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RESEARCH

Clarifying Effects of Environmental Protections on Freshwater Flows to—and Water Exports from—the San Francisco Bay Estuary

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ABSTRACT

Understanding and resolving conflicts over management of scarce natural resources requires access to information that helps characterize the problem. Where information is lacking, perceived differently by stakeholders, or provided without relevant context, these conflicts can become intractable. We studied water management practices and constraints that affect the flow of water into and through the San Francisco Bay estuary—home to six endangered fish species and two water export facilities owned by the state and federal governments that serve millions of people and large expanses of agricultural land in California. Media reports reflect widely held beliefs that environmental regulations, and particularly protections for endangered fish species, frequently limit water diversions and substantially increase freshwater flow to San Francisco Bay. We analyzed long-term trends in freshwater flow to San Francisco Bay relative to annual runoff from its Central Valley watershed, and the frequency and magnitude of specific regulatory and physical constraints that govern operations of the water export facilities. We found that the percentage of Central Valley runoff that reached San Francisco Bay during the ecologically sensitive winter-spring period declined over the past several decades, such that the estuary experienced drought conditions in most years. During a 9-year period that included a severe natural drought, exports were constrained to maintain salinity control as often as to protect endangered fish populations. Salinity-control and system-capacity constraints were responsible for Delta outflow volumes that dwarfed those related to protection of fish and wildlife populations, endangered or otherwise. These results run counter to common media narratives. We recommend rapid synthesis and easily accessible presentation of data on Central Valley water diversions and constraints on them; such data should be contextualized via comparison to regional hydrology and water management system capacity.

KEY WORDS

Endangered Species Act, Clean Water Act, environmental water, ecosystem management, Chinook Salmon, Delta Smelt, drought, environmental conflict, San Francisco Bay estuary, water supply

INTRODUCTION

Conflicts between protecting and consuming natural resources become more intense as the resources become scarce (Nie 2003). Endangered species management illustrates this relationship (Doremus and Tarlock 2008). Managing or resolving such conflicts requires access to information that helps decision-makers and the public understand the conflict, identify potential solutions, and evaluate trade-offs among proposed actions. Where information is lacking, misunderstood, or perceived by stakeholders differently, resource conflicts may become intractable (Redpath et al. 2015). Furthermore, without relevant data and analyses, resource conflicts may be exacerbated in the media as conflict is highlighted to sensationalize it rather than educate the public (Redpath et al. 2013; Olson 2009).

In California's Central Valley, applying fresh water to protect ecosystems rather than for agricultural and municipal uses exemplifies how conflicts can be exacerbated by assumptions formed when relevant information is inaccessible or obscure (Gartrell et al. 2017). The Central Valley watershed is the site of hundreds of large dams and water diversions that capture runoff for consumption, flood control, and hydropower generation. The two largest diversions are water pumping facilities of the federal Central Valley Project (CVP) and State Water Project (SWP), which facilitate inter-basin transfer of water (export) from the Sacramento River and its tributaries to the San Joaquin Valley and municipalities in the Bay Area and southern California. (Frequently used terms and acronyms are defined in Table 1.) These export pumps partially supply approximately 25 million Californians and roughly 1.2 million hectares (3.0 million acres) of agriculture (PPIC 2016). Central Valley runoff that is not diverted or stored flows into the San Francisco Bay estuary.

Water management infrastructure and operations in the Central Valley have contributed to the severe decline of native fish and aquatic wildlife species over the last half-century (Moyle 2002; Lindley et al. 2006; SWRCB 2010). The estuary and its Central Valley watershed are home to a unique assemblage of species, including fish populations that support commercial and recreational fisheries (Moyle 2002). Many fish and aquatic wildlife populations display strong correlations between abundance or recruitment and freshwater flows through the estuary during winter and spring (e.g., Kimmerer 2002; MacNally et al. 2010; SWRCB 2017). Populations of six native fishes that are listed as threatened or endangered under either or both the federal or state Endangered Species Acts (ESAs) rely on fresh and low-salinity regions of the estuary to complete parts of their life cycle, including Longfin Smelt (*Spirinchus thaleichthys*), Delta Smelt (*Hypomesus transpacificus*), Central Valley Steelhead (*Oncorhynchus mykiss*), Green Sturgeon (*Acipenser medirostris*), and winter-run and spring-run Chinook Salmon (*Oncorhynchus tshawytscha*). To protect these imperiled species, other flow-dependent fisheries and wildlife populations, a variety of human uses, and the water management infrastructure itself, the SWP and CVP (collectively, "the projects")—and particularly their water export facilities—are regulated by a suite of laws, including the ESAs, the federal and state Clean Water Acts, and the federal Rivers and Harbors Act.

Despite the economic importance and ecological effects of water exports, it is difficult to determine what constrains the amount of water exported by the projects at any given time (Gartrell et al. 2017). The lack of public access to information on the diversity, intended benefits, and the specific effects of constraints on the projects' water exports has led to widely-held beliefs about environmental applications of water in California. In the news media, competing demands for Central Valley water supplies are commonly framed as a struggle between agriculture and endangered fish (e.g., Kasler and Sabalow 2016; Worth and Mizner 2017). In particular, ESA protections for Delta Smelt are frequently identified as the main cause of reduced water deliveries from the projects' water export facilities (e.g., Parker and Fong 2009). This framing centers on claims about applications of water for ecosystem protection, including: (1) that environmental regulations imposed over the last 3 decades resulted in substantial increases in the runoff from the Central Valley that reaches San Francisco Bay; (2) that ESA regulations are the most common limit on project water exports; and (3) that ESA regulations are the principal constraint on the volume of Project water

Table 1 Frequently used terms and abbreviations

Term	Abbreviation	Description
Actual Delta outflow	---	Net Delta Outflow Index calculated from a Delta water balance found in the Dayflow database (CDWR 2018b)
Additional uncaptured outflow	AUO	Volume of Delta outflow on a given day that exceeded daily capacity of the project water export system
Biological Opinion	BO	Regulatory review under the Endangered Species Act by the U.S. Fish and Wildlife Service or National Marine Fisheries Service regarding effects of Central Valley Project and State Water Project water export operations on one or more endangered species
California Department of Water Resources	CDWR	State agency responsible for managing the State Water Project
Central Valley Project	CVP	Series of federal dams, diversions, and canals, including large water export pumps in the southern Delta
Central Valley Project Improvement Act of 1992	CVPIA	Federal legislation that redefined the CVP purpose and applied 0.987 $10^9 m^3$ (0.8 maf) of annual project yield toward implementing the ecosystem protection purposes (CVPIA §3406 b(2))
Endangered Species Act	ESA	Federal or state versions of a law that protects listed species that are regarded as in danger of extinction
Hydraulic salinity barrier	HSB	The maintenance of freshwater conditions in the Delta, as required by the Bay–Delta Water Quality Control Plan, achieved when Delta outflows move the estuarine salinity field to the west
Old and Middle River flows	OMR	Tidally averaged net rate of flow in the Old and Middle River distributaries of the San Joaquin River. As a result of reduced flow into the Delta and project water exports, OMR is commonly negative (indicating net flow away from San Francisco Bay). The RPAs for endangered anadromous fish (NMFS 2009) and Delta Smelt (USFWS 2008) limit the magnitude of negative flows under certain conditions during particular times of year.
Reasonable and Prudent Alternative	RPA	Section of a Biological Opinion that describes a suite of actions and operations required to avoid jeopardy to endangered species
State Water Project	SWP	Series of state-owned dams, diversions, and aqueducts, including large water export pumps in the southern Delta
State Water Resources Control Board	SWRCB	State agency responsible for developing and implementing water quality standards in compliance with federal and state Clean Water Acts
System capacity	---	Maximum allowable volume of daily project water exports from the South Delta, as constrained by physical limits (of pumps, canals, and storage facilities) and by requirements of the U.S. Army Corps of Engineers and Project water rights permits
Temporary urgency change order	TUC	Temporary waiver of standards in the Bay–Delta Water Quality Control Plan issued by the State Water Resources Control Board
Bay–Delta Water Quality Control Plan	WQCP	Plan produced under state and federal Clean Water Acts that sets water quality standards for San Francisco Bay and the Delta
Bay–Delta Water Quality Control Plan, fish and wildlife	WQCP F&W	Flow and salinity standards of the Bay–Delta Water Quality Control Plan intended for the general protection of estuarine fish and wildlife populations
Unimpaired Delta outflow	---	Index of Central Valley discharge to San Francisco Bay that would occur in today's landscape absent storage, diversions, or imports

exports—and are thus responsible for most water that flows from the Central Valley to San Francisco Bay.

To investigate the accuracy of these claims, we compared estimated total Central Valley runoff during the winter and spring for each year in the 89-year period of recorded data to the estimated volume of runoff that actually reached San Francisco Bay each year during the winter and spring, and we quantified the frequency and magnitude of factors that restricted daily water exports in a 9-year period during which current ESA regulations were in effect (2010-2018). To analyze volumetric effects, we expanded on an accounting framework and approach described by Gartrell et al. (2017) that attributed freshwater flow volumes to various water supply system and/or ecosystem requirements. Our analyses differed from previous efforts to account for Central Valley environmental water in that we: (1) placed different applications of water in the context

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of hydrological conditions throughout the Central Valley; (2) analyzed empirical data on the source of project water export constraints for each day of a 9-year study period; and (3) accounted separately for different sub-categories of environmental protection, including those provided by the state and federal ESAs and Clean Water Acts. Our objective was to better understand the role of environmental safeguards in controlling water exports from—and freshwater flows through—the San Francisco Bay estuary.

METHODS

Study Area

San Francisco Bay's Central Valley watershed covers over one-third of California's landmass. Runoff from mountain ranges that surround the Central Valley drains to the San Francisco Bay estuary, which includes the Sacramento–San Joaquin Delta (Delta), the embayments which form the San Francisco Bay, and the adjacent Pacific Ocean (Figure 1). Runoff is stored and diverted throughout the Central Valley; the largest diversions are the CVP and SWP water export facilities in the southern Delta. On average, since 1967, these pumping plants exported $5.427\ 10^9 m^3$ (4.4 million acre-feet; maf) of water per year (CDWR 2018b; USBR 2019b). Regulations that protect Delta water quality for municipal, industrial, and agricultural uses—and the estuarine ecosystem—include minimum Delta outflow rates that modify the position of the estuarine salinity field.

We conducted three analyses to investigate how hydrologic conditions, diversions, and constraints on diversions affected Delta outflow. The first was to determine whether Delta outflow increased relative to Central Valley runoff (proportional Delta outflow) in response to new environmental protections applied in recent decades. In this analysis, we compared estimates of actual Delta outflow during the years 1930–2018 with the estimated volume of Central Valley runoff that would flow through the Delta in those years if there were no dams, diversions, or exports. This long-term analysis also provided geographical, hydrological, and historical context for our focused and detailed analyses of project export operations. To understand the specific effect of recent regulations on Delta exports and proportional Delta outflow, we conducted two additional analyses. First, we tabulated factors that governed daily project exports in years 2010–2018, using information produced by the California Department of Water Resources (CDWR), the U.S. Bureau of Reclamation (Reclamation), the State Water Resources Control Board (SWRCB), and fisheries management agencies. This let us evaluate the relative frequency of different constraints on project water exports from the Delta during all complete water years to date in which current ESA regulations for fish species in this estuary have been in place. (Unless otherwise noted, years refer to "water years," which run October–September and are named for the calendar year in which they end). Second, to assess the volumetric influence of different project water export constraints on Delta outflow during 2010–2018, we parsed the incremental effects of various regulatory and physical factors that limited daily project water export volumes.

Proportional Delta Outflow

For each year from 1930 to 2018, we compared the volume of fresh water that reached San Francisco Bay (actual Delta outflow) during February–June to the estimated volume of runoff from the Central Valley (unimpaired Delta outflow) during those months (CDWR 2016, 2018a, 2018b; USBR 2019b). We studied Delta outflow during February–June because flows during this period are ecologically important, highly modified, and subject to numerous regulations. These months correspond to important life-history transitions for a variety of species that live in or migrate through the estuary (Moyle 2002; SWRCB 2017). Flows into and through the Delta are highly modified during February–June because reservoirs are filled in the winter and early spring for later water deliveries (Hutton et al. 2017). As a result, most regulations that govern freshwater flow from the Central Valley to San Francisco Bay to protect fish and wildlife are in effect during February–June, making this a key time-period to explore how environmental protections affect Delta outflow and water project exports.

We employed estimated monthly indices of both net actual Delta outflow and unimpaired Delta outflow (CDWR 2016, 2018a, 2018b; USBR 2019b).

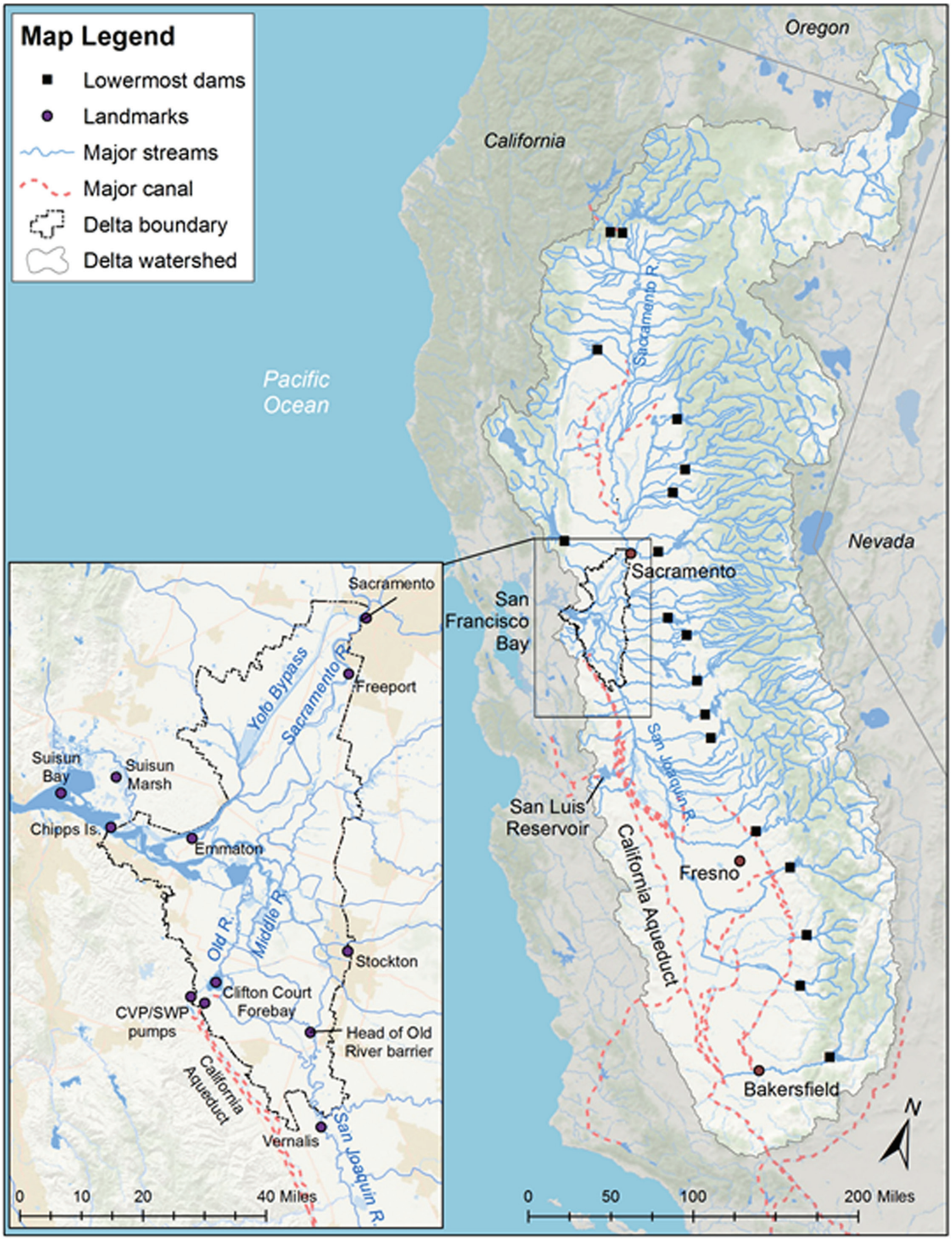

Figure 1 San Francisco Bay and its Central Valley watershed, including components of the water management projects and key locations mentioned in this paper. The black dotted line defines the legal boundaries of the Delta.

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Unimpaired Delta outflow estimates the water volume that would reach San Francisco Bay from the Central Valley in the current landscape if there were no dams and diversions upstream. Although streamflows that would occur without the influence of water management or modern land use patterns (natural flows) have been estimated (e.g., Zimmerman et al. 2017), we use unimpaired Delta outflow. This is because the statistically significant relationships between flow (or its functional correlates) and focal species' population dynamics (e.g., Kimmerer 2002; Mac Nally et al. 2010; SWRCB 2017) have been documented in this ecosystem since the historical landscape was replaced by current land use patterns and channel geometries; this metric is also locally well established and accessible. Unimpaired Delta outflow provides an index of hydrology in the Central Valley and, when compared to actual Delta outflows, reveals the net effect of water storage, diversion, and project water export operations on Delta outflow. The unimpaired data series was last updated through 2014 (CDWR 2016); however, it is very closely correlated with other measures of Central Valley runoff (the difference being that unimpaired Delta outflow estimates runoff downstream of major Central Valley reservoirs). We extended the 1922–2014 unimpaired data set to include 2015–2018 by applying a regression that related unimpaired Delta outflow to the sum of flows in the ten rivers that make the largest contribution to the Delta (10 River Index) as follows:

$$\text{Unimpaired Delta outflow}_{\text{Feb–Jun}} = 1.31(\text{10 River Index}_{\text{Feb–Jun}}) - 2270.96 \; (R^2 = 0.99;\; p < 0.001;\; n = 93). \quad (1)$$

We assessed trends through time in proportional Delta outflow in two ways. First, we used Kendall's rank correlation (Kendall's Tau) to identify trends in the percentage of unimpaired Delta outflow during the 1930–2018 period and in two sub-periods: 1968–1994 (after the onset of major SWP export operations in the south Delta) and 1995–2018 (after a revision of water quality regulations in the Bay–Delta Water Quality Control Plan (WQCP) by the State Water Resources Control Board [SWRCB]). Second, we evaluated changes in the frequency of categories of annual hydrology across three different time-periods. We categorized water years based on quintiles of February–June unimpaired Delta outflows derived from the 1922–2016 data series (CDWR 2016, 2018a; USBR 2019b). For this analysis, we labeled water year type categories, as follows: "wettest" (80^{th}–100^{th} percentile); "above average" (60^{th}–79^{th} percentile); "average" (40^{th}–59^{th} percentile); "below average" (20^{th}–39^{th} percentile); and "dry" (0–19^{th} percentile). In addition, we identified a sub-category of dry years that represented the driest 2% of years, which we called "super critically dry." We then categorized actual Delta outflow in February–June of each year using the same thresholds that defined water year types based on unimpaired Delta outflow; this allowed us to analyze changes in the frequency of hydrologic conditions that organisms downstream of the Delta experienced. We tabulated the frequency of different water year types in the unimpaired and actual Delta outflow data sets for three time periods that corresponded to major changes in water diversion infrastructure and management: 1930–1967 (before major SWP export operations in the south Delta); 1968–1994; and 1995–2018.

Frequency of Different Constraints on Project Water Exports

To determine how often regulations to protect endangered species limited project water exports, we identified the single most restrictive constraint on project water exports for each day during water years 2010–2018, as follows. We reviewed several sets of agency reports, including: CDWR daily Executive Operations Summaries (CDWR 2018c); Delta Operations for Salmonids and Sturgeon reports (NMFS 2018); Smelt Working Group notes (USFWS 2018); and annual CVPIA b(2) water accounting reports (USBR 2019a). In most cases, these sources specified the constraints that governed daily project water exports. The complexity of multiple regulatory and infrastructure constraints—combined with frequent temporary modifications to regulations, non-standardized reporting, and the preliminary nature of the CDWR Executive Operations Summaries—meant that these reports sometimes presented ambiguous or conflicting information about factors that governed exports on a given day. Therefore, we cross-checked the governing factors identified in these sources by comparing exports, Delta outflow, and salinity data (CDWR 2018a, 2018b; USBR 2019b) with underlying protections for endangered species (NMFS 2009;

Table 2 Categories and sources of potential constraint on project water exports in the South Delta

Constraint category *(reference in text)*	Law *(responsible agency)*	Specific regulation *(sub-category abbreviation)*	Description
Infrastructure/hydrologic *(System capacity)*	Clean Water Act of 1972; Porter–Cologne Water Quality Control Act of 1969 *(State Water Resources Control Board; U.S. Environmental Protection Agency)*	SWRCB 2000	Central Valley Project export limit: • 130.26 $m^3 s^{-1}$ (4,600 $ft^3 s^{-1}$), but as low as 121.76 $m^3 s^{-1}$ (4,300 ft^3 s-1) due to physical deterioration State Water Project export limit: • 189.16 $m^3 s^{-1}$ (6,680 $ft^3 s^{-1}$), (3-day average) October through mid-December & mid-March-June; • 189.16 $m^3 s^{-1}$ (6,680 $ft^3 s^{-1}$) (3-day average) + 1/3 of San Joaquin River Flow up to maximum 291.66 $m^3 s^{-1}$ (10,350 $ft^3 s^{-1}$), mid-December through mid-March
	Rivers and Harbors Act of 1899, §10 *(U.S. Army Corps of Engineers)*	USACE 2013	State Water Project export limit: 203.30 $m^3 s^{-1}$ (7,179 $ft^3 s^{-1}$) (3-day average) July-September
Water quality for agricultural and municipal use *[Hydraulic salinity barrier (HSB)]*	Clean Water Act of 1972 & Porter–Cologne Water Quality Control Act of 1969 *(State Water Resources Control Board; U.S. Environmental Protection Agency)*	SWRCB 2000, 2006 as modified by SWRCB c2019	When exports were limited for "salinity control", Delta outflow required to maintain HSB was assumed to equal actual Delta outflow. When other factors limited exports, Delta outflow required to maintain HSB was assumed to be 135.92 $m^3 s^{-1}$ (4,800 $ft^3 s^{-1}$)
Fish and wildlife *(WQCP F&W)*	Clean Water Act of 1972; Porter-Cologne Water Quality Control Act of 1969 *(State Water Resources Control Board; U.S. Environmental Protection Agency)*	SWRCB 2000, 2006 as modified SWRCB c2019 *(Delta outflow)*	Monthly Delta outflow index prescribed by formula, which incorporates hydrology in the previous month. Outflows are related to positioning of the estuarine salinity field
		SWRCB 2000, 2006 as modified SWRCB c2019 *(Ratio of export to total Delta inflow; E/I Ratio)*	Limits exports to a fraction of inflow to the Delta
		SWRCB 2000, 2006 as modified SWRCB c2019 *(Ratio of Delta inflow from San Joaquin River to exports; Vernalis 1:1)*	Limits exports to 100% of flow in the San Joaquin River at Vernalis or 42.48 $m^3 s^{-1}$ (1,500 $ft^3 s^{-1}$) (whichever is greater) from mid-April to mid-May
Fish and wildlife *[CVPIA b(2)]*	Central Valley Project Improvement Act 1992 (CVPIA) *(U.S. Bureau of Reclamation)*	CVPIA section 3406 b(2)	Up to 0.987 $10^9 m^3$ (0.8 million acre-ft) of project yield to be used for the benefit of anadromous fishes. Typically accounted for as an offset to water supply impacts when Endangered Species Act or Water Quality Control Plan protections are invoked
Endangered species *(Delta Smelt RPA and Anadromous Fish RPA)*	Endangered Species Act of 1973, California Endangered Species Act of 1970 *(National Marine Fisheries Service; California Department of Fish and Wildlife)*	NMFS 2009 San Joaquin Old and Middle River flow *(OMR)*	Limits negative Old and Middle River flows at certain times and when fish are detected in certain locations
		NMFS 2009 Salvage density *(salvage)*	Export limits apply when salvage of fish per unit of exported water exceeds thresholds
		NMFS 2009 ratio of San Joaquin River inflow to export *(SJR I/E)*	During April-May, export limited to a proportion of flow in the San Joaquin River at Vernalis or 42.48 $m^3 s^{-1}$ (1,500 $ft^3 s^{-1}$), whichever is greater
	Endangered Species Act of 1973, California Endangered Species Act of 1970 *(US Fish and Wildlife Service; California Department of Fish and Wildlife)*	USFWS 2008 *(Fall X2[a])*	In the fall following Wet and Above Normal years, additional outflow required for maintaining the estuarine salinity field farther downstream than would otherwise be required (e.g., under the Water Quality Control Plan)
		USFWS 2008 San Joaquin Old and Middle River flow *(OMR)*	Limits on negative Old and Middle River flows at certain times and when fish are detected in certain locations
	Endangered Species Act of 1973, California Endangered Species Act of 1970 *(U.S. Fish and Wildlife Service; California Department of Fish and Wildlife)*	Voluntary export reductions *(Voluntary reductions)*	Reductions in Project exports not resulting from ESA enforcement of that were implemented in order to avoid triggering restrictions under the Reasonable and Prudent Alternatives

a. A local measure of the position of the estuarine low salinity zone, indexed as the distance (km) of the 2 ppt bottom isohaline from the Golden Gate.

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Table 3 Timing of ecosystem protections that may constrain project water exports in the South Delta; *shading* indicates when regulations to protect water quality, fish and wildlife, and endangered species normally apply, years indicate the water year (Oct–Sep) when weakened regulations were in effect due to temporary administrative changes or court injunctions.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
WQCP[a]	2015, 2016	2016	2015		2014, 2015	2014, 2015	2014, 2015	2014, 2015	2014, 2015	2014, 2015	2015	2015
AF RPA[b]					2010, 2015	2014	2010, 2012	2010, 2012, 2018	2010			
DS RPA[c]	2018		2015		2010, 2016	2018		2010				2011, 2017

a. Bay–Delta Water Quality Control Plan requirements for salinity control and protection of fish and wildlife in general (SWRCB 2006).
b. Reasonable and Prudent Alternative requirements for protection of endangered anadromous fishes (NMFS 2009).
c. Reasonable and Prudent Alternative requirements for protection of endangered Delta Smelt (USFWS 2008).

USFWS 2008), and water quality regulations (SWRCB 2000), as they were modified year to year (Tables 2 and 3). Finally, we calculated the percentage of time that different constraint categories governed export rates.

Daily project water exports from the south Delta were governed by infrastructure/hydrologic limitations, water-quality safeguards, or protections for endangered species. Furthermore, in rare cases, provisions of the Central Valley Project Improvement Act (CVPIA) that protect anadromous fisheries constrained exports. Infrastructure and hydrologic limitations included: current capacity of project water export facilities and the canals they supply; maintenance that temporarily reduced system capacity; limited demand for exported water and limited storage space in a major off-channel reservoir supplied by the export facilities (San Luis Reservoir; Figure 1); export facility operational limits related to project water rights (i.e., from the SWRCB); and navigation or flood protection limits (i.e., from the U.S. Army Corps of Engineers; Table 2). Water quality constraints on exports included WQCP protections for fish and wildlife in general, and requirements to maintain salinity conditions to protect agricultural and municipal uses (Table 2). Because the project water export facilities are near sea level, brackish water can intrude into the Delta and approach the project water export infrastructure; sufficient flow of fresh water from the Delta to San Francisco Bay creates a hydraulic salinity barrier (HSB) that prevents brackish water from intruding into the Delta. On several occasions during the study period, water quality and flow standards in the WQCP were altered by the SWRCB via temporary urgency change orders (TUCs) and protections under the ESAs were weakened administratively or as a result of court injunctions (Table 3).

Project water exports may also be constrained by a variety of protections for endangered fishes, as set forth in the reasonable and prudent alternative (RPA) sections of the National Marine Fisheries Service Biological Opinion for endangered anadromous fish species (NMFS 2009; Anadromous Fish RPA), and the U.S. Fish and Wildlife Service Biological Opinion for Delta Smelt (USFWS 2008; Delta Smelt RPA). The RPAs were intended to prevent CVP and SWP water export operations from jeopardizing the continued existence and recovery of endangered species, and were premised on the operation and enforcement of other regulations, including those described here. In addition, the California Department of Fish and Wildlife issued an incidental take permit to the SWP under the California ESA for Longfin Smelt (CDFW 2009) that was premised, in part, on implementation of the federal Delta Smelt RPA. Because each of these ESA protections was issued during water year 2009, we began our analyses of the effect of specific regulations and physical constraints on project water exports in water year 2010, the first full year in which all ESA protections were operational.

Volumetric Effect of Different Constraints on Project Water Exports

To understand the volumetric effect of constraints on Project exports, we used a building block accounting approach similar to that outlined by Gartrell et al. (2017) to parse daily reductions in project water exports among different constraints as they operated in parallel each day. We calculated volumetric limits on daily project water exports for several sub-categories of ecosystem protections, including: salinity standards described in the WQCP to protect fish and wildlife in general (WQCP F&W); Delta outflow to protect anadromous fisheries under the CVPIA; and protection of endangered species. The latter category was divided into sub-categories for the Anadromous Fish RPA, Delta Smelt RPA, and instances where both RPAs governed exports. Finally, we accounted for voluntary export reductions intended to protect endangered species (i.e., not the result of regulatory enforcement). Daily volumes attributable to each category of constraint were summed within and across water years. Note that cumulative results may not reflect "typical" outcomes because the years in our study period represented a particular mix and sequence of hydrologic conditions and peculiarities regarding enforcement of ecosystem protections. However, this period represented almost the entire time during which current RPA protections have been in effect; thus, the cumulative results portray empirical effects of various export constraints during a multi-year period when the RPAs were first enforced—and when they generated significant public controversy.

To simplify analysis of daily export operations over the 9-year study period, we employed several assumptions about the different constraints (Table 4). These simplifying assumptions tended to underestimate the volumetric effect of HSB maintenance and infrastructure/hydrologic limitations on water exports, and to overestimate the effect of ecosystem protections.

Parsing Fish and Wildlife and Endangered Species Constraints on Project Water Exports

The volumetric effect of system capacity constraints (i.e., infrastructure/hydrologic limits) on Delta outflow was transparent on days when they governed project water exports. Export capacity for the SWP was design capacity as modified by water rights permits and the U.S. Army Corps of Engineers permit; SWP export capacity varied depending on hydrologic conditions (Table 2). From 2010 through April 2012, export capacity for the CVP was lower than design capacity because of degradation of the Delta–Mendota canal (USBR 2009). Thus, we estimated CVP capacity during this period to be approximately the maximum CVP export observed during this period ($121.76\,m^3\,s^{-1}$; $4{,}300\,ft^3\,s^{-1}$). After the canal was repaired in May 2012, we assumed export capacity equaled design capacity through 2016. However, indications that CVP export capacity declined during the drought (e.g., as a result of subsidence) caused us again to use an empirical estimate for water years 2017 and 2018.

We assumed that project water exports could not exceed system capacity on a given day; thus, on days when exports were limited by system capacity, actual Delta outflow beyond that attributable to HSB maintenance was categorized as Additional Uncaptured Outflow (AUO; Figure 2). Similarly, when project water exports were below system capacity on a given day, the volume of actual Delta outflow attributed to the factor that governed project water exports equaled the estimated remaining, unused system capacity. When system capacity was limited by maintenance or lack of both demand and storage, we quantified the effects on actual Delta outflow volumes; however, on days when other factors governed exports, we assumed the system would have operated at capacity for that day had the controlling factor not been in effect.

We also assumed that exports could not reduce actual Delta outflow beyond that needed to maintain the HSB because—if salinity standards were exceeded—project water exports would then affect other human uses (Figure 2). On days when salinity control governed exports, all Delta outflow was attributed to HSB maintenance. When salinity control did not govern exports, some amount of Delta outflow was still attributed to HSB maintenance. Following Ligare (2015), we estimated that the Delta outflow needed to maintain the HSB averaged $135.92\,m^3\,s^{-1}$ ($4{,}800\,ft^3\,s^{-1}$). This estimate is coarse; salinity standards change according to hydrologic conditions, and the amount of Delta outflow needed

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Table 4 Simplifying assumptions used to estimate volumetric effects of various export constraints and the likely bias they generated in estimating volumetric effects of other export constraints

Constraint assumption	Resulting bias in estimated effect of constraint	Export constraints affected	Directional effect on volume attributed to export constraint
INFRASTRUCTURE Storage and demand are unlimited unless specifically identified as constraining exports	Overestimates daily project water export capacity, including during periods when export constraints prevented filling of storage, which would later have constrained exports. Because each day's operations affect subsequent days, aggregating the constraints from multiple days requires advanced modeling of system operations.	HSB[a] (WQCP[b])	N/A
		Fish & Wildlife (WQCP F&W)	Overestimate
		Anadromous Fish RPA (ESA[c])	Overestimate
		Delta Smelt RPA (ESA)	Overestimate
		Voluntary (ESA)	Overestimate
		Infrastructure	Underestimate
INFRASTRUCTURE Nominal capacity of Project facilities is attainable and can be maintained indefinitely (e.g., will not necessitate maintenance that reduces exports)	Overestimates daily project water export capacity if actual capacity is less than estimated capacity or if infrastructure cannot sustain maximum exports for an extended period. This includes periods when maintenance reduces export capacity but is unreported.	HSB (WQCP)	N/A
		Fish & Wildlife (WQCP F&W)	Overestimate
		Anadromous Fish RPA (ESA)	Overestimate
		Delta Smelt RPA (ESA)	Overestimate
		Voluntary ESA	Overestimate
		Infrastructure	Underestimate
INFRASTRUCTURE Export capacity during July-September increased by 14.16 $m^3 s^{-1}$ (500 $ft^3 s^{-1}$) as per USACE (2013) in all years regardless of other applicable constraints in the USACE (2013) permit	Overestimates daily State Water Project export capacity when other constraints on exports in the U.S. Army Corps of Engineers permit would be in effect.	HSB (WQCP)	N/A
		Fish & Wildlife (WQCP F&W)	Overestimate
		Anadromous Fish RPA (ESA)	N/A[d]
		Delta Smelt RPA (ESA)	N/A[d]
		Voluntary ESA	N/A[d]
		Infrastructure	Underestimate
WATER QUALITY CONTROL PLAN (WQCP) Fish and wildlife protections were achieved by Delta outflow rather than by satisfying other, alternative water quality requirements (e.g., attaining electrical conductivity standards)	Overestimates volume needed to attain fish and wildlife standards of the WQCP[b]. Under our building block accounting approach, this overestimation leads to underestimates of Delta outflow attributed to other environmental protections.	HSB (WQCP)	N/A
		Fish & Wildlife (WQCP F&W)	Overestimate
		Anadromous Fish RPA (ESA)	Underestimate
		Delta Smelt RPA (ESA)	Underestimate
		Voluntary ESA	Underestimate
		Infrastructure	N/A
HYDRAULIC SALINITY BARRIER (HSB) When other factors limited exports, Delta outflow of 135.92 $m^3 s^{-1}$ (4,800 $ft^3 s^{-1}$) was necessary to maintain HSB (Ligare 2015)	Our estimated average flow necessary to maintain the HSB appears to be conservative (Gartrell et al. 2017). Under our building block accounting approach, underestimation of outflow required to maintain HSB[a] produces overestimates of outflow attributed to fish and wildlife protection.	HSB (WQCP)	Underestimate
		Fish & Wildlife (WQCP F&W)	Overestimate
		Anadromous Fish RPA (ESA)	N/A
		Delta Smelt RPA (ESA)	N/A
		Voluntary ESA	N/A
		Infrastructure	N/A
ECOSYSTEM PROTECTIONS Daily averaging of multi-day average standards	When more than one regulation was in effect, this could lead to underestimation of the volume attributed to a standard that was not controlling and overestimation of the controlling standard.	HSB (WQCP)	N/A
		Fish & Wildlife (WQCP F&W)	Underestimate
		Anadromous Fish RPA (ESA)	Overestimate
		Delta Smelt RPA (ESA)	Overestimate
		Voluntary ESA	Overestimate
		Infrastructure	N/A

a. Hydraulic Salinity Barrier.
b. The Bay-Delta Water Quality Control Plan (SWRCB 2006).
c. Endangered Species Act.
d. Endangered Species Act constraints were not present July–September during the period of our study.

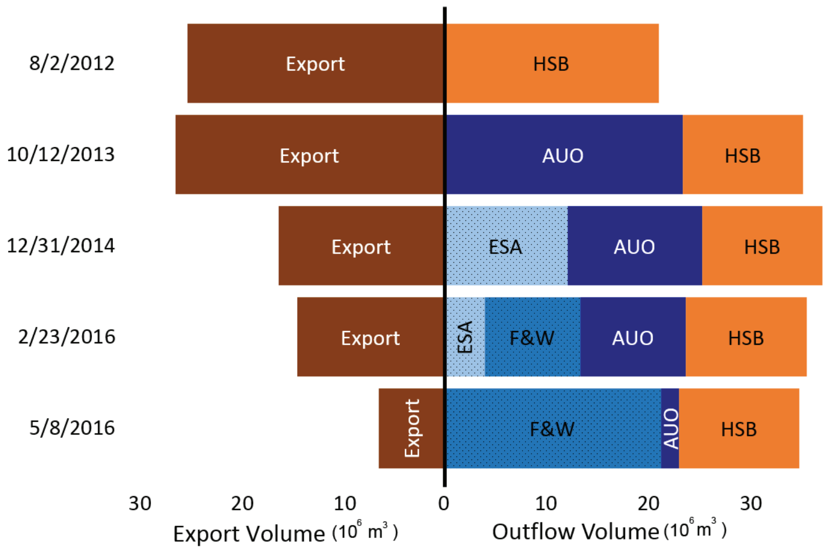

Figure 2 Examples of our approach to parsing daily volumes attributed to various project water export constraints. Bars show the volumes of project water exports (*left of vertical line*) and actual Delta outflows (*right of vertical line*) on particular days; dates for each example are indicated in parentheses. The *bar bordering the right side of the vertical line* represents the factor governing project water exports. If this constraint were eliminated, its associated volume of water could hypothetically have been exported (up to the point that project water export capacity was limiting). *Stippling* indicates water that might have been exported on a given day in the absence of protections for fish and wildlife in general (F&W) or endangered species (ESA). Outflows in excess of system capacity on a given day (AUO) and those needed to avoid salinity impacts to agricultural and municipal uses (HSB) were assumed to be unavailable for export.

to maintain any given salinity standard varies with recent hydrologic and other environmental conditions (Gartrell et al. 2017). However, developing a more precise estimate of Delta outflow needed to maintain the HSB was beyond the scope of our analysis, and we subsequently determined the static estimate to be conservative in most cases (2017 email from S. Ligare, SWRCB, to G. Gartrell and G. Reis, unreferenced, see "Notes"; Gartrell et al. 2017).

When exports were constrained by regulations intended to protect ecosystem attributes (i.e., under the WQCP, CVPIA, or RPAs), the volume of water attributable to these safeguards was not reported, and so we derived these values from available data. Water attributed to these ecosystem protections represented the incremental volume in excess of that needed to meet other regulatory requirements operating at the same time, including HSB maintenance. Thus, on days when factors other than salinity control or system capacity governed exports, we used a water balance approach to disaggregate the volume of Delta outflow related to different project water export constraints (Figure 2).

RESULTS

Proportional Delta Outflow Through Time

The percentage of unimpaired Delta outflow that became actual Delta outflow declined in the periods 1930–2018 (Kendall's tau = –0.36, $p < 0.001$), 1968–1994 (Kendall's tau = –0.31, $p < 0.05$), and 1995–2018 (Kendall's tau = –0.29, $p < 0.05$; Figure 3). Between 1930 and 2018, the wettest February–June period was 1983 (unimpaired Delta outflow = 61.07 $10^9 m^3$, 49.51 maf;) and the driest occurred in 1977 (unimpaired Delta outflow = 4.04 $10^9 m^3$, 3.27 maf; Figure 3). Unimpaired Delta outflow estimates indicate that 37% to 43% of years matched our criteria for "wettest" or "above average" hydrology during the 1930–1967, 1968–1994, and 1995–2018 time-periods. Actual Delta outflows corresponded to "wettest" or "above average" conditions in 15% to 22% of years during those time-periods (Table 5). Unimpaired Delta outflows reflected "dry" conditions in 13% to 30% of years in the three study periods, whereas actual Delta outflows corresponding to "dry" conditions increased from 45% during 1930–1967 to 63% of years in the 1995–2018 period. Based on unimpaired hydrology, 1977 was the only "super-critically-dry" year during the 89-year time-series; actual Delta outflows in this sub-category occurred during 38% of years between 1995 and 2018 (Figure 3; Table 5).

Frequency of Limitations on Project Water Exports in the South Delta

Our analysis of the effects of constraints that governed project water exports during 2010–2018 revealed that exports were limited to maintain salinity

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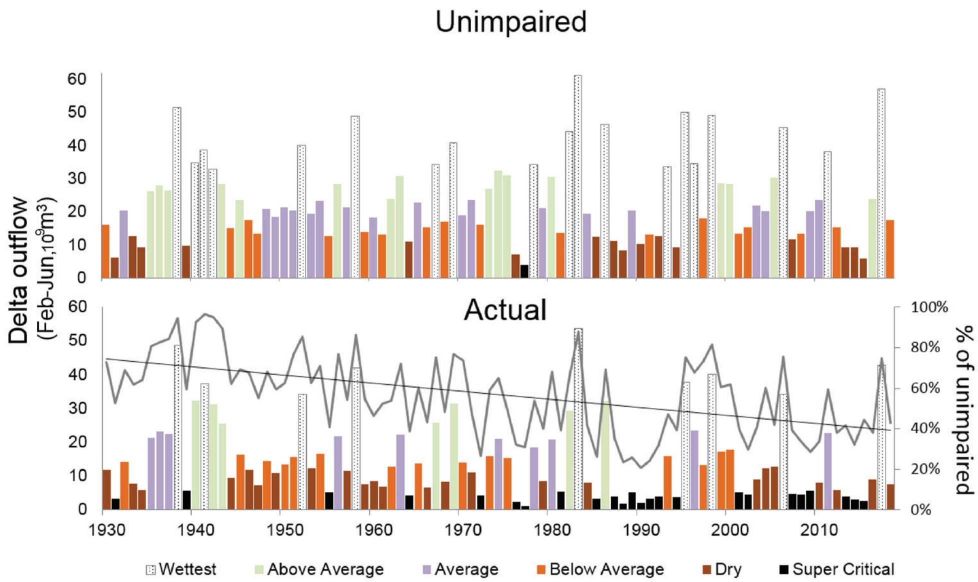

Figure 3 Trends in February–June Delta outflow relative to Central Valley runoff. Unimpaired flow out of the Sacramento–San Joaquin Delta into San Francisco Bay (*top panel*) compared with actual Delta outflow (*lower panel*) from 1930–2018. The percentage of unimpaired flow reaching the bay (*line in lower panel; right y-axis*) declined significantly during this time-period (Kendall's tau = −0.36, $p<0.001$), including since 1995 (Kendall's tau = −0.29, $p<0.05$). Hydrologic categories are based on unimpaired flow volumes from 1922–2016 (see Table 5).

Table 5 Threshold unimpaired February–June Delta outflow used to categorize year types and relative frequency of those year types, for three different time periods

		1930–1967		1968–1994		1995–2018	
Year type[a]	Unimpaired Delta outflow ($10^9 m^3$)	Unimpaired frequency	Actual frequency	Unimpaired frequency	Actual frequency	Unimpaired frequency	Actual frequency
SC	<5.876	0%	13%	4%	44%	0%	38%
D	<12.838	13%	45%	30%	59%	17%	63%
BA	12.838-18.304	21%	21%	15%	15%	25%	13%
A	18.305-23.625	26%	13%	19%	11%	17%	8%
AA	23.626-32.798	21%	11%	15%	11%	17%	0%
W	>32.798	18%	11%	22%	4%	25%	17%

a. Year type category definitions represent quintiles of unimpaired Delta outflow in the 1922–2016 data series designated: wettest (W), above average (AA), average (A), below average (BA), and dry (D); a sub-category of dry years, super-critically dry (SC), represents the driest 2% of years in the period.

standards for human water use (i.e., HSB) on 29% of days, or as often as exports were governed by ESA enforcement and voluntary limits combined (Figure 4, Table 6). Salinity control considerations governed exports more frequently during drier years, and this constraint was particularly common during 2014–2016, when other water quality regulations were weakened (Table 3). Export restrictions intended specifically to protect endangered anadromous fishes occurred on some days in each year of our study. Exports were not governed by enforcement of the Delta Smelt RPA on any days during 2011, 2014, or 2015, although voluntary reductions in exports intended to benefit smelt occurred during 2015 (as well as 2016 and 2017). Exports were governed by WQCP protections for fish and wildlife in general on one-quarter of the days in our study period; this constraint was least common in wet years and more common in dry years, despite being weakened substantially during 2014–2016. Infrastructure/hydrologic constraints governed exports on some days in 6 of our 9 study years, and were by far the most common governing constraint during wet years (2011 and 2017; Table 6). Project water exports occurred on all but 2 days of the 9-year study period; the exception occurred in March 2011 when San Luis Reservoir—used to store project water exports when there is no immediate demand—was full (CDWR 2018a).

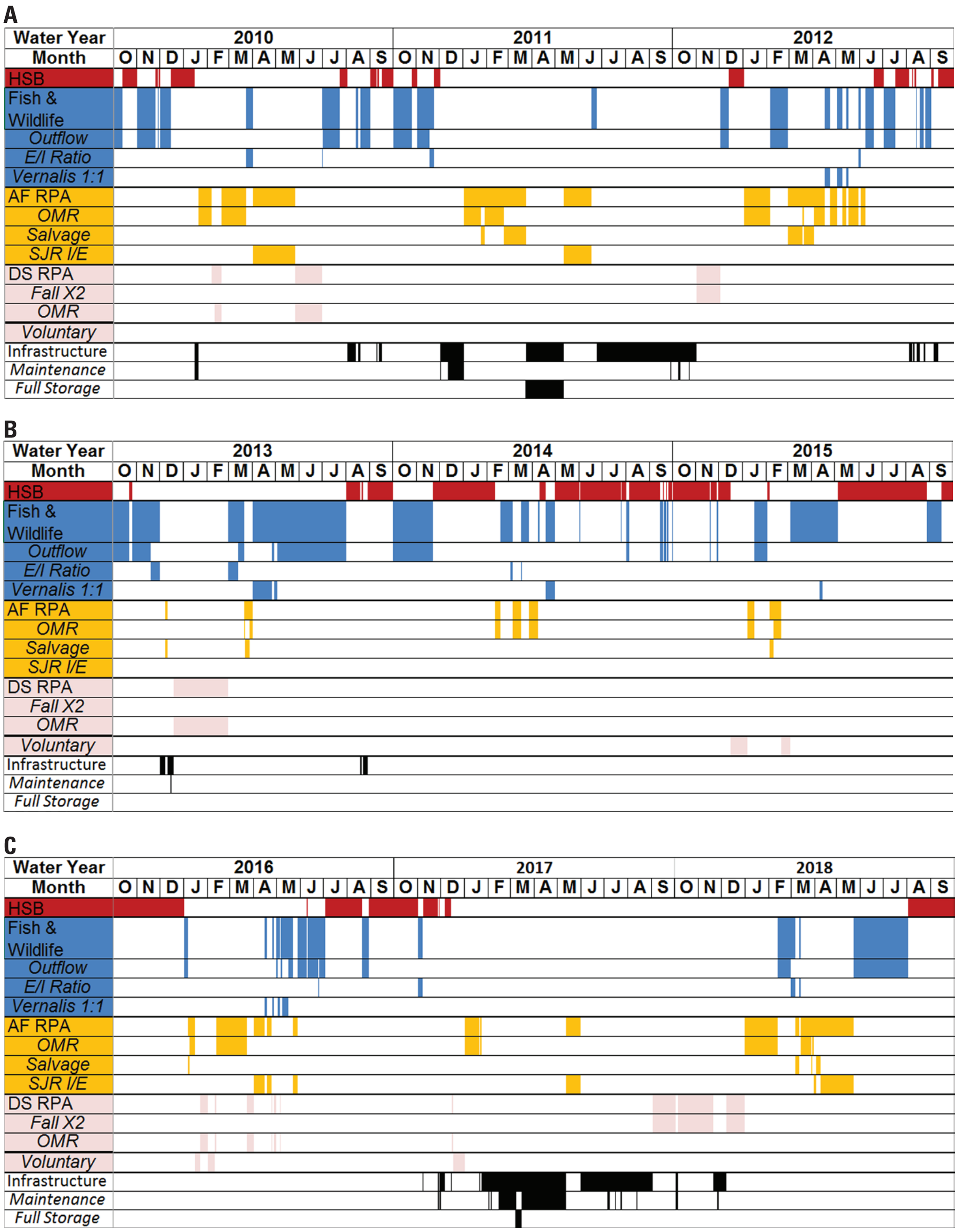

Figure 4 Daily record of factors limiting project water exports during water years (Oct–Sep, months labeled with first letter of month) 2010–2018. *Bars* represent limitation of exports by various constraints; select subcategories of the overarching regulation are listed separately in *italics*. Abbreviations and constraint categories are described in Tables 1 and 2, respectively. Export limitation as a result of the Central Valley Project Improvement Act (not shown as a sub-category), occurred once for 7 days during the study period.

Volume of Limitations on Project Water Exports in the South Delta

Project water exports during our study period totaled 46.65 $10^9 m^3$ (37.82 maf) and ranged from 2.27 $10^9 m^3$ (1.84 maf) in 2015 to 8.11 $10^9 m^3$ (6.57 maf)—a record high—in 2011. Approximately one-quarter of Central Valley runoff that entered San Francisco Bay during the 9-year study period (40.86 $10^9 m^3$, 33.12 maf) was attributed to maintenance of the HSB that protects agricultural and municipal uses of the Delta's fresh water (Table 7). The relative effect of HSB maintenance on actual Delta outflow was largest during the most severe drought years (78% in 2014 and 64% in 2015). By contrast, outflows that exceeded system capacity (i.e., AUO) were greatest in wetter years; for example, in 2017, AUO accounted for 90.5% of actual Delta outflow.

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Table 6 Frequency (percentage of all days in a water year) with which different categories and sub-categories of constraints limited project water exports during 2011–2018. Left justified row labels are major regulatory categories; right-justified row labels are specific regulations within the major category above them. Constraint categories are defined in Table 2.

Water year	2011–2018	2010	2011	2012	2013	2014	2015	2016	2017	2018
HSB[a] (WQCP[b])	29%	25%	4%	21%	16%	62%	56%	48%	16%	16%
FISH & WILDLIFE	25%	27%	15%	26%	55%	30%	28%	20%	2%	26%
Delta outflow (WQCP)	18%	24%	11%	20%	40%	18%	5%	16%	0%	24%
E/I Ratio (WQCP)	2%	3%	2%	1%	7%	1%	0%	0%	2%	2%
Vernalis 1:1 (WQCP)	2%	0%	0%	5%	8%	3%	1%	4%	0%	0%
TUC[c] (WQCP)	3%	0%	0%	0%	0%	7%	21%	0%	0%	0%
CVPIA b(2)[d]	0.3%	0%	2%	0%	0%	0%	0%	0%	0%	0%
ANADROMOUS FISH RPA[e] (ESA[f])	19%	28%	32%	31%	4%	8%	7%	20%	11%	32%
OMR[g]	11%	13%	13%	23%	1%	8%	5%	13%	6%	16%
Salvage Density	3%	0%	9%	9%	2%	0%	1%	1%	0%	3%
SJR I/E[h]	6%	15%	10%	0%	0%	0%	0%	7%	5%	13%
DELTA SMELT RPA[e] (ESA[f])	8%	13%	0%	8%	19%	0%	0%	7%	8%	20%
Fall X2	4%	0%	0%	8%	0%	0%	0%	0%	8%	20%
OMR	4%	12%	0%	0%	19%	0%	0%	7%	1%	0%
Voluntary	2%	0%	0%	0%	0%	0%	9%	4%	4%	0%
INFRASTRUCTURE / HYDROLOGIC	16%	7%	49%	13%	6%	0%	0%	0%	59%	5%
Maintenance	4%	1%	6%	1%	0%	0%	0%	0%	25%	1%
Storage	2%	0%	13%	0%	0%	0%	0%	0%	2%	0%
Pump/Canal Capacity	10%	5%	29%	12%	6%	0%	0%	0%	32%	4%

a. Hydraulic salinity barrier.
b. Bay–Delta Water Quality Control Plan.
c. Temporary Urgency Change.
d. Water attributable to section 3406 b(2) of the Central Valley Improvement Act.
e. Reasonable and Prudent Alternative.
f. Endangered Species Act.
g. Old and Middle River flows.
h. San Joaquin River inflow/export ratio.

Water Quality Control Plan requirements to protect estuarine fish and wildlife in general (WQCP F&W), which do not include additional protections for endangered fishes, resulted in additional outflow volumes that might otherwise have been available for export that ranged between up to 0.21 $10^9 m^3$ (0.17 maf) in 2011 to as much as 1.93 $10^9 m^3$ (1.56 maf) in 2013 (Table 7). These estimates likely overstate the effect of WQCP F&W because flows necessary to maintain HSB were underestimated (Table 4). As the drought continued beyond 2013, flow standards intended to protect fish and wildlife populations were reduced by TUCs (Table 3). During June 2011, exports were limited under CVPIA b(2) to protect non-endangered salmon from the San Joaquin Basin (USBR 2019a); because the resultant increase in outflow was not an offset for ESA or WQCP export restrictions (i.e., not reflected in other export constraint categories), we accounted for it as a separate sub-category of actual Delta outflow.

Annual protections for fishes under the state and federal ESAs involved at most 1.37 $10^9 m^3$ (1.11 maf) of additional Delta outflow in 2018; the lowest volume associated with ESA protections (0.18 $10^9 m^3$, 0.15 maf) occurred in 2014 (Table 7). Export constraints attributed to ESA protections represented 5.3% of annual actual Delta outflow and 2.9% of annual unimpaired Delta outflow during the study period. Proportional volumetric effects of ESA protections for endangered fish on Delta outflow were lower during the driest and wettest years in our

Table 7 Annual Delta water balance for 2011–2018, including estimated effects of project water export constraints expressed relative to unimpaired and actual Delta outflow. Major categories of export constraint that contribute to Delta outflow have *bold labels*; *bold-italic row labels* are sub-categories of export constraints related to the Endangered Species Act (Table 2); underlined values indicate when the relevant regulation was weakened (Table 3). Assumptions regarding export constraints and resulting biases in estimates are described in Table 4.

	Volume ($10^9 m^3$)	% unimpaired Delta outflow	% actual Delta outflow	Volume ($10^9 m^3$)	% unimpaired Delta outflow	% actual Delta outflow	Volume ($10^9 m^3$)	% unimpaired Delta outflow	% actual Delta outflow	Volume ($10^9 m^3$)	% unimpaired Delta outflow	% actual Delta outflow	Volume ($10^9 m^3$)	% unimpaired Delta outflow	% actual Delta outflow
	2010–2018			WY 2010			WY 2011			WY 2012			WY 2013		
Unimpaired Delta outflow	299.20	100.0		32.05	100.0		56.46	100.0		20.70	100.0		21.87	100.0	
Upstream net use	90.19	30.1		13.77	43.0		15.20	26.9		4.62	22.3		5.59	25.6	
Delta inflow	224.55	75.1		19.50	60.9		42.37	75.0		17.56	84.8		17.85	81.6	
Delta net use	10.74	3.6		1.08	3.4		0.92	1.6		1.46	7.1		1.33	6.1	
Other exports	1.73	0.6		0.17	0.5		0.13	0.2		0.26	1.3		0.25	1.1	
Project exports	46.65	15.6		5.72	17.8		8.11	14.4		5.87	28.3		5.02	23.0	
Delta outflow	165.43	55.3	100.0	12.54	39.1	100.0	33.21	58.8	100.0	9.96	48.1	100.0	11.25	51.5	100.0
HSB[a]	40.86	13.7	24.7	4.53	14.1	36.1	4.43	7.8	13.3	4.58	22.1	46.0	4.29	19.6	38.2
WQCP F&W[b]	8.87	3.0	5.4	1.29	4.0	10.3	0.21	0.4	0.6	1.45	7.0	14.6	1.93	8.8	17.1
CVPIA b(2)[c]	0.05	0.0	0.0	0	0.0	0.0	0.05	0.1	0.1	0	0.0	0.0	0	0.0	0.0
ESA[d]	8.74	2.9	5.3	1.35	4.2	10.7	1.17	2.1	3.5	1.04	5.0	10.4	1.07	4.9	9.5
Anadromous fish RPA[e]	4.63	1.5	2.8	0.75	2.3	6.0	1.17	2.1	3.5	0.81	3.9	8.1	0.05	0.2	0.4
Delta Smelt RPA[e]	2.04	0.7	1.2	0.41	1.3	3.3	0	0.0	0.0	0.23	1.1	2.3	0.60	2.7	5.3
Simultaneous anadromous fish & Delta Smelt RPAs	1.51	0.5	0.9	0.19	0.6	1.5	0	0.0	0.0	0	0.0	0.0	0.42	1.9	3.7
Voluntary reductions	0.56	0.2	0.3	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
Additional uncaptured outflow	106.79	35.7	64.6	5.25	16.4	41.9	27.35	48.4	82.3	2.89	13.9	29.0	3.96	18.1	35.2
	2014			WY 2015			WY 2016			WY 2017			WY 2018		
Unimpaired Delta outflow	11.93	100.0		11.71	100.0		33.98	100.0		85.62	100.0		24.88	100.0	
Upstream net use	4.11	34.5		3.87	33.0		16.26	47.9		19.23	22.5		7.53	30.3	
Delta inflow	9.31	78.0		10.97	93.6		19.55	57.6		68.46	80.0		18.99	76.3	
Delta net use	1.50	12.5		1.46	12.5		1.18	3.5		0.50	0.6		1.32	5.3	
Other exports	0.22	1.8		0.11	1.0		0.21	0.6		0.18	0.2		0.20	0.8	
Project exports	2.29	19.2		2.27	19.4		4.12	12.1		7.79	9.1		5.46	22.0	
Delta outflow	5.30	44.4	100.0	7.12	60.8	100.0	14.05	41.3	100.0	59.99	70.1	100.0	12.01	48.3	100.0
HSB[a]	4.15	34.8	78.4	4.59	39.2	64.4	5.02	14.8	35.7	4.88	5.7	8.1	4.39	17.6	36.5
WQCP F&W[b]	0.47	4.0	8.9	0.24	2.0	3.3	1.44	4.2	10.2	0.02	0.0	0.0	1.77	7.1	14.8
CVPIA b(2)[c]	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
ESA[d]	0.18	1.6	3.5	0.49	4.2	6.9	1.30	3.8	9.2	0.78	0.9	1.3	1.37	5.5	11.4
Anadromous fish RPA[e]	0.18	1.6	3.5	0.19	1.7	2.7	0.33	1.0	2.3	0.38	0.4	0.6	0.76	3.1	6.4
Delta Smelt RPA[e]	0	0.0	0.0	0	0.0	0.0	0.12	0.4	0.9	0.16	0.2	0.3	0.52	2.1	4.4
Simultaneous anadromous fish & Delta Smelt RPAs	0	0.0	0.0	0	0.0	0.0	0.74	2.2	5.3	0.07	0.1	0.1	0.08	0.3	0.7
Voluntary reductions	0	0.0	0.0	0.30	2.5	4.2	0.10	0.3	0.7	0.16	0.2	0.3	0	0.0	0.0
Additional uncaptured outflow	0.49	4.1	9.2	1.81	15.4	25.4	6.30	18.5	44.8	54.32	63.4	90.5	4.43	17.8	36.9

a. Hydraulic salinity barrier.
b. Water Quality Control Plan protections for fish and wildlife.
c. Central Valley Project Improvement Act section b(2). CVPIA b(2) allocates up to 0.99 $10^9 m^3$ per year for ecosystem protection. Protection of salmonids under the WQCP F&W or ESA may be assessed to this annual volume. To avoid double counting, only potential project export volumes solely attributable to CVPIA b(2) are reported in this row.
d. Endangered Species Act.
e. Reasonable and Prudent Alternative.

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study period, compared with years of intermediate–dry hydrology. Over the entire study period, voluntary export limits and enforcement of the Delta Smelt RPA alone (i.e., excluding times when both the Delta Smelt RPA and Anadromous Fish RPA governed project water exports simultaneously) accounted for less than 1.5% of actual Delta outflow (annual maxima ranged from 0% to 5.3%) and 0.9% of unimpaired Delta outflow (0% to 2.7%; Table 7).

DISCUSSION

Media coverage of environmental issues necessarily involves prioritizing information to include in reporting, and the frame that results from these decisions can influence public perception of conflict (Bendix and Liebler 1999). The lack of access to information on natural resource management sets the stage for misunderstanding the costs and benefits of environmental protection (Lee 1993). A persistent frame for media coverage of water management in California's Central Valley watershed emphasizes conflict between ecosystem protection and agricultural water use, and—in particular—the effect on water deliveries presumed to result from protections for endangered fish species. Political and policy dialogue on ESA safeguards for San Francisco Bay estuary's endangered fish often mirrors this media narrative (e.g., Worth and Mizner 2017). Our analyses indicate that the common framing of fish–human conflict overstates the relative and absolute effect of ecosystem protections on the volume of fresh water that flows through the San Francisco Bay estuary, and the volumes of water that the SWP and CVP export.

The historical context for current debates over the application of ecosystem water is that the volume of fresh water that reaches the San Francisco Bay complex has declined over time, relative to unimpaired Central Valley runoff (Figure 3; Table 5). This trend was not reversed by water quality protections adopted in the mid-1990s and endangered species safeguards implemented beginning in 2009 (Figure 3). In the period after adoption of the most recent substantive amendments to the WQCP (1995–2018), 38% of years had actual Delta outflows that were lower than those that would have occurred under unimpaired runoff conditions in the driest 2% of years (Table 5). The percentage of Central Valley runoff that is diverted increases as unimpaired flow decreases and vice-versa (Figure 3), but this reflects diversion rates that are relatively unresponsive to hydrological conditions; the time trend we detected in proportional Delta outflow is not explained by trends in unimpaired flow (Table 5; Hutton et al. 2017).

We found little support for the claim that regulations specifically intended to protect endangered fishes were the dominant governing constraint on project water exports during our study period. Project water exports were governed by the need to maintain the HSB—including more than half of days during the two driest years of our study (2014 and 2015)—as often as they were by ESA regulations and voluntary limits combined. In 4 of the 9 years we studied, the Anadromous Fish RPA governed exports for 28% to 32% of days, but only 4% to 11% in 4 other years (Table 6). Provisions of the Delta Smelt RPA constrained exports less frequently than the Anadromous Fish RPA in all but 1 year (2013) of our study period, and enforcement of the Delta Smelt RPA did not occur at all in 3 years of our study (although exports were voluntarily constrained to protect Delta Smelt in 1 of those years (2015). Conversely, in the 2 wettest years we studied (2011 and 2017), infrastructure and hydrologic limitations governed project water exports on most days.

Also, ESA-related constraints were not the principal constraints applied to annual project water export volumes, nor did these safeguards generate a large portion of Delta outflow during the 2010–2018 study period (Table 7). Cumulative ESA-related project water export constraints amounted to no more than 5.3% of actual Delta outflow (2.9% of unimpaired Delta outflow), and were much less than those attributable to maintenance of the HSB (24.7% and 13.7% of actual and unimpaired Delta outflow, respectively) and slightly less than those attributable to general protection of fish and wildlife populations (5.4% and 3.0% of actual and unimpaired Delta outflow, respectively; Table 7). Constraints on project water exports related exclusively to Delta Smelt protection (both RPA enforcement and voluntary export reductions) were regularly among the smallest contributions to actual Delta outflow, accounting for at most 1.5% of actual Delta outflow during the 2010–2018 study period.

Several assumptions that underlie our accounting methodology clearly overestimate the volumetric effects of ecosystem protections on project water exports (Table 4). For example, we assumed that currently attainable maximum export rates could be sustained for extended periods, in the absence of ecosystem protection constraints. Periods of infrastructure maintenance and repair after extended periods when exports approached system capacity in 2011 and 2017 (Figure 4) suggest that this assumption inflated both long-term system capacity and the cumulative effect of regulatory constraints on project water exports. Also, our estimates of the Delta outflow necessary to maintain the HSB were generally less than those of Gartrell et al. (2017), indicating that our static estimate was an underestimate. As a result, we probably overestimated the volume of outflow generated by export constraints related to WQCP safeguards for fish and wildlife (Table 7).

Taken together, AUO and those outflows needed to maintain the HSB accounted for the vast majority of actual Delta outflow (Table 7). In wet years, Delta outflows that occurred from AUO dwarfed other constraint categories; we note that some of this flow was required by ecosystem protections, but it was beyond the export system's capacity to capture it (by definition). Had ecosystem protections been eliminated, this volume of water still could not have been exported without affecting other uses (e.g., consumption or navigation) and/or risking damage to the export infrastructure. On more than half of days during 2014 and 2015, Project water exports were limited by the lack of flow in excess of that needed to maintain the HSB (Table 6), and HSB maintenance alone required at least 34.8% and 39.2% of total Central Valley runoff, respectively (Table 7). Temporary changes in water quality standards (TUCs) that were in effect during those years reduced Delta outflow requirements in order to increase water deliveries and upstream reservoir storage above what would have occurred under existing WQCP requirements (SWRCB 2015); thus, these modified standards increased the frequency with which HSB maintenance limited project water exports.

Previous efforts to account for the sources of Delta outflow (Gartrell et al 2017) cautioned that project water export restrictions do not necessarily translate to water costs for recipients of water exported from the Delta. Our temporal and volumetric analyses revealed that aggregating daily project water export constraints can overstate the annual effect of ecosystem protections because exports that are unconstrained by environmental regulations will eventually (if temporarily) satisfy demand and fill available water storage facilities. For example, San Luis Reservoir filled in March 2011 and March 2017, triggering storage-related project water export constraints; so the extended periods of limited exports attributed to ESA and WQCP safeguards earlier in those years likely had little or no effect on annual project water exports (Figure 4). Furthermore, during the 2010–2018 study period, much of the CVP export constraint attributed to protection of anadromous fish was "charged" to an annual block of water [CVPIA b(2) water (USBR 2019a)] that is dedicated toward ecosystem protection. During the 2010–2018 study period, CVPIA b(2) offset ESA or WQCP effects in a range between 0.247 $10^9 m^3$ (0.2 maf; 2015) and 0.987 $10^9 m^3$ (0.8 maf; 2012).

Our results differ in some regard from findings of other recent efforts to account for environmental applications of water in the San Francisco Bay estuary and watershed. Gartrell et al. (2017) reported that ecosystem water requirements have risen with environmental regulations implemented since 1995. Although true in the most basic sense, these additional requirements do not appear to have increased actual Delta outflows relative to Central Valley runoff. Our analysis of proportional Delta outflow, which is affected by diversions and storage throughout the Central Valley, revealed declines in the percentage of winter–spring Central Valley runoff that reached San Francisco Bay over 9 decades, including the period following the adoption of the 1995 WQCP (see also Hutton et al. 2017); annual proportions (not shown) follow a similar trend. The decline likely stemmed from increased ability to capture and store water that was not required to flow out of the Delta (e.g., via increased south-of-Delta storage and increased efficiency from coordinated operations and reservoir reoperation). Also, Gartrell et al. (2017) reported a decline in average project water

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exports in the years after the ESA safeguards for fish were adopted; however, their results demonstrate that interpretation of trends in absolute export volumes must account for the mix of hydrological conditions in any given time-period (see also Hutton et al. 2017). Most of the years after the RPAs for Delta Smelt and anadromous fish were published had below-normal to critically-low unimpaired runoff, and this limited project water exports during those years; indeed, project water exports reached an all-time high during water year 2011, when wet conditions prevailed.

MBK Engineers and HDR (2013) also attempted to account for application of ecosystem water in the Central Valley. One of their simulations involved projecting changes in Delta exports related to implementation of the Biological Opinions; they reported results according to CDWR water year types. Our results suggest that MBK Engineers and HDR (2013) overestimated how the ESAs affected project water exports in all but 1 year (2018). Differences between our two studies showed no clear pattern for water year type and ranged from 0.45 $10^9 m^3$ in 2017 (or 36% lower than the MBK Engineers and HDR [2013] simulated effect in wet years) and 0.44 $10^9 m^3$ in 2014 (70% lower than the simulated effect) to –0.01 $10^9 m^3$ in 2018 (<1% more than the simulated effect). We cannot fully explain the differences between our results and those modeled by MBK Engineers and HDR (2013), but they do suggest that where actual data exist, empirical studies are preferable to modeled outcomes, particularly when implementation of various regulatory standards is inconsistent over time.

Recommendations

The value or cost of decreased Central Valley water diversions depends on one's perspective (Cloern et al. 2017), but the relative frequency and magnitude of different factors that limit diversions should not. Our results reinforce earlier calls for government agencies to provide transparent, comprehensive, and accurate accounting of water attributed to various public and private uses in California (Cloern and Hanak 2013; Gartrell 2017a). Such accounting can be automated using web-based data-harvesting techniques, and should be updated frequently throughout the year and rectified periodically as more accurate flow estimates become available.

In addition, recent efforts to account for application of environmental water in this region reveal the need to establish clear and relevant baselines for comparison. Comparisons of different regulatory scenarios that report changes in outflow or project water exports only in terms of absolute volumes (e.g., MBK Engineers and HDR 2013) may be misinterpreted if they are not placed in the context of available surface water or historical hydrological modification in this region. Similarly, comparisons of project water exports to either actual Delta inflow or actual Delta outflow (e.g., Kasler and Sabalow 2016) ignore the effect of upstream diversion and storage operations on hydrological conditions and project water export operations in the Delta. We used unimpaired Delta outflow as a hydrological baseline because it provided an objective and transparent index of Delta hydrology under current land-use conditions that can reveal the magnitude of human water development in the Central Valley watershed relative to annual or seasonal hydrology. Estimates of unmodified flow in the current Central Valley landscape, such as unimpaired Delta outflow, impose a spatial, temporal, regulatory, and hydrological context that improves the transparency of accounting for ecosystem applications of water in the Central Valley.

Finally, any discussion of regulatory effects on project water exports or other diversions must account for the physical limits of the diversion system. Daily project water exports cannot continue if they facilitate salinity intrusion that jeopardizes other human uses of water, if there is no demand or storage space for exported water, or if the export infrastructure is closed as a result of maintenance. Ignoring the infrastructural and hydrologic limits of the water management system fosters misinterpretations about the frequency of environmental protections and the magnitude of their effects. In our 9-year study period, at least one-quarter of actual Delta outflows were needed to maintain Delta water quality for human use, and almost two-thirds of actual Delta outflows exceeded demand or the export system's capacity (Table 7).

Decision-makers should be aware that indicators of current ecosystem status reflect contributions to Delta outflow from salinity control and additional uncaptured outflows that vastly exceed the effect of ecosystem protections on project water exports.

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