivers greater and more widely shared benefits.

Figure 3-1 Increased Levels of Flood-MAR Implementation through Multi-Sector Solutions and Partnerships



Note: GSAs = groundwater sustainability agencies.

Previous page: The James Irrigation District uses pumps from DWR's Emergency Pump Program to divert water for groundwater recharge in Fresno County, California. Photo taken May 26, 2023.

3.1 Connecting Climate Change Vulnerability and Multi-Sector Flood-MAR Adaptation Performance

The water management sectors assessed (flood risk, water supply, and ecosystems) are all vulnerable to climate change. Understanding the vulnerabilities of each can provide a shared understanding of water management challenges and direction for adaptations. This study acknowledges our uncertain climate future, reflecting a range of climate change effects by reporting the expected value for two future planning horizons at 2040 and 2070.

Three (one for each level) of the nine Flood-MAR adaptation strategies explored in the study are listed below to illustrate adaptation performance for a selection of study metrics:

1. Level 1 Initial. A Flood-MAR strategy based on California State Water Resources Control Board's (State Water Board) streamlined permitting guidance for recharge using the 90th percentile/20-percent method, where diversions of up to 20 percent of the flow when flow exceeds the 90th percentile daily historical flow are recharged using district canals.
2. Level 2 FIRO-MAR. A strategy that adds reservoir reoperation with forecast-informed reservoir operations combined with managed aquifer recharge (FIRO-MAR) on agricultural lands.
3. Level 3 Recharge Pool-MAR. A strategy that adds reservoir reoperation with a recharge pool concept that vacates additional flood control space by releasing water for MAR using agricultural lands and includes expanded infrastructure, such as expanded turnouts and new recharge basins.

TIR 4 provides detailed information on the configuration of each of these strategies, as well as the remaining six Flood-MAR adaptation strategies explored in the study, and their adaptation performance.

3.1.1 Recharge Operations at Watershed-Scale

Recharge is an essential element of a Flood-MAR strategy. This study includes recharge using an existing canal network, an existing dedicated recharge basin, and agricultural fields. As shown in Table 3-1, increasing amounts of recharge are applied under progressive levels of Flood-MAR strategies and under higher levels of climate change. These results indicate the scale of recharge operations needed to achieve the multi-sector benefits under the increasing levels of Flood-MAR implementation explored in this study. Although more recharge is made possible through Flood-MAR reservoir reoperation strategies in Levels 2 and 3, the area of on-farm land needed for recharge is extensive – up to 34,000 acres, or approximately one-quarter of MID agricultural lands served – in some years. Infrastructure investments considered in Flood-MAR Level 3, such as increased turnout capacity for fields and removal of conveyance bottlenecks, vastly reduces (more than 35 percent) the on-farm acreage used for recharge application. This type of infrastructure investment can be used to improve recharge efficiency and achieve greater recharge and related benefits of at-scale recharge operations with fewer willing landowners in the watershed. The recharge optimization tool used in this study selects agricultural fields for recharge based upon several factors, including crop type/compatibility for recharge, soil type, and aquifer characteristics. See TIR 2 for a more detailed description of this groundwater recharge assessment tool.

Table 3-1 Applied Recharge Increases with Higher Levels of Flood-MAR and Climate Change

Flood-MAR	**Annual Recharge Maximum (Average)** thousand acre-feet			**On-Farm Recharge Area Maximum** acres		
Level of Strategy	Current	2040	2070	Current	2040	2070
Level 1 Initial	72 (17)	74 (18)	77 (21)	0 (No On-Farm Recharge. Canal Recharge Only)		
Level 2 FIRO-MAR	425 (65)	450 (73)	478 (85)	33,900	34,300	34,800
Level 3 Recharge Pool-MAR	565 (99)	563 (105)	584 (118)	22,400	22,300	22,300

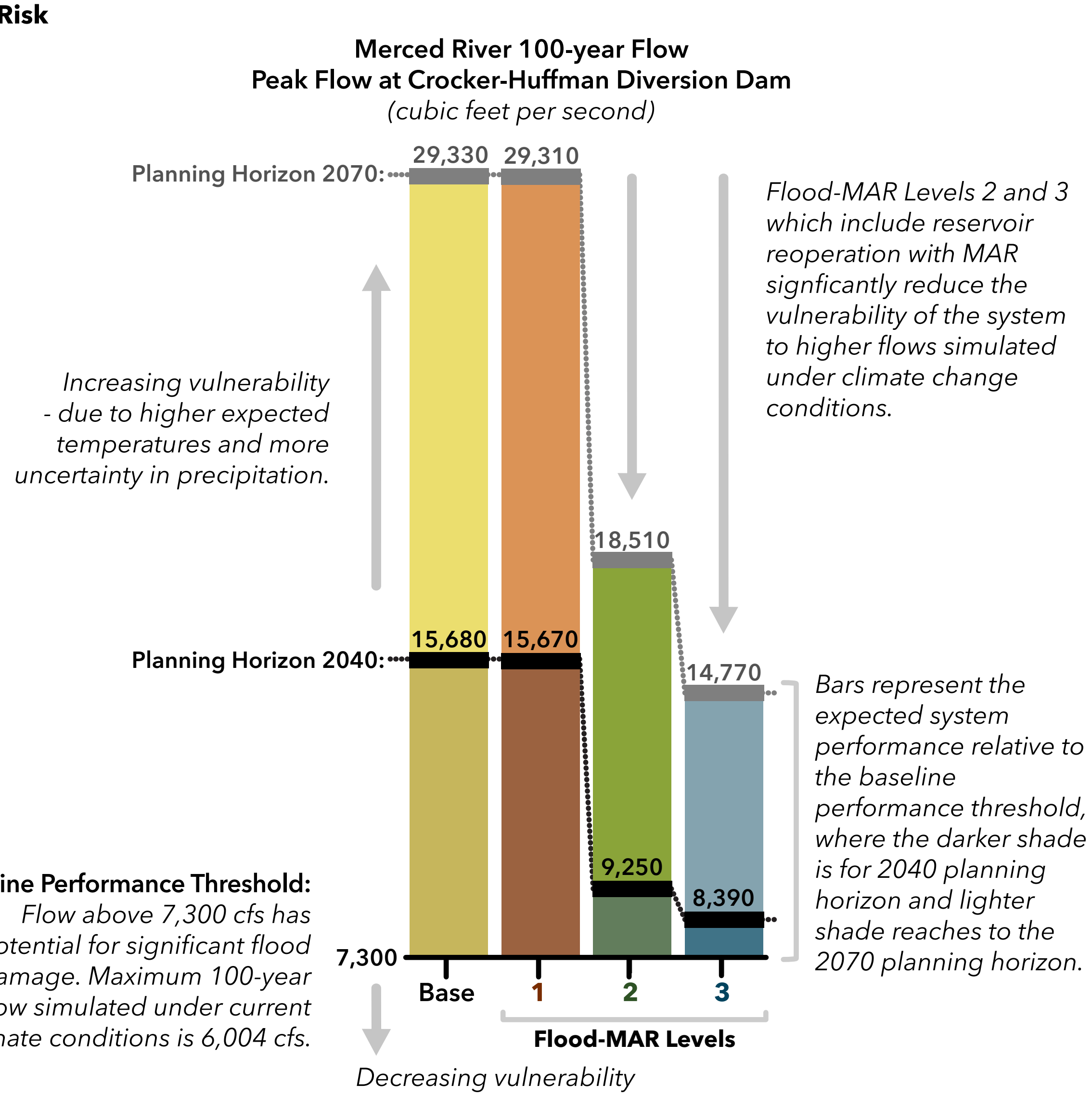
Notes: Recharge is reported as the maximum annual and average annual (in parenthesis) over the 100-year period of simulation. On-farm acreage is reported as the maximum acres used in the wettest year of the 100-year period of simulation. Flood-MAR = floodwater used for managed aquifer recharge; FIRO-MAR = forecast-informed reservoir operations combined with managed aquifer recharge; Recharge Pool-MAR = recharge pool concept that vacates additional flood control space by releasing water for managed aquifer recharge using agricultural land.

3.1.2 Flood Risk Sector

Flood risk is both vulnerable to the effects of climate change and responsive to Flood-MAR adaptations that provide a range of performance improvements. Under current climate conditions with no Flood-MAR actions, the simulated Merced River 100-year peak flow at Crocker-Huffman Diversion Dam is 6,000 cfs, reflecting a managed flow within channel capacity. Under the climate conditions at 2040 and 2070, Figure 3-2 shows increasing flood risk vulnerability expected under the baseline (no Flood-MAR action) condition and a reduction of vulnerability under the three Flood-MAR adaptation levels summarized as follows:

- With no actions (i.e., baseline) Merced River 100-year peak flow increases to 15,680 cfs and 29,330 cfs for 2040 and 2070, respectively, reflecting flows significantly greater than the 7,300 cfs threshold at which significant flooding is expected to occur.
- Flood-MAR Level 1 provides insignificant reduction of peak river flow, reflecting the limited ability of opportunistic diversion to provide flood sector benefits.
- Substantial flood management improvements associated with Merced River peak flow are possible with reservoir reoperation combined with MAR – from 15,680 cfs in baseline to 9,250 cfs under Level 2 and 8,390 cfs under Level 3 for 2040.
- The reductions of flood risk vulnerability under Levels 2 and 3 Flood-MAR actions are robust, as the expected percentage reductions are similar for 2070 compared with 2040. Level 2 peak flow reduction ranges from 41 to 37 percent for 2040 and 2070, respectively; Level 3 peak flow reduction ranges from 46 to 50 percent for 2040 and 2070 respectively.

Figure 3-2 Flood-MAR with Reservoir Reoperation Reduces Flood Risk Vulnerability



Increasing vulnerability - due to higher expected temperatures and more uncertainty in precipitation.

Flood-MAR Levels 2 and 3 which include reservoir reoperation with MAR signficantly reduce the vulnerability of the system to higher flows simulated under climate change conditions.

Bars represent the expected system performance relative to the baseline performance threshold, where the darker shade is for 2040 planning horizon and lighter shade reaches to the 2070 planning horizon.

Baseline Performance Threshold: *Flow above 7,300 cfs has potential for significant flood damage. Maximum 100-year flow simulated under current climate conditions is 6,004 cfs.*

Decreasing vulnerability

3.1.3 Water Supply Sector

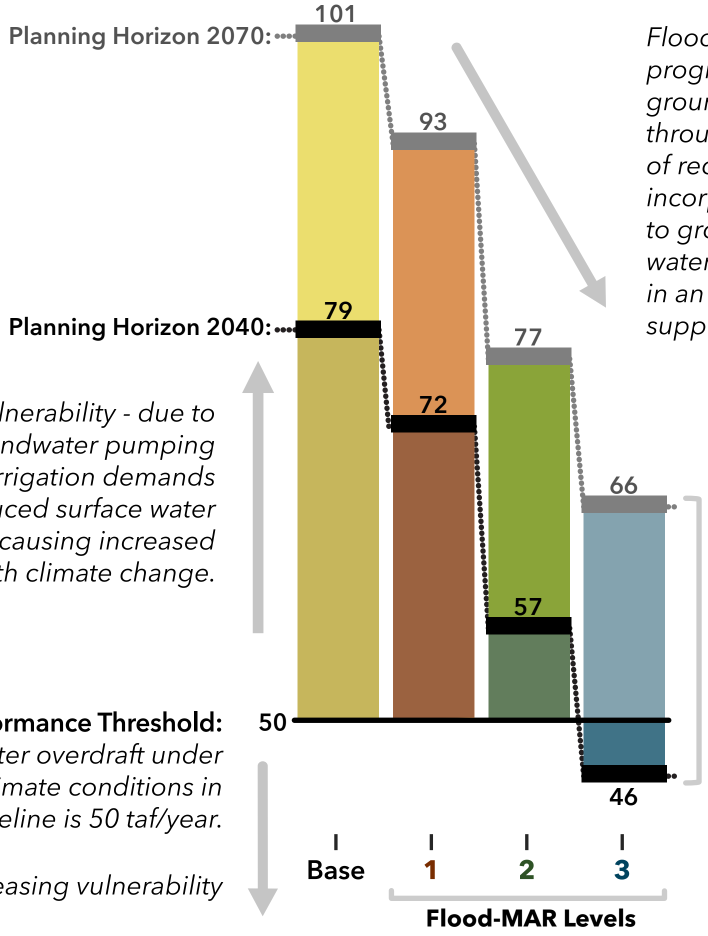
Water supply is vulnerable to the effects of climate change and responsive to Flood-MAR adaptations that provide a range of performance improvements. Because the study design assumes that water demand is always met, any reduction in the surface water supply is met with a corresponding increase in groundwater pumping. Because of this, any changes in the total water supply of the system results in a change in groundwater storage simulated in the study. Higher levels of overdraft under climate change conditions reflect significantly greater stress on the groundwater system to meet increased agricultural irrigation demands and to make up for the reductions in surface water supply in dry years. For this study, an increase in overdraft reflects an increase in water supply vulnerability and a diminished water supply, and a decrease in overdraft reflects a decrease in water supply vulnerability and an improved water supply. Flood-MAR adaptations involve progressively greater levels of conjunctive (surface and groundwater) management that reduce the vulnerability of water supply as a whole and are summarized in Figure 3-3 as follows:

- With no actions, groundwater overdraft increases from 50 thousand acre-feet (taf) per year to 79 taf per year and 101 taf per year for 2040 and 2070, respectively.
- Flood-MAR Level 1 reduces groundwater overdraft by 7 taf per year for 2040, demonstrating that opportunistic diversion of high flows consistent with streamlined water rights permitting can meaningfully improve water supply conditions and increase resilience to climate change.
- Flood-MAR Level 2 reduces groundwater overdraft by 22 taf per year for 2040, showing that integrating FIRO with MAR can triple the water supply benefits compared to streamlined diversions.
- Flood-MAR Level 3 — up to 100 taf of water stored in the conservation space of the reservoir can be released for groundwater recharge — achieves 33 taf per year in overdraft reduction for 2040. This conjunctive reservoir reoperation can leave drought years with less surface water storage in some years, but given the study design, does not impact the total water supply in the watershed. In fact, water supply is significantly improved as indicated by higher groundwater levels and groundwater storage throughout the 100-year simulation period.
- The reductions of water supply vulnerability, indicated by reduced overdraft, under all three levels of Flood-MAR actions are robust, as the expected improvements are even higher for 2070 compared to 2040.

Figure 3-3 Increasing Levels of Flood-MAR with Conjunctive Management Help Recover Groundwater Overdraft

Water Supply

Groundwater Basinwide Average Annual Overdraft
(thousand acre-feet per year)



Flood-MAR Levels 1, 2, and 3 progressively reduce groundwater overdraft through increasing volumes of recharge. Levels 2 and 3 incorporate operational shifts to groundwater and surface water management, resulting in an increase of net water supply in the watershed.

Increasing vulnerability - due to increased groundwater pumping to meet rising irrigation demands and reduced surface water in dry years, causing increased overdraft with climate change.

Bars represent the expected system performance relative to the baseline performance threshold, where the darker shade is for 2040 planning horizon and lighter shade reaches to the 2070 planning horizon.

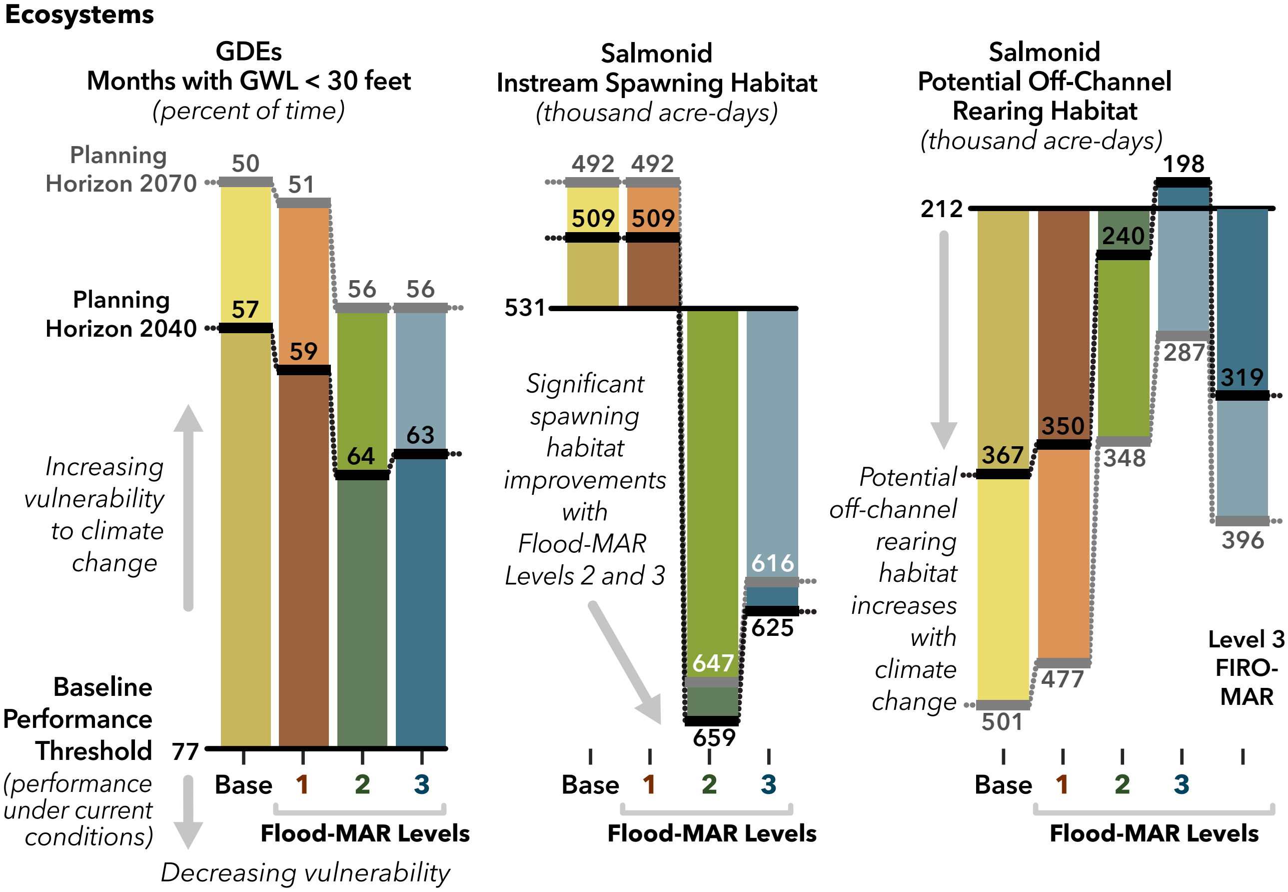
Baseline Performance Threshold: *Groundwater overdraft under current climate conditions in the Baseline is 50 taf/year.*

Decreasing vulnerability

3.1.4 Ecosystems Sector

Three indicators are highlighted to illustrate the effects of climate change and Flood-MAR on the ecosystems sector. GDEs and salmonid spawning habitat both exhibit vulnerability to climate change and significant reduction of vulnerability with Flood-MAR Levels 2 and 3. In contrast, potential salmonid off-channel rearing habitat shows improvement with climate change and is degraded with Flood-MAR. These results, quantitively presented in Figure 3-4, are discussed for each indicator in the subsections below. Results from a fourth adaptation strategy, Level 3 FIRO-MAR, are added to demonstrate flexibility to lessen effects to salmonid potential off-channel habitat.

Figure 3-4 Flood-MAR with Reservoir Reoperation Reduces GDE Habitat Vulnerability and Can Support Salmonid Habitat



Note: Modeled water temperature data and other information, such as field surveys, to determine the habitat quality of these areas or potential impacts to predatory species are beyond the scope of this reconnaissance study. The inclusion of additional information would be expected to show greater vulnerability of salmonids to climate change. GDE = groundwater-dependent ecosystem; GWL = groundwater level.

3.1.4.1 Groundwater Dependent Ecosystems

The maximum rooting depth of GDEs in the Merced subbasin is assumed to be 30 feet. GDE habitat is expected to experience adverse effects if the groundwater levels in areas surrounding GDEs drop below the 30-foot threshold. All Flood-MAR strategies involve diverting excess flows for recharge and, therefore, help improve the groundwater conditions in the Merced subbasin. The greater the amount of water recharged, the greater the expected benefits to the GDEs.

- With no actions, the percentage of months with groundwater levels supportive of GDEs decreases from 77 percent to 57 and 50 percent for 2040 and 2070, respectively, reflecting the vulnerability of groundwater storage and levels to climate change as discussed above.
- Flood-MAR Level 1 provides minor improvements (1 to 2 percent), increasing the percentage of months to 59 and 51 percent for 2040 and 2070, respectively.
- Increased levels of recharge under Flood-MAR Levels 2 and 3 provide more significant improvements (6 to 7 percent), increasing the percentage of months to 64 percent and 56 percent for 2040 and 2070, respectively.

3.1.4.2 Instream Salmonid Spawning Habitat

Salmonid spawning habitat is maximized between 140 and 800 cfs (Figure 3-4). A shift in runoff timing to earlier in the season is expected to increase the frequency of flow outside this preferred range, thus decreasing the available instream salmonid habitat.

- With no actions, instream salmonid spawning habitat is expected to decrease by 4 and 7 percent for 2040 and 2070, respectively.
- Although diversion of flows under Flood-MAR Level 1 (i.e., using steamlined permitting guidance) reduces instream flows, the reduction is not large enough to increase the likelihood of flows within the preferred flow range.
- Combination of MAR with reservoir reoperations in Flood-MAR Levels 2 and 3 provides an opportunity to actively manage stream flows within the preferred flow range. As a result, instream spawning habitat increases by 29 to 32 percent with Flood-MAR Level 2 and by 23 to 25 percent with Flood-MAR Level 3, compared to no action.

3.1.4.3 Potential Off-Channel Salmonid Rearing Habitat

Off-channel salmonid rearing habitat occurs at a minimum of 1,800 cfs flow that inundates the overbank reaches to the required depth. In addition to streamflow, the vegetation structure and cover of off-channel habitat necessary to provide food and shelter for salmonid juveniles is currently lacking in the Merced River. For this reason, this indicator is considered as potential habitat in the study. Flood-MAR strategies are designed to divert excess flows that lower the frequency and duration of high flows. As a result, potential off-channel rearing habitat is expected to decline with Flood-MAR actions.

- With no Flood-MAR actions, potential off-channel habitat is expected to increase by 73 percent and 136 percent above current climate for 2040 and 2070, respectively. As previously shown in Figure 2-5, this gain is a result of the expected increase in the frequency and duration of flows above the 1,800 cfs threshold under climate change.
- Compared to no action, potential off-channel habitat declines by 5 percent in Flood-MAR Level 1 – from 367 to 350 thousand acre-days for 2040 and 501 to 477 thousand acre-days for 2070. Because FloodMAR Level 1 opportunistically diverts excess flows, recharge only occurs during availability of excess flows and consequently has minimal impact on potential off-channel habitat.

- Potential off-channel habitat declines by 31 to 35 percent with FloodMAR Level 2 and 43 to 46 percent with Flood-MAR Level 3. The combination of MAR with reservoir reoperation in Flood-MAR Levels 2 and 3 reduces the reliance of aligning MAR with the occurrence of flows above the streamlined threshold, resulting in a tighter control on downstream releases and consequently a larger reduction in potential off-channel rearing habitat.

Flood-MAR Levels 2 and 3 strategies can be designed to minimize the impact on off-channel rearing habitat for salmonids while diversifying total ecosystem benefits. The Flood-MAR Level 3 FIRO-MAR strategy shown in Figure 3-4 represents such a configuration with off-channel habitat enhancements and a dedicated storage account (referred to as the "eco pool account") to provide flows for off-channel habitat inundation and spring outmigration pulse flows. The potential off-channel habitat is still reduced but by one-third less than the Flood-MAR Level 3 Recharge Pool-MAR shown in Figure 3-4. Moreover, Flood-MAR Level 3 FIRO-MAR's dedicated releases for off-channel habitat inundation more than double the frequency of inundation events compared to no action. See TIR 4 for additional details on Flood-MAR Level 3 FIRO-MAR.

3.2 Increasing Levels of Flood-MAR with Reservoir Reoperation Reduces Flood Risk and Supports Ecosystems

The existing system of required flood space in Lake McClure and the downstream channel capacity on the Merced River have prevented catastrophic flooding since New Exchequer Dam was constructed in 1967, though minor flooding and flood risk can still occur. This study shows that flood risk is increased under potential future climate conditions and that flows will exceed the capacity of the existing system.

Flood-MAR strategies reduce flood risk for both the Merced River and local creeks. Level 1 strategies that rely on the diversion and recharge of flood flows, without changes in reservoir operations, have minimal effect on the Merced River and a minor effect on local streams. The existing diversion and conveyance facilities were designed for irrigation and lack the capacity to significantly reduce peak flood events. Levels 2 and 3 strategies that include changes in reservoir operations reduce flood risk by reducing the maximum encroachment at Lake McClure. These Flood-MAR strategies provide the most flood risk reduction benefits under potential future climate conditions.

Ecosystem needs are a key component of multi-sector Flood-MAR strategies. This study focused on multiple areas of the ecosystem to demonstrate a range of potential benefits and assess potential impacts. The results show that Flood-MAR strategies benefit non-aquatic species, such as shorebirds and GDEs that rely on groundwater and surface water affected by recharge actions. Possible indirect benefits of improved groundwater conditions may result in higher baseflows in streams, either by reducing the volume of water that leaves the stream and enters the aquifer system or increasing the stream gain from the surrounding aquifer. These changes in baseflow that result from recharge occur after the recharge actions and improve river flows in the summer and future droughts.

Aquatic species reliant on instream flows may see both impacts and benefits from Flood-MAR operations. Flood-MAR is an increased diversion from the surface water system, but diversions can occur at volumes that minimize impacts. Impacts to aquatic species can be partially offset by including operations designed to improve instream conditions, improving off-channel habitat for specific life-stages, and providing multi-benefit pulse flows to trigger key environmental processes.

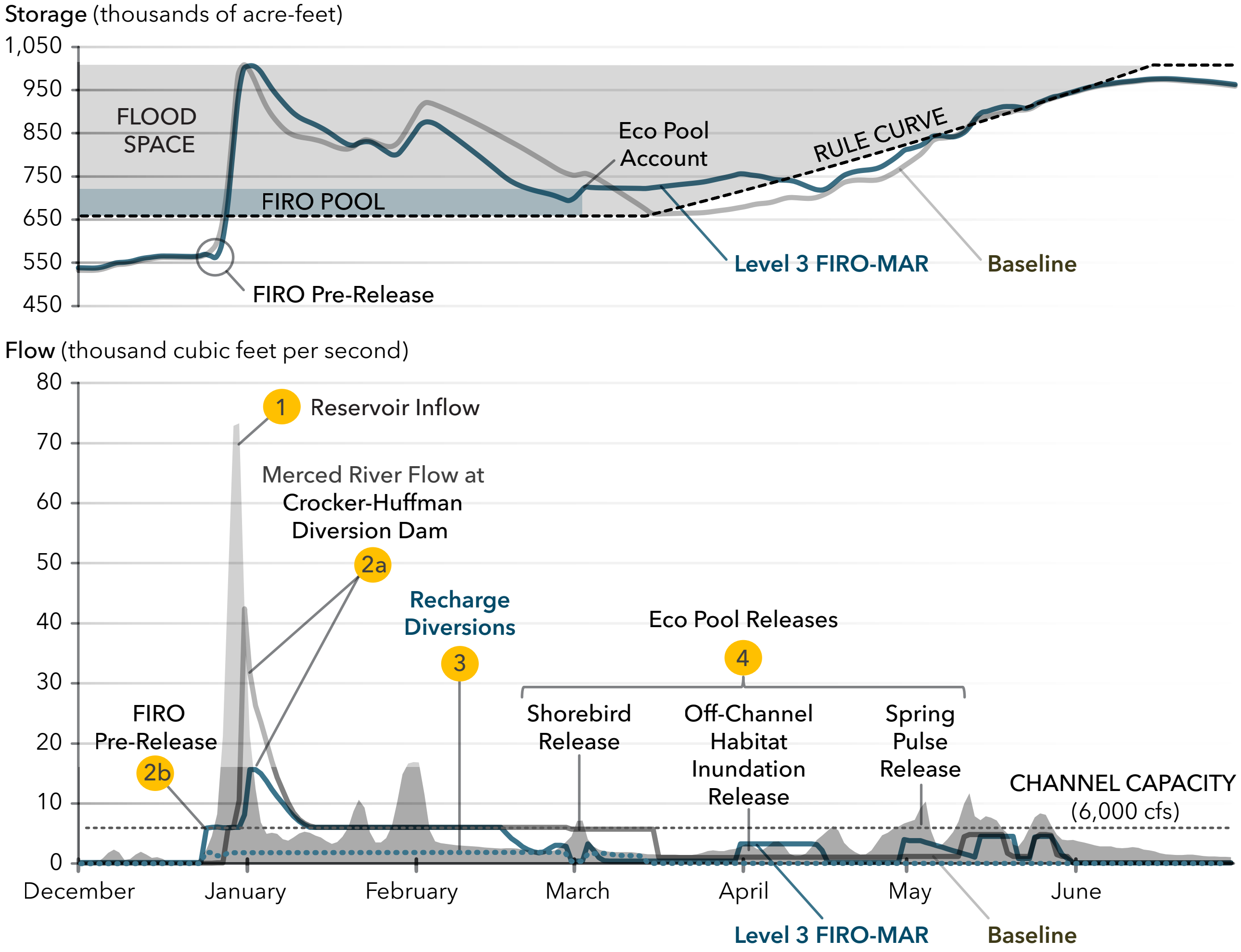
Additionally, Flood-MAR strategies store additional water and can dedicate a portion of this stored water toward ecosystem goals, as described above.

Figure 3-5 demonstrates the Level 3 Flood-MAR (FIRO-MAR) strategy's ability to provide significant flood risk and ecosystem benefits under a climate change condition that is 3 °C warmer with 10 percent more precipitation. Under this scenario, reservoir storage rapidly reaches the top of Lake McClure's flood space because of a climate change-induced increase in inflow (Figure 3-5, marker 1), which triggers emergency operations and flood control releases higher than the downstream channel capacity (Figure 3-5, marker 2a).

However, the FIRO-MAR pre-release operation (Figure 3-5, marker 2b) of the Level 3 FloodMAR strategy — which includes approximately 1,800 cfs additional release of water for recharge diversions — creates additional reservoir space just preceding the event that is sufficient to reduce peak outflow by approximately 26,800 cfs. Following the flood event, releases for recharge diversions continue (Figure 3-5, marker 3) and more rapidly reduce flood space encroachment, thereby allowing flood releases to drop from 6,000 cfs approximately one month earlier than the baseline operation.

In addition, water preserved through FIRO operations as an "eco pool account" is used to create shorebird habitat, inundation of potential off-channel habitat, and an enhanced migratory spring pulse flow (Figure 3-5, marker 4). The eco pool account is opportunistically managed and does not use water from the reservoir's conservation space to create these benefits; therefore, as shown in Figure 3-5, reservoir storage for the baseline and Level 3 FIRO-MAR overlap by the end of the eco pool releases.

Figure 3-5 Performance of Level 3 FIRO-MAR for a Storm Event with a Wetter-Warmer Future Climate

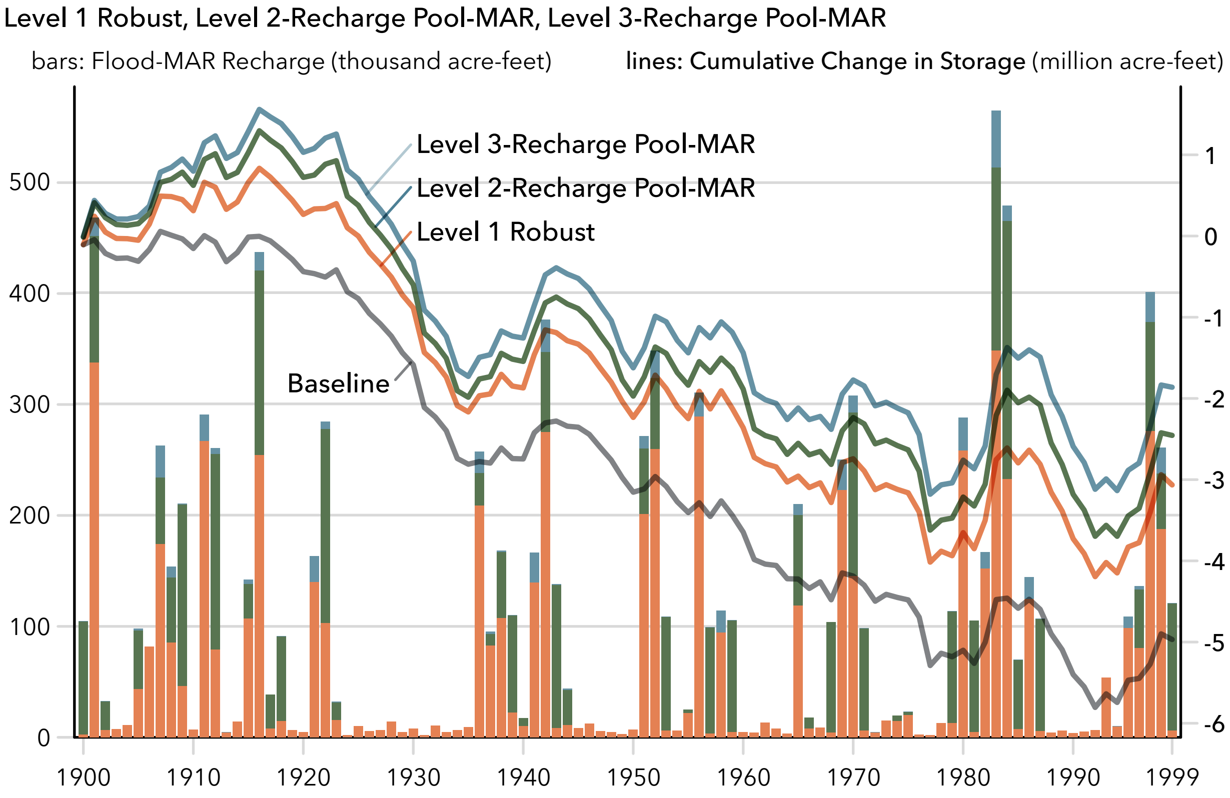


Notes: Modeling results shown for Lake McClure storage (top figure) and Merced River inflow to Lake McClure and flow at Crocker-Huffman Diversion Dam (bottom figure). Results are for a climate change condition that is 3 degrees Celsius warmer and has 10 percent more precipitation than current climate. Markers 1 through 4 are discussed in Section 3.2. CFS = cubic feet per second; FIRO-MAR = forecast-informed reservoir operation with managed aquifer recharge.

3.3 Enhanced Recharge Volumes Improves Water Supply

Additional recharge is needed to support current and projected levels of groundwater reliance within the Merced groundwater subbasin. All Flood-MAR strategies can improve water supply resilience by providing additional recharge that reduces groundwater overdraft in the basin (see Figure 3-6). Changes to reservoir operations expand water supply benefits by increasing the opportunities for water to be released at a rate that maximizes recharge. Infrastructure improvements that increase conveyance capacity do not increase the total volume of recharge by much, but do substantially increase the efficiency of applied recharge, achieving the same volume of recharge with half the acreage.

Figure 3-6 Groundwater Overdraft Recovery Under Increasing Levels of Flood-MAR



Notes: Modeling results shown for the change in Merced subbasin groundwater storage (lines, left axis) and Flood-MAR recharge (bars, right axis). Results are representative of expected conditions under climate change at the 2040 planning horizon. Flood-MAR = flood-managed aquifer recharge.

Groundwater conditions in the neighboring groundwater subbasins have a significant impact on the outcome of Flood-MAR strategies. The study evaluated Flood-MAR strategies within the Merced groundwater subbasin independent of changes in water supplies and demands in neighboring subbasins that would be necessary to support groundwater sustainability. Under this assumption, results show that approximately one-third of recharged water remains within the Merced subbasin and one-half would flow (through the subsurface) to neighboring subbasins. The remaining amount flows to streams. A sensitivity analysis (not included in this report) indicates that approximately two-thirds of recharged water would remain in the Merced subbasin if neighboring subbasins are managed to the measurable objectives in their groundwater sustainability plans. See TIR 4 for details about the outcomes from the sensitivity analysis.

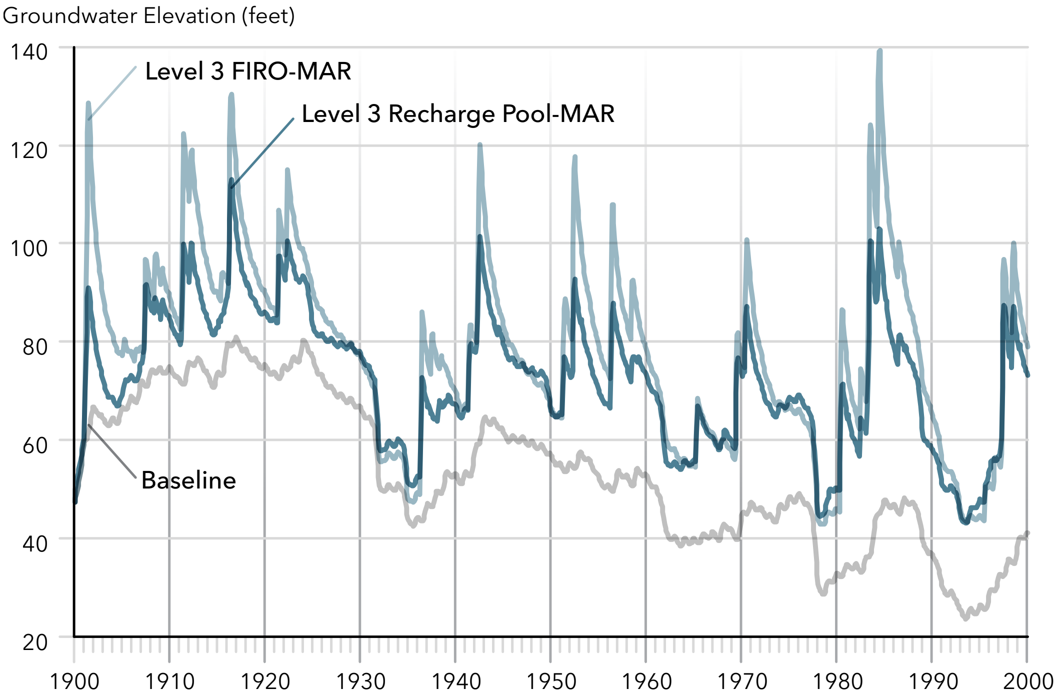
3.4 Targeted Recharge Application Can Support Disadvantaged Communities, Subsidence-Prone Areas, and Groundwater-Dependent Ecosystems

The multi-sector outcomes highlighted in this report include use of recharge management areas that demonstrate a potential for targeted recharge benefits. The study shows that subsidence mitigation, groundwater levels supportive of GDEs, shorebird, and pollinator habitats, and water supply reliability for disadvantaged communities (DACs) can all be accomplished with targeted recharge applications. In other words, where recharge occurs matters at certain times and spatial scales.

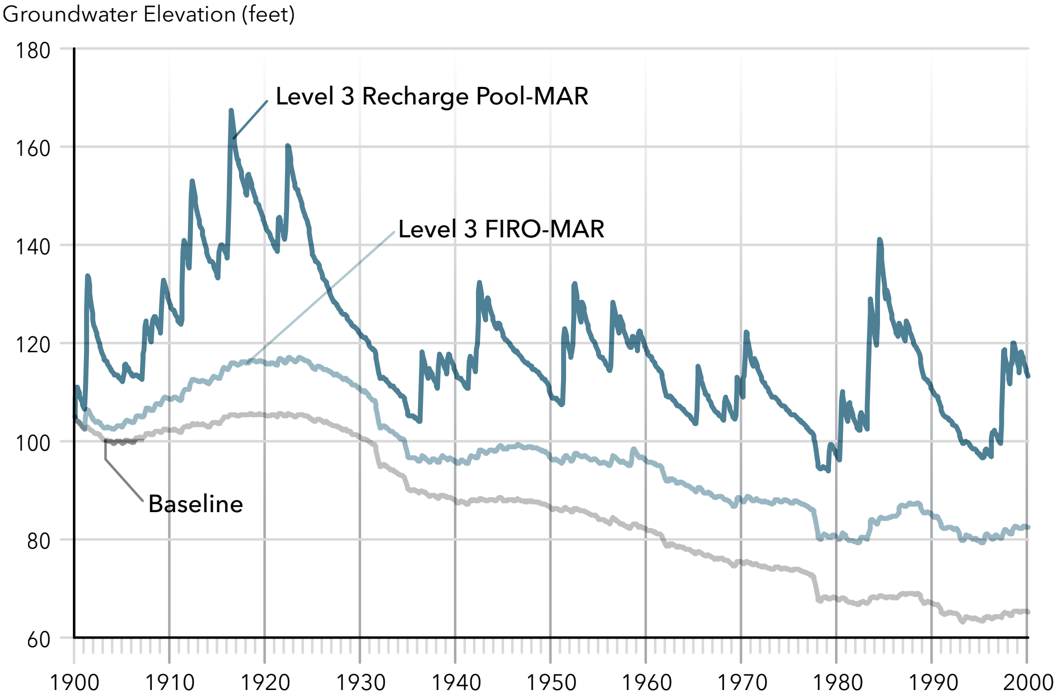
As shown in Figure 3-7, the FIRO-MAR strategy that targets recharge application near GDEs (Hydrograph 1302 above the Corcoran Clay) results in higher groundwater levels in GDE areas. GDEs tend to be closer to the Merced and San Joaquin rivers, so the higher groundwater levels also result in higher seasonal baseflows because of increased groundwater discharge into the streams. Alternatively, the Recharge Pool-MAR strategy, which targets recharge application near DACs (Hydrograph 1304 East of Corcoran Clay), results in higher groundwater levels in DAC areas. These targeted recharge benefits are generally realized in years of increased recharge activity but, when considered over the long term, do not change the relative benefits of groundwater conditions across the subbasin.

Figure 3-7 Groundwater Levels Near GDEs (Hydrograph 1302) and DACs (Hydrograph 1304) are Enhanced through Targeted Recharge Applications

Hydrograph 1302 (Above Corcoran Clay)



Hydrograph 1304 (East of Corcoran Clay)



Notes: FIRO-MAR = forecast-informed reservoir operations combined with managed aquifer recharge; Recharge Pool-MAR = recharge pool concept that vacates additional flood control space by releasing water for managed aquifer recharge using agricultural land.

Chapter 4. Conclusions

Climate change is driving weather whiplash and altering surface runoff patterns. All sectors — flood, water supply, ecosystem — are vulnerable to climate change, and the vulnerabilities are interconnected. To address these risks, the study finds that Flood-MAR solutions are flexible and scalable and can be implemented adaptively over time in a stepwise manner as follows:

- Using existing infrastructure and following current streamlined water rights guidance to divert flood waters for groundwater recharge could improve water supply, measured as a reduction in groundwater overdraft, by approximately 8 taf per year on average.
- Planning and partnering with flood and ecosystem managers on multifaceted Flood-MAR projects that incorporate FIRO operations and MAR can significantly enhance flood protection (up to 10,800 cfs peak flow reduction), improve water supply (up to 24 taf per year on average), and provide flow benefits to aquatic and terrestrial ecosystems.
- Combined with infrastructure improvements that increase the efficiency of applied recharge (i.e., achieving the same amount of recharge with less land area), a more extensive reservoir reoperation of conservation storage to supplement recharge opportunities can further reduce flood risk (a 14,560 cfs peak flow reduction) and improve water supply (up to 35 taf per year on average).

This study finds that Flood-MAR strategies that include changes in reservoir operations are essential to achieving multiple benefits across multiple water management sectors. Combining MAR with reservoir reoperations provides the greatest flood risk reduction benefits under potential future conditions when flows are expected to exceed the capacity of the existing system. Reservoir operations improve water supply by recharging water into the aquifer, lessening groundwater overdraft, and more efficiently regulating surface water supplies to cope with the expected shift in seasonal runoff. Finally, additional surface water conserved through Flood-MAR reservoir reoperation strategies along with infrastructure improvements can be used to create ecosystem improvements such as instream and off-channel salmonid habitat, and sustained shorebird habitat.

These findings, in addition to a broader array of metrics and indicators of performance across flood, water supply, and ecosystem water management sectors, are discussed in greater detail in TIRs 3 and 4.

Previous page: At this groundwater recharge FloodMAR site in the Dunnigan area of Yolo County, pumped water is discharged from the outlet into the standing water in this field. Photo taken January 18, 2023.

Chapter 5. Lessons Learned and Next Steps

This study demonstrates that multi-sector and at-scale Flood-MAR can be a key component to assisting the State, federal, and local agencies in addressing the water management challenges of a changing climate. The Merced study generated a new toolset, data, and insights about climate change vulnerability and Flood-MAR adaptation potential needed to support watershed-scale, multi-benefit planning, design, and implementation of Flood-MAR actions in the Merced watershed. The methodology and toolset will be transferred to local agencies to enhance their water planning capacity to implement Flood-MAR and FIRO-MAR actions.

Significant lessons were learned from the Merced reconnaissance-level study, including:

- Climate vulnerability and adaptation – framed by a decision-scaling approach to climate analysis – are important for understanding and planning watershed scale Flood-MAR solutions to increase climate resilience.
- A watershed approach and multi-sector toolset is needed to effectively evaluate Flood-MAR strategies comprised of increasing levels of operational complexity and infrastructure changes.
- The toolset requires an appropriate level of modeling detail and data to yield planning-level insights deemed credible by multiple water management sectors for adaptation strategy implementation.

Using this exploratory study as a springboard, DWR is applying the lessons learned to watershed studies for all five tributary watersheds of the San Joaquin River, including the Calaveras, Stanislaus, Tuolumne, Merced, and Upper San Joaquin (also including Chowchilla and Fresno rivers) tributaries of the San Joaquin River, shown in Figure 5-1. These watershed studies scheduled for completion in 2025 are a collaborative effort by DWR and its partners including local water supply, flood, and ecosystem managers (local partners) and the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and Center for Western Weather and Water Extremes (regional partners), all engaged in or responsible for the San Joaquin River Basin planning and operations. The watershed-scale toolsets, climate change assessments and adaptation strategies evaluated by these studies can address and help overcome current and future water management risks. However, to realize the potential adaptation evaluated in the Merced study will require significant collaboration and co-management among water sectors.

DWR is also assisting local water managers to implement Flood-MAR pilot projects. With the integrated modeling tools developed for this study, DWR has provided technical assistance to

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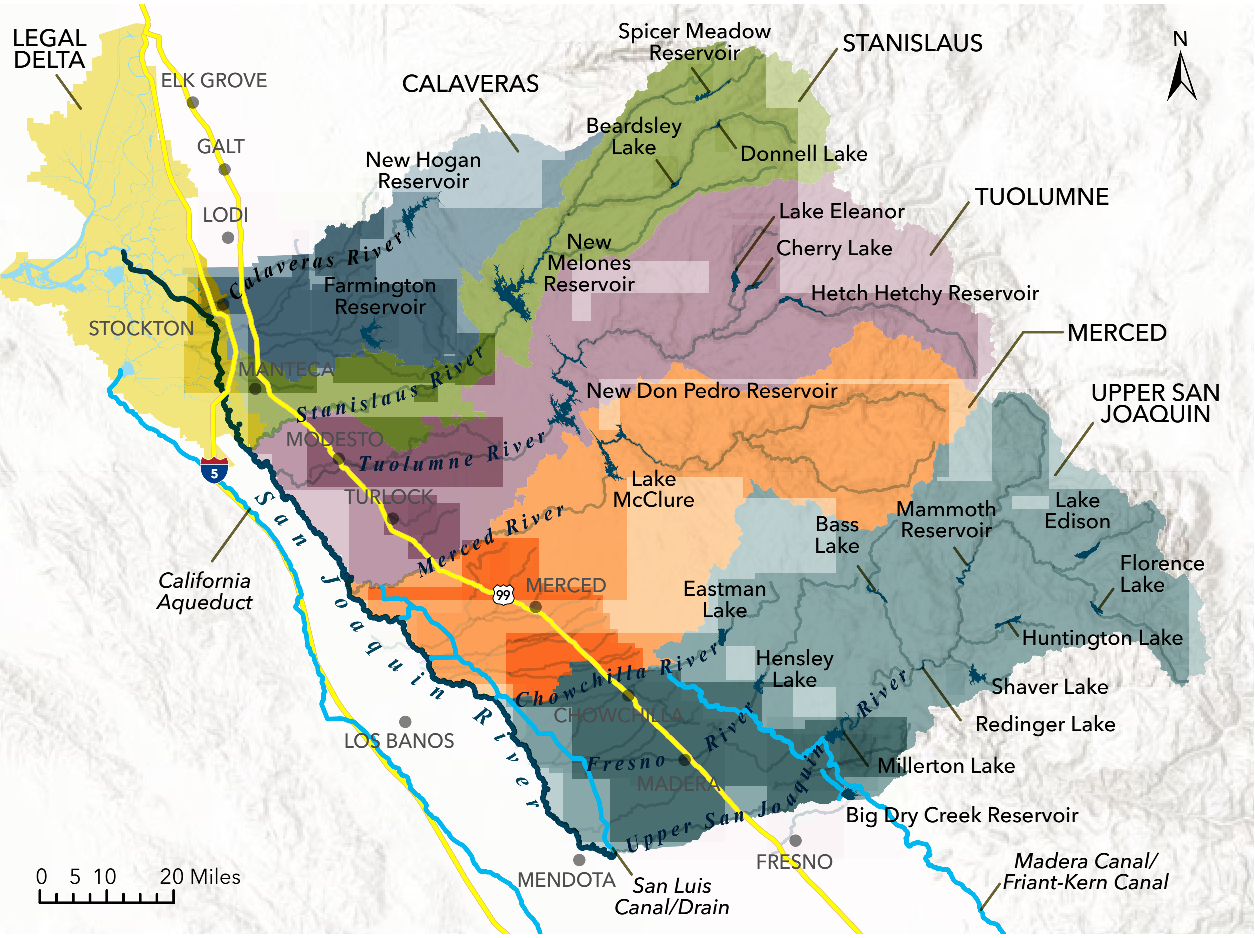
Previous page: An overview of a groundwater recharge basin being built on August 14, 2023, at Central and Bethel in Sanger, California, in Fresno County.

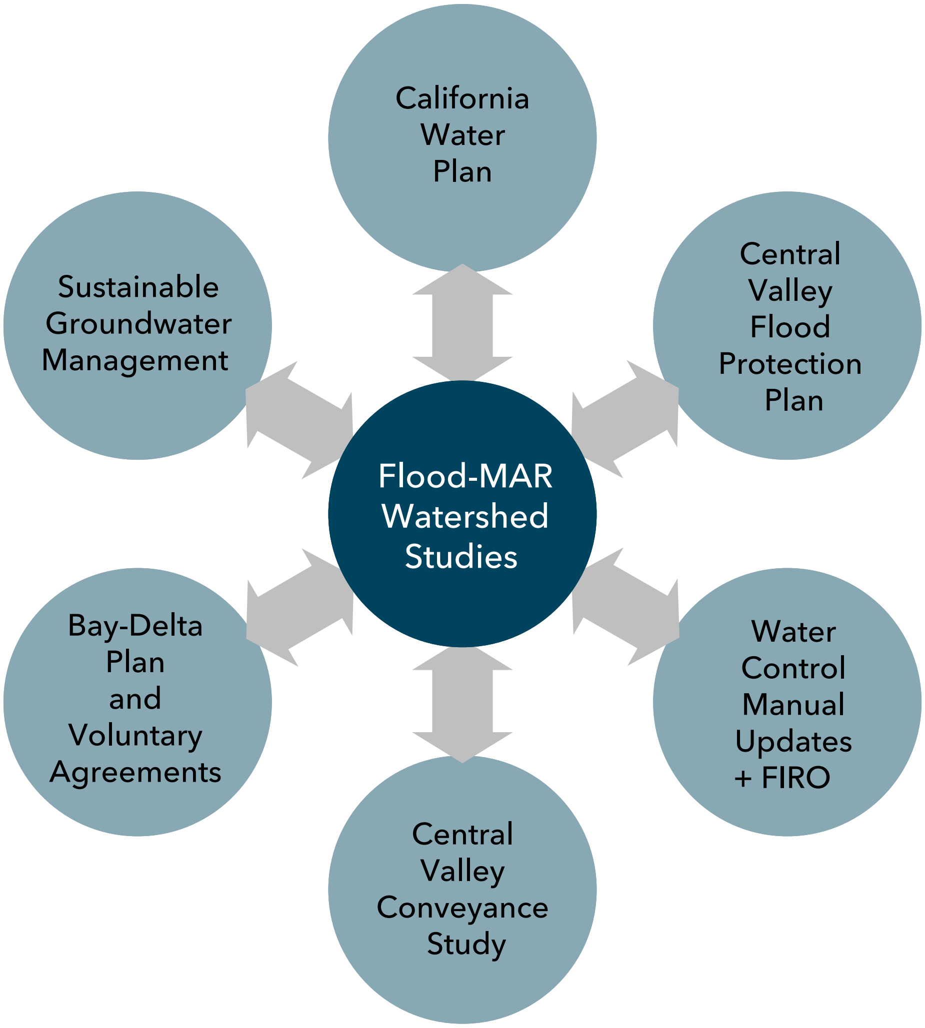
local efforts in preparing temporary water right permits and taking emergency groundwater recharge actions in winter 2022–2023. Pilot projects bring FloodMAR concepts to landowners whose participation is critical to cost-effectively recharge significant volumes of water across working landscapes. DWR is continuing its technical assistance in 2023–2024 in partnership with local agencies, the State Water Board, and California Department of Fish and Wildlife to expedite permitting for Flood-MAR pilot projects, identify and overcome impediments, and demonstrate the potential of Flood-MAR in the field. Water rights are a key component to implementing Flood-MAR at-scale and will require coordination across multiple State agencies. Temporary, pilot, and emergency Flood-MAR actions are typically at smaller scale than the watershed scale solutions described in this study. These more readily implemented actions are important first steps to plan, design, and implement at-scale Flood-MAR actions evaluated in the Merced study.

Figure 5-1 Area of Study



DWR recognizes how Flood-MAR strategies are interconnected with many programs and planning efforts underway at the local, State, and federal level. Coordinating the planning efforts shown in Figure 5-2 will provide opportunities to advance and implement multi-sector and at-scale Flood-MAR strategies. For example, for several San Joaquin River Basin reservoirs, managers and operators are currently evaluating updates to water control manuals. These updates may provide opportunities to consider the kinds of solutions described in this study, including FIRO, MAR and ecosystem improvements.

Figure 5-2 **Connections of Flood-MAR Watershed Studies with Ongoing Local, State, and Federal Water Resource Management Planning Efforts**



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