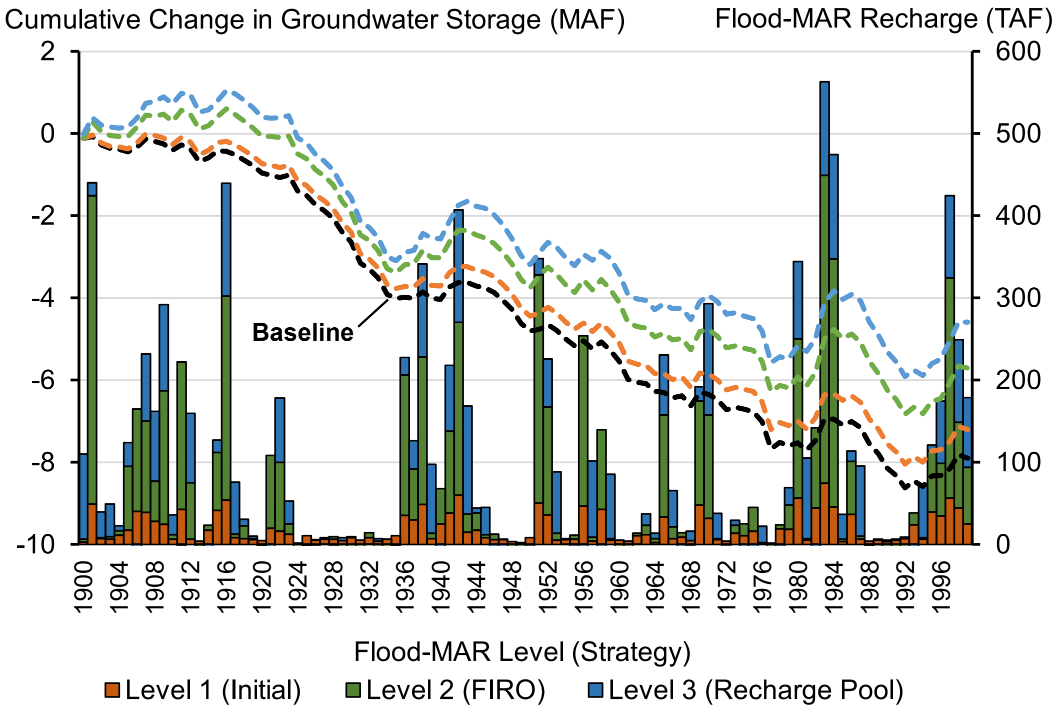
State of California
California Natural Resources Agency
Department of Water Resources

Merced River Watershed Flood-MAR Reconnaissance Study

Adaptation Strategy Performance



Technical Information Record

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Acronyms and Abbreviations

CEFF	California Environmental Flows Framework
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	floodwater used for managed aquifer recharge
GDE	groundwater-dependent ecosystem
Hybrid-MAR	hybrid managed aquifer recharge
MID	Merced Irrigation District
OFR	on-farm recharge
Recharge Pool-MAR	recharge pool reoperation for managed aquifer recharge
SAGBI	Soil Agricultural Groundwater Banking Index
SGMA	Sustainable Groundwater Management Act
study	Merced River Reconnaissance Study
taf	thousand acre-feet
TIR	technical information record
TIR 3	Baseline Performance and Climate Change Vulnerability
WAFR	water available for recharge
WUA	weighted usable area
°C	degrees Celsius

Executive Summary

The California Department of Water Resources (DWR), in partnership with the Merced Irrigation District (MID), is conducting a reconnaissance study to assess modeled (1) water management vulnerability resulting from the effects of climate change, and (2) use of high flows for managed aquifer recharge (Flood-MAR) to reduce flood risk, increase water supply reliability, and enhance ecosystems in the Merced River watershed.

Flood-MAR is an integrated and voluntary resource management strategy that addresses the risks of changed climate conditions to multiple sectors of water management including flood risk, water supply, and ecosystems. This technical information record (TIR), the final in a series of four, assesses the effectiveness of recharge-related strategies to reduce flood risk, increase water supply reliability, and enhance ecosystems in the Merced River watershed. The study developed and analyzed nine different Flood-MAR strategies to explore and demonstrate the potential for Flood-MAR to create multi-sector benefits and outcomes from headwaters to groundwater in the Merced River watershed and Merced groundwater subbasin.

ES.1 Flood-MAR Strategies and Performance

Flood-MAR strategies include diversion during high flows, reservoir reoperations, and investments in infrastructure. Increasing levels of Flood-MAR strategies also represent increasing coordination and participation among agencies and partners to implement more complex strategies over time. Three different strategies were crafted for each of three Flood-MAR strategy levels (nine strategies total) to assess sensitivity to strategy characteristics and the ability to focus benefits on one or more water management sector(s).

ES.2 Key Conclusions

Flood-MAR strategies take advantage of wetter periods to store water in groundwater subbasins that provides 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. In general, the study determined that:

- Flood-MAR strategies that include changes in reservoir operations provide the most flood risk reduction benefits under potential future conditions when flows may exceed the capacity of the existing system.

- Flood-MAR strategies can improve water supply conditions by recharging water into the aquifer, thereby reducing long-term overdraft of groundwater storage and contributing to groundwater sustainability.
- Flood-MAR strategies that involve recharging water withdrawn from the water supply storage space of the surface reservoir might marginally impact surface water supply carryover in subsequent years, though the combined surface and groundwater supply is significantly improved.
- Flood-MAR strategies that entail reservoir reoperation can be designed to create ecosystem improvements such as salmonid spawning habitat and shorebird habitat. In addition, improving groundwater conditions helps to support groundwater-dependent ecosystems.

Finally, the performance of Flood-MAR strategies relative to the baseline condition (i.e., no change in system operations or infrastructure) is similar under both current and future climate conditions. This finding suggests that Flood-MAR strategies are robust and can provide multi-sector benefits under a wide range of future climates. Table ES-1 summarizes the multi-sector performance of the Flood-MAR strategies under current and future (2040) climate conditions for the Merced watershed.

Table ES-1 **Flood-MAR Strategy Performance Under Current and Future Climate Conditions for Merced Watershed Water Management Sectors**

Sector	Metric (Indicator)	Current Climate Baseline	Current Climate Flood-MAR	Future Climate (2040) Baseline	Future Climate (2040) Flood-MAR	Units
Flood-MAR Recharge	Average annual volume of recharge.	N/A	17 to 99	N/A	18 to 105	taf/year
Flood Risk	Merced River 100-year maximum simulated peak flow (Nov – Jun 30).[1]	6,000	6,000 to 7,000	16,200	8,400 to 16,200	cfs
Water Supply (Groundwater)	Basinwide average annual change in groundwater storage.[2]	-50	-44 to -19	-79	-72 to -45	taf/year
Water Supply (Surface water)	Number of years MID's surface water availability is at or below 80 percent.	7	7 to 10	10	10 to 13	Years
Ecosystems	Proportion of months with depth to groundwater less than 30 feet.	77	79 to 85	57	59 to 66	Percent
	Merced River instream salmonid spawning habitat (Sep – Apr).	531	531 to 671	509	509 to 659	Thousand acre-days
	Potential Merced River off-channel juvenile rearing habitat during qualified events (Dec – May).	212	88 to 224	367	198 to 350	Thousand acre-days
	Number of years with additional managed shorebird habitat.	N/A	0 to 63	N/A	0 to 60	Years

Notes: [1]Simulated outflow downstream of Lake McClure reservoir at Crocker-Huffman Diversion Dam. [2]Groundwater conditions assume that no actions or projects are implemented in Merced or neighboring subbasins to comply with the Sustainable Groundwater Management Act.

cfs = cubic feet per second; Flood-MAR = floodwater used for managed aquifer recharge; MID = Merced Irrigation District; taf/year = thousand acre-feet per year. N/A = not applicable.

Chapter 1. Introduction

The California Department of Water Resources (DWR), in partnership with the Merced Irrigation District (MID), is conducting a pilot reconnaissance study of using high flows (i.e., floodwaters) for managed aquifer recharge (Flood-MAR) to reduce flood risk, increase water supply reliability, and enhance ecosystems in the Merced River watershed. Flood-MAR is an integrated and voluntary resource management strategy that uses floodwaters resulting from, or in anticipation of, rainfall or snowmelt events for groundwater recharge on agricultural lands, working landscapes, and managed natural lands. The Merced River Reconnaissance Study (study) explores the effectiveness of Flood-MAR concepts and assesses strategies to overcome barriers to project planning and implementation.

This technical information record (TIR) covers the following:

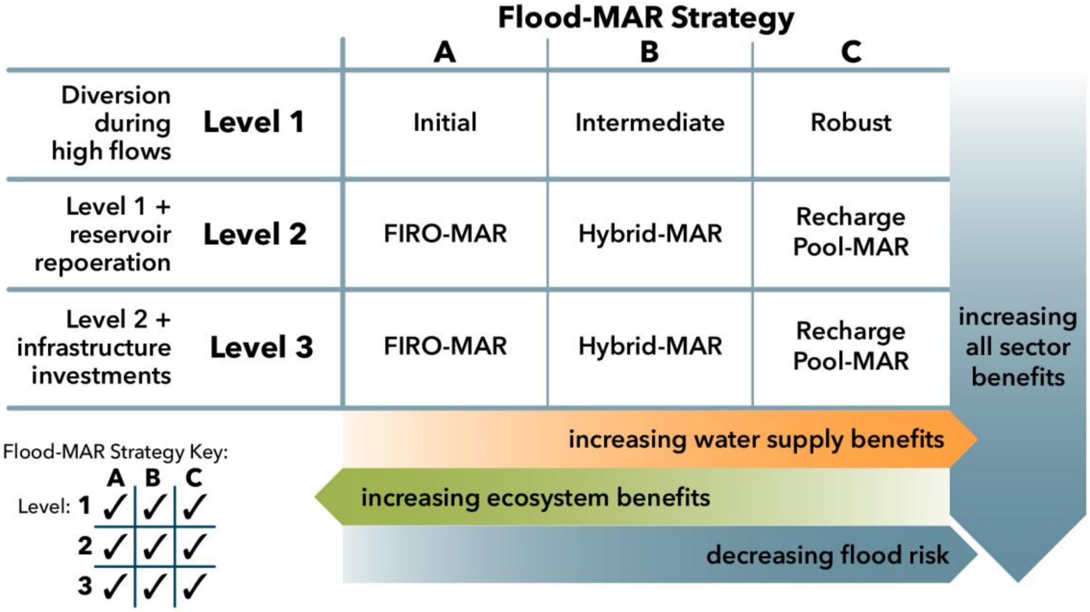
- Description of Flood-MAR strategies.
- Multi-sector Flood-MAR strategy performance and adaptation to climate change.
- Conclusions and key findings.

Chapter 2. Flood-MAR Strategies

The Flood-MAR strategies developed for this study demonstrate the potential for Flood-MAR to create multi-sector benefits from headwaters to groundwater in the Merced River 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 climate change conditions.

Figure 2-1 illustrates how benefits to different sectors are expected to perform across the nine Flood-MAR strategies analyzed in the study. The Flood-MAR strategies are grouped by levels, where Level 1 includes relatively simple diversion during high flows with minimal investments; Level 2 adds reservoir reoperation; and Level 3 adds more complex changes, including additional infrastructure investments. The benefits for all three sectors are expected to increase with higher level strategies. The range of strategies helps illustrate potential tradeoffs and synergies between the water management sectors.

Figure 2-1 **Flood-MAR Strategies Analyzed in Study**



		Flood-MAR Strategy		
		A	**B**	**C**
Diversion during high flows	**Level 1**	Initial	Intermediate	Robust
Level 1 + reservoir repoeration	**Level 2**	FIRO-MAR	Hybrid-MAR	Recharge Pool-MAR
Level 2 + infrastructure investments	**Level 3**	FIRO-MAR	Hybrid-MAR	Recharge Pool-MAR

2.1 Level 1 Strategies

Level 1 strategies are the simplest Flood-MAR strategies. Level 1 strategies target water supply improvements and explore potential flood risk reductions while attempting to limit potential harm to ecosystem functions. Diversions of water available for recharge (WAFR) occur only during qualified high-flow events under existing reservoir operations and using existing infrastructure. Level 1 strategies are "passive" in that there are no actions taken other than diversions when flows exceed a defined threshold. Level 1 strategies (Initial, Intermediate, Robust) vary based on the threshold used when diversions can occur, the season for potential diversions, and where water is recharged. Table 2-1 provides a summary of key features that define Level 1 strategies.

Table 2-1 Summary of Level 1 Flood-MAR Strategies

	Level 1 Strategies		
	Initial	**Intermediate**	**Robust**
Diversion Season	December through March	November through March	
Diversion Threshold	Daily 90th Percentile	Monthly 90th Percentile	500 cfs[1]
Diversion Limit	Minimum of (1) flow above the 90th percentile, or (2) 20 percent of the total flow	Diversion/Conveyance Capacity	
Recharge Location	Canals	Canals and Farms	
Delta Conditions	Delta in true excess when inflows to Delta exceed flows required to meet regulatory standards.[2] South Delta exports are not limited by Delta inflow.		

Notes: [1] 500 cfs exceeds all existing minimum flow requirements on the Merced River during the Flood-MAR diversion season. [2] Based on State Water Resources Control Board Water Rights Decision 1641 and the National Marine Fisheries Service's 2008–2009 Biological Opinions.

cfs = cubic feet per second; Delta = Sacramento-San Joaquin Delta.

2.2 Level 2 Strategies

Level 2 strategies add reservoir reoperation to diversion during high flows to expand the potential benefits of Flood-MAR across all sectors and increase the effectiveness of Flood-MAR as an adaptation to climate change. In general, reservoir reoperations are expected to increase the frequency, duration, and volume of water that can be recharged. Level 2 strategies include 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). These two operational strategies are also combined into a hybrid operation (Hybrid-MAR). Level 2 strategies attempt to increase water supply benefits relative to Level 1 strategies, create meaningful flood risk reductions, particularly with climate change, and dedicate a portion of the additional water supply to improving ecosystem functions. Table 2-2 provides a summary of key features that define Level 2 strategies.

Table 2-2 Summary of Level 2 Flood-MAR Strategies

	Level 2 Strategies		
	FIRO-MAR	**Hybrid-MAR**	**Recharge Pool-MAR**
Management Objectives	Diversify ecosystem, water supply, and flood benefits with emphasis on maximizing ecosystem benefits.	Diversify ecosystem, water supply, and flood benefits with emphasis on maximizing public water supply benefits.	Maximize water supply and flood benefits with limited ecosystem actions and limiting harm to ecological functions incidentally provided for in the baseline.
High-Flow Diversion Criteria	Same as Level 1 Intermediate Strategy (see Table 2-1).		
Reservoir Management (season)	50-taf FIRO space (November through March) plus eco-actions (March through April)	50-taf Recharge Pool (November through February), plus 50-taf FIRO space (November through March), plus eco-actions (March through April)	100-taf Recharge Pool (November through February)
Ecosystem Management (season)	Improved spawning flows (November through March) Shorebird habitat (March)[1] Spring pulse flow (April)[1]		Improved spawning flows (November through March)
Recharge Management	Emphasize recharge locations that benefit GDEs and stream baseflow.	Emphasize recharge locations that benefit DACs and subsidence-prone areas.	Emphasize recharge locations that maximize retention in Merced subbasin.

Notes: [1]Actions taken using the additional water stored through FIRO or by reshaping the snowmelt management releases.

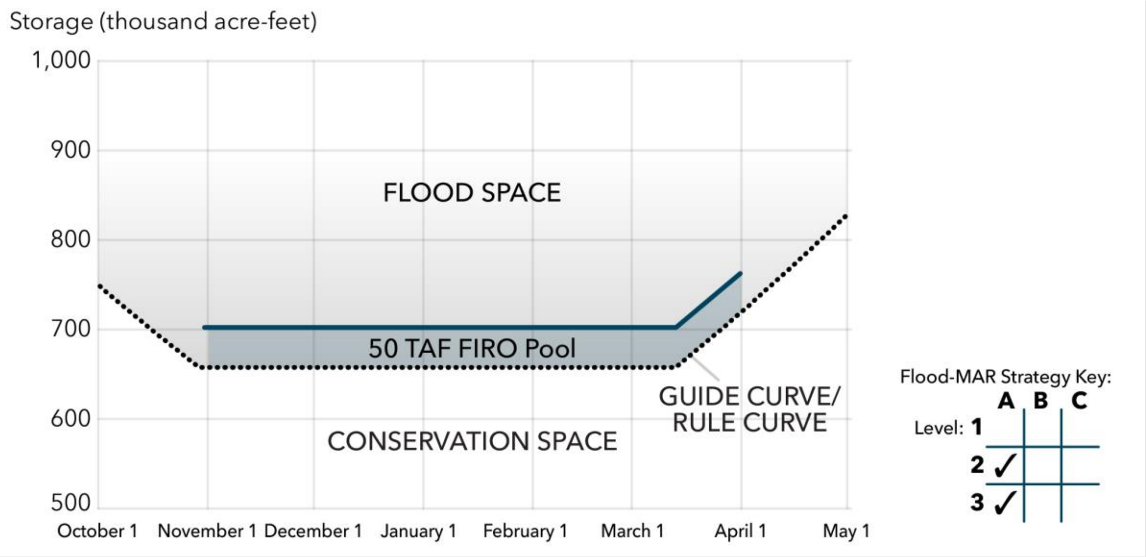
DAC = disadvantaged community; FIRO = forecast-informed reservoir operations; GDE = groundwater-dependent ecosystem; MAR = managed aquifer recharge; taf = thousand-acre feet.

2.2.1 Reservoir Management

2.2.1.1 Forecast-Informed Reservoir Operations (FIRO)

Traditionally, flood control space is operated based primarily on dates and seasons, with more flood control space required during the winter when storms are historically more likely. FIRO builds upon this traditional operation to flexibly use a portion of the existing flood control space based on forecasted inflows. Accordingly, FIRO allows for increased reservoir storage (i.e., “encroachment” into the reservoir’s flood space) when weather and hydrologic forecasts indicate it is safe to do so (i.e., there is little precipitation and manageable inflows). In addition, FIRO draws reservoir levels lower (i.e., “drafting” into the reservoir’s conservation space) to provide increased capacity that can attenuate peak inflows when large storms are forecasted; this operation is known as a “pre-release.” The added flexibility provided by FIRO is expected to provide benefits as California’s climate warms because of climate change. Figure 2-2 illustrates the FIRO operation for Lake McClure that creates up to 50 thousand acre-feet (taf) of storage in the historical flood control space from November through March. The 50-taf volume size was selected for this study based on 6,000 cubic feet per second (cfs) downstream channel capacity and five-day inflow forecast period such that this volume could be evacuated if the forecast indicates a risk of flood operations.

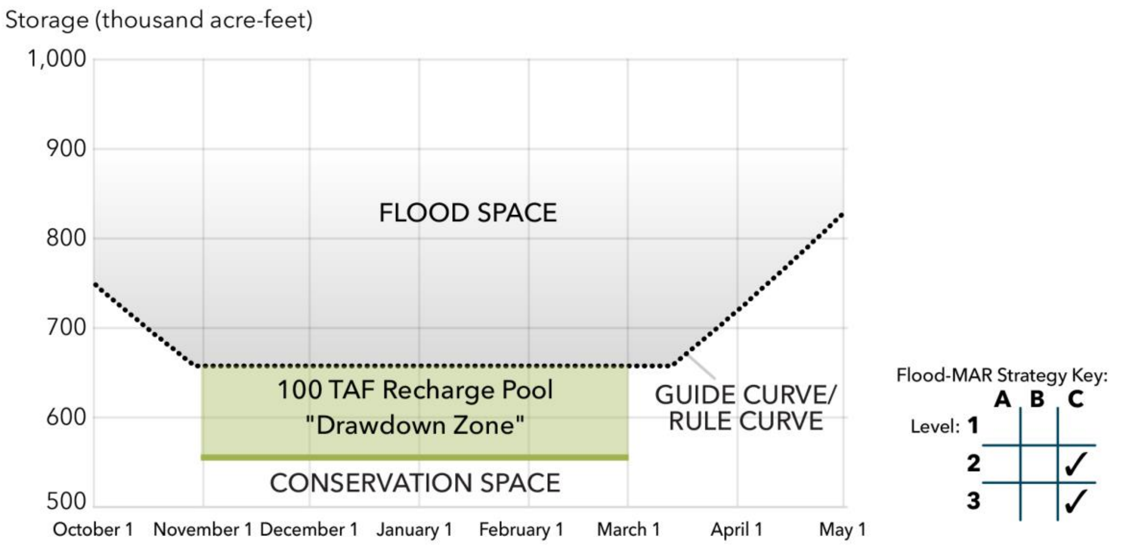
Figure 2-2 FIRO Diagram



2.2.1.2 Recharge Pool

The recharge pool is a reservoir storage zone created in the conservation space, just below the flood space. Water held in the recharge pool is released from the reservoir at a rate such that maximum water can be diverted for recharge. The recharge pool refills when storm events generate inflow into the reservoir that exceeds the rate at which water can recharge the aquifer. The recharge pool is operated for only a portion of the year, from November through February, to allow the reservoir to refill as flood space requirements decrease throughout the spring and reservoir inflows typically increase. The study further limited the ability to refill the vacated recharge pool to months when the Delta is in true excess and would have spilled under the baseline operations. This constraint is meant to limit the effect of recharge pool operations on downstream water users. Figure 2-3 illustrates the 100-taf Recharge Pool-MAR drawdown zone for Lake McClure.

Figure 2-3 Recharge Pool Diagram

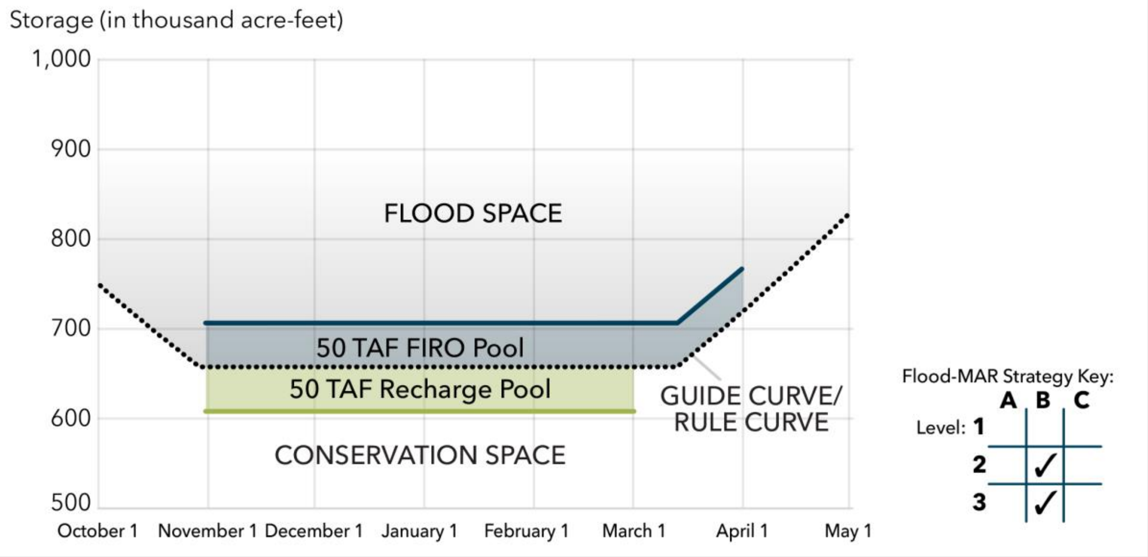


The recharge pool strategy is to increase the total water supply in the Merced watershed as a combination of surface storage in Lake McClure and groundwater storage in the Merced subbasin. Flood control releases and spills are more likely to occur when reservoir storage is near the top of the conservation space. For this reason, managed releases of water from the conservation space (i.e., the recharge pool "drawdown zone") that replenish groundwater storage increase total water supply, as a combination of surface and groundwater sources and decrease spill events. However, keeping surface storage at a lower level can sometimes reduce the available surface water supply when the reservoir does not refill by the end of the snowmelt season.

2.2.1.3 Hybrid-MAR

Hybrid-MAR combines the FIRO and recharge pool operations to achieve greater shared benefits across ecosystem, flood control, and water supply sectors. The strategy includes all reservoir and eco-management actions used in the FIRO-MAR strategy and adds a 50-taf recharge pool zone from November through February. Figure 2-4 illustrates the combined 50-taf FIRO pool and 50-taf recharge pool drawdown zone for Lake McClure.

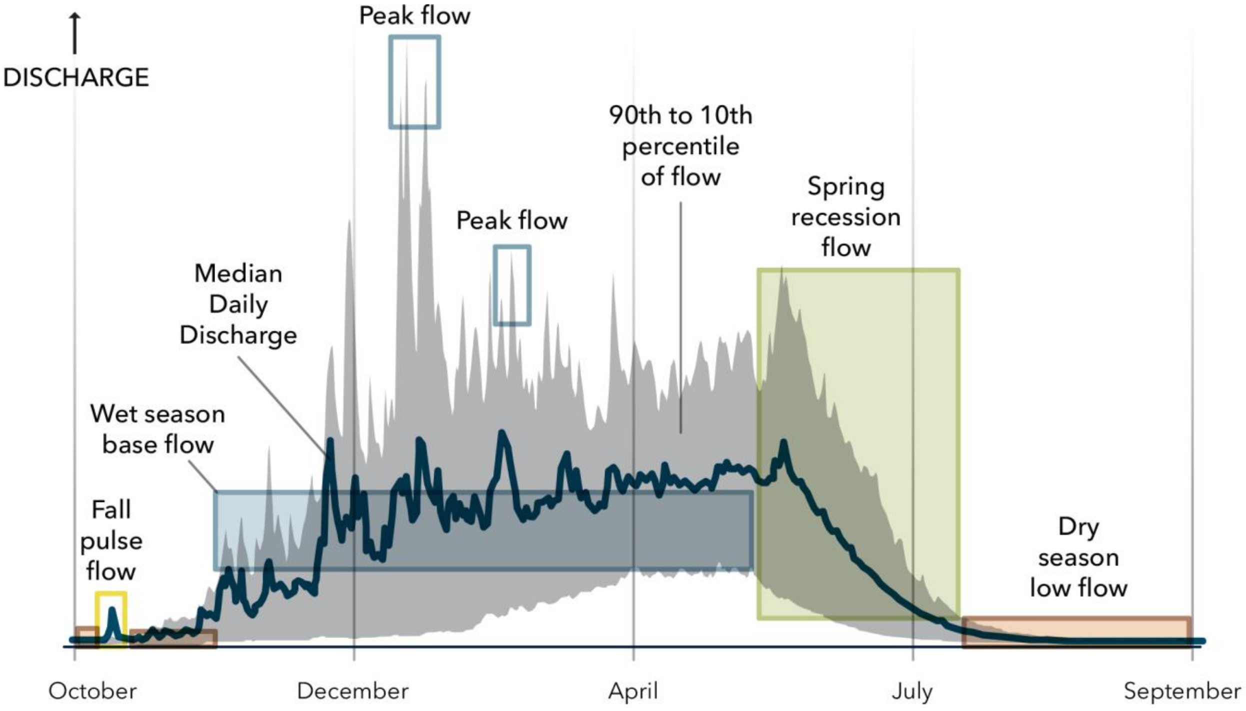
Figure 2-4 Hybrid (combined FIRO and Recharge Pool) Diagram



2.2.2 Ecosystem Management

Level 2 strategies have the potential to increase the total water stored in Lake McClure and the Merced subbasin. A portion of the additional water stored is used to provide supplementary benefits to the ecosystem by targeting specific improvements. The development of specific ecosystem improvements for the Merced River included review of the functional flow components described in the California Environmental Flows Framework (CEFF) (University of California, Davis 2024). The CEFF functional flow framework is a holistic approach to identifying and managing environmental flows that contribute to ecosystem health. A “functional flow” is a component of the hydrograph that provides distinct geomorphic, ecologic, or biogeochemical function and is reflective of the stream’s natural flow patterns over space and time. Figure 2-5 illustrates the CEFF functional flow components.

Figure 2-5 Functional Flow Components of the California Environmental Flows Framework



Level 2 Flood-MAR reservoir reoperation are designed to use the additional water made available from FIRO-MAR operations during the wet season to create functional flows, currently missing from the existing Merced River minimum instream flow requirements, targeting the salmonid life cycle and to create shorebird habitat. These ecosystem benefits are discussed in the following three subsections.

2.2.2.1 Spawning Flows

Baseflows during the wet season are critical for the creation of suitable habitat for salmonid spawning. Wet-season baseflow recommendations for all Level 2 Flood-MAR strategies were intended to maximize the quantity of in-channel spawning habitat. Weighted usable area (WUA) curves developed by MID (2013) were applied to identify targeted flow levels. During the peak spawning period for salmonids overlapping the Flood-MAR period, the reservoir was reoperated to remain within 80 to 100 percent of the maximum WUA by maintaining flows at the following levels:

- November through December: 140 to 250 cfs
- January to February: 160 to 400 cfs

During March, as juvenile salmonids begin to emerge and rear, a minimum instream flow target of 160 cfs was targeted to prevent redd dewatering (i.e., locations selected by females for laying eggs).

2.2.2.2 Spring Pulse Flow

Although most peak flow events occur naturally during winter, these events are attenuated by Flood-MAR actions. To provide a planned peak flow event, reservoir operations included releases to meet flow levels that provide some function for both peak magnitude flows and spring recessional flows. The pulse flow exceeded 1,200 cfs (over-banking flow) for a period of three days followed by an 11-day period with gradual reduction to baseflow.

2.2.2.3 Additional Managed Shorebird Habitat

Managed inundation of seasonally flooded wetlands and cropland habitats provides important plant and invertebrate foods for waterbirds during the late winter and early spring period. Suitable shorebird habitat is defined as ponded habitat of 2 to 4 inches of depth that is continuously inundated for a minimum of 28 days to allow time for primary and secondary food production to occur. The period from March through April was identified as a period of low habitat availability for shorebirds within the *Central Valley Joint Venture Implementation Plan* (2020). Level 2 Flood-MAR strategies include using WAFR in March on idle land with poor to very poor infiltration, based on the Soil Agricultural Groundwater Banking Index (SAGBI) soil type, to encourage ponding at a continuous 2-inch water depth for 28 days duration. This recharge emphasis identified several field parcels totaling 521 acres of potentially suitable shorebird habitat. However, the acres of shorebird habitat created in each field parcel is constrained by the acreage that can be effectively maintained at the desired 2-inch ponded depth using the existing turnout capacity. Shorebird habitat could not be evaluated for the climate vulnerability assessment because baseline models do not capture the inundation depth and duration at a parcel resolution and, consequently, cannot quantify the availability of incidental shorebird habitat.

2.2.3 Recharge Management

Level 2 strategies also explore recharging water in specific locations to target specific benefits, such as improved groundwater levels for disadvantaged communities (DACs) and groundwater-dependent ecosystems (GDEs), combating subsidence, and managing when and where recharged water may discharge from the Merced subbasin. The concept behind recharge management is to investigate whether Flood-MAR strategies can be used to achieve specific targeted outcomes based on where water is recharged, for example, whether it is possible to improve groundwater levels for GDEs or DACs by recharging in specific locations within a subbasin. Another example would be to identify potential shorebird habitat in areas where applied WAFR is likely to remain ponded and then emphasizing delivery of water to these areas to create an ecosystem sector benefit.

Additionally, Level 2 strategies increase the volume of WAFR and the current capacity to recharge the water can become a limiting factor. Therefore, assumptions for recharge-eligible lands and crops were expanded to increase the capacity to match the increased WAFR and expand the multi-sector benefits of Flood-MAR strategies.

2.3 Level 3 Strategies

As illustrated above in Figure 2-1, the Flood-MAR levels build upon each other and incorporate actions from the previous levels. Level 3 strategies incorporate diversions of high-flow events from Level 1 Intermediate and adopt the three different reservoir operations strategies (FIRO-MAR, Hybrid-MAR, and Recharge Pool-MAR) from Level 2. Specific areas where additional investment could improve the efficiency of Flood-MAR operations or increase benefits to a specific sector were identified based on the simulation results of Levels 1 and 2 strategies. Table 2-3 provides a summary of key conditions and capacity changes that define Level 3 strategies.

Table 2-3 Summary of Level 3 Flood-MAR Strategies

	Level 3 Strategies		
	FIRO-MAR	**Hybrid-MAR**	**Recharge Pool-MAR**
Management Objective	Same as Level 2 (see Table 2-2).		
High-Flow Diversion Criteria	Same as Level 1 and 2 (see Tables 2-1 and 2-2).		
Reservoir Management	Same as Level 2 (see Table 2-2).		
Ecosystem Management (season)	Same as Level 2 (see Table 2-2; except spring pulse flow in May instead of April[1]), plus spring inundation flow (April)[1]		Same as Level 2 (see Table 2-2)
Recharge Management	Same as Level 2 (see Table 2-2).		
Infrastructure investments:			
Field Turnout Capacity	Increased turnout capacity from 5 cfs to 10 or 15 cfs, depending upon field size.		
Diversion Capacity	N/A	Increased diversion capacity from local creeks.	
Conveyance Capacity	N/A	For example, removed conveyance constraints to El Nido (subsidence-prone region).	N/A
Recharge Capacity	Multi-benefit flow-through basins.	N/A	Additional dedicated recharge basins.
River Habitat	Merced River off-channel habitat improvement.	N/A	N/A

Notes: [1]Actions taken using the additional water is stored through FIRO or by reshaping the snowmelt management releases.

cfs = cubic feet per second; FIRO= forecast-informed reservoir operations;
MAR = managed aquifer recharge; N/A = not applicable.

2.3.1 Infrastructure Investments

Three components emerged as the main constraints on Flood-MAR: (1) WAFR, (2) the capacity to convey available water to recharge areas, and (3) the capacity of those areas to recharge water. Because of these constraints, Level 3 strategies evaluate how investments in infrastructure could increase the benefits of Flood-MAR by addressing those constraints.

Increased capacity to convey water from local canals onto specific fields (turnout capacity) was assumed in all Level 3 strategies. Turnout capacity was identified as a limiting factor for recharge on excellent and good soil types, as defined by SAGBI. These soil types can recharge water at a higher rate than may be possible with existing field turnouts. Increased turnout capacity creates the ability to recharge more water on fewer fields. Increased diversion capacity from local creeks was assumed for two of the three Level 3 strategies to increase the benefits from these sources where water can be available in large volumes, but for shorter durations.

Investments in dedicated recharge basins were combined with Recharge Pool-MAR to recharge more of the water available for water supply, and relieving canal conveyance, such as constraints for the El Nido area allowed more water to be recharged near the severely DAC of El Nido and directly to subsidence prone areas.

Additionally, current off-channel habitat on the Merced River has limited suitability for salmonid rearing given the lack of structure, cover, and vegetation that are important for rearing success. Therefore, potential off-channel habitat improvement opportunities were included in Level 3 strategies.

Lastly, flow through basins were set up along the local creeks to reduce flood risk and improve riparian habitat along the small streams area of Merced County. The benefits of investment in off-channel habitat along the Merced River and multi-benefit flow through basins along local creeks were explored in Level 3 FIRO-MAR.

2.3.2 Spring Inundation Flow

Off-channel habitat improvements were combined with additional spring inundation flows to illustrate the potential for additional ecosystem benefits. Under Level 3 FIRO-MAR, the reservoir operations include a single off-channel habitat inundation flow of 1,800 cfs during April for a two- to four-week duration dependent on water availability. Following the inundation period, flows were reduced linearly down to 1,200 cfs (current over-bank flow-level) for two days to avoid fish stranding before reducing to the baseflow levels.

Chapter 3. Performance of Flood-MAR Strategies and Adaptation to Climate Change

The following sections summarize the performance of the nine Flood-MAR strategies using metrics defined in TIR 3 – *Baseline Performance and Climate Change Vulnerability* (TIR 3) (California Department of Water Resources 2024) for the three water management sectors: flood risk, water supply, and ecosystems. In addition, two metrics were added to the Flood-MAR strategy analysis because they are influenced only by the system operations under different Flood-MAR operations: (1) average annual recharge, and (2) number of years with additional managed shorebird habitat.

The first section presents Flood-MAR strategy performance for current climate conditions, where each strategy's performance is compared to system performance under the baseline (i.e., "no action") condition. The second section summarizes the performance of Flood-MAR strategies under future climate conditions using the decision-scaling, risk-based framework introduced in TIR 3. Adaptive capacity can be quantified as future performance under the baseline condition compared to the future performance with a Flood-MAR strategy, where any improvement is interpreted as adaptive capacity in a water management sector. In addition, the adaptive capacity can also be compared to the level of vulnerability determined in TIR 3 (i.e., baseline performance under future climate compared to current climate) to understand how Flood-MAR strategies mitigate climate change-driven risks.

3.1 Performance Under Current Climate

Table 3-1 summarizes the multi-sector performance of the Flood-MAR strategies under current climate conditions. The table is organized to present results first for flood risk, then groundwater supply, surface water supply, and ecosystems. The baseline performance value is shown in the left-most column and performance for each strategy are in columns to the right.

Table 3-1 **Multi-Sector Performance of Flood-MAR Strategies Under Current Climate Conditions**

				Level 1			Level 2			Level 3		
Sector / Metric	**Indicator**	**Units**	**Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Flood-MAR Recharge	Average annual recharge from Flood-MAR strategies.	taf/year	0	17	43	62	65	86	93	66	92	99
Flood Risk:												
Lake McClure	Maximum encroachment at Lake McClure (Nov 1 – Mar 15).	Percent	61	61	60	58	44	43	30	44	43	30
Merced River	Merced River 100-year maximum simulated peak flow (Nov 1 – Jun 30).[1]	cfs	6,004	6,004	6,004	6,004	7,044	7,033	7,041	6,053	6,019	6,025
	Total number of years Merced River at Crocker-Huffman Diversion Dam is above 7,300 cfs (Nov 1 – Jun 30).	Years	0	0	0	0	0	0	0	0	0	0
Local Creeks	Bear Creek 100-year maximum simulated outflow.[2]	cfs	14,615	13,152	13,152	13,152	13,152	13,152	13,152	11,070	13,037	13,037
Water Supply / Groundwater:												
Δ GW Storage	Basinwide average annual change in groundwater storage.[3]	taf/year	-50	-44	-36	-31	-31	-25	-21	-33	-24	-19

				Level 1			Level 2			Level 3		
Sector / Metric	**Indicator**	**Units**	**Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Δ GW Levels	Average annual change in groundwater levels in subsidence prone region.	Feet/year	-0.8	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.7	-0.6	-0.5
	Average annual change in groundwater levels in aquifer underlying DACs east of Corcoran Clay layer.	Feet/year	-0.6	-0.5	-0.3	-0.2	-0.2	0.0	0.0	-0.2	0.1	0.1
GW Pumping	Average annual total groundwater pumping to meet agricultural uses in the Merced watershed.	taf/year	466	466	466	466	469	471	472	469	471	472
Water Supply / Surface Water:												
SW Deliveries	Average annual total surface water deliveries to agricultural users in the Merced watershed.	taf/year	355	355	355	355	352	350	349	352	350	349
	Number of years MID's surface water availability is at or below 80 percent.	Years	7	7	7	7	10	10	9	10	10	9
Lake McClure	Average annual Lake McClure storage at the end of the irrigation season (Oct 31).[4]	taf/year	518	518	518	517	511	487	462	511	487	462

				Level 1			Level 2			Level 3		
Sector / Metric	**Indicator**	**Units**	**Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Ecosystem:												
GDE Habitat	Proportion of months with depth to groundwater less than 30 feet.	Percent	77	79	82	84	84	84	84	85	84	83
Salmonid Habitat	Merced River instream salmonid spawning habitat (Sep – Apr).	Thousand acre-days	531	531	531	544	671	655	639	661	656	638
	Potential Merced River off-channel juvenile rearing habitat during qualified events (Dec – May).	Thousand acre-days	212	203	133	118	119	103	88	224	95	87
Shorebird Habitat	Number of years with additional managed shorebird habitat.	Years	0	0	0	0	63	49	0	63	49	0

Notes: [1]Simulated outflow downstream of Lake McClure Reservoir. 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 because of 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. [2]Bear Creek outflow into Eastside Bypass. [3]Groundwater conditions assume that no actions or projects are implemented in Merced or neighboring subbasins to comply with the Sustainable Groundwater Management Act. [4]Maximum Lake McClure carryover storage capacity is 675,000 taf.

cfs = cubic feet per second; DAC = disadvantaged community; feet/year = feet per year; FIRO = forecast-informed reservoir operations; GDE = groundwater-dependent ecosystem; GW = groundwater; MAR = managed aquifer recharge; MID = Merced Irrigation District; SW = surface water; taf/year = thousand acre-feet per year.

3.1.1 Level 1 Strategies

Level 1 strategies have minimal effect on flood risk reduction on the Merced River as there is little change in Lake McClure operations and no reduction in the maximum simulated flows. However, Flood-MAR diversions on Bear Creek do reduce the maximum simulated flow by approximately 10 percent.

Level 1 strategies improve groundwater conditions with increasing benefits as more water is diverted for recharge. The average annual recharge for Level 1 strategies ranges from 17 to 62 taf, which leads to reductions in annual average overdraft by 10 to 40 percent compared to baseline conditions. The reduction in overdraft slows the decline of water levels near DACs and subsidence prone regions and increases the number of months when water levels may support GDEs. Level 1 strategies do not affect surface water supplies for MID or the operation of Lake McClure for water supply.

Ecosystem effects vary across the Level 1 strategies with improved groundwater levels for GDEs, potential for improved spawning habitat when diversions of high flows improve conditions, and reductions in potential off-channel juvenile salmonid rearing habitat when diversions of high flows reduce the downstream flows in the river. Providing shorebird habitat is not an objective of Level 1 strategies because it is challenging to provide water for the necessary duration when relying on the opportunistic diversion of high flows.

3.1.2 Level 2 Strategies

Level 2 strategies provide flood risk reduction by reducing the maximum encroachment into the flood reservation space at Lake McClure with the Recharge Pool-MAR strategy creating the largest reduction. The change in reservoir operations does not translate into significant changes in the maximum downstream flow under current climate conditions as the existing system is able to control current peak inflows. Although, similar to Level 1 strategies, the maximum simulated flow on Bear Creek is reduced by 10 percent because of Flood-MAR diversions.

The changes in reservoir operations under Level 2 strategies make additional water available for recharge and improve groundwater conditions above what is achieved with most Level 1 strategies. The average annual recharge for Level 2 strategies ranges from 65 to 93 taf — the larger amounts produced through recharge pool operations — which leads to reductions in annual average overdraft by 40 to 60 percent. However, recharge pool operations, which draw up to 100 taf of water from Lake McClure’s conservation space to store in the aquifer, tend to reduce carryover storage and therefore can reduce surface water supplies in subsequent years. For example, the Recharge Pool-MAR strategy reduces the annual average overdraft by 29 taf but also reduces surface water deliveries by 6 taf. The reduction in overdraft helps slow the decline of water levels near DACs. Two of the strategies hold long-term average water levels near DACs stable because of the combination of the volume and location of recharge. All Level 2 strategies provide a similar level of benefit to subsidence prone regions and GDEs.

Level 2 strategies include targeted ecosystem improvements to improve flows for specific salmonid life stages and provide shorebird habitat. There are improvements to salmonid spawning habitat achieved through targeted releases for this purpose. Additionally, although there are also targeted releases for spring inundation and pulse flows when water is available, these additional flows do not offset the reduction in flows in other years when high flow events are reduced because of changes in reservoir operations and diversions for recharge. This results in a reduction in the potential off-channel rearing habitat. The Level 2 FIRO-MAR and Hybrid-MAR strategies include shorebird habitat as an objective and use Lake McClure releases to provide water for the necessary duration in up to 63 of the 100 years in the simulation period.

3.1.3 Level 3 Strategies

Results from Level 3 strategies are similar to those described above for Level 2, with some additional benefits. The infrastructure investments allow for more water to be recharged during high-flow periods without additional risk to surface water supplies. The average annual recharge for Level 3 strategies increases slightly from what was possible under Level 2 strategies and ranges from 66 to 99 taf, which leads to even greater reductions in annual average overdraft and improved groundwater levels (particularly for DACs) in the recharge pool and hybrid Flood-MAR strategies.

The effects of Level 3 strategies on ecosystem metrics are very similar to Level 2 strategies, the only difference being an improvement in the potential Merced River off-channel juvenile rearing habitat under the Level 3 FIRO-MAR strategy resulting from a combination of off-channel habitat improvements and supplemental spring inundation flow releases from Lake McClure using the water banked in the FIRO space.

3.2 Adaptation to Climate Change

All nine Flood-MAR strategies under Levels 1, 2, and 3 were simulated under the future climate conditions of changes in precipitation and temperature described in TIR 3. The results of the Flood-MAR strategy performance are summarized for the 2040 planning horizon, where expected value and risk is calculated using weights on the climate conditions that are based on the projections of many global climate models. As an important point of reference shown in Table 3-2, approximately 97 percent of the climate-informed probability is covered by +1 to +2 degrees Celsius (°C) of warming and -10 to +10 percent change in precipitation at the near-term 2040 planning horizon.

Table 3-2 GCM-Informed Conditional Probabilities of Future Climate Conditions at a 2040 Planning Horizon

2040 Planning Horizon		Change in Precipitation -20%	-10%	0%	+10%	+20%	+30%
Change in Temperature	**0**	0%	0%	0%	0%	0%	0%
	+1 °C	0%	5%	15%	8%	1%	0%
	+2 °C	0%	9%	36%	22%	2%	0%
	+3 °C	0%	0%	1%	0%	0%	0%
	+4 °C	0%	0%	0%	0%	0%	0%

Note: °C = degrees Celsius

Table 3-3 summarizes the multi-sector expected value performance of the Flood-MAR strategies and the baseline conditions under future climate change at the 2040 planning horizon. As shown for the baseline conditions and covered in detail in TIR 3, it is more likely than not that future performance for all three sectors will worsen by 2040. Increases in precipitation and temperature are drivers for increased flood risk and result in volumes of inflow over short periods (one to seven days) that exceed the existing system's modeled capacity and operational rules to manage. Risks to water supply from climate change involve multiple factors in the system's watershed conditions, reservoir operations, and groundwater response. Increased groundwater extraction to meet rising agricultural evapotranspiration demands from increasing temperature and a lack of carryover surface storage under warmer and drier conditions leads to an increase in the rate of long-term, basin-wide groundwater overdraft. For ecosystems, GDE habitat availability closely tracks the groundwater conditions and are likely to experience a decrease in groundwater availability under climate change, likely impacting GDE sustainability. Finally, both instream and potential off-channel salmonid habitat are highly sensitive to shifts in the magnitude and timing of Merced River flow.

A key observation from the results summarized in Table 3-3, as compared to those in Table 3-1, is that the benefits, tradeoffs, and trends for Flood-MAR strategies under current climate conditions are maintained at the 2040 planning horizon. This assumed stability indicates that Flood-MAR strategies are generally robust and would be expected to deliver similar changes in performance under the majority of potential future climate conditions. For the flood risk and water supply sectors, modeled Flood-MAR strategies that include reservoir reoperation (Levels 2 and 3) are key to managing periods of increased runoff and increasing utilization of Merced subbasin groundwater resources.

Table 3-3 Multi-Sector Performance of Flood-MAR Strategies under Climate Change Conditions (Expected Values at Planning Horizon 2040)

				Level 1			Level 2			Level 3		
Sector / Metric	**Indicator**	**Units**	**2040 Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid -MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Flood-MAR Recharge	Average annual recharge from Flood-MAR strategies.	Taf/year	0	18	54	74	73	92	97	75	100	105
Flood Risk:												
Lake McClure	Maximum encroachment at Lake McClure (Nov 1 – Mar 15).	Percent	79	79	79	79	70	66	54	70	66	54
Merced River	Merced River 100-year maximum simulated flow (Nov 1 – Jun 30).[1]	Cfs	15,677	15,667	14,919	14,506	9,248	9,082	8,559	9,084	8,952	8,384
	Total number of years Merced River at Crocker-Huffman Diversion Dam is above 7,300 cfs (Nov 1 – Jun 30).	Years	3	3	2	2	2	1	1	1	1	1
Local Creeks	Bear Creek 100-year maximum simulated outflow.[2]	Cfs	15,056	13,656	13,667	13,780	13,718	13,657	13,657	11,567	13,559	13,561
Water Supply / Groundwater:												
Δ GW Storage	Basinwide average annual change in groundwater storage.[3]	Taf/year	-79	-72	-62	-56	-57	-52	-49	-59	-50	-46

				Level 1			Level 2			Level 3		
Sector / Metric	**Indicator**	**Units**	**2040 Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid -MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Δ GW Levels	Average annual change in groundwater levels in subsidence prone region.	Feet/year	-1.1	-1.1	-1.0	-1.0	-1.0	-0.9	-0.9	-1.0	-0.9	-0.9
	Average annual change in groundwater levels in aquifer underlying DACs east of Corcoran Clay layer.	Feet/year	-1.0	-0.9	-0.6	-0.5	-0.5	-0.4	-0.4	-0.6	-0.3	-0.3
GW Pumping	Average annual total groundwater pumping to meet agricultural uses in the Merced watershed.	Taf/year	494	494	494	494	497	499	501	497	499	501
Water Supply / Surface Water:												
SW Deliveries	Average annual total surface water deliveries to agricultural users in the Merced watershed.	Taf/year	359	359	359	359	356	353	352	356	353	352
	Number of years MID’s surface water availability is at or below 80 percent.	Years	10	10	10	10	11	12	13	11	12	13
Lake McClure	Average annual Lake McClure storage at the end of the irrigation season (Oct 31).[4]	Taf/year	479	479	478	478	473	451	425	474	451	425

				Level 1			Level 2			Level 3		
Sector / Metric	**Indicator**	**Units**	**2040 Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Ecosystem:												
GDE Habitat	Proportion of months with depth to groundwater less than 30 feet.	Percent	57	59	63	65	64	64	64	66	65	63
Salmonid Habitat	Merced River instream salmonid spawning habitat (Sep – Apr).	Thousand acre-days	509	509	509	525	659	647	625	657	647	625
	Potential Merced River off-channel juvenile rearing habitat during qualified events (Dec – May).	Thousand acre-days	367	350	249	235	240	208	202	319	199	198
Shorebird Habitat	Number of years with additional managed shorebird habitat.	Years	0	0	0	0	60	47	0	59	47	0

Notes: [1]Simulated outflow downstream of Lake McClure Reservoir. [2]Bear Creek outflow into Eastside Bypass. [3]Groundwater conditions assume that no actions or projects are implemented in Merced or neighboring subbasins to comply with the Sustainable Groundwater Management Act. [4]Maximum Lake McClure carryover storage capacity is 675,000 taf.

cfs = cubic feet per second; DAC = disadvantaged community; feet/year = feet per year; FIRO = forecast-informed reservoir operations; GDE = groundwater-dependent ecosystem; GW = groundwater; MAR = managed aquifer recharge; MID = Merced Irrigation District; SW = surface water; taf/year = thousand acre-feet per year.

3.2.1 Level 1 Strategies

Interim and robust Level 1 strategies have a minor effect on flood risk reduction on the Merced River by diverting high flows; however, the maximum simulated flows still exceed downstream channel capacity and are approximately twice the historically observed maximum flows. The maximum simulated flow on Bear Creek is reduced approximately 10 percent because of Flood-MAR diversions, but still increases from current conditions.

Level 1 strategies improve groundwater conditions with increasing benefits as more water is diverted for recharge. The average annual recharge for Level 1 strategies ranges from 18 to 74 taf. Recharge increases at a 2040 planning horizon as the shift in the timing of available water changes. Water supply and ecosystem results are similar to current conditions, though baseline performance is frequently worse at a 2040 planning horizon. Similar results indicate Flood-MAR strategies are robust in providing benefits with expected climate change and have similar tradeoffs with climate change for metrics such as off-channel juvenile rearing habitat.

3.2.2 Level 2 Strategies

Level 2 strategies provide flood risk reduction by reducing the maximum simulated flow in the Merced River with the Recharge Pool-MAR strategy creating the largest reduction. Level 2 strategies can make it possible to manage future inflow events with the existing infrastructure. The maximum simulated flow on Bear Creek is reduced approximately 10 percent because of Flood-MAR diversions, the same as under Level 1 strategies.

The changes in reservoir operations under Level 2 strategies make additional water available for recharge and improve groundwater conditions above what is achieved with most Level 1 strategies. The average annual recharge for Level 2 strategies ranges from 73 to 97 taf, an increase compared to current climate conditions. Water supply and ecosystem results are similar to current conditions, demonstrating Flood-MAR strategies are robust in providing benefits and have similar tradeoffs with expected climate change.

3.2.3 Level 3 Strategies

Results from Level 3 strategies are similar to those described above for Level 2, with some additional benefits. The assumed infrastructure investments allow for more water to be recharged during high-flow periods without additional risk to surface water supplies. The average annual recharge for Level 3 strategies increases slightly from what was possible under Level 2 strategies and ranges from 95 to 105 taf.

3.3.4 Risk-Based Adaptation Performance of Flood-MAR Strategies

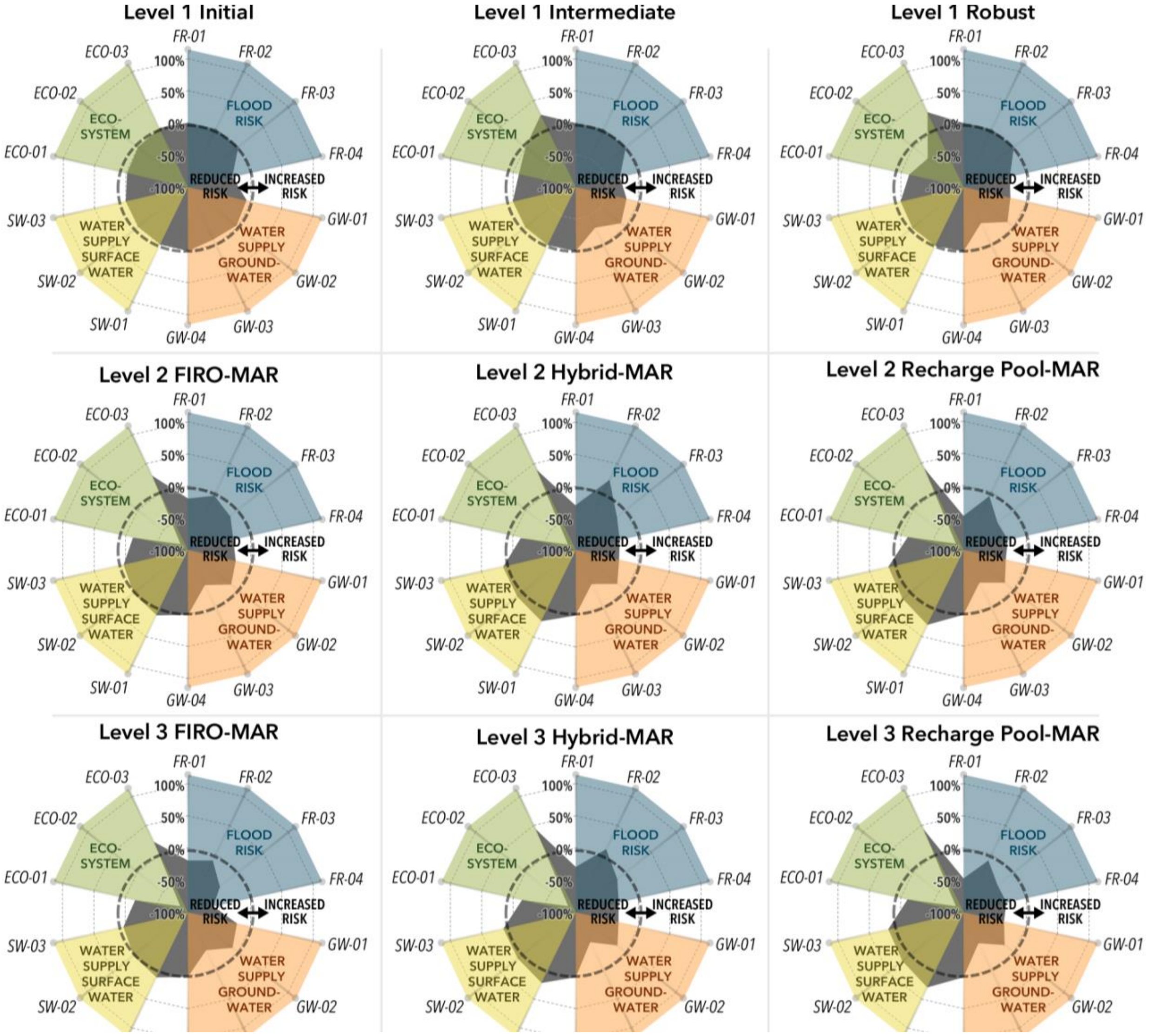
The probabilistic characterization of joint changes in precipitation and temperature shown in Table 3-2 can be transferred into distributions of changes for each sector metric. This analysis quantifies the cumulative risk of being “worse-off” under future climate conditions compared to a specified level of performance. The plots in Figure 3-1 show the change in cumulative risk of worsening conditions at the 2040 planning horizon for each Flood-MAR strategy compared to the baseline conditions, where cumulative risk is shown as reduced (increased) if the dark grey shaded area falls inside (outside) the dashed black line.

Starting with Level 1 Initial — the simplest of all strategies — diverting high flows reduces the risk of flooding along the local creeks and mitigates some groundwater overdraft risk. With the expanded recharge footprint and volume of Level 1 Intermediate and Robust strategies, greater risk reductions accrue to water supply groundwater metrics; but, changes in risk for the ecosystem sector are mixed, where instream spawning habitat risk falls and potential off-channel rearing habitat rises.

The reservoir reoperation strategies introduced under Levels 2 and 3 result in greater conjunctive management of surface water and groundwater resources, particularly with recharge operations. So, Level 2 and Level 3 strategies tend to marginally increase the risk to surface water conditions (e.g., years with surface water availability less than 80 percent) and groundwater pumping while significantly decreasing the risk of worsening groundwater conditions (e.g., overdraft) as more of the water supply is “moved” from the surface water reservoir into the groundwater aquifer. Compared to Level 1 strategies, the Level 2 and Level 3 FIRO-MAR, Hybrid-MAR, and Recharge Pool-MAR strategies all significantly reduce the flood risk along the Merced River in terms of encroachment into Lake McClure’s flood space, decrease the years with flood flows above the safe threshold, and lower the magnitude of the peak flows. Combining Flood-MAR with reservoir reoperations provides additional opportunities to effectively manage the system and significantly reduce flood risk, but the tradeoff is either (1) reduced Lake McClure storage under Recharge Pool-MAR operations, or (2) aggressive releasing of Lake McClure storage from the flood space during transition months under FIRO-MAR operations, which results in lower surface water availability or lower end of the irrigation season storages.

Changes in cumulative risk are mixed for the ecosystem sector. GDE habitat benefits from improved groundwater conditions resulting from Flood-MAR operations and, as a result, the cumulative risk reduces across all strategies. Because the Merced River is a highly channelized stream system, instream spawning habitat benefits as well from reduced flows with lower velocities associated with Flood-MAR operations. Yet, potential off-channel rearing habitat relies on flood flows to inundate the overbank reaches, and consequently shows greater cumulative risk under the Flood-MAR strategies that reduce flood risk. However, this risk can be significantly managed by investing in off-channel improvement and providing spring inundation flow when water is available as seen in Level 3 FIRO-MAR.

Figure 3-1 **Change in the Cumulative Risk of a Loss in Performance for the 14 Multi-Sector Indicators at the 2040 Planning Horizon by Flood-MAR Adaptation Strategy**



Notes: See Table 3-4 for metrics' abbreviated labels and the 2040 baseline risk. See Table 3-1 for baseline current condition performance thresholds.

Table 3-4 Change in the Cumulative Risk of a Loss in Performance for the 14 Multi-Sector Indicators at the 2040 Planning Horizon by Flood-MAR Adaptation Strategy

				Level 1			Level 2			Level 3		
Sector / Metric	**Label**	**Indicator**	**2040 Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Flood Risk:												
Lake McClure	FR-01	Maximum encroachment at Lake McClure (Nov 1 – Mar 15).	85%	0%	0%	0%	-19%	-29%	-47%	-19%	-29%	-47%
Merced River	FR-02	Merced River 100-year maximum simulated flow (Nov 1 – Jun 30).[1]	63%	0%	0%	0%	-6%	22%	-7%	-11%	9%	-11%
	FR-03	Total number of years Merced River at Crocker-Huffman Diversion Dam is above 7,300 cfs (Nov 1 – Jun 30).	76%	0%	0%	0%	-16%	-17%	-32%	-36%	-17%	-32%
Local Creeks	FR-04	Bear Creek 100-year maximum simulated outflow.[2]	62%	-29%	-29%	-26%	-28%	-29%	-29%	-59%	-32%	-32%
Water Supply / Groundwater:												
Δ GW Storage	GW-01	Basinwide average annual change in groundwater storage.[3]	75%	-7%	-19%	-25%	-24%	-30%	-33%	-22%	-32%	-35%
Δ GW Levels	GW-02	Average annual change in groundwater levels in subsidence prone region.	72%	-3%	-10%	-13%	-14%	-17%	-18%	-11%	-17%	-18%

				Level 1			**Level 2**			**Level 3**		
Sector / Metric	**Label**	**Indicator**	**2040 Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
	GW-03	Average annual change in groundwater levels in aquifer underlying DACs east of Corcoran Clay layer.	76%	-9%	-30%	-38%	-40%	-42%	-43%	-34%	-48%	-47%
GW Pumping	GW-04	Average annual total groundwater pumping to meet agricultural uses in the Merced watershed.	98%	0%	0%	0%	+1%	+1%	+1%	+1%	+1%	+1%
Water Supply / Surface Water:												
SW Deliveries	SW-01	Average annual total surface water deliveries to agricultural users in the Merced watershed.	29%	0%	+1%	+1%	+13%	+22%	+30%	+12%	+22%	+30%
	SW-02	Number of years MID's surface water availability is at or below 80 percent.	66%	0%	0%	+2%	+8%	+15%	+21%	+8%	+15%	+21%
Lake McClure	SW-03	Average annual Lake McClure storage at the end of the irrigation season (Oct 31).[4]	80%	0%	0%	+1%	+3%	+15%	+20%	+3%	+15%	+20%

				Level 1			Level 2			Level 3		
Sector / Metric	**Label**	**Indicator**	**2040 Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Ecosystem:												
GDE Habitat	ECO-01	Proportion of months with depth to groundwater less than 30 feet.	81%	-2%	-9%	-13%	-12%	-13%	-11%	-16%	-14%	-11%
Salmonid Habitat	ECO-02	Merced River instream salmonid spawning habitat (Sep – Apr).	85%	0%	0%	-29%	-85%	-85%	-85%	-85%	-85%	-85%
	ECO-03	Potential Merced River off-channel juvenile rearing habitat during qualified events (Dec – May).	16%	+2%	+25%	+29%	+29%	+40%	+41%	+22%	+43%	+43%

Notes: [1]Simulated outflow downstream of Lake McClure Reservoir. [2]Bear Creek outflow into Eastside Bypass. [3]Groundwater conditions assume that no actions or projects are implemented in Merced or neighboring subbasins to comply with the Sustainable Groundwater Management Act. [4]Maximum Lake McClure carryover storage capacity is 675,000 taf.

cfs = cubic feet per second; DAC = disadvantaged community; FIRO = forecast-informed reservoir operations; GDE = groundwater-dependent ecosystem; GW = groundwater; MAR = managed aquifer recharge; MID = Merced Irrigation District; SW = surface water.

Chapter 4. Deep Dive into Flood-MAR Management and Adaptation

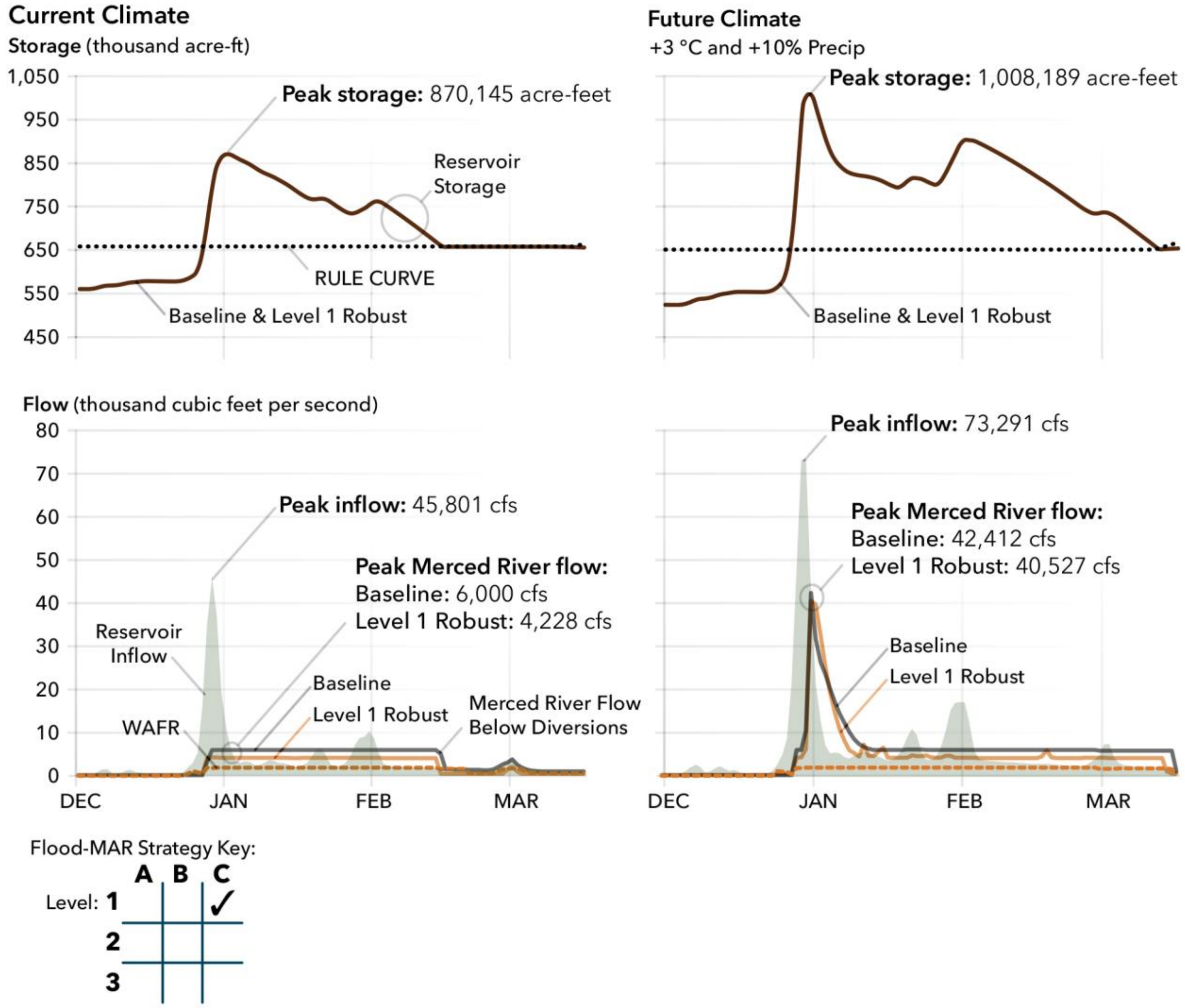
The previous chapter provided a thorough summary of expected performance of Flood-MAR strategies under current and future climate according to the metrics defined for the three sectors. To develop a more detailed understanding of system management and operations that drive changes in expected performance, Chapter 4 explores the Flood-MAR strategies with respect to reservoir, ecosystem, groundwater, and recharge management. Because of the detailed nature of the information in this chapter, some figures only show results for certain Flood-MAR strategies. Additionally, some figures and tables focus on a particular future climate scenario — 3 °C increase in temperature and 10 percent increase in precipitation — rather than the 2040 Planning Horizon.

4.1 Flood-MAR Reservoir Management

4.1.1 Level 1 Operations

Level 1 Flood-MAR operations divert flow off the Merced River during high-flow conditions. In general, this operation reduces flood peaks downstream of the WAFR diversion point and creates opportunities for canal and on-farm recharge (OFR). As shown in Figure 4-1, Level 1 operations are effective in reducing flood risk for the 1956 high-flow event simulated under current conditions where peak outflow is reduced from 6,000 cfs to 4,100 cfs by diverting 1,900 cfs for recharge. But, under a possible modeled future climate of +3 °C and +10 percent precipitation where the reservoir is forced into emergency operations and releases an uncontrolled peak outflow of 42,400 cfs, Level 1 Flood-MAR can reduce it only to 40,500 cfs. So, Level 1 operations are not adequate for reducing the flood risk for larger inflow events that become possible under warmer and wetter conditions.

Figure 4-1 **Simulated Event (Water Year 1956) for Baseline and Level 1 Robust Operations for Current Climate and Climate Change Conditions (+3 °C, +10 percent precipitation)**



4.1.2 Level 2 and Level 3 FIRO and Recharge Pool Operations

The reservoir operations strategies in Levels 2 and 3 were developed to address the increasing peak flows seen under future climate conditions that would significantly raise flood risk on the Merced River. The FIRO operations use a forecasted inflow volume entering the reservoirs that allows for a pre-release when storage is projected to rise near or to the top of the flood control space. In addition, the Flood-MAR operations allow for an increase in the release capacity accounting for channel capacity downstream of the reservoir and the available capacity in the irrigation canals. The combination of these two operations reduces the peak flow from 42,400 cfs to 15,600 cfs, as shown in Figure 4-2 for the Level 3 FIRO-MAR strategy. In addition to the peak-flow reduction, FIRO operations monitor the inflow volume when the storage is in the FIRO Pool. When inflow over the next one to five days is not predicted to exceed the FIRO pool, the reservoir switches from flood control release to FIRO-MAR-managed releases from the FIRO space to maximize recharge opportunities and reduce the duration of high flows on the Merced River below the Flood-MAR diversion point, thereby relieving stress on levees.

Water stored in the flood control space at the end of FIRO operations (on March 1) is tracked to establish the eco pool account used for additional ecosystem operations. Depending on the volume of water in the eco pool account and the projected snowmelt runoff volume in excess of the in-basin demand and end of snowmelt season storage target, the following ecosystem operations were performed: shorebird release in March, off-channel habitat spring inundation release in April, and spring pulse release in May. As shown in Figure 4-2, the 1956 event simulated under climate change conditions (+3 °C, +10 percent precipitation) includes all three of these actions.

Figure 4-2 Simulated Event (Water Year 1956) for Baseline and Level 3 FIRO-MAR Operations Under Climate Change Conditions (+3 °C, +10 percent precipitation)

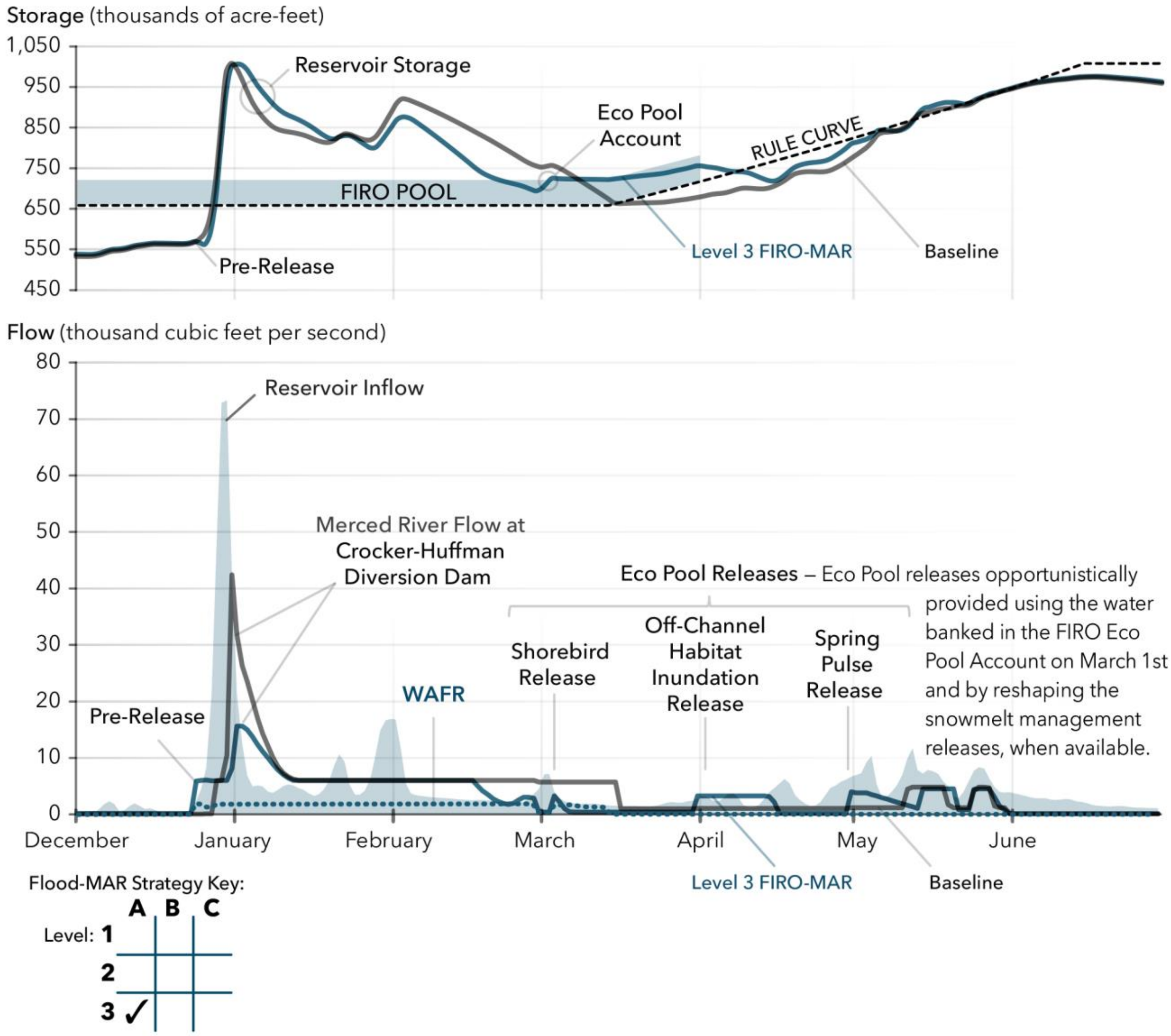
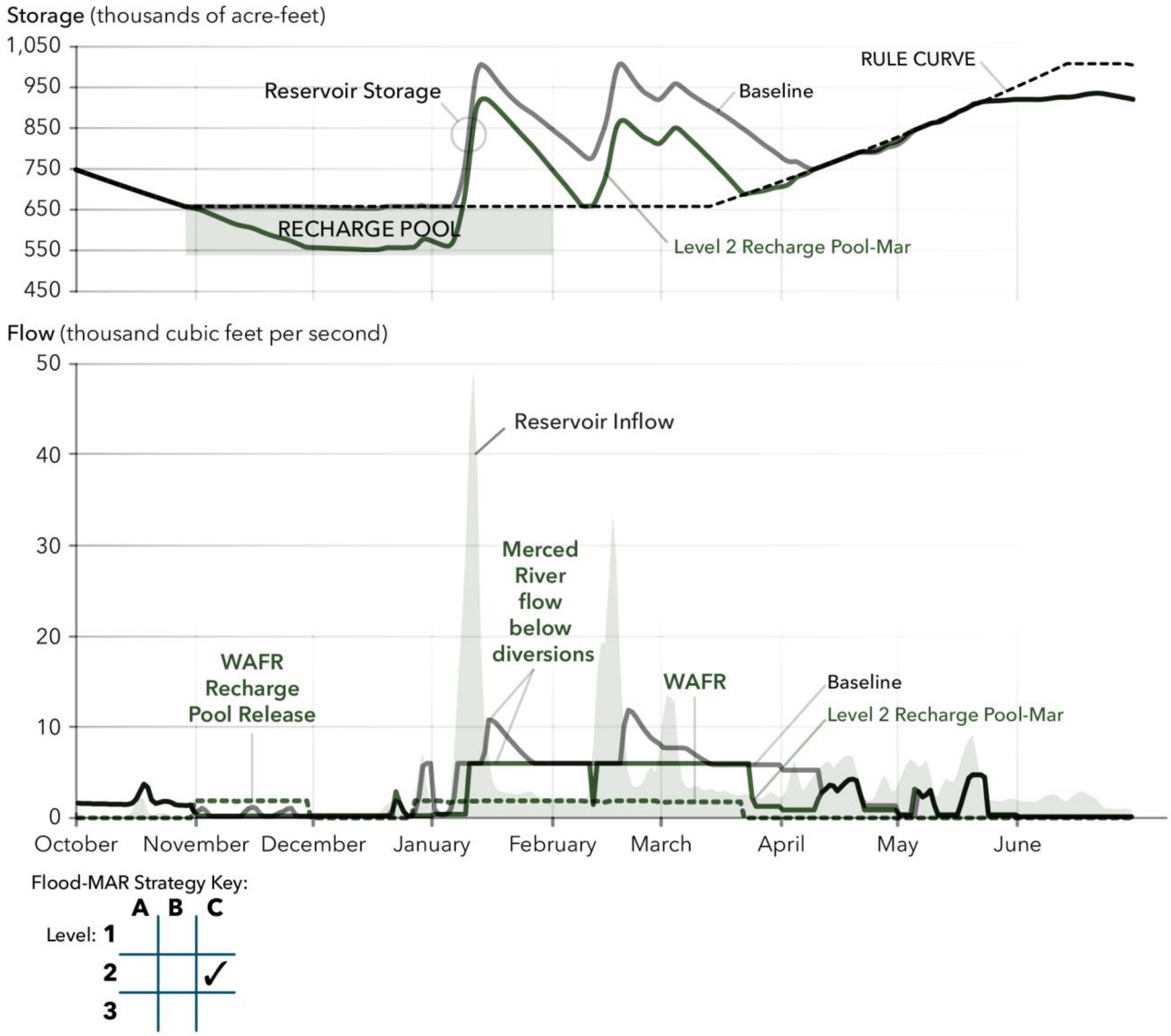


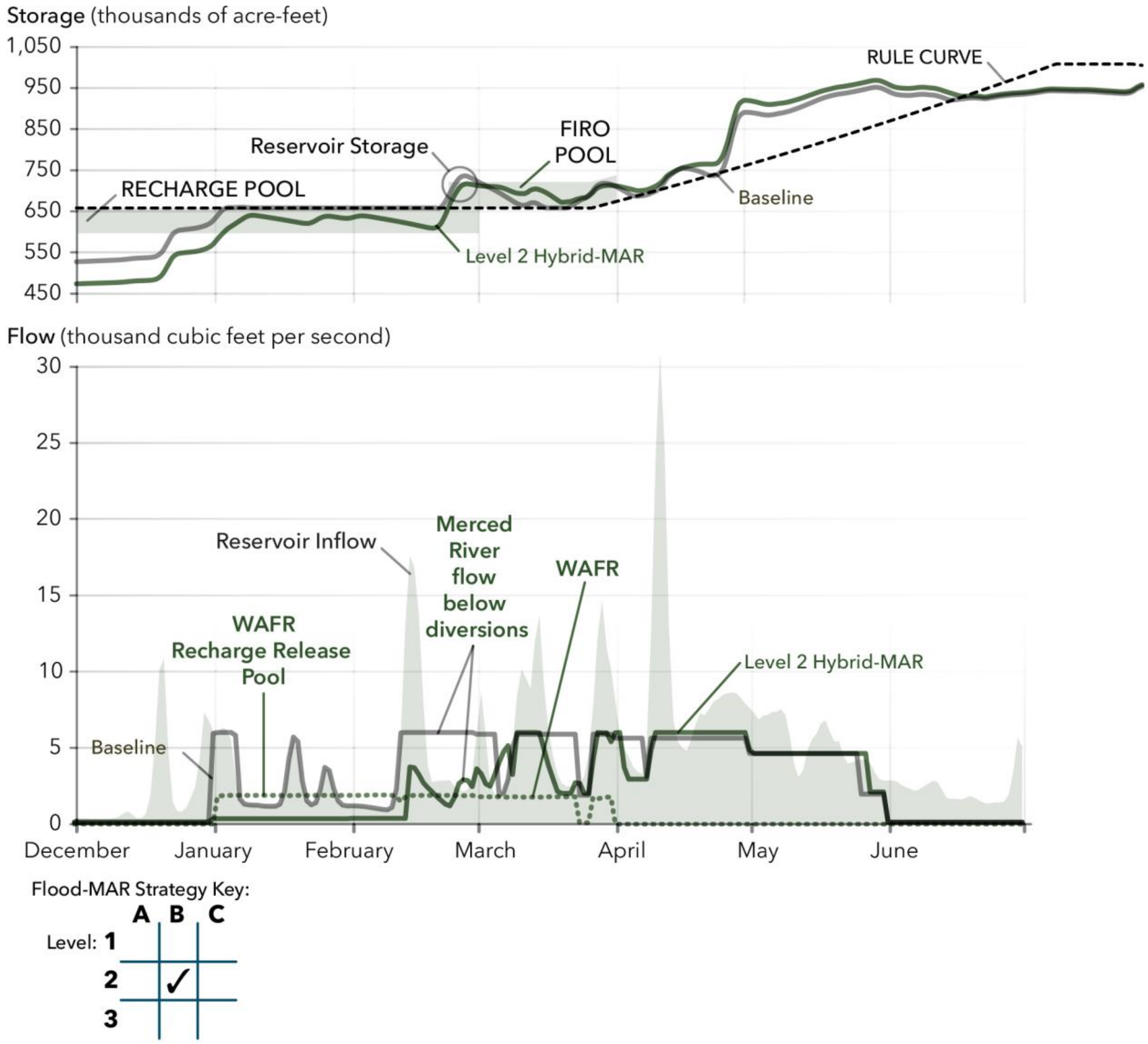
Figure 4-3 shows reservoir operations for the baseline and Level 2 Recharge Pool-MAR strategy for the 1942 event simulated under climate change conditions (+3 °C, +10 percent precipitation). In contrast to FIRO-MAR operations, no forecast (and therefore no pre-release) is used in the Recharge Pool-MAR strategy. Instead, this strategy reduces flood risk by creating more flood control space in the reservoir. As shown in Figure 4-3, Flood-MAR releases during November and just before the event (end of December and beginning of January) draw reservoir storage down into the conservation zone (i.e., the recharge pool) by 100,000 acre-feet. This allows the reservoir to “absorb” the peak event inflow with lower encroachment into the flood control space. That, together with the additional downstream channel capacity enabled by the Flood-MAR diversion, reduced peak Merced River flows below the diversion point for the water year’s two major events.

Figure 4-3 **Simulated Event (Water Year 1942) for Baseline and Level 2 Recharge Pool-MAR Operations Under Climate Change Conditions (+3 °C, +10 percent precipitation)**



Levels 2 and 3 Hybrid-MAR operations combine recharge pool and FIRO operations as shown for the 1982 simulated event in Figure 4-4. In this simulation, recharge pool operations in prior water years lowered reservoir storage relative to baseline operations. Storage recovers with the first few minor inflow events and Flood-MAR releases are triggered through January and the beginning of February, creating increased space in the reservoir to absorb the peak inflow in mid-February. Following the February event, FIRO operations balance flood-control releases and WAFR to maximize recharge opportunities while limiting encroachment above the FIRO pool. Additional releases for ecosystem operations from the eco pool account are masked by the large snowmelt runoff simulated in Water Year 1982.

Figure 4-4 **Simulated Event (Water Year 1982) for Baseline and Level 2 Hybrid-MAR Operations Under Climate Change Conditions (+3 °C, +10 percent precipitation)**

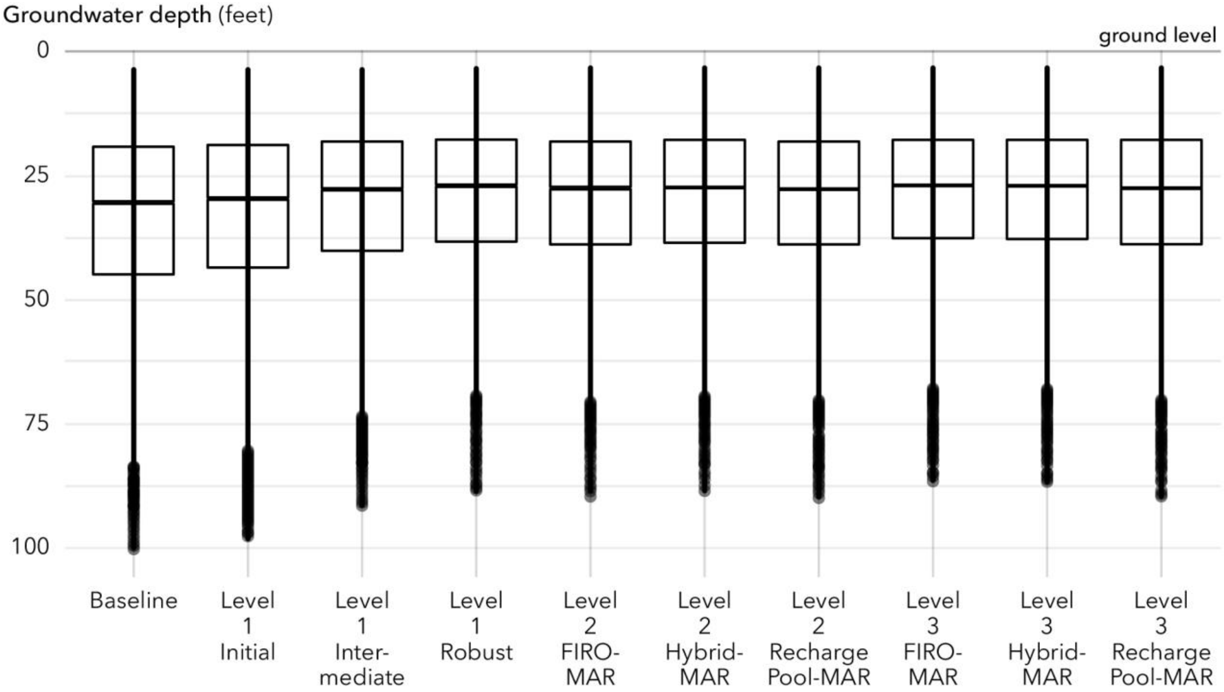


4.2 Flood-MAR Ecosystem Management

4.2.1 Groundwater-Dependent Ecosystems

GDEs likely will experience an increase in groundwater availability under Flood-MAR adaptation strategies because of elevated groundwater levels along the San Joaquin River and the lower reach of the Merced River. Figure 4-5 shows a box and whisker plot of the spatially averaged monthly groundwater depth underlying the GDE extent in the Merced subbasin at 2040 planning horizon for the 100-year simulation period under each Flood-MAR strategy compared to the 30-foot depth threshold. As shown in the figure, the average monthly depth to groundwater underlying GDEs decreases with increasing recharge intensity. Level 1 Initial shows the lowest groundwater availability across all levels and strategies, whereas Level 1 Intermediate and Robust show shallower groundwater levels, or lower depths to groundwater, because of additional recharge. Similar improvements are seen in the Levels 2 and 3 strategies. Although the benefits to GDEs in FIRO strategies are similar to the Hybrid-MAR and Recharge Pool-MAR strategies, the benefit to GDEs is realized using 70 to 80 percent of the WAFR under Level 2 and Level 3 Hybrid-MAR and Recharge Pool-MAR strategies, underscoring the benefit of targeted recharge.

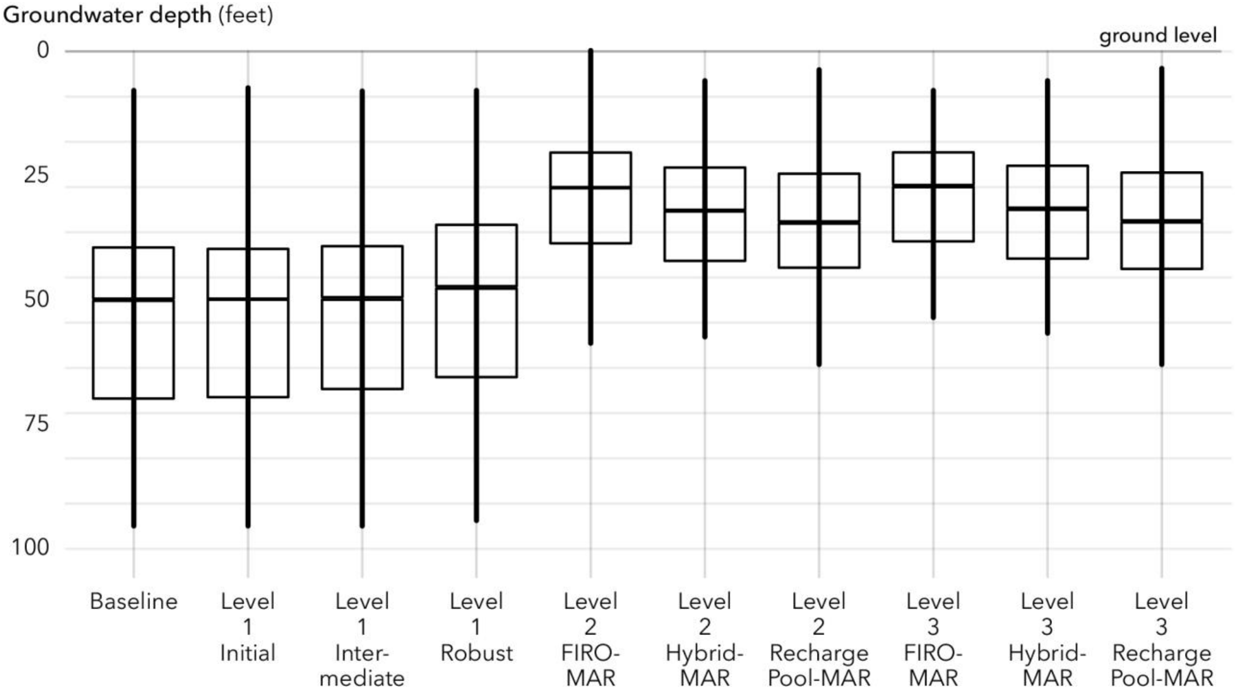
Figure 4-5 **Spatially Averaged Monthly Groundwater Depth underlying GDE Extent in Merced Subbasin Under 2040 Planning Horizon for each Flood-MAR Strategy**



4.2.2 Instream Spawning Habitat

Levels 2 and 3 Flood-MAR strategies target flows to maximize spawning habitat for salmonids based on the WUA relationships. As shown in Figure 4-6, the total spawning habitat was highest for the FIRO-MAR strategy, followed by the Hybrid-MAR and Recharge Pool-MAR strategies under Level 2 and Level 3. Flows were more tightly managed to achieve WUA-based targets for spawning habitat under the FIRO strategies resulting in the greatest increases of instream spawning habitat. Modeled water temperature data were not available to inform this analysis. The inclusion of water temperature data would be expected to show greater vulnerability of salmonids to climate change than modeled by habitat quantity alone.

Figure 4-6 Instream Spawning Habitat Under 2040 Planning Horizon for each Flood-MAR Strategy



4.2.3 Potential Off-Channel Rearing Habitat

The off-channel inundation footprint along the Merced River decreases across all Flood-MAR strategies because of upstream diversion of high flows for recharge (see Table 4-1). Note that the current off-channel habitat on the Merced River has limited suitability for salmonid rearing given the lack of structure, cover, and vegetation that are important for rearing success. Because the quality of inundated habitat cannot be determined, this habitat is considered to be potential rearing habitat.

Level 1 strategies rely on passive approach to ecosystem management. Flood-MAR actions are limited to diverting a portion of available high flows for recharge. Impacts to the potential off-channel rearing habitat are inversely proportional to the upstream diversion of high flows. Because Level 1 Initial has the most restrictive high-flow diversion criteria, the potential off-channel rearing habitat was highest under Level 1 Initial, followed by the Level 1 Intermediate and Robust strategies.

Combining Flood-MAR actions with reservoir reoperation under the Level 2 and Level 3 strategies provided an opportunity to actively manage for ecosystem support. These strategies were designed to diversify ecosystem benefits while limiting potential impacts to salmonids resulting from flood flow reductions by targeting pulse flows. As a result, despite diverting 1.5 to 2 times the water for recharge under the Level 2 and Level 3 strategies, the potential off-channel habitat is similar to the Level 1 Intermediate and Robust strategies. For Levels 2 and 3, potential off-channel rearing habitat was highest under the FIRO-MAR compared to the Hybrid-MAR and Recharge Pool-MAR. Higher habitat amounts were associated with the implementation of the spring pulse flow under Level 2 and Level 3 FIRO-MAR and Hybrid-MAR and spring recessional flows and off-channel habitat improvements under the Level 3 FIRO-MAR strategy.

A monthly breakdown of the potential off-channel habitat shows that most of the potential rearing habitat is created during the winter months (January–March) under baseline and Level 1 strategies when high flows are incidentally available in the system (see Table 4-1). Level 2 and Level 3 strategies were designed to delay the inundation events to later in the spring season (April–May) and create the spring recessional flow component that was previously missing from the baseline operations. The targeted off-channel habitat inundation flows and improvement actions under Level 3 FIRO-MAR in April resulted in the highest monthly estimate of potential off-channel rearing habitat in acre-days across all Flood-MAR strategies and the baseline conditions.

Table 4-1 Potential Off-Channel Rearing Habitat (Acre-Days) Under 2040 Planning Horizon for each Flood-Mar Strategy

Month	Baseline	Level 1			Level 2			Level 3		
		Initial	Inter.	Robust	FIRO-MAR	Hybrid-MAR	Recharge Pool-MAR	FIRO-MAR	Hybrid-MAR	Recharge Pool-MAR
December	33,005	30,130	15,231	14,890	18,236	14,618	17,220	20,396	14,547	17,157
January	87,586	82,172	42,205	41,660	46,077	37,043	40,346	53,150	36,514	40,012
February	80,526	76,352	46,090	42,704	41,411	35,371	32,643	40,368	31,602	30,116
March	82,881	77,747	60,913	52,287	36,197	37,245	38,737	23,287	32,545	36,694
April	44,939	45,363	45,646	44,806	58,933	45,096	36,296	119,054	45,115	36,320
May	38,048	38,490	38,883	38,913	39,107	38,941	37,410	62,557	38,990	37,459
Dec – May Total	**366,985**	**350,254**	**248,968**	**235,260**	**239,961**	**208,314**	**202,652**	**318,812**	**199,313**	**197,758**

Notes: FIRO = forecast-informed reservoir operations; Inter. = intermediate; MAR = managed aquifer recharge

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4.2.4 Additional Managed Shorebird Habitat

For the Level 2 and Level 3 Hybrid-MAR and FIRO-MAR strategies, several field parcels with idle crop type overlaying poor and very poor SAGBI soil classification totaling 521 acres were fully or partially inundated at a depth of 2 inches for 28 days beginning on March 1 if water was available in the eco pool account (see Figure 4-2) to create suitable shorebird habitat. In 60 of the 100 years in the simulation period, managed shorebird habitat was created under the Level 2 and Level 3 FIRO-MAR strategy (see Table 4-2). Similarly, in 47 of the 100 years, managed shorebird habitat was created under the Level 2 and Level 3 Hybrid-MAR strategies.

Table 4-2 Total Number of Years with Additional Managed Shorebird Habitat Under 2040 Planning Horizon for each Flood-MAR Strategy

		Level 1			Level 2			Level 3		
	Baseline	Initial	Inter.	Robust	FIRO-MAR	Hybrid-MAR	Recharge Pool-MAR	FIRO-MAR	Hybrid-MAR	Recharge Pool-MAR
Number of Years	0	0	0	0	60	47	0	59	47	0

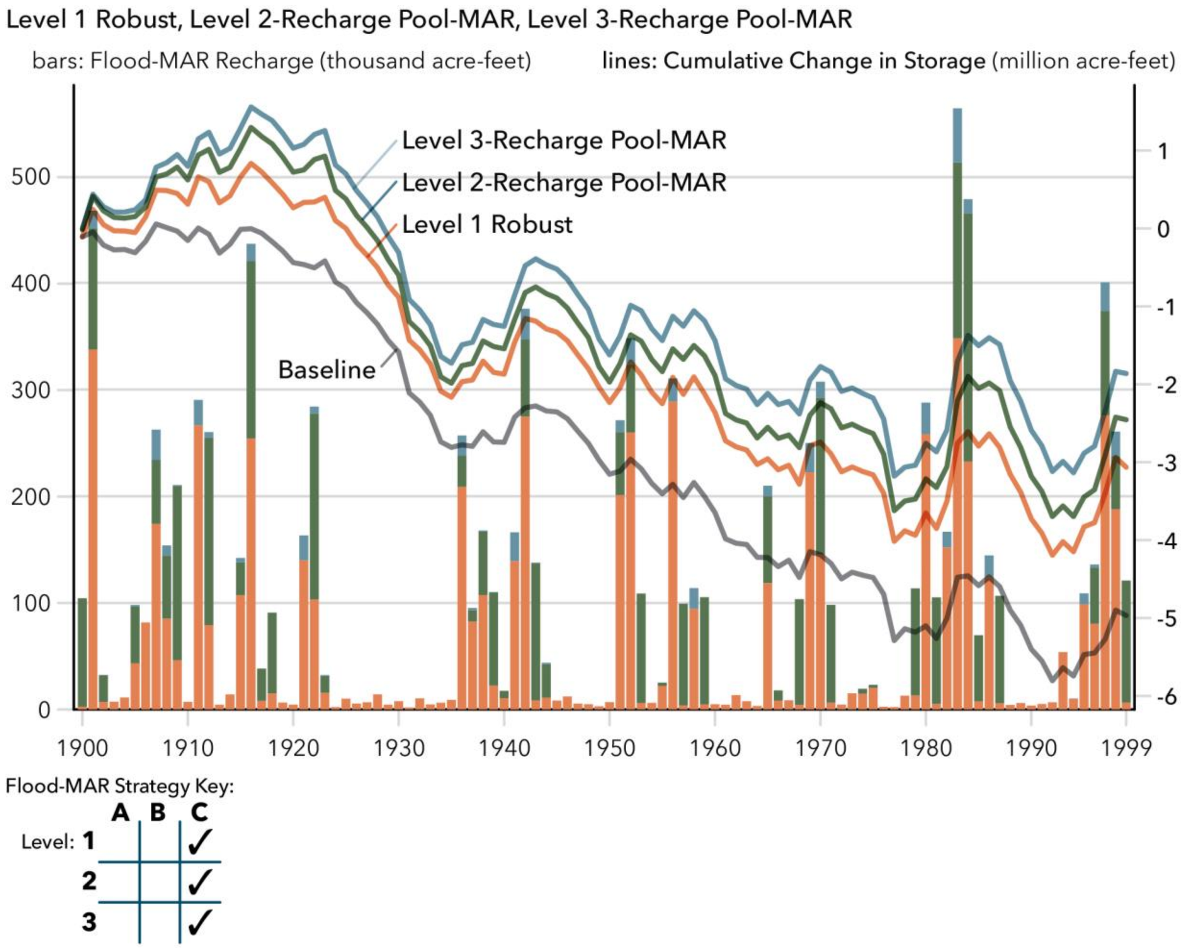
Notes: FIRO = forecast-informed reservoir operations; Inter = intermediate; MAR = managed aquifer recharge.

4.3 Flood-MAR Groundwater Management

4.3.1 Increasing Total Water Supply Through Recharge

Figure 4-7 displays the strategies with the highest recharge volume from each Flood-MAR strategy level to illustrate the additional resiliency with each tier of Flood-MAR. Each level introduces a new action to increase recharged water, from reoperating reservoirs to expanding infrastructure and turnout capacity. Even though reservoir reoperations for Flood-MAR result in a reduction of surface water supplies for irrigation in dry years, the volume of recharge on a basinwide scale exceeds the surface water supply reduction and a portion of recharged groundwater is pumped to make up for the loss in surface water supply. As the volume of recharged water increases, the rate of groundwater overdraft diminishes, with the highest recovery of groundwater storage conditions occurring in the Level 3 Recharge Pool-MAR strategy.

Figure 4-7 **Annual Recharge and Cumulative Change in Storage – Level 1 Robust and Level 2 and Level 3 Recharge Pool Under Current Climate Conditions**

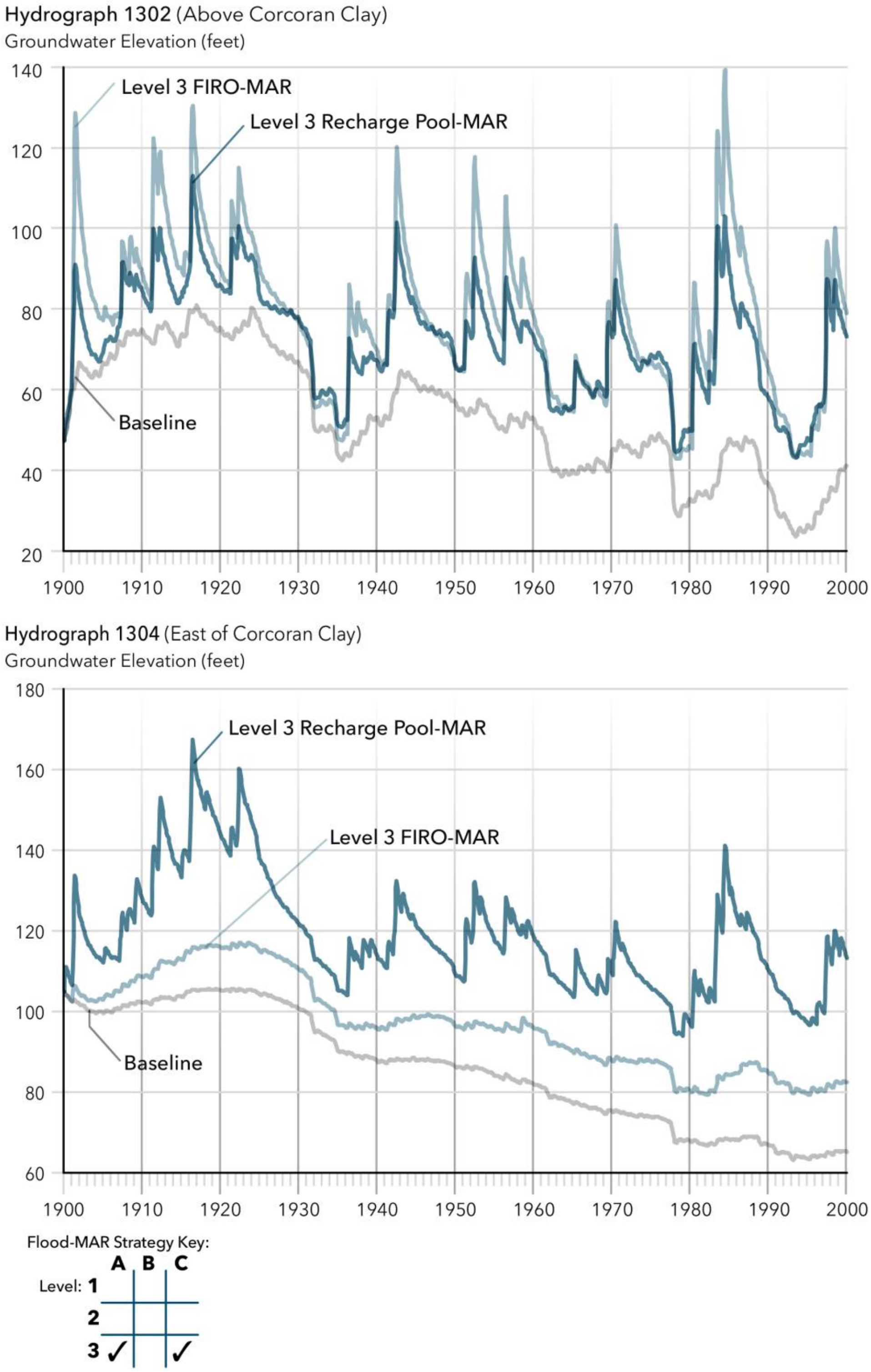


4.3.2 Groundwater Conditions in Recharge Management Areas

This study demonstrates that intentional placement of recharge can support management objectives and provide flexible water management. In the Level 2 and Level 3 FIRO-MAR strategies, which emphasize GDEs and discharge to streams, groundwater levels are higher closer to the Merced River, San Joaquin River, and adjacent GDEs, compared to the Hybrid-MAR and Recharge Pool-MAR strategies, even though the cumulative volume of basinwide recharge is lower. This difference can be seen for Hydrograph 1302 in Figure 4-8 by the higher groundwater elevations of the Level 3 FIRO-MAR strategy relative to the Level 3 Recharge Pool-MAR strategy above the Corcoran Clay near GDEs and the Merced River. Conversely, groundwater levels are higher near DACs and the center of the subbasin in the Level 2 and Level 3 Hybrid-MAR and Recharge Pool-MAR strategies, which have DACs and in-basin retention as management objectives, respectively. This difference can be seen for Hydrograph 1304 in Figure 4-8 by the higher groundwater elevations of the Level 3 Recharge Pool-MAR strategy relative to the Level 3 FIRO-MAR strategy east of the Corcoran Clay.

This variation in groundwater levels demonstrates that the intentional placement of Flood-MAR can help to achieve specific management objectives and subbasin priorities. In other words, where recharge occurs matters at certain times and spatial scales.

Figure 4-8 **Groundwater Levels near GDEs (Hydrograph 1302) and DACs (Hydrograph 1304) are Enhanced through Targeted Recharge Applications**



4.3.3 Fate of Recharged Water

The recharged water contributes to the stream systems and neighboring aquifers, in addition to in-basin groundwater storage. The range of distribution of the recharged water to groundwater storage, discharge to streams, and changes in subsurface flow to neighbors are presented as percentages on a pie chart in Figure 4-9. On average, assuming 100 years where conditions in all neighboring subbasins continue under existing pre-2015 Sustainable Groundwater Management Act (SGMA) operations, approximately one-third (27 to 37 percent) of recharged water remains in the Merced subbasin. Approximately one-fifth (14 to 22 percent) of recharged water is discharged back to the stream system. Increased groundwater levels from aquifer recharge can improve the hydraulic connection of the groundwater and stream system, which can potentially change losing streams to gaining streams in some water years and seasons or extend duration of gaining streams for a longer period. The remaining water (45 to 52 percent) leaves the Merced subbasin as subsurface flows to surrounding subbasins because of the gradient in groundwater levels.

Figure 4-9 Range of Fate of Recharged Water for all Flood-MAR Strategies Under Current Climate Conditions

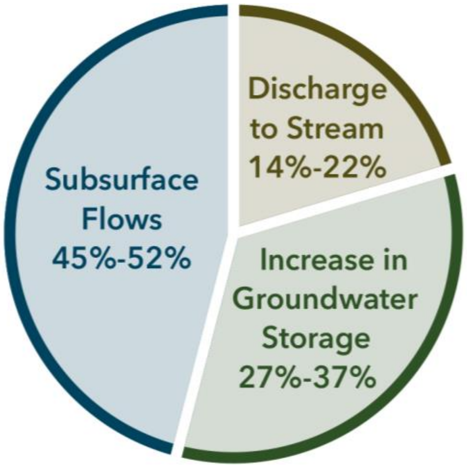
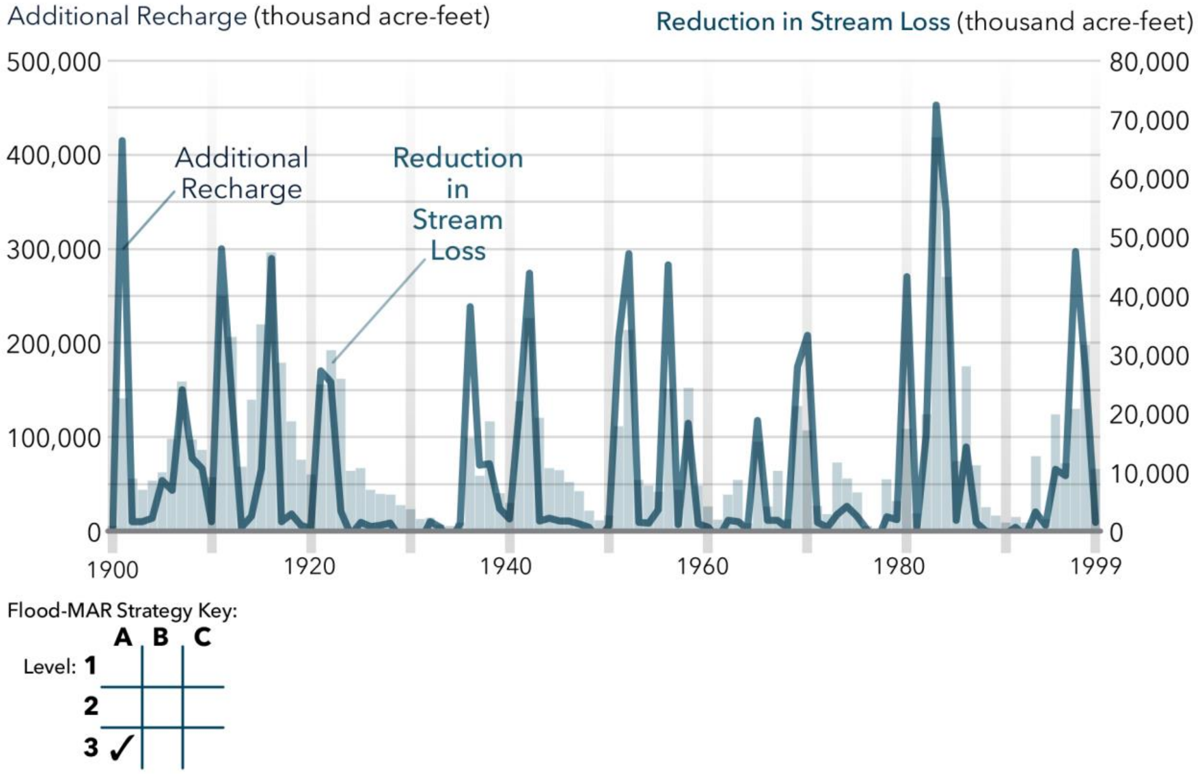


Figure 4-10 displays the temporal difference in stream-aquifer interactions relative to applied recharge. The reduction in stream loss represents the water that remains in the stream system under the Flood-MAR strategy, as opposed to leaving the stream and entering the groundwater or the additional water that will enter the stream from groundwater. Even in years with minimal Flood-MAR, streams retain water in the years following a large Flood-MAR event because of the extended increases in groundwater levels.

Figure 4-10 **Flood-MAR Contribution to Stream Time Series for Level 3 FIRO-MAR Under Current Climate Conditions**

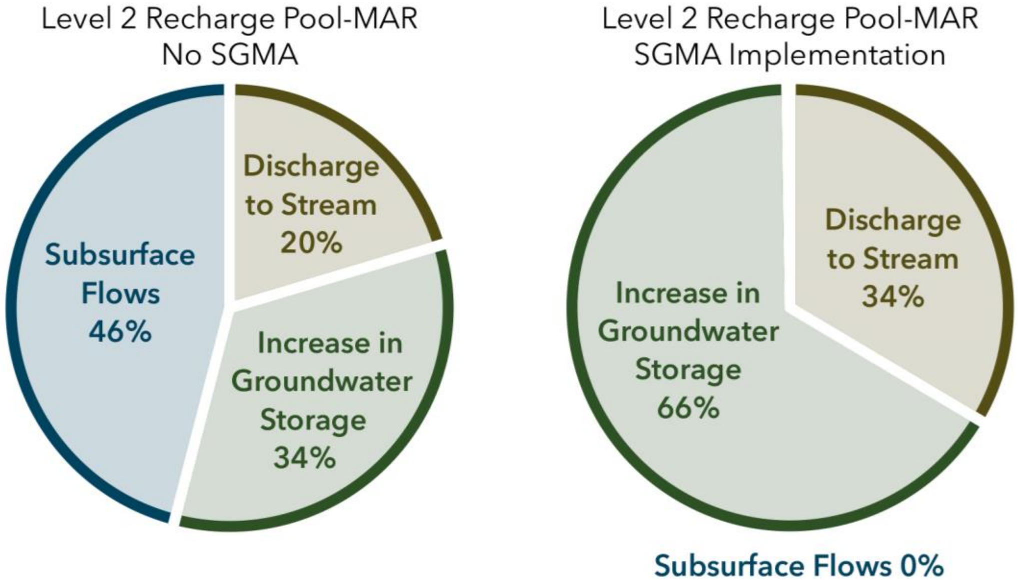


4.3.4 Effects of Sustainable Groundwater Management Act Implementation on Fate of Recharge

The average fate of recharge distribution described above assumes that the efforts to bring groundwater conditions under sustainable management are limited only to the Merced subbasin and that all neighboring subbasins are continuing under existing pre-SGMA operations. This results in continual groundwater decline outside of the Merced subbasin. As a result, the difference in groundwater levels is relatively higher between Merced and its neighbors and the efficiency of Flood-MAR in terms of groundwater retention within the Merced subbasin is reduced.

A SGMA implementation scenario was performed to simulate a sustainable condition in neighboring subbasins, where boundary groundwater levels are fixed to initial GSP-reported measurable objectives (note: these objectives were interpreted from GSPs prior to their final approval and adoption and thus may not reflect the latest GSPs). Under SGMA conditions for the Level 2 Recharge Pool-MAR strategy, approximately two-thirds of recharge remains in aquifer storage within the Merced subbasin and one-third discharges to the stream, with negligible contribution of recharge to subsurface flows (see Figure 4-11). Whereas the pre-SGMA condition provides a relatively conservative estimate of the efficiency of Flood-MAR, the SGMA scenario presents an optimistic bookend, demonstrating how subbasins would benefit from working together to achieve groundwater sustainability.

Figure 4-11 Fate of Recharge Water for With and Without Neighboring SGMA Implementation Scenarios



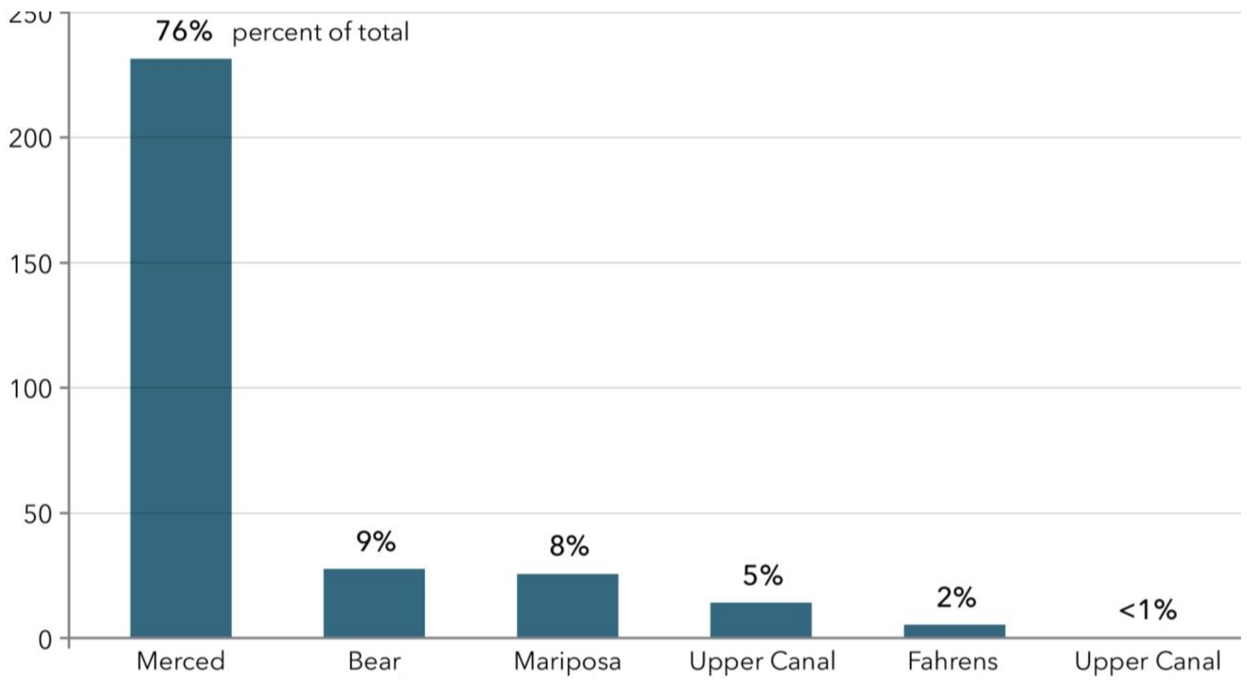
4.4 Recharge Management (Conveyance and Distribution)

Recharge is an essential element of a Flood-MAR strategy. Many benefits of Flood-MAR strategies are provided by the volume and location of the managed aquifer recharge.

4.4.1 WAFR Source

WAFR is available from the Merced River and several local creeks that originate in the foothills east of MID and flow into and through the district. Figure 4-12 illustrates the WAFR available by source for a typical wet year when the majority of the watershed’s overall WAFR (over the span of 100 years) is available. Merced River provides most (76 percent) of the total watershed WAFR in wet years. The local creeks are ephemeral in nature and can remain dry part of the year but collectively can provide up to 24 percent of the total WAFR in wet years and more frequently from these largely unregulated and rainfed watersheds.

Figure 4-12 **Percentage of Total WAFR by Source in a Wet Year**



4.4.2 WAFR Utilization

Figure 4-13 shows how the total cumulative volume of WAFR changes with various climate conditions and Flood-MAR strategy levels. Approximately 90 to 99 percent of WAFR can be recharged (“used” WAFR) even under future climate conditions and higher-level strategies where the total volume of WAFR increases.

Figure 4-13 100-Year Cumulative WAFR for Level 1 Intermediate, Level 2 FIRO-MAR, and Level 3 Recharge Pool-MAR Strategies (Current and 2040 Planning Horizon)

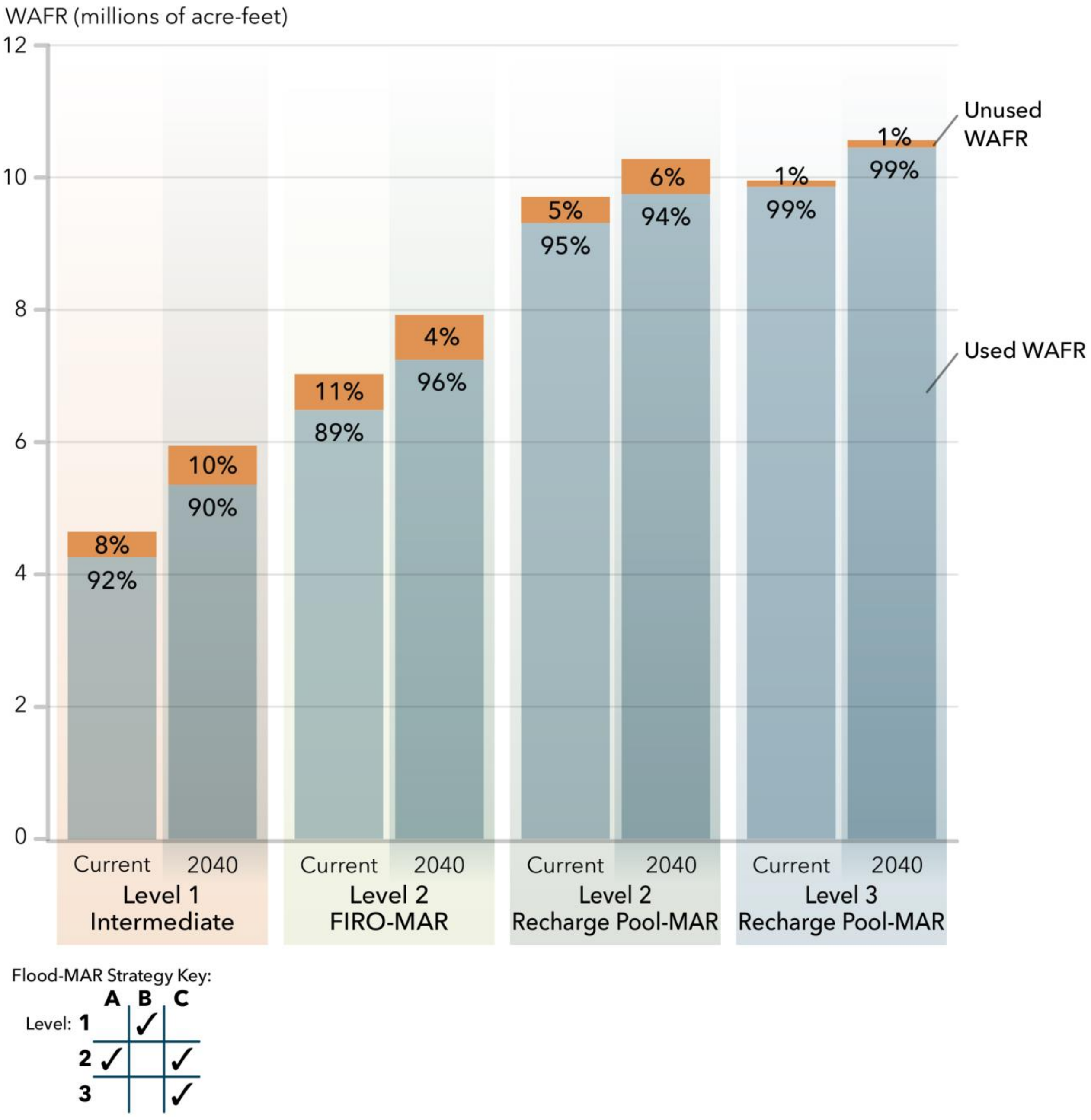


Table 4-3 provides the average annual and maximum annual applied recharge. The amount of applied recharge increases under higher levels of Flood-MAR and with climate change because of the increasing opportunities for recharge and the shift in runoff to earlier during the flood management season.

Table 4-3 **Average Annual and Maximum Annual Applied Recharge Under Current Climate and 2040 Planning Horizon Conditions (Thousand Acre-Feet)**

	Level 1			Level 2			Level 3		
	Initial	Inter.	Robust	FIRO-MAR	Hybrid-MAR	Recharge Pool-MAR	FIRO-MAR	Hybrid-MAR	Recharge Pool-MAR
Current Climate									
Average Annual	16.5	47	70	74	94	99	71	97	101
Maximum Annual	73	305	428	485	515	567	473	540	592
2040 Planning Horizon									
Average Annual	18.5	59	84	84	103	105	81	106	108
Maximum Annual	75	376	458	525	540	575	525	565	600

Notes: FIRO = forecast-informed reservoir operations; Inter = intermediate; MAR = managed aquifer recharge.

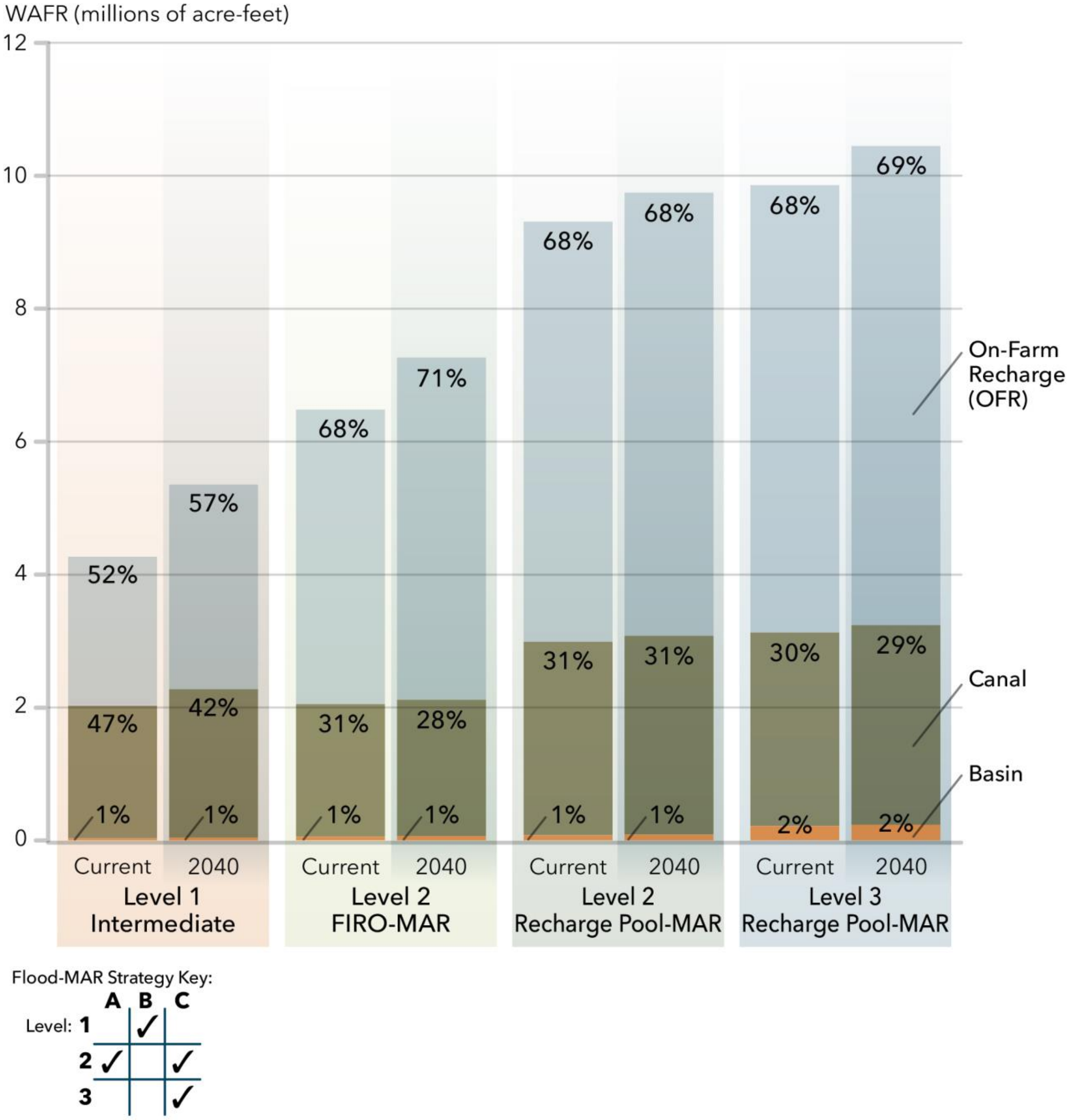
The comparison of both Level 2 and Level 3 Recharge Pool-MAR strategies illustrates the effect of the infrastructure investments that help increase the total volume of WAFR with improvements such as additional or increased diversion capacity from local creeks and reduction of the percentage of unused WAFR with investments in conveyance and dedicated recharge basins.

4.4.3 Recharge Type

The study utilized a combination of unlined canals, OFR, and dedicated recharge basins to get WAFR into the aquifer. Figure 4-14 illustrates how WAFR is recharged across these methods. Results show the unlined canal network traditionally used to deliver irrigation water also can be used for recharge during the winter season. Canals can be important avenues for recharge because they are often owned and operated by a single agency that can simplify coordination and operations and there is no risk to existing crops. But, the use of canals may require changes to scheduled maintenance and improvement projects that are typically completed during the non-irrigation season. The results also show how OFR can be scaled up in response to increased WAFR. Recharge through canals increases slightly with increased WAFR, and OFR increases by a factor of three from Level 1 to

Level 3 Flood-MAR strategies. Meanwhile, the use of dedicated recharge basins increases only slightly under Level 3 strategies, although this is dependent on the assumption of the size of investment in new recharge basins for the watershed.

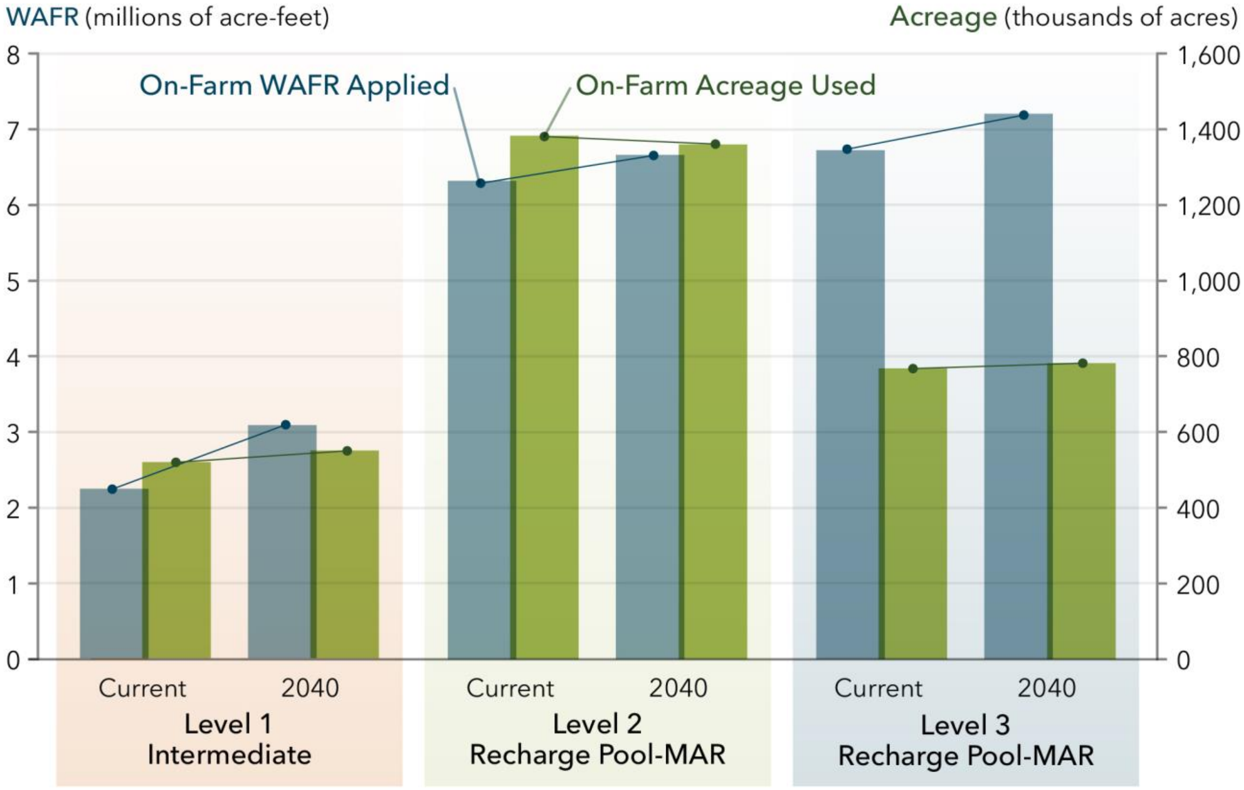
Figure 4-14 100-Year Cumulative Applied WAFR by Recharge Type Under Level 1 Intermediate, Level 2 FIRO-MAR, and Level 3 Recharge Pool-MAR Strategies (Current and 2040 Planning Horizon)



4.4.4 Recharge Efficiency

Figure 4-15 shows the cumulative volume of OFR recharge and acreage used to accomplish that recharge over the 100-year simulation period. The volume of recharge more than doubles under Level 2 and Level 3 strategies, but investment in conveyance and turnout capacity in the Level 3 strategy increases the volume of water applied on the best available fields for recharge. Accordingly, the recharge intensity (acre-foot recharge per acre used) increases, allowing more water to recharge with a smaller farm acreage footprint. This is an important consideration for implementing Flood-MAR if grower participation is limited.

Figure 4-15 100-Year Cumulative On-Farm Recharge and On-Farm Acreage Used under Level 1 Intermediate and Level 2 and Level 3 Recharge Pool-MAR Strategies (Current and 2040 Planning Horizon)



Flood-MAR Strategy Key:

Level	A	B	C
1		✓	
2			✓
3			✓

Chapter 5. Conclusions and Key Findings

5.1 Flood Risk Reductions

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, although minor flooding and flood risk is still a possibility. Flood risk is increased under potential future climate conditions and can 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 (see Figure 4-1). The existing diversion and conveyance facilities were designed for irrigation and lack the capacity to significantly reduce peak events. Level 2 and Level 3 strategies that include changes in reservoir operations reduce flood risk by reducing encroachment into Lake McClure’s flood control reservation space (see Table 3-1). These Flood-MAR strategies provide the most flood risk reduction benefits under these potential future conditions (see Table 3-3 and Figure 4-2, Figure 4-3, and Figure 4-4).

5.2 Net Increase in Water Supply

Additional recharge is needed to support current and projected levels of groundwater reliance by increased agricultural evapotranspiration demands within the Merced subbasin. All Flood-MAR strategy levels can improve water supply resilience by providing additional recharge, with higher levels of Flood-MAR strategies increasing the volume of water that can be recharged (see Table 3-1 and Table 3-3). Changes to reservoir operations expand water supply benefits by increasing the opportunities for water to be released at a rate that maximizes recharge (and Figure 4-2, Figure 4-3, and Figure 4-4). These operations improve the total water supply of both surface and groundwater, although recharge pool operations tend to increase the number of years when reservoirs do not refill, and subsequent year’s surface water deliveries may be affected.

Groundwater conditions within a subbasin and the surrounding subbasins have a significant impact on the outcome of Flood-MAR strategies. The study evaluated Flood-MAR strategies within the Merced subbasin independent of changes in water supplies and demands in neighboring subbasins that would be necessary to achieve groundwater sustainability. Results show that approximately one-third of recharged WAFR remains within the Merced subbasin and one-half recharged WAFR would flow (subsurface) to neighboring subbasins if they are not managed sustainably (see Figure 4-9). In the SGMA scenario where neighboring subbasins are managed to the measurable objectives in their groundwater sustainability plans, the portion of the recharged WAFR that remains within the Merced subbasin almost doubles (see Figure 4-11).

5.3 Ecosystem Support

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 their potential impacts. The results show that Flood-MAR strategies can benefit non-aquatic species such as shorebirds and GDEs that rely on groundwater and surface water affected by recharge actions. There are also some indirect benefits of improved groundwater conditions that will 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 managed recharge occur after the recharge actions and improve river flows in the summer and future droughts (see Figure 4-9).

Aquatic species reliant on instream flows may see both benefits and impacts from Flood-MAR. Flood-MAR operations increase diversion from the surface water system, but diversions can occur at times and volumes that minimize impacts. Impacts to aquatic species can be partially offset by better managing reservoir operations 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 both in the aquifer and the FIRO pool (i.e., encroachment into the flood space) and can dedicate water left in the FIRO pool toward ecosystem goals.

5.4 Recharge

5.4.1 Water Available for Recharge

Multiple factors influence the amount of water potentially available for recharge. This study considered the effects of climate, watershed runoff, season, location, diversion threshold, applied water demands, environmental needs, and downstream Sacramento-San Joaquin River Delta conditions. Approximately 65 to 85 percent of the total WAFR volume in the Merced watershed is provided by the Merced River, particularly in wetter years with above average runoff (see Figure 4-7 and Figure 4-12). Smaller, local creeks provide the remaining 15 to 35 percent of the WAFR volume, and this water can remain available in years with below average runoff. There is considerable variability in the timing of WAFR. Reservoir operations can help manage the interannual and daily variability to increase opportunities — and thus the volume — of water available for recharge (see the increase in WAFR with Level 2 strategies as compared to Level 1 in Figure 4-13).

5.4.2 Location of Recharge

WAFR can be applied in multiple ways and places. This study considered unlined conveyance facilities, working agricultural lands, and dedicated recharge basins. Existing canal networks provide substantial temporary storage space and capacity for recharge (see Figure 4-14). Although canals can be used without some of the challenges of OFR, canal maintenance often occurs during months when water is available for recharge. Recharge capacity is significantly increased when OFR is included. Factors such as the daily availability of water, diversion and conveyance capacity, hydro-geologic site suitability, and crop compatibility were included in the analysis to better understand limitations associated with OFR. In addition, the location of recharge is important, and targeted recharge can focus benefits on select objectives such as providing water supply for DACs, limiting subsidence, or maintaining water levels below GDEs (see Table 3-1, Table 3-3, and Figure 4-8).

5.4.3 Infrastructure Expansion

Level 3 Flood-MAR strategies revealed how investments in infrastructure can change the benefits and implementation of Flood-MAR. Investments in infrastructure to increase conveyance and recharge capacity will increase recharge by utilizing greater proportions of WAFR (see Figure 4-13).

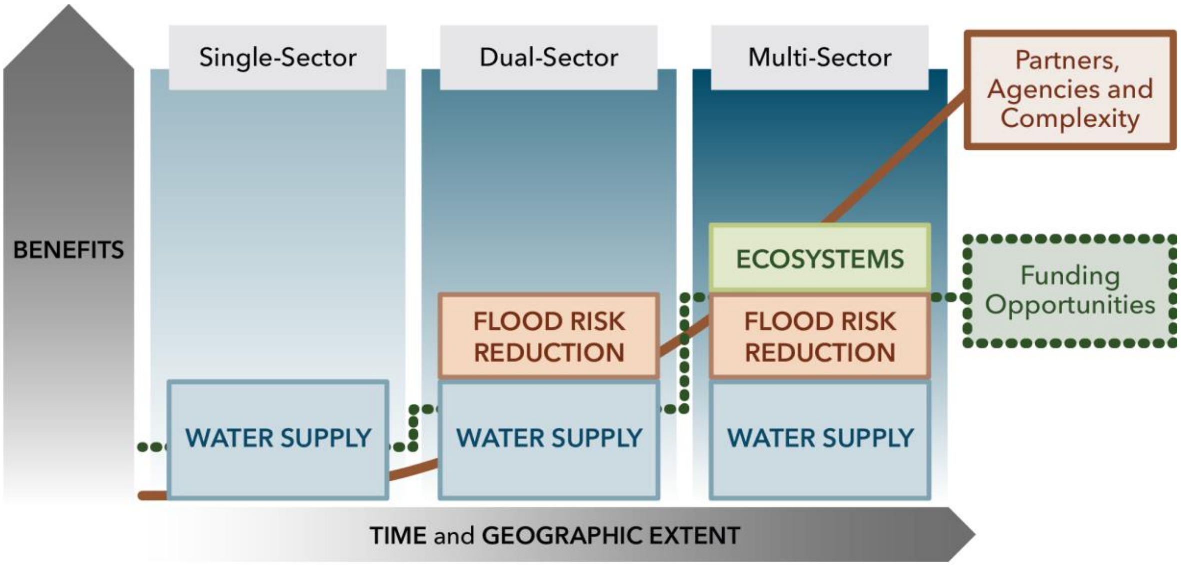
The turnout capacity — or the capacity to release water from the conveyance system onto a field — is a primary constraint for application of WAFR. Expanding turnout capacity from what is typically used for irrigation allows more water to be recharged using fewer sites (see Figure 4-15).

This study assumed a willingness by all landowners within Merced ID to participate in Flood-MAR. Results show that investments in infrastructure, such as increased turnout capacity, can accomplish the same recharge with significantly fewer fields. This type of infrastructure investment can be used to maximize recharge for willing landowners.

5.5 Multi-Sector Implementation for Watershed Resilience

Flood-MAR strategies are robust and provide multi-sector benefits under a wide range of future climates (see Table 3-1 and Table 3-3). Flood-MAR strategies take advantage of wetter periods and cycles to store water in groundwater subbasins that provide resilience during increasingly dry cycles. The multiple levels of Flood-MAR analyzed in the study demonstrate that the strategies are scalable — both spatially and temporally — which allows flexibility in adapting to future climates. Figure 5-1 illustrates the concept of starting with small projects and expanding to a watershed-scale program over time.

Figure 5-1 **Flood-MAR Strategies Scale in Time and Space to Expand Benefits and Access to Funding with Increased Complexity**



A local water agency can implement a simple Flood-MAR project by recharging water through existing conveyance facilities. Expanding this concept to a region, partnering with landowners, and bringing in reservoir operators and flood control agencies can increase and diversify benefits. Broad coalitions that add environmental interests and partners at a watershed scale can create multi-sector benefits, increase access to funding, and further build support for implementation as the complexity of the program expands. At a watershed scale, Flood-MAR allows consideration of multi-sector challenges and can provide multi-sector opportunities.

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Appendix A

Multi-Sector Performance of Flood-MAR Strategies under Climate Change Conditions (Expected Values at Planning Horizon 2070)

Table A-1 **Multi-Sector Performance of Flood-MAR Strategies under Climate Change Conditions (Expected Values at Planning Horizon 2070)**

				Level 1			Level 2			Level 3		
Sector / Metric	**Indicator**	**Units**	**2070 Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid -MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Flood-MAR Recharge	Average annual recharge from Flood-MAR strategies.	taf/year	0	21	65	87	85	104	107	89	114	118
Flood Risk:												
Lake McClure	Maximum encroachment at Lake McClure (Nov 1 – Mar 15).	Percent	87	87	87	87	81	78	69	81	78	69
Merced River	Merced River 100-year maximum simulated flow (Nov 1 – Jun 30).	cfs	29,327	29,308	28,222	26,972	18,506	17,027	15,105	18,312	16,627	14,765
	Total number of years Merced River at Crocker-Huffman Diversion Dam is above 7,300 cfs (Nov 1 – Jun 30).	Years	5	5	5	5	3	3	2	2	3	2
Local Creeks	Bear Creek 100-year maximum simulated outflow.	cfs	15,382	13,903	13,918	14,075	13,990	13,905	13,905	11,832	13,805	13,810

				Level 1			Level 2			Level 3		
Sector / Metric	**Indicator**	**Units**	**2070 Baseline**	**Initial**	**Inter-mediate**	**Robust**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**	**FIRO-MAR**	**Hybrid-MAR**	**Recharge Pool-MAR**
Water Supply / Groundwater:												
Δ GW Storage	Basinwide average annual change in groundwater storage.	taf/year	-101	-93	-80	-75	-77	-71	-69	-78	-69	-66
Δ GW Levels	Average annual change in groundwater levels in subsidence prone region.	feet/year	-1.3	-1.3	-1.2	-1.2	-1.2	-1.1	-1.1	-1.2	-1.1	-1.1
	Average annual change in groundwater levels in aquifer underlying DACs east of Corcoran Clay layer.	feet/year	-1.3	-1.2	-0.9	-0.7	-0.8	-0.6	-0.6	-0.8	-0.5	-0.5
GW Pumping	Average annual total groundwater pumping to meet agricultural uses in the Merced watershed.	taf/year	515	515	516	516	519	521	523	519	521	523
Water Supply / Surface Water:												
SW Deliveries	Average annual total surface water deliveries to agricultural users in the Merced watershed.	taf/year	359	359	359	359	356	354	352	356	354	352
	Number of years MID's surface water availability is at or below 80 percent.	Years	12	12	13	13	14	14	16	14	14	16

Sector / Metric	Indicator	Units	2070 Baseline	Level 1 Initial	Level 1 Inter-mediate	Level 1 Robust	Level 2 FIRO-MAR	Level 2 Hybrid-MAR	Level 2 Recharge Pool-MAR	Level 3 FIRO-MAR	Level 3 Hybrid-MAR	Level 3 Recharge Pool-MAR
Lake McClure	Average annual Lake McClure storage at the end of the irrigation season (Oct 31).	taf/year	436	436	436	436	432	416	395	433	416	395
Ecosystem:												
GDE Habitat	Proportion of months with depth to groundwater less than 30 feet.	Percent	50	51	55	57	56	56	56	58	57	56
Salmonid Habitat	Merced River instream salmonid spawning habitat (Sep – Apr).	Thousand acre-days	492	492	492	509	647	641	616	648	642	616
	Potential Merced River off-channel juvenile rearing habitat during qualified events (Dec – May).	Thousand acre-days	501	477	349	331	348	312	295	339	300	287
Shorebird Habitat	Number of years with additional managed shorebird habitat.	Thousand acre-days	0	0	0	0	57	46	0	58	46	0

Notes: cfs = cubic feet per second; DAC = disadvantaged community; feet/year = feet per year; FIRO = forecast-informed reservoir operations; GDE = groundwater-dependent ecosystem; GW = groundwater; MAR = managed aquifer recharge; MID = Merced Irrigation District; SW = surface water; taf/year = thousand acre-feet per second.

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