DRAFT (DO NOT CITE)

Summary of Science Gaps and Uncertainties to Inform Future Delta ISB Review Topics

November 21, 2025

Background

The Delta Independent Science Board's (ISB) role, as designated by the Delta Reform Act of 2009, is to provide scientific oversight of scientific research, monitoring, and assessment programs to support adaptive management in the Delta. As such, the Delta ISB conducts topical reviews in the Delta. To help inform potential future Delta ISB review topics, a list of information gaps and uncertainties is synthesized from scientific and management documents that the Delta ISB has been tracking. All documents are from 2023 to 2025, including:

1. Healthy Rivers and Landscapes Draft Science Plan (2024)
2. Draft Water Quality Control Plan for the San Francisco Bay and Sacramento-San Joaquin Delta (2025)
3. Delta Adapts Adaptation Plan (2025)
4. Delta Plan Five-year Review (2024)
5. The Council's Tribal and Environmental Justice Issue Paper (2025)
6. The Delta Science Strategy (including the 2022-2026 Science Action Agenda, the Grand Challenges in Delta Science report used to inform the Delta Science Plan update, and articles from the 2023 and 2025 State of Bay-Delta Science)

The goal of this document is to summarize what is new since last selecting review topics in 2023 (e.g., food-webs, decision-making under deep uncertainty, and subsidence). Common themes of needs, gaps and uncertainties are synthesized across all documents. Additional topical gaps and uncertainties identified within each source are summarized in Appendix A.

This document was synthesized using Google's NotebookLM. This platform enables users to upload source materials, such as reports and journal articles, to generate summaries or ask questions to uncover new insights. These summaries include in-line citations that link directly to the source document. The NotebookLM used to generate this document is available upon request by emailing disb@deltacouncil.ca.gov. **This document does not reflect the views of the Delta ISB and is not a product of the Delta ISB.**

Table of contents

Prompt: Summarize information from the source documents on science gaps and uncertainties present in the management of natural resources in the Delta. Organize by topic and use academic language

The management of natural resources in the Sacramento-San Joaquin Delta (Delta), a system recognized for its complexity and deep uncertainty, is critically constrained by persistent scientific gaps spanning mechanistic understanding, data infrastructure, and governance structures. These uncertainties often compound, complicating assessments of risk and impeding the prioritization of adaptive management strategies.

The primary science gaps and uncertainties, identified through collaborative scientific and management prioritization, are categorized as follows:

I. Ecological and Mechanistic Uncertainties

Significant mechanistic uncertainty exists regarding the cumulative impacts of stressors and the fundamental biological responses of managed species.

A. Interacting Stressors and Species Thresholds

- There is considerable uncertainty regarding the **nature and magnitude of synergistic effects** arising from co-occurring flow and non-flow stressors (e.g., predation, contaminants, competing species) on native species populations and overall ecosystem health.
- A key knowledge gap is determining the precise **thresholds of survival and health** for managed fish and wildlife species relative to environmental variables such as flow, temperature, and dissolved oxygen.
- Uncertainty persists concerning the **sources, exposure pathways, and impacts of contaminant mixtures** (including legacy and emergent pollutants like PFAS, microplastics, and 6PPD-quinone) on all life stages of native fish and their food sources. It is also uncertain how flow variability, particularly during extreme events, impacts contaminant loading.
- The **causal effects of Harmful Algal Blooms (HABs) on food web productivity** remain insufficiently quantified. Additionally, scientists lack a complete understanding of the detrital contributions of primary producers from the Delta and

its watershed to food webs and how the **quality of organic matter** from different species affects these contributions.

B. Invasive Aquatic Vegetation (IAV) Dynamics

- Scientific understanding is limited regarding **innovative and effective methods for control or management of IAV** in tidal portions of the Delta. Specifically, control programs have had mixed results, and efficacy among new herbicide agents and specific IAV species (e.g., *Ludwigia spp.* and *A. philoxeroides*) has not been widely compared.
- Major knowledge gaps remain concerning the **roles of IAV in nutrient cycling, evapotranspiration (ET), carbon, and sediment dynamics**.
- A critical deficiency in estimating consumptive water use is the specific knowledge gap of **how IAV influences consumptive water use at the scale of the Delta**.
- It remains **unclear to what extent the proliferation of submerged aquatic vegetation (SAV) has directly contributed to commensurate native fish species declines**, as many native species can thrive in vegetated habitats.
- To refine food web models, there is a recommendation to **measure productivity rates of individual floating aquatic vegetation (FAV) and SAV species** alone and in mixed assemblages under current and predicted future conditions.

C. Harmful Algal Blooms (HABs)

- Significant mechanistic uncertainties surround the **environmental drivers** (e.g., nutrients, temperature, water residence time, flow) that cause HABs to proliferate at specific locations and times. Furthermore, it is not clear that all pathways of nutrient transformations are fully accounted for in existing budgets.
- Gaps exist concerning the **health impacts of aerosolized toxins** from HABs, and the **fate and transfer of toxins** within the airshed, watershed, and food web.
- There is a lack of data on the presence of **multiple toxins** and the implications of chronic exposure to a suite of toxins for animals and humans.
- The Delta lacks specialized **instruments or sensors for real-time HAB detection** and a cohesive framework for developing and disseminating forecasts of HAB extent, toxicity, and health impacts.

II. Climate Change, Hydrology, and Physical Systems

Uncertainties related to climate change impacts and physical infrastructure resilience complicate anticipatory planning and adaptation strategies.

- **Climate Signal Detection:** The naturally high hydroclimate variability in California makes it statistically **challenging to confidently detect long-term trends and signals** associated with climate change in models and observations.
- **Water Management Under Change:** There is a major knowledge gap in determining how **ecological flow scenarios and water allocation/supply decisions should be modified** under projected climate change to maintain habitat and manage species interactions.
- **Infrastructure Vulnerability (Measurement Uncertainty):** Research is needed for **improved forecasts of sea level rise and other climate change impacts on flood risk**. Knowledge gaps persist regarding the **effects of seismicity on levee integrity**, specifically concerning observations of Delta ground motions and improved estimates of liquefiable materials beneath levees. Data on levee conditions are often retained in paper reports by individual agencies, hindering a clear system-wide understanding of risks.
- **Carbon Flux and Restoration Sustainability:** There are **data gaps in measuring carbon flux (CO2, CH4, and N2O)** for freshwater tidal marshes, SAV, and FAV habitats, which limits the accurate estimation of regional greenhouse gas (GHG) budgets.
- The **fate of wetland soils as a millennial-scale carbon sink is highly uncertain**, driven by intertwined climate and land-use factors. Furthermore, it is uncertain whether restored tidal wetlands will receive **sufficient sediment budgets to sustain their persistence** under projected sea-level-rise scenarios.

III. Data, Monitoring, and Modeling Deficiencies

Gaps in data quality, integration capacity, and advanced analytical tools impede the implementation of adaptive management processes.

- **Monitoring Design and Integration:** Monitoring programs require systematic evaluation and updating to ensure they track climate change impacts, emerging stressors, and species distribution shifts effectively. There is a **limited ability to integrate data across disparate monitoring efforts** due to a lack of publicly accessible repositories and standardized data sharing protocols.

- **Population Metrics:** Statistically appropriate **population estimates with associated uncertainty measures are lacking** for several native species, including California Bay shrimp, Sacramento splittail, and Longfin smelt. Current reliance on seasonal abundance indices inhibits robust assessment of management impacts.
- **Modeling Limitations:** Quantitative models linking improvements in fish populations to specific types of habitat restoration (e.g., tidal wetland or floodplain restoration) are **generally undeveloped**. Models are needed that link separate parts of the system to understand system-wide effects of climate change and extreme events.
- **Forecasting Gaps:** Gaps remain in the availability of forecasting products relevant to immediate Delta issues, such as soil moisture, soil salinity, and economic metrics. The lack of an integrated forecasting system for anticipating issues like HABs is a critical need.

IV. Socio-Ecological and Governance Lacunae

The resource management enterprise is challenged by insufficient integration of human dimensions, institutional fragmentation, and barriers to knowledge mobilization.

- **Social Science Deficit:** Applied social science research has **lagged behind** biological and physical components of the system, resulting in a **dearth of social data and research** necessary for effective and equitable management.
- **Community Knowledge Gaps:** There is a crucial need to develop a thorough understanding of how human communities' **values, livelihoods, well-being, and uses** of Delta resources vary across demographics and time. Social science analysis of how **droughts specifically affect Delta residents** remains limited.
- **Governance Barriers:** The highly **polycentric structure** of Delta governance, combined with high levels of conflict and power asymmetries, contributes to **"governance gridlock"** and challenges coordination across the multiplicity of organizations managing the Delta.
- **Knowledge Mobilization:** Scientific information flows are **decentralized and poorly connected** to decision-makers and communities. Investigation is required to identify **psychological, social, and structural barriers that inhibit institutional learning**, coordination, trusting, and the effective use of scientific information.
- **Traditional Knowledge Siloing:** Traditional Knowledge, especially from Tribal Nations, remains **siloed from conventional decision-making and resource management**, limiting the benefits of diverse knowledge systems to resource management.

References:

Boyer, K. E, Safran, S. M, Khanna, S., & Patten, M. V. (2023). Landscape Transformation and Variation in Invasive Species Abundance Drive Change in Primary Production of Aquatic Vegetation in the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science*, 20(4). http://dx.doi.org/10.15447/sfews.2023v20iss4art2 Retrieved from https://escholarship.org/uc/item/92705867

California Natural Resources Agency (2024). Healthy Rivers and Landscapes Science Plan. Available From: https://resources.ca.gov/-/media/CNRA-Website/Files/Initiatives/Voluntary-Watershed-Agreements/Draft_VA_Science_Plan.pdf

Christman, M. A, Khanna, S., Drexler, J. Z, & Young, M. J. (2023). Ecology and Ecosystem Effects of Submerged and Floating Aquatic Vegetation in the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science*, 20(4). http://dx.doi.org/10.15447/sfews.2023v20iss4art3 Retrieved from https://escholarship.org/uc/item/6h86h42r

Colombano, D. D; Rudnick, J.; Rowlands, N. A; Christman, M. A; Dahm, C. N; Thompson, J. K, et al. (2025). Five Perspectives to Advance Science-Informed Decision-Making in the Era of Climate Change and Extreme Events. *San Francisco Estuary and Watershed Science*, 23(3). http://dx.doi.org/10.15447/sfews.2025v23iss3art1 Retrieved from https://escholarship.org/uc/item/9wx7t02k

Conrad, J. L; Thomas, M.; Jetter, K.; Madsen, J.; Pratt, P.; Moran, P., et al. (2023). Invasive Aquatic Vegetation in the Sacramento–San Joaquin Delta and Suisun Marsh: The History and Science of Control Efforts and Recommendations for the Path Forward. *San Francisco Estuary and Watershed Science*, 20(4). http://dx.doi.org/10.15447/sfews.2023v20iss4art4 Retrieved from https://escholarship.org/uc/item/2v20x6zp

Dahm, C. N, Colombano, D. D, & Dalgren, R. A. (2025). Recent Findings and Future Prospects for Water Quality Effects from Catastrophic Wildfires in California, USA. *San Francisco Estuary and Watershed Science*, 23(3). http://dx.doi.org/10.15447/sfews.2025v23iss3art2 Retrieved from https://escholarship.org/uc/item/157618mx

Delta Stewardship Council (2022). 2022- 2026 Science Action Agenda a Vision for Integrating Delta Science. Available From: https://scienceactionagenda.deltacouncil.ca.gov/pdf/2022-2026-science-action-agenda.pdf

Delta Stewardship Council (2024). Grand Challenges in Delta Science Planning for Science in a Dynamic System. Available From:

https://deltascienceplan.deltacouncil.ca.gov/sites/default/files/2024-11-20-grand-challenges-in-delta-science-essay.pdf

Delta Stewardship Council (2024). Delta Plan Chapter 7: Reduce Risk to People, Property, and state Interests in the Delta. Available From: https://deltacouncil.ca.gov/pdf/delta-plan/2024-01-30-chapter-7.pdf

Delta Stewardship Council (2024). Delta Plan Five-Year Review. Available From: https://deltacouncil.ca.gov/pdf/delta-plan/2024-09-26-2024-five-year-review.pdf

Delta Stewardship Council (2025). Delta Adapts Adaptation Plan: Creating a Climate Resilient Future. Available From: deltacouncil.ca.gov/pdf/delta-plan/2025-06-26-delta-adapts-adaptation-plan.pdf

Delta Stewardship Council (2025). Tribal and Environmental Justice in the Sacramento-San Joaquin Delta. Available From: https://deltacouncil.ca.gov/pdf/2025-04-24-tribal-and-environmental-justice-in-the-sacramento-san-joaquin-delta-issue-paper.pdf

Gershunov, A.; Hatchett, B.; Weyant, A.; Dettinger, M.; Su, L.; Rhoades, A., et al. (2025). Atmospheric Rivers and Floods in California's Changing Hydroclimate. *San Francisco Estuary and Watershed Science*, 23(3). http://dx.doi.org/10.15447/sfews.2025v23iss3art3 Retrieved from https://escholarship.org/uc/item/1kw1d94p

Hartman, R., Knowles, N., Fencl, A., & Ekstrom, J. (2025). Drought in the Delta: Socio-Ecological Impacts, Responses, and Tools. *San Francisco Estuary and Watershed Science*, 23(1). http://dx.doi.org/10.15447/sfews.2025v23iss1art3 Retrieved from https://escholarship.org/uc/item/8c756578

Hestir, E., & Dronova, I. (2023). Remote Sensing of Primary Producers in the Bay–Delta. *San Francisco Estuary and Watershed Science*, 20(4). http://dx.doi.org/10.15447/sfews.2023v20iss4art5 Retrieved from https://escholarship.org/uc/item/82k2j1s9

Kudela, R. M, Howard, M. D, Monismith, S., & Paerl, H. W. (2023). Status, Trends, and Drivers of Harmful Algal Blooms Along the Freshwater-to-Marine Gradient in the San Francisco Bay–Delta System. *San Francisco Estuary and Watershed Science*, 20(4). http://dx.doi.org/10.15447/sfews.2023v20iss4art6 Retrieved from https://escholarship.org/uc/item/1dz769db

Larsen, L. G, Bashevkin, S. M, Christman, M. A, Conrad, J. L, Dahm, C. A, & Thompson, J. (2023). Ecosystem Services and Disservices of Bay-Delta Primary Producers: How Plants and Algae Affect Ecosystems and Respond to Management of the Estuary and Its Watershed. *San Francisco Estuary and Watershed Science*, 20(4). http://dx.doi.org/10.15447/sfews.2023v20iss4art1 Retrieved from https://escholarship.org/uc/item/2c4037fp

Mahardja, B., Bashevkin, S. M, Pien, C., Khanna, S., Pearson, D., Davis, B., & Basu, R. (2025). Heatwaves and Rising Temperatures in the Upper San Francisco Estuary: Trends and Effects on Ecosystems and Humans. *San Francisco Estuary and Watershed Science*, 23(1). http://dx.doi.org/10.15447/sfews.2025v23iss1art4 Retrieved from https://escholarship.org/uc/item/7n14h0pq

Rudnick, J., Heikkila, T., Koebele, E., Morrison, T., & Batavia, C. (2025). Assessing the State and Efficacy of Climate Governance Research and Practice in the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science*, 23(1). http://dx.doi.org/10.15447/sfews.2025v23iss1art2 Retrieved from https://escholarship.org/uc/item/67w3k56z

State Water Resources Control Boards (2025). Draft Water Quality Control Plan for the San Francisco Bay/ Sacramento-San Joaquin Delta Watershed. Available From: https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/docs/rev-draft-sacdelta-bdplan-updates.pdf

State Water Resources Control Board (2023). Final Draft Scientific Basis Report Supplement in Support of Proposed Voluntary Agreement for the Sacramento River, Delta, and Tributaries Update to the San Francisco Bay/Sacramento-San Joaquin Delta Water Quality Control Plan. Available From: https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/2023/staff-report/app-g2.pdf

Thompson, J. K, Dahm, C. N, Christman, M. A, Colombano, D. D, Rowlands, N. A, & Windham-Myers, L. (2025). The State of Bay–Delta Science: An Introduction to the 2025 Extreme Events Edition. *San Francisco Estuary and Watershed Science*, 23(1). http://dx.doi.org/10.15447/sfews.2025v23iss1art1 Retrieved from https://escholarship.org/uc/item/19x978df

Windham–Myers, L., Oikawa, P., Deverel, S., Chapple, D., Drexler, J. Z, & Stern, D. (2023). Carbon Sequestration and Subsidence Reversal in the Sacramento–San Joaquin Delta and Suisun Bay: Management Opportunities for Climate Mitigation and Adaptation. *San Francisco Estuary and Watershed Science*, 20(4). http://dx.doi.org/10.15447/sfews.2023v20iss4art7 Retrieved from https://escholarship.org/uc/item/97n052p9

Appendix A: Science Gaps from each source document

Prompt: For each of the 23 source documents, identify science gap and uncertainties on the management of natural resources in the Delta. Answer in the form of a list and use academic language

Drawing comprehensively upon the provided source documents, the following is an identification and summary of the specific science gaps and uncertainties related to the management of natural resources in the Sacramento-San Joaquin Delta (Delta), organized by the source document. These uncertainties span mechanistic, measurement, governance, and social domains, collectively impeding adaptive management and long-term resilience planning.

Healthy Rivers and Landscapes Science Plan

- **Population Metrics and Data Deficiencies:**
    - For non-salmonid native species (California Bay shrimp, Sacramento splittail, Longfin smelt, Delta smelt), current surveys provide **only abundance estimates** that **lack uncertainty estimates** and it is **not clear whether they correlate with true population abundance**.
    - Existing monitoring **does not yet collectively provide an estimate of abundance in major spawning areas** during the spawning season for Longfin smelt.
    - Existing monitoring uses **different methodologies, making comparisons and data integration difficult**.
    - **Standardized data collection methods, schemas, encodings, and processing protocols** are needed for tributary surveys (e.g., rotary screw traps).
    - A priority information gap is **data availability and centralization** to support coordinated data analysis and reporting.
- **Mechanistic and Modeling Gaps:**

  - Researchers have **not yet developed quantitative relationships between fish populations and many types of habitat restoration**, including floodplain habitat and tidal wetland habitat.
  - Uncertainty exists regarding the **thresholds of predator densities and invasive aquatic vegetation coverage** above which native fish survival is impaired or restored habitat is avoided.
  - The **mechanisms behind the flow-abundance relationships vary by species and are not fully understood**.
  - The White Sturgeon population model **was not developed to assess population growth rate in response to changes in habitat or flow**.
  - There is **no evidence that increased outflows during the spring season will affect the abundance of Microcystis or other cyanobacteria taxa and associated toxicity levels later in the same year**.
  - Evidence has **not yet been found conclusively demonstrating net export of food resources** from tidal wetlands into open-water channels.

- **Stochastic and Temporal Uncertainty:**
  - Population-level responses to Non-flow Measures **may not be observed during the term of the Program (8 years)** due to incremental implementation and the potential for **stochastic events or inter-annual variability to obfuscate trends**.
- **Knowledge Sovereignty:**
  - Data management plans are required to **protect the sovereignty of Tribes and not disclose sensitive or confidential information**.

Final Draft Scientific Basis Report Supplement in Support of Proposed Voluntary Agreement for the Sacramento River, Delta, and Tributaries Update to the San Francisco Bay/Sacramento-San Joaquin Delta Water Quality Control Plan

- **Modeling Relationships (Mechanistic Gaps):**
  - Researchers have **not yet developed quantitative relationships between fish populations and many types of habitat restoration**, including floodplain habitat and tidal wetland habitat.

  - The **mechanisms behind the flow-abundance relationships vary by species and are not fully understood**.
  - Evidence has **not yet been found conclusively demonstrating net export of food resources** from tidal wetlands into open-water channels.

- **Implementation Uncertainty:**
  - Uncertainty remains in **how effective increases in both flow and non-flow habitat will be** in achieving population goals.
  - The **sources of water purchases** (flow assets) **are not fully known**.
- **Monitoring Deficiencies:**
  - Uncertainty is introduced by the **current limitations of monitoring, modeling, and management knowledge**.

Draft Water Quality Control Plan for the San Francisco Bay/ Sacramento-San Joaquin Delta Watershed

- **Flow Calculation Accuracy (Measurement Uncertainty):**
  - There is a need to **evaluate methods for improving Delta outflow calculations**, including the methodology for calculating the Net Delta Outflow Index (NDOI), to ensure the use of the best available information.
- **Monitoring Gaps:**
  - Additional monitoring requirements will be identified for the tributary watersheds and the Bay-Delta estuary to **fill monitoring and information gaps**.
  - Any proposed changes to monitoring must consider the **need to preserve the integrity of the long-term data record**.
- **Ecological Impacts of Management:**
  - Need to **compile data, conduct studies, and review literature to determine the influence that large trees and other vegetation types have on levee and floodway safety**.

  - Research is needed to **develop and evaluate physical and non-physical barrier designs** to maximize their effectiveness in reducing adverse impacts on native fish and wildlife.
  - Research is needed to **reduce impacts that non-native predators and competitors have on native fish** and to **modify habitats which currently favor non-native fish over native fish**.

- **Governance and Integration:**
  - A **unified science plan has potential for increased efficiency and effectiveness** and may also **reduce management uncertainty**.

2022–2026 Science Action Agenda

- **Mechanistic and Environmental Thresholds:**
  - Uncertainty exists regarding the **dominant factors that produce a harmful algal bloom (HAB)** at a particular place or time in the Delta.
  - A critical knowledge gap is the ability to identify **thresholds in the survival and health** of managed fish and wildlife species relative to environmental variables (e.g., flow, temperature, dissolved oxygen).
  - The **nature and magnitude of synergistic effects** arising from co-occurring flow and non-flow stressors (e.g., predation, competing species, contaminants) on native species populations are **not well understood**.
  - Uncertainty surrounds **how environmental drivers** (e.g., nutrients, temperatures, water residence time) **interact to cause HABs** in the Delta.
  - The **health impacts of aerosolized toxins from HABs** are in need of investigation.
  - Research is needed to understand the **sources, exposure pathways, and impacts of contaminant mixtures** on all life stages of native fish species and their food sources in the Delta.
  - There is a need to resolve how uncertainties regarding **sea-level rise, increasing temperatures and hydrologic variability, and changing sediment supply interact with wetland restoration approaches**.

  - Uncertainty exists concerning how **water quality** and its elements change **under different management scenarios**.
  - Knowledge is needed on **how invasive aquatic vegetation influences consumptive water use at the scale of the Delta**.

- **Data, Monitoring, and Forecasting Deficiencies (Measurement Uncertainty):**
  - Currently, there are **no instruments or sensors that can feasibly detect HABs in real-time**.
  - There are **gaps in the availability of forecasting products** relevant to priority Delta issues (e.g., soil moisture, soil salinity, ability to meet water allocations, economic revenue).
  - Despite abundant monitoring data, there is a **limited ability or lack of standardized data sharing protocols to integrate across disparate monitoring efforts**.
  - A need exists to identify **fundamental aquatic and terrestrial environmental datasets** that are **missing, out of date, or not consistently collected**.
  - Monitoring programs require **evaluation and updating** to effectively track **climate change impacts, emerging stressors, and changes in species distributions**.

- **Socio-Ecological and Governance Gaps:**
  - **Applied social science research in the Delta has lagged behind** research on biological, physical, or other aspects of the system.
  - A **dearth of social data and research on how human communities live, work, and interact with the Delta** limits effective and equitable management.
  - Research is needed to identify **what key psychological, social, and structural barriers inhibit institutional learning, coordination** across diverse stakeholders and agencies, and the effective use of scientific information.

- There is a need to develop an understanding of how human communities' **values, and uses of cultural, recreational, agricultural, and natural resources vary** across geography, demographics, and time.
- Few studies overall have **informed adaptations to climate change, particularly regarding human behavior**.
- Uncertainty exists regarding how the **costs and benefits of economic development and ecosystem management** are distributed across Delta communities.

Delta Plan Chapter 7: Reduce Risk to People, Property, and state Interests in the Delta

This chapter on risk reduction identifies data and research gaps concerning physical infrastructure vulnerability.

- **Data Deficiencies and Transparency (Measurement Uncertainty):**
  - Information about levee conditions and threats that is kept by the almost 100 agencies involved is **not easily shared**, often retained only in **paper reports held by individual agencies or firms**. This results in California **not having the clearest possible understanding of risks** in the Delta.
- **Physical and Seismic Risk Uncertainty:**
  - Research is needed to better understand **dynamic issues such as climate change, seismicity, sea level rise, subsidence, and other areas**.
  - There is a need for **updated flood stage-probability functions**.
  - Improved **technologies for assessing levee integrity** are needed.
  - **Disagreements remain about the significance of the risks** posed by threats to Delta levees, despite long acknowledgment of these threats.
- **Ecological Effects of Management:**
  - Understanding is required regarding the **impacts on floodplain ecosystems and Delta flood management from upstream flood management infrastructure operations**, including reservoir operations.

- **Scientific Basis and Adaptive Management Deficiencies:**
    - Appeals of covered actions have identified **recurring topics that would benefit from additional research and synthesis**, specifically concerning **harmful algal blooms, salinity, and related water quality issues**, and **restoration project designs that minimize the presence of invasive species**.
    - Certifying agencies have faced challenges regarding the **inclusiveness, relevance, and objectivity criteria** of the Best Available Science policy during appeals.
    - Adaptive management plans submitted often **do not include robust treatment of data storage, data sharing, and communication strategies**.
    - Project-specific adaptive management plans have frequently failed to include clear statements that describe **how the project will manage the collection and dissemination of monitoring data**.
- **Data and Metric Gaps:**
    - Specific **performance metrics and analysis methods for environmental water supply reliability should be developed** and employed.
    - **Estimation methodology should be updated to reflect accumulated and expected climate change effects, combined with uncertainty analysis**.
    - A need exists to **compile a suite of indicators that describe the socioeconomic trends of Delta residents and communities**.
    - Research is needed to identify **metrics to quantify areas of deeply subsided public lands**, land leases supporting subsidence, and the **rate and amount of subsidence occurring**.
    - **Assessments of the Delta as a Place progress** were **limited due to a lack of available data**.
- **Research Integration:**
    - There is a need to fund scientific research that addresses emerging resource management gaps, including the need for more **collaborative,**

participatory science, interweaving traditional ecological knowledge and science, and integrating social and environmental science.

Grand Challenges in Delta Science Planning for Science in a Dynamic System

This essay outlines four "Grand Challenges" that represent major, systemic impediments to science-informed management.

- **Anticipatory Policy and Layered Stressors (Grand Challenge #1):**
    - Managers must anticipate a world where **environmental conditions and regulations may be fundamentally different** from those faced today.
    - **Layered stressors will interplay in complex and unpredictable ways**.
    - The threats to listed species and the broader ecosystem are **ever-increasing and for the most part still poorly understood**.
    - **Emergent pollutants**, such as PFAS, microplastics, and 6PPD-quinone, are capable of significantly damaging ecosystem structure and function.
    - **Current aquatic weed control protocols are not working (efficiently)** in many places.
    - New control methods and **expanded monitoring for submerged aquatic vegetation** are needed.
- **Pace of Science (Grand Challenge #2):**
    - **Rapid environmental change is outpacing the traditional pace of science**, requiring decisions to be made under greater uncertainty.
    - A **high degree of uncertainty will likely remain or increase**.
- **Knowledge Decentralization (Grand Challenge #3):**
    - Flows of scientific information **remain decentralized and poorly connected to decision-makers and communities**.
    - Scientists **poorly understand the managers' needs, perspectives, and strategies**.
    - A **lack of trust amongst competing interests** will likely lead to decision-making inefficiencies.

- **Social Science and Equity (Grand Challenge #4):**
    - **Tribes still feel that they are not being brought into the decision-making process in a meaningful way**.
    - The topic of **integrating human dimensions, equity, and environmental justice has been underrepresented** in the conventional science paradigm.
    - There are **limitations associated with funding mechanisms** (e.g., slow prioritization or language restrictions like Prop 1) that inhibit social science research.
    - The Delta science community **lacks a long-term vision for social science integration**.
    - There is a large deficit in **scientific monitoring capacity** to provide an effective monitoring enterprise without substantial additional investment.
    - The subjects of **contaminants and aquatic vegetation comprise critical unmet needs** for IEP and Estuary-related science.

Tribal and Environmental Justice in the Sacramento-San Joaquin Delta

- **Social and Environmental Justice Data Deficit:**
    - **Peer-reviewed literature and empirical data on environmental justice issues in the Delta are limited**.
    - Analysis of the Delta is needed for **areas outside the legal Delta boundary** (e.g., how issues manifest upstream and downstream in the watershed).
    - There is a need to increase **research and data analysis on tribal and environmental justice issues** to help with decision-making.
- **Public Health and Contaminant Exposure:**
    - There is a need for **increasing monitoring for harmful algal bloom (HAB) development and HAB toxin exposure (water and air)** using rigorous epidemiological methods to create better HAB management and mitigation strategies where vulnerable communities are most exposed.
    - Concerns persist regarding **mercury contamination** and **other emerging contaminants of concern** (e.g., PFAS or microplastics).

    - When freshwater flows are low, communities experience **drinking water contamination** and **increased concentration of pollutants**.

- **Traditional Knowledge and Data Sovereignty:**
    - There is a need to **facilitate dialogue among tribes, agencies, and other partners to increase the interweaving of Traditional Knowledges into the Delta science enterprise**.

Delta Adapts Adaptation Plan: Creating a Climate Resilient Future

- **Implementation and Knowledge Gaps:**
    - To ensure the efficacy of all adaptation strategies, **new research should be undertaken to fill specific knowledge gaps**.
    - A need exists for **more research on HABs and their impacts on people**, and a **better understanding of HAB impacts on air quality**.
    - Concerns are noted about **mercury contamination** and **other emerging contaminants of concern** (e.g., PFAS and microplastics).
    - Need to **conduct an updated assessment of the Delta sediment budget** to guide sediment management actions.
    - Research is needed to **restore more natural stream flows and functions** and **allow for sediment transport**, upstream of and within the Delta.
- **Monitoring and Modeling:**
    - Need to **apply integrated flood risk and emergency preparedness models** to simulate and predict the impacts of single and multiple levee failures across the Delta, including assessing scenarios of levee overtopping and flood dynamics under various climate conditions.
- **Governance and Coordination:**
    - Goals, metrics, objectives, understandings, and areas of concern should **reflect the diverse perspectives in the Delta**, requiring consensus on metrics for tracking progress.
    - There is a need to **address disconnects between how science is created and used**.

State of the Bay-Delta Science 2023 – Ecosystem services and disservices of Bay-Delta plants and algae

Larsen et al. 2023: Introduction: Ecosystem Services and Disservices of Primary Producers

- **Food Web and Detrital Dynamics (Mechanistic Uncertainty):**
    - Important gaps remain in **quantifying the interactions** between primary producers' ecosystem services and disservices.
    - Knowledge gaps exist in **quantifying the causal effects of HABs on food web productivity**.
    - A clear gap is understanding **detrital contributions of primary producers from the Delta and its watershed to food webs** and **how the quality of organic matter** from different species affects these contributions.
    - The general **drivers of the estuarine food web are poorly understood** in the Delta.
- **System-Level Physical Interactions:**
    - There is a need to understand the **effects of Delta-scale sediment and vegetation interactions on wetland persistence**.
- **Data and Quantification:**
    - Specific **carbon flux data gaps** exist in **freshwater tidal marshes and SAV and FAV habitats**.
    - It is necessary to quantify how **changing Delta inflows drive HABs and primary productivity** in general.
- **Governance and Decision-Making:**
    - How decisions on managing and controlling ecosystem services and disservices are made, **given uncertainty**, remains an open question.

Boyer et al. 2023: Landscape change and variation in invader abundance drive primary production of aquatic vegetation

- **Measurement and Modeling Limitations:**
    - Estimates of aquatic vegetation production incorporate **uncertainty in the per-unit area productivity of each individual plant species**.

  - Researchers **had difficulty finding productivity rates for some of the species found in the Delta**.
  - Many studies report productivity rates of **mixed field assemblages** and thus could not be used for models seeking individual species' rates.
  - The uncertainty in production estimates is **much more sensitive to the area covered by each species** than to the species' productivity rates.

- **Mechanistic Ecology:**
  - There is a need to **measure productivity rates of individual FAV and SAV alone vs. in mixed assemblages**, under current and predicted future conditions, because **species interactions are mediated by abiotic conditions**.
  - The potential effects of **more frequent or perpetual frost-free winters on tropical invasive aquatic vegetation** are uncertain regarding the rate and magnitude of increase in coverage.

Christman et al. 2023: Ecology and ecosystem impacts of aquatic vegetation

- **Mechanistic Gaps (Aquatic Vegetation):**
  - **Remaining knowledge gaps underlie understanding of aquatic macrophyte effects** on Delta ecosystems, including their roles and relationships with respect to **nutrients and nutrient cycling, evapotranspiration (ET) and water budgets, carbon and sediment, and emerging effects on fish species**.
  - The effects of macrophyte communities on **ET is poorly studied**, particularly for non-native FAV species, and the **lack of ET rates for Delta aquatic macrophytes represents a significant gap** in water budget understanding.
  - Much still remains to be learned about the **ecosystem engineering capabilities of SAV on flows and sediment dynamics**.
  - Specific research is needed to understand the effects of macrophyte communities on sediment dynamics in **flooded islands**.
  - The **potential effects of FAV spread** (*Ludwigia spp.* and *A. philoxeroides*) on **marsh biogeochemistry and the resilience of infested marshes to sea level rise have yet to be investigated**.

    - Understanding is required regarding how **episodic events/disturbances** (i.e., atmospheric rivers, droughts, changes in nutrient status) **affect ecological processes and key species**.

- **Monitoring and Modeling:**
    - **Consistent monitoring of aquatic vegetation is currently lacking**.
    - A **broader suite of studies** encompassing **multiple SAV species in various environments** is needed to construct models capable of projecting the impacts of SAV on flows and sediment dynamics across the entire Delta.

Conrad et al. 2023: Management of invasive aquatic vegetation

- **Control Efficacy and Data Gaps:**
    - The science of control efforts in the Delta is **nascent**.
    - The results of large-scale herbicide control programs have been **mixed** due to the challenge of applying herbicides effectively in a tidal system.
    - Biological control agents for water hyacinth have provided **negligible control benefit** due to unsuitability for the temperate Delta climate.
    - The existing literature on the Delta **does not cover physical controls** such as benthic mats and floating barriers.
    - **No local studies have been published on control outcomes** for *Phragmites australis* or *Arundo donax* in the Delta.
    - Studies on chemical control often are limited by the **inability to compare treated sites to untreated areas for the same period**.
    - Adaptive management of IAV control is currently **stymied by the lack of a consistent monitoring program**.
    - There is a **lack of necessary modeling tools to evaluate trade-offs across alternative treatment plans**, including appropriate **climate-matching for candidate biological control agents**.
- **Non-Target Effects:**
    - This review highlights major knowledge gaps in understanding the **non-target effects** of current treatment approaches.

Hestir et al. 2023: Remote Sensing of Primary Productivity

- **Monitoring and Data Production:**
    - **Challenges associated with continuity and data latency remain**.
    - There is **no systematic monitoring mandate for airborne remote-sensing data collection**.
    - University researchers **do not have the mandate, scope, or funding to produce products operationally** beyond the research phase.
    - Federal agencies **do not provide the regionally-tuned products** necessary for location-specific management decisions.
    - Need for **standardization of large-data-file management and sharing** to meet user needs and legislative requirements (e.g., AB 1755).
- **Integration and Feedback:**
    - A notable **gap still exists on the connections between "land" and "water" domains**.
    - There is **limited understanding of feedback points** regarding how wetland transitional zones respond to the combined effects of **warming temperatures, sea-level rise (SLR), and changing salinity patterns**.
    - There is still a **gap between map generation and management decisions**.
    - Products need to be generated in a way that includes **well-quantified and well-communicated uncertainties**.

Kudela et al. 2023: Status, trends, and drivers of harmful algal blooms

- **Monitoring and Data Quality:**
    - There is a **lack of consistent monitoring of both phytoplankton and toxins**.
    - Underlying technical issues with how counts were completed introduce **undesirable uncertainty in the historical data sets**.
    - The number one priority should be to **effectively integrate existing monitoring programs** to create an effective monitoring and forecasting system.
- **Mechanistic and Health Gaps:**

    - The **fate and transfer of toxins within the airshed, watershed, and food web are largely unknown**, leading to large gaps in understanding potential exposure routes and effects on both the ecosystem and humans.
    - It is **not clear that all pathways of nutrient transformations are accounted for** in existing budgets.

- **Modeling and Mitigation:**
    - It is **not clear that the ability to predict environmental responses** to long-term mitigation strategies (hydrological modification and nutrient reduction) is acceptable.
    - **HAB abundance models spanning the freshwater-to-marine continuum are lacking**, as are **watershed-scale models** that focus on HABs.

Windham-Myers et al. 2023: Carbon sequestration and subsidence reversal

- **GHG Flux and Measurement Uncertainty:**
    - The **largest uncertainties** in 40-year climate mitigation estimates derive from **uncertainties in flow and water operations**, which drive projections of aquatic habitat extent and condition.
    - The **fate of wetland soils, as a millennial-scale Carbon (C) sink, is very uncertain**, due to intertwined climate and land-use drivers.
    - Changes in annual flux rates of **methane (CH4) and nitrous oxide (N2O) are highly uncertain** and are **currently not sufficiently quantified** to estimate the benefits of GHG mitigation in Delta freshwater tidal habitats.
    - For FAV and SAV habitats, a key limitation for their inclusion in mitigation strategies is **uncertainty in their distribution** and **uncertainty in their net atmospheric exchanges** (e.g., CO2 and CH4).
- **Modeling Limitations:**
    - Current data and tools are **insufficient for dynamic future conditions** given changing climate, landscape, and operational drivers.
    - Necessary hindcast and forecast models for **past and future C fluxes** in deep channels and transgressive uplands **do not exist**.
- **Restoration Efficacy:**

- **Long-term monitoring is still required** to quantify the climate-mitigation benefit of adaptation actions.

State of the Bay-Delta Science 2025 Edition – Extreme Events

Thompson et al. 2025: Introduction to the Extreme Events Edition

- **Systemic Complexity:**
  - Extreme events are **adding new and challenging dimensions to an already "wicked" management setting**.
- **Modeling Resolution:**
  - Understanding of future scenarios will continually evolve as researchers **refine regional models with better resolution on the drivers of variability**.

Rudnick et al. 2025: Governance and Climate Adaptation

- **Governance Structure and Efficacy:**
  - The combination of high polycentricity, conflict, and power asymmetries contributes to what can feel like **"governance gridlock"** and an inability to change the status quo.
  - The literature on Delta governance only **sparsely addresses governance features or the implications of Delta history** on the governance system today—a key gap in knowledge.
  - Delta governance actors continue to **struggle in navigating substantial fragmentation** both geographically and across resource sectors.
  - The **lack of a shared overarching framework that defines regional climate-governance objectives** may limit progress.
- **Research Deficit:**
  - **Peer-reviewed literature on specific climate-governance efforts in this specific region is slim**.
  - Research explicitly assessing the evolution of **politics and power dynamics** in the governance system and its effects on climate adaptation outcomes are **very limited**.

    - There is **very limited evidence of ongoing research trying to systematically or rigorously evaluate the efficacy of climate-governance efforts** in the Delta.
    - Analysts need **better measures of desired outcomes**, including the capacity for greater coordination and conflict management.
    - Need to develop **better quantitative and qualitative indicators of equity** in governance processes and outcomes.
    - The review **only briefly addresses Tribal climate governance**, reflecting **limitations in the availability of peer-reviewed or gray literature**.
- **Monitoring and Scale Mismatches:**
    - Questions have been raised about the **adequacy of some parts of the science system—such as the effectiveness of the Delta's monitoring enterprise**—to adequately track changing conditions over time.
    - Projected outcomes affecting stakeholders **outside the legal Delta boundary** have **rarely been incorporated into Delta decision-making processes** focused on the legal Delta boundary.

Hartman et al. 2025: Droughts

- **Social Science Deficit (Drought):**
    - **Further social science research on how drought affects the Delta's communities is needed**, as existing research focuses largely on upstream or export-reliant regions.
- **Mechanistic and Ecological Gaps:**
    - **Exactly when, where, and what species will form algal blooms remains unknown**.
    - The **role of nutrient inputs and contaminants**—which may increase in concentration during droughts—on the ecosystem is **poorly understood**.
    - Understanding is required as to **why Delta Smelt range is limited to less than 6 psu in dry years** (despite higher laboratory tolerance).
    - Mechanistic studies of species' **thermal tolerance** and **responses to drought** are needed.

    - The mechanism of how the interaction of warming and drought affects **evaporation demands remains unclear** (uncertainty exists on whether physiological limits or evaporative loss will dominate).

- **Management Efficacy and Data:**
    - Most tidal restoration sites in the Delta are **too new for their effectiveness to be evaluated**.
    - A **better understanding of the tools we currently have for mitigating ecosystem effects** is needed, as some drought actions have had mixed results.
    - There is a need for **scientific evaluation of the effectiveness of previous drought actions**.

Mahardja et al. 2025: Heatwaves

- **Thermal Flow Benefits (Mechanistic Gap):**
    - The **amount of flow required to provide a meaningful temperature benefit for fish species in the Delta has not been quantified**.

Dahm et al. 2025: Wildfires and water quality

- **Wildfire and Atmospheric Deposition (Mechanistic Gap):**
    - **Atmospheric deposition of small particles linked to smoke from wildfires** is an important topic for future research in the Delta watershed, because they affect both humans and ecosystems.
    - Human-health effects and effects on sensitive high-elevation lakes and reservoirs **deserve special attention**.

Gershunov et al. 2025: Atmospheric Rivers

- **Hydroclimate Uncertainty:**
    - The projected increase in hydroclimate volatility, driven by atmospheric rivers, **hampers the ability to detect emerging hydroclimatic trends with statistical confidence**.
    - Global Climate Models (GCMs) may be **deficient in their representation of hydroclimate variability** in California.

Colombano et al. 2025: Synthesis and Perspectives

- **Climate Modeling and Data Uncertainty:**
    - **Climate change signals can be difficult to detect** as a result of California's variable hydroclimate.
    - **Greater levels of uncertainty as a result of evolving climate models** can present challenges for decision-making.
    - The science community needs to **develop guiding principles for AI use in the Delta** to balance costs and benefits, review **major ethical considerations of contributing to greenhouse gas emissions while running energy-intensive AI models**, and establish rules for **protecting scientific integrity while using generative AI**.
- **Socio-Ecological Monitoring Deficit:**
    - The Delta is **lacking a comprehensive monitoring of human dimensions**.
    - Existing socio-economic monitoring efforts **do not yet have support for long-term replication and continuity—nor for integration with environmental and ecological monitoring programs**.
    - Quantifying the **complex effects of climate change on socio-economic dimensions** of the Delta is a priority area of research.
- **Institutional and Decision-Making Gaps:**
    - There is a **great need to link separate models that describe different parts of the system** to understand the system-wide effects of climate change and extreme events.
    - The **difficulty of making decisions using imperfect or incomplete information cannot remain a hindrance to climate action**.
    - The Delta science and management community needs to become **capable and comfortable with decision-making under continually changing conditions and lower levels of scientific certainty**.