2024

Grand Challenges in Delta Science

Planning for Science in a Dynamic System

Delta Science Program

DELTA STEWARDSHIP COUNCIL

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Introduction

California's climate is defined by extremes. From droughts to floods, wildfires to mudslides, these extremes create inherent and complex social and ecological challenges that are only increasing with climate change[1]. These challenges are especially prominent in the Sacramento-San Joaquin Delta, where over a century of human-caused modifications has reshaped the landscape[2] to convey water across the state and promote agriculture and industry.

Challenges in the Delta have many dimensions (e.g., physical, socioeconomic, water supply) and sometimes conflicting solutions, so much so that Luoma et al., 2015 describes managing them as "Problems like the Delta are formally 'wicked' problems that cannot be 'solved' in the traditional sense, but they can be managed with appropriate knowledge and flexible institutions"[3].

Box 1: The Coequal Goals

The Delta Reform Act states:

"'Coequal goals' means the two goals of

1. Providing a more reliable water supply for California and
2. Protecting, restoring, and enhancing the Delta ecosystem.

The coequal goals shall be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place." (Cal. Wat. Code § 85054)

The Sacramento-San Joaquin Delta Reform Act of 2009 (Delta Reform Act)[4] identifies coequal goals for the State of California to inform its management of the Delta (Box 1) and requires that best available science be used (Cal. Wat. Code §§ 85084 and 585302(g)). To promote best available science, it's helpful to unpack the "wicked" problem that is the Delta by focusing on the "grand challenges" to Delta

[1] Franklin and MacDonald 2024
[2] Whipple et al., 2012
[3] Luoma et al., 2015
[4]California Water Code § 85000 et seq. *found at https://leginfo.legislature.ca.gov/faces/codes_displayexpandedbranch.xhtml?tocCode=WAT&division=35.&title=&part=&chapter=&article=&nodetreepath=35)

Science. The term grand challenges, in the context of this essay, is inspired by a 2001 report by the National Research Council (NRC)[1] identifying the most important environmental research challenges of the next generation. In this report, NRC identified eight so-called grand challenges in the environmental sciences (Appendix A)—major scientific tasks that are compelling for both intellectual and practical reasons, that offer potential for major breakthroughs based on recent developments in science and technology, and that are feasible given current capabilities and improved dedication of resources.

Given the dynamic nature of the Delta and drawing inspiration from Luoma et al., 2015 and the NRC's report, the Delta Science Program proposes framing its next update of the Delta Science Plan around grand challenges in Delta science. This approach will support the development of vision, principles, and approaches to better coordinate Delta science and the long-term attainment of the coequal goals through the shared framework of the Delta Science Plan.

Catalyzing Science Coordination through the Delta Science Plan

The Delta Science Program is in the process of updating the Delta Science Plan[2] for the third time. The Delta Science Plan, recommended in the Delta Plan[3], is collaboratively developed with the Delta science community that aims to provide the vision, principles, and approaches for coordinating Delta science actors and communicating the outcomes of science activities and their management implications to decision-makers.

In considering how best to update the Delta Science Plan, the Delta Science Program is proposing to take a slightly different approach compared to past plans. Rather than documenting what the community already does well, the focus of the updated plan is on specific grand challenges that, when addressed through coordination and collaboration, can better advance shared goals and accelerate scientific understanding and decision-making. With this more targeted approach, the 2025 Delta Science Plan will build on past Science Plans but be more forward-looking and serve as a rallying cry for better coordination of Delta science to advance the coequal goals.

[1] https://nap.nationalacademies.org/catalog/9975/grand-challenges-in-environmental-sciences
[2] DSC 2019.
[3] https://deltacouncil.ca.gov/delta-plan/

To gather and distill the grand challenges in Delta science, the Delta Science Program conducted a literature review and synthesis of grand challenges to orient the community around common goals. This essay lays out the grand challenges before going forward with the full Delta Science Plan update. Ultimately, the 2025 Delta Science Plan will establish strategies and tools that the Delta science community can implement or optimize to address the grand challenges.

Identifying Grand Challenges

To identify and synthesize grand challenges, we reviewed visionary documents that are widely referenced by scientists and managers that are relevant to the science of the Delta, its watershed, and the broader San Francisco Estuary. The visionary documents include peer-reviewed literature, agency and workshop reports, scientific reports, official memos, and review products from the Delta Independent Science Board (Delta ISB). Through this literature review, we brought together ideas from diverse voices and organizations to curate a list of overarching gaps and challenges to Delta science. This essay is not meant to substitute these visionary documents, but rather to collate their contents to build out actionable steps to address the grand challenges.

Box 2: Criteria for Grand Challenges

Following the National Research Council (2001), problem must be:

- Compelling for intellectual and practical reasons and offer the potential for major breakthroughs in science or science governance (i.e., potential for impact).
- Feasible to address given current capabilities and assuming a significant infusion of resources.

Methods

We restricted our analysis to papers, reports, and conference/symposia white papers that:

1. focused on Delta issues;
2. addressed larger, overarching issues (i.e., grand challenges); and
3. were published since 2007 when the Delta Vision Blue Ribbon Task Force[1] laid the foundation for the Delta Reform Act.

[1] Isenberg et al., 2008

This resulted in a total of 32 documents (Table 1, Appendix B). The documents were split up amongst the authors to read and identify any "candidate" grand challenges for further review by the entire team.

Grand Challenge Refinement

A total of 125 relevant candidate grand challenges were identified from the reviewed documents (Appendix B). We then reviewed the candidate grand challenges and evaluated them against the criteria in Box 2. Removal of candidate challenges that did not meet the criteria resulted in a shortened list of 17 candidates (Appendix B). The authors then grouped these 17 candidates into thematic areas that coalesced into four overarching grand challenges (Figure 1). The first three grand challenges are drawn from this literature review. The fourth grand challenge was not well reflected in the visionary documents reviewed, but is supported by the broader scientific literature, including recent agency documents and policies. The fourth grand challenge was developed to ensure the list of top grand challenges fully reflects the challenges of a diverse and forward-looking Delta.

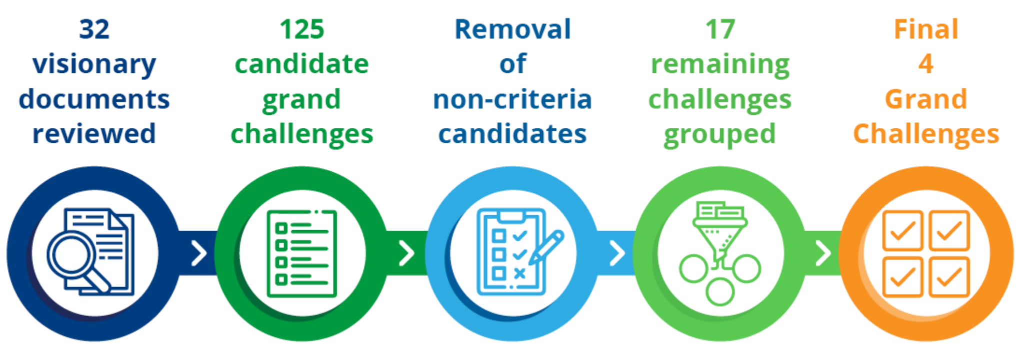

Figure 1. Grand Challenges development process, starting with review of 32 visionary documents on the Bay-Delta system. This resulted in 125 candidate grand challenges pulled from the literature review which were reviewed against the grand challenges criteria (described above) and finally compiled into the final four grand challenges.

Table 1. List of papers reviewed for Grand Challenges in the Delta. More extensive information can be found in Appendix B.

Title	Type of Document
Delta Vision Strategic Plan (Isenberg et al. 2008)	Peer Review Panel Report
Envisioning Futures for the Sacramento-San Joaquin Delta (Lund et al. 2007)	Scientific Report
Delta Plan (Delta Stewardship Council (DSC) 2013)	Management Plan
Challenges facing the Sacramento-San Joaquin Delta: Complex, Chaotic, or Simply Cantankerous? (Luoma et al. 2015)	Journal Article
A Case Study in Integrated Management: Sacramento–San Joaquin Rivers and Delta of California, USA (Lacan and Resh 2016)	Journal Article
San Francisco Estuary BluePrint (San Francisco Estuary Partnership 2016)	Strategic Plan
Science Enterprise Workshop: Executive Summary (DSC and United States Geological Survey (USGS) 2018)	Workshop Report
Science Enterprise Workshop: Complete Proceedings (DSC and USGS 2018)	Workshop Proceedings
Developing Biological Goals for the Bay-Delta Plan: Concepts and Ideas from an Independent Scientific Advisory Panel (Ruggerone et al. 2019)	Panel Report
A Review of the Interagency Ecological Program's Ability to Provide Science Supporting Management of the Delta (Delta ISB 2019a)	Delta ISB Review Report
Comments on the Draft Delta Plan Ecosystem Amendment Performance Measures (Delta ISB 2019b)	Comment Letter - Unpublished
Delta Science Funding and Governance Initiative Implementation Report (DSC 2020)	Implementation Report
Review of the Preliminary Public Draft Delta Plan Chapter 4 Ecosystem Amendment (Delta ISB 2020a)	Memorandum
A Social Science Strategy for the Delta: Observations and Recommendations (Delta ISB 2020b)	Memorandum
Building an Effective Delta Science Enterprise (Delta ISB 2020c)	Delta ISB Review Report
Critical Needs for Control of Invasive Aquatic Vegetation in the Sacramento-San Joaquin Delta (Conrad et al. 2020)	Journal Article
A Social Science Strategy for the Sacramento-San Joaquin Delta (Biedenweg et al. 2020)	White Paper
How to Respond? An Introduction to Current Bay–Delta Natural Resources Management Options (Sommer 2020)	Journal Article
Excerpts from the Draft Science Needs Assessment: Agency-Spanning Science for a Rapidly-Changin Delta (Delta ISB 2021a)	Meeting Proceedings
The Science of Non-Native Species in a Dynamic Delta (Delta ISB 2021b)	Delta ISB Review Report
Science Needs Assessment Integrating Science for a Rapidly Changing Delta: Principal Science Recommendations (Delta ISB 2021c)	Delta ISB Review Report
Delta Adapts: Creating a Climate Resilient Future (DSC 2021)	White Paper
Preparing Scientists, Policy-Makers, and Managers for a Fast-Forward Future (Norgaard et al. 2021)	Journal Article

Title	Type of Document
Outcomes from the 2021 Science Advisory Committee meeting on Bay-Delta Integration (DSC 2021)	Meeting Report - Unpublished
Early Detection Rapid Response Draft Framework (Delta Interagency Invasive Species Coordination Team 2021)	White Paper - Unpublished
IEP Science Strategy 2020-2024 (IEP 2022)	Strategic Plan
Review of the Monitoring Enterprise in the Sacramento-San Joaquin Delta (Delta ISB 2022a)	Delta ISB Review Report
Collaborative Adaptive Management Team Assessment of Reviews (Conrad and Moffatt 2022)	White Paper
2022-2026 Science Action Agenda: A Vision for Integrating Delta Science (DSC 2022)	Science Action Plan
San Francisco Estuary Blueprint (San Francisco Estuary Partnership 2022)	Strategic Plan
Review of Water Supply Reliability Estimation Related to the Sacramento-San Joaquin Delta (Delta ISB 2022b)	Delta ISB Review Report

Grand Challenges

The four grand challenges are:

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

Below we elaborate on these grand challenges. For the 2025 Delta Science Plan, we intend to engage with the public to identify strategies, tools, and other actions to address these grand challenges. This will translate the current list of challenges into a suite of coordinated actions for the Delta science community.

Grand Challenge #1

Grand Challenge #1:
Scientists and managers must anticipate a world in which environmental conditions and regulations may be fundamentally different from those faced today.

Much of the science conducted in the Delta is driven by state and federal regulations focused on listed species of fish, and water quality. As species become functionally extinct or shift in their range, or water scarcity in upstream reservoirs makes existing water management targets impossible to meet, science needs to inform and help adapt regulations accordingly. Further, potential changes to flow regulations (e.g., through updates to the Bay-Delta Water Quality Control Plan), food web disruption, habitat degradation, legacy and emergent contaminant pollution, species invasions and range shifts[1], and other environmental stressors will continue to influence the underlying drivers of Delta ecosystems. Managers must expect that these layered stressors will interplay in complex and unpredictable ways. Without a holistic management approach, we may overlook key signals of species' decline until it's too late. Laying a scientific foundation for policy that is adaptive to accommodate future novel conditions requires early anticipation of those needs[2]. Therefore, scientists and managers must anticipate and prepare for a world in which environmental conditions and regulations may be fundamentally different from those faced today.

Managing this challenge requires scientists to coordinate research activities with decision-makers[3]. While scientists may be able to assess future environmental conditions, decision-makers should similarly anticipate future policy needs and work with scientists to determine the scientific uncertainties associated with possible future policies. For example, Delta management is already predominantly limited to management of species listed on federal or state endangered species acts, while the threats to those species and the broader ecosystem is ever-increasing and for the most part still poorly understood. For example, emerging

[1] Delta ISB, 2021b
[2] Norgaard et al., 2021; Delta ISB 2020c
[3] Sommer et al., 2023

pollutants, such as PFAS[1], microplastics[2], and 6PPD-quinone[3], are capable of significantly damaging ecosystem structure and function.

With recent droughts nearly decimating cohorts of Winter-run Chinook salmon[4] and dwindling survey detections of Delta Smelt[5], scientists and decision-makers will need to consider new policy strategies for protecting or restoring key species and ecosystems should either species go extinct, and current species and habitat protections thereby disappear or change. Conversely, as additional Delta species (e.g., Longfin smelt) are faced with increasingly perilous status, the current approach to managing the system appears to not be protective for listed or unlisted species. The Delta Stewardship Council's recent Ecosystem Amendment to the Delta Plan[6] seeks to balance the hydrodynamics of the Delta with improving ecosystem health, suggesting an interest by managers to shift away from single-species management and toward ecosystem function and multiple-species management. Recent studies have emphasized functional flow management (e.g., North Delta flow actions that stimulate phytoplankton blooms)[7] and multi-benefit solutions (e.g., wetland restoration for habitat, recreation, and salinity management)[8]. These studies demonstrate a widespread interest in a shift toward managing for improved ecosystem function outcomes.

Such a shift, at a large scale, would require focused and coordinated scientific efforts at the watershed/estuary scale to understand complex interactions between species, management activities, and ecosystem effects (e.g., drivers of food webs; cumulative effects of wetland restoration on flows, sediment, and salinity; temperature and other water quality impacts of reservoir operations and their impacts on ecosystems)[9]. Others[10] have called for policy that is flexible enough to accommodate a dynamic, heterogeneous, and variable Delta, which carries a similar set of science needs as functional management. An ecosystem-level

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[1] Dean et al., 2020
[2] Yusuf et al., 2022
[3] Tian et al., 2020
[4] Hassrick et al., 2022
[5] Bork et al., 2020
[6] https://deltacouncil.ca.gov/pdf/delta-plan/2022-06-29-chapter-4-protect-restore-and-enhance-the-delta-ecosystem.pdf
[7] Frantzich et al., 2021; Yarnell et al., 2015, Yarnell et al., 2020
[8] Milligan et al., 2020; Milligan 2022
[9] Isenberg et al., 2008
[10] Lund et al., 2007

recovery will require coordination and support across local, state, and federal levels.

Preparing for an uncertain future may be most effectively accomplished through a scenario-based approach[1] that uses models to project how different management strategies will interact with future environmental conditions and assess tradeoffs, or a stress-testing approach in which solutions result in acceptable system performance over the widest range of potential climate change[2]. Using models to evaluate scenarios and tradeoffs, in turn, requires breaking down barriers to the use, transparency, communication, and linking of models and data[3].

Anticipating future policy decisions and how human values and changing economic conditions influence human use of the Delta and its resources requires expanding the capacity for social science[4]. Meeting science needs associated with future policies also requires improved interagency coordination and collaboration[5] and increased research coordination (i.e., monitoring, knowledge transfer) at the watershed and estuary scale[6], together with an expanded capacity to perform synthesis[7]. Scientists must also be able to horizon scan[8], referring to the systematic search for potential threats and opportunities, to identify future challenges not yet present within the system or currently of only marginal importance[9]. Finally, the widespread uptake of adaptive management is crucial to addressing this grand challenge. Expanding our capacity to support adaptive management over decades, rather than the more frequent 5-10-year adaptive management plans currently in use, will be instrumental in increasing our ability to grapple with managing novel ecosystems with novel regulations.

[1] Lacan and Resh 2016; Sutherland and Woodroof 2009
[2] Poff et al., 2016; Ray et al., 2020
[3] Delta ISB 2021c; Wilkinson and Edinow 2008; Flynn et al., 2018
[4] Biedenweg et al., 2020
[5] Delta ISB 2020c
[6] San Francisco Estuary Blueprint, 2022; Delta ISB 2021c; Delta Stewardship Council 2022a
[7] Baron et al., 2017; Interagency Ecological Program (IEP) 2022
[8] See Sutherland and Woodroof 2009 for a toolkit of methods
[9] Delta ISB 2021c; Norgaard et al. 2021

Grand Challenge #2

Grand Challenge #2:
Environmental change is outpacing the traditional pace of science.

The second grand challenge is that rapid environmental change is outpacing the traditional pace of science, requiring decisions to be made under greater uncertainty. Approaches to managing this challenge can focus on allowing for quicker decision-making or by prolonging environmental tipping points and minimizing surprises.

Allowing for quicker decision-making invokes the need to develop new rapid-response funding processes for targeted studies[1] with associated mechanisms for executing and reporting on those studies in a timely fashion. Additionally, preliminary results might be made available prior to the traditional peer review cycle (e.g., preprints) or alternative rapid-response peer review processes for management-relevant results should be sustained, such as those facilitated by the Delta Science Program[2]. This grand challenge also invokes the need to expand adaptive monitoring programs that can address emerging change while continuing to document long-term trends, relevant to the needs of multiple agencies[3]. Voluntary and collaborative groups may be well suited to address this need and could build on successes of such existing and past groups like the Collaborative Science and Adaptive Management Program[4] (CSAMP). Such groups serve as venues that bring together many interests to focus on cross-perspective information needs for water and ecosystem management.

Prolonging environmental tipping points and minimizing surprises requires analysis—especially through modeling and adaptive management experimentation—of how management interventions can slow the pace of rapid change and generate more time for adaptation[5]. Examples of these interventions include strategies to minimize the introduction and spread of invasive species, flow or habitat operations to create thermal refugia, or targeted tidal marsh restoration

[1] Delta ISB 2022a; Delta Stewardship Council 2020; Interagency Adaptive Management Implementation Team 2019
[2] https://deltacouncil.ca.gov/delta-science-program/scientific-peer-review
[3] Delta ISB 2022a; Luoma et al., 2015
[4] https://csamp.baydeltalive.com/
[5] Vlieg and Zandvoort 2013; Ruggerone et al. 2020

to slow the rate of local inundation or the rate of change of the tidal prism[1]. Novel techniques like machine learning and artificial intelligence, using long-term records of field and remotely sensed data, leverage such tools[2]. At a local level, communities may seek to slow environmental change by improving regional resilience to climate change which can be done through actions such as those detailed by the Delta Stewardship Council's draft Delta Adaptation Plan (Delta Adapts)[3].

An important aspect of this grand challenge is that, despite strategies to better align the pace of management-relevant science with that of environmental change, a high degree of uncertainty will likely remain or increase[4]. Ensuring that robust decision-making under uncertainty[5] is synthesized and effectively communicated to decision-makers and the broader public is an important aspect of managing this grand challenge and ensuring continual expansion and uptake of adaptive management. Delta-specific social science investigations and syntheses could lead to improved governance structures[6] or decision-making practices. The Delta ISB's ongoing review of decision-making under deep uncertainty[7] could offer recommendations and tools for stakeholder engagement and anticipatory planning that could help address this grand challenge.

[1] Conrad et al., 2020; Ebersole et al., 2020; Cordoleani et al., 2021; Stark 2017; Stark et al. 2017
[2] Tillotson et al., 2022
[3] https://deltacouncil.ca.gov/delta-plan/climate-change
[4] Delta ISB 2023
[5] Greve et al., 2018; Kochenderfer 2015; Polasky et al., 2011
[6] Rittelmeyer et al., 2024
[7] https://deltacouncil.ca.gov/pdf/isb/meeting-materials/2023-08-04-isb-final-prospectus-dmdu.pdf

Box 3. Adaptive Governance[4]

Adaptive governance can build on learning and change to the way systems are managed:

- Adaptive management is a science-based, structured approach to improving understanding of the problems and uncertainties of environmental management.
- It supports, and is supported by, complex governance systems, including diverse structures, processes, and rules for managing natural resources.
- Adaptive governance occurs when governance systems can facilitate ongoing and regular interactions between vested actors and organizations.

With these many, varied approaches for managing ecosystems in the face of uncertainty, it is important to keep in mind the ecosystem trade-offs of carrying out different management actions (e.g., different species benefit from different flow regimes at different times). "Turn-taking" optimization[1] is an approach that allows managers to optimize conditions for priority ecological indicators, depending on the needs of the system at different times, rather than trying to optimize all ecological indicators at all times. Lastly, minimizing surprises requires investment in science tools that help anticipate near-future conditions, as well as the long-range planning forecasts called for in Grand Challenge #1, including modernized forecasts of water supply, water quality, and ecosystem conditions relevant to management[2]. Adaptive governance can be used to manage natural resources in a manner that is based on learning and anticipates change[3]. Adaptive governance is an institutional framework that would support the uptake of these various approaches and facilitates management under unforeseen circumstances.

[1] Alexander et al. 2018
[2] Norgaard et al. 2021; Delta ISB 2021c; Delta ISB 2022b
[3] https://deltacouncil.ca.gov/pdf/science-program/information-sheets/2024-08-28-final-governance-of-adaptive-management-information-sheet.pdf

Grand Challenge #3

> **Grand Challenge #3:**
> Flows of scientific information remain decentralized and poorly connected to communities and decision makers.

The third grand challenge to Delta science is that flows of scientific information remain decentralized and poorly connected to decision-makers and communities with a vested interest in the Delta[1]. Scientists are often unaware of decision-maker needs and miss out on opportunities to inform policy development[2]. A review of the use of science in decision-making revealed that this problem is widespread[3]. For their part, scientists may not communicate effectively with managers even when they have the opportunity because they poorly understand the managers' needs, perspectives, and strategies[4]. In general, missed opportunities to draw direct connections between scientists and policymakers have cascading impacts on public perceptions and trust building. The challenge of effective science coordination remains paramount, particularly concerning major topics with wide-ranging and multifaceted impacts that span agency or geographic mandates like salinity management or harmful algal bloom mitigation.

Flows of information and collaboration between actors such as agencies and collaborative groups in the Delta are highly networked, constituting a classic system of polycentric governance[5] (Figure 2a). The decentralization of Delta science is a persistent challenge, but it has seen vast progress in recent decades, with a shift toward increasing centrality but also increasing complexity[6]. In the latter decades of the twentieth century, agency and disciplinary scientists typically focused on narrow questions related to their agency mandates and disciplines, resulting in siloed and disconnected flows of information[7] that led to litigation around divergent science, termed "combat science"[2]. The formation of the Interagency Ecological Program (IEP), as well as CALFED, CALFED Science Program, and CALFED Independent Science Board (subsequently replaced by the Delta Stewardship Council, Delta

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[1] Keeley et al., 2022
[2] Cloern and Hanak, 2013; Layzer 2013; Sommer et al., 2023
[3] Holmes and Clark, 2008; Akerlof 2022
[4] Sommer 2021, Sommer et al., 2023
[5] Eberhard et al., 2017
[6] Lacan and Resh, 2016
[7] Freeman and Farber, 2005

Science Program, and Delta ISB, respectively) and later, interdisciplinary and multi-agency forums, such as the Delta Plan Interagency Implementation Committee (DPIIC)[1] and CSAMP, were attempts to centralize the flow of information between scientists and decision-makers via interagency venues and bridge organizations.

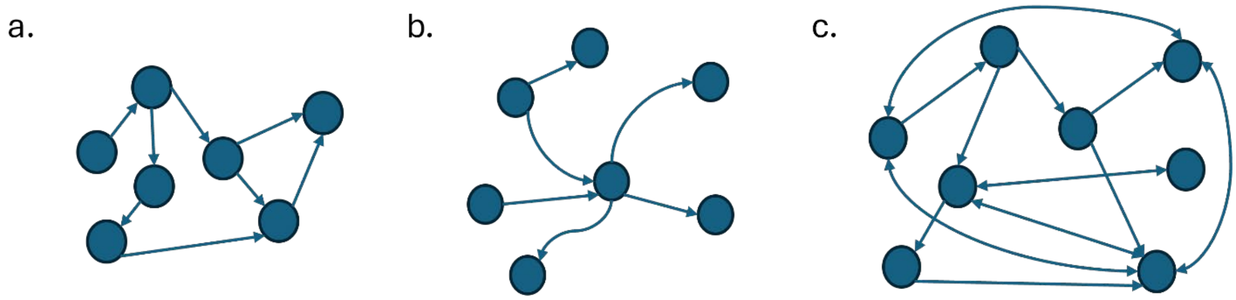

Figure 2. Examples of network governances: (a) indirect network structure; (b) highly centralized network structure; (c) indirect network with cross-scale interactions.

As described in a network structure, flows of information (e.g., scientific information) may permeate the network, but paths from one actor (e.g., individuals or agencies producing science) to another (e.g., legislators and agency decision-makers) may be indirect, passing through many intermediaries, with a higher potential for loss or alteration of the information (Figure 2a). By contrast, in a highly centralized network, one or more actors, such as an existing agency or new administrative agency, may serve as a hub for information transfer by having a high degree of connections to other actors across the network (Figure 2b). To improve the effectiveness of a polycentric governance network, such as in the Delta, cross-scale interactions that minimize this loss of information can be built[2] (Figure 2c). In the Delta, insufficient direct and bidirectional flow of information between scientists and decision-makers has resulted in a disconnect that imposes barriers to adaptive governance[3] and is detrimental to public trust in decision-making[4].

However, the institutional challenges faced in the Delta are not necessarily unique among social-ecological systems[5], which provides opportunities for comparison and learning from other systems. Climate adaptation policy forums in the San

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[1] https://deltacouncil.ca.gov/dpiic/
[2] Cash et al. 2006; Provan and Kenis 2008
[3] Cloern and Hanak 2013; Norgaard, 2017; Rittelmeyer et al., 2024
[4] Norgaard et al. 2009
[5] Lubell 2013; 2015

Francisco Bay have proliferated rapidly, yet despite a recognized need for coordination there is no agreement on the type of network governance to achieve it[1] (e.g., Figure 2). A proposed strategy under investigation by the Bay Adapt[2] process, a regional strategy for climate change adaptation in the Bay Area, is to develop a “climate science services center” that engages diverse stakeholders and provides topically focused engagement for various audiences. This concept has been utilized by the Department of Interior which developed Climate Adaptation Science Centers[3] to connect scientists and communities with a focus on helping resource managers anticipate and adapt to climate change in a way that centers equity and environmental justice. These examples follow widespread recognition of a need to establish topically focused service centers to help translate complex scientific information for decision-makers developing adaptation policy[4] (e.g., Figure 2b).

In the Delta, creating topically focused service centers may support greater centralization in science information flows (Figure 2b) and may only require minor changes to existing institutional networks, as many collaborative venues (e.g., IEP Project Work Teams[5], DSC’s Science for Communities[6]) already focus on specific topics. High network centralization and multiple topical service centers (Figure 2b) that are strongly connected to relevant decision-makers and key actors are positively correlated with collective action in resource governance[7]. However, less centralized networks (Figure 2a) are more capable of solving complex problems, have lower probability of asymmetric representation, and are less vulnerable to removal or dysfunctionality of central actors[8]. Connections of these service centers via cross-scale interactions may be conducted by those with broad science mandates (e.g., Delta Science Program, IEP) to improve information exchange with decision-makers and to attain the efficiency of a centralized network (Figure 2c).

[1] Lubell and Robbins 2022
[2] https://www.bayadapt.org/wp-content/uploads/2021/10/BayAdapt_4-pager_2021.10_ADA.pdf
[3] https://www.usgs.gov/programs/climate-adaptation-science-centers
[4] Moss et al., 2013
[5] https://iep.ca.gov/Science-Synthesis-Service/Project-Work-Teams
[6] https://deltacouncil.ca.gov/pdf/blogs/2022-03-03-accessible-science-for-communities-workshop-info-sheet.pdf
[7] Sandstrom, 2008
[8] Bodin and Crona, 2009

Addressing this grand challenge will require investment in social science research and commitment by all information producers in the Delta to provide timely access to their information in a user-friendly way. Additionally, a lack of trust amongst competing interests will likely lead to decision-making inefficiencies. Efforts like the integrated modeling collaboratory[1] can improve decision-making efficiency by working on high priority topics that span agency responsibilities (e.g., salinity management and harmful algal blooms) through information centralization and dissemination. Additionally, in line with AB 1755: the Open and Transparent Water Data Act[2], the Delta Stewardship Council's Delta Science Tracker[3] is an example of a tool that expands centralization of information and serves to increase accessibility to information. Promoting science-based collaborative forums, increasing transparency where scientific uncertainties exist in regulations, explicitly working on reducing uncertainties, and communicating widely about ongoing improvements in ecosystem knowledge are instrumental to keeping up with environmental change and to addressing this grand challenge.

Grand Challenge #4

> **Grand Challenge #4:**
> Other ways of knowing, especially Traditional Knowledge, remain siloed from decision-making.

Science that includes diverse knowledge improves the effectiveness of science in the long term[4]. Tribal Nations and many communities, including frontline and environmental justice communities, are instrumental in implementing and establishing resilient social-ecological systems[5], and Tribal nations may have resource management knowledge that extends back since time immemorial. Despite this crucial knowledge base, Tribal Nations are often not meaningfully integrated into decision-making. The fourth grand challenge is that other ways of knowing, especially Traditional Knowledge,

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[1] https://deltacouncil.ca.gov/pdf/dpiic/fact-sheets/2023-11-07-dpiic-modeling-fact-sheet.pdf
[2] https://water.ca.gov/ab1755
[3] https://sciencetracker.deltacouncil.ca.gov/
[4] Shinbrot et al., *in prep*
[5] Metcalf et al., 2015; Sterling et al., 2017; Conallin et al., 2018

remain siloed from decision-making yet offer important contributions to understanding of complex social-ecological systems[1].

This grand challenge echoes decades of work by Tribes and environmental and social justice advocates, including vulnerable communities, to have their voice heard in governance. The Delta Plan includes Tribal Traditional Knowledge (TK), the combination of knowledge, practice, and ethics, as an example of a primary source of scientific information for decision-making[2], but such other ways of knowing (e.g., TK) have often been misunderstood, undervalued, and therefore siloed from and by decision-makers despite clear benefits to integration to resource management. For example, over more than a hundred years, Indigenous peoples have been barred from conducting low-intensity cultural burns outside their reservations because of state and federal policies of fire suppression, despite such practices being shown to reduce brush for future fires, limit the spread of invasive beetles, promote forest health and new growth of plants for traditional basket weaving[3]. It was only in 2022, in response to some of California's most extreme wildfires that that law was lifted[4]. The benefits of so-called 'good fire' are only now coming to light for scientists and agency decision makers.

Although there is not as much citable Delta-specific literature to support this grand challenge[5], we believe this is a challenge precisely because this topic has been underrepresented in the conventional science paradigm. Addressing this grand challenge will require a transformation of the Delta science and resource management community into one in which decisions are informed by communities that have historically been marginalized and one that prioritizes equity, diversity, and justice. In interviews conducted by the Delta Stewardship Council, it has been expressed that even with the passage of AB52[6] (requiring tribal consultation as part of the California Environmental Quality Act process), Tribes still feel that they are not being brought into the decision-making process in a meaningful way[7].

In a separate but related effort to help combat the siloing of these knowledge systems, staff in the Delta Science Program initiated a literature review of 89

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[1] DSC, 2024
[2] Delta Plan, Appendix 1A
[3] Lake et al., 2017
[4] https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB332
[5] DSC, 2024
[6] https://opr.ca.gov/ceqa/tribal/
[7] Harris et al., *in prep*

articles focused on benefits, barriers, applications, and approaches to interweaving Tribal Knowledge and the predominant science paradigm[1]. This work complements the Delta Stewardship Council's development of a tribal and environmental justice issue paper in which staff conducted a thematic literature review, a series of consultations with Tribes and interviews with representatives of environmental justice communities in the Delta[2], with the broad goal of informing our understanding of tribal and environmental justice issues through elevating marginalized voices.

There have been recent successes in diversifying voices in governance, like the release of federal government-wide guidance[3] to include Indigenous Knowledge in federal research, policy, and decision-making, as well as the State of California's fifth Climate Assessment which provided explicit funding for supporting tribally led climate change research initiatives[4]. In the Delta, a Delta Residents Survey[5] was completed to better understand Delta residents' perspectives on regional and environmental issues. The State Water Board also provided listening sessions for environmental justice communities in seeking to identify Tribal beneficial uses in the update to the Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta[6]. The Delta Science Program has committed to including environmental justice and coproduction in products relevant to decision-making, and to dedicating staff time to understanding best practices for the interweaving of Traditional Knowledge in the Delta science enterprise. However, this is scratching the surface of the work that needs to be done to repair relationships damaged by a long history of exploitation and distrust[7].

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[1] Shinbrot et al., *in press*
[2] https://deltacouncil.ca.gov/pdf/council-meeting/powerpoints/2024-04-25-item-6c-tribal-and-environmental-justice-issue-paper-presentation.pdf
[3] https://www.whitehouse.gov/ceq/news-updates/2022/12/01/white-house-releases-first-of-a-kind-indigenous-knowledge-guidance-for-federal-agencies/
[4] https://opr.ca.gov/climate/icarp/climate-assessment/tribal-research.html
[5] https://ktomari.github.io/DeltaResidentsSurvey/
[6] https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/
[7] DSC, 2024: Section 4.

Conclusions

The grand challenges in this essay are four major impediments facing the Delta. By design, the grand challenges are rooted in transdisciplinary literature and encompass the needs of many organizations. The grand challenges are intended to be a starting point for conversation among Delta scientists, communities, and decision-makers. Indeed, the resilience of the Delta's social-ecological system depends on all vested parties of the Delta working together to create strategies to address these challenges and prioritize tools that can advance progress.

The Delta Science Program seeks to use these grand challenges as scaffolding upon which we will build the next Delta Science Plan. The draft version of these grand challenges was released for a 45-day public review period, May 28 to July 12, 2024, to solicit community input and determine whether they resonate with the Delta science community. A total of five comment letters and four survey responses were received, which are posted to our webpage. The comments have been included in this version and greatly improved the document. In addition to edits to this version of the grand challenges essay, many comments are being used to inform the 2025 Delta Science Plan. Details for addressing these grand challenges will be included in the 2025 Delta Science Plan. Public engagement will continue throughout the development of the 2025 Delta Science Plan, especially to garner input on strategies, tools, and actions to address the grand challenges.

To stay informed and to participate in any further engagement in developing the Delta Science Plan please sign up for our email contact list at https://lp.constantcontactpages.com/su/UZzT2rz.

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Appendix A. The National Research Council's Grand Challenges in Environmental Sciences (2001)

Grand Challenge 1: Biogeochemical cycles

The challenge is to understand how the Earth's major biogeochemical cycles are being perturbed by human activities; to be able to predict the impact of these perturbations on local, regional, and global scales; and to determine how these cycles may be restored to more natural states should such restoration be deemed desirable.

Grand Challenge 2: Biological diversity and ecosystem functioning

The challenge is to understand the regulation and functional consequences of biological diversity, and to develop approaches for sustaining this diversity and the ecosystem functioning that depends on it.

Grand Challenge 3: Climate variability

The challenge is to increase our ability to predict climate variability, from extreme events to decadal time scales; to understand how this variability may change in the future; and to assess its impact on natural and human systems.

Grand Challenge 4: Hydrologic forecasting

The challenge is to predict changes in freshwater resources and the environment caused by floods, droughts, sedimentation, and contamination in a context of growing demand on water resources.

Grand Challenge 5: Infectious disease and the environment

The challenge is to understand the ecological and evolutionary aspects of infectious diseases; to develop an understanding of the interactions among pathogens, hosts/receptors, and the environment; and thus to make it possible to prevent changes in the infectivity and virulence of organisms that threaten plant, animal, and human health at the population level.

Grand Challenge 6: Institutions and resource use

The challenge is to develop a systematic understanding of the role of institutions—markets, hierarchies, legal structures, regulatory arrangements, international conventions, and other formal and informal sets of rules—in shaping systems for natural resource use, extraction, waste disposal, and other environmentally important activities.

Grand Challenge 7: Land-use dynamics

The challenge is to develop a systematic understanding of changes in land uses and land covers that are critical to biogeochemical cycling, ecosystem functioning and services, and human welfare.

Grand Challenge 8: Reinventing the use of materials

The challenge is to develop a quantitative understanding of the global budgets and cycles of key materials used by humanity and of how the life cycles of these materials may be modified. Among the materials of particular interest for this grand challenge are those with documented or potential environmental impacts, those whose long-term availability is in some question, and those with a high potential for recycling and reuse. Examples include copper, silver, and zinc (reusable metals); cadmium, mercury, and lead (hazardous metals); plastics and alloys (reusable substances); and CFCs, pesticides, and many organic solvents (environmentally hazardous substances).

Appendix B. Grand Challenges development process

The 32 documents in Table 1 were reviewed and 125 candidate grand challenges within those documents were extracted, as detailed in Table A1.

These 125 candidates were evaluated against the NRC definition of a grand challenge to remove any that did not rise to the level of a grand challenge. Additionally, some candidate grand challenges were similar and could be combined. This resulted in the 17 candidate grand challenges (Figure A1).

Finally, the 17 finalist candidate grand challenges were workshopped in a Mural (Figure A1) by the authors until the final 3 grand challenges were honed to encapsulate the intent of the 17 candidate grand challenges in a more straightforward manner. The fourth grand challenge was constructed as explained in the Methods section above.

Table A 1. List of 32 visionary documents reviewed and 125 resulting candidate grand challenges.

Document Title	Candidate Grand Challenges
Delta Vision Strategic Plan (Isenberg et al. 2008)	• A revitalized Delta ecosystem will require reduced diversions—or changes in patterns and timing of those diversions upstream, within the Delta, and exported from the Delta—at critical times. • New facilities for conveyance and storage, and better linkage between the two, are needed to better manage California's water resources for both the estuary and exports. • Institutions and policies for the Delta should be designed for resiliency and adaptation.
Envisioning Futures for the Sacramento-San Joaquin Delta (Lund et al. 2007)	• A Delta that is heterogeneous and variable across space and time is more likely to support native species than is a homogeneously fresh or brackish Delta. Accepting the vision of a variable Delta, as opposed to the commonly held vision of a static Delta, will allow for more sustainable and innovative management. This is a legal and political necessity as much as it is an ecological one. • The health of the Delta's 1100 miles of levees, on which both Delta land use and water supply systems depend.

Document Title	Candidate Grand Challenges
Challenges Facing the Sacramento-San Joaquin Delta: Complex, Chaotic, or Simply Cantankerous? (Luoma et al. 2015)	• Current management will sustain neither the Delta ecosystem nor high-quality water exports. • Sustainable management of the Delta ecosystem and California's highly variable water supply, in the face of global climate change, will require bold political decisions that include adjustments to the infrastructure but give equal emphasis to chronic overuse and misuse of water, promote enhanced efficiency of water use, and facilitate new initiatives for ecosystem recovery. • Plethora of institutions with their own visions and contradicting missions; monitoring programs plentiful yet uncoordinated; management programs inconsistently coordinated and evaluated.
A Case Study in Integrated Management: Sacramento–San Joaquin Rivers and Delta of California, USA (Lacan and Resh 2016)	• Having both the environment and water supply reliability as goals - the "co-equal" goals. • The challenge today is to manage the Delta habitats, water quality, and flows in a manner that promotes recovery of the recently damaged fish populations and degraded habitats, while intensively pursuing state-wide water policies and management strategies that will allow for gradually adjusting the water export rates to sustainable and predictable levels, and all the while learning how best to protect the Delta residents from floods.
Science Enterprise Workshop (Executive Summary) (DSC/USGS 2018)	• The need for more funding and supporting critical science investigations. • Making science more useable and on-point for management decisions. • Being better organized and efficient, and determining what governance structures works best to inform decision-making. • Drawing more attention to the California Bay-Delta and create better recognition of the estuary’s importance.
Science Enterprise Workshop (Proceedings	• Avoiding “reinventing the wheel” in efforts to better coordinate and integrate science, including integrative approaches to deal with social, biological, chemical, and physical aspects of complexity. • Identifying practical means by which science programs manage financial and intellectual resources and ensure the relevance of ongoing lines of research and monitoring.

Document Title	Candidate Grand Challenges
Report) (DSC/USGS 2017)	• The need for more networking among programs and experts. • Limitations of traditional approaches to applied science.
Developing Biological Goals for the Bay-Delta Plan: Concepts and Ideas from an Independent Scientific Advisory Panel (Ruggerone et al. 2019)	• The San Francisco Estuary and its inflowing rivers need. to be treated as novel ecosystems, consisting of a mixture of native and non-native species living and interacting in a highly altered environment. • The combined effects of climate change, increasing water demand, and local modifications are resulting in trends that can have substantial effects on the riverine and estuarine ecosystems. and their fishes. These changes should be considered when setting and evaluating progress towards biological goals. • There is a need for experimental (adaptive) management to test the results of management actions. • Defining biological goals for managing and restoring aquatic ecosystems is challenging....The job is particularly challenging for the complex landscape of the San Francisco estuary.
A Review of the Interagency Ecological Program's Ability to Provide Science Supporting Management of the Delta (ISB 2019)	• In an earlier review, Herrgesell (2012) noted that IEP's funding model would likely be an ongoing issue because of agency needs (or priorities) to maintain their own staff, competition for resources, and the consequent need for trust among agencies, stakeholders, and participants.
Delta Science Funding and Governance Initiative	• More consistent and reliable funding for science is needed, along with a better understanding of what is being funded and why and what level of funding is needed to support science informing robust decision-making in the Delta.

Document Title	Candidate Grand Challenges
Implementation Report (DSC 2020)	
ISB Memo: Review of the Preliminary Public Draft Delta Plan Chapter 4 Ecosystem Amendment (ISB 2020a)	• Changes in the Delta are becoming less predictable due to increased rates of change, complex interactions, unknown thresholds and greater frequency and intensity of episodic events…One way to address this is to acknowledge that the Delta is a dynamic system and incorporate adaptive management practices into the Performance Measures. • The vision for a restored, yet dynamic, ecosystem is admirable, and emphasis on large scale interconnected ecosystem with natural (and human) communities is appealing…It is also pleasing to see the emphasis on functional flow to achieve the vision. While discussions on challenges and possible solutions are well worthy, and have become communal and at time repetitious, the bane is the lack of quantitative understanding of flow-ecosystem interactions at different scales.
ISB Memo: A Social Science Strategy for the Delta: Observations and Recommendations (ISB 2020b)	• Communication across disciplinary cultures requires considerable time and effort, more than the already-considerable effort needed to integrate the knowledge of hydrologists, toxicologists, fisheries ecologists, ecosystem scientists, etc. in the natural sciences.
Building an Effective Delta Science Enterprise (ISB 2020c)	• What will decision-makers need to know in the future? What are the implications of these future changes on management and stakeholder needs? • What do we need to know to support the future decisions? What do we need to know to answer these management needs and questions and what science needs to be done to provide that information? • How do we develop a structure to support, encourage, and accomplish our science needs? What scientific capabilities and expertise are needed to answer likely management and policy-focused questions as they arise? What governance and funding structure would support us

Document Title	Candidate Grand Challenges
	looking farther into the future to better anticipate and prepare for long-term challenges for the Delta? • What do we know now about the future? What can we forecast about future changes in environmental drivers?
Critical Needs for Control of Invasive Aquatic Vegetation in the Sacramento-San Joaquin Delta (Conrad et al. 2020)	• Current aquatic weed control protocols are not working (efficiently) many place in the Estuary /Delta. • New control methods and expanded monitoring for submerged aquatic vegetation to protect state investment in restoration projects and ensure flow for the pumping facilities.
A Social Science Strategy for the Sacramento-San Joaquin Delta (Biedenweg et al. 2020)	• How can the limitations associated with funding mechanisms (e.g., slow prioritization process within State agencies) and by the language in funding mechanisms (e.g., Prop 1 cannot easily fund social science projects) be addressed and overcome to support more social science research? • What resources are needed to implement and facilitate economic development efforts including branding, marketing, permitting and regulatory assistance, planning and coordination and managing a Delta Investment Fund? • To improve the integration of social sciences into the science, management, and policy institutions that address Delta issues; and to improve social science integration into decision-making about the Delta. • There is a lack of social science capacity and investment. • Research activities are ongoing, but there is no long-term vision for social science integration. • The adaptive management process is not informed by the social sciences.
How to Respond? An Introduction to Current Bay–Delta Natural Resources	• Awareness by managers and scientist of the currently available tools to address resource management issues • Used for actionable science

Document Title	Candidate Grand Challenges
Management Options (Sommer 2020)	• Increasingly important with rapid environmental changes
Excerpts from the Draft Science Needs Assessment: Agency-Spanning Science for a Rapidly-Changing Delta (ISB 2021a)	• Long-term management insights and science enterprise organization are needed to better address complex, challenging, and rapid environmental problems. • Currently there is a lack of forecasting in decision-making and adaptive management. Forecasting can be used as a focus to organize multi-agency science integration, to set management/policy priorities across agencies for tool development, and to develop a collaborative and formal Delta scientific enterprise.
The Science of Non-native Species in a Dynamic Delta (ISB 2021b)	• Climate warming, sea-level rise, and more extreme environmental conditions affect all species and habitats in the Delta, accelerating changes in species pools and facilitating the establishment of new non-native species. • Science, however, is only one element among many fiscal, sociological, and political considerations that ultimately drive allocations of resources to deal with non-native species. ...Because human activities and values differ among ecosystems and among people, developing appropriate management and policy for invasive species depends on the specific ecological, biological, and social contexts.
Science Needs Assessment Integrating Science for a Rapidly Changing Delta Principal Science Recommendations (ISB 2021c)	• There is a concern that much of science planning for the Delta is fragmented and short term and does not adequately consider long range and irreversible trends in the Delta; more science integration is needed! • The most promising approach for integrating and applying interagency science to address a complex and changing system is the development of an integrated forecasting system through collaborative institutional strategies.

Document Title	Candidate Grand Challenges
	• Major drivers of change that threaten coequal goals: climate change, sea level rise, population growth, earthquakes, flooding, invasive species, increasing water diversion demands, land use shifts, infrastructure, and environmental regulation changes.
Delta Adapts: Creating a Climate Resilient Future (Delta Stewardship Council 2021)	• Develop and implement an equitable regional approach to climate change adaptation and mitigation. • Requires coordination and teamwork among many stakeholders.
Preparing Scientists, Policy-Makers, and Managers for a Fast-Forward Future (Norgaard et al. 2021)	• Science (and scientists) will have problems keeping up with the rapid change in the environment- change in what to monitor, and the speed of collection & analysis. Change happens too fast for it to be studied and understood. • Science needs to be directed not only toward immediate management priorities, but also to inform management of likely future conditions. • How can science more quickly and effectively inform policy and management of the implications of new conditions or changes in the foreseeable conditions?
Outcomes from the 2021 Science Advisory Committee meeting on Bay-Delta Integration	• $5 million a year of federal funding for water quality and restoration projects in the Bay. This isn't enough for the Bay, let alone the estuary. • Challenge is science, funding and improved permitting (pilot effort BRITT) Big issue is funding. • Challenge is science, funding and improved permitting (pilot effort BRITT). • Limited tools for integration though some positive movement (EcoAtlas, CRAM). • Science being driven by old regulations (geriatric regulations). • System doesn't regulate private enterprise (which is reason we're in this mess). • Challenge of closing the loop, after science is funded and bringing answers back to policymakers and legislators. • Historical divide between upper and lower estuary is surface water management (i.e., water projects/operations). This is a self-reinforcing divide that has led to siloed institutions, science funding, collaboration, management objectives, etc.

Document Title	Candidate Grand Challenges
	• Establishing a common science program for the whole watershed (not just estuary) is fundamentally political. • History of unsuccessful efforts to replicate the Puget Sound, Chesapeake, Great Lakes model in the Bay-Delta. • Cultural, social and political constructs/differences between bay and Delta (e.g., extent of restoration effort between Delta conservancy and Coastal Conservancy). • Political will is the bigger issue. • Science being driven by old regulations (geriatric regulations). • System doesn't regulate private enterprise (which is reason we're in this mess). • Science governance in Bay is less coordinated than in the Delta. • State-federal programs require political answers and have to be viewed as belonging to politicians. • Need to counteract possible notion in Congress that Delta is only a water problem. • Not enough engagement with public policy process. • Lack of bridge between DSP and legislature. • Hard to get at a holistic process-oriented science program with the coequal goals. • Challenge is demonstrating need for integrated science. Perhaps could be done through a bond? • Challenge is that Delta isn't part of social consciousness in CA (not like SF Bay). Similar situation in the Everglades. • Challenge of drought and salinity management. • Taking 60% of water is ecologically destructive and science can't solve that problem. • Our challenge is to show benefits of science across the estuary (water flows, water quality, habitat restoration, food, and include social science).
DIISC Early Detection Rapid Response	• There are few structures to coordinate actions among groups with existing EDRR [Early Detection, Rapid Response] programs, few communication structures between broader

Document Title	Candidate Grand Challenges
Framework Draft (DIISC 2021)	prevention and monitoring efforts and EDRR programs, and no analysis that highlights gaps in the Delta's EDRR capacity.

IEP Science Strategy 2020-2024 (IEP 2022)	• We cannot provide an effective monitoring enterprise without substantial additional investment and participation from our academic, NGO, and water agency partners. At current levels of fiscal and personnel support the IEP cannot achieve all requests made to us for data collection, analysis, and information synthesis when supporting management decision making.
	• Difficult science questions and management problems require a multi-pronged approach to decrease existing uncertainty; open communications and repeated exchange of views between scientists and managers are crucial to maintain relevant conversations and meaningful approaches to providing information of value.
	• Single-minded or isolated investigations are quickly losing relevance in our complex ecological and multi-faceted interagency world. To this end, IEP often uses different categories and combinations of approaches. These include:
	  ○ Long-term monitoring surveys subject to periodic review and revision to ensure integrity and relevance,
	  ○ Modeling (both quantitative and conceptual),
	  ○ Special studies focused on multidisciplinary observational and experimental science, and
	  ○ Interdisciplinary and interagency synthesis of status, trends, climate impacts, and emerging issues of concern.
	• Science prioritization proceeds in top-down and bottom-up directions, but science excellence is largely driven by the interactions between the scientists themselves rather than via institutional arrangements
	• Largest data collection effort in the Delta focuses on mandated compliance science and cannot practically include every important issue or management objective.

Document Title	Candidate Grand Challenges
	• The combination of SLR, reduced snowpack, earlier snowmelt, more intense storms, and warmer summer water temperatures will challenge both water operations infrastructure and management of aquatic resources. • The subjects of contaminants and aquatic vegetation comprise critical unmet needs for IEP and Estuary related science over the next five years. While we agree that an Estuary monitoring program should include monitoring for pesticides and contaminants there has been no nexus for a mandate or funding within the Delta that allows clear articulation of annual plan elements the IEP might implement as part of its compliance science or regulatory requirements.
Review of the Monitoring Enterprise in the Sacramento-San Joaquin Delta (ISB 2022a)	• The monitoring enterprise is not nimble enough to respond to rapidly changing management needs and emphasizes long-term monitoring at the expense of directed special studies. • Major monitoring (and therefore data collection efforts) for the Delta is funded through water projects and to address water project questions- this obscures other questions about the Delta not directly tied to water projects. • Capacity limitations for agencies is a barrier for improving monitoring particularly for "a system driven by the frequent emergence of crises that divert attention from the long-term efforts.". Inflexibility in funding and permits is a barrier to rapid responses- monitoring programs largely difficult to address. • Barriers to coordinated monitoring: "siloed nature of organizational structures, perceived risks associated with changing monitoring programs, the time and effort required when monitoring staff have other priorities, the regulatory and legal constraints, funding, lack of leadership, a disconnect with management needs, and poor communication, among others. Funding and organizations working in silos were identified as the biggest barriers for improving coordination or filling gaps. • The monitoring enterprise must operate as a whole in order to address the complex questions that Delta resource managers must face.

Document Title	Candidate Grand Challenges
	• Major monitoring (and therefore data collection efforts) for the Delta is funded through water projects and to address water project questions- this obscures other questions about the Delta not directly tied to water projects.
Collaborative Adaptive Management Team: Assessment of Reviews of Long-Term Monitoring Programs and Objectives (Conrad and Moffatt 2022)	• Providing support (staffing resources) for iterative reviews. • Monitoring both for long term trends and for current management questions.
2022-2026 Science Action Agenda: A Vision for Integrating Delta Science (Delta Stewardship Council 2022)	• Assess and anticipate impacts of climate change and extreme events to support successful adaptation strategies. • Expand multi-benefit approaches to managing the Delta as a social-ecological system Build and integrate knowledge on social process and behavior of Delta communities and residents to support effective and equitable management. • Improve coordination and integration of large-scale experiments, data collection, and evaluation across regions and institutions. • Enhance monitoring and model interoperability, integration, and forecasting. • Build and integrate knowledge on social process and behavior of Delta communities and residents to support effective and equitable management. • Acquire new knowledge and synthesize existing knowledge of interacting stressors to support species recovery and ecosystem health.
San Francisco Estuary BluePrint (San Francisco	• Moving forward, management actions must occur in the context of change. Sustaining a healthy Estuary while addressing climate change, prolonged drought, and rising seas will

Document Title	Candidate Grand Challenges
Estuary Partnership 2016 and 2022)	require collaboration, adaptation, flexibility, and resilience among all engaged communities and agencies from now on. • The health of the whole Estuary would benefit from greater efficiencies in human use of the system's fresh water, as well as changes in upstream water management. • The Bay's wetlands remain at risk unless we take a watershed-based, regional approach to managing sediment and fresh water as essential resources, and allow for tidal wetlands to migrate landward. • The upper Estuary (Suisun Bay and the Delta) is in fair to poor condition and getting worse, while the lower Estuary (San Francisco Bay) is in better health but jeopardized by climate change. • Human activities have severely altered the physical processes that create and maintain estuarine habitats. • Freshwater inflows and beneficial floods now exert such a small fraction of their former influence that they no longer build and maintain the physical structure of habitats in the Estuary, drive historical seasonal changes, or support critical ecological functions. • In the lower Estuary, similar changes to the hydrology of Bay watersheds and the diking of tidal areas have deprived estuarine wetlands of the sediment they need to build up their elevation in relation to sea-level rise. • This impairment of critical physical processes is intertwined with habitat loss, degradation, and fragmentation. • These losses of physical processes and habitats have reverberated through biological systems, contributing to unproductive food webs, smaller and declining native fish and wildlife populations, and the dominance of invasive species. • Restoring the health of the upper Estuary will require significant investment in restoring critical physical processes and habitats, as well as managing nonnative species and preventing new arrivals.

Document Title	Candidate Grand Challenges
	• Wildlife conservation efforts should aim to ensure successful reproduction and habitat connectivity over time as climate change alters landscapes.

Additional documents reviewed, but no candidate grand challenges identified:

- Delta Plan (https://deltacouncil.ca.gov/delta-plan/) and recent amendments
- Review of Water Supply Reliability Estimation Related to the Sacramento-San Joaquin Delta (ISB 2022b) (https://deltacouncil.ca.gov/pdf/isb/products/2022-06-16-isb-water-supply-reliability-review.pdf)
- ISB letter on draft Ecosystem Amendment performance measures (Delta ISB 2019b) (https://deltacouncil.ca.gov/pdf/isb/products/2019-09-27-isb-delta-plan-pm-comments.pdf)
- ISB Memo to DPIIC on Science Needs Assessment (Delta ISB 2019c)

Grand
Challenges_Mural.p

Figure A 1. PDF version of the Mural that shows the 17 final grand challenge candidates and how they were workshopped into the three final grand challenges that were defined through the literature review.