Storing Water for the Environment

Technical Appendix B: An Experimental Reservoir Model for Storage and Allocation of an Ecosystem Water Budget

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CONTENTS

Introduction **2**

Rim Dams and Freshwater Ecosystem Management **3**

Methods **5**

- Experimental Reservoir Overview 5
- Ecosystem Water Budget Demands 6
- Other Water Demands 10
- Water Right Priorities 11
- Water Balance Model 12
- Water Temperature Model 15
- Model Runs 17

Results **18**

- Performance on Ecosystem Water Budget Objectives 18
- Performance on Other Water Demands 22
- Reservoir Storage and Cold-Water Pool Volume 27
- Example Ecosystem Water Budget Performance in 2019–21 33
- New Environmental Storage 35

Summary **36**

References **37**

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Introduction

Dams alter flow regimes, fragment rivers, and harm freshwater ecosystems (Munsch et al. 2022; Barbarossa et al. 2020). Yet, freshwater ecosystems are increasingly dependent on surface reservoirs for environmental flows and suitable water temperatures as rivers have become irrevocably altered by water development, consumptive water uses, land use change, and climate change (Grantham et al. 2020; Yarnell et al. 2020). This creates a paradox where dams have contributed to freshwater ecosystem decline, but are now instrumental for managing environmental water and enhancing downstream ecosystems.

California has historically relied on regulatory environmental flows and water quality standards for ecosystem protection, making environmental water a constraint on water operations, rather than a priority objective in multipurpose water management.[1] A consequence is that management strategies like water transfers, conjunctive use, in-lieu exchanges, and carryover storage across seasons and years are inaccessible for environmental purposes. These types of management strategies could provide ecosystem managers seasonal and inter-annual flexibility to efficiently manage environmental water and freshwater ecosystems.

Efforts are underway to design functional flows (Grantham et al. 2020) and develop environmental flow frameworks (Stein et al. 2021) to use environmental water most efficiently for freshwater ecosystems in California and elsewhere (Chen and Olden 2017). While methods to quantify and manage environmental water use efficiency are worthwhile, questions remain, including how to store water to shape reservoir releases into functional flows, how to manage water quality, and how to quantify and manage trade-offs with non-ecosystem water demands.

This appendix accompanies a report that recommends granting the environment an ecosystem water budget (EWB)—with a proportion of inflow and a proportion of reservoir storage capacity to manage it—and with a functional equivalent of a senior water right (Null et al. 2022). The report summarizes some highlights of a modeling exercise that examines the performance of several different types and sizes of EWBs. Here, we describe the model and methods used and present more detailed results to provide context and nuance to our findings.

We developed a simple temperature and operations model of a large, multi-purpose, experimental reservoir, based loosely on Shasta Reservoir. We used this model to test two management approaches: (1) bypass of a percentage of inflows for an EWB; or (2) a percentage of inflows and a percentage of reservoir storage capacity for an EWB. In some runs, we constrain minimum reservoir storage to increase the likelihood of more cold water in storage for downstream water temperature objectives, and in some runs we add new environmental storage to capture reservoir spills for environmental water demands.[2] We evaluate alternative proportions of inflow and reservoir storage space for an EWB to quantify trade-offs between EWB and non-EWB demands.

This approach applies to large, multi-purpose reservoirs, so this appendix starts with a description of California's rim dams and their importance for freshwater ecosystem management. We explain our simplified EWB demands: a combination of environmental baseflows for habitat and water quality maintenance, additional water that operators or environmental trustees could shape into seasonal functional flows, and—because California has many native cold-water fish species—cold water reservoir releases to manage stream temperatures. We explain how we prioritize these ecosystem objectives for three representative species, fall-run Chinook salmon, late fall-run Chinook salmon, and federally-listed winter-run Chinook salmon. We explain our simplified non-EWB

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[1] The main report has a more thorough explanation of this distinction.

[2] The main report and Appendix C describe efforts to expand storage with Proposition 1 funding, which requires public benefit from new storage projects, including providing new water for the environment.

demands: in-basin urban and agricultural uses, wildlife refuge deliveries, system water to maintain salinity for water supply, and out-of-basin exports. Next, we describe our coupled water balance and reservoir temperature model, focusing on governing equations, data, and assumptions. Model runs evaluate bypassing 10 percent to 40 percent of inflow to an EWB compared to allocating a proportion of inflow and a proportion of reservoir storage capacity to an EWB. Model runs enable us to isolate the benefits of water storage for an EWB versus different levels of EWB inflow allocations. We present and explain results, focusing on: (1) the frequency that EWB objectives could be met; (2) effects on non-EWB water deliveries and storage; (3) reservoir storage changes with an EWB; and (4) cold-water pool volume and temperature of releases from our hypothetical reservoir. And finally, we describe model runs that explore how the creation of new environmental storage downstream of the reservoir could create additional opportunities to meet environmental water demands. We conclude with a summary of key findings.

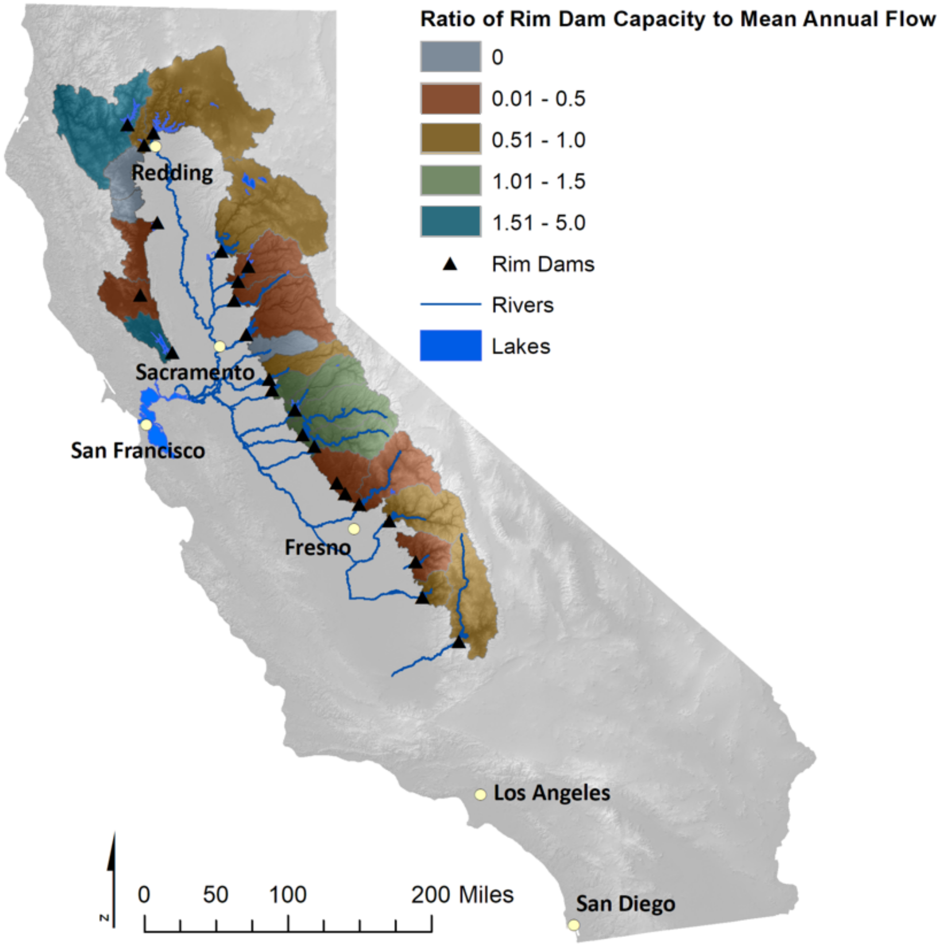
Rim Dams and Freshwater Ecosystem Management

This analysis focuses on rim dams in California's Central Valley. As their name connotes, these dams form large, multi-purpose reservoirs that "rim" the valley and block access to upstream salmon spawning and rearing habitat. Rim dams release water to meet downstream regulatory environmental flows and standards, while supplying water for other demands–generating hydropower, managing flood protection, and sometimes creating recreation opportunities. Figure B1 shows the size of reservoirs relative to watershed mean annual discharge. Most rim dams store less than mean annual discharge. A small number of basins have rim dam reservoir capacity that exceeds mean annual discharge. These include Putah (Monticello Dam), Trinity (Trinity Dam),[3] Calaveras (New Hogan Dam), Tuolumne (New Don Pedro Dam), Merced (Exchequer Dam), and Stanislaus (New Melones Dam) (Figure B1). Only three significant watersheds—Cosumnes, Elder/Thomes, and Cottonwood—have no major dams. Although large diversions block salmon migration in these undammed basins, they are often valued for ecosystem benefits such as floodplain habitat and natural flow regimes (Jeffres et al. 2008).

[3] The Trinity River is a major tributary to the Klamath River. However, it was included here because water is transferred from the Trinity River to the Sacramento River via an underground tunnel to Clear Creek.

FIGURE B1

Storage capacity for large multi-purpose Central Valley rim dams



SOURCE: CDEC; CDWR (2021) (Dams within the jurisdiction of the State of California).

NOTES: Figure shows storage capacity for the largest multipurpose dams (e.g., Oroville, New Bullards Bar). Green and blue hues indicate watersheds with rim dam capacity that exceeds mean annual flow, and brown and yellow hues indicate watersheds where rim dam capacity is less than mean annual flow. Watersheds shown in gray have no major dams.

Because rim dams generally have capacity that exceeds 200,000 acre-feet (af),[4] they are instrumental for environmental releases and cold-water management (Null et al. 2013). This is particularly true in northern and central Sierra Nevada watersheds, where median rim dam capacity is 990,000 af. Overall, larger and deeper reservoirs have stronger temperature stratification—and thus more stable cold-water pools—than smaller and shallower reservoirs.

Although dam removal is sometimes a promising approach to restore freshwater ecosystems, rim dams are unlikely to be removed because they provide multiple benefits, including protecting human health and safety through flood control. For that reason, we focus here on storage and bypassing of inflows to support the environment. The bypass approach is exemplified by new flow objectives for the Lower San Joaquin River. As part of its update of the Bay–Delta Water Quality Control Plan (Bay–Delta Plan), the State Water Board adopted amendments that set aside an average of 40 percent of the February–June unimpaired flows on the Lower San Joaquin River and its tributaries, the

[4] Exceptions include Success Dam (Tule Basin), Camp Far West Dam (Bear Basin), Buchanan Dam (Chowchilla Basin), Black Butte Dam (Stony Basin), and Terminus Dam (Kaweah Basin).

Merced, Tuolumne, and Stanislaus Rivers.[5] To meet these flow standards, reservoir operators will be required to bypass the equivalent volume of water. Although the program does not preclude storing water to meet the ecosystem objectives, neither does it require doing so. Further upstream on the San Joaquin River, there is also precedent in California for allocating a percentage of unimpaired inflow for the environment along with storage to manage it. The San Joaquin River Restoration Program is allocated a percentage of unimpaired inflow into Millerton Reservoir. This inflow is stored and released to provide ecosystem benefits to the San Joaquin River, focusing principally upstream of its confluence with the Merced River (SJRRP 2022).

Storage provides flexibility in timing EWB water delivery across seasons and years, allowing environmental managers to balance ecosystem temperature and flow objectives. Allocating storage capacity to an EWB is allowed under Australia's Commonwealth Water Act (2007), which purchased environmental water entitlements following their Millennium Drought (Mount et al. 2016). Australia's environmental water can be used, stored as carryover for the following year, or traded for equal or greater environmental benefit in regulated basins (Commonwealth Environmental Water Office 2013). Carrying over water increases the likelihood of ecosystem water in dry years and provides infrequent, high magnitude pulse flows to reintroduce hydrologic variability (Docker and Robinson 2014).

Methods

Experimental Reservoir Overview

To examine EWB trade-offs with non-EWB water demands and understand temperature dynamics, we represented a large, multi-purpose Central Valley reservoir—similar to Shasta Reservoir—using a simple priority-based water balance operations model coupled with a one-dimensional reservoir temperature model that stratifies vertically (Figure B2). Our reservoir has highly variable seasonal and interannual inflows, temperature stratification during summer, minimum operational levels (dead pool), and seasonal flood storage requirements. The experimental reservoir has storage capacity of 4.5 million acre-feet (maf), equal to Shasta Reservoir. This allowed us to use Shasta Reservoir inflow data (Shasta Dam–USBR station from CDEC) for inflows, evaporation, outflows, and flood storage. Our experimental reservoir has similar depth to Shasta Reservoir, but releases from the model reservoir were represented in a simplified way. with a temperature control device that has three openings at 25 m, 65 m, and 95 m above the reservoir bed.[6] It was outside the scope of this modeling to represent actual operations or contracts, or to represent multiple reservoirs. We ran the model on a monthly timestep for water years 1996–2021 to capture the range of historical hydrologic variability. The water balance model estimated storage and releases for all water demands including EWB demands, then storage and release data were passed to the reservoir temperature model to represent reservoir cold-water volume and release temperatures.

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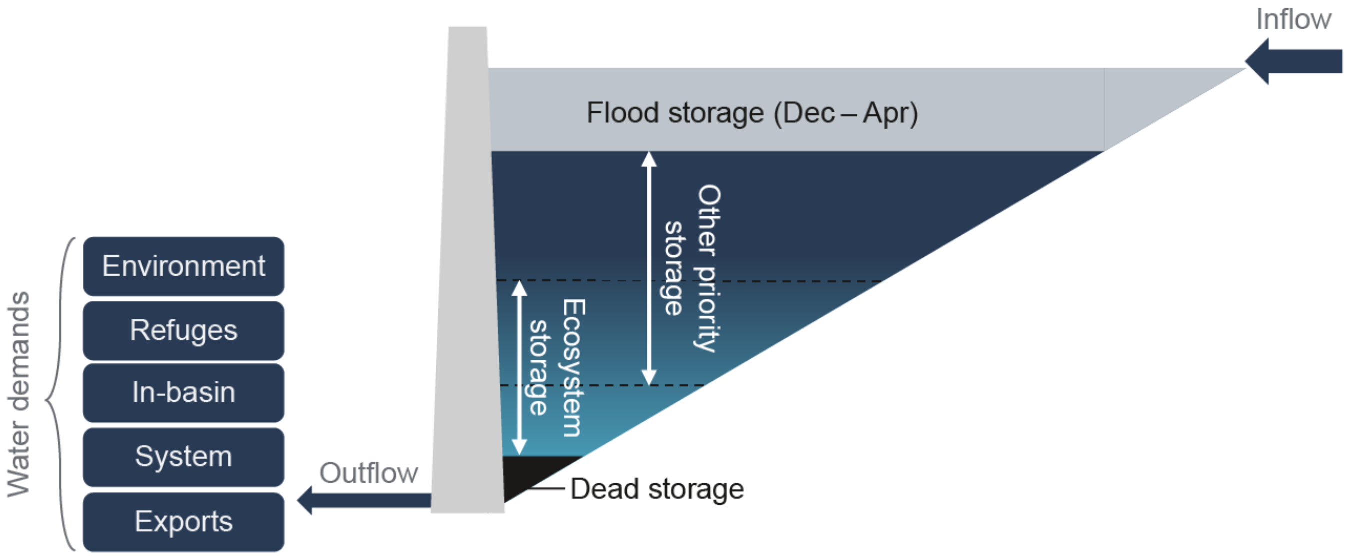
[5] See SWRCB (2019). The unimpaired flow standard has an allowed adaptive range between 30 and 50 percent from February through June.

[6] Shasta Reservoir has temperature control gates approximately 46 m, 61 m, 91 m, and 122 m above the reservoir bed, and the upper three gates have multiple shutters that can be opened to manage release temperatures.

FIGURE B2
Modeled inflows and ecosystem water budget reservoir storage with stylized water demands



SOURCE: Developed by the authors.

NOTES: The diagram depicts different categories of storage volume in the reservoir and the objectives of flow releases. Reservoir colors represent summer reservoir temperature stratification, with warmer water at the surface and cooler water at depth. See text for a full description.

Ecosystem Water Budget Demands

While EWBs could be broadly beneficial for improving ecosystem function, we focus on Chinook salmon to demonstrate a proof-of-concept and elucidate potential benefits and trade-offs. We summarized environmental objectives for winter-run Chinook salmon, fall-run Chinook salmon, and late fall-run Chinook salmon, based on the best available science. One of these species, Sacramento River winter-run Chinook salmon, is listed as an endangered species at high risk of extinction and in need of urgent protection (Federal Register 1994). See Appendix A for detailed information about conservation status and impacts of dams for these and other California fishes. We developed four EWB water demand objectives, ranked as follows:

1. Environmental baseflows to account for minimum instream flows and water quality standards,[7]
2. *Suitable* water temperatures to provide habitat and protect salmonids,
3. Seasonal blocks of water for functional flow objectives, and
4. *Optimal* water temperatures, which require colder water than needed for merely suitable temperatures to restore salmonid populations.

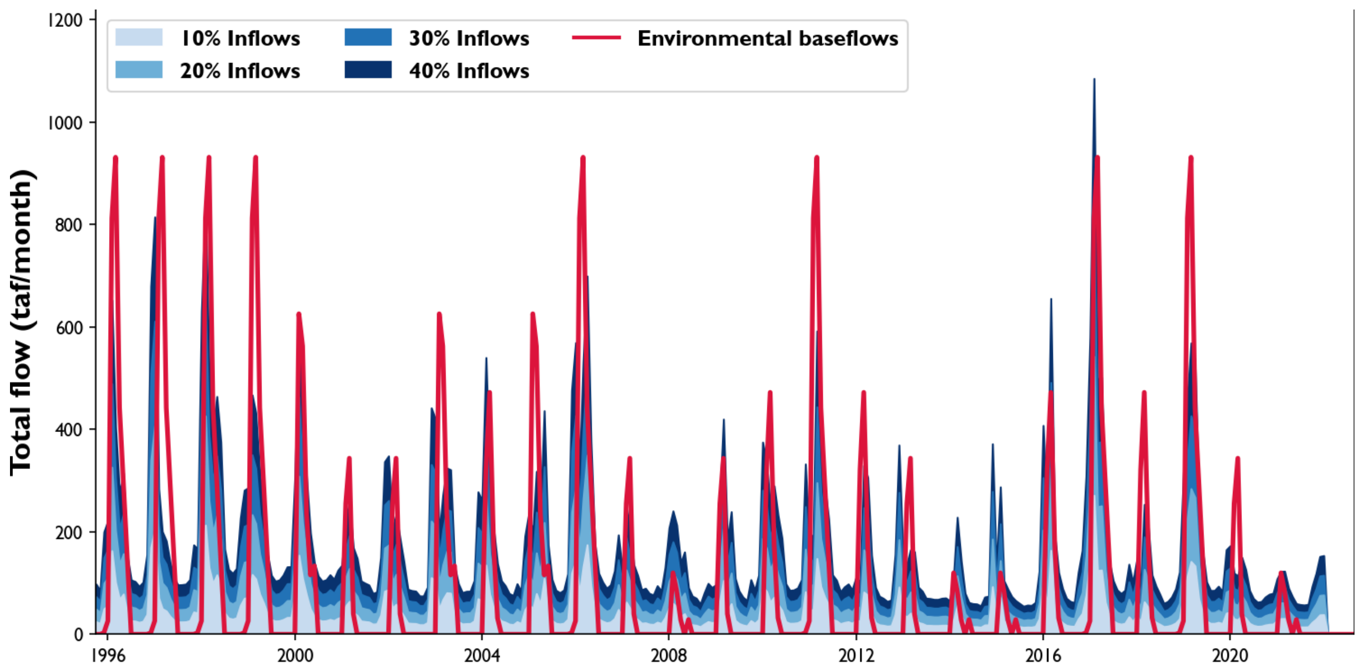
The first objective was to deliver monthly environmental baseflow demands, which represent regulatory streamflow requirements and water quality standards other than salinity to meet requirements for agricultural and urban uses ("system water," described below with non-ecosystem water demands). Environmental baseflow demands are adapted from the Delta water accounting defined in Gartrell et al. (2017), which attributed partially multipurpose releases into distinct "buckets" for water demands. In particular, Delta outflows are required to keep

[7] Environmental baseflows are based on "ecosystem water" requirements estimated by Gartrell et al. (2017 and 2022). We used the incremental amount required to meet ecosystem demands, above and beyond the "system water" required to meet salinity objectives for in-Delta and export water demand. This system water also fulfills some ecosystem regulatory requirements. System water is also included in our model under other (non-EWB) demands, as described below.

the Delta fresh enough for agricultural and urban water uses and to meet certain ecosystem needs, and there is some overlap in these requirements. Ecosystem water in Gartrell et al. (2017) is defined as the incremental water required to support fish and wildlife.[8] We scaled ecosystem water by the fraction of water that Shasta Reservoir contributes to the Delta. Environmental baseflows vary monthly and by water year type, reflecting regulatory requirements that supply more water to the environment in wetter years and less in drier years (Gartrell et al. 2017; Gartrell et al. 2022) (Figure B3). Environmental baseflows average about 8 percent of reservoir inflow.

FIGURE B3

Ecosystem water budget bypass allocations compared to historical environmental baseflows (sometimes called ecosystem water)



SOURCE: Ecosystem water is from Gartrell et al. (2017 and 2022). Inflows proportions are derived from Shasta Reservoir inflow data (Shasta Dam USBR station from CDEC). Environmental baseflows are about 8 percent of total inflow to the Delta (Gartrell et al., 2017).

NOTES: The figure shows average monthly data from water years 1996–2021, and ecosystem water budget allocations ranging from 10 to 40 percent of reservoir inflows. Environmental baseflows are depicted using ecosystem water estimates from Gartrell et al. (2017 and 2022).

Table B1 summarizes the factors considered for the remaining three ecosystem water budget objectives—suitable temperatures, functional flows, and optimal temperatures. The second objective (priority 2 in the table) was to deliver water temperatures *suitable* to protect native salmonids, specifically, stream temperatures cooler than 12°C to reduce winter-run Chinook salmon egg mortality from June through October, and year-round temperatures under 17°C to reduce mortality of winter-run, fall-run, and late fall-run Chinook salmon juveniles (Yoshiyama et al. 1998; Richter and Kolmes 2005; Zarri et al. 2019) (Table B1 and Figure B4). These temperatures also support pre-spawn survival for all Chinook salmon stocks throughout the year (Yoshiyama et al. 1998; Bowerman et al. 2018).

[8] According to Gartrell et al. (2017), ecosystem water demands are primarily determined under the federal Clean Water Act and Endangered Species Act (ESA), and state law counterparts. Ecosystem flow requirements are administered by the State Water Board and federal and state fish and wildlife agencies.

TABLE B1

Freshwater ecosystem priorities, goals, criteria, and timing

Priority	Category	Goal	Criteria	Timing	References
2	Temperature control	Reduce winter-run egg mortality	T_w <= 12 °C	Jun – Oct	(Zarri et al. 2019)
2	Temperature control	Reduce mortality of winter-run, fall-run, and late fall-run juveniles	T_w <= 17 °C	Year-round	(Yoshiyama et al. 1998; Richter and Kolmes 2005)
2	Temperature control	Reduce pre-spawn mortality among winter-run adult spawners	T_w <= 20 °C	Dec – Jul	(Yoshiyama et al. 1998; Bowerman et al. 2018)
2	Temperature control	Reduce pre-spawn mortality among fall-run and late fall-run adult spawners	T_w <= 20 °C	June – Apr	(Yoshiyama et al. 1998; Bowerman et al. 2018)
3	Functional flows	Spring recession to flush fine sediment and cue out-migrating fish	Flow >= 99,150 AF/mo	Apr – Jun	(Nobriga et al. 2021)
3	Functional flows	Winter pulse to inundate off-channel habitat for winter-run, fall-run, and late fall-run.	Flow >= 130,722 AF/mo	Jan – Mar	(del Rosario et al. 2013; Sturrock et al. 2020)
3	Functional flows	Fall pulse to flush fine sediment from fall-run and late fall-run spawning gravels. Cue out-migrating juvenile winter run and upstream fall-run.	Flow >= 24,788 AF/mo	Oct – Nov	
4	Temperature control	Reduce winter-run egg and early fry mortality	T_w <= 11.5 °C	Jun - Dec	(Zarri et al. 2019)
4	Temperature control	Reduce mortality of winter-run, fall-run, and late fall-run juveniles	T_w <= 15 °C	Year-round	(Yoshiyama et al. 1998; Richter and Kolmes 2005)
4	Temperature control	Reduce pre-spawn mortality among winter-run adult spawners	T_w <= 12.8 °C	Jun – Mar	(Yoshiyama et al. 1998; Richter and Kolmes 2005)
4	Temperature control	Reduce pre-spawn mortality among fall-run and late fall-run adult spawners	T_w <= 12.8 °C	June – Apr	(Yoshiyama et al. 1998; Richter and Kolmes 2005)

SOURCES: Provided in last column.

NOTES: T_w = water temperature, juveniles include all life stages, functional flow volumes are in addition to environmental baseflows. Priority denotes the level of priority of the goal within the ecosystem water budget.

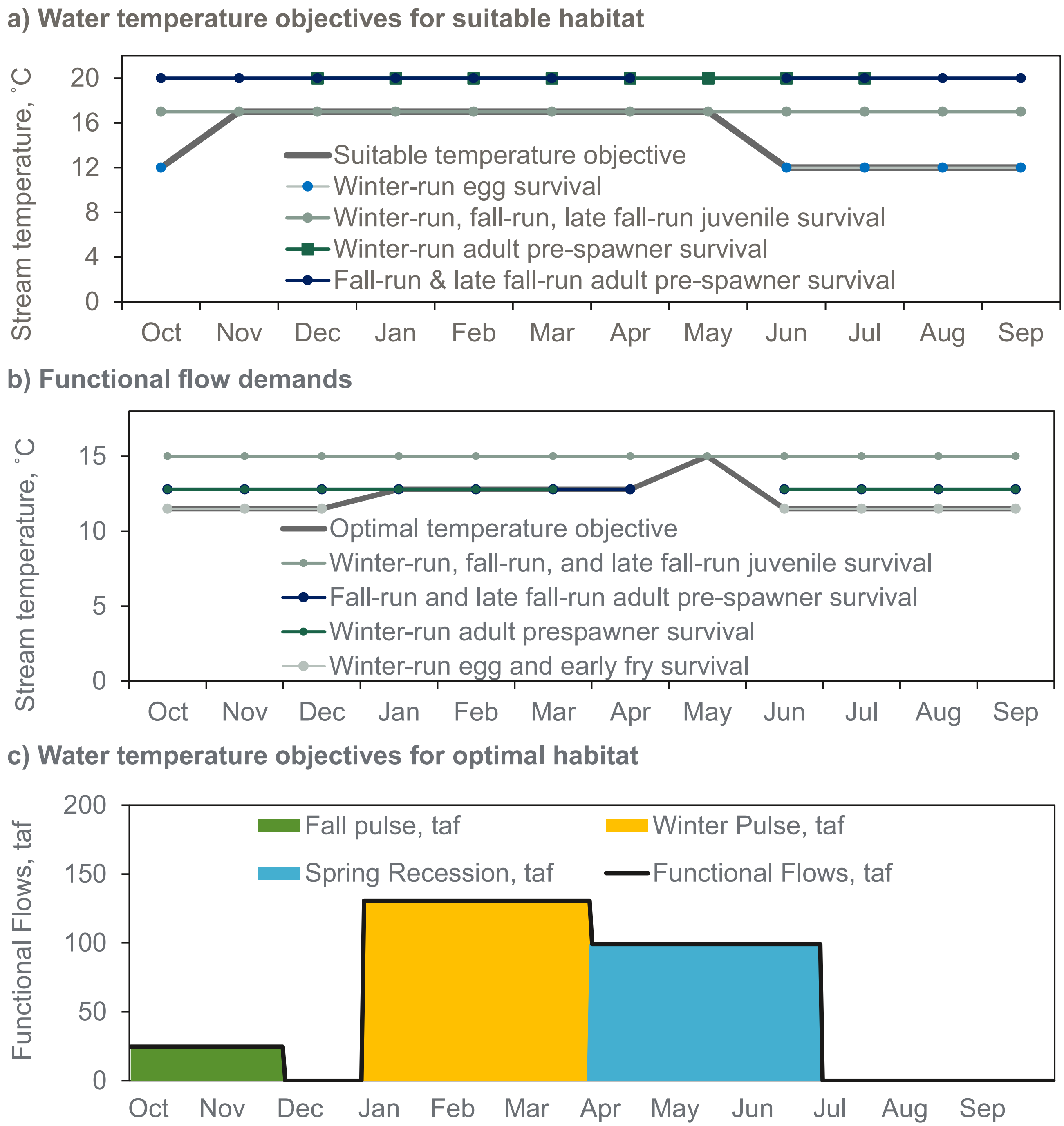
The third objective allocated a seasonal volume of water representing a fall pulse, winter pulse, and spring recession—which environmental water managers could shape into functional flow releases (Table B1). A spring recession flushes fine sediment and cues out-migrating fish, a winter pulse inundates off-channel habitat for all salmon fish stocks, and a fall pulse flushes fine sediment from spawning gravels and cues out-migrating juvenile winter-run Chinook salmon and returning fall-run Chinook salmon (del Rosario et al. 2013; Sturrock et al. 2020; Nobriga et al. 2021). Functional flows supplemented environmental baseflows and averaged about 14 percent of reservoir inflow volume. In our model, neither the total annual volume nor the within-year distribution of functional flow demands varies by year type. In practice, daily reservoir operations would likely alter the timing, magnitude, duration, frequency, and rate of change of functional flow water volumes differently among years to best meet downstream ecological objectives (Grantham et al. 2020).

The fourth objective was water temperatures *optimal* to enhance salmonid populations, with temperatures colder than 11.5°C from June through December to improve winter-run egg and early fry survival, temperatures colder than 12.8°C from December through April to improve pre-spawn survival for all Chinook salmon stocks, and temperatures less than 15°C the rest of the year to improve juvenile survival for all stocks (Yoshiyama et al. 1998;

Richter and Kolmes 2005; Zarri et al. 2019) (Table B1). Allowing for two temperature objectives—both suitable and optimal—allowed satisfactory outcomes, rather than an overly constrained approach that returned only optimal outcomes.

FIGURE B4

Timing and magnitude of suitable and optimal stream temperatures and functional flows



SOURCE: See Table B1 and text for full description and references.

NOTES: *Suitable* stream temperatures are based on ecosystem objectives 1–4 in Table B1, functional flow targets are based on ecosystem objectives 5–7, and *optimal* stream temperatures are based on ecosystem objectives 8–11. Functional flows were represented with a seasonal volume of water for a fall pulse, winter pulse, and spring recession, and ecosystem managers could release functional flows any time within the functional flow window to maximize ecological benefits.

Other Water Demands

To estimate other existing water demands (in simplified form), we surveyed large, multi-purpose reservoirs in the Central Valley—including CVP and SWP reservoirs and those managed by individual water districts. From this we developed four categories of water demand and assigned a timeseries of monthly demands that were defined as a function of the Sacramento River Index water year type (Figure 5).[9] For simplicity, hydropower generation and recreation were ignored. Non-EWB demands include:

1. Wildlife refuge water demands
2. In-basin urban and agricultural uses
3. System water for salinity maintenance
4. Out-of-basin water exports

The first three demands—refuge, in-basin urban and agricultural, and system water for salinity maintenance—share highest priority in the model, but demand varies depending on the time of year. The last—out-of-basin exports—is junior to the other demands. Despite our simplified accounting, water for some demands was multi-purpose—for example water to meet temperature standards could be reused to meet other demands (Gartrell et al. 2017).[10]

Wildlife refuge water demands were separate from the EWB demands because refuge water demands have an existing water right priority. Refuge demands for wetland habitats reflected the Level 2/Full Level 4 allocations assigned by the federal Central Valley Project (CVP) Refuge Water Supply Program (USBR 1989). Refuge demands in wet and above normal water years are equal to the combined Level 2/Full Level 4 allocation (555 taf), while demands in below normal, dry, and critically dry water years are equal to the Level 2 allocation alone (422 taf). Monthly values were estimated using seasonal deliveries to wildlife refuges managed by the CVP (USBR 2022). EWB allocations do not augment refuge demands.

In-basin urban and agricultural demands have a senior priority and provide water for cities and farms, which we combined for simplicity. Seasonal in-basin demands were modeled on CVP deliveries to the Sacramento Settlement Contractors and the Tehama-Colusa Canal. These demands increased relative to other demands in drier years (Figure B5). Given their senior priority, these users are generally in a position to take more surface water in dry years to compensate for less local precipitation and soil moisture.

System water demands were taken from the Delta water accounting study (Gartrell et al. 2017 and 2022). System water is Delta outflow necessary to meet salinity standards in the Delta for in-Delta urban and agricultural uses and exports. While these flows also provide ecosystem benefits, ecosystem function is not the primary objective, so system water is not counted as EWB water.

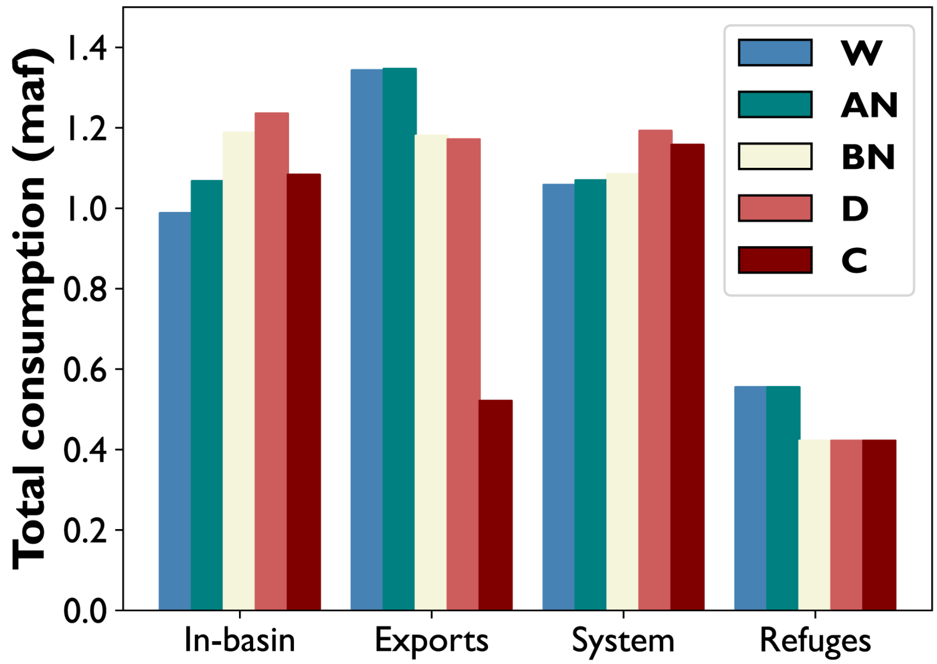
Out-of-basin export demands were modeled after observed pumping through the Tracy and Banks pumping plants located in the Delta. Export demands were highest in wetter years, and significantly lower in critically dry years. These patterns reflect their junior water right priority, which limits their access to water in drier years.

[9] Sacramento Valley Index water year types are available at CDEC's Water year Hydrologic Classification Indices webpage and methods are explained in CDWR (1989) and Null and Viers (2013)

[10] For example, water released for temperature control or to meet the Vernalis salinity objective can also be used to meet Delta salinity or outflow objectives, or it can be diverted for urban or agricultural uses or storage in groundwater basins.

FIGURE B5

Total annual water demand for the four non-ecosystem water demands by water year type



SOURCE: System water represents salinity maintenance as defined in Gartrell et al. (2017 and 2022). Refuge water demands reflect Level 2 allocations assigned by the CVP Refuge Water Supply Program (USBR 1989). In-basin water uses reflect seasonal patterns observed in USBR deliveries to long-term Sacramento River contracts (USBR 2022). Exports reflect seasonal patterns observed in the combined pumping at the Harvey O. Banks and C.W. Bill Jones pumping plants in the Delta (CDWR 2022).

NOTE: This figure shows average annual demands by water year type for 26 years of hydrologic conditions spanning water years 1996–2021.

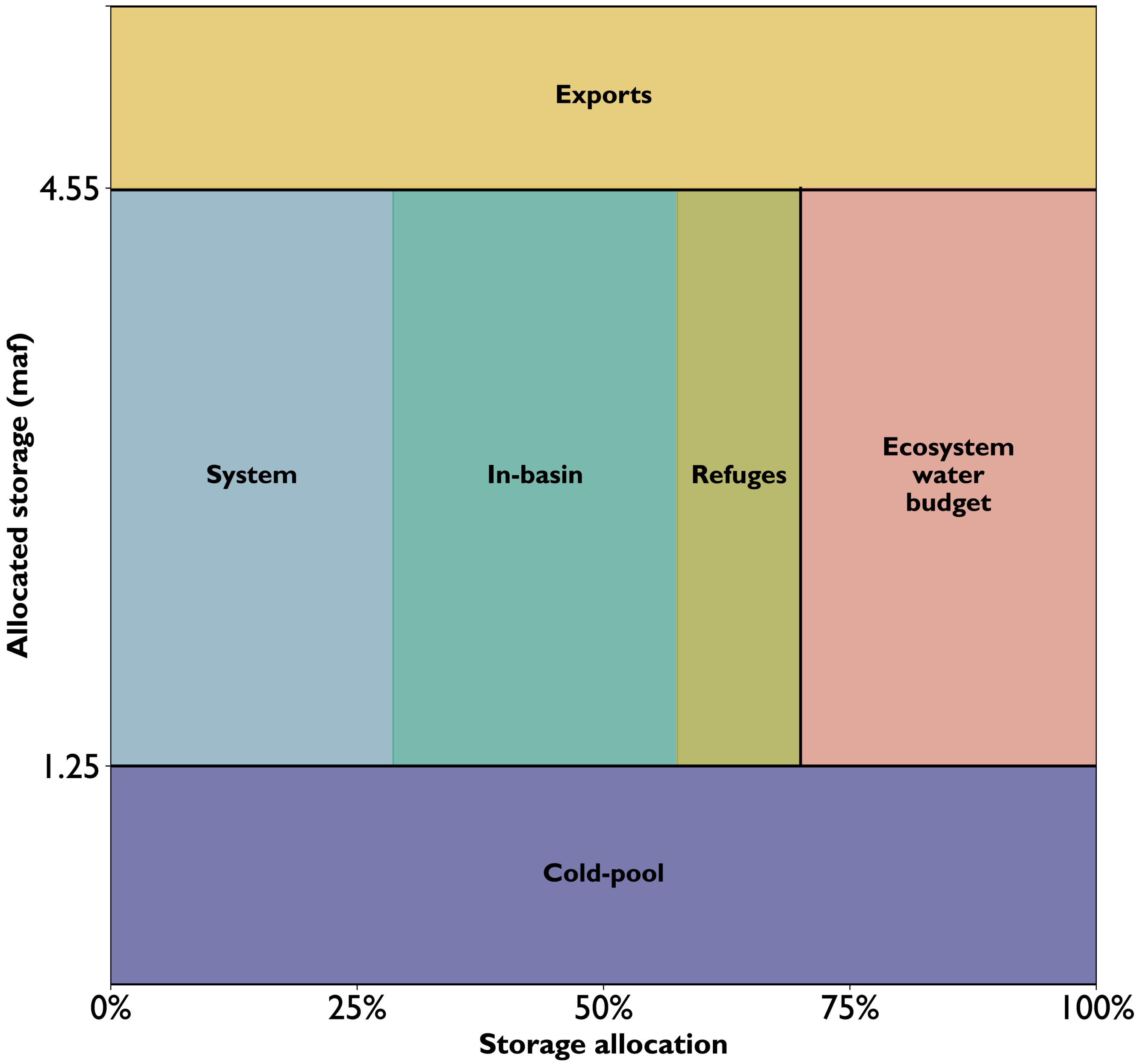
Water Right Priorities

Priority-based inflow and storage allocations enabled simulations to distinguish between senior water demands, which in times of shortage have their allocations filled first, and junior water demands, which cannot receive any water until senior water demands have been met. The EWB is given senior priority and receives a percentage (10–40%) of reservoir inflow. In-basin urban and agricultural demands, refuges, and system water have senior priority for the remaining portion (60–90%) of reservoir inflows. Out-of-basin exports have junior priority and water is only delivered when other non-EWB demands have been met.

By manipulating the volume and seniority of storage and inflow allocations, we created realistic priorities within our simple reservoir model. Figure B6 shows a three-tiered system in which five water demands share space in the hypothetical reservoir, with minimum storage designated to maintain cold water deep in the reservoir. Minimum storage was a constant constraint in some model runs. In effect, this expanded the "dead space" in the reservoir that could not be used to meet downstream demands, but helped preserve cold water in the reservoir that could be accessed with a reservoir temperature control device in a subsequent season (described below in the temperature modeling section).

FIGURE B6

Storage and flow allocations for five water demands and minimum storage to maintain a cold-water pool



SOURCE: Developed by the authors.

NOTES: This figure shows the seniority and volume of storage allocated to different water demands with 1.25 maf minimum storage and a 30 percent EWB allocation. After 1.25 maf of water for minimum storage, the remaining 3.3 maf of storage capacity is split proportionally between the EWB and the senior water demands (system, in-basin, and refuge demand). Out-of-basin exports (the junior priority demands) can use excess reservoir storage capacity when it exists, but stored junior supplies are the first to be spilled when the reservoir fills.

Water Balance Model

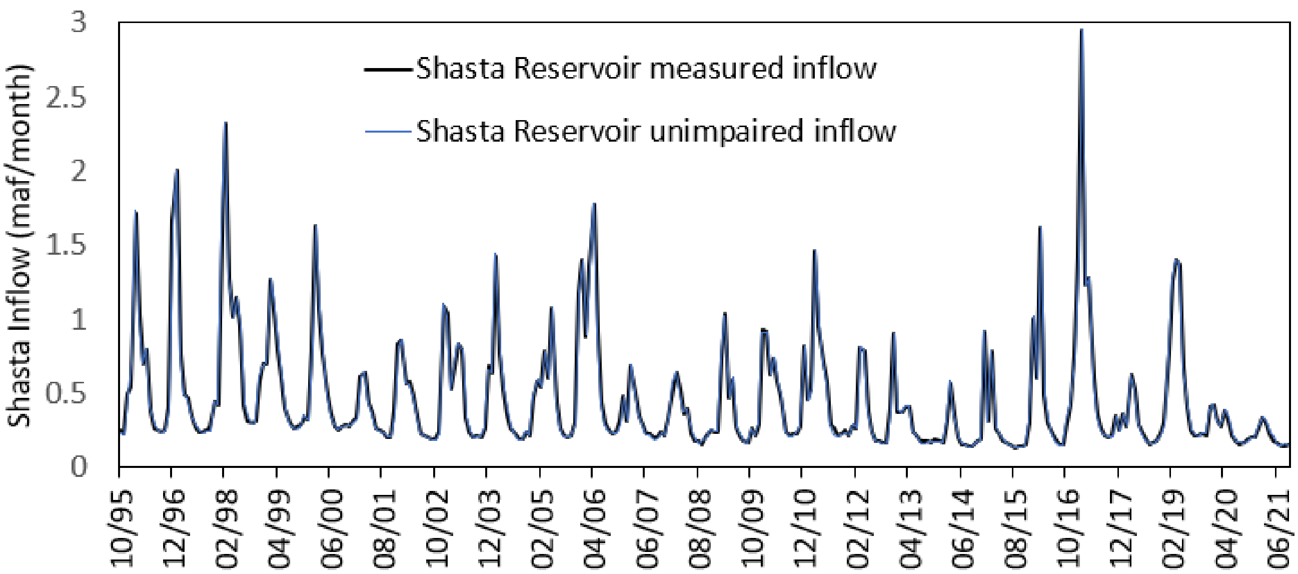
We demonstrated the impact of EWB assets, including dedicated storage for the environment, using water balance simulations designed to measure the ability of our experimental reservoir to meet downstream demands, including environmental baseflow, temperature objectives, functional flows, and other water demands with existing water allocations. The simplified water balance evaluated changes in reservoir storage at a monthly timestep during a 26-year period (October 1, 1995 to September 30, 2021), subject to: (a) reservoir inflows, modeled after historical inflows into Shasta Reservoir, (b) monthly reservoir evaporation, modeled after historical reservoir evaporation from Shasta Reservoir, (c) reservoir releases to meet EWB and other non-EWB demands, and (d) flood releases of any storage that encroached into the reservoir flood pool, as defined by US Army Corps of Engineers operating rules for Shasta Reservoir (USACE 1977), such that:

$$S_{t+1} = S_t + I_t - E_t - RDD_t - RFC_t \quad (1)$$

where *S* is storage (af), *I* is reservoir inflow (af/month), *E* is reservoir surface evaporation (af/month), *RDD* is releases for downstream demands (af/month), *RFC* is releases for flood control (af/month), and *t* is the monthly timestep. We used measured historical inflows to Shasta Reservoir because this effort was meant to be a proof-of-concept model rather than account for upstream dams and diversions, and because historical inflows and unimpaired full natural flows into Shasta Reservoir were similar (Figure B7).

FIGURE B7

Measured and unimpaired inflow to Shasta Reservoir



SOURCE: Developed by the authors.

NOTES: Measured inflow data is from USBR's Shasta Dam (SHA) gage and unimpaired inflow is from Full Natural Flow at Shasta Dam. This figure shows average monthly data from water year 1996–2021.

Average annual water demand for in-basin users, system water, and exports comprised the balance of non-flood control releases from Shasta Reservoir during the 26-year simulation period, such that:

$$D_{IB} + D_{SAL} + D_{EX} = \frac{1}{26}\sum_{t=WY1996}^{2021} R_t - ECO_t - WET_t - RFC_t \quad (2)$$

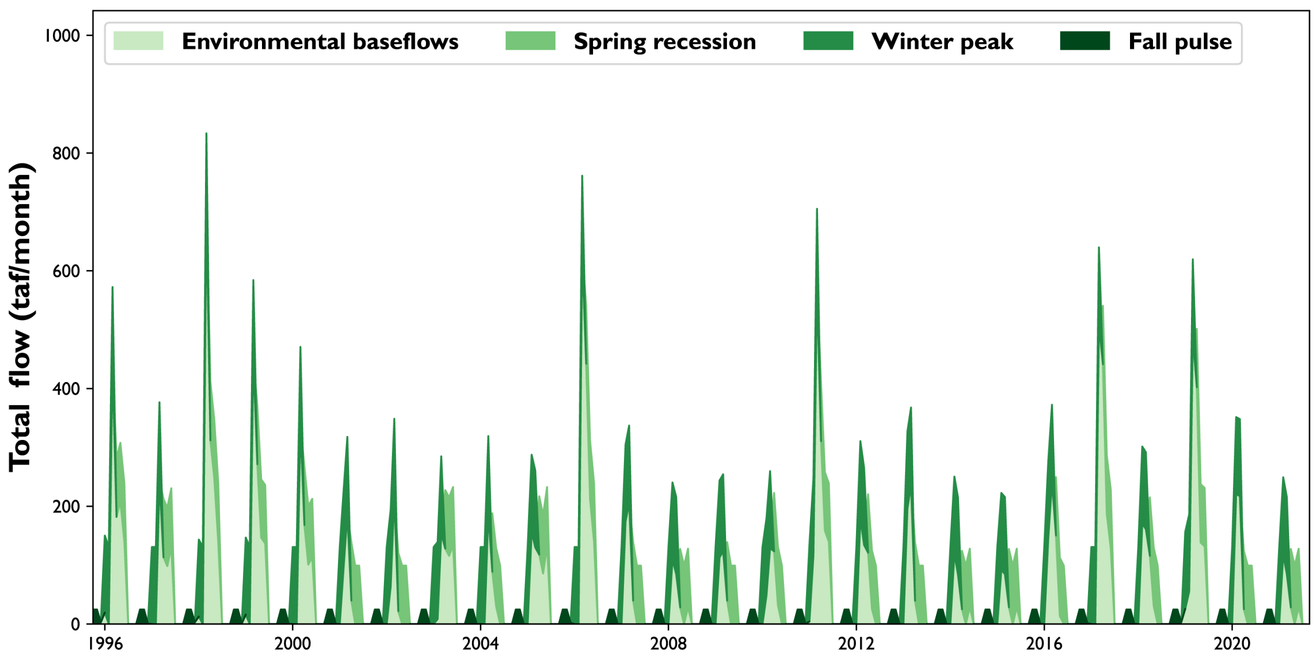
where *D* is total demand (af/year), *IB* is in-basin demand (-), *SAL* is system water demand (-), *EX* is export demand (-), *R* is total releases from Shasta Reservoir (af/month), *ECO* is releases for EWB demands (af/month), *WET* is releases for wetland refuge habitat (af/month), and *RFC* is releases from Shasta Reservoir when the flood control pool is encroached upon (af/month).

On average, historical reservoir releases were split evenly among in-basin agricultural and urban demands, system water, and out-of-basin exports (e.g., DIB = DSAL = DEX), although inter-annual and seasonal patterns reflected observed differences between the groups.

The EWB expanded environmental water management beyond the environmental baseflow and water quality standards identified in Gartrell et al. (2017, 2022) to include functional flows to support winter-run Chinook salmon, fall-run Chinook salmon, and late fall-run Chinook salmon (Table B1). Functional flow demands were added to environmental baseflow demands (Figure B8) to create a two-tiered system of ecosystem demands, where environmental baseflows were higher priority demands of the EWB and functional flows were considered lower priority demands provided by the EWB. We did this to ensure that regulatory flows were maintained with an EWB. When there was not enough water to meet all functional flows, water was allocated for the spring recession, then winter pulse, and finally the fall pulse flow.

FIGURE B8

Monthly flow volumes to support ecosystem objectives, including environmental baseflows, and functional flows for spring recession, winter pulse, and fall pulse



SOURCE: See text, Figure B3, and Table B1 for full description and references.

NOTE: The figure shows average monthly data for water years 1996–2021.

To manage multipurpose operations within our modeled reservoir, each water demand group was designated a proportion of overall reservoir inflow and the same proportion of reservoir storage capacity (e.g., 10 % inflow and 10% storage capacity, 20% inflow, and 20% storage capacity, etc.). Within each capacity allocation, a water-demand-specific water balance was conducted, such that:

$$S_{g,t+1} = S_{g,t} + k_g * (I_t - E_t) - RDD_{g,t} \qquad (3)$$

and

$$\sum_g k_g = 1.0 \qquad (4)$$

where g is the water demand group (EWB, in-basin, system water, refuge, and exports) and k is the inflow allocation to water demand group g.

Critically, storage for each water demand group (S_g) was not allowed to fall below 0, requiring water demands to experience delivery shortfalls when the volume of stored water was less than the monthly demand, such that:

$$RDD_{g,t} = \min(S_{g,t}, D_{g,t}) \quad (5)$$

and

$$SF_{g,t} = D_{g,t} - RDD_{g,t} \quad (6)$$

where D is equal to the downstream demand of water demand group g in timestep t and SF is equal to the delivery shortfall of water demand group g in timestep t.

Stored water could be carried over for future use when capacity existed; however, carryover water was first to be spilled for flood control. Flood control releases, which are required when reservoir storage encroaches into the flood control pool, were divided among the storage accounts of each water demand. Responsibility for flood control releases was not assigned to all demands equally; instead, releases were assigned in proportion to the demand group's storage held in excess of their capacity allocation. This was represented as:

$$RFC_{g,t} = \max(S_{g,t} - \mathrm{c}_g FC_t, 0.0) \quad (7)$$

and

$$\sum_g c_g = 1.0 \quad (8)$$

where c is the capacity allocation assigned to demand group g and FC is the maximum flood control capacity of the hypothetical reservoir in timestep t.

When flood control conditions were triggered, deliveries to all demands were credited against the spilled water instead of reservoir storage accounts, and demand group storage was only impacted by their portion of the flood control release, such that:

$$S_{g,t+1} = S_{g,t} - RFC_{g,t} \quad (9)$$

Reservoir storage and demand shortfalls were simulated for all five water demands for a range of EWB bypass, EWB storage capacity, and minimum storage alternatives. Reservoir storage volumes were subsequently linked to a one-dimensional reservoir temperature model, enabling simulations to evaluate how EWB storage could be used to manage trade-offs between downstream environmental demands and river temperature objectives.

Water Temperature Model

Reservoir temperatures were estimated with Water Quality for Reservoir-River Systems (WQRRS), a mechanistic one-dimensional Fortran model developed originally by Chen and Orlob (1975) and later distributed by US Army Corps of Engineers–Hydrologic Engineering Center (USACE–HEC 1986). Average monthly inflow, inflow stream temperature, and weather were the inputs, and the model ran on a daily timestep. We averaged water temperature output to a monthly timestep.

One-dimensional reservoir water quality models are appropriate for representing large reservoirs where water temperature changes most in the vertical direction based on atmospheric conditions and water density. We chose WQRRS because it runs quickly and has been widely used (Sharma and Kansal 2013). For instance, it has been previously used to understand whether dams mitigate climate change effects on stream temperatures (Null et al. 2013), to develop reservoir operating policies considering water quality and quantity (Karamouz et al. 2009), to understand climate change effects on Shasta Reservoir water quality (Meyer et al. 1996), and to simulate water quality and quantity for restoring salmonids (Deas and Orlob 1999).

WQRRS is a finite difference model based on the principles of conservation of heat and mass. In this one-dimensional model, heat and mass transferred vertically through advection and effective diffusion, and water was assumed perfectly mixed laterally and longitudinally. The reservoir was segmented into 90 vertical layers and each layer was 2 meters (m) deep, for a reservoir depth of 180 m. Heat and mass transferred across layers, but remained constant within layers. Water temperature was the only water quality constituent modeled. Water temperature was estimated using the heat budget method given the one-dimensional form of the advection-diffusion equation:

$$V\frac{\partial C}{\partial t} + \Delta x Q_x \frac{\partial C}{\partial x} = \Delta x A_x D_c \frac{\partial^2 C}{\partial x^2} + Q_i C_i - Q_o C \pm VS \qquad (10)$$

where C is thermal energy (kcal), V is volume (m^3), t is time (s), x is vertical distance in the reservoir (m), Q_x is advective flow (m^3/s), A_x is surface area (m^2), D_c is the effective diffusion coefficient (m^2/s), Q_i is lateral inflow (m^3/s), C_i is inflow thermal energy (kcal), Q_o is lateral outflow (m^3/s) and S are sources and sinks (kcal/s).

Molecular and turbulent diffusion was based on temperature in WQRRS and convection was based on density gradient. Our hypothetical reservoir had one inflow at the upstream end of the reservoir, making the advection rate slower than if the inflow occurred near the dam. Inflows were instantaneously mixed within the reservoir layer of similar density (USACE-HEC 1986). Stratification was based on the relationship between density and water temperature. Water is most dense at 4 °C (39.2 °F) and is less dense as it warms or cools.

In addition to inflow temperature, reservoir temperatures were driven by atmospheric conditions, which warm or cool the reservoir surface. Large reservoirs, like the one represented here, stratify during spring and summer as atmospheric conditions heat the surface of the reservoir. Colder water remains at depth. In fall, atmospheric conditions cool, causing the reservoir surface to cool. As that cooler and denser water sinks, the reservoir "turns over," becoming well mixed vertically.

Reservoir inflow and outflow timeseries were passed from the water balance model. Inflow temperatures were from the Sacramento River at Delta (DLT) station (CDEC). Average monthly air temperature, wind speed (m/s), and relative humidity (%) were from the Remote Automated Weather Station (RAWS) at Redding Airport for 2002–21 and Lincoln, California prior to 2002. Average monthly air temperature and wind speed were used directly in the model. Relative humidity was used with air temperature to calculate average monthly wet bulb temperature (°C) for model input. Atmospheric pressure was based on elevation and was constant at 29.15 Hg. Cloud cover (% of sky) was unavailable and was estimated to be uniform at 0.5 percent. Together, air temperature, wet bulb temperature, wind speed, atmospheric pressure, and cloud cover formed the atmospheric conditions that drove temperature exchange at the air-water interface and surface layer mixing.

We represented generalized temperature management infrastructure with a basic temperature control outlet. Outflows were modeled using the selective withdrawal allocation method developed by the US ACE Waterways Experiment Station (WES method) to estimate the vertical limit of the withdrawal zone and vertical velocity distribution within that zone (USACE-HEC 1986). We modeled one withdrawal outlet with three opening ports and one spillway. The deepest withdrawal port was 25 m above the reservoir bed, the middle port was 65 m above the bed, and the upper port was 95 m above the bed. The spillway elevation was even with the surface of the dam when it was at capacity.

Model Runs

Twenty model runs were completed to understand performance on environmental objectives and to quantify trade-offs with non-EWB demands (Table B2). We modeled bypass of a percentage of inflow, and allocation of a percentage of inflow to the environment along with a percentage of reservoir storage capacity to manage release timing and amount. In some runs, we also constrained minimum reservoir storage for cold-water management. In a final modeling set we added new EWB storage that could be filled using reservoir spill (not described in the main report). Below we summarize each general modeling set:

- **Bypass of a percentage of inflow.** Eight model runs represented an EWB with 10 percent, 20 percent, 30 percent, and 40 percent of inflows bypassed with no reservoir storage capacity. One modeling set of 10–40 percent EWB bypass inflows included no minimum reservoir storage and the other set included 1.25 maf minimum storage (Table B2).
- **Percentage of inflow and percentage of storage capacity.** Eight runs represented a percentage of inflow and a percentage of storage allocated to an EWB. We varied inflow allocations between 10 and 40 percent and allocated reservoir storage capacity by the same proportion, for example, pairing 10 percent inflow to 10 percent storage, 20 percent inflow to 20 percent storage, etc. Water demands for in-basin uses, system water, refuges, and exports were allocated the remainder of inflows and reservoir storage (60–90 %, depending on the model alternative). These runs had two minimum storage alternatives, 0 maf and 1.25 maf to help preserve cold water in the reservoir that could be accessed with a reservoir temperature control device. Minimum reservoir storage targets have been recommended for large dams.[11]
- **Percentage of inflow, percentage of storage capacity, and new EWB storage.** Four runs represented 1.0 maf of possible future EWB storage from Proposition 1 projects downstream of our experimental reservoir (Table B2), along with 10 to 40 percent of inflow and storage, and 1.5 maf minimum storage for cold pool. We did not distinguish whether new environmental storage was surface or underground. Reservoir inflows allocated to the EWB could be stored using the EWB portion of storage capacity in the upstream hypothetical reservoir and flood control spills could be diverted into the new downstream environmental storage. We evaluated alternative conveyance rates of 500 cfs (approximately 30 taf/mo), 1,000 cfs (around 60 taf/mo), and 2,500 cfs (about 150 taf/mo) from the upstream model reservoir to the new downstream EWB storage. New environmental storage would likely have fewer impacts to other water demands than allocating a proportion of existing storage to an EWB, but would entail new investment costs (Table B2).

[11] Current operations of large reservoirs like Shasta Reservoir aim for minimum storage of 2.3 maf by May 1 (PCFFA and CNRA Decision 2022) and about 1.25 maf by October 1 to provide sufficient cold water to meet temperature objectives for salmonids (Cal EPA/SWRCB Order WR 2021-00xx).

TABLE B2

Model runs with ecosystem water budget inflow percentage, average annual inflow volume, storage capacity percentage, storage volume, and minimum storage to preserve a cold-water pool.

EWB Assets	EWB Inflow, percent	Average Annual EWB Inflow Volume, taf	EWB Storage Capacity, percent	EWB Storage Volume, taf	Minimum Storage for Cold-water Pool, maf
Percentage of inflow (bypass)	10% 20% 30% 40%	548 1097 1645 2194	-	-	0
Percentage of inflow (bypass), 1.25 maf minimum reservoir storage	10% 20% 30% 40%	548 1097 1645 2194	-	-	1.25
Percentage of inflow, Percentage of storage capacity	10% 20% 30% 40%	548 1097 1645 2194	10% 20% 30% 40%	455 910 1365 1820	0
Percentage of inflow, Percentage of storage capacity, 1.25 maf minimum reservoir storage	10% 20% 30% 40%	548 1097 1645 2194	10% 20% 30% 40%	330 660 990 1320	1.25
Percentage of inflow, Percentage of storage capacity, 1.5 maf minimum reservoir storage, 1.0 maf new storage	10% + spill 20% + spill 30% + spill 40% + spill	548 + spill 1097 + spill 1645 + spill 2194 + spill	10% + 1 maf 20% + 1 maf 30% + 1 maf 40% + 1 maf	1305 1610 1915 2220	1.5

SOURCES: Developed by the authors.

NOTE: See text for a full description of this table.

These model runs provide broad estimates of EWB performance for freshwater ecosystem objectives and enable trade-offs with other water demands to be quantified. Our model approach separates the benefit of a percentage of inflow allocated to the EWB for bypass, versus a percentage of storage with allocated inflow. We evaluated both approaches across water year types and examined (1) the frequency that EWB objectives could be met, (2) effects on non-EWB water deliveries and storage, (3) reservoir storage changes with an EWB, and (4) cold-water volume in our hypothetical reservoir.

Results

Performance on Ecosystem Water Budget Objectives

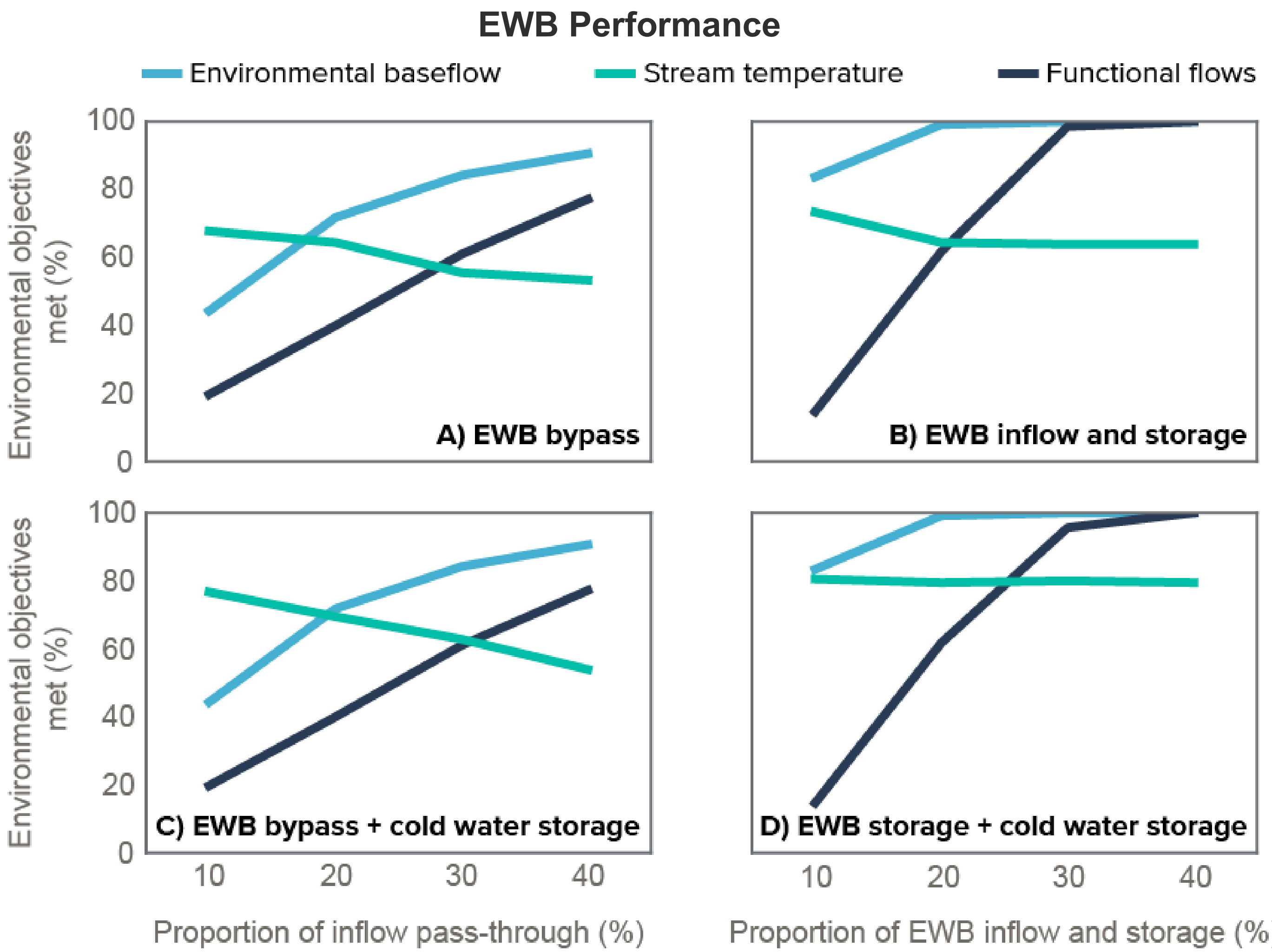
Setting aside a percentage of inflow for EWB bypass provided water for EWB deliveries, but the inability to manage their timing and volume hurt performance on EWB objectives. With 10 percent EWB bypass, environmental baseflows averaged 44 percent of demand and functional flows averaged 20 percent of demand in dry years (Figure B9 panel A). In wet years, environmental baseflows averaged 32 percent of demand and functional flows averaged 30 percent of demand (Figure B10 panel A).[12] With 40 percent of EWB bypass, performance was substantially better: environmental baseflow deliveries averaged 90 percent of demand and functional flow deliveries averaged 76 percent of demand in dry years (Figure B9 panel A). In wet years,

[12] The percentage of time that environmental baseflows were delivered in wet years dropped relative to dry years because environmental baseflows are larger in wet years than in dry years (Gartrell et al. 2017 and 2022).

environmental baseflows averaged 94 percent and functional flows averaged 68 percent of demands (Figure B10 panel A). In many months of wet years, EWB bypass flows exceeded the volumes needed to meet environmental baseflow and functional flow demands. Yet without storage, EWB management opportunities were limited. Also, there were clear trade-offs among EWB objectives.

FIGURE B9

Dry year performance on ecosystem water budget objectives.

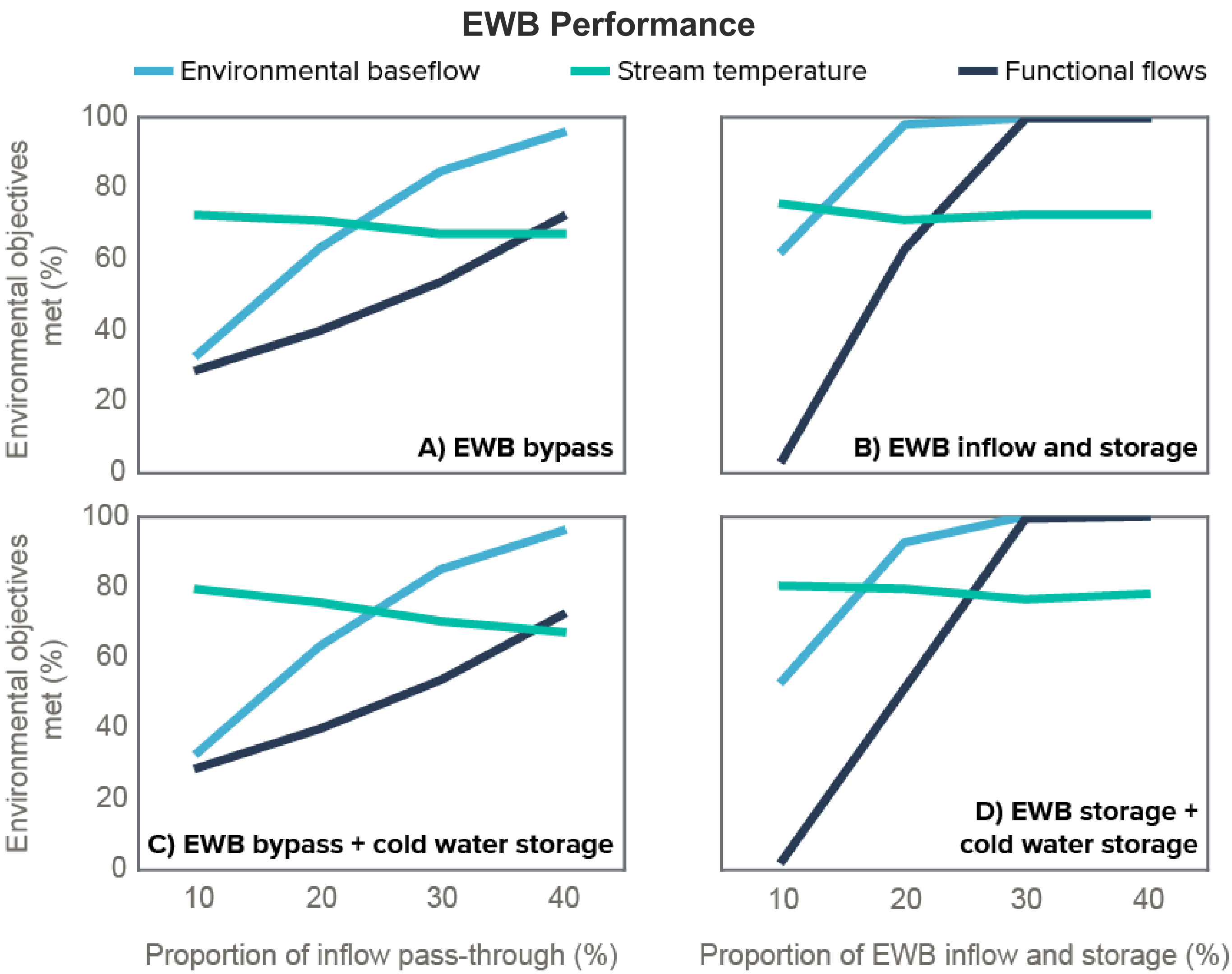


SOURCE: Developed by the authors.

NOTES: Panel a shows EWB objectives with a percentage of EWB bypass flows and 0 maf minimum reservoir storage, panel b shows EWB objectives with a percentage of EWB inflows and a percentage of EWB storage capacity with 0 maf minimum reservoir storage, panel c shows EWB objectives with a percentage of EWB bypass flows and 1.25 maf minimum reservoir storage, and panel d shows EWB objectives with a percentage of EWB inflows and a percentage of EWB storage capacity with 1.25 maf minimum reservoir storage. Dry years include critically dry, dry, and below normal year types. This figure shows average performance across 26 years of hydrologic conditions. For stream temperatures, performance depicts share of months when the optimal temperature objectives are attained.

FIGURE B10

Wet year performance on ecosystem water budget objectives



SOURCE: Developed by the authors.

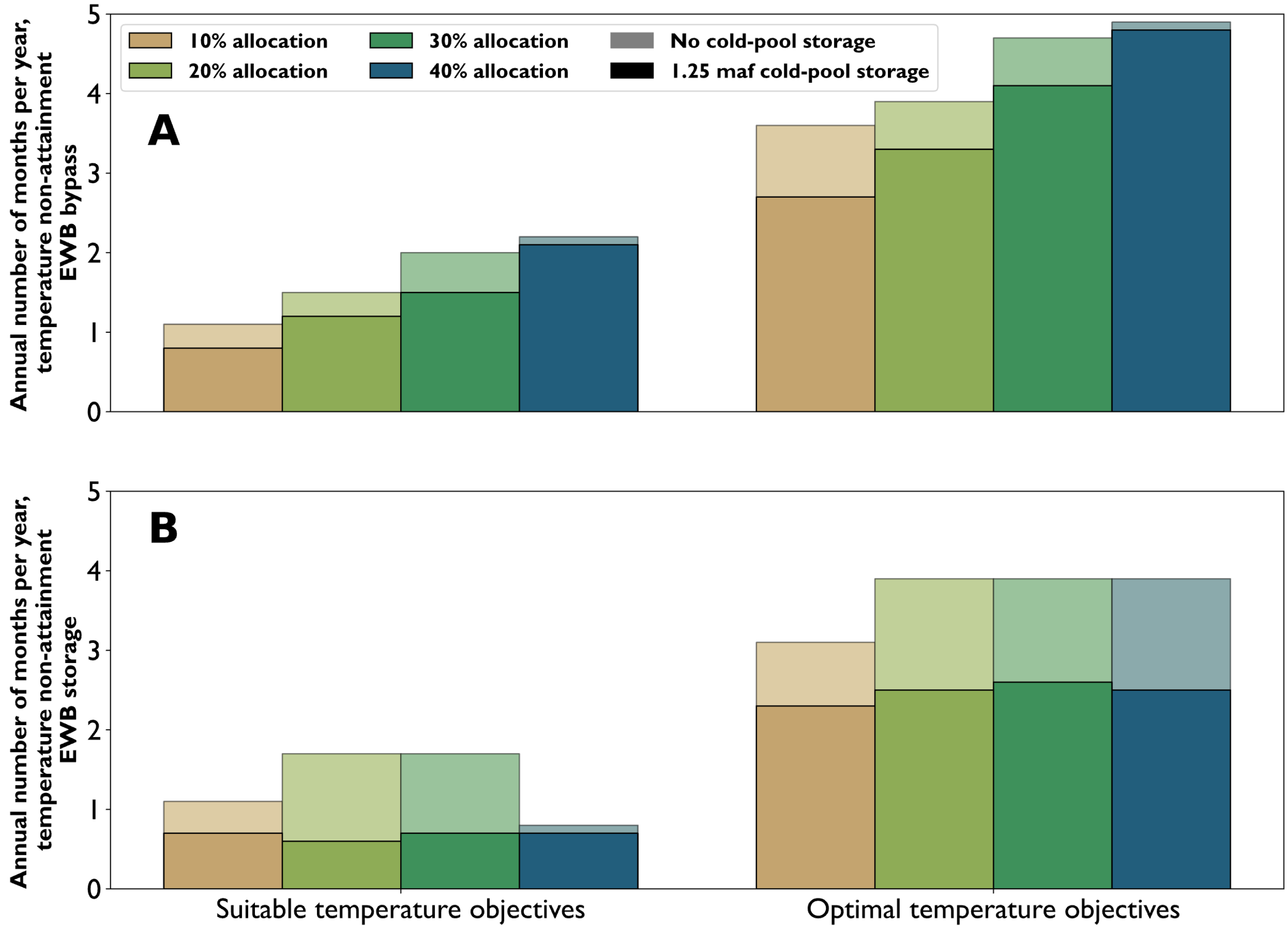
NOTES: Panel a shows EWB objectives with a percentage of EWB bypass flows and 0 maf minimum reservoir storage, panel b shows EWB objectives with a percentage of EWB inflows and a percentage of EWB storage capacity with 0 maf minimum reservoir storage, panel c shows EWB objectives with a percentage of EWB bypass flows and 1.25 maf minimum reservoir storage, and panel d shows EWB objectives with a percentage of EWB inflows and a percentage of EWB storage capacity with 1.25 maf minimum reservoir storage. Wet years include above normal and wet year types. This figure shows average performance across 26 years of hydrologic conditions. For stream temperatures, performance depicts share of months when the optimal temperature objectives are attained.

As the percentage of EWB bypass increased above about 20 percent, performance on temperature objectives worsened as reservoir storage dropped and the cold-water pool was depleted. In dry years, optimal stream temperature objectives were attained about 68 percent of all months with 10 percent EWB bypass flows, but only about 53 percent of the time when EWB bypass flow allocations increased to 40 percent (Figure B9 panel A). In other words, optimal stream temperature objectives could be met in only half of all months with 40 percent EWB bypass. In wet years, the trade-off between ecosystem flow and temperature objectives was reduced, but not eliminated. Optimal stream temperature objectives were attained an average of 73 percent of months with 10 percent EWB bypass flows, and an average of 68 percent of all months with 40 percent EWB bypass flows (Figure B10 panel A). Setting aside a percentage of inflow for EWB bypass while also constraining minimum reservoir storage was marginally useful to preserve cold water at depth in the reservoir (Figures B9 and B10 panel

C). Since EWB deliveries were a percentage of inflows, environmental baseflow and functional flow objectives did not change when minimum reservoir storage was constrained to 1.25 maf.

Recall that the temperature objectives for the EWB, which are enumerated in Table B1, were organized into *suitable* temperatures for salmon and *optimal* temperatures for salmon. Alternatives without EWB storage had worse performance on both temperature objectives than alternatives with EWB storage (Figure B11).

FIGURE B11
Average number of months in which suitable and optimal temperature objectives were not met under different minimum reservoir storage and ecosystem water budget allocation alternatives



SOURCE: Developed by the authors.

NOTES: This figure shows average annual performance across 26 years of hydrologic conditions. Panel a shows results for a bypass EWB, and panel b shows results for an EWB with an allocation of inflow plus storage space.

Allocating a percentage of inflow and a percentage of storage capacity to an EWB is most efficient for meeting EWB objectives.[13] This approach afforded flexibility to meet downstream water temperature and functional flow objectives in many year types. With 20 percent of inflow and 20 percent of storage capacity allocated to an EWB, environmental baseflows were nearly always delivered (Figures B9 and B10 panel b). Functional flows were provided 99 percent of months in dry years (Figure B9 panel b) and 100 percent of months in wet years (Figure

[13] We use the term "efficient" to mean maximizing the ecological return on—or benefits from—the use of water allocated to meet specific ecosystem health objectives.

B10 panel b). However, a trade-off remained between EWB flow and temperature objectives, particularly as the percentage of EWB inflow and percentage of EWB storage increased beyond 10 percent. On average, attainment of stream temperature objectives hovered between 64–73 percent of months in dry years (Figure 9 panel b) and between 71–76 percent of months in wet years (Figure B10 panel b) for all modeled percentages of EWB flows and storage.

In some runs, we managed stream temperatures by preserving the cold-water pool using a minimum reservoir storage constraint. Minimum reservoir storage further improved EWB performance on objectives, since minimum reservoir storage for cold-water preservation is effectively a third EWB asset. Yet even with minimum reservoir storage constrained to 1.25 maf, EWBs with 10 percent of inflow and 10 percent of reservoir capacity did not provide enough water to meet EWB demands (Figures B9 and B10, panel D). There was little buffer or flexibility for critically dry periods, wet years when environmental baseflows were large, or other unforeseen conditions. Ten percent of inflow and 10 percent of storage capacity for the EWB delivered, on average, 83 percent of environmental baseflows and 4 percent of functional flows in dry years (Figure B9 panel D), and 52 percent of environmental baseflows and 14 percent of functional flows in wet years (Figure 10 panel D).[14] When the EWB was allocated 30 percent of inflows and 30 percent of reservoir storage capacity, environmental baseflows were delivered more than 99 percent of the time, on average for wet and dry year types, and functional flows were delivered about 96 percent of the time. When inflows and reservoir storage capacity for the EWB increased to 40 percent, all EWB water demands were met in wet and dry year types. Environmental storage was invaluable for using environmental water effectively.

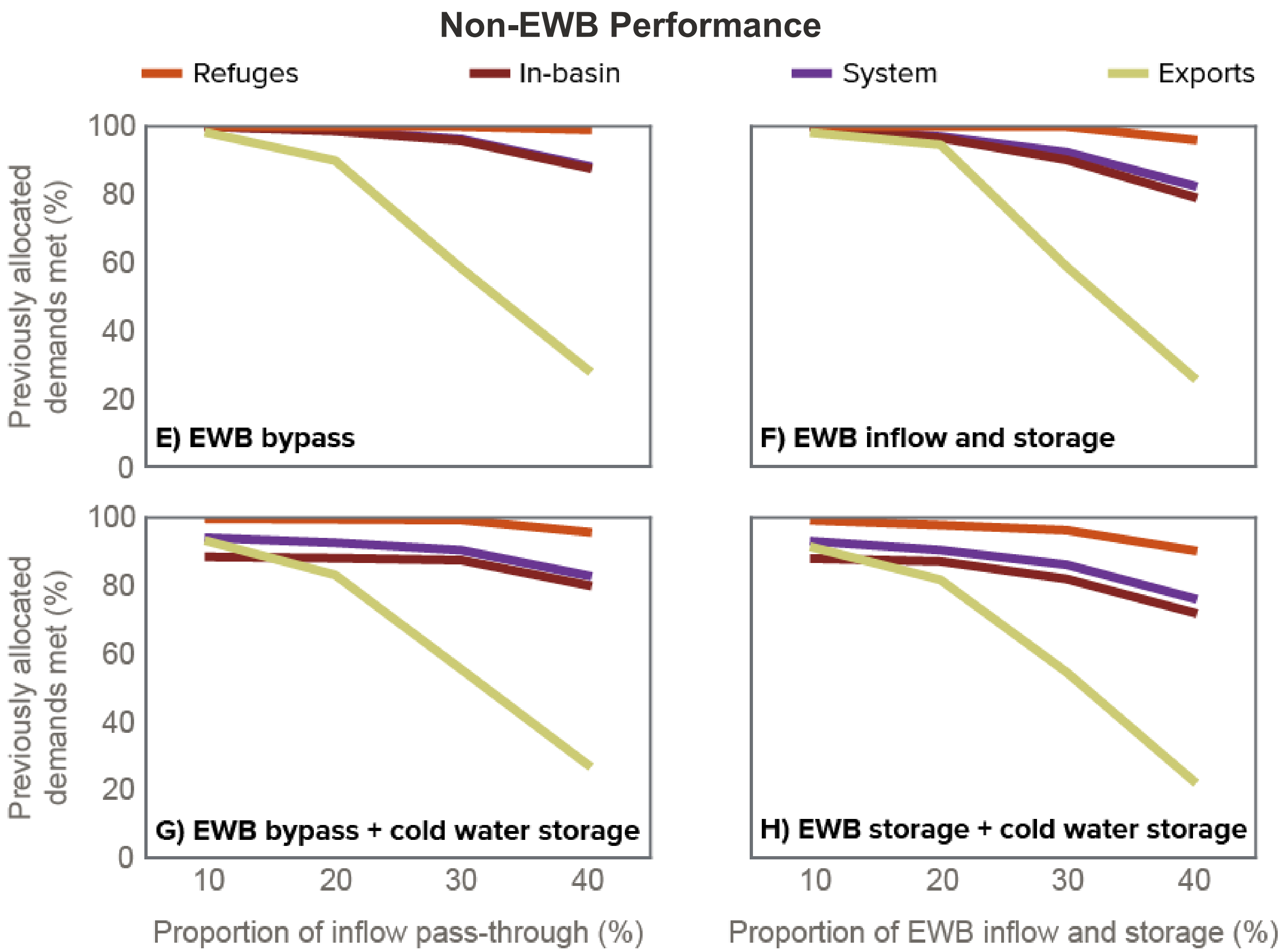
EWB storage capacity and a minimum storage requirement maintained cold water for downstream optimal temperature objectives about 77–80 percent of months across all alternatives and water year types (Figures B9 and B10, panel D). EWB carryover storage naturally increased reservoir storage so that trade-offs between EWB water demands and temperature objectives mostly disappeared (Figure B11 panel B). Our modeling suggests that without EWB storage, a larger allocation to EWB bypass gives a *worse* outcome for temperature.

Performance on Other Water Demands

Larger percentages of inflow allocated to EWB bypass required non-EWB demands (in-basin urban and agriculture, system water, refuges, and exports) to compete for a smaller portion of water. The senior water priorities in our model (in-basin uses, system water, and refuges) incurred average shortages of less than 10 percent of demand, even as bypass flows for the EWB increased toward 40 percent of inflows. In dry years, system water and in-basin demands experienced 12 percent shortages, and refuge demands had shortages of less than 1 percent (Figure B12 panel E). Shortages were greater for refuges in wet years, when refuge demands are higher, but still only reached 7 percent of demand (Figure B13 panel E). Exports, which were modeled as a junior water priority, incurred average shortages of less than 20 percent in wet years, growing to over 70 percent in dry years (Figures B12 and B13 panel E).

[14] As noted above, the percentage of time that environmental baseflows were delivered in wet years dropped because environmental baseflows are larger in wet years than in dry years (Gartrell et al 2017 and 2022).

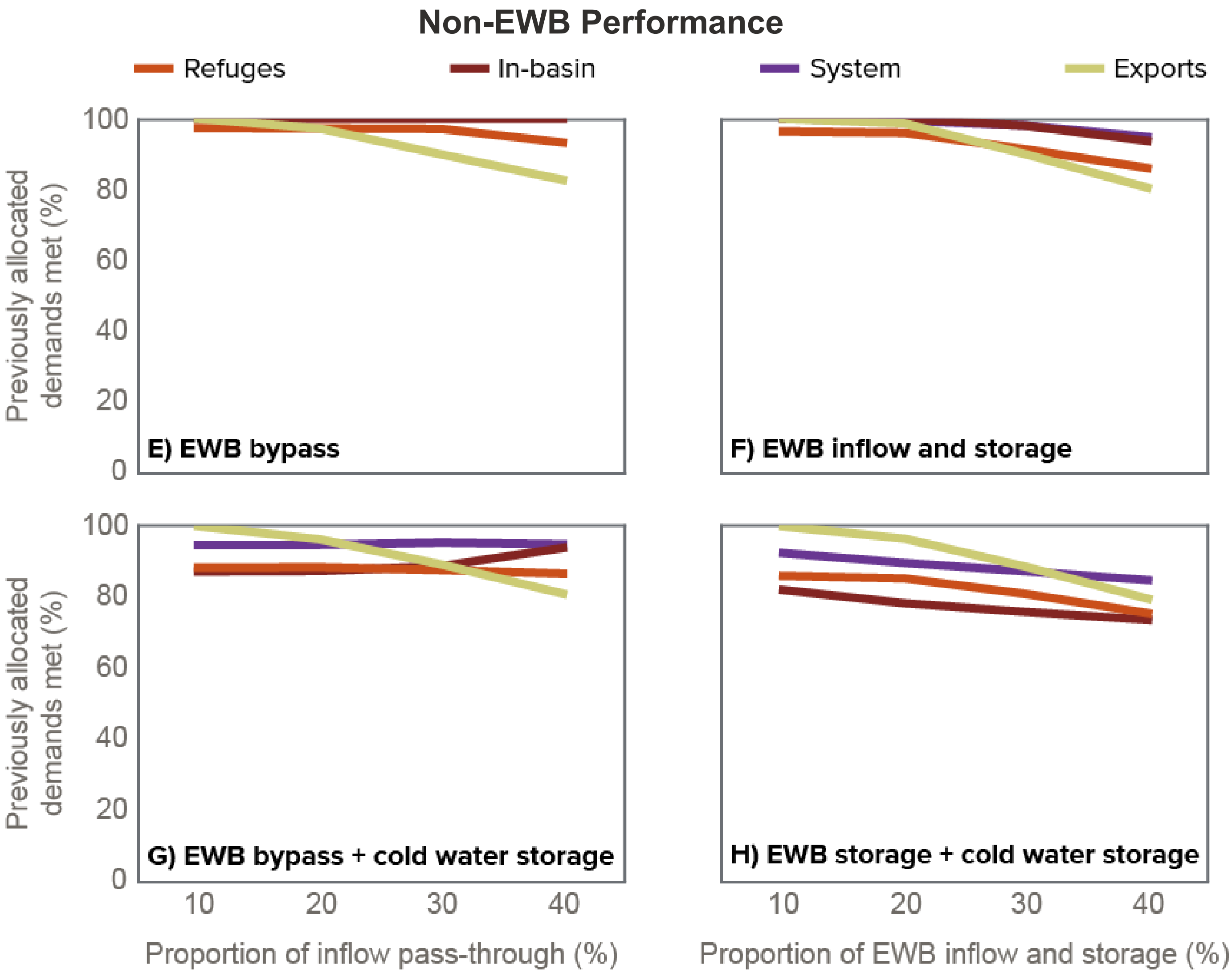
FIGURE B12
Dry year performance on other water demands



SOURCE: Developed by the authors.

NOTES: Panel a shows EWB objectives with a percentage of EWB bypass flows and 0 maf minimum reservoir storage, panel b shows EWB objectives with a percentage of EWB inflows and a percentage of EWB storage capacity with 0 maf minimum reservoir storage, panel c shows EWB objectives with a percentage of EWB bypass flows and 1.25 maf minimum reservoir storage, and panel d shows EWB objectives with a percentage of EWB inflows and a percentage of EWB storage capacity with 1.25 maf minimum reservoir storage. Dry years include critically dry, dry, and below normal year types. This figure shows average performance across 26 years of hydrologic conditions.

FIGURE B13
Wet year performance other water demands



SOURCE: Developed by the authors.

NOTES: Panel a shows EWB objectives with a percentage of EWB bypass flows and 0 maf minimum reservoir storage, panel b shows EWB objectives with a percentage of EWB inflows and a percentage of EWB storage capacity with 0 maf minimum reservoir storage, panel c shows EWB objectives with a percentage of EWB bypass flows and 1.25 maf minimum reservoir storage, and panel d shows EWB objectives with a percentage of EWB inflows and a percentage of EWB storage capacity with 1.25 maf minimum reservoir storage. Wet years include above normal and wet year types. This figure shows average performance across 26 years of hydrologic conditions.

With a percentage of inflows allocated to EWB bypass and 1.25 maf minimum reservoir storage, shortfalls slightly increased for senior water demands (by 6-9 %), depending on the bypass allocated to the EWB (9 % increase for a 10 % EWB allocation, 6 % increase for a 40 % allocation, see Figures B12 and B13 panel G). Average deliveries remained over 85 percent for all demands, even when the EWB was allocated 40 percent of bypass inflows. Refuge demand shortfalls ranged from 11–14 percent depending on the bypass allocation during wet years (Figure B13, panel G), compared to shortages of about 1–5 percent during dry years (Figure B12 panel G).[15] The junior priority export demands experienced considerable shortfalls when the EWB bypass allocation

[15] In our model, refuge demands are smaller in dry years than in wet years, causing wildlife refuge shortages to be smaller in dry years than in wet years.

was set at 40 percent, averaging nearly 40 percent for all year types and reaching 73 percent during dry years (Figure B12 panel G).

When about 30 percent of inflow and 30 percent of storage capacity are allocated to an EWB, non-EWB shortages increase. Dry year shortages are profound for export demands. When 40 percent of inflow and 40 percent of reservoir storage capacity are allocated to an EWB, shortages exceed 20 percent for in-basin urban and agricultural uses in dry years, are near 20 percent for system water, and are less than 5 percent for refuges (Figure B12 panel H). Overall, increasing minimum reservoir storage to manage the cold-water pool has a larger effect on non-EWB demands than EWB demands, because constraining minimum reservoir storage effectively shrunk storage capacity for non-EWB demands and reduced the total volume of water that could be carried over from wet years for use in later years.

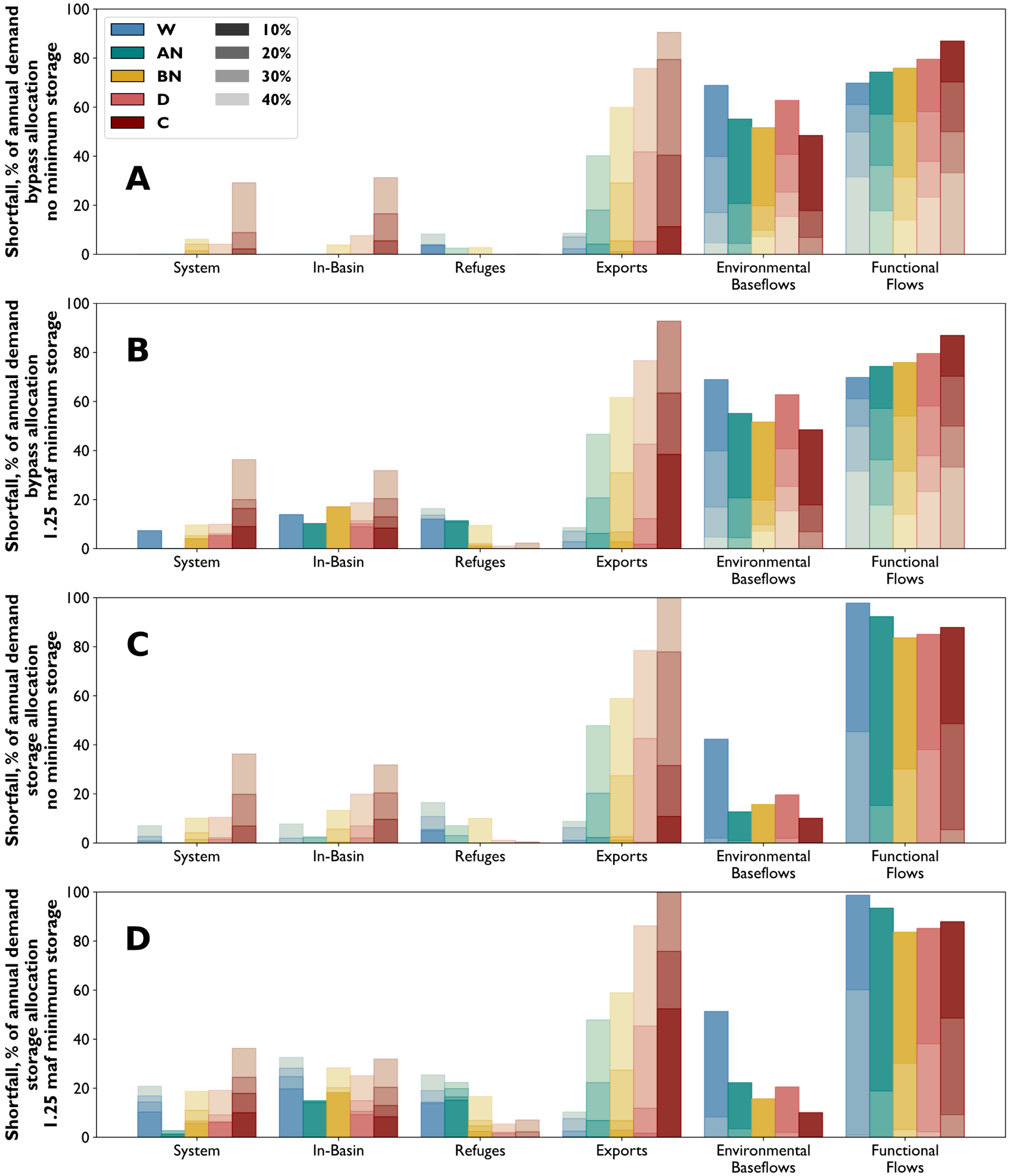
The distribution of shortfalls across water year types was also notable. Shortfalls to each water demand were compared across four alternatives: EWB bypass allocations with and without minimum storage, and EWB inflow and storage allocations with and without a minimum storage requirement (Figure B14). With EWB bypass, senior priorities, including system water, in-basin, and refuge water experienced minimal shortfalls relative to their demands in all year types except in critically dry years when minimum storage was unconstrained (Figure B14 panel A). During critically dry years, even in-basin and system water demands experienced large average annual shortfalls. These shortfalls were caused by increased demand during dry and critically dry years. In drier water year types, limited supplies must be shared with other senior priority demands (system water, refuges, and the EWB). In contrast, EWB shortfalls were largest in wet year types because environmental baseflows—which are set by regulatory criteria—were largest in wet years. For alternatives with 10 percent and 20 percent EWB allocations, reservoir inflows were insufficient to meet EWB demands. Overall, using minimum storage requirements increased shortages for all demands, including environmental baseflows and functional flows when the EWB included a storage allocation (Figure B14 panels B and D). Shortages caused by minimum storage requirements were largest for non-EWB demands, particularly when EWB allocations were also high.

This mismatch between the delivery shortfalls experienced by in-basin uses (highest in critically dry years and when EWB proportions were large) and environmental baseflows (highest in wet years and when EWB proportions were small) suggests that variable allocations, determined as a function of water year type, could reduce overall shortfalls experienced among water demands (e.g., reducing trade-offs between EWB and in-basin demands). Maintaining large EWB allocations in wet and above-normal years would considerably reduce demand shortfalls for both environmental baseflow and functional flow EWB water demands. At the same time, relatively larger allocations for non-EWB demands (in-basin, system water, wildlife refuges, and exports) in drier water year types could reduce shortfalls to those groups. Additional work is recommended to understand if smaller environmental baseflow allocations are inadequate to sustain freshwater ecosystems during severe and prolonged drought.[16]

[16] Gartrell et al. (2022) recommend detailed drought planning for severe droughts with the development of decision trees to allow adequate advanced warning of cutbacks; they also recommend better coordination and development of updated ecosystem regulations that adjust for severe drought conditions that are occurring more frequently.

FIGURE B14

Average annual demand shortfalls for each water demand by water year type



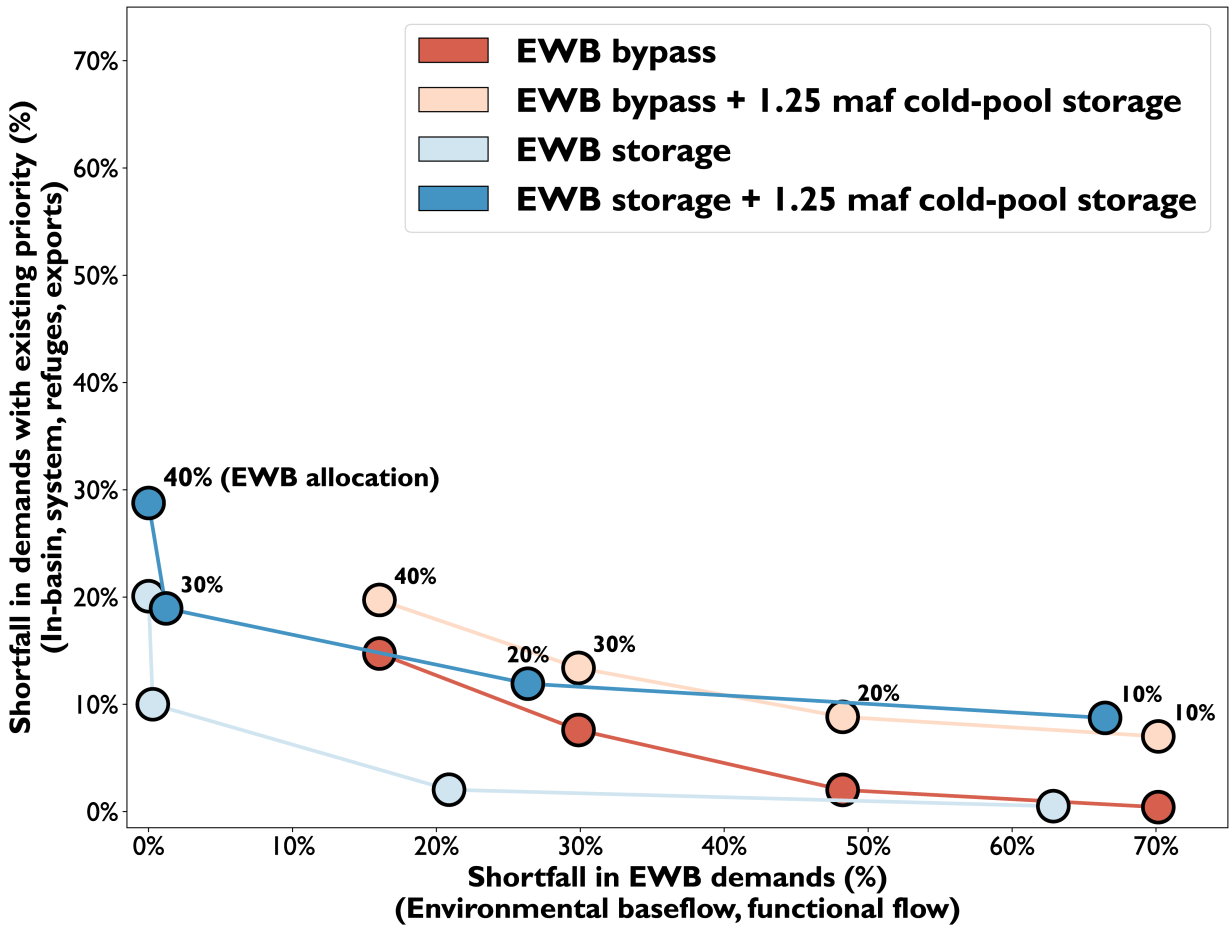
SOURCE: Developed by the authors.

NOTES: This figure shows average annual shortfall across 26 years of hydrologic conditions. Ecosystem water budget assets include a) percentage of bypass with no minimum reservoir storage, b) percentage of inflow with 1.25 maf minimum reservoir storage, c) percentage of inflow and a percentage of reservoir storage capacity with no minimum reservoir storage, and d) percentage of inflow and a percentage of reservoir storage capacity with 1.25 maf minimum reservoir storage.

Trade-offs between EWB and non-EWB demand shortfalls for all four alternatives are shown in Figure B15. As EWB allocations increase—either for bypass or EWB storage—non-EWB shortfalls also increase. When EWB storage and flow allocations exceeded 30 percent, non-EWB demands incur shortages without additional benefits to EWB demands, suggesting that 30 percent of inflow and storage for an EWB may be adequate to meet environmental baseflows and functional flows objectives in our experimental model.

FIGURE B15

Trade-offs between environmental water shortage and other demand shortages



SOURCE: Developed by the authors.

NOTES: This figure shows average annual shortfall across 26 years of hydrologic conditions. The ecosystem water budget was modeled as a portion bypass (warm hues) or a portion of inflow with a portion of reservoir storage capacity (cool hues). Percentages shown with the dots are the share of the EWB allocation of inflows (and in some cases, storage).

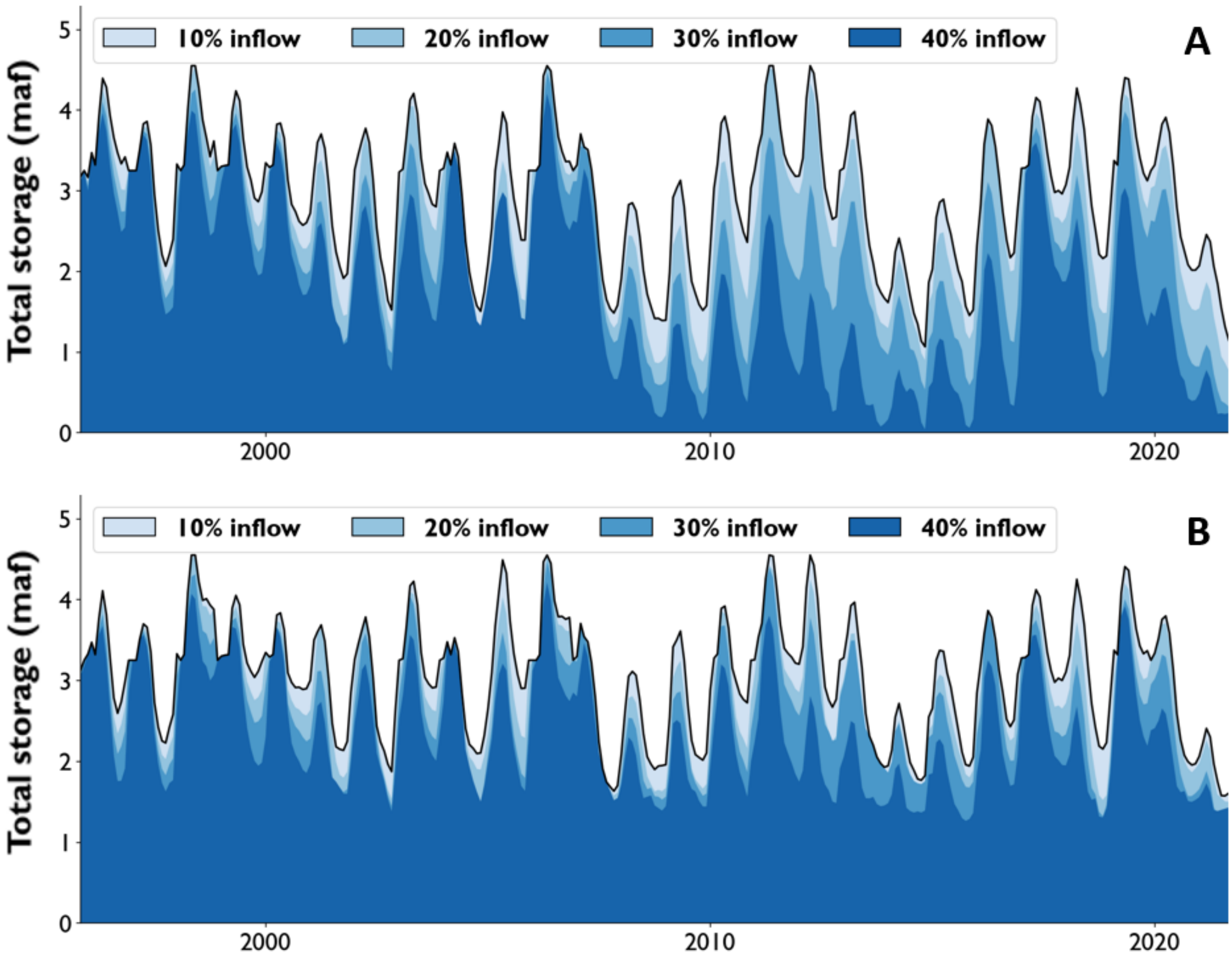
Reservoir Storage and Cold-Water Pool Volume

As EWB bypass percentages increased (Figure B16 panel A), reservoir storage was reduced, and the cold-water pool in the reservoir was depleted (Figure 17 panel A, recent dry years shown in Figure B18 panel A). The latter was true particularly when more than 20 percent of inflows were allocated to EWB bypass. As expected, constraining minimum reservoir capacity increased total reservoir storage (Figure B16 panel B). More reservoir storage preserves cold water, which could allow it to be released to maintain cold-water temperature objectives downstream of the reservoir (Figure B17 panel B, Figure B18 panel B).

Alternatives with a percentage of inflow and a percentage of storage for the EWB maintained higher reservoir levels than bypass flows—even when the EWB was allocated 40 percent of inflow (Figure B19). EWB demands were lowest during the summer dry period, enabling the EWB to carryover storage during summer when other water demands draw down reservoir storage. Increased summer storage provided dual ecosystem benefits, improving the likelihood of meeting winter peak and fall pulse objectives while also maintaining reservoir storage to help meet late summer and fall temperature objectives (Figures B17 panels C and D, Figures B18 panels C and D). When the EWB was allocated 40 percent of inflow and 40 percent of storage capacity—and minimum reservoir storage was implemented—EWB storage was effectively traded for minimum reservoir storage (Figure B19). However, when EWB allocations were smaller—for instance, 10 percent of inflow and 10 percent of reservoir storage capacity—implementing a minimum storage constraint affected non-EWB storage (Figure B20).

FIGURE B16

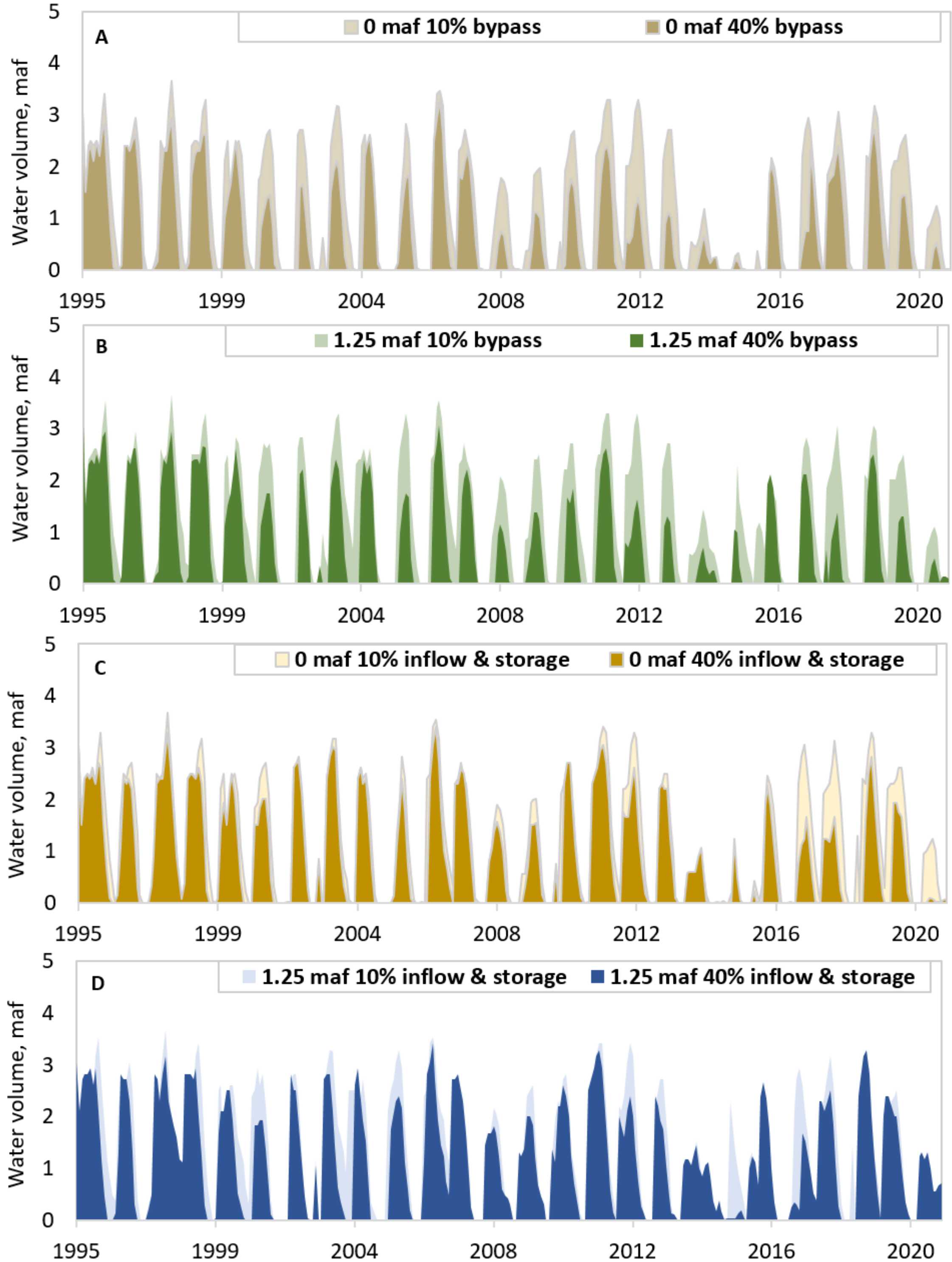
Reservoir storage under different ecosystem water budget bypass alternatives



SOURCE: Developed by the authors.

NOTES: This figure shows average monthly storage for water years 1996–2021 when 10 to 40 percent of inflows were dedicated to bypass with 0 maf minimum reservoir storage (panel A) and 1.25 maf minimum reservoir storage (panel B).

FIGURE B17
Volume of cold water (<= 12 °C) under different ecosystem water budget alternatives

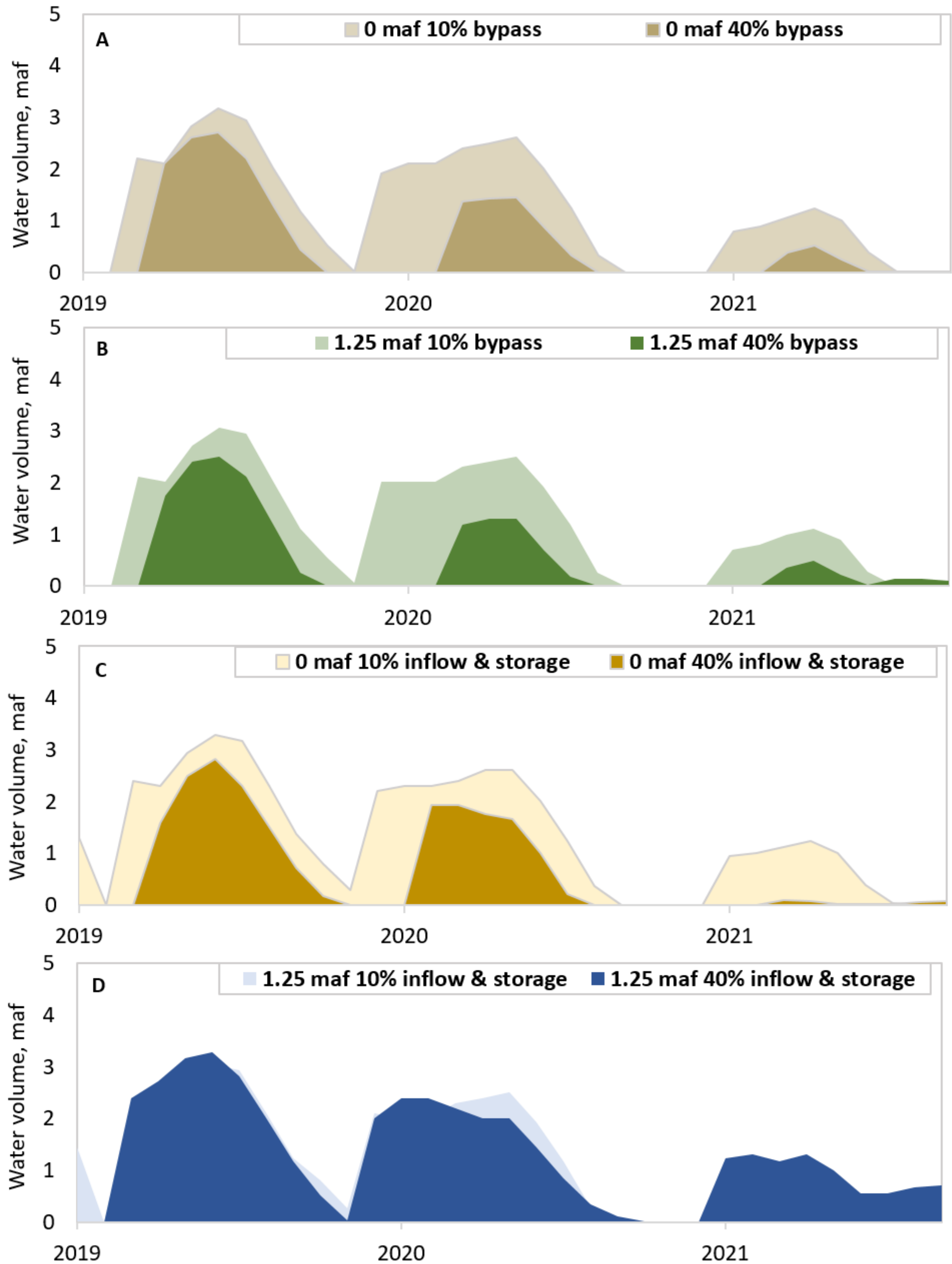


SOURCE: Developed by the authors.

NOTES: Average monthly cold-water volume for water years 1996–2021 with 10 and 40 percent of a) environmental water bypass with no minimum reservoir storage, b) environmental water bypass with 1.25 maf minimum reservoir storage, c) EWB inflow and EWB storage with no minimum reservoir storage, and d) EWB inflow and EWB storage with 1.25 maf minimum reservoir storage. In 2015, water temperature just exceeded 12 °C with 1.25 maf minimum storage, 40 percent of inflow and 40 percent of storage (panel D), whereas water temperature was just under 12 °C with 0 maf minimum storage, 40 percent of inflow and 40 percent of storage (panel C). There was less than 1 °C difference of temperatures at depth in the reservoir between those two alternatives.

FIGURE B18

Volume of cold water (<= 12 °C) in wet year 2019, dry year 2020, and critically dry year 2021 under different ecosystem water budget alternatives

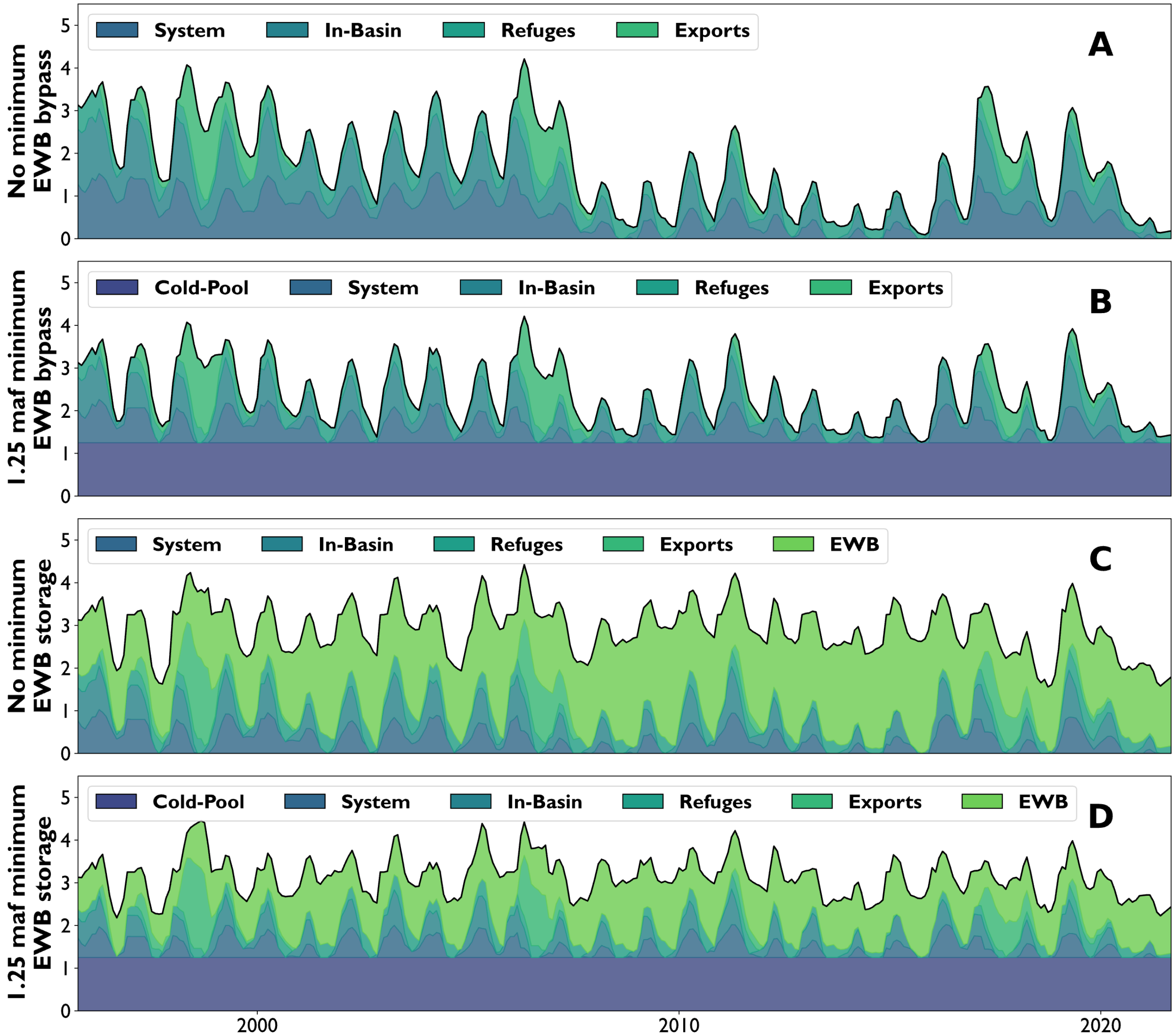


SOURCE: Developed by the authors.

NOTES: Average monthly cold-water volume for water years 2019–21 with 10 and 40 percent of a) environmental water bypass with no minimum reservoir storage, b) environmental water bypass with 1.25 maf minimum reservoir storage, c) EWB inflow and EWB storage with no minimum reservoir storage, and d) EWB inflow and EWB storage with 1.25 maf minimum reservoir storage.

FIGURE B19

Reservoir storage by water demand under different ecosystem water budget alternatives with 40 percent allocations

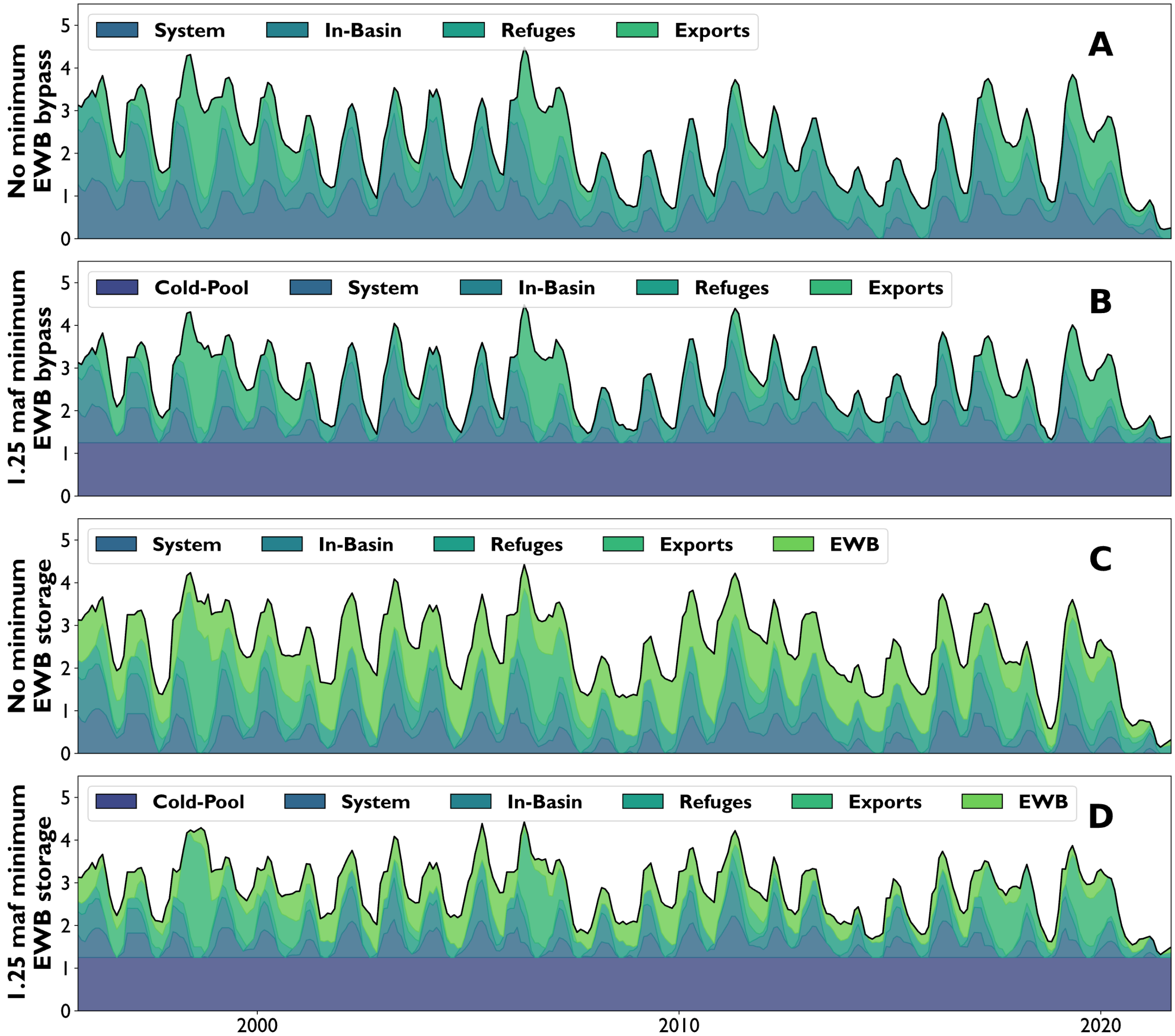


SOURCE: Developed by the authors.

NOTES: This figure shows monthly storage by water demand during water years 1996–2021 with a) 40 percent EWB bypass with 0 maf minimum storage, b) 40 percent EWB bypass with 1.25 maf minimum storage, c) 40 percent EWB inflow and storage with 0 maf minimum storage, and d) 40 percent EWB inflow and storage with 1.25 maf minimum storage.

FIGURE B20

Reservoir storage by water demand under different ecosystem water budget alternatives with 10 percent allocations



SOURCE: Developed by the authors.

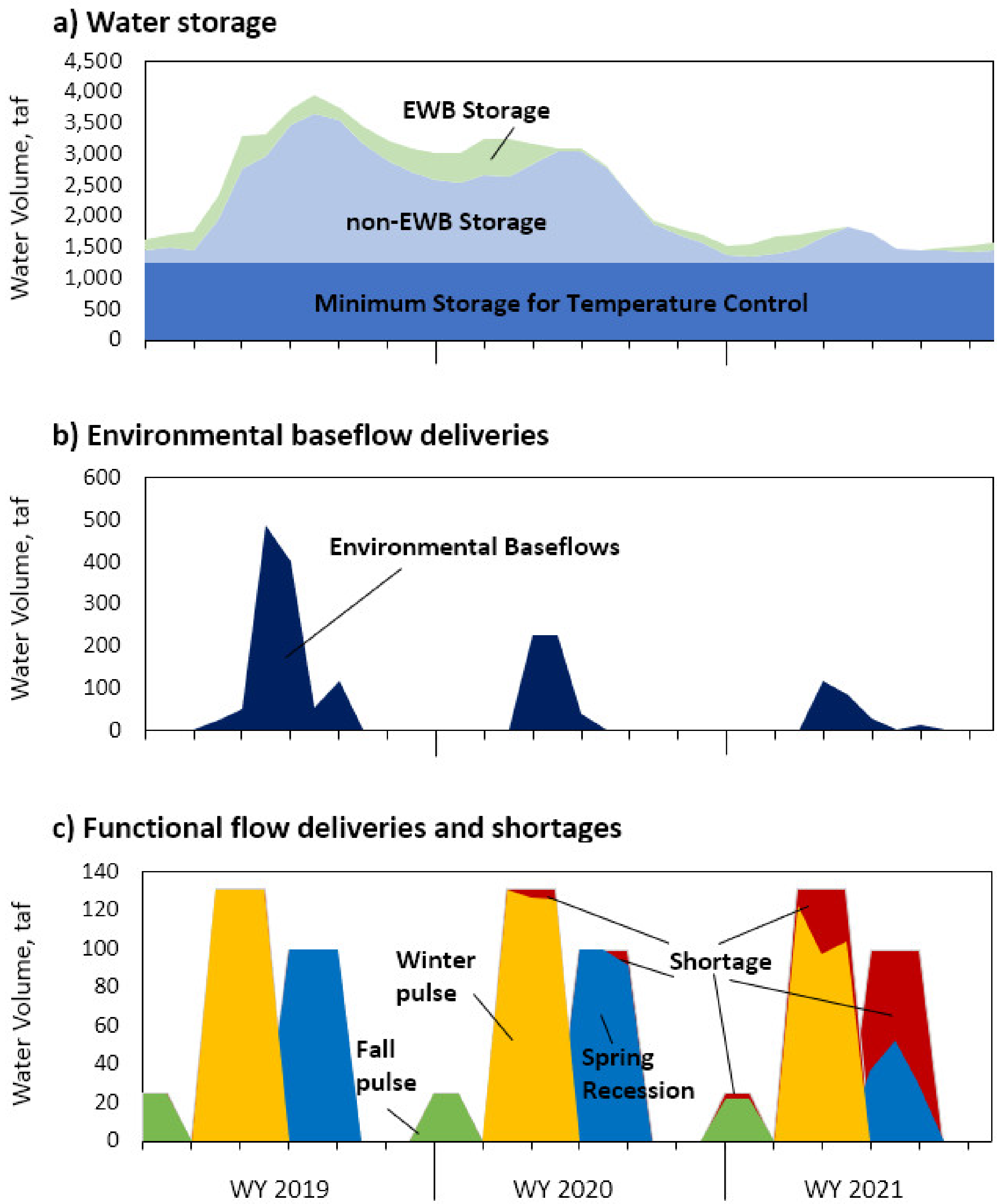
NOTES: This figure shows monthly storage by water demand during water years 1996–2021 with a) 10 percent EWB bypass with 0 maf minimum storage, b) 10 percent EWB bypass with 1.25 maf minimum storage, c) 10 percent EWB inflow and storage with 0 maf minimum storage, and d) 10 percent EWB inflow and storage with 1.25 maf minimum storage.

Example Ecosystem Water Budget Performance in 2019–21

The three-year sequence beginning in 2019—a wet year followed by dry and critically dry years in 2020 and 2021—illustrates the benefits of an EWB that includes a percentage of inflow and a percentage of storage capacity (Figure B21). In this example, we allocated 30 percent of inflow and 30 percent of storage for the EWB, with minimum reservoir storage of 1.25 maf. Figure B21 depicts reservoir operations and volumes of water allocated to environmental baseflows and functional flows over this period. Carryover water stored throughout 2019 and again in the winters of 2020 and 2021 was sufficient to meet environmental baseflow demands fully. (As noted earlier, these demands are lower in dry years, because the model reflects applicable regulatory criteria.) And with a minimum reservoir target of 1.25 maf, the cold-water pool was able to meet downstream temperature standards later in the year, through early autumn. In contrast, as reservoir inflows decreased over this period, the 30 percent inflow allocation that makes up the EWB had less and less capacity to meet functional flow demands, reducing the amount delivered. The significant shortages to non-EWB demands are shown in Figure B14. In 2021, those groups experienced shortfalls ranging from 12 percent (for wildlife refuges) to 92 percent (for exports) of their annual demands. Overall, in the alternative with a 1.25 maf cold-water pool and a 30 percent inflow allocation to the EWB, users with non-EWB allocations experienced a shortfall of 45 percent of their annual demands during 2021, greater than would occur with just an EWB bypass.

FIGURE B21

Environmental storage and deliveries with 30 percent of inflow, 30 percent of storage capacity, and 1.25 maf minimum reservoir storage for the ecosystem water budget, 2019–21



SOURCE: Developed by the authors.

NOTES: Panel A shows water storage, panel B shows environmental baseflow deliveries, and panel C shows functional flow deliveries and shortages over three water years (2019–21).

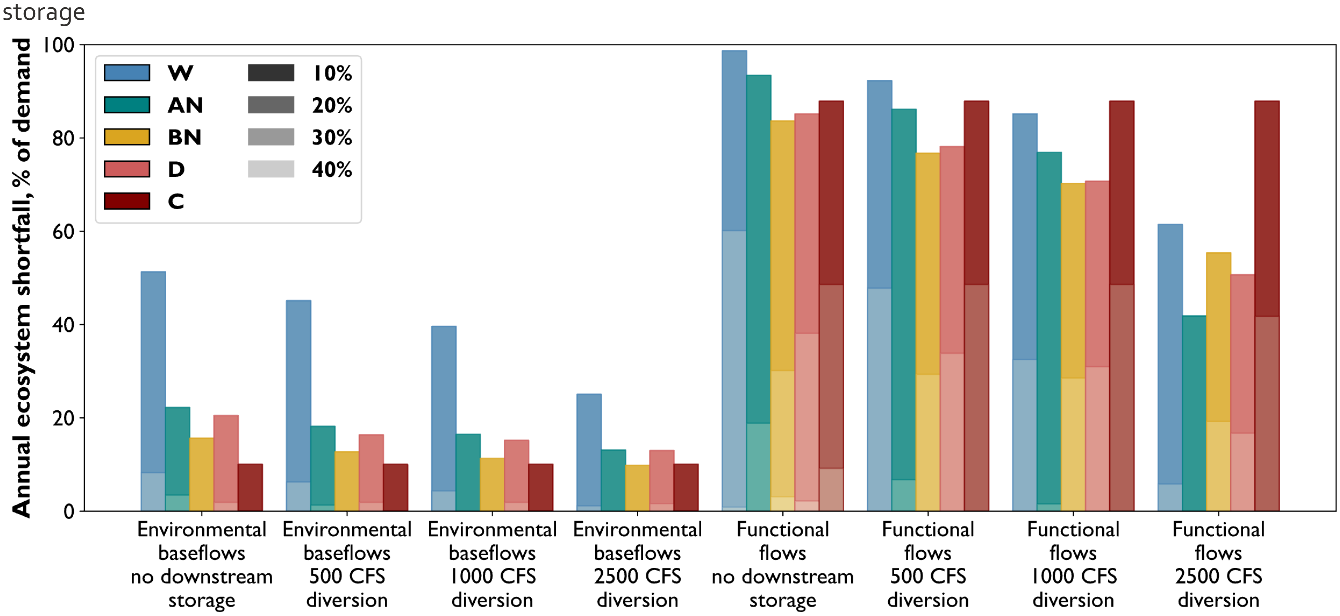
New Environmental Storage

In our final set of model runs, we assumed new downstream storage in which flood releases could be captured after water spilled from the reservoir. The increasing interest in floodplain recharge of groundwater and conjunctive use programs, as well as Proposition 1 funding for new surface and underground storage motivated these runs. As described in the main report and Appendix C, the Water Storage Investment Program (WSIP) of Proposition 1 requires that new storage must include environmental water for public benefit. We did not distinguish here whether the new storage was surface or underground storage. Stored water could be subsequently released to meet EWB demands when assets were insufficient. Figure B22 shows the shortfalls to EWB deliveries using variable assumptions about the diversion rate into the downstream storage and its capacity. Downstream storage was assumed to have a 1.0 maf storage capacity in all alternatives.

Spills were larger and more frequent when minimum reservoir storage was constrained in the original reservoir to preserve cold water. As the diversion rate into downstream storage increased, EWB shortfalls were reduced. Diversions into new downstream storage were available only following brief periods of very high inflows to the upstream reservoir when it spilled to control for flooding. Higher diversion capacities enabled a larger portion of spilled releases to be captured by new downstream storage, increasing overall EWB water supplies. Because only spills were diverted into downstream storage, the additional water stored at the new downstream reservoir did not affect the cold-water pool in the hypothetical upstream reservoir or water available for other demands. Diversion rates of 1,000 cfs (equivalent to approximately 60 taf/month) provided enough storage to nearly eliminate shortfalls to environmental baseflow objectives, and 2,500 cfs (150 taf/month) provided enough storage to nearly eliminate shortfalls to functional flow objectives. This exercise illustrates that new EWB storage would be useful to manage diverse and sometimes competing EWB objectives and would reduce competition with other water demands.

FIGURE B22

Average annual demand shortfalls for environmental baseflow and functional flow objectives with new downstream storage



SOURCE: Developed by the authors.

NOTES: This figure shows average annual shortfall across 26 years of hydrologic conditions for water year types at different diversion rates of spill from the upstream reservoir into new downstream storage. The EWB allocations of inflow and storage in the upstream reservoir range from 10 to 40 percent, with 1.5 maf minimum reservoir storage for cold-water pool.

Summary

Our modeling revealed important insights into how to operate a reservoir that sets ecosystem water budget demand as a primary objective, rather than as a constraint on water supply operations. Based on these results we draw the following conclusions:

- Allocating a percentage of inflow and a percentage of operable storage to an EWB was most efficient for meeting EWB objectives. EWB storage capacity reduced trade-offs among environmental objectives (e.g., water temperatures versus environmental baseflow versus functional flows) that would occur if the EWB was comprised entirely of bypass flows.
- Although temperature management in reservoirs is challenging regardless of the approach, an EWB with only bypass flows created the greatest threat to reservoir cold-water pool. Setting minimum reservoir levels reduced the impacts on water temperature, albeit with costs to EWB and non-EWB objectives. In contrast, creating an EWB with reservoir storage space to manage environmental water on top of minimum reservoir levels did a better job of meeting EWB objectives.
- New surface or underground environmental storage was broadly useful meeting diverse environmental objectives (e.g., environmental baseflows, water temperature, and functional flows). New environmental storage shows promise for capturing reservoir spills produced, in part, from increasing minimum reservoir storage to increase the likelihood that cold water will be held in storage

Our model was quite simple, intended as a proof-of-concept to understand and compare how percentages of inflow and percentages of storage capacity allocated to an EWB could benefit environmental objectives and impact other water demands. It is not intended to be used as a guide for setting specific standards. We did identify "knees" or breakpoints in trade-offs (Figure B15), however, that merit further exploration with more detailed modeling. Knees suggest promising areas for compromise, where decision makers are more likely to cooperate (Null et al. 2021a). Sophisticated water management and water temperature models exist for California's reservoirs and intertied water system.[17] Those models should be applied to further scrutinize and elucidate the potential benefits and impacts of EWBs in real systems.

As the main report explains, without a change in management policies that incorporate both ecosystem water budgets and reservoir storage capacity to effectuate the EWBs, freshwater ecosystems downstream of large dams will be increasingly vulnerable to climate warming and related changes including declining snowpack, increased hydrologic volatility, shifting wet and dry seasonality, and sea level rise. Previous studies have shown that regulatory environmental flows are likely to be significantly affected by climate warming (Null and Prudencio 2016), and reservoirs will be increasingly needed to maintain environmental flows—especially during drought (Gartrell et al. 2022). Establishing EWBs for California's principal reservoirs, and the storage capacity to manage them, would provide a hedge against future drought and climate variability and create a buffer against forecasting, modeling, or operational errors in reservoir management (Mount et al. 2017; Null et al. 2021b).

[17] Models include CalSim, CalLite, CALVIN, the Central Valley Project Water Temperature Modeling Platform, and others.

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