San Francisco Estuary & Watershed Science: A Broad Perspective

THE STATE OF BAY-DELTA SCIENCE 2025

Five Perspectives to Advance Science-Informed Decision-Making in the Era of Climate Change and Extreme Events

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ABSTRACT

California's variable hydroclimate is projected to become increasingly volatile in the 21st century. Yet, there is widespread recognition that extreme events, such as record-breaking heatwaves and catastrophic wildfires, are already becoming the new normal. The 2025 edition of the State of Bay–Delta Science (SBDS) presents the current state of the science on climate change and extreme events affecting the Delta and its watershed, and in doing so, generates new insights on knowledge gaps and promising directions for future research. In this essay we present five perspectives to advance science-informed decision-making in the era of climate change and extreme events. To meet these challenges, Delta scientists and decision-makers can leverage the many effective practices that are already in place, such as long-term monitoring programs, collaborative synthesis venues, science-informed decision-making processes, and Tribal and community partnerships. New and sophisticated tools that harness big data are helping to streamline information flows to scientists. Open science practices are facilitating greater collaboration and improving access to more integrated datasets and to models that link different parts of the system. These assets have strengthened innovation and learning across the Delta. Nevertheless, serious challenges remain. Climate change signals can be difficult to detect as a result of the variable hydroclimate. Greater levels of uncertainty as a result of evolving climate models can present challenges for decision-making. Looking forward, the Delta scientific system can help maintain its relevance to natural resource management by strengthening its capacity for collaborative, open, and actionable science. Such an emphasis is required for anticipating and responding to the new climate and weather realities of the 21st century.

KEY WORDS

Drought, wildfire, heatwave, atmospheric river, climate governance, open science

INTRODUCTION

California is a highly populated state of 40 million people, and an economic powerhouse with a $4.1 trillion annual Gross Domestic Product (BEA 2024). It is also profoundly affected by global climate change (Bedsworth et al. 2018). While the Mediterranean climate is naturally variable, it is projected to become increasingly volatile under current greenhouse gas emissions trajectories. Extreme events such as heatwaves, droughts, floods, and wildfires are becoming the new normal (Grenier et al. 2024). This volatility challenges the current infrastructure, resource-allocation models, and science-informed approaches used to govern and manage the state's natural resources. Decision-makers are often forced to develop rapid-response action plans and to declare states of emergency. These reactive responses are often costly, and they leave less time and fewer resources to address the many sustainability challenges that California faces even in the absence of climate change (Franklin and MacDonald 2024). There is growing recognition that California's scientific system—the institutional structures that support the scientific method, including its actors[1], venues, frameworks, tools, and funding—must adapt if it is to remain relevant and useful to natural-resource management in the 21st century (Norgaard et al. 2021; Lee et al. 2024).

The State of Bay–Delta Science (SBDS) is an ongoing synthesis effort by the Delta Science Program to inform science and policy audiences about the "state of the science" for topics relevant to management of the San Francisco Bay and Sacramento–San Joaquin Delta. The SBDS 2025 edition presents seven articles that cover critically important topics for understanding regional climate change and extreme events in the Sacramento–San Joaquin Delta ("Delta" hereafter) and its watershed. The SBDS editorial board invited experts from universities, state and federal agencies, and non-governmental organizations to explore the state of scientific knowledge and how it can inform decision-making. One article sets the scene; four articles address climate change and extreme events that affect the Delta and its watershed (heatwaves, droughts, floods, and wildfires); one article covers related governance systems; another provides perspectives for future directions. Overall, the articles synthesize information across larger geographic scales (e.g., California, the southwestern US) and over longer time-periods (e.g., 50+ years) than those of previous editions (Thompson et al. 2025). Taken together, the articles underscore the need to understand how global climate drivers manifest at regional and local levels, and how these manifestations may exacerbate the already "wicked" problem of the Delta. As described by Luoma et al. (2015), wicked problems like the Delta cannot be solved so much as managed—provided we have the right knowledge and flexible enough institutions. In this essay, the SBDS editorial board builds on themes from the papers in the SBDS

1. 'Actor' refers to a person, group, agency, or institution.

2025 edition by summarizing the Delta Science Program's four grand challenges to Delta science (Box 1) and presenting five perspectives to advance science-informed decision-making in the era of climate change and extreme events (Box 2), so that readers can examine them together.

BOX 1

Four Grand Challenges to Delta Science

The Delta Science Program recently issued a report called "Grand Challenges to Delta Science: Planning for Science in a Dynamic System" (Lee et al. 2024). This report outlines four "grand challenges" to meeting the Delta Plan's coequal goals of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem:

1. "Scientists and managers must anticipate a world in which environmental conditions and regulations may be fundamentally different from those faced today."
2. "Environmental change is outpacing the traditional pace of science."
3. "Flows of scientific information remain decentralized and poorly connected to communities and decision-makers."
4. "Other ways of knowing—especially Traditional Knowledge—remain siloed from decision-making."

BOX 2

Five Perspectives to Advance Science-Informed Decision-Making in the Era of Climate Change and Extreme Events

- **Perspective 1:** Coordinated monitoring is necessary to track system-wide changes over time and across space.
- **Perspective 2:** Numerous innovative and integrative modeling frameworks and techniques are available to help advance climate change research.
- **Perspective 3:** Science that is collaborative, open, and actionable is required for effective climate-change management.
- **Perspective 4:** Science communication about climate change is more effective when tailored to target audiences.
- **Perspective 5:** Climate governance that is anticipatory, adaptive, and flexible is more effective, and can improve science-informed decision-making under climate uncertainty.

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THE SCIENCE OF EXTREME EVENTS IN THE DELTA

The Delta science community increasingly understands that the ecosystem has been systematically changing in various ways (Cloern et al. 2011; Dettinger et al. 2016). Scientists are observing fast-paced changes in the magnitude, duration, timing, frequency, rate of change, and spatial gradient of many environmental conditions (Table 1). These observed departures from historical baseline conditions are prompting studies on a range of potential future scenarios, such as very extreme events (e.g., mega-floods similar to those that occurred in Sacramento in 1862; Huang and Swain 2022) or the combined effects of extreme events (e.g., accelerating sea level rise and storm surge; Thorne et al. 2024). Water infrastructure (e.g., dams, diversions, levees) and resource-management models (e.g., reservoir operations) were built around 20th-century conditions (Hui et al. 2018; CDWR and USBR 2023a), and recent hydroclimate volatility has been pushing the boundaries of what these systems are designed to handle (as described in Box 3).

Table 1 Environmental variability can be described by six characteristics: magnitude, duration, timing, frequency, rate of change, and spatial extent. *Source: Moyle et al. (2010).*

Characteristic	Definition
Magnitude	The amount of change in an environmental condition.
Duration	Persistence in time of a shift in an environmental condition.
Timing	The timing of changes in magnitude and/or location of an environmental condition.
Frequency	The reliability of change in an environmental condition on a daily, seasonal, annual, or decadal scale.
Rate of change	The length of time it takes to establish a shift in an environmental condition.
Spatial extent	The location of a change in an environmental condition.

Box 4 summarizes the key take-aways drawn from the SBDS 2025 edition that address heatwaves, droughts, atmospheric rivers, wildfires, water quality, and climate governance. Box 5 provides definitions of rapidly evolving climate–change terminology.

BOX 3

California's Variable Hydroclimate May Be Pushing the Delta System Beyond its Design Limits

Water managers in the Delta carefully balance the need for flood protection and water supply. However, the rapid intensification of the water cycle may be pushing the system—including water infrastructure and management—beyond its design limits. For example, the period from 1999 to 2023 had numerous multi-year droughts (e.g., 2001–2002, 2007–2010, 2012–2016, 2020–2022), whereas wet winters only occurred intermittently (e.g., 2006, 2011, 2017, 2019, 2023) (Herbold et al. 2022). The wet year of 2017 ended a 5-year drought, and the wet year of 2023 ended a 3-year drought. The above-normal water year of 2024 marked the first time that 2 consecutive wetter years occurred since 1998. While this recent hydroclimate period has anecdotally been very volatile, there is not yet statistical evidence that volatility has increased over time. However, climate projections indicate that volatility will increase with further warming (Gershunov et al. 2025).

Water managers have used many different tools to manage drought in California, including legislative action, such as the Central Valley Project Act and Delta Reform Act; regulatory standards for water quality, such as Water Right Decisions 1485 and 1641; construction of water storage and delivery systems, such as the Central Valley Project and State Water Project; and emergency actions to relax water-quality standards to preserve the ability to export freshwater (Hartman et al. 2025). More recently, water managers have also constructed temporary rock barriers at West False River to protect the freshwater supply from salinity intrusion (Hartman et al. 2025) and adopted flood-managed aquifer recharge strategies to replenish groundwater supplies in natural and working landscapes across the watershed (Marr et al. 2018).

In wet years following multi-year droughts, reservoir operations have largely focused on maximizing storage by capturing surface runoff from atmospheric rivers and spring snowmelt (Herbold et al. 2022). However, maintaining excessively high reservoir levels may leave dams and spillways vulnerable to overtopping or structural damage in the event of high inflows (Swain et al. 2025). Forecast-informed reservoir operations (FIRO) programs—which are being developed by the Center for Western Weather and Water Extremes (CW3E) in partnership with the California Department of Water Resources (CDWR) and others—can address this issue (Ralph et al. 2022). The goals are to improve atmospheric river-forecasting models, to increase the lead time of information that is delivered to reservoir managers, and, ultimately, to help guide decisions on the timing and magnitude of dam releases to create space for forecasted inflows while minimizing water-supply losses.

Moving forward, the Delta requires continuous system design updates to balance the risks of extreme drought and flood. The water-management system is already designed to withstand hydroclimate variability to some extent, but new approaches are needed that offer more flexibility in the face of uncertainty. Water managers may consider using flexible "co-management" approaches that no longer treat drought and flood as separate management issues and can evolve with environmental changes (Ward et al. 2020; Ficklin et al. 2022; Swain et al. 2025).

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BOX 4

Key Take-Aways from the State of Bay-Delta Science 2025 Edition

Droughts: Hartman et al. (2025)

Drought frequency and severity are predicted to increase over this century, with effects that extend beyond the Delta's borders and are likely to exacerbate conflict between competing water uses. Other effects may include decreased survival of migratory fishes, promotion of harmful algal blooms, and salinization of irrigation water. Droughts often catalyze development of new resource-management tools, including regulations, land-use change, infrastructure, education campaigns, hatcheries, and habitat restoration.

Heatwaves: Mahardja et al. (2025)

Air and water temperatures in the Delta are increasing, with heatwaves becoming more frequent and severe. Potential ecological effects include phenological shifts, increased species invasion, and conditions that favor smaller-bodied individuals of many species. People may suffer adverse health effects that range from dehydration and heat exhaustion to lower birth weight, mental-health problems, and increased rates of violence.

Atmospheric Rivers: Gershunov et al. (this issue)

Climate projections suggest an increasingly variable regional hydroclimate. Precipitation is expected to be less frequent overall, but extreme precipitation events will be more frequent and more intense. Atmospheric rivers are expected to carry more moisture and produce more precipitation in the warmer future climate. Extreme precipitation will drive disproportionately more intense runoff events in the Delta watershed. This will be due primarily to the conversion of snow to rain at low- to mid-elevations — a process which is already underway.

Wildfires and Water Quality: Dahm et al. (this issue)

Mega-fires (fires burning areas larger than 25,000 acres) in California are increasingly large, frequent, and severe. The eight largest wildfires in modern state history, all of which were in the Delta watershed, occurred between 2018 and 2024. Mega-fires affect various aspects of water quality, including water temperature, sediment load, dissolved oxygen, nutrient runoff, and organic and metal contaminant concentrations. Water-quality impairment increases linearly with burn area, and exponentially with burn severity. Urban areas are hot spots for pollutant production and transport.

Climate Governance: Rudnick et al. (2025)

The Delta governance system is largely "polycentric," meaning it encompasses numerous resource domains, is distributed across many governing entities, and includes multiple scales of decision-making. The system's responses to climate change can become more efficient and equitable by improving opportunities for learning, innovation, and civic participation. Resolving long-standing conflicts that result from over-allocation of resources (e.g. water and water rights) requires new solutions. Greater levels of scientific uncertainty can be incorporated into decision-making frameworks. Above all, these efforts require greater coordination.

BOX 5

Rapidly Evolving Climate-Change Terminology

The use of climate-change terminology is rapidly evolving. As climate change progresses and scientists continue to document new phenomena, this terminology will continue to change, necessitating continued conversations among scientists and managers to adopt a shared vocabulary that reflects the current state of science. The following list of terms represents the terminology used in the SBDS 2025 edition:

- **Extreme event:** An event with extreme values in the form of maximum observed values in the historical record or those that exceed pre-existing high thresholds (Stephenson 2008). Defining an event as "extreme" is context-dependent because it is relative to the typical range of conditions at a given time or place (e.g., magnitude, duration, spatial extent).
- **Hydroclimate whiplash:** Sudden, large, and/or frequent transitions from very dry to very wet conditions, which are projected to increase as warming continues (Swain et al. 2025).
- **Atmospheric river:** Strong storms that are likened to "rivers" of water vapor in the sky (Newell et al. 1992). Atmospheric rivers typically transport two to three times more water vapor instantaneously than the average instantaneous flow of the Amazon River; these precipitation events are projected to become less frequent but more intense under climate change (Gershunov et al. 2025).
- **Mega-fire:** Catastrophic wildfires with areal footprints that exceed 25,000 acres (10,000 hectares) that result from single or multiple related ignition events (Linley et al. 2022).
- **Mega-flood:** A term intended to communicate the possibility of extreme flood events with magnitudes that exceed those in the historical record (e.g., the 1862 floods in Sacramento; Huang and Swain 2022).
- **Mega-drought:** Multi-decadal drought. While drought has many definitions, a widely accepted verison is "meterological drought" influenced by factors such as low precipitation and high temperature. Other factors such as high wind, high solar radiation, and low relative humidity increase "atmospheric thirst," leading to increased evapotranspiration and drier soils (Hartman et al. 2025, Figure 1).

OVERVIEW OF PERSPECTIVES

Based on emergent themes from the SBDS 2025 edition, the four grand challenges to Delta science (Box 1), and collective years of experience and observations working in the Delta, the SBDS editorial board developed five perspectives that describe actionable steps to advance science-informed decision-making in the era of climate change and extreme events (Box 2). Specifically, the first four perspectives on monitoring, modeling, collaboration, and communication are intended to help advance the Delta scientific system. Such advances are key to improving the science-informed decisions necessary for effective resource management and governance in a complex and changing system, as described in the fifth perspective (Figure 1). Many of the examples provided throughout these perspectives draw from the robust body of Delta research. In such cases, the science community may consider strengthening its support for this work. However, in other cases the perspectives introduce ideas for new approaches or new areas of work that represent promising avenues for further exploration.

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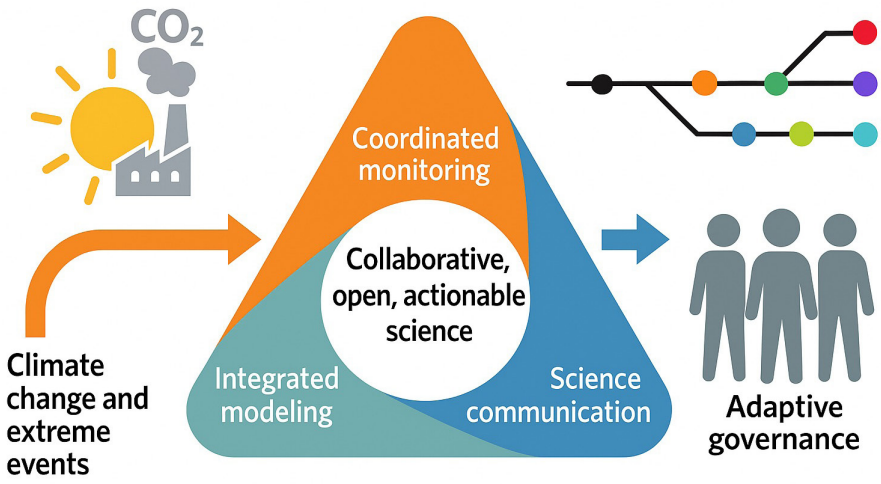

Figure 1 The 2025 SBDS editorial board's conceptual model describing how the five perspectives fit together. Coordinated monitoring of climate-change indicators can help scientists develop robust integrated models to study system-wide change across the Delta and its watershed. Effective communication can help scientists share management-relevant findings to decision makers. The key element of this approach is collaborative, open, and actionable science. These principles and practices can enhance the efficiency of the Delta governance system and facilitate decision-making under uncertainty (depicted as climate adaptation pathways; Haasnoot et al. 2019). *Image credit: ChatGPT.*

PERSPECTIVE 1: COORDINATED MONITORING IS NECESSARY TO TRACK SYSTEM-WIDE CHANGES OVER TIME AND ACROSS SPACE

"In a non-stationary world, continuity of observations is critical."
—*MILLY ET AL. 2008*

State and Federal Monitoring

State and federally mandated monitoring programs are often referred to as the "backbone" of Delta science: Recording physical, chemical, and biological data at regular intervals and stations creates valuable time-series that can be used to track changes over time and across space (Cloern and Jassby 2012). As a result, quantitative studies using monitoring data provide foundational knowledge about departures from 20th-century historical baselines. For example, tremendous insight into the system has been gained via scientists evaluating long-term data for new patterns or outliers. Scientists have detected several regime shifts (or step changes) in environmental trends (Sommer et al. 2023). These include systematic changes in precipitation and unimpaired runoff variability in the Delta watershed (CDWR and USBR 2023a) and in the Pacific Decadal Oscillation (Cloern and Jassby 2012). Similar regime shifts have been detected in biological communities (Tempel et al. 2021). These include the collapse of forage fishes after the invasion of the filter-feeding overbite clam, *Potamocorbula amurensis* (Sommer et al. 2007; Thomson et al. 2010), and the expansion of warm-water fishes after the invasion of Brazilian waterweed, *Egeria densa* (Brown and Michniuk 2007; Mahardja et al. 2017).

Decades of data collection have also provided "lessons learned" about efficiently tracking change over time and across space (as discussed in Cloern and Jassby 2012; Sommer 2020; Sommer et al. 2023). Sentinel stations with long records that represent distinct sub-regions or habitats are particularly important for capturing slower processes that require many time-steps to model (e.g., 20+ years) (Cloern

and Jassby 2012). On the other hand, continuous high-frequency sensor networks are often better equipped to capture the propagation of faster processes that are short-lived, such as water-quality impairments. For example, during the 2022 McKinney fire an atmospheric river produced significant flooding and debris flows, creating anoxic conditions in the Klamath River that resulted in a 95-km fish kill zone (Curtis et al. 2025). A network of continuous, high-frequency water-quality sensors in the river captured this hours-long dissolved oxygen crash. Without the sensors, which are jointly operated by the US Geological Survey (USGS) and the Yurok and Karuk Tribes (see "Indigenous-Led Monitoring"), the resulting fish kill would not have been readily understood (Dahm et al., this issue). In response to catastrophic events such as this one and others (e.g., large winter storms, Gershunov et al. (this issue); harmful algal blooms, Kudela et al. 2023), decision-makers are increasingly looking to scientists to develop early warning systems that can detect change and deliver real-time information on impending threats to the system.

Moving forward, there is a critical need to coordinate system-wide networks designed to monitor key climate-change indicators at sentinel stations across the Delta and its watershed (Sommer et al. 2024). Long-term funding and institutional support for such coordinated monitoring can enable continuity of data collection and analysis, and help to ensure these monitoring networks effectively detect change. Despite the additional costs associated with greater coordination, increasing the region's capacity to respond to system-wide changes is vital to managing the effects of extreme events. State and federal agencies have a range of options for facilitating greater coordination. These include modifying regulatory structures, sharing scientific expertise, and providing resources for data integration (DISB 2022). A good example of coordinated monitoring is the San Francisco Bay Wetlands Regional Monitoring Program (WRMP), which has a governance structure that includes multiple federal and state agencies responsible for estuarine regulation and management (WRMP 2024). The WRMP has developed a suite of standardized metrics that can be monitored by multiple organizations and then integrated into a centralized and publicly accessible data dashboard. The monitoring plan is designed to detect change in wetland ecosystems through repeated surveys, and specifies "indicator thresholds" that, when or where exceeded, trigger management interventions.

Indigenous-Led Monitoring

There is growing awareness in the Delta that Indigenous-led monitoring can be interwoven with predominant science-based monitoring to help inform decision-making (Shinbrot et al. 2025). Indigenous-led monitoring programs provide rigorous, place-based ground-truthing that can complement predominant scientific methodologies (e.g., remote sensing, drones, stream surveys) while centering culturally important indicators such as fisheries and wildlife (Zedler and Stevens 2018). There are good examples in northwestern California, where the Yurok and Karuk Tribal fishery programs have been monitoring riverbeds for spawning of Pacific lamprey (*Entosphenus tridentatus*). These observations, grounded in predominant scientific methodologies, are interwoven with Traditional Knowledge

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(TK) gathered from Tribal elders, to generate new insights on Pacific lamprey life cycles and population declines (Senos et al. 2006). More recently, these fishery programs have started tracking returns of salmon using telemetry methods near former Klamath River dam sites in collaboration with federal agencies and CalTrout (NOAA Fisheries 2024). In these examples, TK is interwoven with predominant science to understand fisheries that are culturally important food sources in the Klamath Basin. However, Indigenous-led monitoring programs across the globe have been shown to provide many additional opportunities and benefits, such as improving: monitoring network coverage (e.g., by filling geographic gaps or increasing temporal resolution), local employment options, intergenerational knowledge exchange, and health outcomes (Reed et al. 2021). Moving forward, there are a range of options for supporting Indigenous-led monitoring in the Delta, such as greater coordination with existing monitoring programs, integration of culturally important indicators into watershed-wide assessments, and long-term funding to help build and sustain monitoring capacity (Shinbrot et al. 2025). Such efforts can be explicitly integrated into climate change research.

Socio-Economic Monitoring

There is also growing awareness that the Delta is lacking a comprehensive monitoring of human dimensions (DISB 2022). In the last few years, efforts have begun to compile census-derived socio-economic characteristics of the Delta population which can be systematically tracked over time (Visser et al. 2018), and to establish a household survey to assess subjective measures of well-being and perceptions of environmental changes and their effects (Rudnick et al. 2023). While these efforts do not yet have support for long-term replication and continuity—nor for integration with environmental and ecological monitoring programs—they are critical to assessing how people living in and relying upon the Delta respond in the face of climate change and extreme events. For example, environmental pressures may affect the socio-economics of residential populations, especially those whose livelihoods and subsistence depend on natural resources. Extreme drought provides a good example because it increases drinking water costs and decreases agricultural production, which negatively affects local economies and labor markets in the Delta (Hartman et al. 2025). Heatwaves also provide a good example because they have direct effects on local residents such as dehydration and heat exhaustion, and indirect effects such as lower birth weight, mental-health issues, and increased rates of violence (Mahardja et al. 2025). Moving forward, quantifying the complex effects of climate change on socio-economic dimensions of the Delta is a priority area of research.

PERSPECTIVE 2: NUMEROUS INNOVATIVE AND INTEGRATIVE MODELING FRAMEWORKS AND TECHNIQUES ARE AVAILABLE TO HELP ADVANCE CLIMATE CHANGE RESEARCH

The Delta's impressive history of scientific progress can be attributed to significant advances in modeling, experimentation, and tool development (Sommer 2020). These advances have shaped the science community's foundational understanding of the system—including past, present, and possible future responses to climate change and extreme events. However, additional and focused research is urgently

needed to meet the Delta's grand challenges (Lee et al. 2024). The modeling frameworks and techniques highlighted in this perspective are innovative and integrative—they can advance Delta science by unifying separate parts of the system in new ways. Many of the frameworks and techniques complement each other (e.g., time-series analysis and multiple-stressors studies); many can be combined in new and creative ways (e.g., spatial analysis and forecasting); some are already used but still deserve much more attention (e.g., integrated modeling); and at least one is promising but still has few example applications in the Delta (e.g., artificial intelligence). Overall, these types of approaches are paving the way for a Delta scientific system that can track and anticipate system-wide changes now and into the future. Each of them represents a promising—and necessary—area for investment in institutional resources, training, and capacity-building.

Time-Series Analysis

In systems like the Delta, where climate change is occurring against a backdrop of tremendous natural variability, time-series methods are particularly useful for parsing signals (predictable variation) from noise (unpredictable variation). Time-series analyses are often used to answer questions about hydroclimate patterns using temperature, precipitation, and discharge data. These methods require data points collected at regular intervals over time and use temporal auto-correlation—the property whereby observations at previous time-steps influence the value of an observation (Shumway and Stoffer 2019). For example, it is generally accepted that water temperature today is more similar to water temperature yesterday than to water temperature a month or a year ago. Understanding temporal autocorrelation, and the different time-scales of variation, are key goals of time-series methods.

Owing to the large amount of long-term, spatially replicated data collected by ecological monitoring programs in the Delta, time-series analyses are also well-suited for answering ecological questions (Cloern and Jassby 2012). Recent examples include studies that quantify the effects of physical drivers such as Delta outflow, temperature, and salinity on the abundance and biomass of zooplankton and fish (Colombano et al. 2022; Pak et al. 2023; Smits et al. 2023). In the case of the commercially valuable Pacific herring (*Clupea pallasii*) fishery in the San Francisco Bay, time-series models have been developed to quantify drivers of population dynamics and risk of fishery closures (Sydeman et al. 2018; Pak et al. 2023). In this case, a forecasting model is used to predict adult spawner biomass for the upcoming winter season, and the fishery is proactively closed when adult biomass is projected to fall below a certain threshold (as a result of the combination of warm ocean temperatures and poor juvenile recruitment), because herring would be vulnerable to over-harvest (CDFW 2019). (See Table 1 in Appendix A for a list of methodologies and examples of their applications.)

Non-Stationarity Concepts

"Everything changes and nothing stands still." —HERACLITUS

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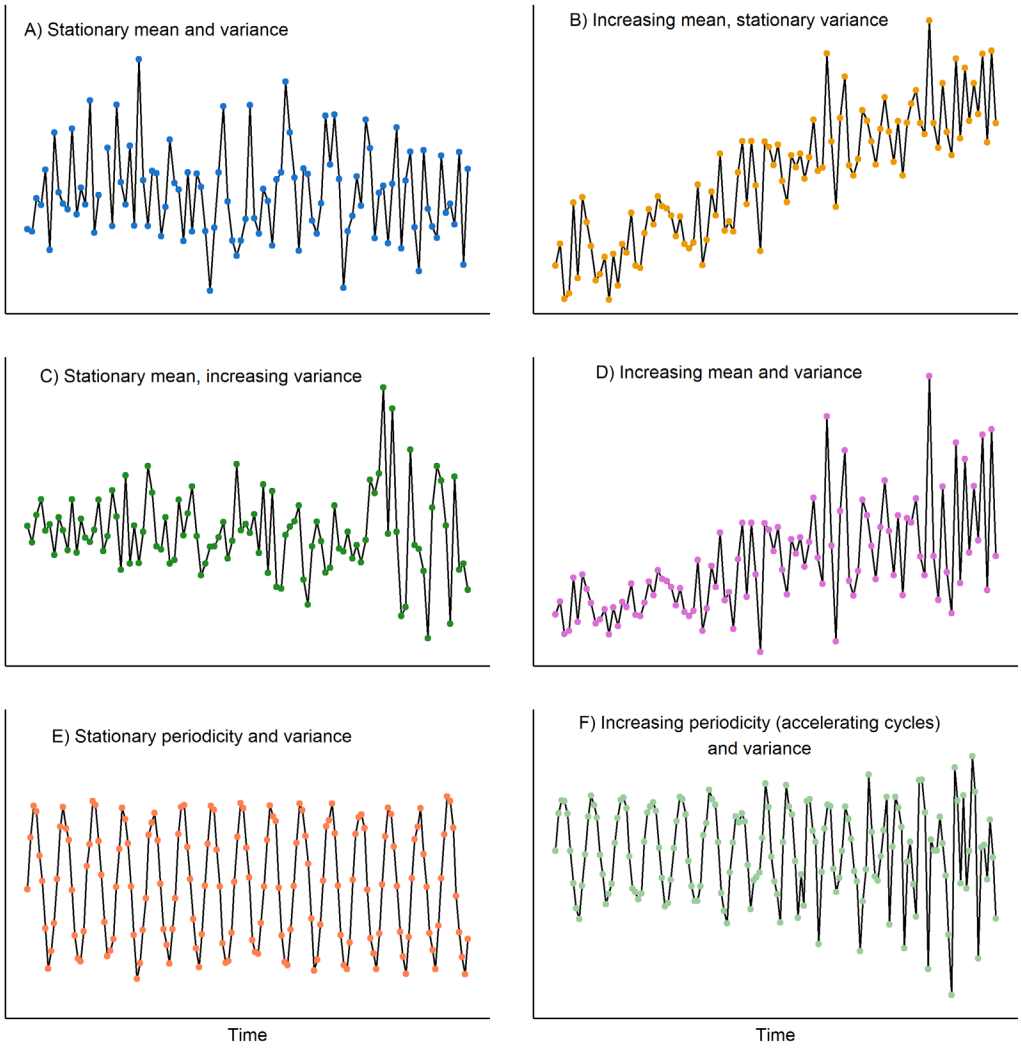

Figure 2 Examples of non-stationary processes. (**A**) Stationary mean (average) and variance (dispersion of points around the mean). (**B**) Increasing mean and stationary variance. (**C**) Stationary mean and increasing variance. (**D**) Increasing mean and variance. (**E**) Stationary periodicity (cycles) and variance. (**F**) Increasing (accelerating) periodicity and variance. Such concepts are important for understanding climate change and extreme events, particularly those resulting from the naturally high variability of the Mediterranean climate, which makes it difficult to statistically parse signal from noise (see Perspective 2, time-series analysis and non-stationarity concepts).

Non-stationarity is a statistical term used to describe time-series with characteristics (e.g., trend, variance, periodicity) that systematically change over time (Figure 2). Trends characterize the long-term increases or decreases over time in the expectation of the mean, whether these changes are linear, nonlinear, gradual, or abrupt. Trends are widespread: For example, a recent analysis of 59,636 water temperature records collected at 405 stations in the Delta from 1969 to 2020 used generalized additive models to estimate long-term trends in the mean; the results showed that water temperatures increased 0.017 $^{\circ}C yr^{-1}$ on average over 50 years (Bashevkin et al. 2022).

In turn, variance characterizes the measure of dispersion, or the spread of data points around the mean. Non-constant variance is observed in the frequency, duration, and severity of atmospheric rivers, where the appearance of a few very strong storms is increasingly responsible for the bulk of annual precipitation and runoff in the Delta watershed (Dettinger and Cayan 2014). This observation

is consistent with historical trends in annual unimpaired runoff in the Feather River (1922–2021), which show significant increases in the standard deviation and coefficient of variation—representing shifts toward wetter wet and drier dry years (CDWR and Reclamation 2023a).

Finally, periodicity (periodic fluctuations in the data) refers to cycles over regular intervals in a time-series, such as seasonal or annual cycles. A good example is California's wildfire season, which typically occurs in the summer dry season. Recent research shows that the fire season is starting earlier in the spring due to earlier snowmelt and lasting later into autumn, resulting in a shift in peak fire activity from August to July (Li and Banerjee 2021). Wildfires are also becoming more frequent, large, and severe (Dahm et al., this issue). These changes represent shifting seasonal patterns over time.

Non-stationary systems are often challenging to study because traditional statistical methods rely on "static" distributions. Some time-series methods do not make assumptions about stationarity and may thus help better quantify if and how events and regimes are changing. For example, frequency methods such as Fourier analysis can partition variation in long-term data into noise and signal; noise is stochastic (or unpredictable) variation, whereas signal is predictable variation such as seasonality, which is characterized by frequencies, amplitudes, and phases (Sabo and Post 2008). More advanced methods such as wavelet analysis, which decomposes signals into different frequency components, allow scientists to question whether periodicity changes over time (e.g., whether seasonal signals get stronger or weaker). For example, Ruhi et al. (2018) showed that dam operations for hydropower dampened natural flow seasonality while introducing signals at novel scales (i.e., daily fluctuations). In turn, Chalise et al. (2023) showed that dams across the US are altering flow periodicity mostly at annual and multi-annual scales. Overall, scientists need to decide ahead of time whether they are assuming non-stationarity or not—and if they are, which components (e.g., trends, seasonality, noise) may be driving it.

Landscape Ecology

Climate change manifests differently at different spatial scales—ranging from global to regional to local—and it is imperative to understand how these manifestations affect and interact with one another across the landscape (Herbold et al. 2022). In the SBDS 2016 edition, Wiens et al. (2016) describes the field of landscape ecology as "the interplay of landscape structure, function, and change at multiple scales," which can be used to quantify these spatial relationships. Two centuries of landscape change have transformed the Delta from a diverse mosaic of habitats (e.g., riparian corridors, floodplains, tidal wetlands) with strong land-water connections, to a homogenized system (e.g., dammed, drained, dredged, leveed, channelized) dominated by open water habitats (Whipple et al. 2012; Manfree 2014). While landscape ecology studies have already been highly impactful in describing the structure and function of the historic ecosystem (Cloern et al. 2021), there is widespread recognition that it is not possible to restore the Delta to its historic state. Instead, there is a large focus on restoring processes

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(e.g., hydrologic connectivity, sediment accretion) to promote ecosystem resilience (Beller et al. 2019). Yet, even with this approach, it is critical to monitor landscape responses to the many changes that are anticipated to occur, often simultaneously or consecutively, under future warming (e.g., stronger atmospheric rivers, sea-level rise; Thorne et al. 2024).

As climate change progresses, Delta ecosystems may be increasingly vulnerable to regime shifts, and in some cases, to tipping points. Several recent modeling studies characterize spatial patterns of tidal wetland vulnerability under different climate-change scenarios (Buffington et al. 2021; Morris et al. 2022). Collectively, these studies identify current wetland surface elevation, proximity to upland transition zones, sediment deposition from atmospheric rivers, and vertical accretion rates relative to sea level rise as key drivers of wetland survival by 2100. Notably, Morris et al. (2022) found that wetlands with average relative surface elevation may reach a tipping point in as little as 50 years, whereby their vertical accretion no longer keeps pace with sea level rise, ultimately leading to drowning. However, a study on Indigenous approaches to tule restoration on slowly degrading landscapes found that these methods can halt and potentially reverse drowning (USACE and TNCE 2023).

Landscape ecology studies increasingly use high-resolution spatial datasets made possible by technological advances in remotely-sensed multi- and hyper-spectral imagery from sensors on unmanned aerial systems, planes, and satellites (Hestir and Dronova 2023). This imagery can be collected systematically over regular intervals, thus creating time-series that can be used for monitoring or combined with other tools or data for further insight. Example monitoring applications in the Delta are surface water temperatures (Gustine et al. 2021), suspended sediment concentrations (Byrd et al. 2016), emergent vegetation (Chapple and Dronova 2017), invasive aquatic vegetation (Hestir and Dronova 2023), and algal blooms (Bouma-Gregson et al. 2024). Another promising, although under-utilized, application of satellite remote sensing is hydrogeodesy, which uses radar and other physical sensors to provide real-time monitoring of surface water and groundwater levels, storage, and movement. Hydrogeodesy can provide insights on multiple water-management issues, including groundwater recharge and withdrawal, extreme runoff events, changes in flood and drought occurrence, and how to adapt hydrological models to a changing climate (Jaramillo et al. 2024). Overall, high-resolution spatial data provide necessary landscape context for a variety of studies related to climate change and extreme events.

Multiple-Stressor Studies

Although the effects of extreme events are often studied separately, the reality is that they occur on the same Delta landscape (Figure 3). Studies that quantify the strength and direction of individual stressor effects lay the foundation for studies that quantify more complex and interacting multiple-stressor effects. A promising approach is the multiple-stressors framework (Crain et al. 2008; Jackson et al. 2016), which can be used to quantify multiple-stressor effects on organisms in estuaries (e.g., warming, drought, salinity intrusion, rising sea levels, hypoxia,

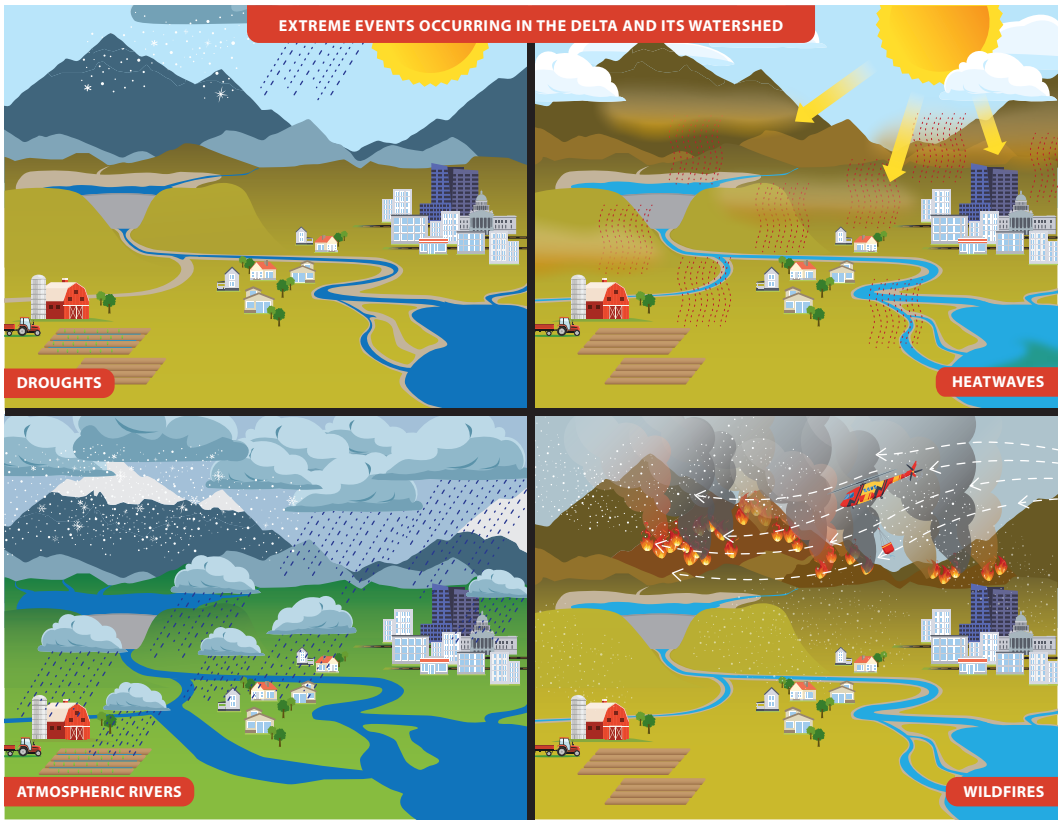

Figure 3 California's hydroclimate is projected to become more volatile in the 21st century. Accordingly, extreme events are expected to increase in magnitude, frequency, duration, rate of change, or spatial extent (see Table 1 for definitions). The extreme events covered in the SBDS 2025 edition are droughts, heatwaves, atmospheric rivers, and wildfires and water quality (see Box 6 for definitions). These extreme events often occur simultaneously or consecutively and thus have the potential to profoundly affect the Delta and its watershed through the combination of multiple interacting stressors. Note: Left panels depict wintertime conditions and right panels depict summertime conditions. *Image credit: Vincent Pascual, Office of State Publishing.*

eutrophication, harmful algal blooms, contaminants, land-use change; Lauchlan and Nagelkerken 2020; Colombano et al. 2021). Specifically, the framework is used to assess the cumulative effects of multiple interacting stressors (i.e., whether the effect of one stressor on an organism depends on the effect of another stressor). The net effects of multiple stressors may be additive (the combined effect is equal to the sum of the individual effects), synergistic (the interaction effect is greater than the additive effect), or antagonistic (the interaction effect is less than the additive effect) (Crain et al. 2008).

Multiple-stressor studies can be conducted in a variety of settings, as illustrated by the following studies from the Delta. Controlled laboratory experiments can be designed to measure physiological and behavioral responses to stressors that are expected to become more frequent or intense under climate change, such as increased temperature and salinity during drought (Herbold et al. 2022). For example, Davis et al. (2019) measured the sensitivity of native and non-native fishes to serial exposures of stressors. The results demonstrated that the non-native Largemouth Bass (*Micropterus salmoides*) experienced an additive effect of increased temperature and salinity, whereby its thermal tolerance limits increased 4 °C when exposed to both stressors. Field studies can be designed to measure biological responses to natural environmental gradients or experimental management actions. For example, Young et al. (2018) characterized

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fish community composition across a salinity gradient, using multivariate mixed-effects models, and Beakes et al. (2020) tracked biological responses to experimental operation of the Suisun Marsh salinity-control gates using ordination and circular statistics. Meta-regressions can be designed to leverage existing data for new insight. For example, Fournier et al. (2024) used trivariate mixed effects models and existing long-term data to quantify phenological responses of zooplankton and forage fishes to temperature and salinity trends, and Rogers et al. (2024) used structural-equation models and existing long-term data to compare the effects of environmental, top-down, and bottom-up drivers on zooplankton and forage fish biomass. The results produced by individual multiple-stressor studies can be combined and analyzed using a meta-analysis framework, which is a popular approach in the multiple-stressor literature (Orr et al. 2024).

Forecasting and Climate Scenario Evaluation

"It is difficult to make predictions, especially about the future." —DANISH PROVERB

Forecasting is a popular method that aims to predict an event or trend over short or medium timescales. For example, weather forecasts are on the order of days, seasonal forecasts are on the order of months, and decadal forecasts are on the order of 10-30 years. Forecasting relies on model fitting and calibration using historical data. A common approach to assess the performance of a forecasting model is hindcasting, in which the forecasting model is tested on a historical dataset to compare its output to known observations, to help identify model biases or weaknesses. Hindcast-forecast methods have been identified as a critical tool for anticipating the many changing patterns in California ecosystems under climate change (Power et al. 2024). Examples of ecological forecasting are projecting near-term trajectories and associated extinction risk of fish and invertebrates (See and Holmes 2015; Ruhi et al. 2016; Sarremejane et al. 2021).

Climate scenario evaluation is another approach to understanding possible climate futures over longer timescales. It is different than forecasting because it compares climate model outputs that are based on different greenhouse gas emissions trajectories (e.g., moderate vs. high emissions scenarios). For example, the USGS Computational Assessments of Scenarios of Change for the Delta Ecosystem (CASCaDE) project uses climate scenario evaluation to understand possible end-of-century watershed hydrology in the Delta. As part of CASCaDE, Knowles et al. (2018) evaluated 20 scenarios and found that all scenarios showed warming trends (mean 4.1 °C), and most scenarios showed increases in precipitation (mean 9%) and in the frequency of extremely high daily flows (up to 175%). CASCaDE model outputs have also served as model inputs to explore fish species responses to changes in habitat suitability and thermal refuge (Brown et al. 2013; Huntsman, Brown, et al. 2024, Huntsman, Wulff, et al. 2024).

Complementing these types of quantitative methods, approaches to generating more creative or unexpected future scenarios are growing in popularity. The trans-disciplinary field of futures studies stems from efforts in sociology and political

science in the early 20th century to anticipate future global conditions. In its contemporary form, it is widely used to explore potential socio-ecological system changes to identify emerging natural-resource-management challenges (Bell 2017). These include: horizon scanning, to identify early signals of change that may precede larger changes or events (Bengston et al. 2024); the exploration of "alternative futures" to explore multiple plausible and preferable—rather than merely probability-based—futures (e.g., popularized and globalized by the RAND Corporation); and expert opinions–based forecasting, which leverages deep expertise to explore complex interactions in systems that could result in novel future trajectories. Other methods identify seemingly far-fetched or hard-to-imagine futures, such as exploring science fiction–inspired world conditions, web-scanning for unconventional and fringe ideas and theories, or "wild cards" scenario planning where unexpected events are introduced into simulation exercises (Glenn and Gordon 2009). These types of methods can help to imagine and plan for futures that are fundamentally different from what has occurred in the past (Norgaard et al. 2021).

Artificial Intelligence

Artificial intelligence (AI) tools are increasingly popular in ecological research because they can streamline workflows through automation of time-intensive processes involving large amounts of information (Pichler and Hartig 2023). AI tools that have become regular parts of scientific workflows include generative AI, deep learning, and machine learning. For example, large language models (LLMs) such as generative pre-trained transformers (GPTs) are machine learning models designed for natural language processing (Cooper et al. 2024). These highly accurate models have been trained on large amounts of text data and can perform tasks such as generating human-like text and answering questions (Kasneci et al. 2023). For scientists, these tools can help in the research and writing phases of a research project. For example, the Google NotebookLM platform allows users to upload source materials such as literature, reports, and web pages, and then prompt the tool to summarize information. These summaries are accompanied by in-line citations that directly link to information in the source materials, which allow users to fact-check the model-generated summaries as needed. Large language model tools like this allow the user to automate the time-consuming process of compiling and extracting information, while controlling the quality of source materials.

Artificial intelligence tools can also be combined with other emerging research technologies to automate data collection and processing. For example, the NASA Jet Propulsion Laboratory's ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) project estimates surface-water temperatures at spatial and temporal resolutions not previously available in the Delta (Gustine et al. 2022; Halverson et al. 2022). A key component of the mission plan and design is an AI tool that optimizes data collection based on several variables (e.g., orbit radiation, illumination) without over-subscribing onboard memory. Delta monitoring programs may similarly benefit from AI by automating labor-intensive tasks typically performed by humans and re-allocating those resources to other monitoring activities. An example of how such freed-up resources could be used

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is installing more stationary sensors in a monitoring network to expand spatial coverage and improve data resolution (Ditria et al. 2022).

Moving forward, the science community could benefit from coordinated, ongoing discussions on AI applications and lessons learned. Such discussions need to review major ethical considerations of contributing to greenhouse gas emissions while running energy-intensive AI models (Ligozat et al. 2022) and protecting scientific integrity while using generative AI (Blau et al. 2024). Both topics have been discussed at length on the national stage. For example, the National Academies of Sciences, Engineering, and Medicine and others have proposed several guiding principles for promoting human accountability and responsibility, which cover topics such as transparency, attribution, verification, documentation, and explanation (Blau et al. 2024). Developing guiding principles for AI use in the Delta is an important step toward balancing the costs and benefits of using these tools.

Integrated Data and Modeling

Synthesis occurs when disparate data, models, concepts, or theories are integrated in ways that yield new knowledge, insights, or explanations (Pickett et al. 2007). Because of the many long-term monitoring programs in the Delta, innovative synthesis science methods that leverage disparate datasets to provide new insights are gaining popularity. Currently, there are over 20 Interagency Ecological Program (IEP) project work teams focused on synthesizing information to inform management decisions. For example, members of the IEP Climate Change Project Work Team synthesized and analyzed long-term water temperature data collected by 11 different monitoring programs with records as far back as 1969. The resulting publication documents spatial and temporal trends in warming in the Delta (Bashevkin et al. 2022). In a separate effort, Herbold et al. (2022) conducted a literature review of climate-change effects on floodplains, tidal wetlands, and open-water habitats in the Delta, and synthesized the findings to provide new insights on how these effects may influence habitat suitability for two fish species of management concern (Chinook salmon, *Oncorhynchus tshawytscha*, and Sacramento splittail, *Pogonichthys macrolepidotus*). As climate change progresses, there will be an even greater need for such synthesis science, including periodic updates on various climate-change topics in outlets such as SBDS.

Sophisticated modeling is commonplace amongst the Delta science community. Prime examples are models developed for water-resources planning, including reservoir releases and water deliveries (e.g., CalSim 3.0; CDWR and Reclamation 2022), estuary hydrodynamics and salinities (e.g., Deltares Delft3D Flexible Mesh; Martyr–Koller et al. 2017), and weather and hydrologic forecasts (e.g., Hydrologic Ensemble Forecast System; Demargne et al. 2014). Many other types of spatial models are now becoming available, such as high-resolution, digital-elevation models (Fregoso et al. 2017) and evapotranspiration models (Gustine et al. 2022; Halverson et al. 2022). In addition, models are increasingly being co-produced with and for Tribes to account for other ways of knowing while ensuring the models are built with the end user in mind (e.g., Franks Tract Futures Reimagined; CDFW

2020). Moving forward, to understand the system-wide effects of climate change and extreme events, there is a great need to link separate models that describe different parts of the system (e.g., CASCaDE; Knowles et al. 2018).

PERSPECTIVE 3: SCIENCE THAT IS COLLABORATIVE, OPEN, AND ACTIONABLE IS REQUIRED FOR EFFECTIVE CLIMATE-CHANGE MANAGEMENT

Rapidly changing conditions in the Delta highlight the urgent need for fresh ways of thinking about management issues and solutions (Norgaard et al. 2021). Adopting the following scientific practices and principles can help address this need. First, strong coordination and resource-sharing across actors, policy venues, and scientific disciplines can help ensure progress on complex problems that are too large for any single entity to tackle alone (i.e., "collaborative science"). Second, the open science principles of transparency, reproducibility, and scientific integrity can help enhance the legitimacy of science as a mechanism to inform decisions (i.e., "open science"). Finally, the practice of co-production between scientists, managers, and Tribes can help promote science outcomes that are aligned with management needs (i.e., "actionable science").

Actionable Science

Actionable science includes data, analyses, projections, or tools—accompanied by guidance on interpretation and application—that can readily support decisions in natural-resource management (Cash et al. 2006; Beier et al. 2016). When scientists, managers, and Tribes scope scientific research projects together, they can tailor study designs to the needs of specific management decisions and ensure that research outcomes are relevant: a process of co-production that helps to make science more actionable (Beier et al. 2016; Shinbrot et al. 2025). Above all, successful co-production requires the creation of relevant and timely scientific information that multiple audiences perceive to be legitimate, which in turn requires that the partners engaged in co-production carefully manage the boundaries between science and policy (Cash et al. 2006).

The demand for actionable science in the Delta has only grown in response to the increasing pace and intensity of climate change (Sommer 2020; Sommer et al. 2023, 2024), as more and more management decisions are required to continue balancing competing needs in a strained system. Scientists need to increase their own understanding of how, when, and where different management approaches integrate science and data—and how they could be improved by new science (Sommer 2020). These management approaches could include regulatory actions (e.g., species listing, water-quality standards), infrastructure operations (e.g., reservoir operations, water treatment), habitat restoration (e.g., floodplain restoration, aquatic weed removal), or ecological intervention (e.g., invasive species removal, hatchery supplementation) (Sommer 2020). Furthermore, if scientists want their research to inform management, they need to clearly distill the implications of their study results into management suggestions, all within the time-frame that managers need to make decisions and implement actions. It is necessary, therefore, for scientists to engage with managers before beginning new

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research and then regularly throughout the process. This can help build scientific understanding among managers, ensure research design remains closely tied to management need, and show managers where the management suggestions came from while bolstering their trust in the results of the science. Moving forward, strong working partnerships among scientists and managers are needed to proactively address knowledge gaps about climate change, and to respond to management emergencies that extreme events present. A prime example is the FIRO program led by CW3E and partners, in which climate and weather forecasts are incorporated into reservoir water-control manuals that guide management decisions on dam releases (Ralph et al. 2022).

Collaborative Science

As described earlier in the "Introduction," California's scientific system comprises the institutional structures that support science, and as that system pertains to the Delta, it includes multiple different actors and venues of different sizes and levels of complexity. In addition to focused efforts on actionable science, the system needs to leverage its distributed network structure to optimize resource sharing and enhance cross-domain information exchange and synthesis. Collaborative venues focused on open science and synthesis have been gaining traction among the Delta community. Such collaborative science spaces facilitate the co-production of science, acting as centralized hubs where users can network and access resources such as data, integrated modeling frameworks, best practices and protocols, training and mentorship in innovative methods, and cyber-infrastructure such as cloud computing. Moreover, they serve as transformative incubators that promote innovation among diverse research teams and across scientific disciplines and agency boundaries, and can include collaboration between scientists, Tribes, decision-makers, and the general public.

There are several well-established collaborative venues in the Delta, such as the IEP, the Collaborative Science and Adaptive Management Program (CSAMP), Delta Regional Monitoring Program (RMP), Delta Interagency Invasive Species Coordination (DIISC) team, and Interagency Adaptive Management Implementation Team (IAMIT), among others (DSC 2019). A new collaborative venue supported by the Delta Science Program organizes cohorts of synthesis working groups that comprise early-career scientists, and provides them with intensive data-science training, using a curriculum developed and taught by the National Center for Ecological Analysis and Synthesis (NCEAS). The working groups apply their newly developed skills to help answer management-relevant research questions using existing data from the Delta. Moving forward, the need for inter-disciplinary and trans-boundary collaborations in collaborative science venues will only grow in importance as climate-change effects become more complex and intractable.

Another particularly important role of collaborative science venues is to foster connections that enable the broader adoption and use of scientific datasets and models. For example, it is not always in the purview of model developers to ensure that their models or outputs align with the needs of other groups interested in

questions that fall outside the developers' primary scope or mandate. However, the collaborative venue structure can support alignment of multiple end users' needs and/or translate scientific outputs for multiple audiences. Moreover, there is often a lack of sustained funding for maintaining or updating large models beyond their initial development. By drawing together multiple different institutions, a collaborative science venue structure may present more opportunities to access funding and pursue long-term maintenance. Such venues could play an increasingly important role as climate change progresses and the scientific models and datasets used to inform management require periodic updates.

Key to the success of these collaborative venues is effective leadership, efforts to build and maintain trust among participating entities, and robust community engagement to ensure continued relevance (Lubell et al. 2025). Thus, investments in the social infrastructure of these venues, which requires dedicating continued resources, can help promote further coordination, engagement, facilitation, conflict mediation, and shared resource management (Box 6). Finally, collaborative science also includes opportunities for Tribal and Delta communities

BOX 6

Streamlining Science through a Delta Collaboratory

In response to the growing need for collaborative venues that support open science and synthesis, the Delta Science Program is facilitating the development of a "Delta Collaboratory." This aims to serve as a centralized hub for open science, synthesis, and modeling to help the Delta science community address management challenges. (This approach is similar to the Chesapeake Bay Collaboratory's "Think, Do, and Innovate Tank" framework; UMCES 2023.) In the near term, the initiative focuses on convening project work teams to evaluate actionable science needs (salinity intrusion, harmful algal blooms, and tidal wetland food production).

The goals of the initial phase are to identify: (1) robust modeling approaches that could fill key knowledge gaps for each project, (2) resources to support approaches for each project, and (3) resources common to all the projects. In the next phase of the initiative, the Delta Collaboratory will help develop strategies to secure common resources for the project work teams (with the ultimate goal of making them available to the larger Delta science community). For example, each project may benefit from a hydrodynamic model that can estimate residence time in the estuary, or technical training on forecasting methods to evaluate climate-change scenarios.

Over the longer term, the goal of the initiative is to develop and sustain a space where anyone can find open science, synthesis, and modeling resources that help with the delivery of relevant and timely scientific information to decision-makers on a broad range of management issues, including those arising from climate change and extreme events.

to participate in defining research needs and to interpret and implement the results. Building mechanisms that allow this kind of involvement can help ensure collaborative venues operate most effectively as climate changes pose new and ongoing challenges.

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Open Science

In addition to actionable and collaborative science practices, advancing the scientific system requires strong open science practices, where transparency, collaboration, visibility, and reproducibility are key outcomes of the research process (Bartling and Friesike 2014). Transparency and reproducibility are critical to improving the legitimacy and credibility of science and how it is used to advance knowledge and make recommendations, and are particularly important in the current "post-truth" era, where public and political trust in science is at an all-time low (Cash and Belloy 2020). Moreover, transparency and reproducibility require, in most cases, making datasets and modeling approaches open-access and publicly accessible, which can facilitate further exploration and additional discovery within the same data. For these and similar reasons, in 2016 California passed AB-1755, the Open and Transparent Water Data Act, which encourages collaborative science to inform water management by mandating state agencies to develop "protocols for data sharing, documentation, quality control, public access, and promotion of open-source platforms and decision-support tools related to water data" (Cantor et al. 2018). Increasingly, the Delta science community is cultivating a culture of openness and information-sharing aligned with the open science movement, as evidenced by the increasing accessibility of data repositories, open-access models, data processing code, and publications (Hale et al. 2015, Baerwald et al. 2020). For example, the IEP Data Utilization Working Group provides standard operating

BOX 7

Tribal Data Considerations for the Open Science Movement

Open data is a core element of the open science movement. For Indigenous peoples, however, data are inseparable from cultural identity, governance, and stewardship of lands and waters. Certain data about Tribal lands, waters, or other natural resources can expose vulnerabilities (Whyte 2017), and as a result, unrestricted sharing can lead to exploitation, misinterpretation, or harm to the Indigenous peoples they are intended to benefit (Williams and Hardison 2013). Additionally, Tribal data may be covered by human subjects protections. These protections, which are required by Institutional Review Boards (IRB), typically focus on individuals, and may not account for the collective rights of Tribes as sovereign nations (Hudson et al. 2020). For this reason, the Karuk Tribe has its own Resources Advisory Board that functions as an IRB to oversee ethical standards for Tribal cultural resources such as data (Karuk Tribe 2015).

Best practices for using Tribal data integrate the following open science principles: findable, accessible, interoperable, and reusable (FAIR), and collective benefit, authority to control, responsibility, and ethics (CARE). FAIR promotes interoperability, while CARE emphasizes that Indigenous Nations retain authority over their data and its use (Carroll et al. 2021). Applying these principles requires an assessment of: who benefits from the data, who controls the data, and how the data is safeguarded. Additional best practices may involve Free, Prior, and Informed Consent (FPIC), data management plans that recognize Tribal intellectual property, and agreements for long-term stewardship or restricted access (UN 2007; Carroll et al. 2021). Overall, these considerations may result in Tribal data with limited openness; for example, by masking geospatial data that could reveal sacred sites or sensitive resources. Moving forward, scientists can adopt best practices that integrate FAIR and CARE principles, co-produce protocols with Tribes, seek FPIC before collecting data, and revisit decisions as projects evolve (Shinbrot et al. 2025).

procedures for data management, quality control and quality assurance, metadata standards, and publishing open data to the Environmental Data Initiative. By continuing to strengthen institutional support, incentives, and mandates for practicing open science, more scientific progress can be made on climate change topics in the Delta.

PERSPECTIVE 4: SCIENCE COMMUNICATION ABOUT CLIMATE CHANGE IS MORE EFFECTIVE WHEN TAILORED TO TARGET AUDIENCES

> *"Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less." —MARIE CURIE*

Effective communication on climate change looks very different for scientific, decision-making, or general-public audiences. Research over the past 15 years identified key challenges related to effective climate communication: (1) **inaccurate assumptions** or understandings of climate effects that arise from the technical complexity of climate-change dynamics; (2) **difficulties disseminating** fact-based, **quality information on climate issues** as a result of media politicization and polarization; (3) the **inaccuracy of the information-deficit model** (i.e., the idea that more information will motivate individuals to behave differently); and (4) **the inefficacy of constant messages** of overwhelm and fear, rather than communication that inspires hope and optimism. (Moser 2010, 2016; Cash and Belloy 2020).

Overcoming each of these challenges requires climate-change communicators to employ strategic tools and approaches tailored to different audiences. For example, climate scientists are often approached by media to assess the degree to which climate change contributed to the effects of a specific extreme event (Stott and Walton 2013). Attribution science, which aims to elucidate the links between extreme event occurrences and a warmer climate, has proliferated as a field over the past 2 decades (Harvey 2022; Otto 2023), and can help climate scientists communicate these linkages with accuracy and the appropriate levels of certainty (Clarke et al. 2022; Lee et al. 2023). Yet, the perceived legitimacy and subsequent effect of such science varies among different audiences based on their values, beliefs, identities, and the information channels through which the findings are shared (Kahan et al. 2012; Moser 2016). Therefore, scientists that study the effectiveness of science communication strategies have been evaluating how different message frames (e.g., optimism vs. pessimism, individual vs. collective responsibility), modes of communication (e.g., visual imagery, narrative storytelling, artistic expression), and messengers affect audiences' uptake, receptivity, and response to climate communications. In short, framing tailored toward specific audiences' priorities, communication that is interactive and educational, and messaging that is actionable have all been found to be more effective than traditional communication approaches. As such, in situations where a management response is necessary, it is important to focus communication on

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the elements of the situation most relevant to the manager and to suggest specific actions supported by evidence.

Although climate communications research is relatively new (in comparison to climate monitoring and modeling), the first examples of longitudinal and comparative studies are now beginning to show results. For example, different audiences' opinions and understandings of climate change—and their openness to different policy or behavioral responses—have started to change over time with exposure to more climate effects and with different approaches to climate communication (Moser 2016; Leiserowitz et al. 2021). Research to assess climate beliefs and policy preferences among people living in the Delta has only just begun (LLF 2021; Rudnick et al. 2023), but early results suggest there are identifiable audience groups with different worldviews for whom climate communication could be tailored more effectively (Rudnick et al. 2023). Expanding research like this to evaluate other groups—including decision-makers—and to monitor changes in climate knowledge and perceptions over time can help to ensure climate communications remain relevant and effective.

Furthermore, these research findings need to be accessible to, and usable by, the people who actually do most of the climate communication (e.g., scientists, decision-makers, and media representatives) (Kahan et al. 2012; Moser 2016). Boundary-spanning organizations (e.g., the Intergovernmental Panel on Climate Change that acts as an interface between climate scientists and governments) can help to ensure that research findings on effective communication strategies are translated into actionable communication practices (Guston 2001; Parker and Crona 2012; Lee et al. 2014). These organizations can help to overcome the broad challenge that "science is not just magically 'loaded' into policy" (Lubell et al. 2025, p. 8). This outcome requires people to translate scientific findings that can inform decisions (Cash et al. 2003). Investing in these organizations—as well as in other forms of partnership development, capacity building, and training—could help scientists to communicate their scientific findings in ways that motivate adaptive management and governance.

Conceptual Models and Scientific Illustrations

Visualizations are valuable tools for science communication. It is common practice for research teams to develop highly technical conceptual models to depict hypotheses about the relationships among components in a system. For example, the Interagency Ecological Program (IEP) Climate Change Project Work Team developed a detailed conceptual model addressing climate-change effects on aquatic ecosystems in the Delta (Figure 4A). While such conceptual models are considered effective communication tools among technical audiences in the science community, simplified scientific illustrations are generally better for reaching a broader audience. Research on this topic suggests that scientific illustrations that meet three criteria—being understandable, accurate, and

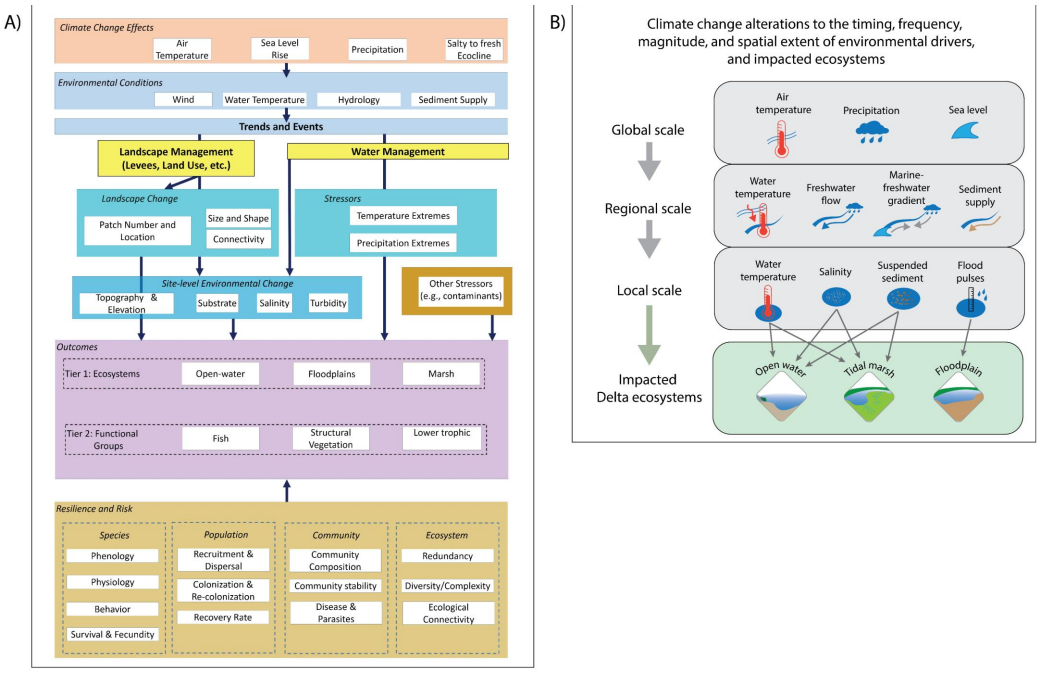

Figure 4 (**A**) The Interagency Ecological Program (IEP) Climate Change Project Work Team developed a conceptual model of climate-change drivers and effects on aquatic ecosystems of the Delta. This conceptual model is published in their technical report and is aimed at a highly technical audience (Climate Change MAST 2022). (**B**) Herbold et al. (2022) adapted the conceptual model into a scientific illustration aimed at a broader audience, including scientists and managers. The illustration is simpler and uses more visually appealing graphics. These examples show how Delta scientists can improve science communication by developing visualizations intentionally tailored to specific audiences.

appealing—are the most effective visualization tool for science communication (Jensen et al. 2023). For this reason, the IEP Climate Change Project Work Team adapted the conceptual model into a simpler scientific illustration aimed at less technical audiences (Figure 4B). Moving forward, Delta scientists may consider how best to develop tailored visualizations as science communication tools intended to target specific audiences with different knowledge, interests, and technical backgrounds.

PERSPECTIVE 5: CLIMATE GOVERNANCE THAT IS ANTICIPATORY, ADAPTIVE, AND FLEXIBLE IS MORE EFFECTIVE, AND CAN IMPROVE SCIENCE-INFORMED DECISION-MAKING UNDER CLIMATE UNCERTAINTY.

> *"To cope with rapid change, new ways of doing science, developing policies, undertaking management, and thinking about the environment are needed."*
> —*NORGAARD ET AL. (2021)*

Adaptive Governance

Climate governance that is anticipatory, adaptive, and flexible can improve decision making under greater levels of scientific uncertainty because of climate change. The Delta's climate governance system—comprising the governance actors, rules, and processes through which decisions around climate change are made—is multi-scale (i.e., including federal, state, local, and Tribal processes), polycentric (i.e., including many policy arenas and decision-making processes), and largely reactive (Lubell et al. 2014; Luoma et al. 2015; Rudnick et al. 2025).

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Distributed governance systems like this are often touted for their potential to distribute power, increase representation of diverse voices, and incorporate local context into decision-making. However, the complexity and huge number of governance actors in these systems also increases the need for strong coordination and mechanisms for managing conflict, which in turn increases resource requirements (Nowell 2009; Morrison et al. 2023; Koebele et al. 2024).

Ten years ago, Luoma et al. (2015) concluded in the SBDS 2016 edition that the Delta's wicked problem points to "the institutional fragmentation [that] creates conflict and slows decisions." Despite numerous scientific and decision-making forums dedicated to collaboration, governance actors struggle to navigate siloed policy domains (e.g., water quality and public health, Lubell et al. 2025) and to reconcile the sometimes-conflicting values and missions among the multiplicity of organizations in the Delta (Rudnick et al. 2025).

As stated in the grand challenges, environmental change is outpacing the traditional pace of science (Lee et al. 2024). It is also outpacing the ability of governance systems to adapt. For example, even if new scientific findings are effectively translated for decision-makers, adaptive management may be hampered by a range of governance challenges such as inflexible regulations, slow bureaucratic processes, and political conflict (Lubell et al. 2025). Thus, transformative governance systems that are both anticipatory and adaptive can help overcome such challenges and include key considerations:

- Learning to embrace greater levels of scientific uncertainty,
- Interrogating many potential futures through data-driven, imaginative, and anticipatory approaches,
- Supporting trust-building and effective leadership that facilitates learning among governance actors,
- Integrating different worldviews and ways of knowing, and
- Explicitly acknowledging and addressing socio-political barriers to decision-making.

Decision-Making Under Uncertainty

To make progress in climate adaptation, scientists, Tribes, and decision-makers need to learn to operate under conditions of increasing uncertainty. Traditionally, scientists have assigned "confidence levels" to their predictions. For example, the Public Policy Institute of California (PPIC) provides a summary of key environmental pressures and an associated confidence assessment of how likely each is to affect California in the future: warming (very high confidence), sea level rise (very high confidence), snowpack loss (high confidence), increased drought intensity (high confidence), increased storm intensity (high confidence), longer dry season (moderate confidence), and increased hydroclimate whiplash

(moderate confidence) (Grenier et al. 2024). While improving prediction confidence can require multiple advances in science and understanding over a period of many years, some of these climate pressures require action now in order to be appropriately prepared for potential future effects. The difficulty of making decisions using imperfect or incomplete information cannot remain a hindrance to climate action (DISB 2024). The Delta science and management community needs, therefore, to become capable and comfortable with decision-making under continually changing conditions and lower levels of scientific certainty, so that decisions made in the short term can achieve climate goals over the long term.

The Delta's polycentric governance structure complicates holistic, coordinated, and anticipatory decision-making (Rudnick et al. 2025). As described in Norgaard et al. (2021), numerous approaches to advancing scientific inquiry and problem-solving under greater levels of uncertainty are now available in the Delta. These approaches further emphasize the need for collaborative, open, and actionable science, and typically center around exploring multiple potential futures. They include frameworks such as decision-making under deep uncertainty (DMDU; Marchau et al. 2019) and post-normal science (Funtowicz and Ravetz 1993). Such frameworks are necessary when people do not know, or cannot agree upon, the most likely future conditions—perhaps as the result of uncertainty over key model variables, parameters, or associated probability- distribution functions. Furthermore, decision-making frameworks that outline shared principles and processes are especially important when the stakes are high or when conflicting values or goals are involved. (See Table B1 in Appendix B for methodologies and references.)

Exploring a range of possible, plausible, and preferable future scenarios provides a way to evaluate what effects different management and policy approaches may have under various future conditions and can facilitate decision-making where risk must be minimized (e.g., decisions that may implicate loss of human life or species). While these approaches do not eliminate the risks associated with different decisions or actions, they can help manage risk by presenting options to adapt management strategies to new conditions as they arise. Decision-makers are empowered to move forward despite existing uncertainties, knowing that inaction may be more costly than waiting for science with improved confidence levels (Haasnoot et al. 2019). The implementation of effective decision-making frameworks depends upon robust and varied input. This includes trans-disciplinary collaborations that incorporate the broad-ranging expertise needed to address complex problems, and transparent engagement with interested parties to bring in diverse viewpoints and build trust in subsequent decisions (Norgaard et al. 2021; DISB 2024). While navigating an uncertain future, it is increasingly important to recognize the limitations of scientific knowledge as a driver for decision-making and management actions (Biesbroek et al. 2013). To research and tailor distillation of scientific findings, it is useful for the scientific community to better understand how decision-making is influenced by factors such as politics, power asymmetries, conflict, and the way that different time-scales affect

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incentives (e.g., economic discounting over long-time horizons, short-term returns on investment, and electoral-cycle motivations).

Strategic Planning

> *"Long-term water infrastructure planning should not only achieve economic, environmental, and social goals, but also be robust and adaptable to non-stationary hydrology." —HUI ET AL. 2018*

In addition to making decisions faster and under greater uncertainty, effective climate adaptation requires holistic strategic planning that can identify interdependencies among management actions—including how the timing and order of actions may affect and constrain subsequent actions. Several recent planning efforts led by state and local agencies have begun to adopt these sorts of big-picture approaches to assessing future management options for the Delta and its watershed. A few illustrative examples of such innovative and holistic strategic planning are provided here, but they are by no means exhaustive. The Delta Stewardship Council's Delta Adapts initiative is a strategic framework for creating a climate-resilient future for the entire Delta (DSC 2021). The first step was to conduct a Vulnerability Assessment, which characterizes the risks that climate change poses to people living in the Delta, water-management and flood-control infrastructure, water supply, and ecosystem health, among other assets. The second step was to develop an Adaptation Plan—the Delta's first-ever comprehensive regional approach to climate resiliency. Notably, this plan addresses environmental justice issues related to vulnerable communities that are more likely to be exposed to climate-change pressures. It also emphasizes a commitment to collaboration among state, federal, local, regional, and Tribal entities to achieve climate goals for the Delta (DSC 2024).

Other strategic plans focus more on updating operations, management actions, and other tools under climate change. For example, the CDWR Climate Action Plan outlines a phased approach including greenhouse gas mitigation, climate-change effect analysis, and vulnerability and adaptation (Arnold et al. 2022). Notably, the climate-change effect analysis uses time-series models to evaluate non-stationarity in unimpaired runoff and how it affects water-delivery capabilities (CDWR and Reclamation 2023a, 2023b). The Yuba Water Agency's Strategic Plan for 2023–2027 outlines climate-adaptation strategies for the Yuba and Feather rivers, including their FIRO program to guide upstream reservoir operations (YWA 2023). These projects show how time-series analyses can directly inform water operations, and represent good examples of translating complex science into adaptive decision-making in the Delta. In addition, the PPIC recently proposed a suite of Climate-Smart Tools, to advance Delta climate adaptation and conservation using a watershed-scale approach, and a legal framework to implement these tools (Sommer et al. 2024; Harder et al. 2025).

Moving forward, goal alignment is necessary to effectively develop and implement flexible climate-adaptation plans across the wide array of governance actors in the

Delta. For example, Rudnick et al. (2025) found that the lack of a shared framework that defines regional climate governance objectives has hampered the ability of the vast governance network to work together to advance progress. Potential solutions are removing communication barriers, building and tending relationships, and developing greater pathways for interaction between scientists, decision-makers, and the general public (Lubell et al. 2025). Such activities could help address resource conflicts among competing user groups and promote productive conversations around shared visions for climate adaptation in the Delta.

CONCLUSIONS

Climate change and extreme events are the new normal: No matter the trajectory of global emissions, a substantial amount of warming has already occurred, with more to come that is already locked in. To meet these challenges, Delta scientists and decision-makers can leverage the many effective practices that are already in place, such as long-term monitoring programs, collaborative synthesis venues, science-informed decision-making processes, and Tribal and community partnerships. New and sophisticated tools are constantly emerging that can harness the big data revolution and streamline flows of information to decision-makers and to early-warning detection systems. Open-science practices are improving access to more integrated datasets, enabling the development of models that link different parts of the system, and enhancing Delta science capacity via collaborative interagency project work teams. These assets have strengthened innovation and learning across the Delta.

Nevertheless, serious challenges remain. Climate change signals can be difficult to parse because of California's variable hydroclimate. Greater levels of scientific uncertainty can present challenges for traditional decision-making processes. Greater coordination across multiple science and policy venues requires additional resources. Looking forward, continued institutional support can help bolster the perceived value of science and shore up the entire Delta scientific system. In the near term, priority actions are those that strengthen support for collaborative venues that facilitate broad participation in synthesis science, integrated modeling, and science communication, with the ultimate goal of delivering trusted science to decision-makers. Open, collaborative, and actionable science principles and practices are the foundation upon which the Delta scientific system can build its capacity to anticipate and respond to new climate realities, and to effectively communicate these realities to diverse audiences. Such avenues can help the Delta scientific system remain relevant to the challenges of natural resource management in the 21st century.

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