PPIC PUBLIC POLICY INSTITUTE OF CALIFORNIA

Tracking Where Water Goes in a Changing Sacramento–San Joaquin Delta

Technical Appendix: Methods and Detailed Results for 1980–2021

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With research support from Gokce Sencan

Supported with funding from the S.D. Bechtel, Jr. Foundation

Introduction

The allocation of water to meet competing needs—particularly during droughts—is a major challenge for water managers in California. Water scarcity is common in all but the wettest years, forcing difficult trade-offs between using water for agriculture, businesses, and homes; retaining water in reservoirs and aquifers as a hedge against future dry years; and leaving water in rivers and wetlands to support ecosystem health.

During the most recent droughts (2007–09, 2012–16, 2020–the present), controversy over allocating water to competing uses has been particularly acute in the Sacramento–San Joaquin Delta and its watershed—California's largest. Debate often centers on regulations that set water quality and flow standards or that limit export pumping from the Delta for the Central Valley Project (CVP) and State Water Project (SWP). Central to these debates is the question: who uses how much?

This technical appendix examines how runoff available in the Delta watershed is used to meet water supply and environmental goals. It updates a previous study on water accounting in the Delta (Gartrell et al. 2017) that examined the period 1980–2016. This study expands that work to include data from 2017–21. It also looks at the policies and management decisions that affected where water was used and makes suggestions for improvements.

The 2017 report introduced the methodology for water accounting in the Delta and provided new information on how much water was needed to keep the Delta fresh enough for urban and agricultural uses, how much additional water was required to benefit ecosystem functions, and how much was either used in the Delta or exported. We compared those quantities to estimated upstream uses and made recommendations regarding water measurement and accounting as well as policies for managing the Delta. In this update we use the accounting to provide insights regarding water management in the Delta and its watershed in a changing environment.

The additional five years of information are vital to understanding how a changing climate—with warmer temperatures and more intense droughts—is impacting water use in the watershed. These new data also allow further exploration of the role of changing environmental regulations. We review and update the methods for tracking water use and translating water quality requirements into water flow requirements, along with the challenges and uncertainties associated with the chosen methodology. While one focus is on the apportionment of water that flows into the Delta, we also look upstream. Particularly in drought years, both water held in storage and water used upstream of the Delta—within the Sacramento and San Joaquin River basins that comprise its watershed—play a predominant role in Delta water balances. As a case study of the Delta during drought, we examine in detail the very dry water year 2021, including measures taken to reduce outflow requirements while maintaining water quality in the Delta. In addition, we examine a very wet water year—2017—and identify opportunities to increase exports from the Delta without changing existing regulations.

Our goal is to provide water policymakers, managers, and regulators with information that will be helpful in managing the Delta and its watershed for multiple objectives as warming conditions increase water demand, reduce snowpack, and make it harder to balance these objectives. An accompanying policy brief summarizes the findings presented here and highlights the major policy recommendations. This appendix provides details and evidence to support those recommendations and is intended for both a technical and policy audience.

In the following sections we first review our approach for categorizing water flows in the watershed, and we review the caveats and limitations of the analysis. We next present key results and discuss several important watershed trends. We then review the management challenges of changing conditions in the Delta in wet and dry years through the lens of detailed water accounting. We conclude with implications for policy and management, including recommendations to improve watershed accounting and adapt the regulatory and management framework to the changing conditions in the watershed. All data assembled for this study, along with the sources and methods used, are detailed in the accompanying *PPIC Delta Water Accounting spreadsheets*.

Methodology for Accounting for Flows in the Delta Watershed

In addition to flood control, management of freshwater inflow to the Delta seeks to support three general, often competing, objectives: (1) diversion by water-right holders for agricultural, domestic, and commercial uses within and near the Delta; (2) exports by the CVP and SWP ("the projects") to farms, cities, and wetlands to the south and west of the Delta; and (3) Delta ecosystem health, including the protection of fish species listed under federal and state Endangered Species Acts (ESAs). To achieve these objectives, a mix of federal and state regulations set flow and water quality standards that vary depending upon location within the Delta, time of year, real-time hydrology, and the overall hydrologic classification of the water year. Regulations also control the timing and volume of export pumping at CVP and SWP facilities for ecosystem protection.

The estimations presented here focus on flows that reach the Delta for the period 1980–2021. We also examine in a more aggregated way how water is used throughout the entire Sacramento and San Joaquin River watershed—including flows that do not reach the Delta because of upstream diversion and use—and how changes in volumes stored in upstream reservoirs augment or subtract from the amount of runoff available in any given year. Box A1 summarizes the new information and analyses in this update.

Box A1. What is New in this Update?

This update to the 2017 report (Gartrell et al. 2017) provides new information and analyses, including:

- The addition of flows for the period January 2017 through December 2021. This includes one of the wettest years on record (2017) and one of the warmest and driest (2021).
- Separation of Delta precipitation from net in-Delta uses (or consumptive use). Precipitation is dealt with as a separate inflow to the Delta, which allows a better comparison of in-Delta uses with other Delta water uses, especially in annual summaries.
- Discussion of new analyses of water consumptively used in the Delta, and their potential effect on how to think about outflow requirements.
- Discussion of new analyses of the effects of ecosystem regulations on Delta exports.
- An overview of the long-term trends of runoff and outflow within the Delta watershed since 1930, and a more detailed review of the period since 1980, as operational regimes and the climate changed.
- Closer examination of the impact of in-Delta and upstream depletions on overall water accounting, especially in the context of recent warm, intense droughts.
- Analyses of how water was used in 2021, a critical period because it was so dry, and 2017, a record wet year.
- An examination of the effect of the construction of a temporary barrier on False River in 2021 on water quality and supply.
- A look at how the federal 2016 Water Infrastructure Improvements for the Nation (WIIN) Act and the 2019 revision of the Biological Opinions (BiOps) affected water supplies and flows.
- Some new recommendations for actions and studies by agencies that regulate flows and water rights and manage water infrastructure.

A few changes have been made to the spreadsheets used in the analyses and in the presentations of results.[1] Results are now presented by water year instead of calendar year.[2] This is a more common way of presenting water supply analyses for California, as it keeps the wet season in one water year.

Characterizing and Assigning Flows

In this report we place all runoff of the Delta watershed into different use accounts. Box A2 provides a general guide to terminology used here. The proper characterization of this water—particularly water that achieves multiple objectives—is complex and somewhat subjective. For example, most inflow to the Delta serves multiple purposes. If minimum outflow for fish and wildlife is also sufficient to meet water quality standards to protect municipal and industrial (M&I) uses and exports, to which category should the water be assigned? The projects often release water from upstream reservoirs to help keep Delta salinity low, pushing back saltwater that is carried into the Delta by the tides. These releases—which result in large outflow volumes—help meet water quality standards for agricultural and M&I users, but also provide benefits to the ecosystem. Conversely, salinity and outflow standards to protect ESA-listed species such as Delta smelt constrain Delta exports, but the improvements in water quality from these standards also benefit in-Delta and export users by helping them meet their own water quality needs.[3]

As in the 2017 study, we take a building-block approach to the assignment of regulatory water and other water uses:[4]

- First, we track water from its origins through outflow, accounting for the various uses by cities and farms, including water stored and released from reservoirs and water used upstream of the Delta, as well as water exports and in-Delta uses.
- Second, we determine the assigned water for any day resulting from flow and water quality regulations to protect water quality for exports and in-Delta uses (termed *system outflow*); in doing this, we further parse system water into outflow needed to maintain water quality for exports, in-Delta M&I, and in-Delta agriculture, respectively.
- Third, we calculate the additional water required on top of that system outflow to meet regulations that protect the ecosystem and endangered species (termed *ecosystem outflow*), and further parse the flows for different regulations, including export reductions for fish protection purposes.
- Finally, we document the inflow that exceeds system and ecosystem outflow needs and results in additional Delta outflow (*uncaptured outflow*).[5]

This building block approach assigns regulatory flows based on the historical order of water regulations. We emphasize this approach because it helps build understanding of the importance of outflow required to support municipal and farm uses: while some system outflow serves ecosystem purposes as well, *this water would be required to support diversions even if there were no ecosystem management objectives in the Delta*. Below

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[1] Some improvements were made in the 1980–2016 spreadsheets; none had a significant effect on the Delta accounting (generally a small shift of flow from system outflow to ecosystem outflow, if any). Also added are new and corrected data on Trinity River imports. All the corrections are discussed in the Index of PPIC Delta Water Accounting spreadsheets.

[2] October 1 of the prior year through September 30 of the current year; for example, water year 2021 ran from October 1, 2020 to September 30, 2021. The PPIC Delta Water Accounting spreadsheets provide the data on a daily, monthly, and annual basis, including both calendar years and water years.

[3] As described in the 2017 main report (Gartrell et al. 2017), water accounting by the California Department of Water Resources in the California Water Plan Updates (Bulletin 160) did not distinguish between system and ecosystem outflow, assigning all this outflow to the environment as "required Delta outflow." This masks, and perhaps fuels misperceptions of, the multiple uses and benefits of this regulatory water—including the fact that much of this outflow would be required to keep the Delta fresh enough for municipal and farm uses, even if there were no ecological management objectives in the region.

[4] See Gartrell et al. (2017), p. 7 for a brief description of these categories.

[5] Uncaptured outflow as we use it differs from a common term of "surplus" water. Surplus water is the outflow above that needed for water quality or flow requirements. Uncaptured outflow excludes an additional component: outflow that results from export limits to protect aquatic resources. Uncaptured outflow is surplus water minus water that goes to outflow because of those export limits.

(Figure A4) we also show how this “multipurpose” outflow—which meets both system and ecosystem requirements—fits into the overall water balance.[6]

The sources and methods used to account for surface water available in the Delta watershed and upstream depletions, and to apportion Delta inflows among use and outflow categories, are summarized in Table A1 and then discussed in detail below and in the PPIC Delta Water Accounting spreadsheets.[7]

An important caveat, discussed further below, is that the water we identify as necessary for meeting system and ecosystem outflow requirements does not always come at a direct cost to Delta exports. When there is significant uncaptured outflow, the water required to meet salinity and flow standards generally does not require tradeoffs with exports because there is more than enough water to meet all needs. In contrast, ecosystem regulations that limit export pumping can reduce export deliveries even when there is uncaptured outflow.

Box A2. Water Use Terminology

Different terms are often used for water use: water right, allocations, diversions, exports, depletions, net and gross consumptive use. Comparing one with the other can be an “apples-to-oranges” exercise. Here is a quick tutorial on the terms we use:

Water right. This is the amount of water that an entity has a right to divert for beneficial use or to store. When examining water rights, one must be careful to not double (or triple) count the quantities, since many water rights overlap (that is, an entity uses one or the other, never both simultaneously, for the same volume of water). The face value of a water right does not inform the terms and conditions placed on the right, nor how it may be used (or not used) in conjunction with other rights held by the same entity. Consequently, simply adding the face value of water rights will lead to a significant overestimation of the total rights allocated. Furthermore, a significant fraction of diverted water under a water right is also returned to the system for reuse by others as irrigation runoff or treated wastewater discharges (“return flows”). Unfortunately, there is still no easy way to find and document how much total water could be used, although evapotranspiration estimates can provide some information. The State Water Resources Control Board (State Water Board) has legal authority over water rights and is starting to address this issue.

Water allocation. This is the maximum amount of water that an entity holding a contract with an agency with a water right can take in a given year. The Department of Water Resources (DWR) holds water rights for the SWP, and the US Bureau of Reclamation (USBR) holds them for the CVP, for example, and their contract years start on January 1st and March 1st, respectively. A contractor might divert less than the allocation.

Water diversions. This is the actual water diverted by a user. Some of this water may be returned to the system as return flows, available for reuse by others.

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[6] The PPIC Delta Water Accounting spreadsheets also present alternative ways of categorizing system, ecosystem, and multipurpose outflow.

[7] For an illustration of the approach, see Figure B1 in Appendix B to the 2017 report, which provides an overview of the monthly share of inflow apportioned to the major categories described above for an above-normal water year and a dry year.

Box A2. Water Use Terminology (continued)

Upstream depletions. Upstream depletions result from diversions, seepage to and from groundwater, return flows, ET from vegetation, evaporation from water surfaces, and precipitation. We estimate it from unimpaired runoff, releases and storage in reservoirs, imports of water into the watershed (from the Trinity River), and inflow to the Delta. Annual summaries of depletions may reflect water put in groundwater storage in one year that becomes available in a later year.

Water exports. This is water diverted and exported out of the watershed or basin. In this analysis, we count as exports the water pumped through SWP and CVP pumping plants in the south Delta (which sometimes includes non-project water). We treat water diverted from the upper Delta watershed and exported to the East Bay Municipal Utilities District (EBMUD) and San Francisco Public Utilities Commission (SFPUC), as well as diversions from the Friant system to the southern San Joaquin Valley, as part of upstream depletions.

Net Delta channel depletions and net Delta consumptive use. Channel depletions in the Delta result from water diversions, water seepage into soils or groundwater (through levees for example), evapotranspiration (ET) from plants (including crops and riparian vegetation), water storage in soils, return flows, evaporation from water surfaces, and precipitation. This differs from net consumptive use, which measures the evapotranspiration from plants, along with evaporation from water surfaces and precipitation. In practice, the main difference between net channel depletions and net consumptive use is from the effects of storage in soils; monthly patterns can greatly differ, but over longer periods they should be similar. Estimates of net depletions in the Delta are important for estimating Delta outflow, and channel depletions in the Delta would provide better estimates of monthly outflow than consumptive use. But some key components—soil storage, seepage, diversions, return flows, etc.—are not measured. For this reason, net consumptive use—estimated based on crop patterns and estimates of ET—is often used and provides a reasonable estimate.

Gross versus net depletion or consumptive use in the Delta. In the Delta, gross measures of depletion or use do not take into account precipitation. Net measures are the gross values less local precipitation.

Rainfall can satisfy some or all of the plant ET; when it exceeds ET, it creates runoff to the Delta, runoff can be created without rainfall exceeding ET: when rainfall exceeds infiltration capacity generates runoff (even without exceeding ET) and net consumptive use or net channel depletions are negative. That creates an issue when making annual summaries: runoff in the winter can offset depletion or use in the summer (for example, in 1983, annual precipitation exceeded annual gross consumptive use, giving the impression there was no use at all that year).

In this report, we treat precipitation as an inflow, and present estimates of gross consumptive use for the Delta. This in-Delta use consists of water diverted and used locally for agriculture, plus channel evaporation and riparian ET, less return flows to the system. In the figures and summary statistics, we generally add to the in-Delta use the diversions of the North Bay Aqueduct and the Contra Costa Water District, both of which are in the legal Delta or immediately adjacent to it. These diversions are also tracked separately in the spreadsheets, as are precipitation and net consumptive use.

A third way of presenting the data is to offset the gross Delta consumptive use with any available precipitation needed to bring the net use to zero, and to report the remainder as runoff or return flow to the Delta. This approach is comparable to the way upstream depletions are estimated. The effect of doing this—relative to the main method we use—is discussed later in this Appendix.

TABLE A1

A brief overview of Delta watershed accounting components and data sources

Category	Definition	Data source or method of calculation
I. Unimpaired runoff	Runoff that would occur in the absence of dams and diversions (but with current channels).	CDEC(c) DWR (2016) Kadir (2021)
II. Reservoir storage/releases	Net change in reservoir storage. Based on data for 10 major rim reservoirs and a correlation with DWR data on total storage that includes smaller reservoirs.	CDEC(c) DWR (2018)
III. Upstream depletions	Net runoff used upstream due to diversions (less return flows), seepage to or from groundwater, riparian ET, and evaporation from water surfaces. Estimated from unimpaired runoff, less storage of water, plus releases of water from storage, plus imports of water from the Trinity River, less Delta inflow. Includes out-of-basin diversions by East Bay Municipal Utilities District, San Francisco Public Utilities Commission, and Friant Water Authority.	CDEC(c) Dayflow(d) DWR (2016) Kadir (2021)
IV. Delta precipitation	Precipitation in the Delta is included as an inflow.	Dayflow(d)
V. Delta diversions	Water diverted for M&I and agricultural use within and around the Delta and in export regions.	See each subcategory; Delta inflow from Dayflow(d)
In-Delta use	Gross in-Delta consumptive use, consisting of channel evaporation, ET by vegetation, both agricultural and riparian, smaller Delta diversions, and diversions by the Contra Costa Water District (CCWD) and North Bay Aqueduct (NBA)(a) less return flows.	DICU (1980–2016) (b) Dayflow (2017–2021) (d)
Delta exports	Diversions from the Banks and Jones Pump Plants in the south Delta, for delivery to SWP and CVP contractors.	CDEC(c) Dayflow(d)
VI. System outflow	Water assigned to keep salinity low enough for Delta diversions. These flows may also provide ecosystem benefits, but they would be required even if there were no regulations to protect the ecosystem.	See each subcategory.
Export water quality (Tracy standard)	Outflow needed solely to maintain water quality sufficient for exports at the Banks and Jones Pump Plants (250 mg/l chloride and 1 mS/cm).	Determined through G-Model relationships (Denton 1993)
M&I and agricultural Delta water quality standards	Outflow needed to meet M&I and agricultural water quality standards under State Water Resources Control Board Decisions 1485 (D1485) and 1641 (D1641) at various locations in the Delta. Includes carriage water, if required (see next row).	Determined through G-Model relationships (Denton 1993). See Appendix B of the 2017 report.
Carriage water	Extra outflow required above the minimum needed for M&I and agricultural water quality standards; it is a function of Delta Cross Channel closures and export pumping when outflow is low, and is generally assigned to Delta M&I and agricultural requirements.	Denton (2006). See Appendix B of the 2017 report.
VII. Ecosystem outflow	Water needed to meet outflow or salinity regulations for ecosystem purposes, or outflow generated by export limits to protect aquatic species.	See each subcategory.
Ecosystem flows	Outflows required by D1641 for ecosystem purposes.	Outflow value from the regulation.
Ecosystem water quality	Outflow necessary to meet water quality regulations established for ecosystem purposes, including spring and fall X2 requirements. Includes carriage water, if required when the Delta Cross Channel is closed for fishery protection.	For X2: the outflow method was used. For other standards: outflow determined by the G–Model relationships (Denton 1993).
Export pumping limits	Water available to be pumped at Banks and Jones that is precluded by export pumping limits. These include limits under D1641 (export-to-inflow ratio of 35% or 65%, the spring pulse-flow limit, and April-May export limits under the Vernalis Adaptive Management Program (VAMP) from 2000–2011); CVPIA (enhanced spring pulse flow); and the 2008–09 ESA BiOps (spring flow limits, Old and Middle River flow limits, San Joaquin River inflow-to-export limit).	Export limits for each category are calculated separately in the spreadsheets but combined in the tables and graphs below.
VIII. Uncaptured outflow	Outflow above that required for system outflow and ecosystem outflow, including export limits. Most uncaptured outflow is beyond the physical capacity of the export facilities to take the water; in some situations, exports are occurring below authorized export limits and there is capacity in the aqueducts, but nowhere to put the water.	Dayflow, CDEC, DICU to obtain total outflow; uncaptured volume determined by subtracting the outflows assigned to system and ecosystem outflow.

NOTES: See text that follows this table for detailed explanations.

[a] CCWD diversions are largely through the CVP but include non-CVP water rights. NBA diversions are from the SWP.

[b] California Department of Water Resources, (1995) "Estimation of Delta Island Diversions and Return Flows. Modeling Support Branch. Division of Planning." for Delta Island Consumptive Use (DICU).

[c] California Department of Water Resources. n.d. California Data Exchange Center;

[d] California Department of Water Resources. n.d. Dayflow data.

Flow Components

Runoff

We interchangeably use "runoff" as shorthand for what is commonly termed "unimpaired runoff"—the volume of water that would have flowed into the Delta watershed absent any storage or diversion facilities. DWR (2016) provides estimates of total unimpaired flow for the watershed for the period 1980–2016, by watersheds and overall. For 2017–2021, we estimated unimpaired runoff from reported unimpaired flows (CDEC "FNF" data) for major rivers, and then expanded this to the whole watershed using a correlation[8] with DWR (2016) data for total unimpaired flow and the ten-river unimpaired flow data from CDEC.[9] The results checked favorably against recent DWR draft data (Kadir 2021).

Reservoir Storage and Releases

Most runoff in the Delta watershed passes through major multipurpose reservoirs. Within every year these reservoirs store and release a portion of this runoff, impacting total flows into the Delta. The reservoirs also have some capacity to carry over runoff from one year to the next. During wetter periods, a portion of this runoff is carried over to the next year, reducing Delta inflows. In dry periods these stored waters are released, increasing Delta inflows. For this report we recorded net storage and release on an annual basis from end-of-year storage levels of 10 major reservoirs.[10] These were correlated with DWR estimates of total watershed storage to estimate watershed storage changes.[11] For imports from the Trinity River (situated outside of the Delta watershed in the North Coast hydrologic region), we used flows from CDEC.[12]

Upstream Depletions

Net upstream depletions result from water that is removed from the watershed before it reaches the Delta. These can be diversions for urban and agricultural uses upstream of the Delta (less any return flows), seepage to (or from) groundwater, losses due to wetland and riparian ET, and evaporation from soils and channels. As will be seen, this consumes a significant portion of the total annual runoff in the watershed.

We estimate net upstream depletions by difference on an annual basis. Known inflows are the unimpaired runoff from the upper watersheds (DWR 2016), storage releases, and imports from the Trinity River. Known removals are stored water and Delta inflow. The difference is an estimate of the remaining factors: the net depletions due to diversions minus return flows, net seepage, ET, precipitation, and evaporation.[13] Note that some return flows may not come back in the same water year. For example, diverted water that goes onto rice fields in one water year may not drain off until the next; there may also be net seepage into aquifers in one year and net seepage out in another. The estimates are a reasonable depiction of the overall use upstream on an annual basis. Yet as described below, developing more accurate and timely estimates of the major components of net upstream depletions is a major priority for operating the system more effectively during droughts.

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[8] Correlation r-squared of 0.998

[9] CDEC stations SBB, FTO, YRS, AMF, CSN, MOK, SJF, SNS, TLG, MRC.

[10] Shasta, Oroville, New Bullards Bar, Englebright, Folsom, Camanche, New Melones, New Don Pedro, New Exchequer, Millerton.

[11] Correlation r-squared of 0.979

[12] CDEC station JCR. Over the 1980–2021 period, these imports averaged just under 750,000 acre-feet annually, and slightly lower in the past two recent decades.

[13] DWR (2016) estimates unimpaired flow from measured flow with adjustments for storage. This approach may not account for all upstream diversions above the point of measurement (in most cases, rim dams). Although these diversions are small relative to overall supplies in most years, they may be significant enough in very dry periods to affect the overall accounting of water availability (or unavailability).

Delta Precipitation

In this update we separate out precipitation in the Delta and treat it as an inflow. This allows us to show the total consumptive use in the Delta.

In-Delta Use

Delta outflow—which is important to document for an array of regulatory standards as well as operations of the CVP and SWP—is Delta inflow minus the combination of Delta exports and net in-Delta use (water used by farmers plus evaporation from water surfaces and ET by riparian vegetation minus precipitation in the Delta). While exports and municipal diversions are measured directly at the pumps, most agricultural and riparian in-Delta uses are estimated because diversions and net water use by farms in the Delta are not monitored sufficiently to be useful for management. In the figures and tables presented in this appendix, we include in-Delta M&I diversions of the North Bay Aqueduct (NBA) and Contra Costa Water District (CCWD) as in-Delta use. Historically, these diversions have been small relative to other water uses in the Delta.[14]

The methods used to estimate in-Delta use, which in turn are used to calculate Delta outflow, create great uncertainty for CVP and SWP managers and regulatory agencies, particularly during drought (Box A3):

- **Dayflow.** The primary measure of in-Delta use for operational purposes is found in Dayflow. These estimates were developed in the 1960s based on data available at the time, and they are fixed across years. In-Delta depletions are based on monthly measures of acreage of crops and assumptions about their net water use, plus assumptions about seepage rates from channels onto farms (most of the Delta's islands are below sea level, so water seeps onto the islands continuously), and estimates of evaporation from water surfaces and wetlands. Dayflow provides an interpolation of monthly data into daily values (as a consequence, one should take this into account when examining "daily" outflow); these data are used by DWR and USBR to estimate daily outflow and to aid in determining if outflow regulations are being met.
- **Delta Island Consumptive Use (DICU).** DWR's DICU estimates (DWR, 1995) were developed for operational modeling. DICU data rely on more updated cropping patterns and other meteorological data, including monthly evaporation estimates, that are often used in Delta salinity and operational models. They are thought to provide better estimates of Delta uses than Dayflow values.
- **Delta Channel Depletions (DCD).** Several recent studies (DWR, 2018; Hutton et al. 2021) have sought to improve estimates of in-Delta use by estimating channel depletions. This work led to the creation of a new estimate of Delta consumptive use, "Delta Channel Depletions" (DCD). It is too early to determine the accuracy of the DCD method, but the use of the new DCD values could have implications for regulatory and operational practice, and for our estimates of Delta outflow (Box A3).

In our 2017 report, we used a recent version of DICU to approximate in-Delta use through 2016. For more recent years included in this update, we used values from Dayflow, as DICU data are not available.

Delta Exports

The CVP and SWP export relatively large amounts of water from the Delta, ranging from 1.5 million acre-feet (maf) to 6.7 maf annually in the 42-year period examined here. These projects are generally responsible for meeting flow and water quality standards, regardless of the magnitude of upstream depletions and in-Delta use.[15] Pumping schedules and volumes are regulated by water quality control plans and Biological Opinions (BiOps).[16] In all but the wettest years, export pumping needs to be curtailed and/or inflows from reservoirs increased to meet

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[14] Typically, the NBA diverts about 45,000 acre-feet (af) per year and CCWD diverts about 120,000 af per year; in-Delta depletions are about 1,800,000 af per year, of which about 200,000 af evaporates from water surfaces. CCWD has its own water rights in addition to the CVP supply.

[15] For a detailed discussion of the regulatory framework, see Appendix A of the 2017 report.

[16] Water Quality Control Plans as set forth in the State Water Board Decisions 1485 and 1641; BiOps were issued under the federal Endangered Species Act by US Fish and Wildlife Service and National Marine Fisheries Service starting in 1993–94. See Appendix A of the 2017 Report. In addition, the California Department of Fish and Wildlife has issued Incidental Take Permits, generally similar to the BiOps, but not always. As noted below, they conflicted with the 2019 BiOps.

water quality and flow standards. Export pumping is often greatest in winter, summer, and fall, with less pumping in spring when various limits are imposed to protect fish. Since 2008, when additional export pumping limits were imposed, pumping is often low from January through June in drier years. Exports are among the most accurate data series available for this accounting exercise. We used data from Dayflow, and USBR and DWR daily reports for CVP and SWP daily pumping.

Box A3. Comparing Different Delta Depletion and Use Estimates

Delta outflow estimates are important for operating the projects and meeting regulatory standards. This outflow is calculated, not measured, based on assumptions about in-Delta use and channel depletions. Medellín-Azuara et al. (2018) provided a comparison and an excellent discussion of a number of different estimates. Two recent studies have indicated that the standard Dayflow and Delta Island Consumptive Use (DICU) estimates of in-Delta use are inconsistent with the salinity patterns seen in the Delta when models are compared to field data (DWR 2018, Hutton et al. 2021). The studies show a possible seasonal bias in the distribution of consumptive use that affects how Delta outflow is calculated. In dry periods, in-Delta use can be of the same order of magnitude as the calculated outflow; consequently, any large errors in estimated Delta use (including a seasonal bias) will give a large error in calculated outflow.

When averaged over the 1980–2016 period, the three methods—Dayflow, DICU, and the new Delta Channel Depletion (DCD)*— agree closely: they are all within 3 percent of each other. When individual years are compared, the annual amounts can differ from 0 to 0.4 maf per year (up or down) or at most 3 percent of inflow and 5.5 percent of outflow.

Although annual totals do not vary much, the three methods differ more substantially at the monthly scale. For example, relative to results using Dayflow numbers, the July and August levels for the DCD data imply almost 2,600 af/day (about 1,300 cfs) *less* depletions (–35%)—or a comparable increase in calculated outflow. Conversely, for March, DCD and DICU find about 2,000 af/day (about 1,000 cfs) *more* depletions (and less outflow) than in Dayflow (up to 125% more). DICU and Dayflow are about the same in January, but DCD is about 2,800 af/day (1,400 cfs) higher.

We compared the assignment of Delta flows for 1980–2021 using the various depletion estimates and found that very little changed on an annual basis, with two exceptions that would be expected: total outflow and uncaptured outflow (the residual after subtracting system and ecosystem outflow). Other categories changed little (less than 0.02 maf over a year, for the most part). However, DICU and DCD data (developed using different models) both decline by about 0.2 to 0.3 maf over the study period, whereas Dayflow uses a single set of gross consumptive use estimates developed in the 1960s that does not vary across years.

Since calculated outflow depends directly on the assumed in-Delta use, a change of in-Delta use from the Dayflow values used in operations to another method of estimation will change the calculated outflow. For instance, calculated outflow using DICU and DCD is about 0.2 to 0.3 maf higher than outflow using Dayflow from the mid–1990s onward. Looking ahead, if the new DCD data are correct, the outflow data that were used to calibrate salinity models used in Delta management and regulation were not correct. This is of particular importance in July through September, when salinity is generally high and outflow low. Models would need to be recalibrated to give better estimates of the amount of water it takes to maintain salinity in the Delta; these efforts are ongoing now (Denton 2022).

If the DCD data are found to provide better estimates of in-Delta depletions, that could mean a change in the estimated amount of water it takes to keep the Delta fresh. This would have implications for how regulations are established (for example, the X2 flow regulations) and how their impacts are estimated. For example, a lower consumptive use level in July and August would mean that outflow is higher than previously calculated in those months. Salinity-outflow models would have to be recalibrated, and they could indicate that even more outflow is needed for system outflow and X2 requirements than previously thought.

* Dayflow, DICU and DCD data can be found in the PPIC Delta Water Accounting spreadsheets.

System Outflow

To sustain in-Delta uses and exports—regardless of any regulations to protect the Delta ecosystem—Delta salinity must meet specified levels. The State Water Board regulates salinity levels to protect drinking water, industrial uses, and crop production. The CVP and SWP are responsible for meeting these standards.[17] For the period of analysis here, these regulations are imposed through State Water Board Decision 1485 (D1485), in force from 1978 to 1994, and Decision 1641 (D1641), in force since 1995.[18] Figure B2 in Appendix B of the 2017 report shows the main locations for these salinity standards. These standards vary with hydrologic conditions; the classification of water year types plays an important role. Both the data and formulas used to classify year types—and the reliance on a limited number of discrete year types rather than real-time hydrology to set standards—may merit revisiting (Box A4).[19]

System outflow reflects regulatory standards intended to benefit three types of uses:

- **Export water quality.** Substantial Delta outflow is needed throughout the year to keep salinity low enough for exports. This is in part due to the location of the pumps in the south Delta, in proximity to poor water quality flowing in from the San Joaquin River, and tidal action that brings salinity in from Suisun Bay and the Carquinez Strait. Outflow is also needed at times (depending on export levels and whether the Delta cross-channel gates are closed) to offset the effects of pumping on central and south Delta water quality.[20] We track flows to meet "export water quality," also known as the "Tracy standard," to provide information on how much water is needed for that purpose compared to Delta M&I water quality at other locations and Delta agricultural water quality.[21] If the Delta M&I water quality standards are met, "export water quality" will be too, as the latter requires somewhat less outflow. In all but the wettest years, a large portion of Delta inflow is needed to keep the Delta fresh enough for export users. During dry periods, such as the recent droughts, the volume of system outflow assigned to support export water quality exceeds the amount of water exported. Details on how this was calculated are found in Appendix B of the 2017 report.
- **Delta M&I water quality.** The Delta contains multiple intake points that divert water for M&I uses in cities throughout the region. Many of these intakes are in locations that are vulnerable to salinity intrusion (for a map, see Figure B2 in Appendix B to the 2017 report). They require system outflows that are usually above those needed to maintain water quality for export uses. The State Water Board protects Delta M&I water quality through salinity standards that are defined and monitored at several locations, including the Contra Costa Canal, Antioch, the North Bay Aqueduct (NBA), and the Banks and Jones Pump Plants. However, because high salinity arrives principally from the west and does not intrude near the NBA, if the standard is met at the Contra Costa Canal, it is met at the other locations.[22] When natural runoff is insufficient, the CVP and SWP must comply with these standards by releasing water from their upstream reservoirs or by reducing export pumping. The locations and levels of salinity standards vary by month and water year type, but some standards are required throughout the year. During some periods of high export pumping and low outflow, the amount of outflow required to meet the standards may exceed the levels needed when export pumping is lower. This "carriage water" is included in the accounting. Details on how

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[17] One purpose of the CVP was to provide salinity control in the Delta (Calif. DPW, 1930); the Delta Protection Act (Water Code 12200-12205) provides that salinity control is a function of the SWP and that no water shall be exported that is necessary for the provision of an adequate salinity in the Delta.

[18] D1641 was formally adopted in 1999, but it contains regulations adopted by the SWRCB in its 1995 Water Quality Control Plan; the projects operated to the same regulations starting in 1995 as part of the Delta Accord (see Technical Appendix A in the 2017 report).

[19] Beyond the problem with thresholds in regulatory outcomes by water year type described in Box A4, there are other examples of sharp jumps in regulatory and management outcomes that bear revisiting. For instance, the CVP Settlement and Exchange Contractors allocations are reduced from 100 percent to 75 percent when total inflow to Shasta Reservoir is less than 3.2 maf. For the settlement contractors with the SWP, the threshold for cutbacks is an April–July forecast or actual inflow of less than 0.6 maf. (See footnote 62 for more information on these contracts.)

[20] This refers to "carriage water." It is extra outflow above the minimum needed for M&I and agricultural water quality standards; it is a function of Delta Cross Channel closures and export pumping when outflow is low.

[21] Historically, the maximum salinity desired for export uses was referred to as the "Tracy standard," which is equivalent to about 250 mg/l chloride or about 1 mS/cm electrical conductivity at the Jones Pump Plant near Tracy.

[22] In practice, SWP and CVP operators closely follow the salinity at Jersey Point, the location of one of the agricultural standards, to meet the salinity requirements at the Contra Costa Canal, since the salinity at the Contra Costa Canal is related to the salinity at Jersey Point, with a lag of a week to 10 days.

the flow needed to meet M&I water quality standards was calculated are found in Appendix B of the 2017 report.

- **Delta agricultural water quality.** The State Water Board also sets salinity standards in the Delta to protect in-Delta agricultural diversions from April 1 through August 15. In most years it takes additional system outflow—on top of outflows to meet export and Delta M&I standards—to maintain salinities low enough for agricultural diversions in the western Delta. As with Delta M&I water quality, the CVP and SWP are responsible for meeting these standards through releases from upstream reservoirs or reduced export pumping. The largest amount of system outflow is required in wet years, when the agricultural standard requires the freshest water (0.45 mS/cm at Jersey Point) from April to mid-August; system outflow is reduced in June in dry years, when a higher salinity is allowed (1.35 mS/cm at Jersey Point starting June 15); and a high level of salinity is allowed for the whole period in critically dry years (2.2 mS/cm at Jersey Point, 2.78 mS/cm at Emmaton). Details on how the flow needed to meet agricultural water quality standards was calculated are found in Appendix B of the 2017 report.

System outflow to provide adequate water quality for exports and in-Delta M&I uses is required all year; outflow to provide adequate water quality for in-Delta agriculture is required from April to mid-August. Consequently, the requirements overlap, and each provides benefits to the others, as well as to the Delta ecosystem.

Box A4. Challenges with Using Water Year Type for Water Quality Regulations

Since 1978, Delta water quality regulations from the State Water Board include a classification of water year types as wet, above normal, below normal, dry, or critically dry. The current D1641 index that determines the year type is based on three components: (1) the October–March runoff from the eight largest rivers in the watershed; (2) the April–July runoff forecast for those watersheds; and (3) a fraction of the prior year's index. The greatest weighting is for the April–July forecast (40% for the Sacramento River watershed, 60% for the San Joaquin). The current indices were developed in the early 1990s using data for the period 1922–91.

Several things about this regulatory approach are worth noting—and possibly reconsidering as regulations are updated: (1) increasing drought intensity; (2) declining snowpack; and (3) inconsistencies that arise in outcomes when crossing from one year type to the next.

Increasing drought intensity. As described later in this report, conditions in the Delta watershed are changing. Over the past two decades, increases in temperature and related evaporative demand have made drought conditions more severe, impacting all uses of water. This level of drought intensity is not captured in the 1922–1991 period used to establish water year types. Regulations that are based on historical water year type do not take into account these changing conditions and may fail to meet regulatory objectives, particularly for environmental protection.

Declining snowpack. The heavy weighting of the April–July runoff forecast in the water year typology reflects historical reliance on snowpack as integral to water supply. As we describe below, with hotter and drier spring conditions, there is less runoff coming from snowmelt in the April–July period. A striking example is in 2021, when lower-than-anticipated runoff in this period played a key role in management difficulties. Moving toward a regulatory approach that can adapt more readily to lower spring/early summer runoff will be important.

Inconsistent outcomes. Under D1641 (and D1485 before it), the year type is used to provide increasingly lower salinity for M&I and agricultural water quality in wetter periods. This approach works like a step function, producing thresholds that can require vastly different amounts of outflow for minor differences in hydrologic conditions. For example, a year with an index of 5.5 (dry) will require 0.7 maf more outflow than a year with an index of 5.4 (critically dry). Conversely, this approach can require the same outflow for vastly different hydrologic conditions but the same year type: years with indices of 7.9 or 9.1, both above normal but different in runoff, will have the same requirements. Moving toward a regulatory approach based on a hydrologic continuum would enable more consistent management reflecting actual conditions.

For ecosystem management, D1641 regulations took a helpful step in this direction. In particular, the "X2" salinity standard used to regulate water quality for the ecosystem depends on the prior month's measured runoff rather than water year type. However, some more recent ecosystem regulations have reverted to using water year type, with notable problems. The fall X2 standards in the 2008–09 BiOps and the related California Department of Fish and Wildlife (CDFW) Incidental Take Permit are based on water year type, leading to prescriptions that do not always match available water. Similarly, the San Joaquin inflow/export regulations under these BiOps regulate exports based on year type, with "steps" that vary greatly and are not tied to current inflow conditions. The regulation can allow greater exports in drier years than in wetter.

Ecosystem Outflow

It is complicated to estimate the volume of water used to support the Delta ecosystem. One issue is the significant changes since the late 1970s in the laws and regulations that protect fish and other instream beneficial uses. But even more importantly, regulators use a mix of direct and indirect ways to manage flows and water quality.

Moreover, multiple state and federal agencies set, monitor, and enforce these requirements, not always in unison. For the period under analysis here, ecosystem outflow has been required by regulations under D1485 (1978–94), D1641 (since 1995), federal BiOps that implement the ESA (since 1993, revised in 1995, 2008–09 and 2019), the California Department of Fish and Wildlife (CDFW) Incidental Take Permit (ITP), the Vernalis Adaptive Management Program (VAMP, 2000–11), and the Central Valley Project Improvement Act (CVPIA, since 1992). As with salinity standards for water supply, the CVP and SWP are responsible for meeting these standards. See Appendix A of the 2017 report for details.

There are three general classes of ecosystem outflow created by the complex array of regulations, with significant overlaps. All of them overlap with, and are bolstered by, system outflow requirements. For details on how they are calculated, see Appendix B of the 2017 report.

- **Ecosystem flows.** Depending on the season and water year type, regulators will stipulate that a certain volume of water must flow into the Delta from the San Joaquin River and its tributaries, or they will define how much water must flow out of the Delta into Suisun Bay. On any given day, multiple regulations can establish these inflow and outflow requirements. We calculated all of them and used the flow standard that resulted in the highest total required for a given day (on the assumption that the other standards are met if the highest is met). Ecosystem flows were required under D1485 and were entirely revised under D1641 in 1995. Additional ecosystem flows were required under the CVPIA, VAMP, and ESA.
- **Ecosystem water quality.** State and federal regulators have set multiple salinity standards throughout the Delta to improve conditions for native fish. We have estimated the volume of Delta outflow needed to meet these standards, which are often higher than those set for agriculture and M&I uses. As with ecosystem flow requirements, ecosystem water quality requirements often overlap, and the satisfaction of one standard at one location can also satisfy different standards at multiple locations.[23] Ecosystem water quality requirements to enhance conditions for striped bass were promulgated in 1978 under D1485. Almost all those standards were replaced in D1641 with the X2 salinity standard and ecosystem flows discussed above. ESA BiOps in 2008–09 added a fall X2 level. When the Delta Cross Channel is closed for fishery protection, additional outflow can be required to meet the Delta M&I and agricultural standards; this added carriage water is assigned to ecosystem water quality.
- **Export pumping limits.** The CVP and SWP pumps have direct and indirect impacts on native fishes. To reduce these impacts, regulators limit the timing and volume of pumping. This can have the net effect of increasing Delta outflows by reducing the amount diverted for exports (see caveats discussion below). Controls on pumping include: setting limits on the volume of exports during a certain period; limiting pumping based on the total amount of inflow or, at times, just the San Joaquin River inflow; controlling pumping to reduce reverse flows in Delta channels (which functionally limits exports to about 50% of the San Joaquin River inflow plus a fixed amount of flow); and restricting pumping to reduce entrainment ("take" or potential "take") of fish. D1485 set export pumping limits from May through July to protect striped bass. These were replaced in 1995 (in the Delta Accord and D1641) with pumping limits throughout the year, based on a percentage of Delta inflow, with additional pumping limits based on San Joaquin River inflow during the spring pulse-flow period. ESA BiOps, the related CDFW ITP, the CVPIA, and VAMP—all implemented after 1992—combined to add more export pumping limits during the pulse-flow period. In 2008–09, revisions to the ESA BiOps led to additional pumping limits through limits on the net flow in Old and Middle Rivers as well as limits based on fish entrainment. The 2019 BiOps reduced some of the 2008–09 export limits under certain circumstances and conflicted with the CDFW ITP, which was consistent with the 2008–09 BiOps.[24] While we measure the effects of water quality and outflow requirements from the "bottom up" (i.e., from zero outflow up to the required daily level), we measure the effect of export limits

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[23] For example, the X2 requirement in February requires 2 ppt at Collinsville, much lower than the Suisun Marsh standards that require 8 mS/cm at the same time. If the X2 standard is met (which requires about 7,100 cfs outflow), the Suisun Marsh standard at Collinsville is also met, as is the 150 mg/l M&I standard which requires about 5,500 cfs.

[24] Box A5 below discusses the role of the 2019 BiOps and the resolution of the conflict for 2019 through 2021.

from the “top down.” That is, the ecosystem is assigned the amount of water that would have been available for pumping, up to the limit of the pumping capacity.

In our building-block accounting approach, ecosystem outflow is the additional outflow required to protect fish and other instream beneficial uses, above and beyond the flows required to protect water quality for Delta diversions (system outflow). There is significant overlap between system outflow requirements and both ecosystem flow and quality requirements. In contrast, export pumping limits do not have overlapping requirements with system outflow, so they are always counted as additional outflow for ecosystem purposes.

Ecosystem flow and water quality requirements increase with the amount of annual runoff. Although they always overlap with system outflow requirements, they are not always larger. System outflow is slightly larger in late summer and fall; hence ecosystem outflow is small or zero in those months (see Figure B1in Appendix B to the 2017 report). Ecosystem outflow is greatest in the winter and spring; this is when X2 water quality requirements and export pumping limits are the largest.

Uncaptured Outflow

Uncaptured outflow occurs, in general, when inflows exceed all other demands in the Delta, including in-Delta uses, exports, system outflow, and ecosystem outflow. This is most common during winter high-flow pulses or periods of high snowmelt runoff, when upstream reservoirs are close to capacity and are spilling water. It is not uncommon in wet years that some uncaptured outflow results when export pumping is cut back to levels below those allowed by regulations. For example, this occurs in wet years when CVP and SWP aqueducts and south-of Delta storage (e.g., San Luis Reservoir) lack capacity for additional exports. Cutbacks in export pumping also sometimes occur for maintenance and repairs.

Uncaptured outflow helps meet salinity regulations by freshening the Delta so that, later, when inflows subside, the salinity levels can remain low for an extended period, reducing pressure on reservoirs to meet water quality standards.[25]

Appendix B to the 2017 report gives detailed examples of uncaptured outflow through two years, including a discussion of how it is estimated and why it sometimes can be negative, which occurs when the outflow index is less than what is normally needed to meet water quality standards. This is important for estimating the impacts of actions taken to reduce the water needed to meet water quality standards in 2015 and 2021. Since we estimate uncaptured outflow by difference, after accounting for all other components of Delta inflows, any errors will accumulate into the uncaptured category. Readers are therefore advised against an interpretation of the results on too fine a time scale, for example a weekly or daily basis.

Caveats and Limitations of this Analysis

It is important to recognize several caveats and limitations of this analysis to avoid misinterpreting the results.

Equating Regulatory Outflows and Cost to Water Exports

Because the CVP and SWP are responsible for meeting the various water quality and flow requirements in the Delta, these regulations can affect the volumes of water available for export from the CVP and SWP pumps. However, our estimates of system and ecosystem outflow required by regulations do not measure the actual impact of regulations on export volumes. This is the result of several factors:

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[25] When there are uncaptured flows, salinity in the Delta will generally fall below the maximum levels allowed by regulations; when flows are reduced later in the season, the Delta slowly responds because salinity intrusion, driven by tidal flows, is a relatively slow process. Thus, the effect of high flows can linger for weeks and months, allowing higher diversions (and lower outflows) than would otherwise be necessary.

- **Salinity.** Salinity limits in the Delta are critical for meeting both system and ecosystem water quality requirements. Yet salinity levels are not simply a function of outflow or the volume of diversions at a given time. They depend on the magnitude of outflows over the previous few months, along with other factors such as tides and winds. For example, in 2011, exceptionally high volumes of uncaptured outflow kept the Delta unusually fresh, with low salinities all the way to San Pablo Bay well into summer. Under these conditions, little to no upstream releases or pumping reductions were needed to meet salinity standards. This phenomenon even occurs in drier years when winter flow pulses freshen the Delta; less inflow is needed to meet salinity standards for an extended period. Under such conditions, the actual cost of regulations to export water deliveries can be zero since the salinity requirements are met by high runoff. However, in our accounting scheme we still assign the volumes needed to meet salinity standards to system and ecosystem outflow in these periods.
- **Export pumping limits.** In contrast to salinity and flow standards, export pumping limits often represent a direct cost to export capacity when they are being enforced. However, it is sometimes possible for the CVP and SWP to make up the losses by holding water in storage until later in the year and pumping when restrictions are relaxed.[26] And sometimes in wet years after San Luis Reservoir fills, pumping is reduced below the export limits because there is no place to put the water. Below we show how this occurred in the very wet year of 2017.

Thus, it would be incorrect to cite system and ecosystem outflow volumes shown here as the cost to project operations. In general, our estimates will be greater than the actual loss of deliveries to the projects. In some cases—typically during dry years or dry months of any year—they can be nearly the same. In the 2017 report, we compared our results with the findings of a study that looked at the effects of changing ecosystem regulations since the mid-1990s on Delta exports (MBK Engineering and HDR 2013). In the discussion section below, we further explore the effect of changing regulations on exports.

Converting Salinity Standards to Assigned Water

As noted above, salinity conditions in the Delta are a function of many factors, including inflow, pumping, outflow, winds, and tidal conditions over time (Monismith 2016). Combinations of these factors can lead to the same salinity conditions, leaving no unique result. The fact that salinity depends upon the history of outflow, not just the current outflow, makes it difficult to assign a unique outflow for a given level of salinity without making some simplifying assumptions that allow for good approximations.[27]

The methodology used for addressing this complexity is based on a “G-model” method developed by Denton (1993) and discussed in detail in Appendix B of the 2017 report. It bears emphasizing that because multiple factors that interact over time control salinity in the Delta, calculations for a given day are likely to exhibit considerable uncertainty and should not be used for precise evaluation. However, these complexities average out over time to give a reasonable estimate of outflow/salinity relationships.

An additional complexity comes from an apparent increase in outflow required to meet a given salinity level during the period under review, found with the G-Model. Based upon the calibration of salinity models to field data, it appears that somewhat less outflow was required prior to the mid– to late–1990s than more recently. This

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[26] This was quite common from 1995 to the mid–2000’s and a feature of the 1994 Bay-Delta Accord, which allowed for pumping limits (to reduce harm to fish) to be made up later. Under the 1995 Biological Opinions, regulatory agencies could propose—and the projects could accept—pumping limits if the pumping could be made up later. From 1995 to 2000, this was often done; export losses were almost always easily recovered because it was a very wet period. After 2000, the Environmental Water Account provided another means to ensure the lost water was made up. In very dry periods like 2014, 2015, and 2021, low availability of water from runoff and upstream reservoirs were the principal limit on exports, so export pumping limits sometimes had a smaller additional impact, and on some days, none at all, simply because there was no water available to be pumped, with or without the limit.

[27] In periods when the outflow is very high compared to the minimum flow for a salinity standard, the outflow is often allowed to go lower than the minimum later, yet the standard is still met. This exemplifies not only the complexity, but also the need to use caution in looking at any single day rather than an average.

finding differs from those of a longer-term analysis by Hutton et al. (2015), which found the relationships to be relatively stable over many decades. Their study used Dayflow outflow (which has invariant gross channel depletions), whereas we used DICU, which, like the new DCD, shows a decline in in-Delta consumptive use. This issue relates to the discussion in Box A3 concerning the relationship between outflow estimates and in-Delta use estimates. A number of factors are believed to be changing the salinity-outflow relationship (the Montezuma Slough control gates, channel dredging, sea level rise, flooding of new tidal habitat) and this will be a continuing area of research. See also the discussion in Appendix B to the 2017 report, especially Table B2, for how system outflow was estimated.[28]

Distinguishing the Effects of Regulatory Changes from Hydrology

In the results and discussion that follow, we try to show how regulatory changes have affected flows. Regulatory requirements shift with changes in runoff and water year type, so it is essential to be able to compare across similar hydrologic conditions to gauge effects. Yet it can be challenging to separate out the effects of regulatory change from hydrology. There have been multiple revisions of environmental standards over the past 42 years, and this leads to small sample sizes for any given year type for a given set of regulations. For example, it has been 17 years since the last "above normal" water year type occurred, and the past 22 years have been relatively dry compared to the previous 20 years. This unequal distribution of year types, alongside changing regulations, makes it difficult to compare the effects of regulations across periods.

We address this challenge in two ways. First, we use consistent methods to calculate water uses over the past 42 years, so that specific year types can be compared. Second, when describing trends, we normalize accounting based on runoff or Delta inflow. This allows a direct comparison of the impact of regulations relative to water available in the watershed. While we believe that these methods make it possible to draw reasonable insights about the effects of regulatory changes, it should be recognized that the specific numerical results reflect a limited number of data points.

Tracking Flows in the Delta and its Watershed from 1980–2021

In this section, we review the apportionment of Delta inflows between water diversions (in-Delta and exports), water assigned by regulations for system water quality and ecosystem protection, and uncaptured outflows. The results for the period 1980–94, when the primary regulations for Delta flows were included in the State Water Board's D1485 water quality control plan, are unchanged from the 2017 report but are presented again here, this time in water year format and with the Delta consumptive use not reduced by precipitation. We then examine the period 1995–2021, which operated under D1641 and multiple other environmental laws that governed ecosystem flows. Finally, we examine the 1980–2021 period for the entire Delta watershed to illustrate how upstream runoff, reservoir storage and release, and depletions affect the overall water balance.

1980–94: Assigned Water under D1485 and Other Regulations

During the period 1980–94, the State Water Board's D1485 regulations were the primary determinant of regulatory flows in the Delta. In addition, ESA export pumping limits were imposed in 1993 and 1994 to reduce harm to winter-run Chinook salmon. Figure A1 summarizes the apportionment of Delta inflows annually by water year. Panel A1a accounts for all the Delta inflow—collapsing the different categories of system and ecosystem outflow into two summary categories—and shows uncaptured outflow, which is quite large in some years. Panel

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[28] The only more recent addition that would be warranted to Table B2 in Appendix B of the 2017 report would be the use of the flow requirement at Threemile Slough (4,100 cfs) during the June through August 15 period in 2021 because of the Temporary Urgency Change (TUC) order in effect; as the 2017 report notes, this was also done in 2015.

A1b provides a detailed breakdown of water assigned to different categories of system outflow and ecosystem outflow, omitting uncaptured outflow to make the details more visible. Each year shows the D1485 hydrologic year classification used for regulatory purposes.

The following are key observations about the 1980–94 period:

- Assigned system outflow required a minimum of 3.1 maf per year during critically dry years and averaged 4.1 maf per year in below normal, above normal, and wet years.
- Under D1485, there were few protections for the ecosystem in dry years beyond that provided by system outflow for diversion water quality, particularly during the 1987–92 drought. Assigned ecosystem outflow during this drought was approximately 0.2 maf per year—less than 5 percent of the amount diverted (exports plus in-Delta uses) and 2 percent of total inflow.
- In dry years, very little water was assigned to ecosystem outflow through export pumping limits. These limits were in effect from May to July under D1485. However, inflows were so low in these dry years that exports were also very low, and the ecosystem limits had no effect.
- In wet years, annual ecosystem outflow averaged approximately 1.8 maf—approximately 28 percent of the volume diverted from the Delta and 4 percent of total Delta inflow. Meeting the ecosystem outflow requirements often did not require export reductions or additional reservoir releases, as runoff provided ample flow.[29]

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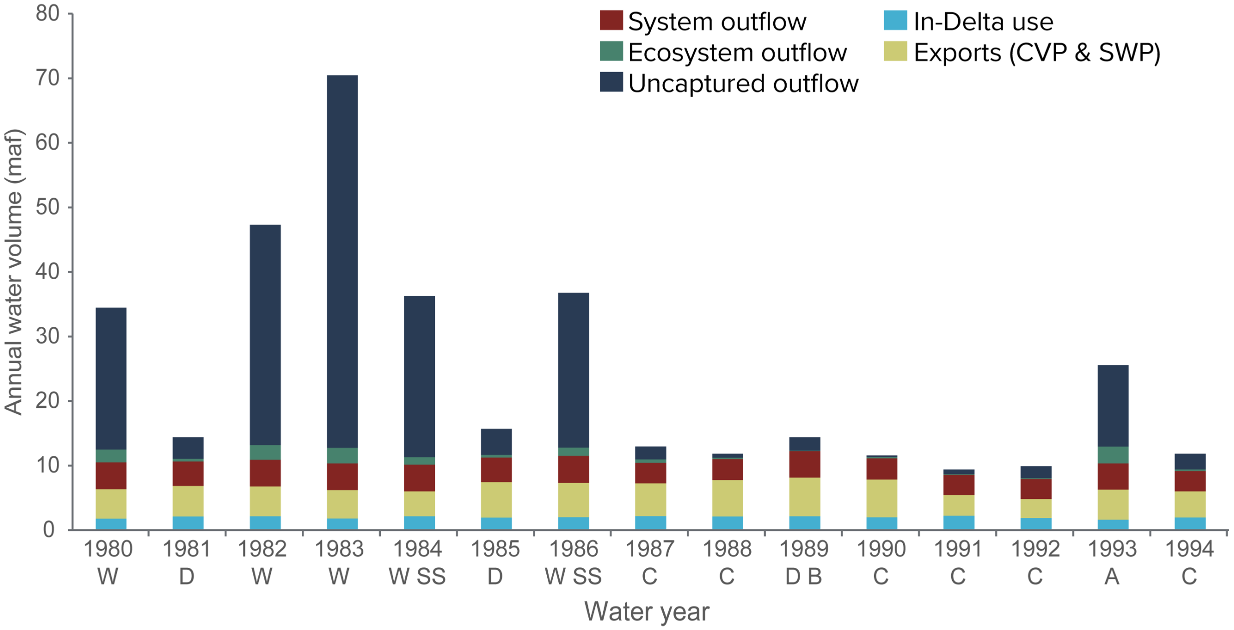
[29] This can be seen easily by the fact that the export levels were often below the allowable levels in these periods, while at other times there was no uncaptured flow. Up until the early 1990s, when additional pumps were added at the SWP's Banks Pumping Plant, exports were also limited by a lower pumping capacity (6,400 cfs).

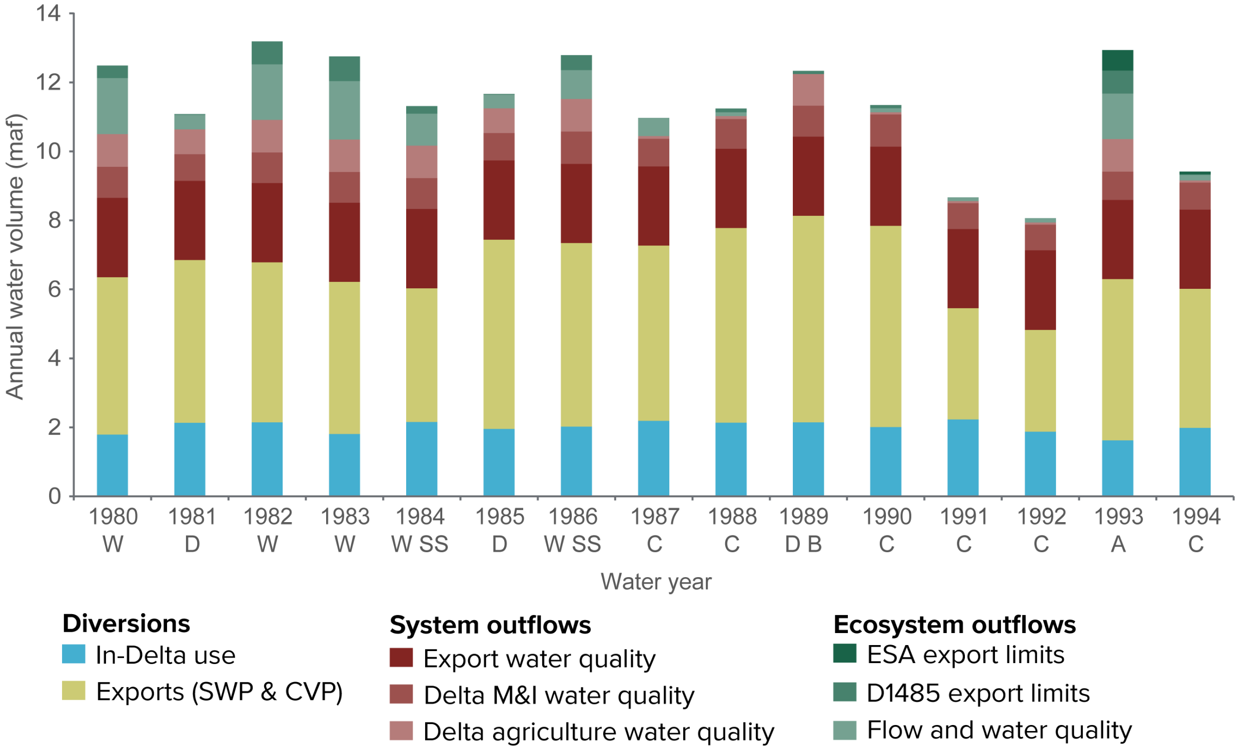
FIGURE A1

Where Delta water went, 1980–1994

a) Overview of flows



b) Details of system and ecosystem outflows



SOURCES: See Table A1.

Notes: Hydrologic classifications are based on D1485. W=wet, A=above normal, B=below normal, D=dry, C=critically dry. SS indicates a year with subnormal snowmelt, when D1485 allowed relaxations. 1989 followed a critically dry year, and therefore had a dry classification for ecosystem outflows, and below normal for system outflows. In-Delta use includes NBA and CCWD and excludes Delta precipitation.

- Based on these results, the following “rules of thumb” can be applied to assigned water in this period:
    - **In dry and critically dry years**, for every acre-foot of water diverted for use in-Delta or as exports, just over 0.5 af of system outflow was needed to maintain water quality for that use. Another 0.03 af of ecosystem outflow was needed to meet fish protection regulations. In total, 0.55 af of outflow was needed for every af diverted. In these years, when water was scarce, there were direct tradeoffs between required outflows and other uses.
    - **In wet years**, for every acre-foot of water used, approximately 0.6 af of system outflow was needed to maintain water quality for that use. An additional 0.27 af of ecosystem outflow was needed to meet regulations for the health of the Delta ecosystem. In total, 0.9 af of outflow was required for every af diverted. In these years, when water was abundant, many of the system and ecosystem outflow requirements could be met without causing tradeoffs with other uses.

1995–2021: Assigned Water under D1641 and Other Regulations

In 1995, D1641 replaced D1485 as the set of system- and ecosystem-water regulations administered by the State Water Board.[30] System outflow regulations to protect diversion water quality remained unchanged, but there were several changes to ecosystem outflow requirements. The striped bass protections of D1485 were replaced with the X2 salinity requirement, which requires minimum outflow or equivalent water quality levels from February through June and minimum outflows in each of the other months (July through January) for fish protection. In addition, export pumping limits were included for every month.

This period also saw the increasing influence of several other regulatory programs affecting ecosystem outflow. The ESA BiOps, CVPIA, and VAMP increased export limits during the spring pulse-flow period. In 2008–09, the revised BiOps included new export restrictions from mid–December through June, at times greatly limiting exports, especially in wet periods. In 2019, the BiOps were revised again, generally allowing for fewer pumping restrictions in wetter periods.[31] Figure A2 summarizes the apportionment of flows in this period.

Table A2 reports the average volumes of water for different uses for the entire 1980–2021 period. It breaks the 42-year span into three sub-periods, reflecting different regulatory regimes: the 1980–94 years when D1485 was in effect, the 1995–2007 years under D1641, and the 2008–21 years when D1641 was still in effect but some ESA regulations became stricter (particularly export pumping limits).[32] This table shows values for different water year types, highlighting key differences between wet and dry years.

We note that in-Delta use seems to have declined by about 0.2 to 0.3 maf per year from the mid–1990s onward compared to the 1980–1994 period, which is the opposite one would expect from rising temperatures. One possible explanation is a shift in a measurement location for estimating evaporation rates in the Delta for DICU, the dataset we use to estimate in-Delta use.[33] Yet two separate sources are consistent with this downward shift. First, DCD data, developed with different methods, show a similar trend: higher in-Delta use prior to the mid-1990s compared to the period after. Second, detailed land use estimates from DWR for 1991 and 2007 show that irrigated acreage in the Delta fell by 74,000 acres over this period relative to a 500,000 acre baseline, as a result of urbanization and other changes (Medellín-Azuara et al. 2012). In percentage terms, this acreage decline is roughly on par with the observed decline in gross in-Delta use (15%). For a given volume of Delta inflow, lower in-Delta

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[30] The Delta Accord was implemented under the BiOps from 1995 until D1641 was adopted in 1999; it applied the standards put in place under the Accord (see Appendix A to the 2017 report).

[31] This led to a conflict with the CDFW ITP, and a state-federal conflict as lawsuits were filed over the 2019 BiOps. At the time of this writing, state and federal regulators were cooperating on a revision of the BiOps.

[32] While the 2019 BiOps allowed for fewer restrictions on export pumping, especially under wet conditions, we show in the discussion section below that, because 2020 and 2021 were so dry, the 2019 changes had little or no effect in those years.

[33] DICU data take into account actual measured evaporation rates, and have different land uses for dry years compared to other years. DWR (2017) states that the DICU evaporation pan used changed from Davis to Manteca around 1991.

use leads to more water available for export or outflow. See Box A3 for a discussion of some of the issues regarding in-Delta use estimates, highlighting the need for further research and a resolution on how this key series is estimated for purposes of management and regulation of Delta flows.

As in 1980–94, the volume of system and ecosystem outflow during the 1995–2021 period varied widely, depending primarily on the quantity of inflow across several wet periods and two multi-year droughts:

- System outflow under D1641 ranged from approximately 3.5–4.8 maf per year, an increase of 0.4–0.7 maf per year to meet salinity regulations that were essentially the same as those in place under D1485. As described in Appendix B to the 2017 report, the causes of this increase are not well understood, but may include changes in in-Delta use (which is estimated), operation of the Montezuma Slough Salinity Control Structure, sea level rise, channel changes, a shift in the timing of exports (from spring to summer and fall), and improved model calibration with a larger field data set.
- The lowest volume of system outflow—3.5 and 3.2 maf per year—occurred in 2015 and 2021, respectively, when salinity standards were relaxed under a Temporary Urgency Change (TUC) order granted by the State Water Board, and a salinity barrier was installed to reduce the need for reservoir releases. Normally about 3.6 maf per year of system outflow is needed to meet salinity standards in critically dry years.[34]
- From 1995 to 2021, total annual ecosystem outflow for flow and water quality varied from 0.1 to 5.5 maf per year—a significant increase over D1485.
- During dry and critically dry years, total annual ecosystem outflow averaged 1.2 maf, versus just 0.3 maf under D1485. In wet years, annual ecosystem outflow averaged 4.9 maf, versus 1.8 maf under D1485. However, given the large amount of uncaptured outflow in wet years, the ecosystem outflow had a more limited impact on Delta exports in these years.
- D1641 export pumping limits (not including CVPIA, VAMP, and ESA limits) created from zero to over 0.7 maf per year of ecosystem outflow.[35] In dry and wet years, these limits had the lowest annual cost to exports (averaging around 0.15 maf), while in above- and below-normal years they rose to about 0.5 maf.

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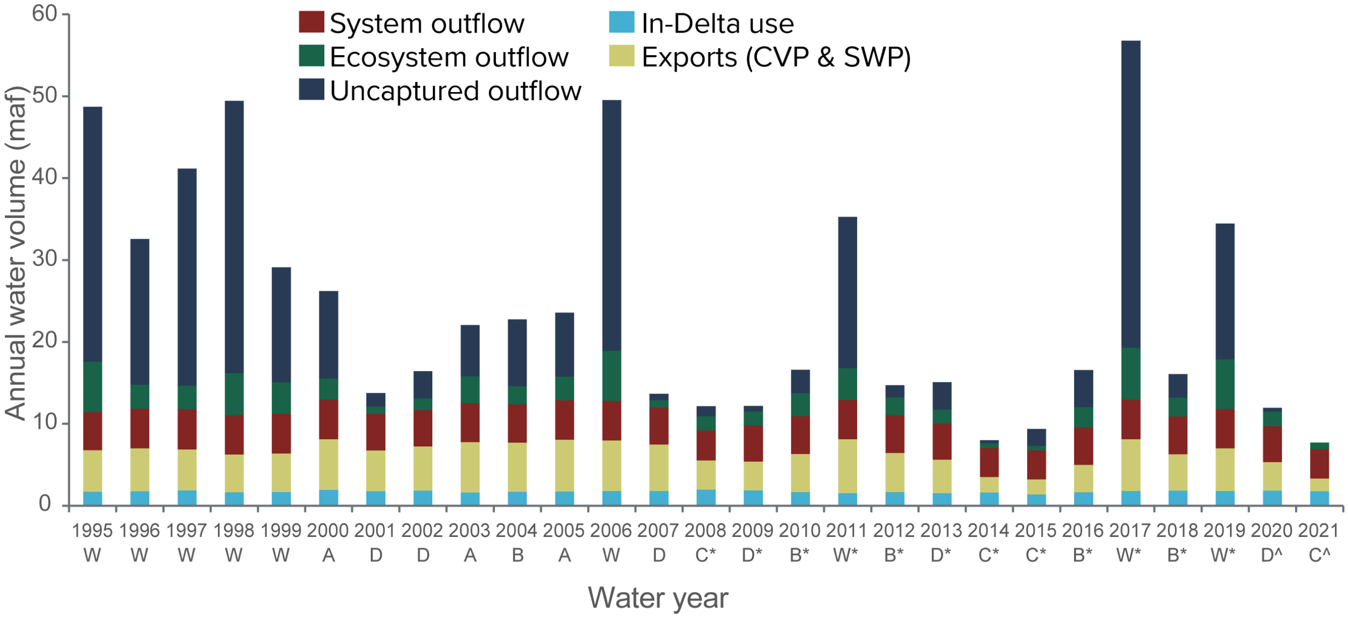
[34] In 2014 and 2015, the projects estimated that they reduced outflows by more than 1 maf under the TUC orders. These relaxations affected both system and ecosystem outflow. As discussed below, the outflow reduction from the barrier and TUC order in 2021 is estimated at 400,000 af.

[35] In 1998, an extremely wet year, D1641 pumping limits had no effect because inflows were so high that exports were not limited under the export/inflow limits.

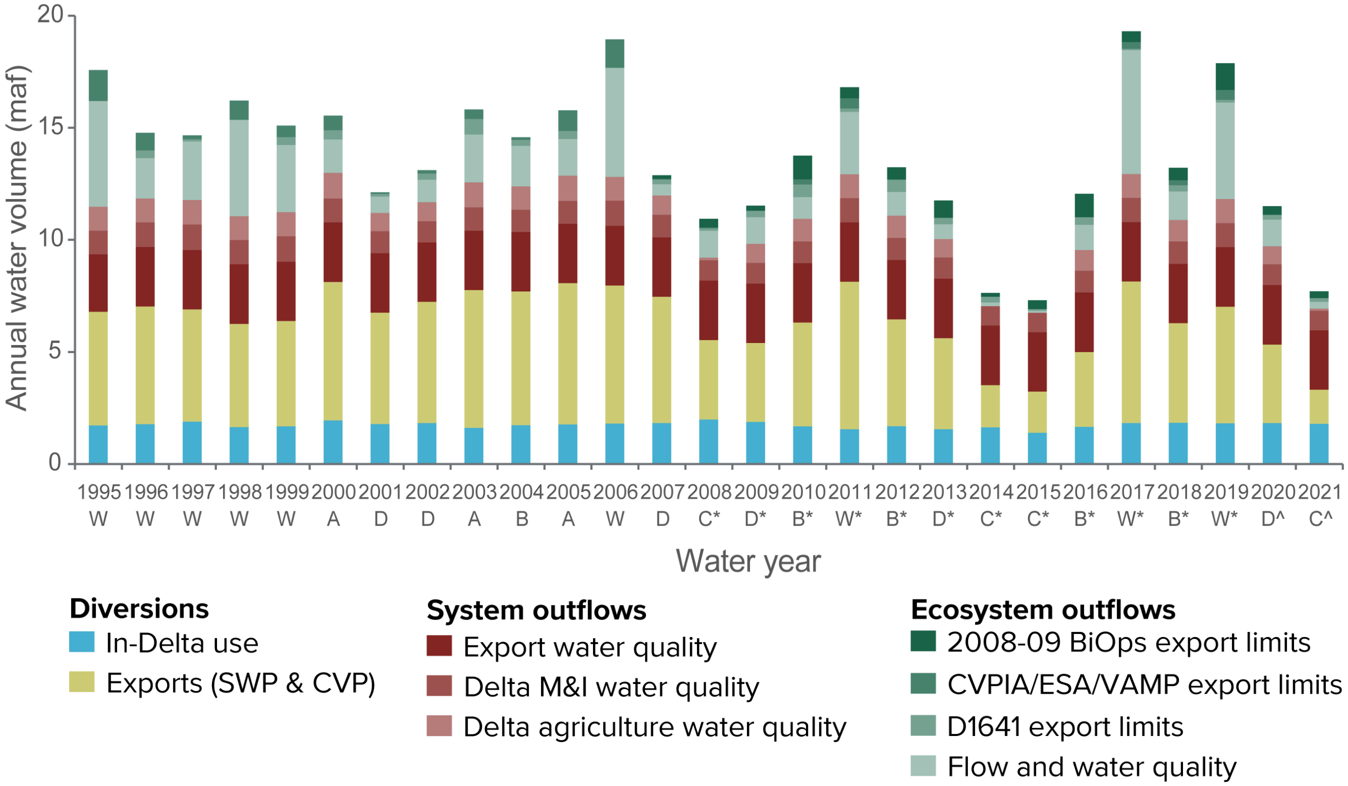
FIGURE A2

Where Delta water went, 1995–2021

a) Overview of flows



b) Details of system and ecosystem outflows



Sources: See Table A1.

Notes: Hydrologic classifications are based on D1641. W=wet, A=above normal, B=below normal, D=dry, C=critically dry. *: post–2008–09 BiOps, ^: post–2019 BiOps. In-Delta use includes NBA and CCWD diversions and excludes Delta precipitation.

TABLE A2

Average annual water use and assigned regulatory flows in three periods (1980–2021)

Period and year type	Number of years	Total inflows (maf)	Delta diversions (maf)		System outflow (maf)	Ecosystem outflow (maf)		Uncaptured outflow (maf)
			In–Delta use	Delta exports		Flow and water quality	Export pumping limits	
D1485 (1980–94)								
Critically dry	6	11.3	2.1	4.5	3.2	0.2	0.0	1.3
Dry	2	15.1	2.0	5.1	3.8	0.4	0.0	3.7
Below normal	1	14.4	2.1	6.0	4.1	0.0	0.1	2.1
Above normal	1	25.6	1.6	4.7	4.1	1.3	1.3	12.6
Wet	5	45.7	2.0	4.6	4.1	1.3	0.5	32.5
D1641 (1995–2007)								
Dry	3	14.6	1.8	5.3	4.5	0.7	0.3	1.9
Below normal	1	22.8	1.7	6.0	4.7	1.8	0.4	8.2
Above normal	3	23.9	1.8	6.2	4.8	1.8	1.2	8.2
Wet	6	41.8	1.8	5.1	4.8	3.6	1.0	25.2
2008–21*								
Critically dry	4	9.2	1.7	2.2	3.5	0.4	0.5	0.8
Dry	3	13.1	1.8	3.7	4.4	1.0	0.7	1.5
Below normal	4	16.0	1.7	4.3	4.6	1.1	1.3	2.9
Wet	3	42.2	1.7	6.0	4.8	4.2	1.2	24.2

Notes: The data are reported in water years. The number of years column shows the number of years included in the average values shown in each row. Not all hydrologic classifications were represented in each period. Inflows include precipitation on the Delta. In-Delta use includes NBA and CCWD diversions and excludes Delta precipitation.

*The 2008–21 period includes D1641, the 2008-09 BiOps, the federal WIIN Act (enacted in December 2016), and the 2019 BiOps (adopted in October 2019).

- Before the implementation of the 2008–09 BiOps, pumping limits imposed by the CVPIA, VAMP, and ESA created an average of 0.03 maf per year of ecosystem outflow in dry years, and over 0.9 maf per year in wet years, rising to over 1.3 maf in the wettest years. Post–2008, these pumping limits generated from 0.2 to 2 maf per year of ecosystem outflow, with larger amounts coming in wetter years, but over 1 maf in below normal years. In critically dry years, they averaged about 0.4 maf per year.
- Although two recent regulatory changes—the 2016 WIIN Act and the 2019 BiOps—relax regulatory requirements under some conditions, neither appear to have had an appreciable effect on exports or outflow to date, as hydrologic conditions have been either too dry or too wet (Box A5).
- In 2015, water assigned to the ecosystem hit a low of 0.55 maf. This was one-third the volume exported that year, and 6 percent of total inflows to the Delta. Total system outflow—required to maintain salinity levels suitable for Delta agriculture—was 3.5 maf, over twice the quantity of water exported in 2015 (about 1.6 maf); in 2021, system outflow was 2.4 times the volume exported.
- Based on these results, the following "rules of thumb" can be applied to assigned water under regulations from 2008 onwards:[36]

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[36] The sample size for this comparison is small (14 years) and dominated by the droughts in 2012–16 and 2020–21, so these averages are useful only as approximations for results in different year types.

    - **In dry and critically dry years**, for every acre-foot of water diverted, about 1.5 af of system outflow are needed to maintain sufficient water quality for in-Delta uses and exports. An additional 0.2 af is needed to meet ecosystem flow and water quality regulations, for a total of 1.7 af outflow per af diverted. In these years, there were direct tradeoffs between required outflows and other uses.
    - **In wet years**, for every acre-foot of water used, approximately 0.8 af of system outflow is needed to maintain water quality for that use. An additional 0.7 af of outflow is needed to meet ecosystem standards, for a total of 1.5 af of outflow per af diverted. In these years, many of the system and ecosystem outflow requirements could be met without causing tradeoffs with other uses, but restrictions related to export limits could still pose tradeoffs.

Delta Flows Compared with Total Water Available in the Watershed, 1980–2021

The uses of water that flows into the Delta can affect water management throughout the watershed, especially when water releases from project reservoirs or reductions in exports are needed to maintain regulatory requirements. To assess this, we compare assigned water with the watershed's overall water balance since 1980.

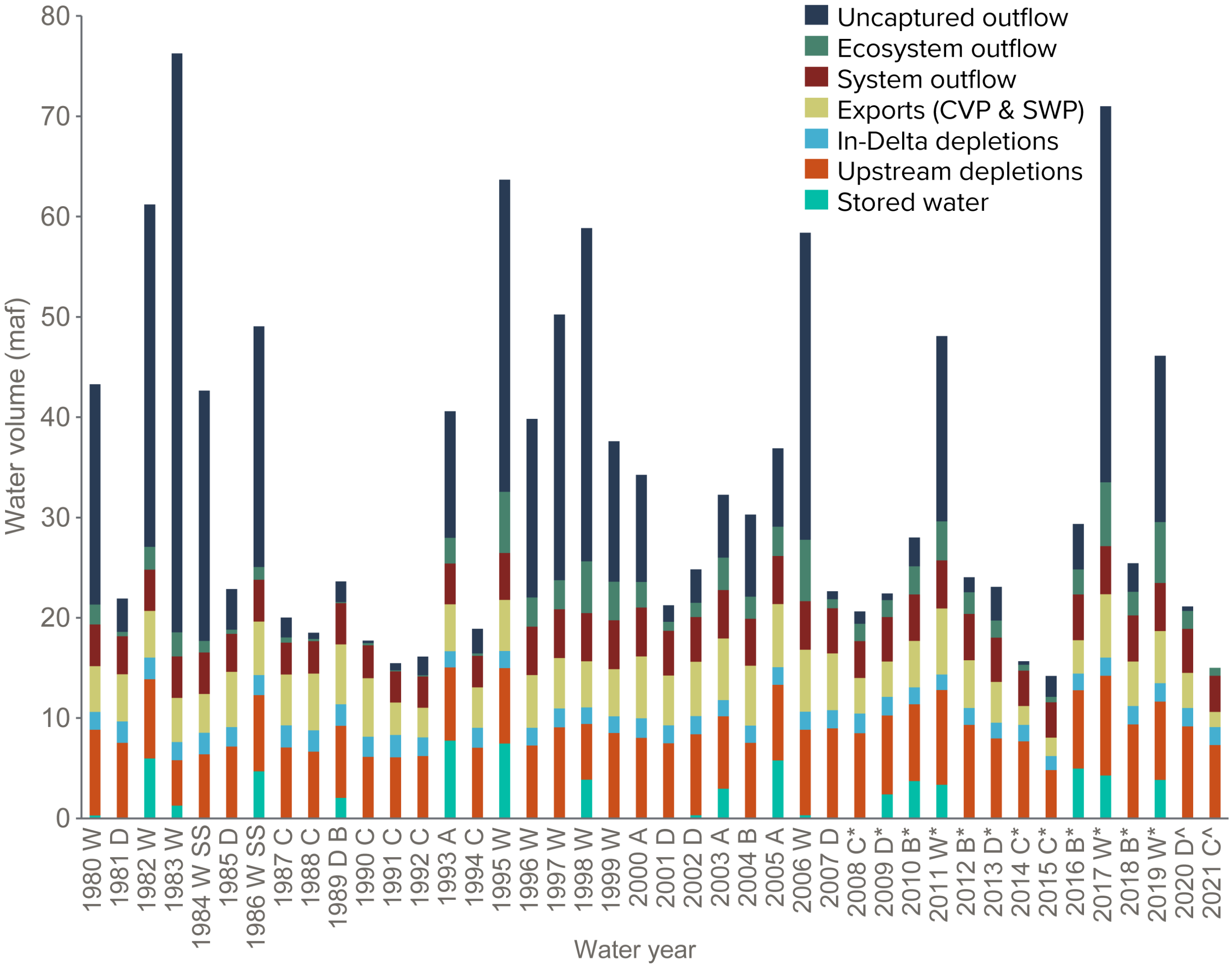
Figure A3 presents an overview of these results, including volumes apportioned to each use. Stored water depicts net increases in water stored in upstream reservoirs; years in which there was a net release of stored water show no water going to storage.

Water use in the watershed varied considerably over the past 42 years, principally due to large swings in precipitation. Of note:

- Uncaptured outflow is highly variable, representing approximately half of all water available in the watershed during wet years, less than 10 percent in drier years, and nearly nothing in 2021.
- Upstream water use is less affected by drought than are Delta exports. This is because many upstream users have more senior water rights and settlement contracts that limit cutbacks. Upstream depletions tend to be large in wet years, reflecting seepage to groundwater, and less in dry years, reflecting water transfers and withdrawals from groundwater.
- Gross in-Delta water use is the most consistent use in the watershed, varying between 1.4 and 2.1 maf per year with little change due to hydrology (2015, at 1.4 maf, was low due to fallowing during the drought). This is because this region always has an abundance of water; farmers often must pump water off of their lands to keep it from flooding the root zones of crops. When precipitation that just meets monthly in-Delta use is considered (i.e., excluding the excess precipitation—see Box A2), in-Delta use ranges from about 0.9 maf to 1.6 maf per year; this is the range that should be compared to upstream depletions. (See also Box A3 and the earlier discussion on the change in DICU in the 1990s.)
- Total water use in the Delta watershed, including in-Delta use, exports, and upstream depletions, accounts for about a quarter of total water available in wet years, and as much as 75 percent in drier years.
- System outflow varies relatively little across years in volume (3.5 maf per year in dry years to 4.9 maf in wet years) but considerably more as a share of the total available water in dry years (less than 10 percent in wetter years to as much as 25 percent in dry years).
- In contrast, ecosystem outflow varies considerably both in volume (from as little as 0.5 maf per year in dry years to as much as 6.3 maf in wet) and as a share of water available (from a low of 4% to a high of about 10%).

FIGURE A3

Total Sacramento–San Joaquin Valley water balance, 1980–2021



Source: See Table A1, discussion in text, and PPIC Delta Water Accounting spreadsheets.

Notes: Hydrologic classifications are based on D1485 for 1980–94 and D1641 thereafter. W=wet, A=above normal, B=below normal, D=dry, C=critically dry. *: 2008–09 BiOps, ^: 2019 BiOps. In-Delta use includes NBA and CCWD diversions but excludes precipitation. When subtracting monthly precipitation that just meets monthly in-Delta consumptive use, the range of in-Delta use is from 0.9 to 1.6 maf per year, compared to the range of upstream depletions of 4.5 maf per year (in 2015) to almost 10 maf per year (in 2017).

Box A5. Effect of the WIIN Act and the 2019 BiOps on Delta Operations

Two recent changes have the potential to relax regulatory requirements—and increase exports—under some conditions: the 2016 WIIN Act and the 2019 revision of the Biological Opinions. Our analysis of the 2017–21 period finds that they have not had an appreciable effect in that limited timeframe, largely because the extreme hydrologic conditions did not enable managers to take advantage of the added flexibility.

WIIN Act. In December 2016, P.L. 114–322, also known as the Water Infrastructure Improvements for the Nation (WIIN) Act, became law. Sections 4000–4005 pertained to Delta operations, providing for more flexible operations that would increase water supplies to CVP contractors while protecting other water-right holders. The WIIN Act did not overturn the 2008–09 BiOps, but it called for more flexible regulations when they could be justified. For example, it allowed use of a three-day average for inflows on the rising limb of a pulse flow and a 14-day average on the falling limb (thereby allowing more pumping sooner in a flow pulse). It also called for allowing the Old and Middle River flow limits at a level of –5,000 cfs rather than more stringent levels, whenever possible, thereby allowing more export pumping. And it called for more flexibility in operations to allow more pumping when inflow to the Delta was very high.

We examined the operational regime from 2017–21 and compared it to that of the 2008–16 period. In 2017, a very wet year, the operations were not affected by the WIIN Act, according to the Delta Operations Salmonids and Sturgeon Technical Working Group (DOSS 2017). In fact, in 2017, exports were reduced in February and March for many weeks for maintenance and because San Luis Reservoir was full, and there was no place to put water (as discussed elsewhere in this report). In 2019, the same thing occurred. In 2020 and 2021, the opposite occurred: there was so little water, most of the reductions in exports were made to support the minimum outflow requirements, and Old and Middle River flow limits less negative than –5,000 cfs were not really a factor. In 2018, there were a few short flow pulses when the Old and Middle River limit was –5,000 cfs. These lasted just a few days, and the WIIN Act may have played a role, but the records are not available to indicate the magnitude of the impact, if any. Overall, the period was either so wet—or so dry—that the WIIN Act does not appear to have made much of a difference.

2019 BiOps. The 2019 BiOps revised the 2008–09 BiOps and went into effect in October 2019. The 2019 Delta smelt BiOps moved the fall X2 requirement from 74 kilometers (km) to 80 km—a change that could reduce outflow requirements and enable more exports under some conditions in wet and above normal years. This would have been the case in fall 2019—coming off a wet year—but USBR and DWR had already begun implementing the earlier fall X2 requirements, and they kept it at 74 km for the rest of that season. Under state law, DWR was required to continue to operate the SWP under CDFW's ITP, which conflicted with the new BiOps. In 2020, CDFW revised the ITP and adopted the same 80 km requirement for fall X2. But 2020 and 2021 were too dry for the new X2 rules to apply, so they had no substantive effect.

The 2019 BiOps also changed pumping regulations for Old and Middle River flows and the San Joaquin River inflow/export ratio to allow more opportunities to export more water, especially during high–flow events, also in conflict with the ITP. However, water years 2020 and 2021 were classified as "dry" and "critically dry" respectively. As a result, the evidence from daily operations suggests that these changes in the 2019 BiOps had no practical effect on pumping, simply because there was so little water available. DWR confirmed that the 2020–21 operations were essentially unaffected by the 2019 BiOps (Nemeth 2021).

Upstream operations (in particular, cold-water management at Shasta Reservoir) in 2020 and 2021 also took place under the 2019 BiOps. Although they might have influenced planned operations, actual operations in these years were not substantively different from those in 2014 and 2015 under the 2008–09 BiOps.

Although the 2019 BiOps are still legally in force, the federal regulatory agencies are currently revising them once again, and a court-approved interim operations plan is guiding project operations this year (which is in alignment with the ITP). If, at the end of this process, the conditions in the 2019 BiOps are maintained and the ITP is changed to conform, this could allow more exports in above-normal and wet years.

A Note about "Multipurpose Outflow"

We have taken a building-block approach to account for water used to meet ecosystem objectives on top of system flows, reflecting their relative historic priority. We emphasize this approach to apportioning outflow because it can help dispel misunderstandings about the relative importance of different regulatory objectives affecting Delta outflow: *system water would be required to meet salinity standards for water supply, even if there were no specific requirements for the ecosystem*.[37]

Yet as noted, system outflow often simultaneously helps to fulfill ecosystem outflow needs and meet water quality standards. For example, in every year, there are periods when the X2 salinity standard for fish requires more outflow than would be required for salinity standards for in-Delta use and exports (generally in the winter and spring). Conversely, there are periods when system outflow to meet salinity standards exceeds the flow standards for fish protection (generally starting around August). To illustrate this concept, in Figure A4 we show three categories of outflow under D1641 for different year types for 1995–2021:

1. Multipurpose water that fulfills both system and ecosystem requirements;
2. System outflow that is required exclusively to meet diversion water quality standards (and does not meet any ecosystem standards); and
3. Ecosystem outflow required exclusively to meet ecosystem flow and quality standards.

Figure A4 shows these levels only for post-D1641 conditions (there simply was not enough ecosystem water under D1485 to make a useful chart). The chart shows the categories according to water year type and the different BiOps. Because of the short records, some year types have no data.

Under most conditions, multipurpose outflow is large relative to the amount of water assigned exclusively to system outflow or to ecosystem flows and water quality. The exception occurs in wet years, where the additional outflow required to meet ecosystem flow standards is also quite large.

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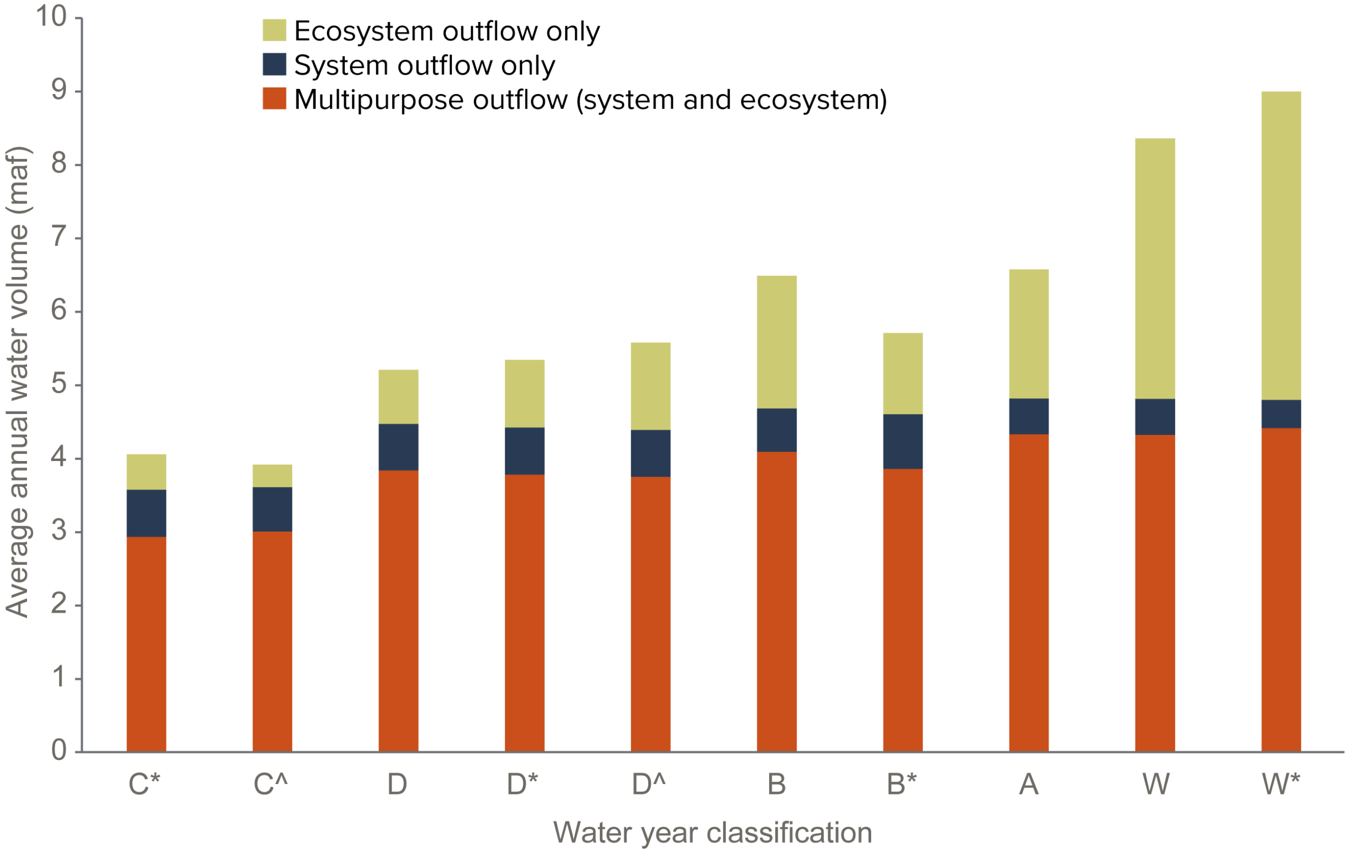
[37] As noted above, salinity control in the Delta has also been a primary charge of the projects from early on (Calif. DPW, 1930); the Delta Protection Act (Water Code 12200-12205) provides that no water shall be exported that is necessary for the provision of an adequate salinity in the Delta.

FIGURE A4

Multipurpose, system-only, and ecosystem-only outflow under different year types, 1995–2021



Source: PPIC Delta Water Accounting spreadsheets.

Notes: Hydrologic classifications are based on D1641 (wet, above normal, below normal, dry, critically dry). *: D1641 and the 2008–09 BiOps; ^: D1641 and the 2019 BiOps. The figure does not show ecosystem outflow for export pumping limits, which cannot be met by system outflow. 1980–94 is not shown here because there was little ecosystem outflow in most years under D1485 (see Appendix B to the 2017 report).

Unpacking Major Trends in the Delta Watershed

Here we draw on our review of where water has gone in the Delta watershed since 1980—along with some important analyses of longer-term changes—to explore several major trends with implications for water regulation and management: (1) increasing drought intensity over the past two decades—reflecting warmer conditions in the watershed; (2) increasing ecosystem outflow requirements (and decreasing exports) in drier years since regulatory changes in the mid-1990s; (3) a flattening in Delta outflow as a share of supplies in the watershed, following long-term declines, consistent with mid-1990s regulatory changes for ecosystem outflow and the possible increase in system outflow required to keep the Delta fresh enough for exports and in-Delta uses (see Box A3 and prior discussion).

In reviewing these trends, it is important to recognize that the regulatory changes starting in the mid–1990s were a response to significant deterioration in conditions in the Delta, including the expansion of numerous invasive species and the decline in multiple species of native fish. The 1987–92 drought—when there were few protections for the environment—saw lows in outflow as a share of water available in the system (see Figure A9, below) and rapid decline in ecosystem conditions. Also, while there has been an increase in outflow requirements in dry years since the mid-1990's, the drier overall conditions of the watershed mean that the ecosystem has been stressed more frequently by drought. Our analysis does not address whether the changes in ecosystem outflow requirements are sufficient to meet the multiple ecosystem objectives for this outflow, but we note that these changes have not led to demonstrable improvements in the status of most Delta fishes—many are at historic lows.

Warming and Increasing Drought Intensity

California's climate has been warming (Figure A5), and this appears to be making droughts more intense and difficult to manage. Warming is a major contributor to "evaporative demand"—or what can be thought of as the "thirst of the atmosphere." [38] Recent climate studies have identified major increases in evaporative demand in the western US since 2000 (Albano, et al. 2022). High atmospheric demand dries out the landscape, drawing moisture out of vegetation and soils, and in turn making the landscape thirstier. Increasing evaporative demand is likely contributing to increasing drought intensity; it may help explain why upstream depletions appear to have been rising as a share of runoff in the Delta watershed in dry years (Figure A6).[39] Compared to an average of 47 percent of runoff in these years since 1980, upstream depletions exceeded 70 percent of runoff twice in the two most recent, warm droughts—in 2014 (71%) and 2021 (84%). In 2015, also a critically dry year, this share fell to 37 percent, reflecting significant reductions in surface water allocations to upstream users. These findings for the period after 1980 are consistent with the results of Hutton et al. (2017, Figure 10). As we describe further below, rising upstream depletions make meeting other management objectives for the watershed—including salinity control, ecological flows, and downstream water supplies for in-Delta and export uses—all the more challenging.

Increasing evaporative demand and warming have also led to significant declines in snowpack (Mote et al. 2018), especially in dry years. As we describe further below, these conditions have disrupted forecasting of snowmelt runoff, which relies heavily on the use of historic conditions as a guide. This has led to significant disruptions of planned operations—particularly for the CVP and SWP, which rely heavily on snowpack for part of their storage. DWR has recognized that changing conditions are disrupting forecasting and operations and is revising its methods for runoff projections (DWR 2022).

It also bears noting that California has been in a relatively dry spell over the past two decades, following a relatively wet period in the second half of the 1990s (Figure A3). While these dry conditions also make water management in the Delta watershed more challenging, they are unlikely to be permanent. Most climate models project that there will be alternations between wet and dry periods, likely with increasing volatility—with wetter wet periods and drier dry periods. In contrast, warmer temperatures are expected to be an enduring feature of the region's climate.

Key takeaways:

- Warming temperatures are contributing to increasing evaporative demand, or atmospheric thirst—making droughts more intense.
- Upstream depletions appear to be rising as a share of runoff in the Delta watershed in dry and critically dry years, increasing management challenges. Increasing evaporative demand may be contributing to this shift.
- Warming and higher evaporative demand are also contributing to declining snowpack, particularly in dry years, posing challenges for forecasting spring runoff.

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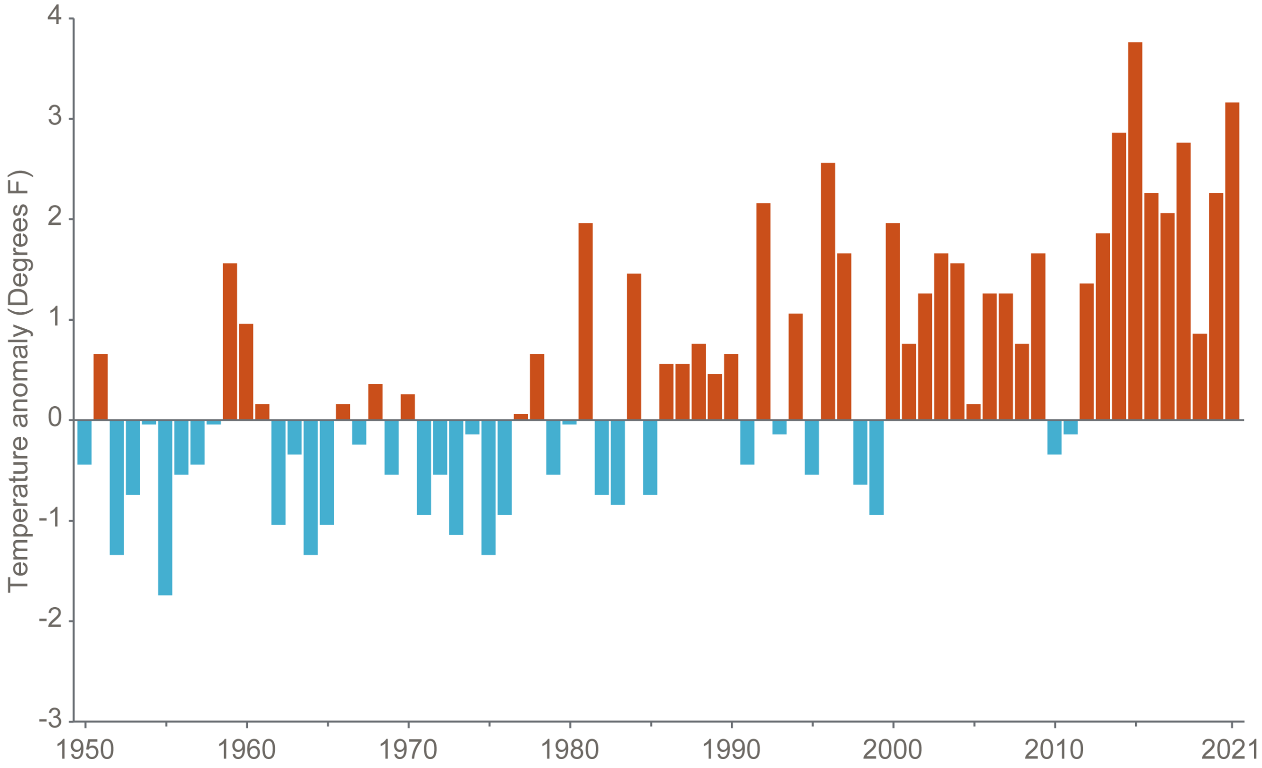
[38] For a discussion of evaporative demand, see the interview with Michael Dettinger in Pottinger (2020) *Droughts Aren't Just About Water Anymore.* In addition to temperature, humidity, wind, and solar radiation are contributing factors.

[39] Several tests that suggest upstream depletions are rising in dry and critically dry years. Average upstream depletions in such years were 6.8 maf from 1980–99, versus 7.8 maf from 2000–21, constituting 44 percent and 49 percent of unimpaired runoff, respectively. T-tests reject the hypotheses that upstream depletions in the first and second periods have the same means (p=0.034) and variances (p=0.033), and a Kolgomorov-Smirnov test rejects that they have the same underlying distributions (p=0.012). We also found a statistically significant positive time trend on the ratio of upstream depletions to unimpaired runoff for dry and critically dry years over the 1980–2021 period (p-value of the t-statistic=0.043).

FIGURE A5

Temperature deviations from the mean in California since 1950

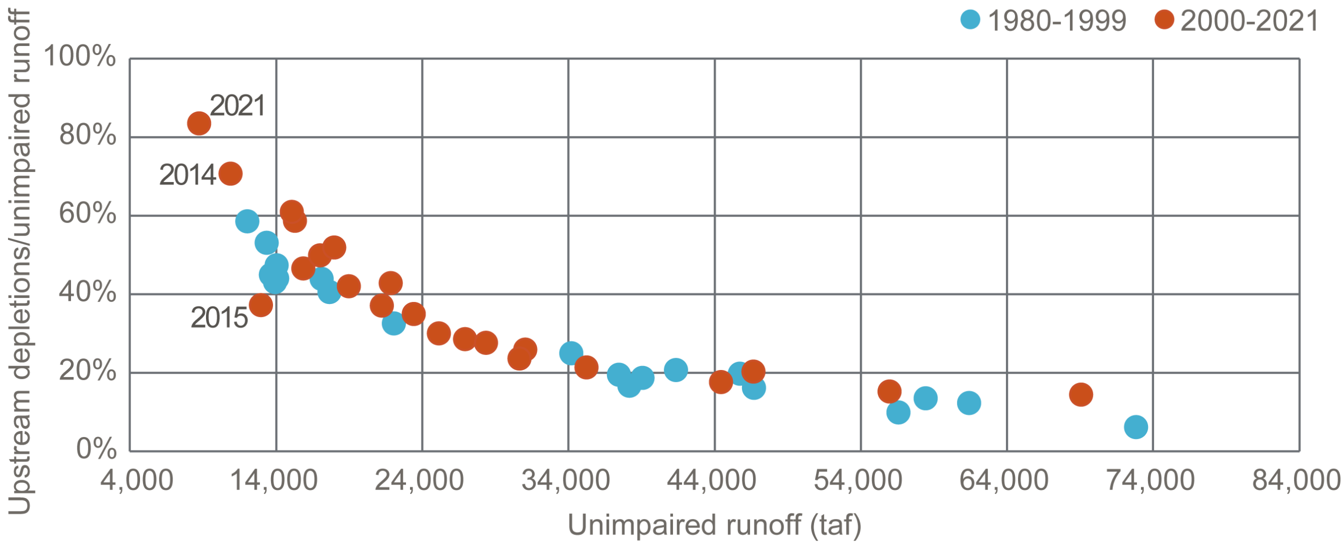


Source: NOAA, NCEI.

Notes: The figure shows deviations in average statewide temperatures compared to a baseline of 1950–2000. We start at 1950 because earlier temperature records did not have representative coverage across the state, and they tend to skew cooler.

FIGURE A6

Upstream depletions as a share of unimpaired runoff in the Delta watershed



SOURCE: *PPIC Delta Water Accounting spreadsheets*.

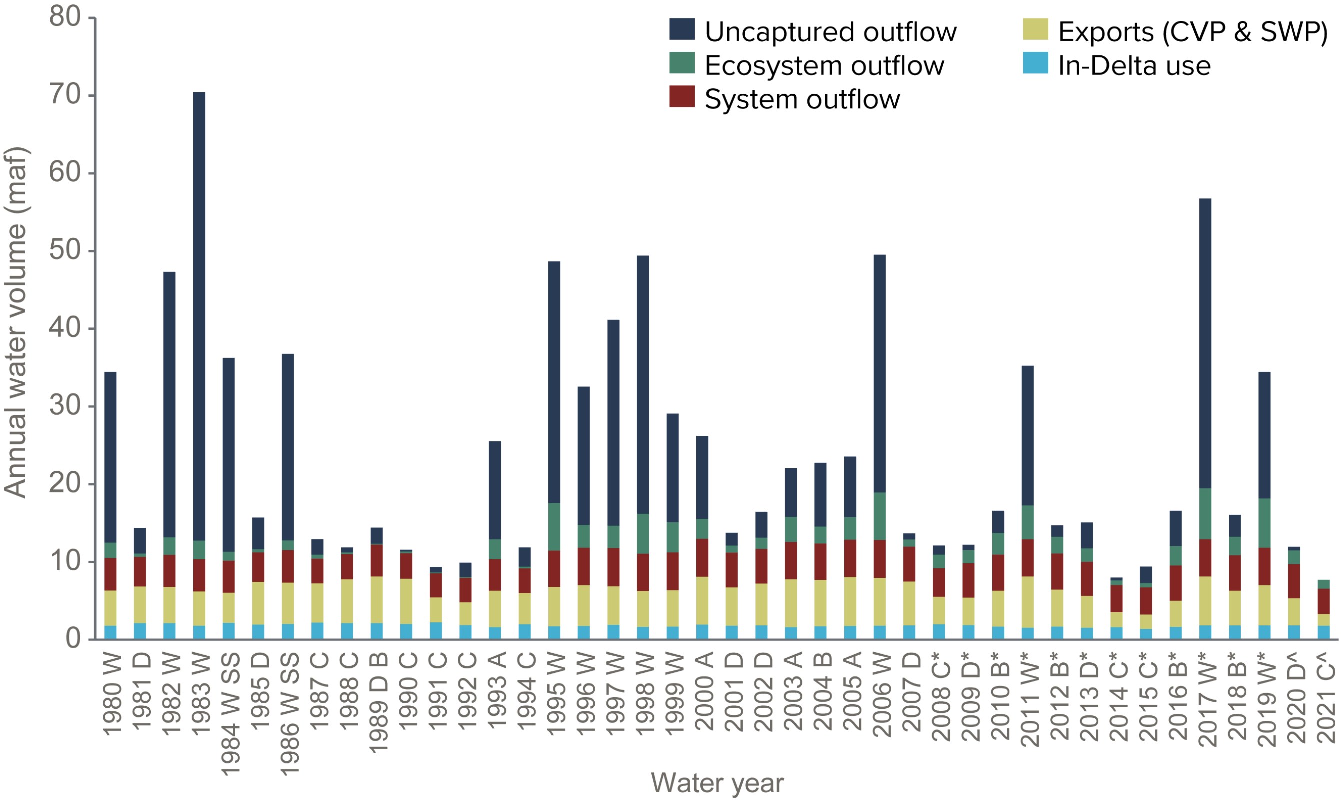
NOTE: The figure shows the ratio of upstream depletions to unimpaired runoff in the Delta watershed for each water year from 1980–2021.In dry years (runoff < 24 maf), the years since 2000 often have higher levels of upstream depletion for a given level of runoff. The exception (2015) reflects a year with significant cutbacks in upstream water deliveries and water transfers. For reports on statistical tests of the trends in this ratio during dry and critical years, see the text.

Shifts in Ecosystem Outflow and Exports

In Figure A7 we summarize where water went after entering the Delta for the entire 42 years of our analysis. Exports and ecosystem outflow vary considerably with hydrology. In addition—as shown in our 2017 report and confirmed with this update—there appear to have been notable shifts following the implementation of D1641 and the 2008–09 BiOps (Table A2). Here we seek to better elucidate the effects of these regulatory changes under different hydrological conditions. We also discuss how our findings compare with some other recent studies.

FIGURE A7

Where Delta water went, 1980–2021



Sources: See Table A1.

Notes: Hydrologic classifications are based on D1485 (1980–1994) and D1641. W=wet, A=above normal, B=below normal, D=dry, C=critically dry, and SS=subnormal snowmelt (under D1485 only). *: 2008–09 BiOps, ^: 2019 BiOps. For detailed breakdowns of system and ecosystem outflows, see Figures A1b and A2b. In-Delta use includes NBA and CCWD diversions and excludes Delta precipitation.

Separating out the effects of hydrology and regulations

Because the last two decades have been relatively dry, it is difficult to separate the effects of hydrology from changes due to new regulations. To help sort out the trends, Figure A8 compares key series, distinguishing four regulatory periods: (1) D1485 (blue dots), (2) D1641 from 1995–2007 (beige dots), (3) D1641 from 2008–19 (following the adoption of the 2008–09 BiOps, orange dots), and (4) D1641 in 2020–21 (following the adoption of the 2019 BiOps, green dots).

Figure A8a compares exports with Delta inflow. In drier years (years with less than 20 maf of inflow), exports have averaged about 1.5 maf per year lower, for similar inflows, since 2008.[40] In wetter years, wet-year exports increased from 1995 onwards, as D1641 shifted exports away from drier years to wetter years. The projects also increased capacity to take the water, with increased SWP pumping capacity in the early 1990s, construction of the Central Coast Branch Aqueduct, and expansion of south of Delta storage (e.g., Kern Water Bank and Diamond Valley Lake).

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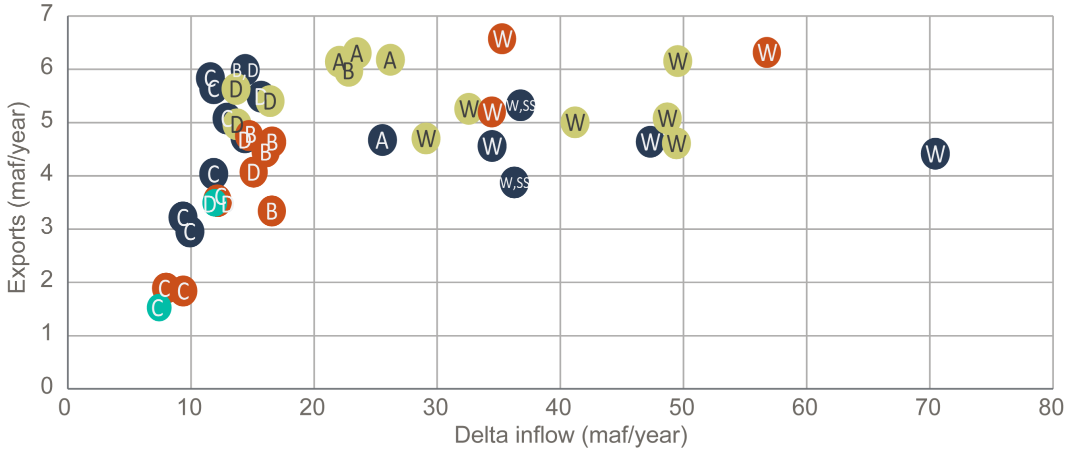
[40] The comparison is for dry and below-normal years; there are no critically dry years from 1995–2007 to compare with the critically dry years in the post–2008 period.

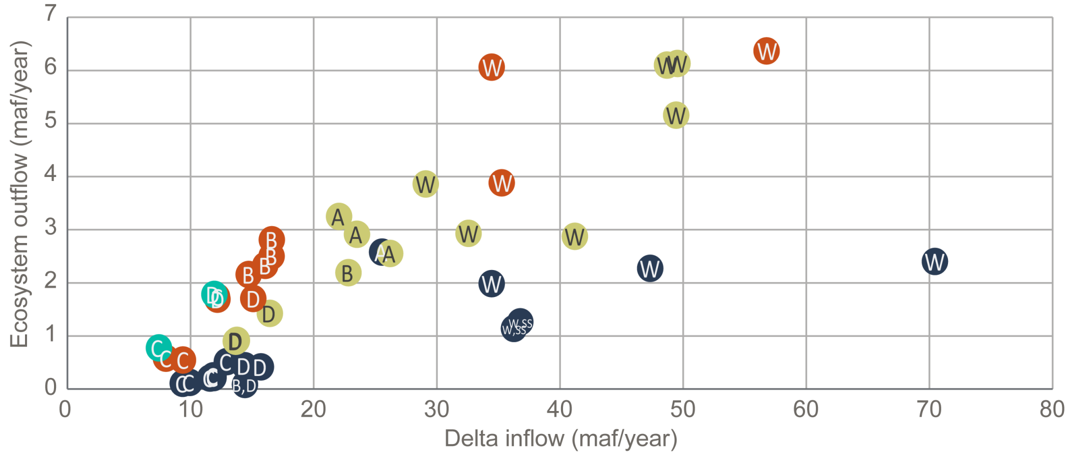
FIGURE A8

Comparison of Delta exports, Delta inflows, and ecosystem outflow under different hydrology and regulatory periods

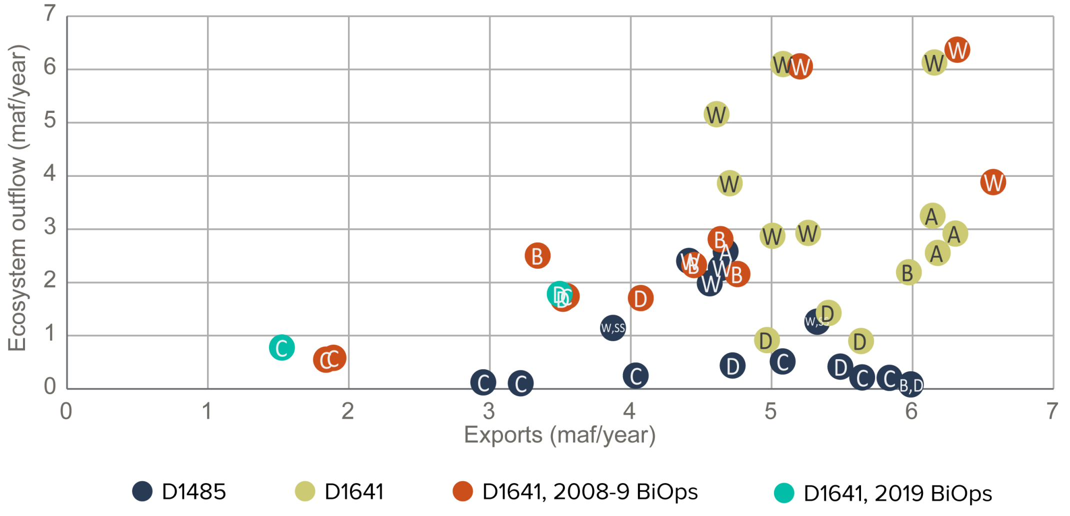
a) Delta exports compared to total Delta inflow, all years



b) Ecosystem outflow compared to Delta inflow



c) Ecosystem outflow compared to Delta exports



Sources: *PPIC Delta Water Accounting spreadsheets*.

Notes: Hydrologic classifications based on D1485 (1980–1994) and D1641 (1995–2021). W=wet, A=above normal, B=below normal, D=dry, C=critically dry, SS=subnormal snowmelt (under D1485 only).

Figure A8b compares ecosystem outflow with Delta inflow. Before 1995, when D1485 was the main controlling regulation, ecosystem outflow increased only modestly with the volume of inflow. This reflected the way environmental regulations—principally focusing on striped bass—were crafted to minimize impacts on water diversions. Following the implementation of D1641 and other ecosystem regulations from 1995 onwards, a better-defined relationship was established, where more inflow to the Delta was matched by more water assigned to the environment. The amount of ecosystem outflow increased again with the implementation of the 2008–09 BiOps. (To see this, compare the points vertically to get a sense of the increase in ecosystem outflow.)[41]

Figure A8c plots ecosystem outflow against total exports, and it highlights the potential increase in the cost of ecosystem export limits and other ecosystem regulations in terms of reduced exports. Following implementation of D1641—particularly from 2008 onwards—a relationship developed (within the limits of the short record) with lower exports and higher ecosystem outflows in the drier years. The two years regulated under the 2019 BiOps show levels similar to the years under the 2008–09 BiOps (see Box A5, above).

As noted above, outflow increases do not always translate directly into export declines, because in wetter periods some or all of the ecosystem flow requirement is met with runoff that cannot be captured. In addition, regulations that reduce exports in one period might be recovered shortly after. And finally, the sample sizes for different regulatory periods are relatively small. Nevertheless, our data suggest that the export losses due to the combined D1641 and the 2008–09 BiOps (i.e., post-2008) were typically on the order of 0.5 to 1.5 maf per year in below normal and dry years compared to D1485 (pre-1995).

Comparison with the literature

The magnitude of the tradeoff between ecosystem outflow requirements and export volumes has been a matter of some debate. Here we compare our results with two influential studies—one funded by a consortium of water and hydropower users (MBK Engineers and HDR 2013), and another conducted by a team from two environmental organizations (Reis et al. 2019).

- **Methods.** Reis et al. use a very similar methodology to ours—a daily, building block approach to adding up the effects of different regulations—but over a shorter time period (2010–18).[42] MBK and HDR's methodology is quite different—they use a water operations model with fixed water demands (level of development) for a long hydrologic period (1922–2003), apply operating rules simulating various regulatory regimes, and report results by water year type.[43] Differences are to be expected between estimates for a limited number of actual years and modeling averages developed over an 80-year hydrology, which includes multiple years for each water year type.
- **MBK and HDR results.** Despite the differences in methods, the MBK and HDR results are roughly similar to ours. They found an annual average of 1.3 maf per year reduction in exports over the 80 years modeled. Their approach may overstate the impact of the 2008–09 BiOps in wet years, however, because operations studies do not include actions sometimes found in real situations (e.g. maintenance outages and lack of a place to put water in wet years).[44]
- **Reis et al. results.** Reis et al. report much lower costs to exports of the 2008–09 BiOps than MBK and HDR. But they focus on a subset of regulations (export limits under the BiOps) for three years within their sample, and because of the limited time period they cannot compare to the period before the 2008–09 BiOps. Reis et al. also implicitly and incorrectly assumed that export limits were the only effect of the

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[41] We do not address whether this relationship is sufficient to meet the multiple objectives for ecosystem outflow in the Delta.

[42] They used a less detailed method than ours for determining the outflow necessary for salinity requirements.

[43] D1485 was their base case; then they ran the model for D1641 rules and, finally, using D1641 plus 2008–09 rules.

[44] They found a 1 maf per year loss in these years, whereas our results show little impact in the wet years of 2011 and 2017, both with over 6 maf in exports. In 2019, also wet, there may have been some effect: exports were 5.2 maf, and BiOp-related export reductions were about 1.6 maf. Some of this likely created a loss in exports in the spring that might not have been made up.

BiOps on exports, whereas MBK and HDR took into account other actions like carryover storage requirements that affect export allocations. Reis et al.'s results are actually very similar to ours—and closer to MBK and HDR results—when reviewed for the full nine years they studied.[45] If they had developed a longer time series using this same building block approach, Reis et al. would likely have shown similar results to ours across different hydrology and regulatory regimes.

In sum, all three studies are consistent with the finding that more stringent regulations since 2008 have reduced exports. We think our approach gives a more accurate picture of the trade-off between exports and environmental regulations; MBK and HDR tend to give an upper bound. But the estimates should be considered as ranges, as variability due to hydrology and other changing conditions is also large.

Key takeaways

- There appear to be important and demonstrable trade-offs between exports and ecosystem outflow.
- Ecosystem outflow has increased with changes in regulations, including D1641 and the 2008-09 BiOps.
- Exports in below average runoff years have declined 0.5 to 1.5 maf per year compared to pre-1995 levels, with the greatest reductions in below-normal and dry year types. Effects were lower in the critically dry years because of an overall lack of water.
- Wet-year exports have increased over time, reflecting both increased demand and regulations that shift pumping from dry to wet periods. The effect of export limits on pumping in wet years is difficult to quantify but is probably less than 1 maf per year in most wet years.
- The 2019 BiOps—which are currently undergoing revision—would allow more exports in certain wet periods, but because 2020 and 2021 were dry, they seem to have had no impact on exports in those years.

Trends in Delta Outflow

Delta outflow is the fraction of total runoff that remains after upstream depletions, storage, in-Delta uses, and exports. Outflow is an important measure of Delta conditions and is used in D1641 regulations. It is also a contested hydrologic measure because of its historic relationship with an abundance of some pelagic fishes.

Long-term trends in Delta outflow have also been the subject of recent influential studies. In a study funded by water users, Hutton et al. (2017) examined the period 1922–2015. The study by the same environmental team noted above (Reis et al. 2019) looked at 1930–2018. Both teams focused on a normalized measure of outflow as a share of water available;[46] this allows a clearer picture of outflow trends rather than simply using outflow volumes, which vary significantly depending on water year.[47] Reis et al. focused on the February to June period, which is especially important for fish; both teams analyzed trends for entire water years.

Although they use similar data, the studies report very different results. Hutton et al. found a decline in normalized outflow in dry years until about 1990, then a flattening or possible slight increase; they also found an overall decline in wet years.[48] This is consistent with our finding of significant increases in ecosystem outflow post-1995, as well as the increases in system outflow of about 400,000 af annually (see Box A3 and prior

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[45] As with wet years, where the operations modeling approach can miss actions found in real situations, the MBK and HDR modeling does not include relaxations in standards under the TUC orders in 2014 and 2015—years that Reis et al. feature in their comparison. One would therefore expect Reis et al. estimates to be lower in those years.

[46] Hutton et al normalized by runoff from the eight major rivers in the Sacramento and San Joaquin watersheds, and Reis et al. normalized by unimpaired outflow from the watershed: the unimpaired runoff for the Sacramento and San Joaquin River basins, plus precipitation in the Delta, minus 1.2 maf/year unimpaired Delta depletions. For the comparisons shown here (Figure A9) we use the same normalization method as Reis et al.

[47] Hutton et al. found no long-term trend in the volume of outflow; this is unsurprising since the outflow trend is heavily influenced by very wet years (e.g., outflow in 1983 was about nine times the outflow in 2014; 2017 was also a record-breaking wet year).

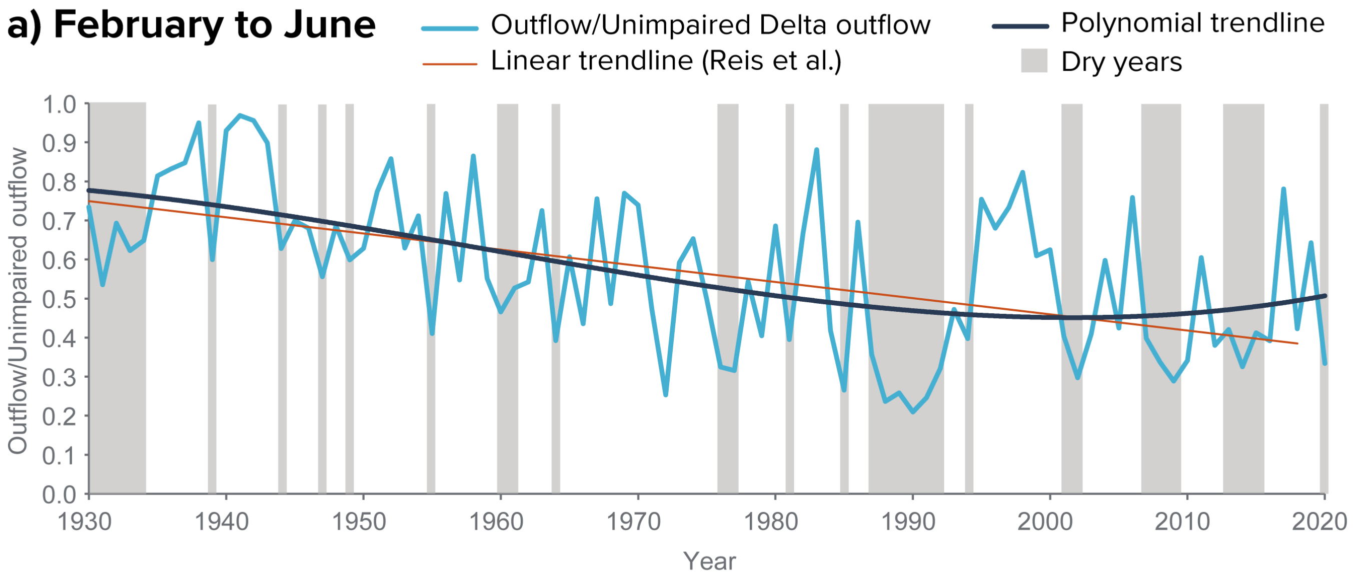
[48] See their Figure 10. Hutton et al. (2017) also found that exports normalized with unimpaired runoff increased until the 1990s, then decreased for dry years, while in wet years they found a steady increase. As noted in the text, new facilities and increased demand contributed to the increase in wet-year exports.

discussion). Both changes should increase normalized outflow. In contrast, Reis et al. found that the February–June normalized outflow has declined steadily since 1930.

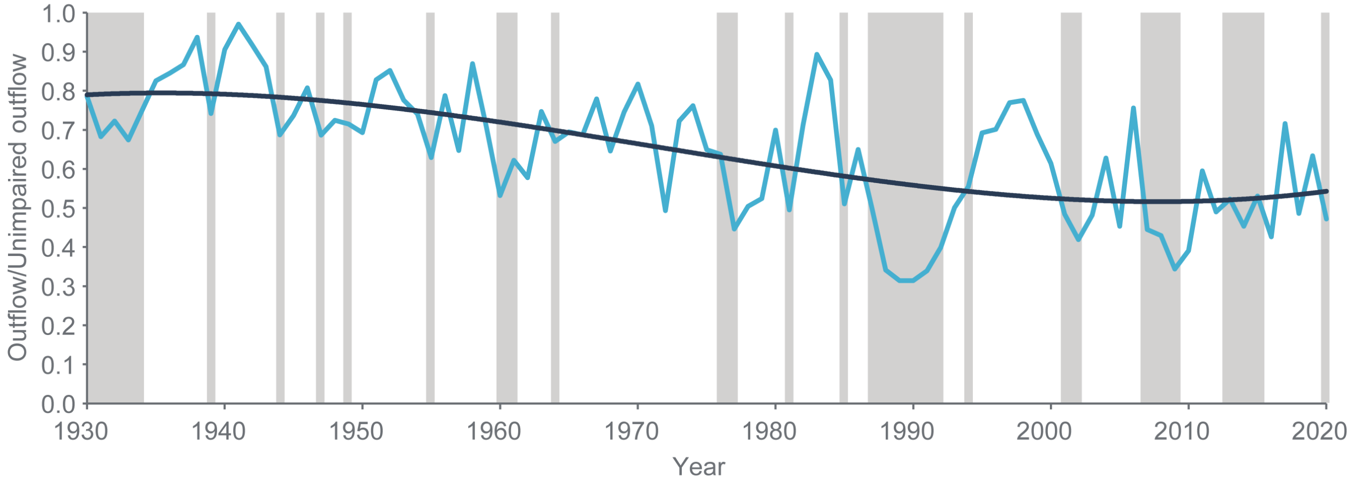
FIGURE A9

Trends in normalized Delta outflow, 1930–2021

a) February to June



b) Full water year



Sources: Dry years: California Cooperative Snow Survey; Delta outflow: Dayflow; unimpaired Delta outflow from CDEC, DWR (2016), Kadir (2021) for 2015-20. Data are available in *PPIC Delta Water Accounting* spreadsheets.

Notes: The trend curves are 3rd-order polynomials fit to the data. The red line in panel a is the linear trendline from Reis et al. (2019) for the 1930–2018 period; extending it to 2020 shows similar results. Dry years are those classified as critical or dry in the Sacramento Valley based on the California Cooperative Snow Survey. To maintain consistency with the approach used in Reis et al. (2019) and Hutton et al (2017), we used the Delta outflow from Dayflow calculated with the Dayflow estimate of in-Delta use. For the period from the early 1990s onward, Dayflow's outflow provides an estimate of annual outflow that is about 0.1 maf lower than the outflow estimate we calculate using DICU.

A review of their methods suggests this latter finding is based on incorrect assumptions, however, and that there has indeed been a shift in the long-term outflow trend since the 1990s. One straightforward way to see this is to look at trendlines (Figure A9). Reis et al. used a linear regression to show the trend for the entire 1930–2018 period.[49] However, a linear regression can only show a rising or falling trend, not a more complex trend. Hutton et al. used a non-linear fit to reach their conclusions of a shift in the 1990s.[50]

In Figure A9, we show the normalized outflow series for the 1930–2020 period for February through June (panel a) and the full water year (panel b). We also show a non-linear trendline, which illustrates the long-term decline,[51] followed by a flattening from the mid-1990s onward. Panel a also reproduces the linear trendline shown in Reis et al., which cannot capture this shift.[52] This flattening trend occurs despite the apparent increase in upstream depletions, which reduce inflow to the Delta (Figure A6).

To further unpack the changes in Delta outflow by regulatory regime, Figure A10 compares Delta outflow to inflow—again distinguishing across the four regulatory periods. Because exports in drier years have been controlled in significant part by inflow levels since 1995 (Figure A8a), we should also see this relationship with outflow.[53] For wet periods, there is little change across regulatory periods; both outflows and inflows are high, with little effect from exports. This is seen in Figure A10a, which shows all the data from 1980–2021.

Figure A10b focuses on the dry-year data (years with less than 20 maf of inflow). It clearly shows more outflow since 2008 compared to earlier regulatory regimes under similar inflow conditions, especially relative to D1485.[54] This confirms our 2017 results and those of Hutton et al. (2017). In summary, the normalized outflow data from 1930–2020 do not support a conclusion that normalized outflow has declined over the entire record; since the 1990s, it has flattened. This is true both for annual outflow and for February–June outflow.

It is important to note that although flow and water quality regulations have changed the trajectory of Delta outflow, this has not resulted in significant improvements in Delta conditions. This is reflected well in the continued decline in populations of many fishes considered ecological indicators in the Delta. The causes of these declines are many, but increasing frequency and intensity of droughts are playing a major role (e.g., Mahardia et al. 2021).

Key takeaways

- Delta outflow relative to unimpaired outflow has declined significantly since the 1930s due to increasing depletions upstream and uses within the Delta, including increasing exports.
- Starting in the mid-1990s, environmental regulations and an increase in the volume of outflow needed to meet salinity standards changed that long-term trend, increasing required outflows relative to the earlier period and keeping outflow relative to unimpaired outflow steady. This is despite the apparent increases in upstream depletions as a share of runoff, which result in less water flowing into the Delta.
- However, warmer overall conditions in the Delta, and a spate of dry years, have meant that the ecosystem—and Delta fishes—have had fewer cool, wet years in the past two decades in which to rebound from drought.

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[49] They showed the trendline for the February to June period (see their Figure 3) and stated they found the same trend for annual outflow.

[50] Both studies also employed a Kendall method to determine if the data were rising or falling. The Kendall method looks at whether, for each data point, each subsequent point is higher or lower. Reis et al. reported that normalized outflow fell, according to that methodology, from 1995 forward. But starting in 1995 can bias the results, since the period 1995–99 was extremely wet, and most years following were drier, as we noted earlier in the discussion on short records.

[51] Normalized outflow fell in the February through June period starting around 1940, when large reservoirs were built, but on an annual basis the normalized outflow drop lagged by about 20 years. Before water deliveries increased, reservoirs were filled in the spring but drained for flood control purposes in the fall, so the outflow shifted to later in the year. Later, much of that draining was exported, reducing outflow.

[52] R^2 measurements of goodness of fit for February to June 1930–2020 are 0.31 (polynomial) and 0.27 (linear); for the full water year they are 0.44 (polynomial) and 0.42 (linear). The low values reflect the randomness of wet and dry year timing.

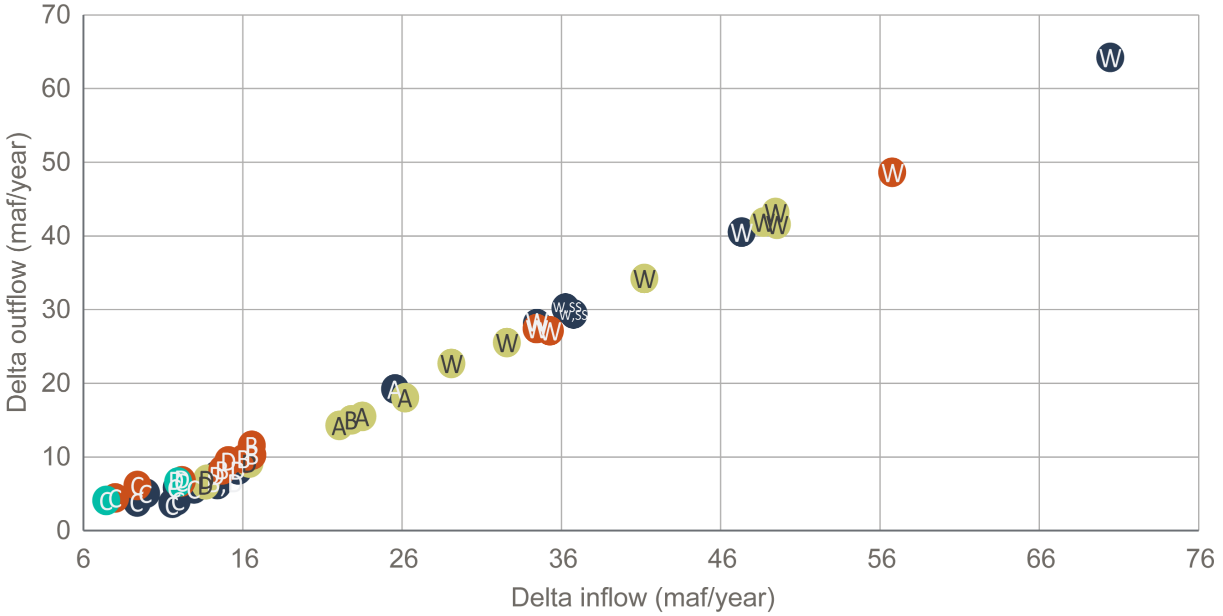
[53] D1641 limits exports using an export-to-inflow ratio limit; Old and Middle River flow limits are effectively a limit based on San Joaquin River inflow, and the 2008–09 BiOps spring pulse export limit is a San Joaquin River inflow to export limit.

[54] Under D1641, year-type classifications are based not just on current-year unimpaired inflow, but in part on the prior year's index, so some years with similar inflow are classified differently.

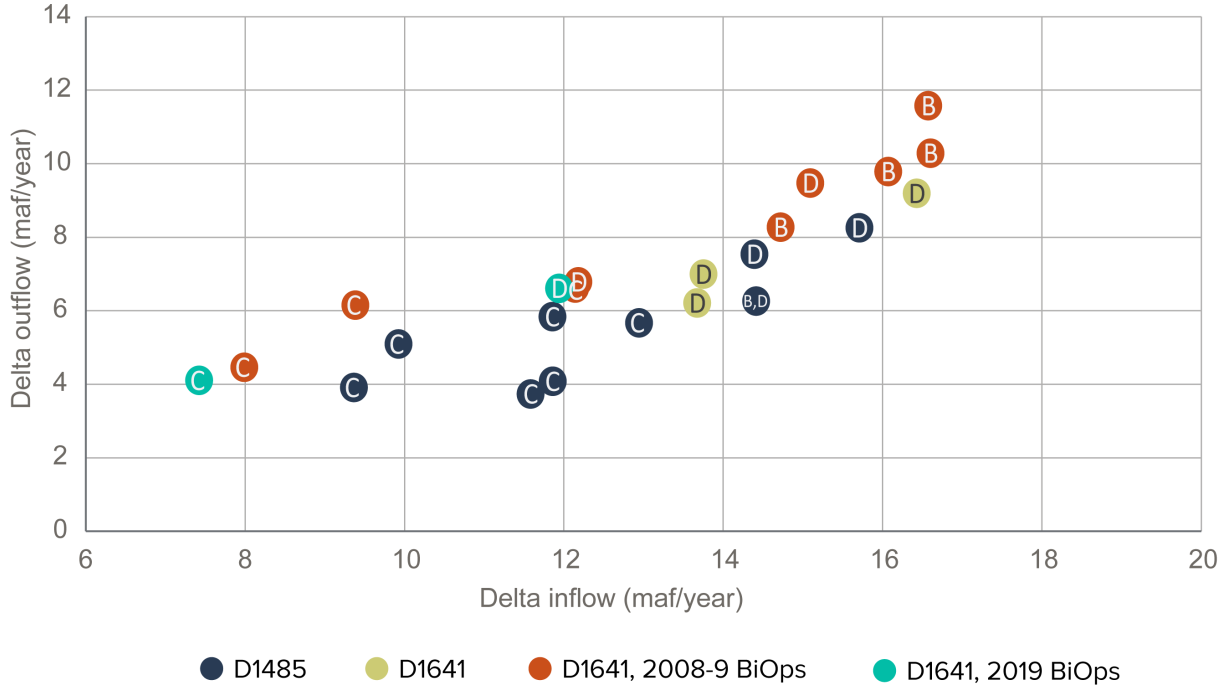
FIGURE A10

Delta outflow compared to Delta inflow, 1980–2021

a) Delta outflow compared to Delta inflow



b) Delta outflow compared to Delta inflow, dry years



Sources: PPIC Delta Water Accounting spreadsheets.

Notes: Hydrologic classifications based on D1485 (1980–94) and D1641 (1995–2021). W=wet, A=above normal, B=below normal, D=dry, C=critically dry, SS=subnormal snowmelt (under D1485 only). *: 2008–09 BiOps ^: 2019 BiOps

Managing a Changing Delta in Dry and Wet Years

The warmer conditions in the Delta watershed have contributed to more intense droughts—with higher evaporative demand, less snowpack, and an apparent rise in upstream depletions as a share of runoff. The region has also been experiencing a dry spell—broken by intensely wet years—compounding the challenges of managing the Delta and its watershed for water supply and ecosystem objectives. To highlight these challenges—and opportunities for adaptation—we profile where water went in two extreme years: the critically dry 2021 and the very wet 2017. We describe how water management affected water accounting, and highlight some policy implications that result from our analysis.

Critically Dry 2021

Coming on the heels of a very dry 2020, water year 2021 was particularly difficult, with near-record low precipitation and unusually warm temperatures, including the highest levels of evaporative demand ever recorded (Albano et al. 2022).[55] The early part of the water year (fall 2020) was particularly dry, with little to no precipitation. At the beginning of January 2021, the main project reservoirs (Shasta, Oroville, and Folsom) had less than 3.6 maf in storage. During a critically dry year, system flow requirements in the Delta are typically around 3.6 maf. Clearly, this was a year that would depend heavily on runoff from rainfall and snowmelt to meet water demands. Unfortunately, precipitation was low, and the actual runoff was much lower than the forecast, leaving the projects unable to meet flow and water quality standards by the spring.

Figure A11 illustrates the water year balance for the Delta watershed (panel a) and within the Delta (panel b). Even though senior upstream water users diverted less water than usual,[56] upstream depletions (7.3 maf) took 84 percent of unimpaired runoff from the watershed (8.7 maf). In combination, upstream and in-Delta uses accounted for more than the entire volume of unimpaired runoff (104%)—and 100% of watershed supplies including rainfall in the Delta, leaving small contributions from the Trinity River (0.6 maf) and 5 maf in releases from storage to make up the gap and meet export demands and flow and water quality standards.[57] Project reservoirs were drawn down rapidly (Box A6).

Of the total Delta inflow (7 maf), in-Delta uses consumed 26 percent, while exports accounted for 22 percent. The remainder—roughly 4.1 maf—became outflow. The vast majority of outflow (78%) was for system outflow, with the balance for ecosystem outflow (20%), and just a small remainder (2%) uncaptured outflow.[58] Although most of the releases from San Joaquin River reservoirs went to upstream water deliveries, keeping the Delta fresh enough for water supply and meeting ecosystem demand used over 70 percent of the water released from carryover storage across the watershed as a whole.

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[55] Water year 2020 was exceptionally dry, but because the previous water year was wet, it was classified as "dry" (Box A6). If 2020 had followed 2021 or any other dry year it would have been classified as critically dry.

[56] CVP Settlement Contractors and districts with settlement contracts with the SWP received smaller allocations (see footnote 62). The State Water Board also issued orders to stop diversions to many senior water-right holders as supplies dropped below levels adequate to sustain their rights, but it is difficult to ascertain the impact this had on depletions (see text). Another group with seniority—the CVP Exchange Contractors—receive their water as Delta exports; they also saw some reductions in allocations.

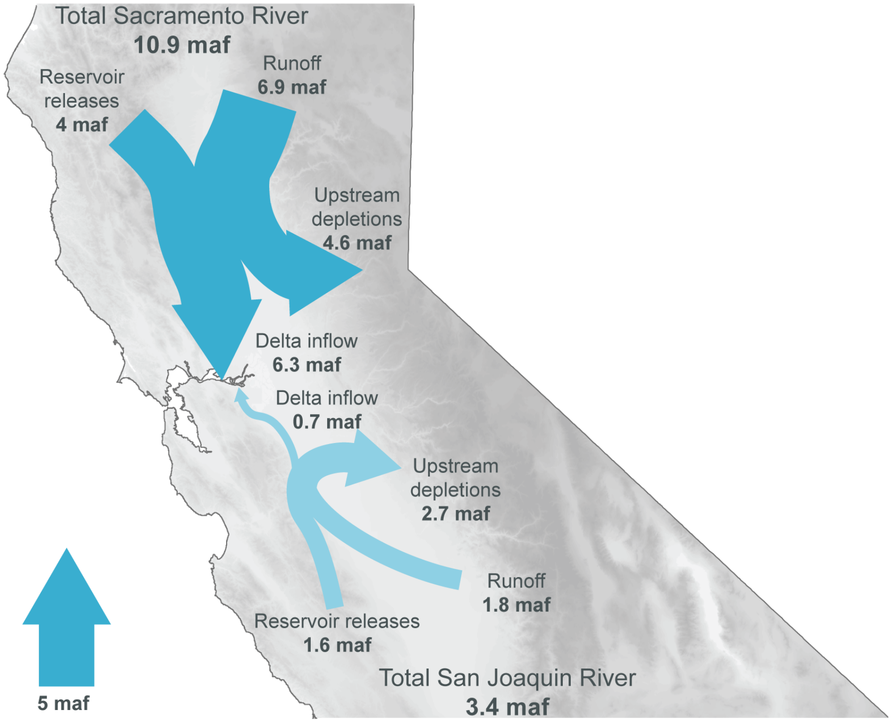
[57] In this very dry year, in-Delta uses consumed most (0.3 maf) of the precipitation in the Delta (0.4 maf); the remainder (0.1 maf) accounts for the small volume of water that was uncaptured outflow in that year. The equivalence of runoff and water used by upstream and in-Delta diverters suggests that on average, there was no runoff remaining for other uses this year. In practice, there were times when these users relied on water from reservoirs. This has implications for improving drought management, as described in the conclusion.

[58] Another way of looking at Delta outflow is that about 3 maf of the 4.1 maf total was multipurpose water (both system and ecosystem), 0.2 maf was exclusively for system outflow (water quality for in-Delta and exports), 0.4 maf was exclusively for ecosystem flow and water quality, and 0.5 maf was ecosystem export reductions.

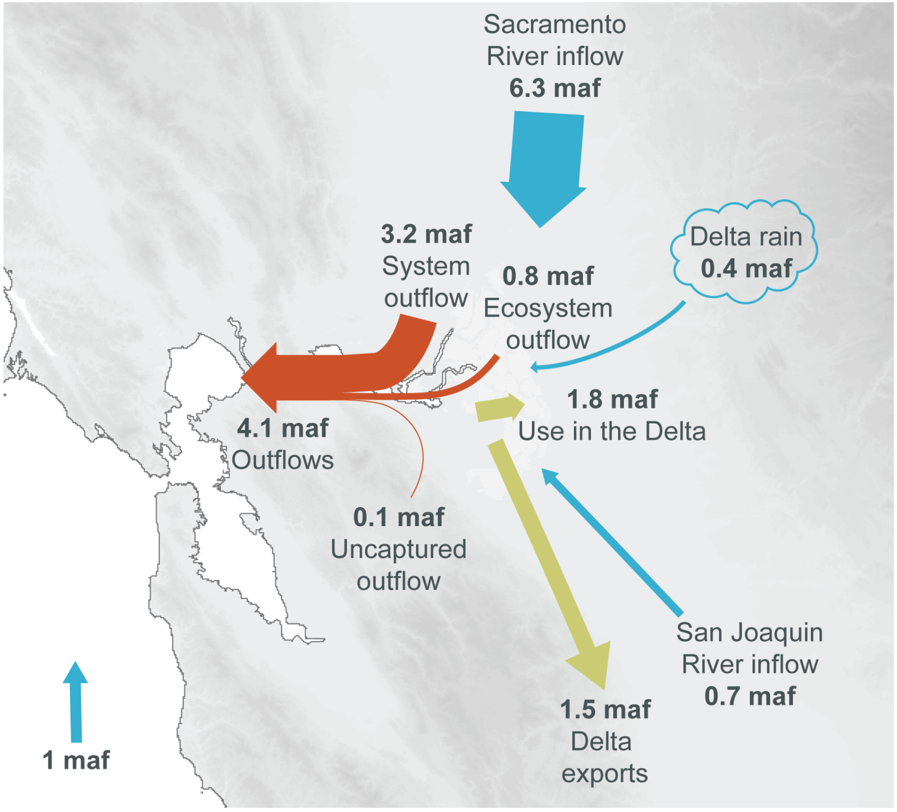
FIGURE A11

2021 water year balance for the Sacramento–San Joaquin watershed

a) Upstream of the Delta



b) Within the Delta



Sources: *PPIC Delta Water Accounting spreadsheets*, CDEC, Dayflow.
Notes: Sacramento reservoir releases include 0.6 maf imported from the Trinity River. Ecosystem flows include 0.3 maf for water quality and flow, and 0.5 maf from export limits.

The 2021 water year illustrates the limits of relying on reservoirs to make up for annual runoff deficits under warm, dry conditions (Box A6). To make matters worse, runoff forecasts—important for managing reservoir release temperatures for salmon and other supply decisions—over-estimated the amount of water likely to be available in the spring.[59] By late spring, there was insufficient storage in reservoirs to meet temperature standards and salinity standards in the Delta.

Emergency Regulatory Tools Used to Manage the 2021 Drought

To cope with the extreme situation, the state used several tools—reserved for emergency conditions—to manage the Delta and its watershed during 2021: Temporary Urgency Change (TUC) orders, water supply curtailments, and a salinity barrier on False River. Both the TUCs and the salinity barrier reduced needed system outflow; these changes are reflected in our accounting.

Temporary Urgency Change (TUC) Orders

In 2021, the State Water Board authorized a variety of temporary changes to Delta water quality and flow standards—something also done at the height of the last drought (2014 and 2015). There was concern that the severity of the drought made it extremely difficult for the CVP and SWP to meet the requirements of D1641 and the BiOps, and that the use of stored water to meet outflow requirements in the spring would deplete cold water in Shasta Reservoir to the point that it would threaten winter-run Chinook salmon eggs and fry. There was also a risk that reservoir storage would fall so low that the projects would lose the ability to control salinity in the Delta.

D1641 does allow for relaxations of standards during drought. M&I and agricultural standards change by water year type, allowing more salinity intrusion in years with less runoff. Some fish and wildlife protection measures are reduced in drier year types as well (SWRCB 1999, Table 3). The X2 standard also has exceptions: the flow standards for January, March, May, and June are relaxed if runoff conditions are very low (see SWRCB Table 3, footnotes 9 and 10).[60]

The extremely dry years of 2014, 2015, and 2021 each had conditions that were not seen in the 1922–93 modeling used to guide the Accord discussions and set standards in D1641. And in all of these years, the models or methods used to project conditions and guide reservoir operations to meet standards missed the mark. Consequently, in all three years DWR and USBR requested TUC orders, asking the board to loosen Delta salinity and outflow standards and to modify several restrictions on project operations. In 2014 and 2015, this primarily covered months that did not already have relaxations, while in 2021 the relaxations were in June through August.[61] Their primary stated goals were to retain water in project reservoirs to meet downstream flow and temperature standards and Delta water quality requirements, while also fulfilling their contractual water service obligations and supplying water for public health and safety.[62]

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[59] In 2021, the April 1 forecast was too high by almost 0.5 maf. Importantly for salmon flows, on April 1 the 90 percent Shasta inflow forecast—a forecast for conditions drier than nine years out of 10—was almost 1 maf; it dropped to 0.76 maf on May 1, and the actual level ultimately was just 0.7 maf. Conditions were so extreme in 2021 that even the 99 percent forecast in April—a forecast for conditions drier than 99 years out of 100—was too high.

[60] These relaxations were included in the 1994 Bay–Delta Accord, based on discussions among representatives of the U.S. Fish and Wildlife Service, NOAA Fisheries, and others, in large part to avoid excessive reservoir releases early in the season that would lead to insufficient flows in the summer and fall (Gartrell 2022). The relaxations resolved the conflict between spring flows for Delta smelt and flows needed later for salmon survival and water quality.

[61] For details of the modifications in 2014 and 2015, see Appendix A of the 2017 report. The 2021 TUC order relaxed the agricultural standard at Emmaton (moving it to Threemile Slough) from June to August 15 and the minimum flows for ecosystem protection to 3,000 cfs in June and July. Exports, as per usual, were limited to 1,500 cfs or less when standards were not met. The relaxed salinity requirement for agriculture in June was not met at times.

[62] USBR has contracts with two groups who held pre-project water rights: the Sacramento River Water Rights Settlement contractors and the San Joaquin River Exchange Contractors. When Shasta inflow is less than 3.2 maf, deliveries from USBR can be cut back by a maximum of 25 percent (during 2021, the Settlement contractors voluntarily cut back to 65% of contract deliveries). The SWP has settlement contractors who can also be cut back during dry years: 50 percent in any one year, but not cumulatively more than one full annual allocation in any seven-year period. In 2021 they were allocated 55 percent of contract water supply. The other CVP and SWP contractors have no minimum water service rights during severe drought. In 2014, 2015 and 2021, CVP water service contractors located south of the

The State Water Board has estimated that the TUC orders conserved water in storage that was available for upstream salmon, CVP and SWP obligations to senior contractors (see note 62), and salinity control later in the year; the estimated volumes conserved were approximately 400,000 acre-feet in 2014 and 688,000 acre-feet in 2015—the latter a year in which the TUC relaxations were combined with a salinity barrier on False River (described below) (SWRCB 2015). We estimate the TUC order in 2021, in conjunction with a new temporary barrier at False River, allowed about 410,000 acre-feet additional water to be conserved in storage. [63] While these measures helped conserve water and manage salinity, they did not completely resolve the cold-water issues for salmon, but they did allow more end-of-September storage and provided water to maintain salinity control in the Delta in the fall. The limited cold-water reserves in Lake Shasta dramatically lowered egg-to-fry survival rate for naturally spawned winter-run Chinook salmon: 95 percent of salmon eggs and fry were lost in 2014, and 98 percent perished in 2015 (Mount et al. 2017). In 2021, estimated mortality was 98 percent.[64]

Box A6. Increasing Pressures on Reservoirs during Drought

At the end of water year 2019, water stored in upstream reservoirs was well above the historical average. The main CVP and SWP reservoirs—Shasta, Oroville, and Folsom—held 9 maf (though only about 7.5 maf is accessible above "dead-storage"). Yet by spring of 2021, there was a crisis. Why such a rapid change in conditions? Several factors contributed to reservoir declines:

- **Flood control releases.** Although reservoirs were unusually full in 2019, they were required to release water in the fall to make space for floods. This limits the amount of carryover storage from wet years to dry years to about 5.3 maf of accessible supplies.
- **Fall X2 releases.** Because 2019 was a wet year, regulations (BiOps and ITP) mandated that the CVP and SWP meet the fall X2 salinity standard, requiring larger fall releases from reservoirs and less export pumping to south of Delta storage in San Luis Reservoir. Oroville in particular was drawn down by about 0.4 maf.
- **Dry-year releases in 2020.** Water year 2020 was classified as "dry" even though the amount of runoff was equal to 2015, a critically dry year. This is because 30 percent of the classification of year type depends on what happened the year before. Dry years have higher system outflow demands than critically dry years (about 0.7 maf more) to meet higher salinity standards, requiring more releases from reservoirs (Box A4).

But the most important factors in the supply crisis lie elsewhere. First, there is a **structural imbalance between available storage and system outflow needs in drought**. For example, it took about 7.5 maf of outflow just to meet system outflow needs over 2020 and 2021, even with the emergency measures employed to reduce outflow requirements in 2021. Less than 5 maf was accessible in reservoir storage at the end of 2019, a wet year. So operators had to hope for winter rains and snowpack to make up the difference.

Second, the **warming climate is reducing snowpack and runoff**. Both 2020 and 2021 had severe deficits in winter runoff and spring snowmelt; in 2021 inflow to Shasta—critical for cold water management—were the lowest on record. Worse, runoff forecasts were initially too high and dropped by 0.5 maf from April to May, with the Shasta inflow forecast dropping 25 percent. In 2021, the runoff was lower than the sum of the upstream depletions and in-Delta uses. Historical runoff patterns are no longer providing accurate estimates of runoff in warmer conditions. This experience underscores the increasing vulnerability of the water supply system to drought in the warming climate—and particularly the CVP and SWP, which are responsible for meeting outflow requirements.

Delta received no project water, while SWP contractors who rely on Delta exports received 5 percent of their state contractual entitlements in 2014, 20 percent in 2015 and 5 percent in 2021 (USBR 2016; MWD 2016, SWRCB 2021).

[63] As described below, the salinity barrier in 2015 did less to improve water quality than the 2021 barrier. However, the combined water savings in 2015 were higher because of differences in the TUC orders for the two years. The 2015 TUC order was issued at the beginning of February, and substantially reduced allowable export levels and outflow requirements. The 2021 TUC order started in June 2021 and covered a shorter period.

[64] According to a January 20, 2022 letter from the National Marine Fisheries Service to Kristin White of the US Bureau of Reclamation. This letter notes that both temperature stress and thiamine deficiencies in adult spawning salmon contributed to this low survivorship.

Water Supply Curtailments

The State Water Board also issued orders for certain water right holders to cease diversions later in the summer of 2021, but because of a lack of accurate and timely accounting, it is difficult to be certain about the amount of water saved (SWRCB 2021a, p. 53). Although the tracking of water rights and reporting of use has improved since 2015 (SWRCB 2021b, 2021c), a considerable amount of work remains. As we discuss further below, full real-time reporting of diversions and return flows, as well as better estimates of runoff (both actual and unimpaired), would greatly enhance the ability to forecast shortages and give advance warning to water users of likely curtailments.

False River Salinity Barrier

In late May 2021, DWR was granted an emergency water quality certification to install a temporary salinity barrier at the head of False River in the western Delta. At the time of this writing, the barrier remains in place, as 2022 is another very dry year.

As background, False River is a channel branching off the lower San Joaquin River at the north end of Jersey Island (Figure A12). Its name derives from the fact that it was a dead-end channel (SFEI 2012). Today, False River is open and enters the Delta through Franks Tract.

Tidal action pumps large volumes of water through False River into Franks Tract and then into the Central Delta; the flow through False River is on the order of 50,000 cfs, moving about 25,000 acre-feet in a six-hour flood tide (and back out on the ebb). When Delta outflows are low and salinity intrudes in the western Delta, this flow pumps salinity into Franks Tract and the Delta interior, degrading water quality for in-Delta water users and exports. Installation of a salinity barrier is designed to block this flow (effectively returning False River to its historical condition) and to reduce the volume of system outflow needed to maintain low salinity.[65]

The salinity barrier's effects occur in conjunction with other salinity management actions, including the TUC order changes and careful management of the Delta Cross Channel gates to try to freshen water in the Delta interior.

Salinity records[66] show that the barrier caused a significant improvement in conditions in Old River in 2021, reducing salinity by as much as 30 percent from June through August 15. Salinity in Middle River was about the same or possibly improved.[67]

The barrier, combined with the TUC orders, allowed a significant reduction in system outflow. The USBR and DWR estimated a savings of 289,000 acre-feet from June to August 15.[68] We calculate the savings for June to August 15 at about the same level but estimate an additional water savings of 120,000 acre-feet from August 15–October 15,[69] for a total of 410,000 acre-feet. These savings reduced pressure on CVP and SWP reservoirs, which were required to release water to meet salinity standards.

A salinity barrier was installed in False River in 2015 at the peak of the last drought. Its improvements in water quality in the south Delta and Old River were less than in 2021. This probably stems from its installation later in

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[65] Other channels to the east with lower salinity supply the tidal flow (about 20,000 acre-feet in a 6-hour flood tide) when the barrier is in place.

[66] See CDEC stations JER, BAC, and VIC.

[67] Typically, Old River near Rock Slough salinity tracks Jersey Point salinity when there is no barrier, but at a level about 40% or so less than at Jersey Point. Middle River salinity is about 25% or less of Jersey Point salinity. From Jersey Point salinity, one can estimate the salinity that would have been found in Old River and Middle River without the barrier.

[68] Some water might have been conserved in June when the agricultural standard was not met, although additional flow was required to come back into compliance. It is not clear if the event saved or cost water overall.

[69] These savings estimates are based on the difference between Delta outflow and our estimates of what would normally be needed for outflow to meet the Emmaton Standard.

the year when salinity had already declined in the Delta, in particular in Franks Tract. It took more time—and more system outflow—to freshen Franks Tract and Old River and restore salinity. This highlights the importance of salinity barrier installation early during severe drought.

In 2021, there was a substantial harmful algal bloom (HAB) in Franks Tract, something that did not occur in 2015 under similar conditions. It is not clear if the barrier caused, contributed to, or was unrelated to the HAB (DWR 2021).

FIGURE A12

The Delta near Franks Tract, showing the location of the False River barrier

SOURCE: DWR (2021)

Policy Implications. Given the increasing frequency and intensity of drought conditions—and the necessity of a drought emergency declaration to act—it is worth assessing whether a more permanent barrier with operable gates should be installed in False River. We know from 2015 and 2021 that it improves water quality in the central and south Delta, but those were also periods of low export pumping. Studies are needed to determine how the barrier would work at higher pumping rates and how both Old and Middle River salinity responds in those conditions.[70] It also is important to examine the biological effects of the barrier. This includes reduction of turbidity events in Franks Tract, movement of juvenile and returning salmon, movement of pelagic fishes, and formation of harmful algal blooms—including whether the capacity to open and close the barrier (possibly with culverts like those in the Sand Mound Slough Barrier) might mitigate any impacts or improve its functions. But the results of 2021—savings of more than 400,000 acre-feet of system outflow and distinct water quality improvement in Old River—make it worthwhile to consider a permanent barrier.

Key takeaways from 2021

- During 2021, upstream and in-Delta uses dominated hydrology, consuming 104 percent of unimpaired runoff, and 100 percent of annual supplies including rainfall in the Delta. Despite considerable improvement since the 2012–16 drought, the state has insufficient capacity to monitor these uses and to effectively administer its water rights program.
- With no runoff to spare, managers relied almost entirely on storage releases to meet Delta salinity and ecosystem standards and to supply exports. Of these uses, system outflow for salinity was largest. Both ecosystem outflow and exports are low during severe drought.
- Abnormally dry and warm conditions, low reservoir storage levels, and errors in runoff forecasting—particularly in the Sacramento watershed—led to the need for emergency measures to manage both water quality for salmon and salinity in the Delta in 2021.
- TUC orders to conserve water by relaxing salinity standards were used in 2021—as they were in 2014 and 2015—and again in 2022. While these measures helped manage salinity in the Delta and increased storage levels, they did not resolve the cold-water issues for salmon and did little to protect them during outmigration.
- Water supply curtailment orders were issued to many senior upstream water right holders in summer 2021, but a lack of accurate and timely accounting makes it difficult to ascertain the amount of water saved and its effect on water accounts.
- In 2021 and 2015, a temporary salinity barrier improved water quality in the central and south Delta. In conjunction with TUC orders, it significantly reduced the amount of system outflow needed. It is worth assessing whether a permanent, operable barrier is warranted.
- The accounting shows that CVP and SWP reservoirs hold less usable stored water in the fall (when drawn down for flood control) than is needed for two years' worth of salinity control in the Delta, or a single year of upstream and in-Delta uses.
- California is highly dependent on snowpack for water supply—even during droughts—yet snowpack is diminishing as the climate warms. The hot conditions and declining snowpack have significantly thrown off spring runoff forecasts—a crucial metric for managing supplies in dry years. Lower spring inflows are also making it extremely challenging to maintain cold water for salmon and salinity in the Delta.
- The latest drought highlights challenges with the current emphasis on water year types, with sharp thresholds for regulatory decisions. Given higher levels of storage coming into the year, water year 2020 was classified as "dry" even though runoff was equal to that of 2015, a critically dry year. This resulted in much higher required outflow and contributed to dwindling reserves.

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[70] Some past modeling suggested the barrier could decrease salinity in Old River but might increase it in Middle River; this did not happen in 2015 and 2021, possibly because of the low export pumping.

- The frequency of emergency response measures—and the changing climate patterns— suggests the need for a new strategy for drought management in the Delta and its watershed. We discuss a range of policy and management implications in the concluding section below.

Very Wet 2017

Even though the Delta watershed has been experiencing a dry spell, wet years still occur. There have been four in the past two decades, consistent with the long-term average of once in four or five years. Wet years have always been essential to water management in the basin, and this is only increasing with the warming climate and the need for water users in many areas to bring local groundwater basins into balance.

Water year 2017 was one of the wettest on record. The water accounting for 2017 is summarized in Figure A13, and by all measures the numbers are impressive. Runoff exceeded 69 maf (more than eight times the volume in 2021). Upstream and in-Delta uses took only 18 percent of this total, while exports, although relatively high at 6.3 maf, accounted for less than 10 percent.

More than 70 percent of runoff became Delta outflow. System outflow demands accounted for 7 percent, and ecosystem outflow—which is largest during wet years—less than 10 percent. The rest went to uncaptured outflow which, at more than 37 million acre-feet, was more than enough to freshen the estuary all the way to the Golden Gate Bridge several times over.

In wet years like this, the system and ecosystem outflow does not necessarily reduce Delta exports. As described below, at times both storage capacity and system maintenance were limiting factors.

Missed Opportunities for Storing Water

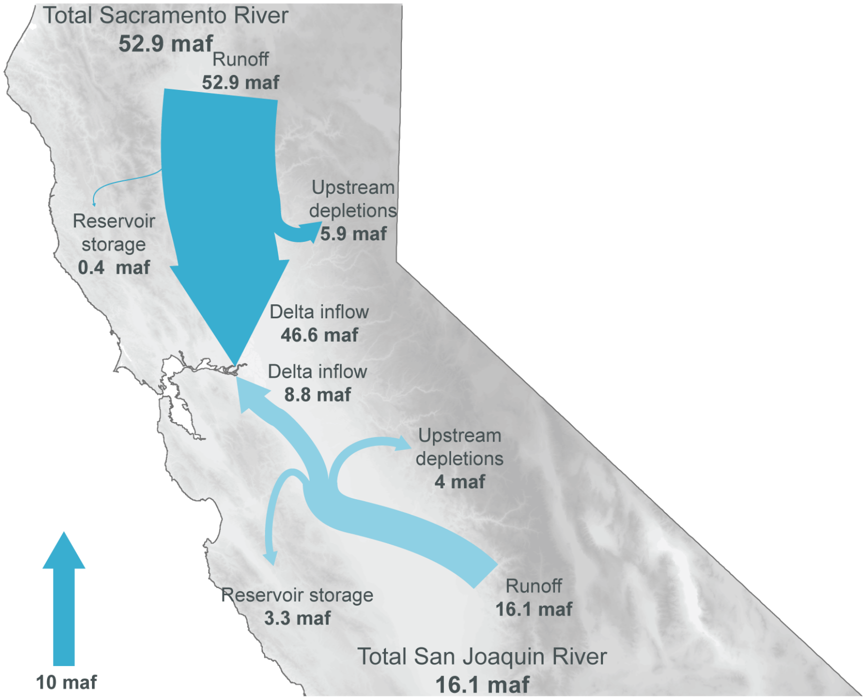
Wet years create opportunities to increase the amount of water stored in reservoirs and groundwater basins for future dry years. This interest is acute in the San Joaquin Valley where unsustainable groundwater withdrawals must end to meet the mandates of the Sustainable Groundwater Management Act (SGMA).

In most wet years—and especially in 2017—reservoirs fill quickly. Large, multipurpose reservoirs like Shasta and Oroville often must make large releases to maintain their flood reserve space (in 2017 this created a crisis at Oroville Reservoir when the spillway failed). In the spring, when flood restrictions are relaxed, these reservoirs have usually filled completely. In addition, off-stream storage like San Luis Reservoir—located south of the Delta pumps—also fills quickly in the winter as water is pumped in. In most wet years—even those following dry years—existing surface storage space fills, leaving little opportunity for storing more water. Groundwater storage—long important in parts of the Central Valley and other regions—is increasingly being developed with an eye to expanding storage capacity. In 2017, San Joaquin Valley managers significantly increased volumes stored, but they also ran into capacity constraints—including developed recharge sites as well as conveyance to get the water to recharge locations (Hanak et al. 2018).

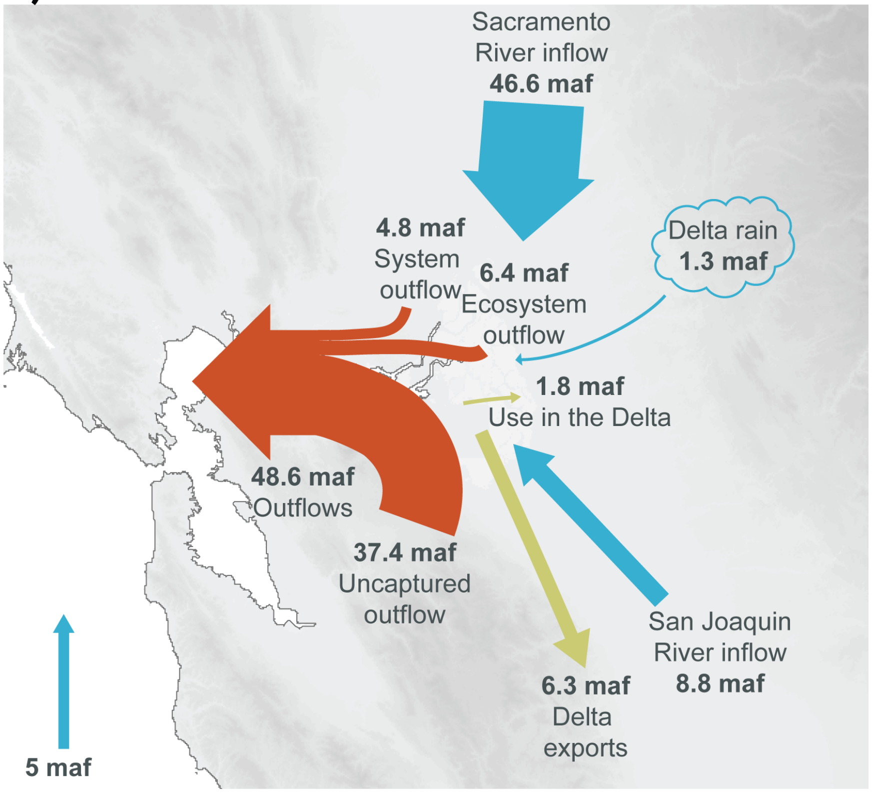
FIGURE A13

2017 water year balance for the Sacramento–San Joaquin watershed

a) Upstream of the Delta



b) Within the Delta



Sources: *PPIC Delta Water Accounting spreadsheets*, CDEC, Dayflow.

Notes: Net 0.4 storage in the Sacramento River included 1 maf removed from runoff to storage and 0.6 maf imported from the Trinity River. The low net surface storage in that region is due to the draining of Oroville following the spillway failure. Ecosystem outflow includes 0.26 maf in water for the Fall X2 and 1 maf in export limits.

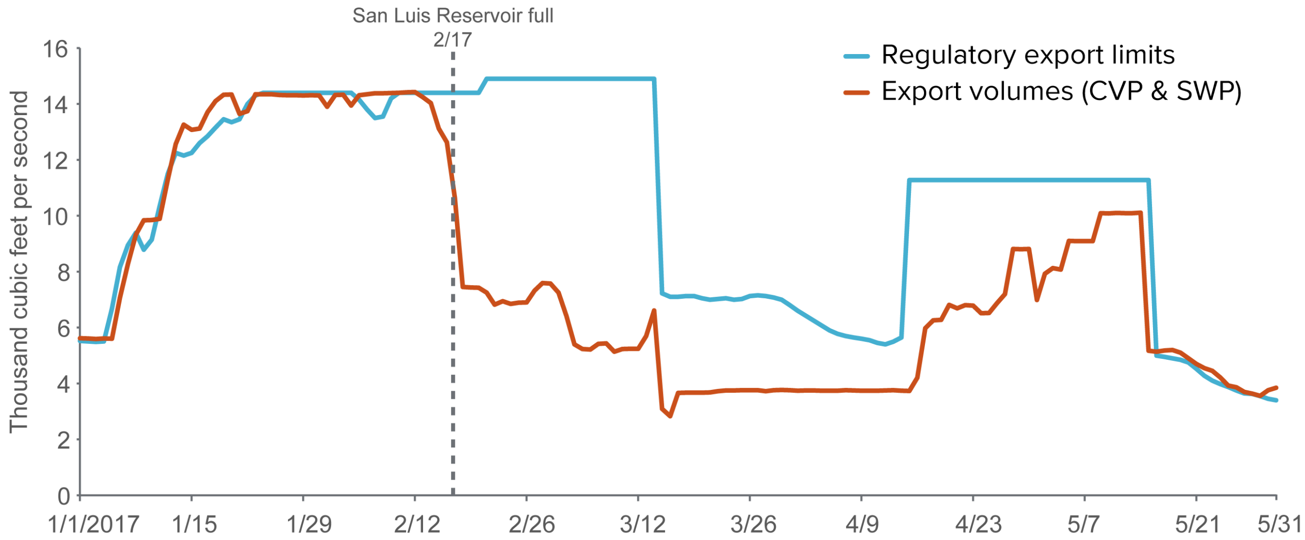
Figure A14 explores the impacts of these infrastructure limitations in the winter and spring of 2017, with a focus on CVP and SWP exports. Panel a depicts export capacity allowed under current regulations along with actual exports. In January and early February, the projects exported as much water as regulations would allow. However, by mid-February, exports were reduced below the amount allowed. This cutback occurred because the projects had few places to put the water, since San Luis Reservoir had filled; there was also a later, temporary shutdown because of a problem with Clifton Court gates.

We estimate the cumulative amount of water that would have been available for storage, while staying within existing regulations on export limits, at 400,000 to 800,000 af. The lower range includes the shutdown for repairs at Clifton Court; the upper range (shown in Figure A14, panel b) is what would have been available in the absence of that shutdown.

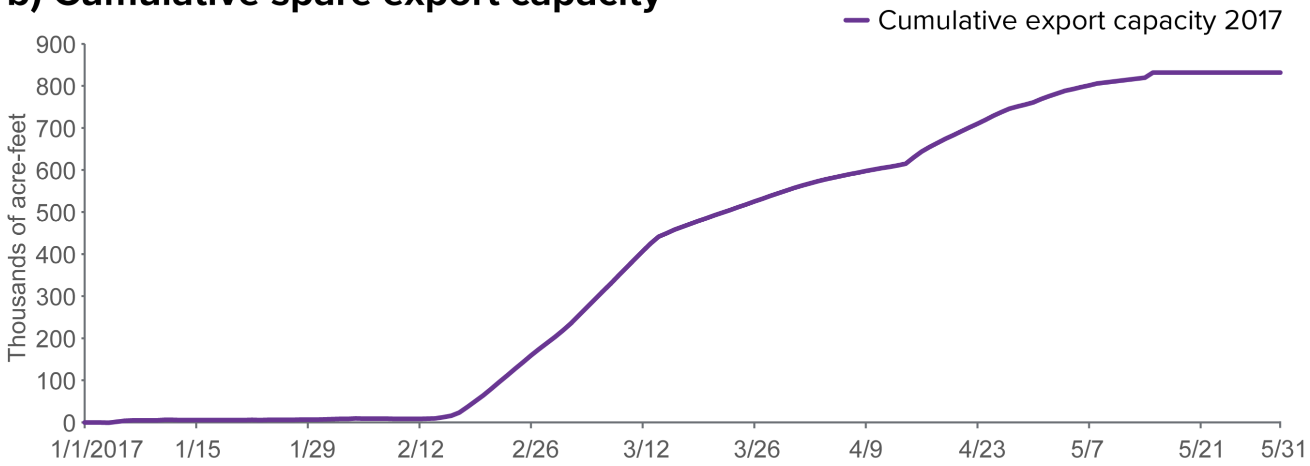
FIGURE A14

Delta exports, export limits, and cumulative volume of available export capacity in 2017

a) Export limits and actual exports



b) Cumulative spare export capacity



Sources: PPIC Delta Water Accounting spreadsheets.

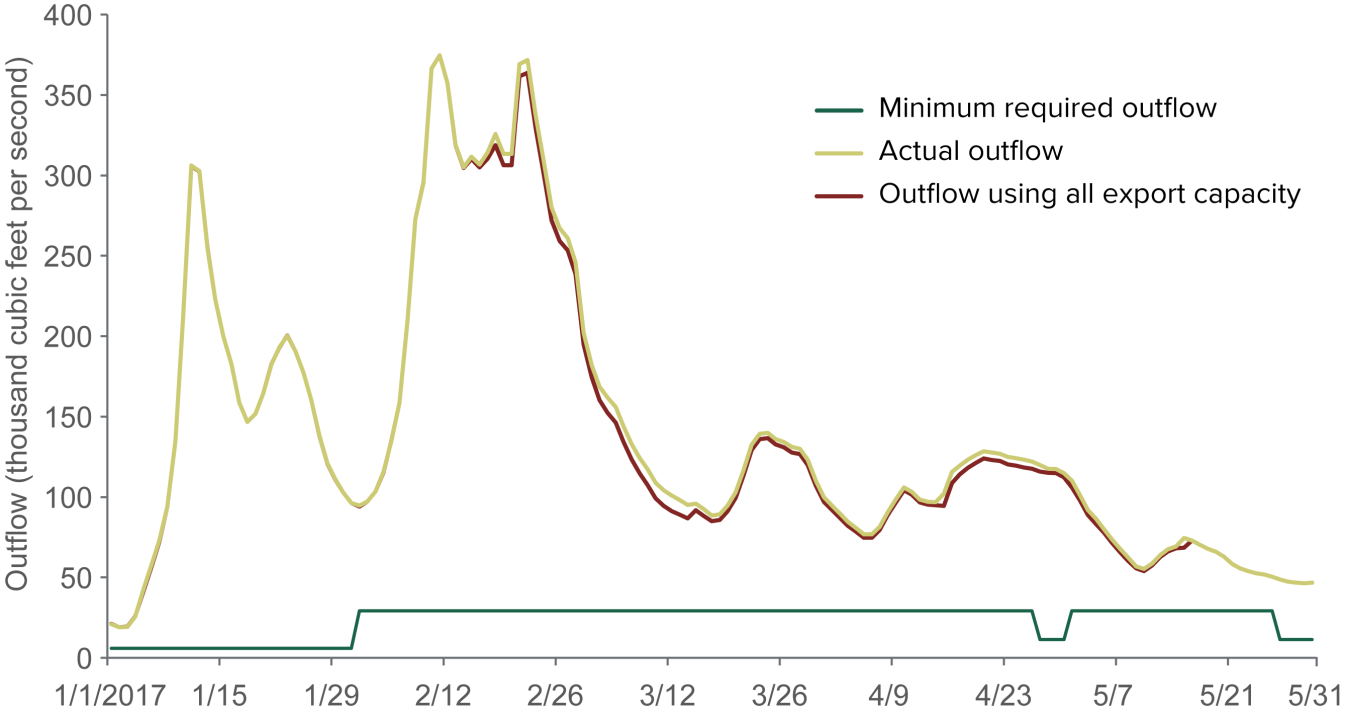
Notes: Cumulative volume if storage were available assumes the export limits were followed the entire period. Small exceedances of exports over limits in January do not imply violations, just measurement and estimation discrepancies.

This inability to make full use of export capacity in winter and spring is common in wet years, especially when flood levels are reached on the San Joaquin River. Since 2000, there have been four years with substantial uncaptured flow: 2006, 2011, 2017, and 2019 (Figure A7). In each case, San Luis Reservoir filled early (in January 2006 and in February or March of the other years), after which there was substantial unused capacity available at the export pumps for about a month. In 2011 and 2019—both years governed by D1641 and the 2008–09 BiOps—capacity was available for another 300,000 to almost 500,000 acre-feet under existing regulations.[71]

This highlights the potential for infrastructure improvements south of the Delta that may help increase groundwater recharge using the CVP and SWP facilities. Yet one of the concerns sometimes raised is that this increased pumping—even within current regulatory limits—may cause harm to the estuary by reducing outflows. We examined this for 2017. Figure A15 plots the actual amount of outflow from the Delta over the winter and spring of 2017, along with the outflow that would have occurred if export pumping had maintained its full capacity allowed by regulation. With outflows between 100,000 and 300,000 cfs, the additional pumping would have had no measurable effect.[72] The same is true for 2011 and 2019.

FIGURE A15

Delta outflow, required outflow, and outflow if available export capacity had been used in 2017



Sources: *PPIC Delta Water Accounting spreadsheets*, Dayflow.

Notes: Outflow using all export capacity assumes the export limits were followed the entire period.

Figure A15 also suggests that there is room upstream to capture and store some of these high wet-year flows, for instance in groundwater recharge areas, without significantly impacting outflows. There also may be some

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[71] The PPIC Delta Water Accounting spreadsheets provide the series on minimum outflow for all years, and estimates of the maximum export limits for 2011, 2017, and 2019.

[72] To illustrate how much water is involved, 300,000 cfs would fill Shasta from empty in 7.5 days.

capacity for increasing exports within the current regulatory bounds in other years, especially in above-normal years, when San Luis Reservoir is likely to fill early, and especially following a wet year. We were unable to do a comparable analysis, however, as there have been no “above normal” years since the 2008–09 BiOps were implemented.[73] In contrast, the projects generally operate at or near capacity allowed by regulations in most below, dry, and critically dry years—leaving little room for additional exports under existing regulations.[74] The challenge is developing cost-effective means to store and move more water in the relatively few wet years, given little opportunity to store more water in the majority of the other years.

Key takeaways from 2017

- In wet years, uncaptured outflow is high. Ecosystem outflow is also high, but abundant Delta inflow reduces its impacts on exports. System outflow demands are a relatively small share of Delta inflows.
- During wet years, surface storage fills quickly. In addition, upstream reservoirs must release large volumes of water to maintain flood reserves. This adds to the high inflows to the Delta.
- In wet years, exports can fall below the amount allowed by regulations due to a lack of capacity to get water to suitable storage locations south of the Delta. This indicates an opportunity to store more water south of the Delta—around 0.4 maf or more in each wet year—with improvements in groundwater recharge.
- Similarly, opportunities exist in wet years to capture and move water to storage upstream.
- Exporting the full amount allowed by regulation during wet years will have minimal impact on Delta outflow volumes and timing, and is unlikely to create measurable environmental effects. There may also be potential for “above normal” years to yield more water, but such years are rare and have not been analyzed.

Implications for Policy and Management

Our analysis shows how the availability and use of water in California’s largest watershed have evolved since 1980. Two important changes have occurred over this period. First is the dramatic shift in climate, with warmer conditions over the past two decades, and the increasing thirst of the atmosphere—including some extreme drought conditions that were not envisaged when the water system was developed. Second is the adoption of a complex, overlapping, and sometimes conflicting or inconsistent mix of environmental regulations since 1995 that affect not only the volume of water allocated to the environment, but also how water is managed throughout the watershed.[75] These regulations—mostly developed for the historical climate—are also struggling to keep up as the climate seems to be changing faster than the regulatory process can adapt.

The severe drought that California is now facing—coming so soon on the heels of the record-breaking 2012–16 drought—underscores the importance of adapting water management in the Delta watershed to the changing climate. Our analysis highlights four broad areas for action.

1. Continue to Improve Delta Water Accounting

There have been some significant advances in water accounting since the last drought. Legislation enacted in 2015 (Senate Bill 88) requires most surface water users to regularly measure and report diversions. The 2014 Sustainable Groundwater Management Act requires groundwater sustainability agencies to develop water budgets for local basins—accounting for both groundwater and surface water use—and to report annually on key metrics

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[73] Indeed, the last above-normal year was 2005.

[74] The exceptions to exporting at the export limit in these years are usually for maintenance or repairs.

[75] Examples include the conflict between the 2019 BiOps and the CDFW ITP (Box A5), and inconsistent outcomes of regulations based on water year type that should really be based on a continuum, such as the fall X2 and the San Joaquin River inflow-to-export ratio (Box A4). In addition, there are very difficult tradeoffs to manage in dry years (when there is limited water held in storage) between the need for stored cold water in the summer and fall for salmon and the need for spring outflow for Delta smelt; this has resulted in TUC orders in 2014 and 2015 and again in the current drought.

(Escriva-Bou et al. 2016). The State Water Board has also been developing a "water unavailability" modeling framework for the state's rivers and streams, to better anticipate when supplies will need to be curtailed during droughts (SWRCB 2021b and 2021c). And the Department of Water Resources has been developing new methods for assessing water use in the Delta (Box A3).

While this all reflects important progress, the pace of change in the Delta watershed makes it imperative to redouble efforts in tracking upstream and in-Delta uses. During the current drought, these two categories have accounted for the vast majority of runoff in the watershed—indeed, *all* runoff in 2021—yet they are the least well measured components in the water accounts. What's needed is not only more frequent and accurate tracking of diversions (building on SB 88 requirements), but also explicit tracking of discharges and return flows—something not currently required of agricultural water users.[76] These improvements are essential for responding effectively to drought in the Delta, and technologies are available to help implement them cost-effectively.[77]

2. Integrate Severe Droughts into Regular Management Practices

Management of water in the Delta and its watershed has relied heavily on historical hydrologic data for operations planning and forecasting and for setting regulations. But conditions have changed, and today's warmer, more intense droughts fall outside the bounds of those conditions. As these more intense droughts become more commonplace, it's become routine to rely on emergency measures to manage them—with emergency declarations to facilitate actions to relax regulatory standards, order curtailments, and install salinity barriers.

The downside of relying on emergency authorities is that they can still involve disputes, delays, and less effective outcomes than might have been possible with more routine practices. The state should pivot in this direction, with the goal of being able to act earlier to manage reservoirs, curtail diversions, and adapt outflow and salinity requirements, without having to resort to TUC orders and other emergency authorities. Priorities include:

- **Adapt forecasting to incorporate more realistic drought conditions.** Using recent hydrology, and incorporating synthetic drought conditions, can help determine earlier in the water year the likely risks of not meeting water quality, flow, and other environmental requirements, and identifying management options. DWR is working on improving forecasting (DWR 2022), but more timely reporting of diversions and return flows (recommended above) would greatly enhance the ability to forecast shortages.
- **Develop decision trees to help anticipate possible actions.** These forecasts can be used to lay out pathways for water management and allocation decisions under severe drought—such as curtailments and environmental water allocations—that can be updated as conditions evolve. Curtailments are likely to become more commonplace and giving water users more advance warning of their possibility will help them manage this risk. Charting out options for environmental water use with an environmental watering plan can provide similar support to environmental managers (Mount et al. 2017).
- **Improve the ability to curtail diversions.** CVP and SWP export contractors are curtailed significantly during droughts. The State Water Board's ability to curtail other water diverters has improved since the 2012–16 drought, and the new water unavailability modeling tool that is being updated and improved continuously—along with better data on upstream diversions—should help make action more timely. Addressing gaps in coverage is another priority. In particular, senior contractors with the CVP and SWP have longstanding contracts with USBR and DWR that limit cutbacks.[78] These limits were developed when the hydrology of the basin was quite different, and the volume of Delta outflow needed for salinity control

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[76] Improvements in diversion tracking should include diversions upstream of the rim dams that may affect inflow to the dams; this is key for improving estimates of unimpaired runoff in the watershed in dry years.

[77] For instance, remote-sensing technologies are proving useful as a way to track crop water use in the Delta (Medellín-Azuara 2018, Melton et al. 2021). Return flows in the Delta mainly consist of water pumped off the islands; tracking electricity use and local tide levels could provide good real-time estimates of these flows.

[78] The CVP's Settlement and Exchange Contractors are supposed to receive at least 75 percent of their contracts, even during severe droughts. The SWP's settlement contractors can be cut as low as 50 percent, but the cumulative cutbacks are not to exceed 100 percent over seven years.

was woefully underestimated.[79] In today's Delta, more flexibility is warranted.[80] With changing conditions, it may also become necessary to curtail senior in-Delta uses in some years.[81]

- **Consider a permanent, operable salinity barrier.** The barriers put in place in 2015 and 2021 improved salinity in the central and south Delta and substantially reduced the required outflow to keep the Delta fresh, and the barrier is being used again in 2022. To cope with more frequent, severe droughts, it is worth assessing the merits of installing a permanent, operable barrier in the Delta. Studies are needed to determine the barrier's biological effects, and how it would work at higher pumping rates.

3. Modernize and Simplify Regulations to Provide Water for the Environment

One of the greatest challenges in our accounting effort was identifying how the complex array of overlapping state and federal regulations have evolved over the past 25 years, and how they have affected the amount of water allocated to the environment—allocations that can change dramatically for different water year types (Box A4). The mix of regulations is unnecessarily complex, rigid, and not always logical. We recommend that regulators consider actions to:

- **Shift away from water year types.** One central change needed is to pivot from a system where regulatory requirements can change abruptly with subtle changes in conditions (or not change at all despite significant changed conditions)—now a feature of many regulations, including those based on water year type—to a system that operates on a continuum based on month-to-month hydrology.
- **Shift toward more flexible rules.** Also key will be to shift from highly prescriptive regulations—such as rigid inflow/export ratios or Old and Middle River flow requirements—to allow more flexibility for managers to adapt to real-time hydrologic conditions. Although contentious in some circles, the 2016 WIIN Act and the 2019 BiOps (Box A5) both aimed to provide this kind of flexibility—though with a narrow focus on water exports. What's needed is more flexibility for both environmental water management and water users.[82]

The State Water Board is doing a comprehensive revision of its water quality control plan for the Delta and the state and federal government are cooperating on a reconsultation over endangered species protections governing operations of the CVP and SWP (e.g., Biological Opinions, Incidental Take Permits). This is an opportunity to simplify and coordinate regulations, make them more rational, and adapt them to rapidly changing hydrologic conditions.

4. Prepare for Wet Years

Increasing intensity of dry periods makes it all the more important that the state not only adopt dry-year strategies, but wet-year strategies as well. And it is important to keep in mind that wet periods—like 1995–99—are likely to occur again. Our analysis highlighted how constraints on the capacity to move and store more water south of the Delta preclude exporting the full amount allowed by current regulations in wet years. Increasing the amount of water stored during wet periods—whether by diverting more water upstream of the Delta or making the best use of export facilities—must be done with care for the environment and other water users. But our results show that there is potential to do a better job of storing water during wet years without harm.

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[79] USBR's estimate in 1962 was that 1,500 cfs—or about 1.1 maf per year—would be adequate to control salinity for the export pumps at Tracy (DWR 1962, p. 64). (At the time there were no separate standards for in-Delta uses.) In critically dry years, when the standards are least stringent, we estimate a minimum of 2.6 maf is required to meet the Tracy standard for export water quality, and a minimum of 3.6 maf including standards for in-Delta agriculture and M&I uses.

[80] The pathways could involve resetting contract terms, or formalizing processes for voluntary lowering diversions below contractually obligated volumes, as has been occurring during the current drought, especially in 2022.

[81] Many of these users have riparian rights, which are senior to appropriative rights held by most other surface water users in the watershed. However, riparian rights are only available when there is sufficient natural streamflow, and this may not be the case in some months during dry times (as in 1991); when there is a shortage it is shared among all the riparian users.

[82] As a governance option, Mount et al. (2017) propose an ecosystem water trustee to have oversight over the environmental water.

Taking advantage of these opportunities will require improvements in conveyance and storage infrastructure, and collaborative approaches among multiple parties (Escriva-Bou et al. 2020). While there may be some scope for the cost-effective expansion of surface storage capacity, groundwater recharge is likely to provide the greatest promise in this regard.

Beyond the wettest years, managers will need to adapt how they manage water storage in the Delta watershed in a warming climate, with more rain and less snow. Strategies to make the most use of surface reservoir capacity will be increasingly important (Escriva-Bou et al. 2019, Hanak et al. 2021). Managing surface and groundwater together can increase their combined potential, while helping manage increasing flood risk. Moving some water from reservoirs into groundwater basins for dry years will be especially valuable. Another promising strategy is using advanced weather forecasting technology to update dam operations, enabling managers decide the best course of action under rapidly changing conditions, such as when to release water to protect downstream areas from flooding, move water to groundwater basins, or keep water in reservoirs for later use. All of these strategies have implications for how water is used within the Delta for both water supply and the environment.

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Acknowledgements

We wish to acknowledge many individuals whose assistance was extremely valuable in preparing this study. Brian Gray, Les Grober, Paul Hutton, Leah Orloff, and Ted Sommers provided very helpful reviews on an earlier draft. Alvar Escriva-Bou served as lead reviewer and provided overall guidance on the project. Gokce Sencan provided tremendous help with developing the figures and preparing the spreadsheet for publication. Sarah Bardeen provided very helpful editorial support. Greg Gartrell would also like to thank Richard Denton, Tariq Kadir, Shey Rajagopal, Greg Reis, Bill Fleenor, and Bob Suits for help in providing and clarifying sources of some of the data used in this report. The authors alone are responsible for conclusions and recommendations, and any remaining errors or omissions.

This publication was developed with support from the S. D. Bechtel, Jr. Foundation. Research publications reflect the views of the authors and do not necessarily reflect the views of our funders or of the staff, officers, advisory councils, or board of directors of the Public Policy Institute of California.

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