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The State of Bay-Delta Science: An Introduction to the 2025 Extreme Events Edition

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INTRODUCTION

The State of Bay–Delta Science (SBDS) is intended 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 ("Bay–Delta") system (Figure 1). When referencing the Bay–Delta system, we include the atmosphere, watershed, politics, and governance at a broad scale.

Each SBDS edition has communicated new insights on a range of high-priority issues by synthesizing the current science and discussing progress on key research questions, knowledge gaps, and proposed future research. Collectively, these editions provide valuable summaries of the physical, biological, and social dimensions of the Bay–Delta. The first edition in 2008 provided a system-wide baseline on history, geography, water quality, ecosystem restoration, levee integrity, water supply, and public policy issues in the Bay–Delta (Healey et al. 2008). Eight years later, the second edition featured research on a dozen priority topics identified by senior scientists and managers working in the Bay–Delta (Healey et al. 2016), ranging from landscape change to migratory fishes to contaminants. Most recently, the third edition addressed research priorities identified in the 2017–2021 Science Action Agenda (DSC 2017), with a focus on the ecosystem services of primary producers (e.g., plants, algae, and their associated carbon) in the Bay–Delta (Larsen et al. 2023). Now, this fourth edition of SBDS focuses on governance and extreme events affecting the Bay–Delta: droughts, heatwaves, wildfires, and atmospheric rivers. The edition explores physical and ecological processes within the Bay–Delta that are responding to changes in large-scale forcing phenomena, primarily those associated with climate change, building on the rich long-term time-series data collected by regional and statewide monitoring programs. These data allow researchers to detect changes in frequency, duration, magnitude, timing, and spatial extent of key variables coincident with the accelerating changes in external forces (e.g., increasing temperature). This SBDS edition offers a regional perspective on the intensifying effects of climate change on the Bay–Delta, rather than event-specific attribution studies and analyses.

Here we give examples of some of the critical findings:

- Summer soil moisture in the southwestern US was below average in 18 of 22 years from 2000 to 2021. This 22-year period was the driest since 800 A.D., representing mega-drought conditions (Williams et al. 2022).

- Average annual air temperatures warmed by 0.008 °C yr^{-1} from 1901 to 2010 in the southwestern US (Hoerling et al. 2013). Water temperatures in the estuary increased 0.017 °C yr^{-1} from 1969 to 2020 (Bashevkin et al. 2022). These average changes are manifested in heatwaves that have become more frequent and intense (Mahardja et al., this issue).

- Catastrophic wildfires in California have rapidly increased in frequency and intensity: eight of the largest fires since 1932 occurred between 2018 and 2024. Each of these fires exceeded the criteria for a mega-fire (burned areas greater than 25,000 acres of land), and each was at least partially located within the Delta watershed (Dahm et al., submitted).

- Atmospheric rivers drive California's extreme variability in hydroclimate. Whether a few large storms appear—or do not appear—makes the difference between wet and dry years (Dettinger et al. 2016). As the climate continues to warm, the frequency of storms is expected to decrease while the intensity of extreme storms is expected to increase (Gershunov et al., submitted).

Articles in this edition highlight the growing importance of regionally downscaled climate projections to understanding possible future scenarios for physical and ecological processes in the Bay–Delta. This understanding will continually evolve as researchers update global climate models and refine regional models with better resolution on the drivers of variability (e.g., El Niño Southern Oscillation). However, there is widespread recognition that climate adaptation cannot wait for perfect information; thus, decision-making strategies that deal with uncertainty are presented throughout. For example, the "adaptation pathways" approach is often described as one that prepares alternative sequences of measures to achieve a well-defined adaptation objective (Werners et al. 2021)—this approach has recently been applied to sea-level rise (California Sea Level Rise Science Task Force 2024) and water issues (Grenier et al. 2024). Approaches like this offer systematic, coordinated, and flexible adaptation strategies that can be applied to a range of issues associated with climate change and extreme events in the Bay–Delta.

The articles that comprise this edition of SBDS are intended to be published in at least two issues of *San Francisco Estuary and Watershed Science*, grouped by the following topics:

Group I

- **Governance.** The first paper prepared for this edition characterizes the Delta's governance system and assesses the ways in which its structural and procedural features contribute toward the efficacy, efficiency, and equity of climate adaptation responses (Rudnick et al., this issue).

- **Drought.** The second paper prepared for this edition discusses current and proposed management actions for water availability as well as the need for multiple adaptation pathways to manage water equitably and effectively. It also explores pre-permitting drought actions and new tools and forecasting methods to mitigate how drought affects Delta plants and animals (Hartman et al., this issue).

- **Heatwaves.** The third paper prepared for this edition evaluates spatial patterns in temperature and heatwaves, and how they potentially affect the ecosystem and human health. It also briefly discusses key concepts and ideas for adaptation strategies (Mahardja et al., this issue).

Group II

- **Wildfires.** The fourth paper prepared for this edition examines water-quality degradation associated with burned landscapes. It covers such topics as the mobilization and transport of contaminants, sediments, and heavy metals through the watershed, which is becoming more common as a result of the increasing frequency and size of mega-fires (Dahm et al., submitted).

- **Atmospheric Rivers.** The fifth paper prepared for this edition discusses the role of atmospheric rivers in the projected increase in volatility of California's hydroclimate. The intensity of storms is expected to increase, resulting in increased flooding and associated risks to water infrastructure and communities (Gershunov et al., submitted).

- **Synthesis.** The sixth and final paper prepared for this edition is a higher-level synthesis of what we have learned so far. The key takeaway is that extreme events are adding new and challenging dimensions to an already "wicked" management setting (Luoma et al. 2015). The paper outlines the SBDS Editorial Board's perspective on promising paths forward for science-informed management (Colombano et al., submitted).

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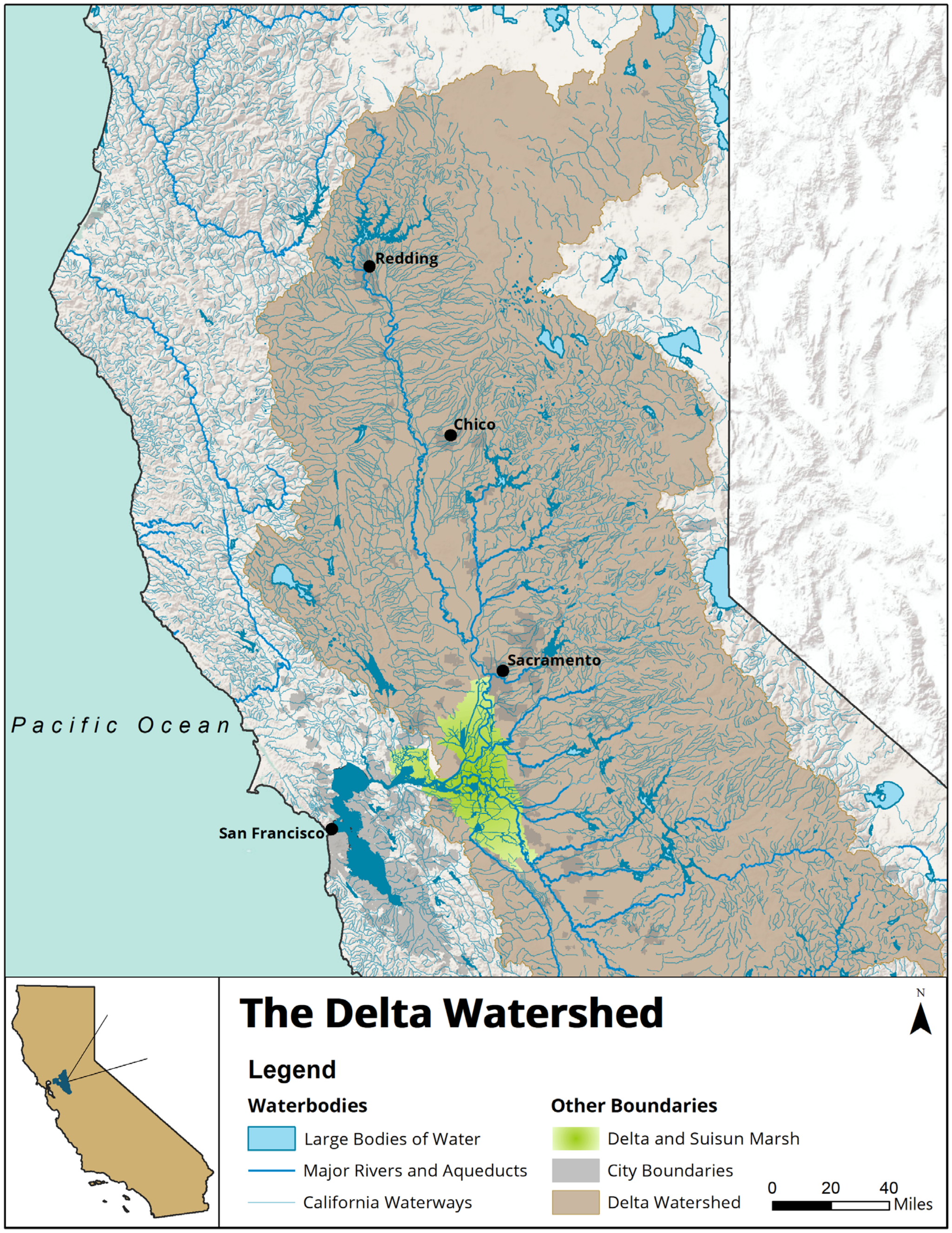

Figure 1 Map of the Sacramento–San Joaquin Delta watershed (*brown*), which drains into the San Francisco Estuary, California, USA. The Delta (*green*) is a large mosaic of rivers and tidal channels that receives freshwater from upstream tributaries along the eastern-facing slopes of the Coast Range and western-facing slopes of the Sierra Nevada, and seawater from the Pacific Ocean. The Delta is a biologically diverse ecosystem that is managed as a water-conveyance system to deliver freshwater to much of the state. It is described as having "wicked" management challenges that cannot be solved with traditional methods but can be managed with appropriate knowledge and flexible institutions (Luoma et al. 2015). Climate change, which affects the entire Delta watershed, further exacerbates these challenges. *Source: Megan Thomson.*

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