Managing Aquifer Recharge to Overcome Overdraft in the Lower American River, California, USA

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Supplementary Information

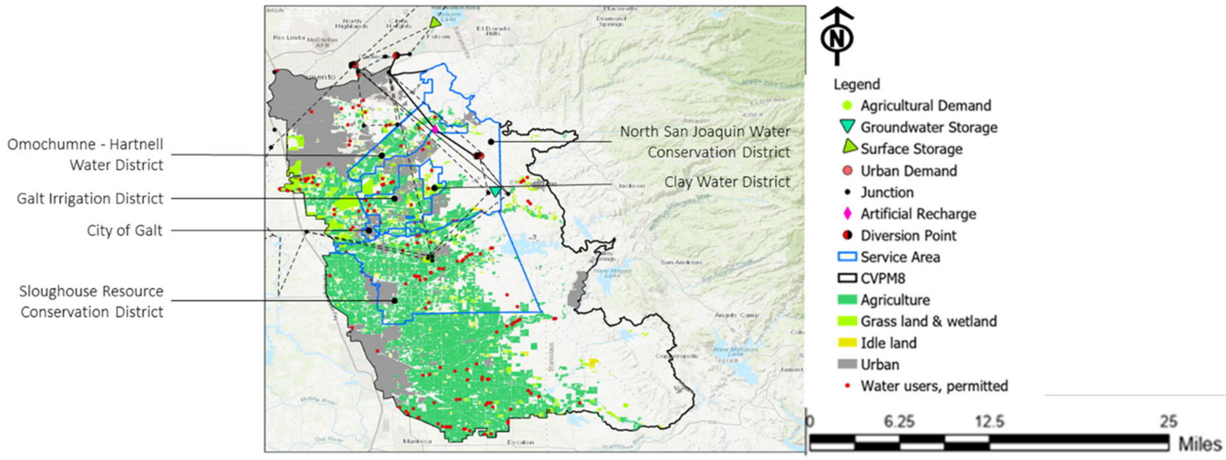

Figure S1. Service areas that with potential benefits from a new recharge facility.

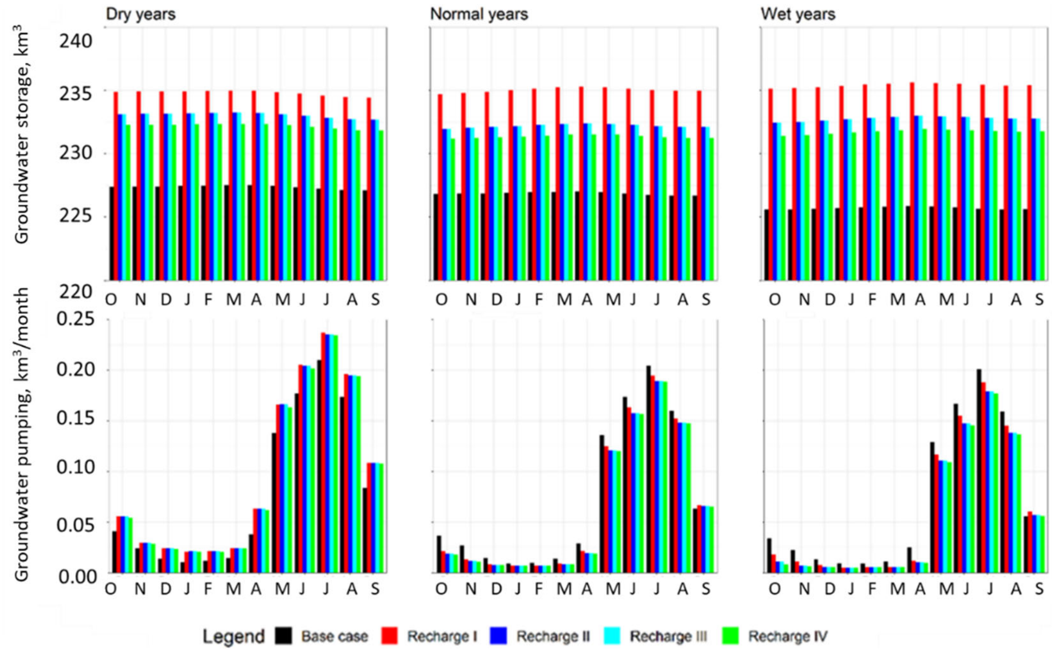

Figure S2. Bar graphs showing average monthly groundwater storage and pumping for different scenarios in dry, normal, and wet water years

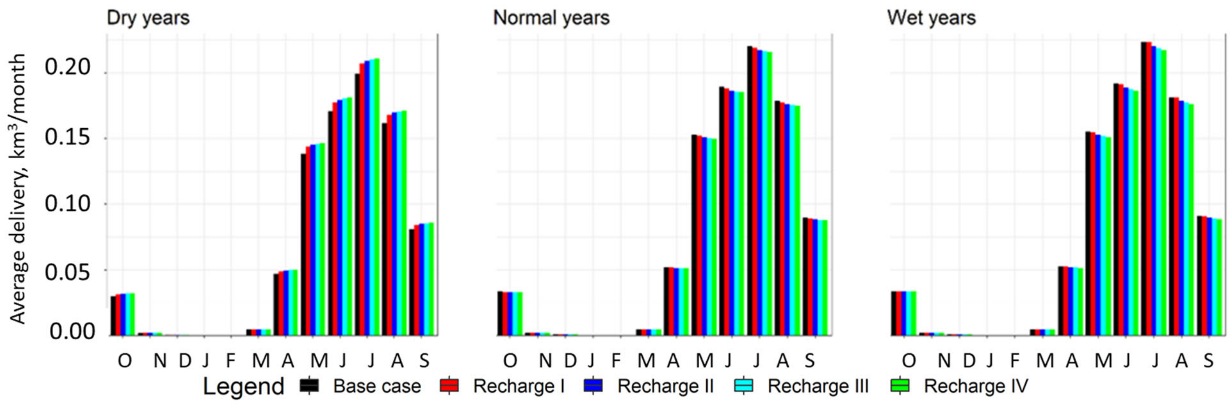

Figure S3. Monthly agricultural water delivery to service area shown in Figure S1

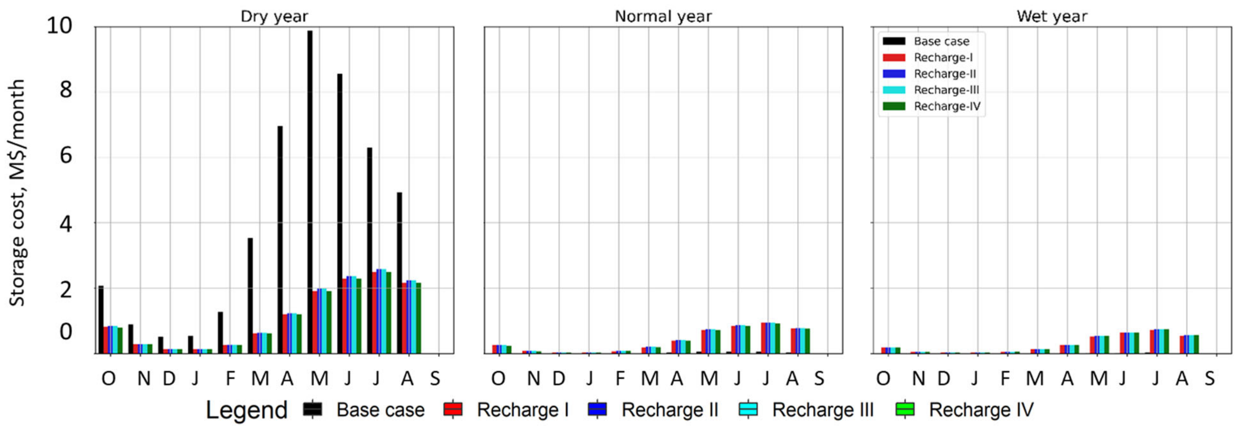

Figure S4. Bar graphs of surface water storage cost in dry, normal, and wet water years for different conditions

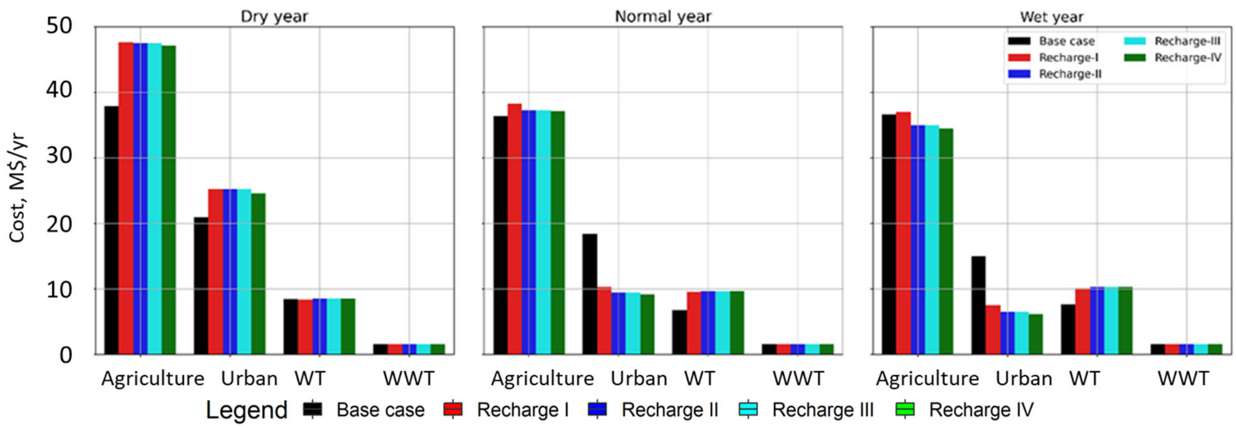

Figure S5. Breakdown of cost to operate water infrastructure facilities below the American River in different water years. WT: Water treatment and WWT: Wastewater treatment

Table S1. Previous applications of CALVIN since its inception.

Author and year	Description
Jenkins et al. (2001)	reviewed the development, calibration, and limitations to confirm its suitability to dictate water availability among different users constrained by water management, policy, and operation planning in California
Newlin (2002)	investigated the economic reliability of importing water from the Colorado River Aqueduct to Southern California
Tanaka and Lund (2003)	Studied the economic effects of Delta export on the Sacramento Valley
Medellin-Azuara (2006)	integrated hydrology, water demands, hydraulic infrastructure, institutional policies, and physical constraints in the Colorado River Delta in the regional water allocation model
Lund et al. (2007)	explored long-term statewide water supply adaptations to Delta water availability changes by increasing the minimum Sacramento-San Joaquin Delta outflow requirement and reducing water exports
Lund (2008)	established an economically promising water supply portfolio for the Delta to respond to future economic, population, climate, policy, and infrastructure conditions
Lund et al. (2010)	explored the CALVIN model's perfect foresight version in managing the Delta water system specific to Tulare Lake Basin underwater supply and demand changes
Tanaka et al. (2006)	described the CALVIN model's applicability in studying the influence of long-term climatic and demographic changes in California's water system
Medellin-Azuara et al. (2009, 2008)	reassessed the economically optimal operational changes and adaptations to cope with water scarcity from the drier climate
Connell (2009)	utilized the CALVIN framework to compare two climate scenarios: a) warmer-drier conditions and b) warmer conditions without any change in total runoff and to predict earlier snowmelt and peak storage and significant management adaptation to both climate scenarios
Harou et al. (2010)	incorporated water trades in the CALVIN model to estimate economic costs and effects on water operations and demands that impose severe burdens on the

	agricultural sector and environmental water uses under prolonged drought
Ragatz (2013)	analyzed the 2050 projected climate and its impact on urban water conservation in addition to Delta export capacity, conjunctive use, salt intrusion, and water recycling.
Sicke et al. (2013)	elucidated the impacts of a severely warmer and drier climate on water supply and discussed the consequences of sea-level rise in the San Fransisco Bay Area
Medellin-Azuara et al. (2007)	estimated operating and water scarcity costs, water scarcity volumes, and marginal economic costs of environmental flows using the CALVIN model for better water supply options and assess the trade-off curves between agricultural and urban economic value and environmental flows
Medellin-Azuara et al. (2008)	used this model to quantify water export's economic value in the South of the Sacramento-San Joaquin Delta
Hersh-Burdick (2008)	investigated the water supply delivery and financial implications of different groundwater management strategies below the Cosumnes River, impacted by the significant development in the 1950s onwards
Harou and Lund (2008)	demonstrated the CALVIN model's capability to analyze the economic effects and water management actions to end overdrafts and quantify its economic costs
Nelson et al. (2016)	studied the effects of ending groundwater and highlighted some economic and policy issues about groundwater usage in a sustainable manner
Dogan et al. (2019)	incorporated the 82-years of hydrology and drainage from the Delta into San Francisco Bay-Delta to assess the effects of overdraft and Delta policies on existing and expanding infrastructure capacities
Dogan (Dogan, 2015)	employs the CALVIN model's revised variant and investigates hydropower revenues from the major dams so that agriculture and urban users do not get less water
Khadem et al. (2018)	introduce economic carryover storage value functions (COSVFs) in the perfect foresight version of the CALVIN to maximize the inter-annual benefits from river basin operations

Table S2. List of water infrastructure facilities within the area around the American River

Designation	Description
A207	Agriculture demand area at CVPM region 8
GW_08	Groundwater basin at CVPM region 8
HGP08	Pumping Facility near CVPM region 8
C173	South Folsom Canal diversion to Mokelumne River
D9	Lake Natomas, where the Hydropower station is located
D85	American River losses
D507	Sacramento River Diversion
D509	Sacramento River towards Delta
D517	CVPM 8 return to Mokelumne River
D515	Confluence of Mokelumne River with Delta
HGP08	Pumping facility at CVPM region 8 for agriculture and urban delivery
HGR08	Calibration node for GW_08
HP207	Diversion node to urban
HSU207C173	Folsom South Canal diversion to CVPM region 8
RECH8	Artificial recharge near CVPM region 8 after South Folsom Canal
SR_FOL	Folsom Lake
U207	Urban demand area at CVPM region 8, representing City of Galt
WTP207	Water treatment plant for CVPM region 8
WWP207	Wastewater treatment for CVPM region 8 for the town of Galt
WTP207	Water treatment plant for CVPM region 8
WTP204	Water treatment plant for CVPM region 7

Table S3. Marginal values and the opportunity cost of surface water storage in \$/ m^3

Scenarios	Dry years		Normal years		Wet years	
	Marginal values	**Opportunity cost**	**Marginal values**	**Opportunity cost**	**Marginal values**	**Opportunity cost**
Base case	2.33	0.20	0.02	<0.01	<0.01	<0.01
Recharge - I	0.50	0.08	0.11	0.06	0.06	0.06
Recharge - II	0.51	0.08	0.11	0.06	0.06	0.06
Recharge - III	0.51	0.08	0.11	0.06	0.06	0.06
Recharge - IV	0.50	0.08	0.11	0.06	0.06	0.06

Table S4. Annual average deep percolation and additional recharge over different water years.

Scenario	Deep percolation, km³/yr			Recharge flow, km³/yr		
	Dry	Normal	Wet	Dry	Normal	Wet
Base case	0.237	0.260	0.263			
Recharge-I	0.254	0.258	0.262	0.000	0.249	0.202
Recharge-II	0.253	0.254	0.254	0.035	0.174	0.194
Recharge-III	0.253	0.254	0.254	0.035	0.174	0.194
Recharge-IV	0.252	0.253	0.253	0.006	0.127	0.188

Table S5. Mass balance at Folsom dam (SR_FOL). All quantities are in m^3

Month	Base case					Recharge case (Recharge-IV)				
	Inflow	Outflow	Storage	Evaporation	Change in storage	Inflow	Outflow	Storage	Evaporation	Change in storage
	I	O	S	E	ΔS	I	O	S	E	ΔS
10/1987	70,308	74,761	206,936	1,017	-5,470	70,308	488,634	531,357	2,611	-420,936
11/1987	83,877	64,229	226,221	363	192,86	83,877	185,919	428,628	687	-102,729
12/1987	191,189	64,893	352,210	307	125,989	191,189	64,893	554,441	483	125,813
1/1988	219,559	64,153	507,190	426	154,980	219,559	64,153	709,251	596	154,810
2/1988	107,313	59,568	554,080	855	46,890	107,313	106,218	709,252	1,094	1
3/1988	125,815	60,305	617,688	1,902	63,608	125,815	60,305	772,384	2,379	63,132
4/1988	134,449	65,131	683,550	3,456	65,862	134,449	56,867	845,691	4,275	73,307
5/1988	97,445	226,959	550,280	3,756	-133,270	97,445	60,181	876,968	5,986	31,277
6/1988	54,273	254,705	346,787	3,061	-203,493	54,273	58,594	865,011	7,636	-11,957
7/1988	30,837	129,646	245,379	2,599	-101,408	30,837	60,675	826,421	8,753	-38,590
8/1988	34,537	68,939	209,079	1,899	-36,301	34,537	60,675	793,081	7,203	-33,340
9/1988	70,308	66,982	212,405	0	3,327	70,308	58,717	80,4672	0	11,591

Table S6. Mass balance at the groundwater basin (GW_08). All quantities are in m^3

Month	Base case				Recharge case (Recharge-IV)			
	Inflow	Outflow	Storage	Change in storage	Inflow	Outflow	Storage	Change in storage
10/1987	59,267	30,933	2.253E+08	28,334	59,267	56,987	2.334E+08	2,280
11/1987	50,860	12,376	2.253E+08	38,485	50,860	30,431	2.335E+08	20,429
12/1987	55,636	9,897	2.254E+08	45,738	55,636	9,897	2.335E+08	45,738
1/1988	46,239	9,863	2.254E+08	36,376	46,239	9,862	2.336E+08	36,376
2/1988	47,903	12,816	2.254E+08	35,087	47,903	19,255	2.336E+08	28,649
3/1988	54,130	22,116	2.255E+08	32,014	54,130	22,116	2.336E+08	32,013
4/1988	68,743	38,199	2.255E+08	30,545	68,743	45,471	2.336E+08	23,272
5/1988	77,030	143,017	2.254E+08	-65,987	77,030	160,800	2.336E+08	-83,770
6/1988	85,844	208,131	2.253E+08	-122,287	85,844	215,404	2.334E+08	-129,560
7/1988	100,361	239,696	2.252E+08	-139,335	100,361	246,968	2.333E+08	-146,608
8/1988	89,523	186,771	2.251E+08	-97,248	89,523	206,378	2.332E+08	-116,856
9/1988	77,643	77,406	2.251E+08	237	77,643	118,599	2.331E+08	-409,56

Table S7. Parameters to calculate surface water storage cost for under different recharge scenarios. This table lists the monthly average of upper duals or opportunity costs of surface water and the range of monthly evaporation for different water year types.

Water years	Parameters	Statistics	Base case	**Recharge scenarios**			
				I	II	III	IV
Dry	Upper dual, \$/m^3	Average	2.26	0.27	0.28	0.28	0.27
	Evaporation range, $\times 10^{-3}$ km^3	Minimum	0.00	0.30	0.30	0.30	0.30
		Maximum	10.71	11.31	11.31	11.31	11.31
Normal	Upper dual, \$/m^3	Average	<0.01	0.09	0.09	0.09	0.09
	Evaporation range, $\times 10^{-3}$ km^3	Minimum	0.00	0.07	0.12	0.12	0.11
		Maximum	12.35	12.29	12.29	12.29	12.29
Wet	Upper dual, \$/m^3	Average	<0.01	0.06	0.06	0.06	0.06
	Evaporation range, $\times 10^{-3}$ km^3	Minimum	0.00	0.17	0.17	0.17	0.17
		Maximum	12.20	12.20	12.20	12.20	12.20

Table S8. Key hydroeconomic metrics for different scenarios in dry years.

Hydroeconomic metrics	Base case	Recharge scenarios			
		I	II	III	IV
Surface water storage, km^3/yr	0.36	0.81	0.81	0.81	0.81
Hydropower generation, MWh/yr	444.20	529.72	529.83	529.83	529.63
Hydropower revenue, M$/yr	10.31	12.87	12.90	12.90	12.87
Groundwater storage, km^3/yr	227.38	234.81	233.08	233.08	232.21
Groundwater pumping, km^3/yr	0.94	1.15	1.15	1.15	1.14
Agriculture Delivery, km^3/yr	0.84	0.90	0.90	0.90	0.89
Surface water storage cost, M$/yr	45.48	12.34	12.79	12.79	12.33
Scarcity volume, km^3/yr	0.10	0.04	0.04	0.04	0.04
Scarcity cost, M$/yr	15.77	2.31	2.63	2.63	2.83
Operating cost, M$/yr	68.81	82.73	82.73	82.73	81.77
Net cost, M$/yr	119.74	84.50	85.26	85.26	84.06
Net Benefit, M$/yr		35.24	34.49	34.49	35.69

Table S9. Key hydroeconomic metrics for different scenarios in normal years.

Hydroeconomic metrics	Base case	Recharge scenarios			
		I	II	III	IV
Surface water storage, km^3/yr	0.57	0.82	0.83	0.83	0.82
Hydropower generation, MWh/yr	872.38	918.35	925.81	925.81	923.61
Hydropower revenue, M$/yr	21.08	22.57	22.71	22.71	22.64
Groundwater storage, km^3/yr	226.88	235.05	232.21	232.21	231.37
Groundwater pumping, km^3/yr	0.88	0.79	0.76	0.76	0.76
Agriculture Delivery, km^3/yr	0.93	0.91	0.90	0.90	0.90
Surface water storage cost, M$/yr	0.31	4.41	4.50	4.50	4.37
Scarcity volume, km^3/yr	0.01	0.02	0.04	0.04	0.04
Scarcity cost, M$/yr	0.95	1.49	2.52	2.52	2.54
Operating cost, M$/yr	63.03	59.68	57.92	57.92	57.58
Net cost, M$/yr	43.21	43.01	42.22	42.22	41.85
Net Benefit, M$/yr		0.20	0.99	0.99	1.36

Table S10.: Key hydroeconomic metrics for different scenarios in wet years.

Hydroeconomic metrics	Base case	Recharge scenarios			
		I	II	III	IV
Surface water storage, km^3/yr	0.70	0.85	0.85	0.85	0.85
Hydropower generation, MWh/yr	1365.87	1431.62	1429.34	1429.34	1428.50
Hydropower revenue, M$/yr	34.03	35.56	35.51	35.51	35.48
Groundwater storage, km^3/yr	225.72	235.42	232.79	232.79	231.74
Groundwater pumping, km^3/yr	0.84	0.73	0.68	0.68	0.67
Agriculture Delivery, km^3/yr	0.94	0.94	0.90	0.90	0.89
Surface water storage cost, M$/-yr	0.12	3.23	3.25	3.25	3.29
Scarcity volume, km^3/yr	0.00	0.00	0.04	0.04	0.05
Scarcity cost, M$/yr	0.00	0.11	2.38	2.38	2.94
Operating cost, M$/yr	60.89	56.21	53.29	53.29	52.51
Net cost, M$/yr	26.99	23.99	23.40	23.40	23.26
Net Benefit, M$/yr		2.99	3.58	3.58	3.73

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