Draft

MAY 2024

Grand Challenges to Delta Science

Planning for Science in a Dynamic System

Delta Science Program

DELTA STEWARDSHIP COUNCIL

Acknowledgements

We would like to acknowledge the valuable contributions made by our Delta Stewardship Council colleagues to this work- Brandon Chapin, Morgan Chow, Dr. Xoco Shinbrot, and Dylan Stern, as well as Sea Grant State Fellow Alexandra Stella. A special thanks to former Delta Stewardship Council Deputy Executive Officer for Science, Dr. Louise Conrad, for her vision and early contributions to this document.

Suggested citation:

Tricia Lee, Laurel Larsen, Rachael Klopfenstein, Henry DeBey, Lisamarie Windham-Myers, Eva Bush. 2024. Grand Challenges to Delta Science: Planning for Science in a Dynamic System.

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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 and are only increasing with climate change. These challenges are especially prominent in the Sacramento-San Joaquin Delta, where over a century of human-caused modifications has reshaped the landscape[1] to convey water across the state and promote agriculture and industry.

The challenges in the Delta have many dimensions (e.g., physical, socioeconomic, water supply) and potentially conflicting solutions, so much so that management in the Delta has been referred to as a "wicked" problem: unsolvable in a traditional sense, but manageable given appropriate knowledge and flexible institutions[2].

> Box 1: The coequal goals
>
> The Delta Plan states:
>
> "Achieve the two coequal 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."

The Delta Reform Act[3] stated coequal goals that must be achieved to manage the Delta (Box 1). To obtain the best available science to manage the Delta toward these coequal goals, it is helpful to detail the "wicked" problem of the Delta or "grand challenges" to Delta Science. In 2001, the National Research Council (NRC)[4] issued a report 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—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 a serious infusion of resources.

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[1] Whipple et al., 2012
[2] Luoma et al., 2015
[3] https://deltacouncil.ca.gov/delta-plan/
[4] NRC 2001

Given the wicked problem that is the Delta, and drawing inspiration from the NRC's report, the Delta Science Program is proposing to frame its next update of the Delta Science Plan around grand challenges. This approach will catalyze the transdisciplinary research needed to better address this wicked problem and support the long-term attainment of the Delta Plan's coequal goals.

Catalyzing Science Coordination through the Delta Science Plan

The Delta Science Program is in the process of updating the Delta Science Plan[1] for the third iteration. The Delta Science Plan is a collaboratively developed plan, stipulated in the Delta Plan, 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 to past plans. Rather than documenting what the community already does well, the focus of the updated plan is specific grand challenges that, through coordination and collaboration, can advance shared goals and accelerate scientific understanding and decision-making. With this more targeted approach, the Delta Science Program hopes that the 2025 Delta Science Plan update will be strategic and forward-looking, serving as a strong rallying cry for coordinating Delta science.

To gather and distill grand challenges to Delta science, the Delta Science Program conducted a literature review and synthesis of grand challenges for Delta science to orient the community around common goals.

Identifying Grand Challenges

To synthesize grand challenges, the authors reviewed literature 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 bring together the ideas of diverse voices and organizations and curate a list of overarching gaps or challenges for Delta science. This essay is not meant to take the place of these visionary documents, but rather to assemble the information

[1] https://deltascienceplan.deltacouncil.ca.gov/

from these works into a centralized location and to build out actionable steps to address the Grand Challenges.

Methods

We restricted our analysis to documents published since 2007 when the Delta Vision Blue Ribbon Task Force[1] laid the foundation for the Delta Reform Act, resulting in a total of 32 documents (Appendix A.). 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 A.). We then reviewed the candidate grand challenges and evaluated them against the criteria in Box 2.

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.

Removal of candidate challenges that did not meet the criteria resulted in a shortened list of 17 candidates. The authors then grouped these 17 challenges into thematic areas that were coalesced into four overarching grand challenges (Figure 1). The first three grand challenges are pulled from this literature review, however, the fourth grand challenge, although supported by peer-reviewed journal articles, is not well reflected in Delta scientific literature brought into decision-making.

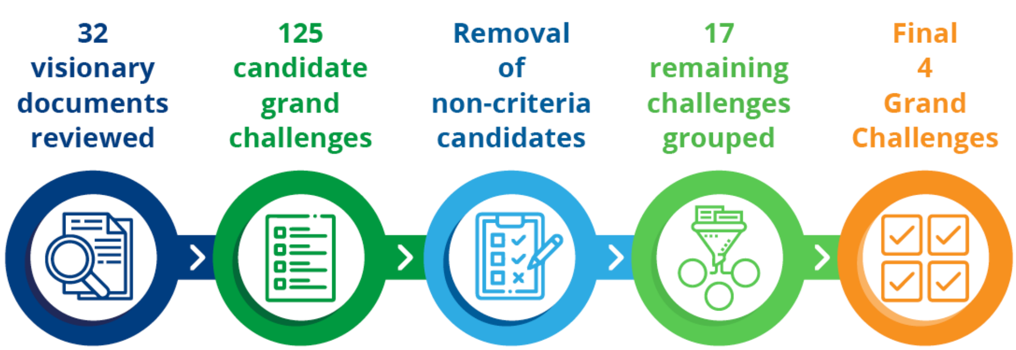

Figure 1. Grand Challenges process

[1] Isenberg et al., 2008

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

Title	Type of Document
Delta Vision Blue Ribbon Task Force report (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 (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
Biological Goals Advisory Panel Report for the SWRCB (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 2019)	Delta ISB Review Report
Delta Science Funding and Governance Initiative report (DSC 2020)	Implementation Report
Delta ISB memo on draft Ecosystem Amendment performance measures (Delta ISB 2020a)	Memorandum
Delta ISB Memo to Delta Social Science Task Force on A Social Science Strategy for the Delta (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
Social Science Task Force Report (Biedenweg et al. 2020)	White Paper
How to Respond? An Introduction to Current Bay–Delta Natural Resources Management Options (Sommer 2020)	Journal Article
Science Needs Assessment (excerpts) (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
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
CAMT Assessment of Reviews (Conrad and Moffatt 2022)	White Paper
Science Action Agenda 2022-2026 (DSC 2022)	Science Action Plan
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 proposed in this essay 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, including 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 transform 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 targets impossible to meet, science needs to inform and help reshape regulations accordingly. Further, climate change, potential alterations to flow regulations (e.g., through updates to the Bay-Delta Water Quality Control Plan), and species invasions and range shifts[1] will continue to alter the drivers of Delta ecosystems. Laying a scientific foundation for policy that is adaptable to accommodate future novel conditions requires early anticipation of those needs[2]. Therefore, scientists and managers must anticipate a

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

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[1]. 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, flow and habitat requirements associated with Biological Opinions for threatened and endangered species are major regulatory mechanisms that provide protections for Delta ecosystems but are narrowly focused on the needs of a limited number of species.

With recent droughts nearly decimating cohorts of Winter-run Chinook salmon[2] and dwindling survey detections of Delta Smelt[3], 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 ecosystem protections thereby disappear. The Delta Stewardship Council's recent Ecosystem Amendment to the Delta Plan[4] 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. Recent studies have emphasized functional flow management (e.g., North Delta flow actions that stimulate phytoplankton blooms)[5] and multi-benefit solutions (e.g., wetland restoration for habitat, recreation, and salinity management)[6]. 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 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

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[1] Sommer et al., 2023
[2] Hassrick et al., 2022
[3] Bork et al., 2020
[4] https://deltacouncil.ca.gov/pdf/delta-plan/2022-06-29-chapter-4-protect-restore-and-enhance-the-delta-ecosystem.pdf
[5] Frantzich et al., 2021; Yarnell et al., 2015, Yarnell et al., 2020
[6] Milligan et al., 2020; Milligan 2022

impacts on ecosystems)[1]. Others[2] have called for policy that is flexible enough to accommodate a dynamic, heterogeneous, and variable Delta (i.e., not static), which carries a similar set of science needs as functional management.

Lastly, preparing for an uncertain future may be most effectively accomplished through a scenario-based approach[3] 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[4]. Using models to evaluate scenarios and tradeoffs, in turn, requires breaking down barriers to the use, transparency, communication, and linking of models and data[5]. Meanwhile, 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[6]. Meeting science needs associated with future policies also requires improved interagency coordination and collaboration[7] and increased research coordination (i.e., monitoring, knowledge transfer) at the watershed and estuary scale[8], together with an expanded capacity to perform synthesis[9]. Scientists must also be able to perform horizon scanning[10], the systematic search for potential threats and opportunities, to identify future challenges not yet present within the system or currently of only marginal importance[11].

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[1] Isenberg et al., 2008
[2] Lund et al., 2007
[3] Lacan and Resh 2016; Sutherland and Woodroof 2009
[4] Poff et al., 2016; Ray et al., 2020
[5] Delta ISB 2021c; Wilkinson and Edinow 2008; Flynn et al., 2018
[6] Biedenweg et al., 2020
[7] Delta ISB 2020c
[8] San Francisco Estuary Blueprint, 2022; Delta ISB 2021c; Delta Stewardship Council 2022a
[9] Baron et al., 2017; Interagency Ecological Program (IEP) 2022
[10] See Sutherland and Woodroof 2009 for a toolkit of methods
[11] 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 either on changing the pace of Delta science to allow for quicker decision-making or slowing the pace of environmental change by prolonging environmental tipping points and minimizing surprises.

Changing the pace of Delta science to allow 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 should potentially be made available prior to the traditional peer review cycle or to developing a rapid-response peer review process for management-relevant results. This grand challenge also invokes the need to coordinate more adaptive monitoring programs that can address emerging change while maintaining a capacity to document long-term trends, relevant to the needs of multiple agencies[2]. Groups such as the Collaborative Science and Adaptive Management Program[3] (CSAMP), a voluntary collaborative focused on science and adaptive management, are best suited to address this need. Such groups serve as venues that bring together many interests to focus on information needs for water and ecosystem management.

Slowing the pace of environmental change 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[4]. 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 to slow the rate of local inundation or the rate of change of the tidal prism[5]. At a local level, communities

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[1] Delta ISB 2022a; Delta Stewardship Council 2020; Interagency Adaptive Management Implementation Team 2019
[2] Delta ISB 2022a; Luoma et al., 2015
[3] https://csamp.baydeltalive.com/
[4] Vlieg and Zandvoort 2013; Ruggerone et al. 2020
[5] Conrad et al., 2020; Ebersole et al., 2020; Cordoleani et al., 2021; Stark 2017; Stark et al. 2017

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)[1].

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., flow to balance habitat conditions for different species of concern). "Turn-taking" optimization[2] 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[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 the norm[4]. Ensuring that robust decision-making under uncertainty[5] is synthesized and effectively communicated to decision makers is an important aspect of managing this grand challenge. Delta-specific social science investigations and syntheses could lead to improved governance structures or decision-making practices. The Delta ISB's ongoing review of decision making under deep uncertainty[6] could offer recommendations and tools for stakeholder engagement and anticipatory planning that could help address this Grand Challenge.

[1] https://deltacouncil.ca.gov/delta-plan/climate-change
[2] Alexander et al. 2018
[3] Norgaard et al. 2021; Delta ISB 2021c; Delta ISB 2022b
[4] Delta ISB 2023
[5] Greve et al., 2018; Kochenderfer 2015; Polasky et al., 2011
[6] https://deltacouncil.ca.gov/pdf/isb/meeting-materials/2023-08-04-isb-final-prospectus-dmdu.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]. 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[2] (Figure 2a). 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 the Delta, cross-scale interactions that minimize this loss of information can be built[3] (Figure 2c). However, 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[4] and is detrimental to public trust in decision-making[5].

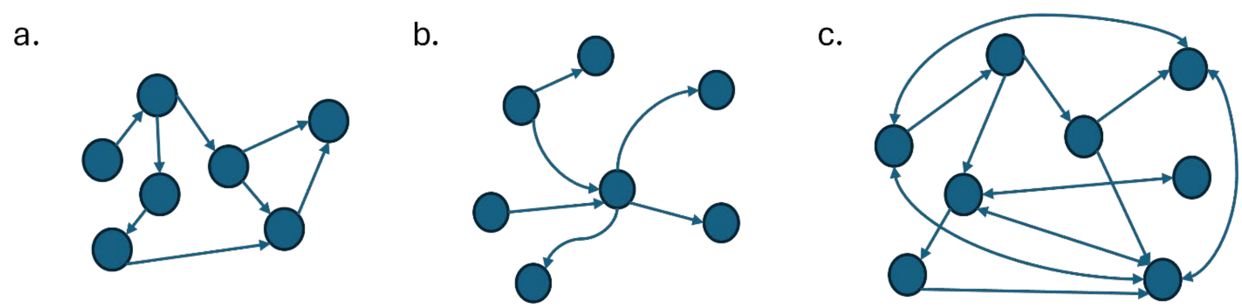

Figure 2. Examples of network governances: (a) indirect network structure; (b) highly centralized network structure; (c) indirect network with cross-scale interactions.

[1] Keeley et al., 2022
[2] Eberhard et al., 2017
[3] Cash et al. 2006; Provan and Kenis 2008
[4] Cloern and Hanak 2013; Norgaard, 2017; Rittelmeyer et al., 2024
[5] Norgaard et al. 2009

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[1]. 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[2] that led to litigation around divergent science, termed "combat science"[2]. The formation of the Interagency Ecological Program, CALFED, CALFED Science Program, and CALFED Independent Science Board, which subsequently was replaced by the Delta Stewardship Council, Delta Science Program, and Delta ISB, and later, interdisciplinary and multi-agency forums such as the Delta Plan Interagency Implementation Committee (DPIIC)[3] and CSAMP, were attempts to centralize the flow of information between scientists and decision-makers via interagency venues and bridge organizations. However, even with these institutional structures, scientists are often unaware of decision-maker needs and miss out on opportunities to inform policy development[4]. In fact, a review of the use of science in decision-making revealed that this problem is widespread[5]. As an example, though the relative value of habitat creation versus flow increments for ecologically significant fish species factored significantly into the 2021 negotiations on the Voluntary Agreements for the proposed update to the Bay-Delta Water Quality Control Plan, some entities perceived a lack of transparency in the development of the science and in the agreement negotiations, leading to mistrust in the process[6]. 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[7]. In general, missed opportunities to draw direct connections between scientists and policymakers have cascading impacts on public perceptions and trust building This includes funding challenges, particularly when science funding needs and potential added value of science to policy development are not well communicated or the connection is not fully understood by legislators and agency managers. The challenge of science

[1] Lacan and Resh, 2016
[2] Freeman and Farber, 2005
[3] https://deltacouncil.ca.gov/dpiic/
[4] Cloern and Hanak, 2013; Layzer 2013; Sommer et al., 2023
[5] Holmes and Clark, 2008; Akerlof 2022
[6] https://mavensnotebook.com/2022/04/27/ca-water-law-symposium-voluntary-agreements-are-the-promises-enough-or-is-it-just-another-delay-tactic/
[7] Sommer 2021, Sommer et al., 2023

coordination remains paramount, particularly with respect to major topics with wide-ranging and multifaceted impacts that span agency or geographic mandates.

The institutional challenges faced in the Delta are widespread among social-ecological systems[1], providing opportunities for comparison and learning. One example worth a deeper dive is that of the San Francisco Bay. There, as in the Delta, the number of adaptation policy forums has grown vastly and rapidly, yet despite a recognized need for coordination, there is no agreement on the network governance mode to achieve it[2]. A proposed strategy under investigation by the Bay Adapt[3] 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 serves as a go-to entity for topically focused engagement with decision-makers. Such a model follows a general recommendation for practice-relevant adaptation science by, for example, establishing topically focused (i.e., climate) service centers to help translate complex scientific information for decision-makers developing adaptation policy[4]. This concept has been utilized by the Department of Interior which developed Climate Adaptation Science Centers[5] 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 (Figure 4).

In the Delta, topically focused “service centers” may provide a mechanism for achieving greater centralization in science information flows and may only require minor changes to existing institutional networks, as many collaborative venues (e.g., IEP Project Work Teams[6]) already focus on specific topics. However, other topics may benefit from an increase in centralized coordination (e.g., drought, flood, habitat restoration, environmental flows)[7]. Multiple, topical service centers that are strongly connected to relevant decision makers and to key actors may present an optimal outcome such that: 1) high network centralization is positively correlated with collective action in resource governance[8], but 2) less centralized

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[1] Lubell 2013; 2015
[2] Lubell and Robbins 2022
[3] https://www.bayadapt.org/wp-content/uploads/2021/10/BayAdapt_4-pager_2021.10_ADA.pdf
[4] Moss et al., 2013
[5] https://www.usgs.gov/programs/climate-adaptation-science-centers
[6] https://iep.ca.gov/Science-Synthesis-Service/Project-Work-Teams
[7] Delta ISB 2021c
[8] Sandstrom, 2008

networks are more capable of solving complex problems, have lower probability of asymmetric representation, and are less vulnerable to removal or dysfunctionality of central actors[1]. 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 create sufficient redundancy in information exchange with decision-makers and to attain the efficiency of a centralized network (Figure 2c).

Grand Challenge #4

Grand Challenge #4: Other ways of knowing, including Traditional Knowledge, remain siloed from decision making.

Effective communication between scientists and decision-makers is vital for establishing science-based policies. Additionally, there is increasing focus on the need for including Tribes and marginalized communities in policy discussions given their direct role in implementing and establishing resilient social-ecological systems[2]. Furthermore, science that is inclusive of diverse knowledge improves the effectiveness of science in the long-term[3]. Given the diversity and abundance of actors with an interest in science-informed decision-making, information flows require a governance network with increased centrality and cross-scale interactions, as mentioned in Grand Challenge #3. In a more centralized system, information can flow bidirectionally between actors and one or more science aggregators, and then between the science aggregators and policy-making bodies[4] (Figure 2c).

Implicit in this Grand Challenge is the need to transform the Delta science and resource management community into one in which decision-making is informed by communities that have historically been marginalized and that prioritize equity, diversity, and justice. For example, better understanding of the networks through which scientific information flows can help diagnose communication deficiencies to provide insight into feasible and effective communication structure modifications. Additionally, to create new connections for knowledge to flow to and from marginalized communities, we need to first understand social values.

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[1] Bodin and Crona, 2009
[2] Metcalf et al., 2015; Sterling et al., 2017; Conallin et al., 2018
[3] Shinbrot et al., *in prep*
[4] e.g., see Bodin and Crona 2008; 2009

Other ways of knowing (e.g., Traditional Knowledge, lived experiences) have been misunderstood, undervalued, and therefore siloed from and by decision-makers. To address such siloing, staff in the Delta Science Program initiated a literature review of 90 articles focused on benefits, barriers, applications, and approaches for interweaving Tribal Knowledge and mainstream Science[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 and conducted a series of consultations with Tribes and interviews with representatives of environmental justice communities in the Delta[2], all of which have been done with a broad goal of including marginalized voices. Functioning like a boundary organization, the Delta Science Program has the opportunity to address such a challenge and interweave different ways of knowing to uphold our mission to support decision-making with the best possible, unbiased information.

This grand challenge reflects decades of work by Tribes as well as environmental and social justice entities, including vulnerable communities, to have their voice heard in governance. 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 and the State of California's fifth Climate Assessment providing explicit funding for supporting tribally led climate change research initiatives[4]. In the Delta, the State Water Board also provided listening sessions for environmental justice communities and is working to identify Tribal beneficial uses in their update to the Water Quality Control Plan for San Francisco Bay/Sacramento-San Joaquin Delta[5]. The Delta Science Program has also committed to including environmental justice and coproduction in products relevant to decision-making, and by dedicating staff time to understanding best practices for the interweaving of Traditional Knowledge in the Delta science enterprise.

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[1] Shinbrot et al., *in prep*

[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://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/

Conclusions

The Grand Challenges in this essay offer a set of goals for the Delta science community to work toward together. By design, the Grand Challenges encompass the needs of many organizations and are intended to be the starting point of a conversation amongst Delta scientists and decision-makers on improving flows of information and needs in both directions. Indeed, the resilience of our 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 the foundation for the next Delta Science Plan. The draft version of these Grand Challenges has been released for public comment to obtain community input and ensure that they meet the needs of the Delta science community. Continued public engagement throughout the development of the 2025 Delta Science Plan will be conducted, especially to garner input on strategies, tools, and actions to address the Grand Challenges.

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Appendix A.

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

Document Title	Candidate grand challenges
Delta Vision Blue Ribbon Task Force report (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.
Challenges facing the Sacramento-San Joaquin Delta (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.

Document Title	Candidate grand challenges
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 of 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 Report) (DSC/USGS 2017)	• 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. • The need for more networking among programs and experts. • Limitations of traditional approaches to applied science.
Biological Goals Advisory Panel Report for the SWRCB (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.

Document Title	Candidate grand challenges
	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.
IEP Review (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.
Science Funding and Governance Initiative report (DSC 2020)	• 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
ISB memo on review of draft 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.

Document Title	Candidate grand challenges
ISB Memo on A Social Science Strategy for the Delta (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 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
Social Science Task Force Report (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

Document Title	Candidate grand challenges
	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 Management Options (Sommer 2020)	• Awareness by managers and scientist of the currently available tools to address resource management issues • Used for actionable science • Increasingly important with rapid environmental changes
Science Needs Assessment (excerpts) (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
ISB Invasive Species report (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,

Document Title	Candidate grand challenges
	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 • 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 studies 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?

Document Title	Candidate grand challenges
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. • 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

Document Title	Candidate grand challenges
	• 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 EDRR Framework Draft (DIISC 2021)	• There are few structures to coordinate actions among groups with existing EDRR [Early Detection, Rapid Response] programs, few communication structures between broader 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)

Document Title	Candidate grand challenges
	◦ Special studies focused on multidisciplinary observational and experimental science ◦ Interdisciplinary and interagency synthesis of status, trends, climate impacts, and emerging issues of concern ◦ Largest data collection effort in the Delta focuses on mandated compliance science and cannot practicably include every important issue or management objective ◦ 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 ◦ 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 • Largest data collection effort in the Delta focuses on mandated compliance science and cannot practically include every important issue or management objective. • 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 ◦ Interdisciplinary and interagency synthesis of status, trends, climate impacts, and emerging issues of concern • 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

Document Title	Candidate grand challenges
	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.
ISB Monitoring Enterprise Review (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. • 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.

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CAMT Assessment of Reviews (Conrad and Moffatt 2022)	• Providing support (staffing resources) for iterative reviews • Monitoring both for long term trends and for current management questions
SAA 2022-2026 (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. • Assess and anticipate impacts of climate change and extreme events to support successful adaptation strategies.

Document Title	Candidate grand challenges
Estuary BluePrint/CCMP (San Francisco Estuary Partnership 2016 and 2022)	• 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 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.

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	• 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. • Wildlife conservation efforts should aim to ensure successful reproduction and habitat connectivity over time as climate change alters landscapes. • 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 require collaboration, adaptation, flexibility, and resilience among all engaged communities and agencies from now on.

Additional documents reviewed, but no candidate grand challenges identified:

- Delta Plan and recent amendments
- Water Supply Reliability Review Report (ISB 2021)
- ISB letter on draft Ecosystem Amendment performance measures (2019)
- ISB Memo to DPIIC on Science Needs Assessment (2019)