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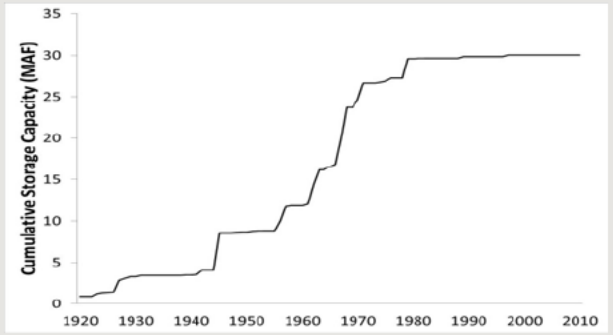
DWR-1385

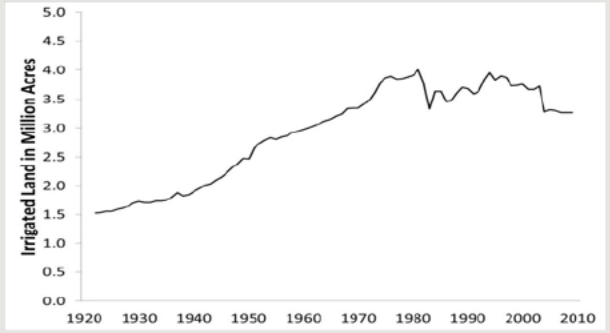
DELTA OUTFLOW & SALINITY:

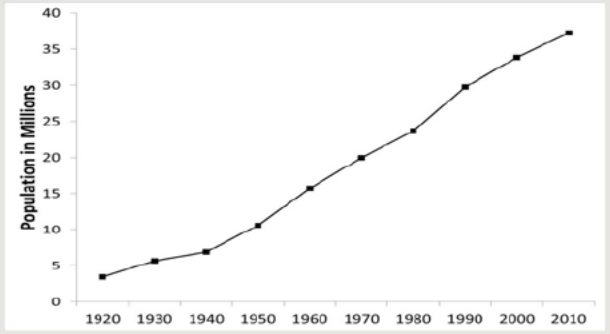
BASELINE, TRENDS & CHANGE ATTRIBUTION

California WaterFix Change Petition, Phase 2 Rebuttal Testimony
Paul Hutton, Ph.D., P.E.


Cumulative Storage Capacity (MAF)
0
5
10
15
20
25
30
35
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010


Shasta Dam - Shasta Lake - Mount Shasta
California, USA
April 18, 2006
Photo by Eric Cassarino
ShastaLake.com


Irrigated Land in Million Acres
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010


Population in Millions
0
5
10
15
20
25
30
35
40
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Nine Decades of Salinity Observations in the San Francisco Bay and Delta: Modeling and Trend Evaluations

Paul H. Hutton[1]; John S. Rath[2]; Limin Chen[3]; Michael J. Ungs[4]; and Sujoy B. Roy, A.M.ASCE[5]

Abstract: The position of the low salinity zone in the San Francisco Bay Delta—given its correlation with the abundance of several estuarine species—is used for water management in a system that supplies water to more th ecosystems on the Pacific coast. This work consolidates legacy and modern sal spanning nine decades. The position of the low salinity zone, which is effectivel to support data cleaning and filling, reveals statistically significant trends con of upstream reservoirs, e.g., increasing salinity trends in wet months and decre particularly apparent in drier years, with greater seasonal variability in the earl the watershed. These data provide a basis for further analysis of how and why t over time. DOI: 10.1061/(ASCE)WR.1943-5452.0000617. *This work is made avai 4.0 International license, http://creativecommons.org/licenses/by/4.0/.*

Introduction

Freshwater inflows have a direct influence on the salinity structure in estuaries. In the San Francisco Bay, the salinity structure has been related to the health of estuarine species in the Suisun Bay and the western Delta (Fig. 1). In particular, the location or position of two parts per thousand (ppt) bottom salinity—hereafter referred to as X2—has been correlated with the abundance of several species (Jassby et al. 1995). Using data collected over different time periods, the low salinity zone in general and the X2 position in particular have been associated with the greatest abundance of pelagic organisms, including the protected longfin smelt (*Spirinchus thaleichthys*) (Jassby et al. 1995) and the Delta smelt (*Hypomesus transpacificus*) (Feyrer et al. 2011). The X2 position has also been associated with the abundance of undesirable species such as the invasive Asian clam (*Corbula amurensis*). The relationship between the low salinity zone and the responses of individual species are a topic of continued research interest (Feyrer et al. 2007, 2011; Kimmerer et al. 2009; Moyle et al. 2010), and the broader science underlying the driving mechanisms between water quality, habitat quality, and species abundance continues to evolve (Reed et al. 2014).

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A hybrid empirical-Bayesian artificial neural network model of salinity in the San Francisco Bay-Delta estuary

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ABSTRACT

This paper reports the refinement of a published empirical model of salinity in the San Francisco Bay-Delta estuary by integration with a Bayesian artificial neural network (ANN) model and incorporation of additional inputs. Performance goals established for the resulting hybrid model are based on the quality of fit to observed data (replicative and predictive validation) as well as sensitivity when compared with a *priori* knowledge of system behavior (structural validation). ANN model parameters were constrained to provide plausible sensitivity to coastal water level, a key input introduced in the hybrid formulation. In addition to representing observed data better than the underlying empirical model while meeting structural validation goals, the hybrid model allows for characterization of prediction uncertainty. This work demonstrates a real-world application of a general approach— integration of a pre-existing model with a Bayesian ANN constrained by knowledge of system behavior—that has broad application for environmental modeling.

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1. Introduction

Artificial neural networks (ANNs) have seen growing application in the modeling of water resources and water quality processes over the past two decades. Reviews by Maier and Dandy (1996), Maier et al. (2010), and Wu et al. (2014) have documented more than 300 publications on the field, and readers are referred to these papers for a broad discussion of potential applications. ANN models are particularly attractive because they can be developed using standardized approaches even where mechanistic representations of a system are unavailable, prohibitively expensive computationally, or are too complex to formulate. As empirical formulations, ANN models are based on data that can be directly observed or simulated, as opposed to abstract processes that are embodied in mechanistic models. To develop such models, sufficient data must be available on the dependent variable of interest as well as independent variables known to affect the dependent variable, and appropriate software must be utilized to encapsulate these relationships through a data fitting (or calibration) process. This data fitting process is commonly referred to as "training", during which the adjustable parameters of an ANN model are estimated using error-minimization algorithms. Data are generally partitioned for training, with a fraction set aside for model validation. A successful model fit matches both the training and validation data. These steps are common to most modeling efforts, whether ANN-based or mechanistically-based, and have been termed "replicative" and "predictive" validity, respectively (Wu et al., 2014).

With the growing maturity of ANN applications in the literature, it has become clear that the "black-box" model relationship between inputs and outputs embodied in ANNs may not adequately represent the physical system being modeled (Jain et al., 2004; Kingston et al., 2005a). Thus, a trained and validated ANN model may fit the aggregate response to multiple inputs well, even though the sensitivity to a specific input is not physically meaningful, or in some cases, not physically plausible. The condition of representing inputs and outputs in a manner that is physically plausible, given an *a priori* understanding of a system, is termed "structural" validity (Wu et al., 2014). For a model to be successful under a wide range of future conditions, both predictive and structural validity are necessary prerequisites and have been the focus of a small subset of recent ANN applications (Jain et al., 2004; Kingston et al., 2005a; Jain and Kumar, 2009). Assessment of predictive validity is often the main criterion in the development of ANN models, as noted in a review of recent literature on water quality-related models by Wu

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WILEY

RESEARCH ARTICLE

Freshwater flow to the San Francisco Bay-Delta estuary over nine decades (Part 1): Trend evaluation

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Funding Information
Metropolitan Water District of California; (California) State Water Contractors and the San Luis & Delta-Mendota Water Authority; U.S. Department of Agriculture, National Institute of Food and Agriculture, Grant/Award Number: 2014-67003-22077

Abstract

The San Francisco Bay-Delta estuary and its up exploration and settlement by Europeans in t alterations supported the growth of California have been accompanied by significant decline to reverse these declines through flow manage ment of freshwater flows to the estuary, we ex evaluate seasonal and annual trends in reported observed in seasonal outflows, with decreasing and November) and increasing trends observed in early-to-mid autumn (September and Octobe in-Delta agricultural water use. In spite of inc found no statistically significant annual trend i annual variability. Linkages between outflow tr developments such as reservoir construction an expansion of irrigated agriculture are discusse change attribution is explored using modelled

KEYWORDS
Central Valley, Delta outflow, Mann-Kendall, t

1 | INTRODUCTION

Estuarine ecosystems worldwide are subject to a variety of stressors, including pollutants, invasive species, habitat loss, and hydrologic alteration (Kennish, 2002). International restoration efforts are ongoing in response to these stressors, with the recognition that impacts to many ecosystems are a consequence of multiple interacting factors that are often poorly understood (e.g., Elliott, Burdon, Hemingway, & Apitz, 2007; Kennish, 1999; Thom et al., 2005; Williams & Orr, 2002). The desired restoration target or baseline is an important consideration in structuring flow regulations and other restoration actions. Because of the general absence of direct observed data from pre-development periods, restoration targets are typically guided by earliest available records, even when it is recognized that these observations reflect some degree of al are themselves no cept termed shifti Conley, Carstens 2011; Wagener et The San Fra California (Figure management effo stressors (Harak, are of great practi and economic de Moore, 2015). W significant fraction has been the stre

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RESEARCH ARTICLE

Freshwater flow to the San Francisco Bay-Delta estuary over nine decades (Part 2): Change attribution

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Funding Information
U.S. Department of Agriculture, National Institute of Food and Agriculture, Grant/Award Number: 2014-67003-22077; Metropolitan Water District of Southern California; California State Water Contractors and the San Luis & Delta-Mendota Water Authority

Abstract

This paper explains observed trends in freshwater flow to the San Francisco Bay-Delta estuary as reported in a companion paper (Hutton, Rath, & Roy, 2017). We employ a historical hydrologic record spanning nine decades and define a set of idealized flow scenarios to identify drivers of change in delta outflow and consequent salinity regime. Flow changes are measured against a baseline scenario representing 1920-level land use and water management conditions. Additional scenarios are defined to represent the system absent state and federal water project reservoir and export operations, absent key non-project reservoir operations, and absent historically-observed sea level rise. These scenarios, in conjunction with the principle of superposition, are used to ascribe outflow and salinity trends to different anthropogenic and natural causes. We find that project and non-project water management are attributed similar responsibility for decreasing outflow trends in April and May and consequent increasing spring salinity trends. In contrast, we find that increasing July and August outflow trends (and lagged decreasing salinity trends) are attributed to flow contributions from project water management; these contributions more than fully attenuate impacts associated with non-project water management.

KEYWORDS
Delta outflow, Mann-Kendall, reservoir operations, trend attribution

1 | INTRODUCTION

The San Francisco Bay-Delta estuary (or "Delta") on the Pacific coast of California, United States and its contributing watershed have been subjected to extensive hydrologic alterations following European settlement in the mid-18th century (Hundley, 2001). These changes have included conversion of natural lands to irrigated agriculture, disposal of hydraulic mining debris into streams, channelization of streams, widespread loss of riparian and tidal wetland habitat, withdrawals of streamflow for irrigation and urban uses, and construction of reservoirs to store winter and spring flows for release in the summer and fall months and other low flow periods. Some of the earliest changes have adversely affected downstream communities in the watershed for well over a century; examples include increased flooding risk due to hydraulic mining waste disposal (Kelley, 1998) and salinity intrusion in the Delta affecting agricultural and urban users as a consequence of irrigation withdrawals further upstream (Department of Public Works, 1931).

By the mid-20th century, evolving societal values led to a growing awareness and concern for the adverse ecosystem effects that resulted from anthropogenic disturbances. In addition to the early hydrologic alterations described above, other evolving disturbances include out-of-basin exports, entry of invasive species and discharges and runoff of pollutants from a highly urbanized estuary margin. Restoration and environmental management efforts have been implemented in the region over the last four decades to address many of these stressors; however, hydrologic alteration (in general) and flow management (in particular) have been the stressor of primary focus. Freshwater flow (i.e., Delta outflow), which is essential for repelling salinity intrusion into the Delta and is critical to the ecosystem health of the estuary, is regulated to support both human uses and aquatic life (CSWRCB, 2006). Precipitation from the upstream watershed is

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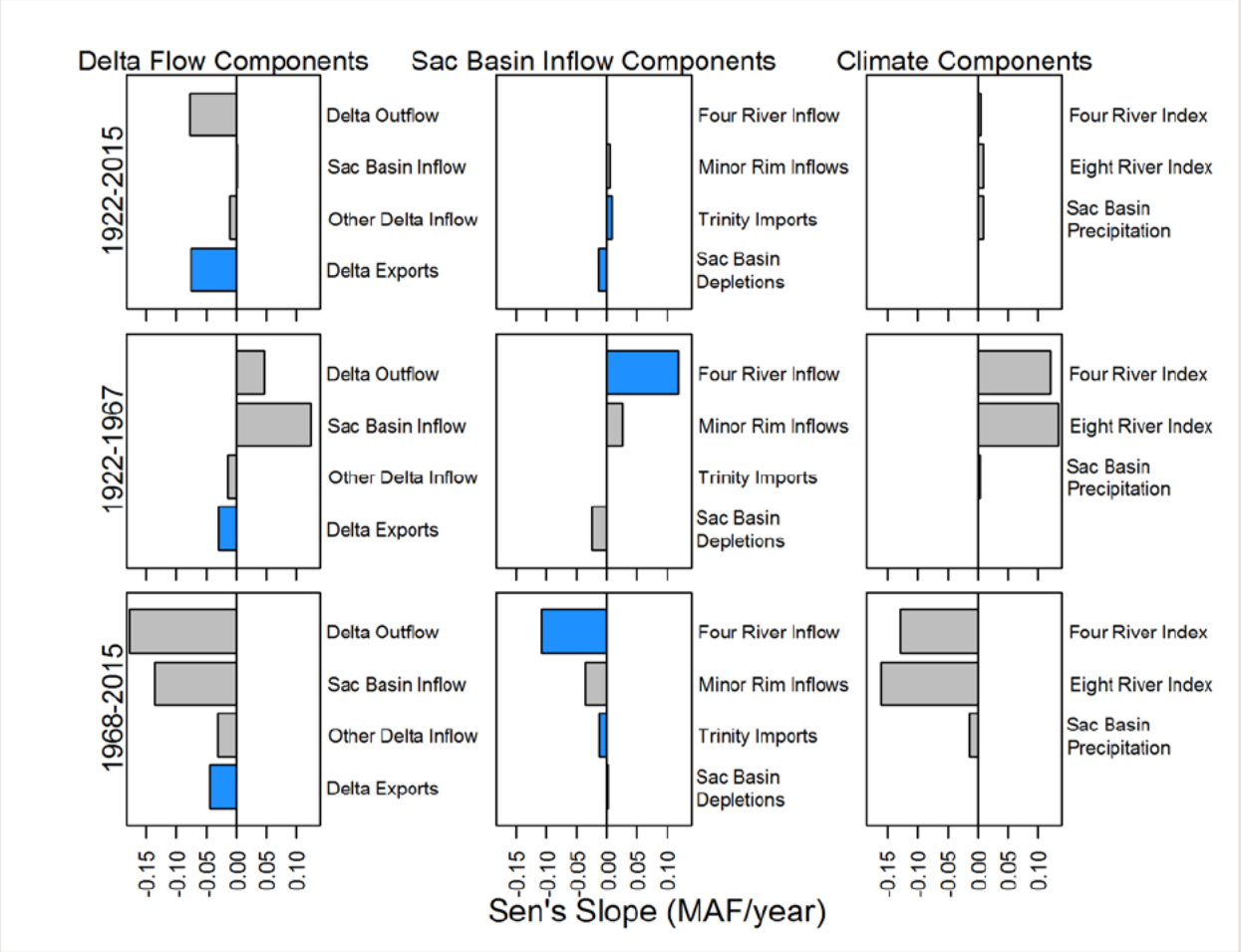
NO SIGNIFICANT ANNUAL OUTFLOW TREND

- **Nominally increasing trend in early part of record; nominally decreasing trend in latter part of record**



Annual Mann Kendall trend and Sen slope results for flow components

NO SIGNIFICANT ANNUAL OUTFLOW TREND (CONT'D)

- **Statistical significance likely masked by large inter-annual hydrologic variability**
- **Decreasing trend noted when normalized to 8 River Index**
- **In drier years, normalized exports and upstream depletions have decreased in latter part of record**

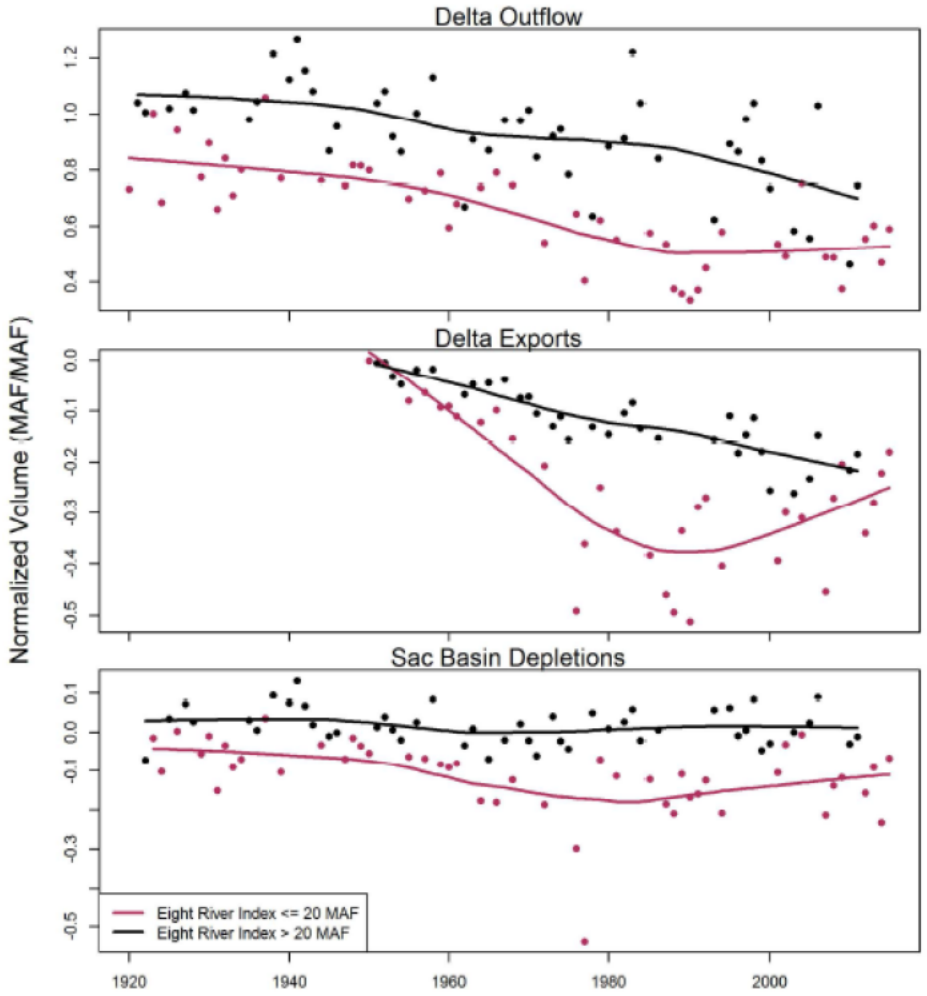
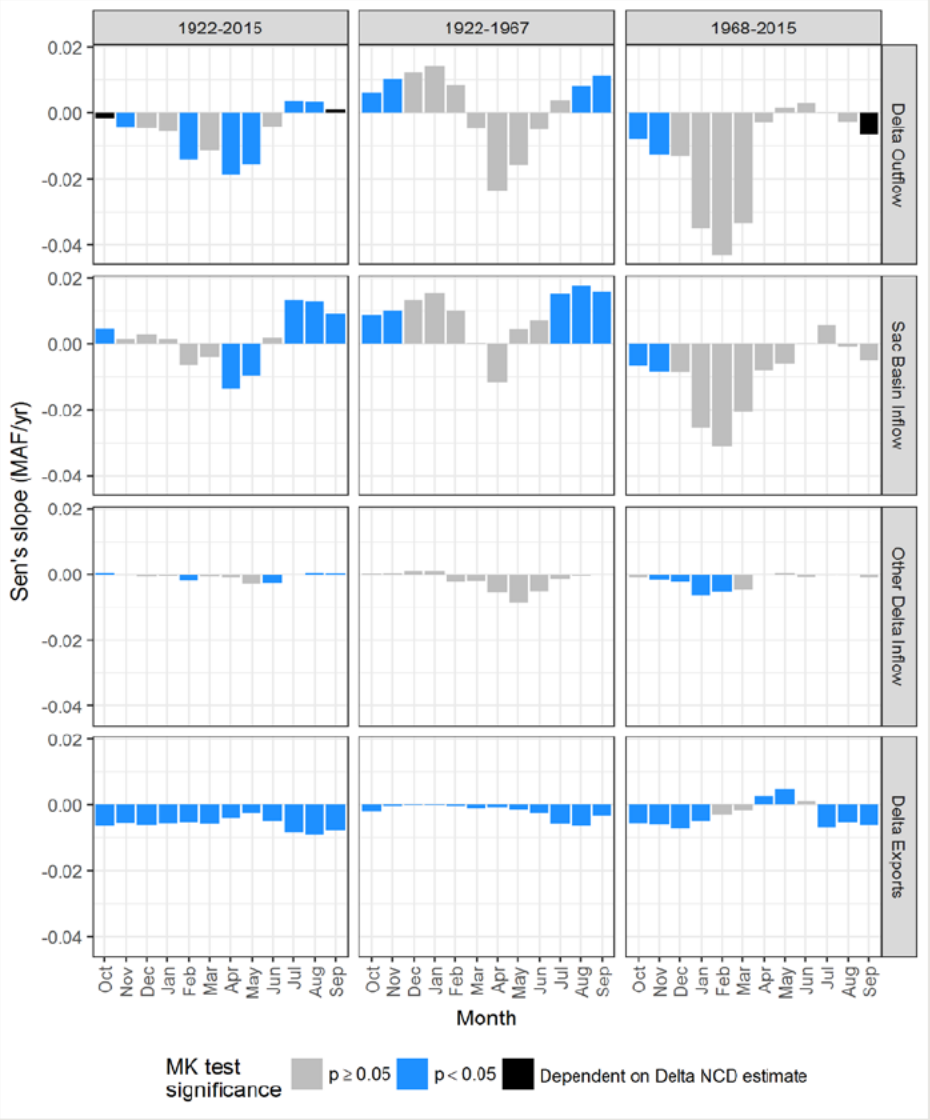


Figure 10. Annual time series of Delta outflow (upper panel), exports (middle panel), and Sacramento Basin net channel depletions normalized to the Eight River Index (lower panel). The trend lines through the points are LOESS fits as described in the text. In drier years, the downward trend in normalized Delta outflow appears to have been curbed (and possibly reversed) over the last few decades due to more restrictive water management (i.e. lower normalized Delta exports) in the estuary and a leveling of water use in the upstream watershed (i.e. flat trend in Sacramento Basin net channel depletions). Increasing volumes of Delta Exports and Sac Basin Depletions are shown as negative trends.

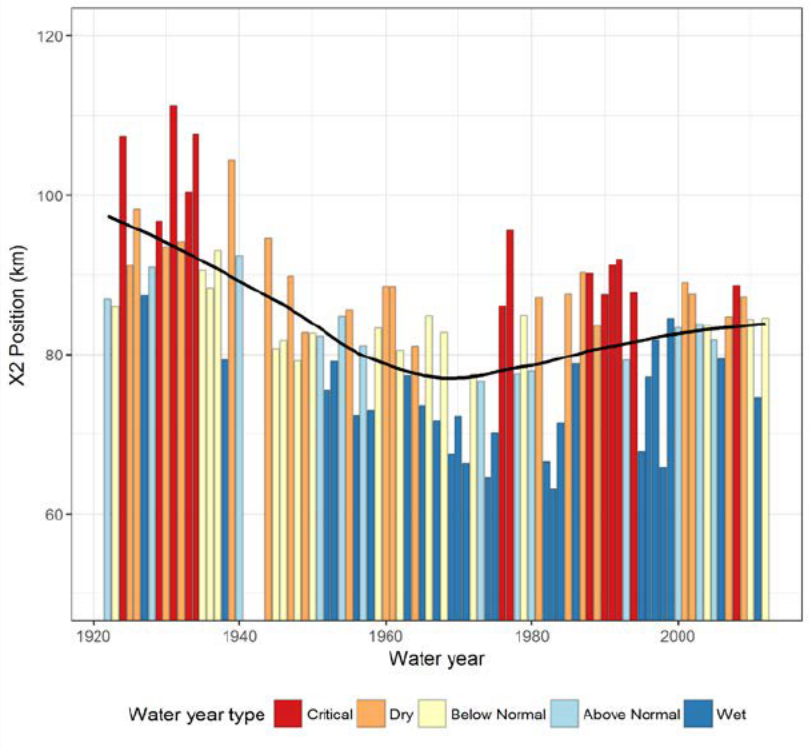
SIGNIFICANT SEASONAL OUTFLOW TRENDS (INCREASING & DECREASING)

- **Decreasing outflow in February, April, May & November**
- **Increasing outflow in July and August**
- **Trends in early (WYs 1922-67) and latter (WYs 1968-2015) part of record are dramatically different**

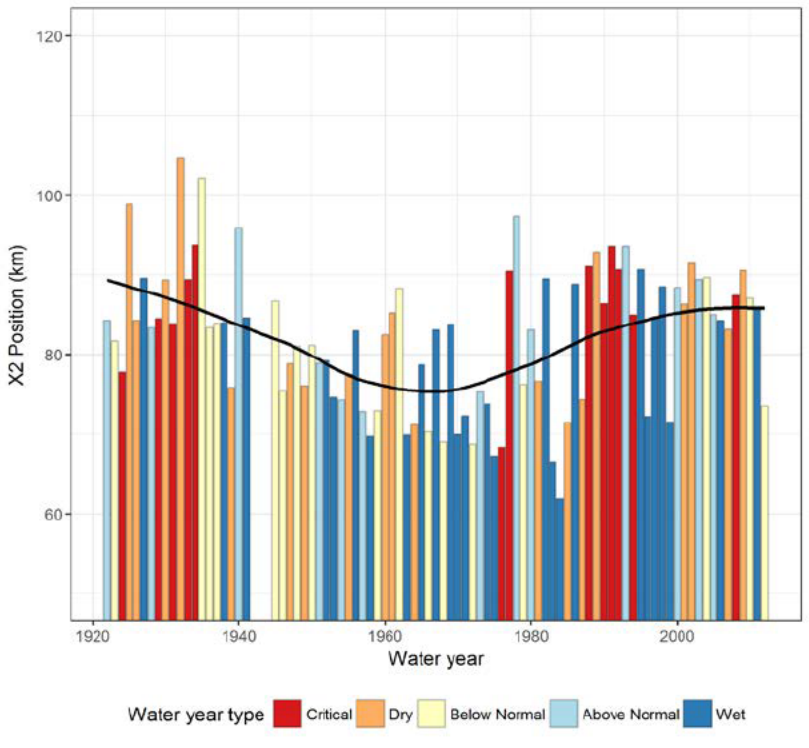


A LONG-TERM UPSTREAM SHIFT IN FALL X2 HAS NOT OCCURRED

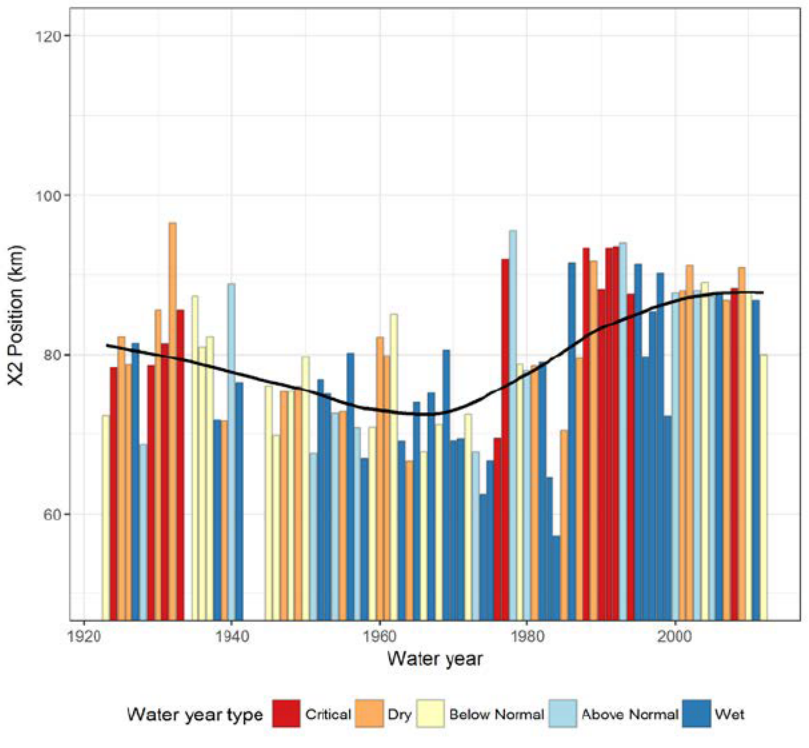
September



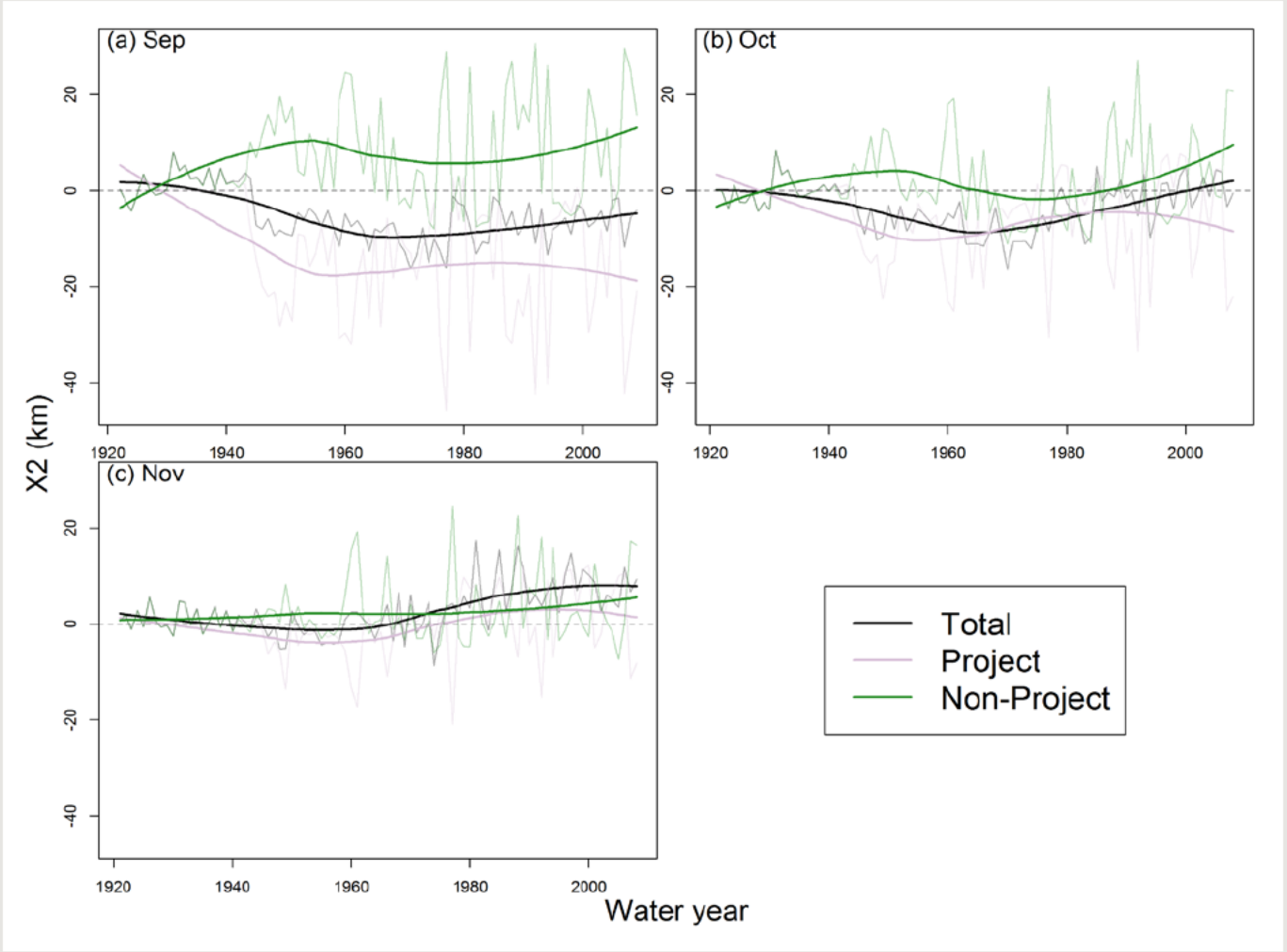
October



November

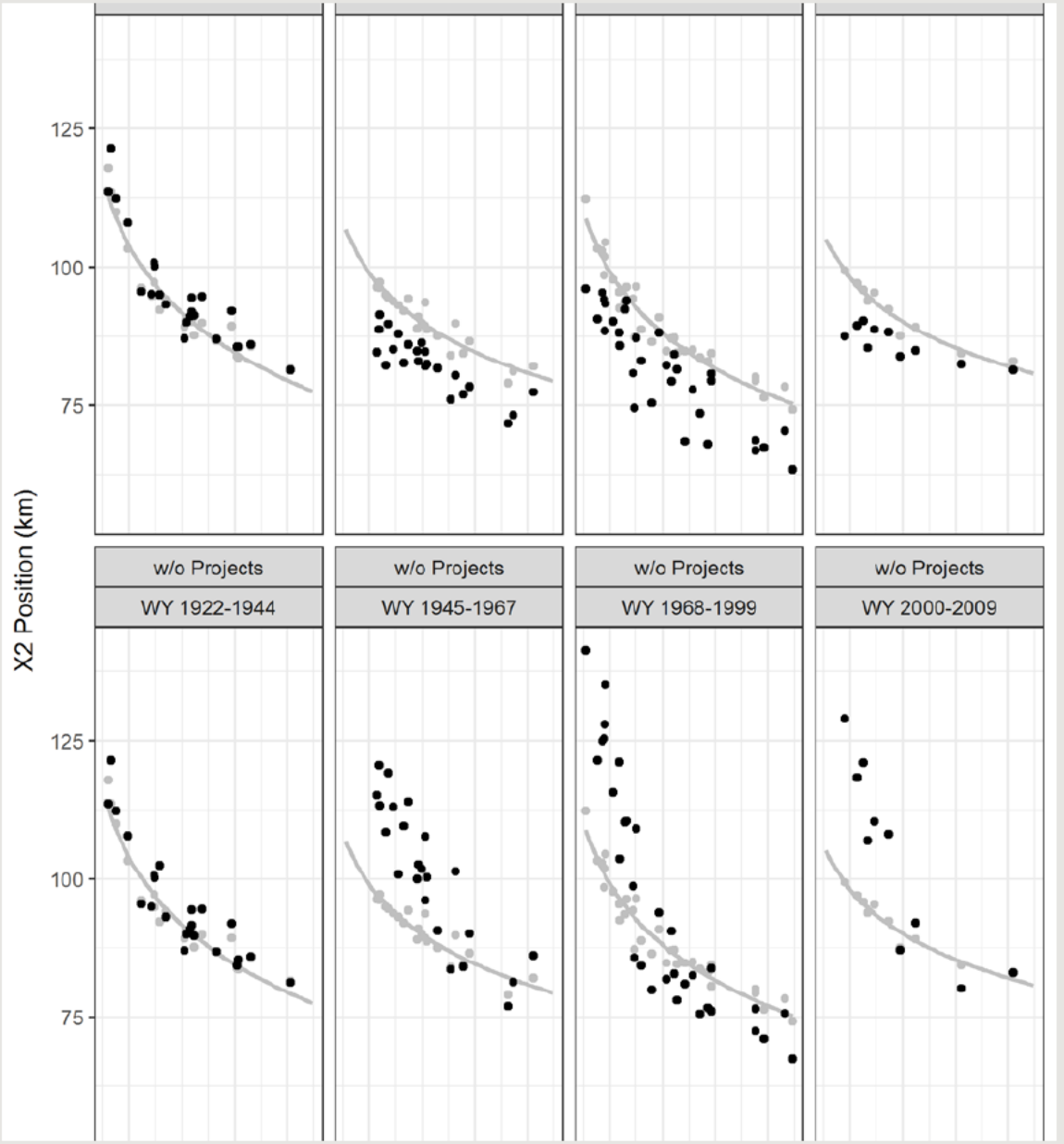


LONG-TERM FALL X2 TRENDS ATTRIBUTED TO MULTIPLE DRIVERS



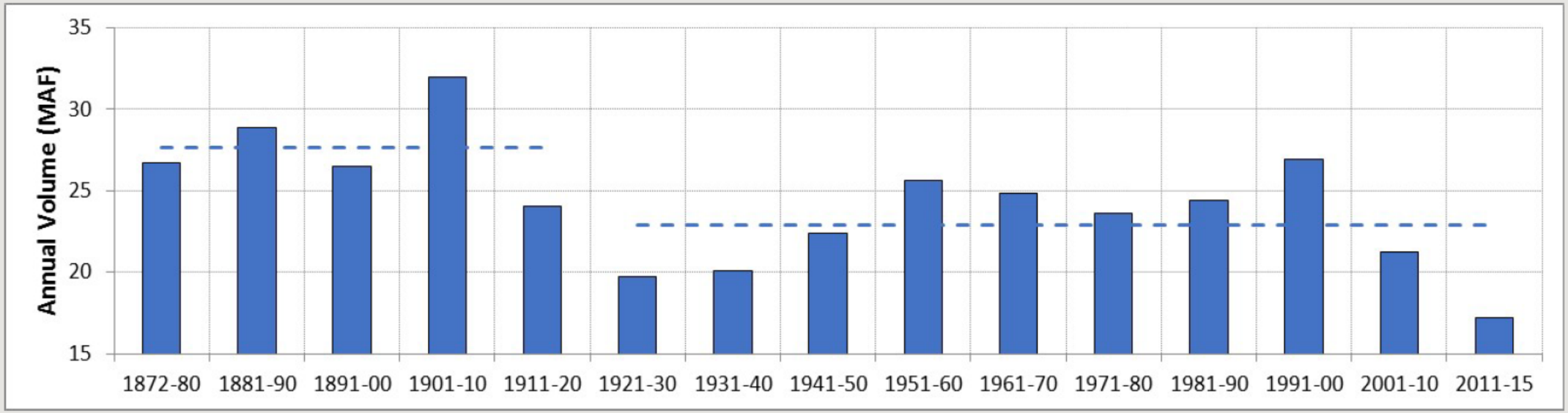
FALL SALINITY IS VARIABLE AND DOES NOT RESEMBLE DRY YEARS REGARDLESS OF HYDROLOGY

- **If there has been a loss of inter-annual variability in fall X2, it is not because all fall months now resemble dry year conditions regardless of water year type.**
- **Rather, CVP-SWP operations have bolstered dry year outflows such that fall X2 (particularly in September and October) now resemble average to wetter years.**



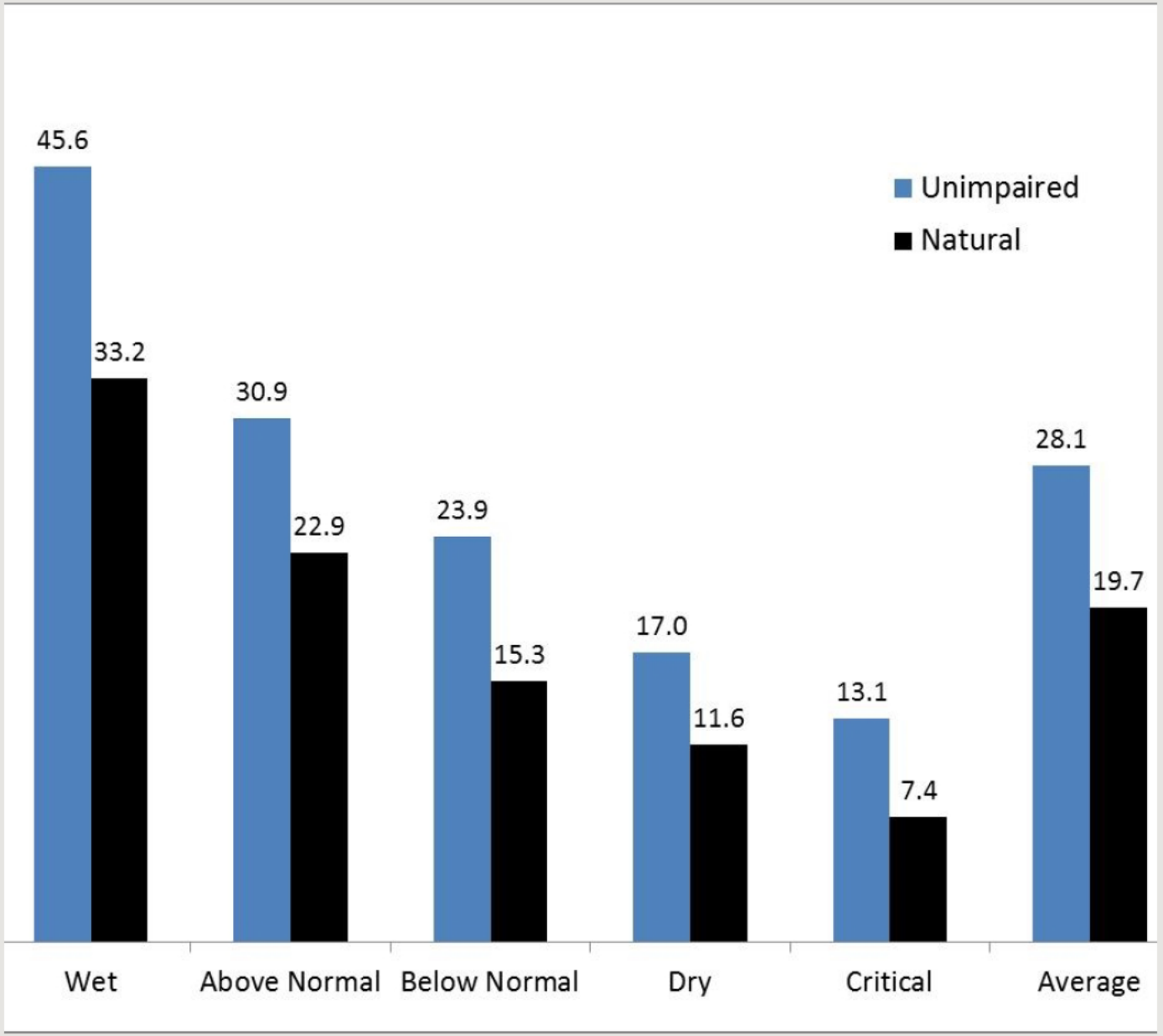
DELTA CONDITIONS IN THE LATTER 19TH AND EARLY 20TH CENTURY PRIOR TO 1917 DO NOT REPRESENT NATURAL CONDITIONS

- **Anthropogenic modifications resulted in a system-wide reduction in ET, likely resulting in higher outflows than would have occurred naturally.**
- **Climatic conditions were much wetter than the subsequent period up to the present.**
- **C&H barge travel data do not provide a representative cross-section of this level of development, let alone represent natural conditions.**



UNIMPAIRED FLOW IS NOT AN APPROPRIATE MEASURE OF NATURAL FLOW ON THE VALLEY FLOOR OR IN THE DELTA

- **Unimpaired outflow is not reflective of the magnitude of the natural outflow to which fish and wildlife have adapted.**
- **Annual unimpaired outflow is more than 40 percent higher than the natural outflow estimate.**



CONCLUDING THOUGHTS

- **The focus on ecological restoration frames the challenges of managing today's Delta squarely in term of comparisons to historical conditions**
- **Biological inferences based on a truncated subset of the historical record are not representative of trends associated with the "full" hydrologic record**
- **Even the "full" hydrologic record is not indicative of natural or pre-development conditions, as well-documented alterations had already occurred by the 1920s**
- **New and relevant scientific baseline information is available and should be considered as part of this proceeding**