INTERAGENCY ECOLOGICAL PROGRAM

IEP *Science Strategy* – Needs for Near-Term Science in Five Areas of Emphasis:

Effects of Climate Change and Extreme Events

Understanding Estuary Food Webs

Ecological Contribution of Restored Areas

Restoring Native Species and Communities

Impacts of Non-Native Species

USBR • USFWS • SWRCB • DFW • USGS • NMFS • USACE • USEPA • DWR

Interagency Ecological Program

COOPERATIVE ECOLOGICAL INVESTIGATIONS SINCE 1970

A Cooperative Program of:

California Department of Water Resources
California Department of Fish and Wildlife
U.S. Bureau of Reclamation
U.S. Army Corps of Engineers
NOAA - National Marine Fisheries Services
State Water Resource Control Board
U.S. Fish and Wildlife Service
U.S. Geological Survey
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Acronyms

BDCP	Bay Delta Conservation Plan
CALSIM	California Statewide Integrated Model
CAMT	Collaborative Adaptive Management Team
CASCaDE	Computational Assessments of Scenarios of Change for the Delta Ecosystem
CDFW	California Department of Fish and Wildlife
CSAMP	Collaborative Science and Adaptive Management Program
CVP	Central Valley Project
CWEMF	California Water and Environmental Modeling Forum
CWQMC	California Water Quality Monitoring Council
Delta ISB	Delta Independent Science Board
DRERIP	Delta Regional Ecosystem Restoration Implementation Plan
Delta RMP	Delta Regional Monitoring Program
DSC	Delta Stewardship Council
DSM2	A 1D model of hydrodynamics, water quality, and particle movement in river networks
DSP	Delta Science Program
DWR	Department of Water Resources
ERP	Ecosystem Restoration Program
FAV	Floating Aquatic Vegetation
FRPA	Fish Restoration Program Agreement
IEP	Interagency Ecological Program
IEP SAG	IEP Science Advisory Group
LOBO	Long term Operations Biological Opinions
MAST	Management Analysis and Synthesis Team
NGO	Non-Governmental Organization
NMFS	National Marine Fisheries Service
NRC	National Research Council
OCAP	Operations Criteria and Plan
PSP	Proposal Solicitation Package
PIT	Passive Integrated Transponder (tag)
PWT	IEP Project Work Team
RBDD	Red Bluff Diversion Dam
RFP	Request For Proposal
*RMA*11	Resource Management Associates' model of water quality
RPA	Reasonable and Prudent Alternative
SAIL	Salmon/Sturgeon Assessment of Indicators by Lifestage
SAV	Submerged Aquatic Vegetation
SCHISM	Semi-implicit Cross-scale Hydroscience Integrated System Model
SRCSD	Sacramento Regional County Sanitation District
SFCWA	State and Federal Contractors Water Agency
SWP	State Water Project
SWRCB	State Water Resources Control Board
UnTRIM	A 3D hydrodynamic model of the Bay-Delta developed by Delta Modelling Associates
USBR	United States Bureau of Reclamation
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WY	Water Year
X2	Position along Bay-Delta axis (measured in km from Golden Gate) where bottom salinity is 2 psu
YCI	Year Class Index

Executive Summary

The San Francisco Bay-Delta is a complex ecosystem that supports a vibrant array of aquatic life, agriculture, recreation, and is the heart of the infrastructure for California's water supply. Managing these diverse uses, with their varied demands on natural resources, requires rigorous science to support management decisions, and the Interagency Ecological Program (IEP) has been meeting these science needs since 1970.

The IEP's mission is to provide and integrate relevant and timely ecological information for management of the Bay-Delta ecosystem and the water that flows through it. This is accomplished through collaborative and scientifically sound monitoring, research, modeling, and synthesis efforts for various aspects of the aquatic ecosystem. Building on the IEP *Strategic Plan*, which identifies the long-term goals and strategies to be implemented by the IEP to achieve its mission, the IEP *Science Strategy* provides direction to interagency science used to inform the management and ecological interests of IEP agencies in the near-term, and is one of a number of inputs used to shape the IEP *Annual Work Plans*. While the IEP *Strategic Plan* states that the *Science Strategy* be drafted for a 3-5 year horizon, a shorter 2-year timeframe for this first IEP *Science Strategy* has been adopted to allow for a more flexible internal development and review process, as well as feedback from the Bay-Delta research and stakeholder community.

This *Science Strategy* lists and describes the topics that the IEP has identified as being the areas where science is most needed to inform management in the near-term. These areas are defined in 5 broad themes:

- Effects of Climate Change and Extreme Events
- Understanding Estuary Food Webs
- Ecological Contributions of Restored Areas
- Restoring Native Species and Communities
- Impacts of Non-Native Species

Within each theme, we present the most important questions for anticipating management needs, followed by the expected monitoring, focused research, and combined synthesis efforts that should be prioritized to meet these needs. The themes are intentionally broad and are not ranked. Rather, the IEP recognizes that the Bay-Delta is dynamic and IEP will continue to respond to shifting priorities, as needed.

The *Science Strategy* is ambitious by design, and the IEP acknowledges that we cannot address all of the relevant questions alone with our current resources. Many other institutions exist within the Bay-Delta and greater Central Valley watershed with overlapping priorities and scope, and the IEP seeks to identify areas where coordination and collaboration could mutually enhance the parallel agendas of IEP and other groups. As such, this *Science Strategy* serves as an invitation to work together toward the coequal goals of preserving and restoring aquatic resources while ensuring a reliable water supply.

Science Strategy Defined

The IEP *Science Strategy* integrates science needs and management challenges, and serves as a subject-matter guide for focusing the planning of scientific studies. Collectively, IEP *Science Strategies* are outlines for identifying and organizing IEP agency science needs, for filling management-critical information gaps, reducing uncertainties in Bay-Delta ecology, and providing a cohesive science strategy that facilitates studies that are credible and integrated across agencies. The goal of the 2016 *Science Strategy* is to provide appropriate institutional, intellectual, and funding priorities to guide the near-term science needs of the IEP member agencies in the context of the larger Delta science and management communities.

While the newly adopted IEP *Strategic Plan* states that the *Science Strategy* be drafted for a 3-5 year horizon, a shorter 2-year timeframe for this first IEP *Science Strategy* allows for a more flexible internal development and review process, as well as feedback from the Bay-Delta research and stakeholder community. Regularly-scheduled programmatic review will provide an opportunity to address the changing needs of the IEP member agencies in the future, and to meet the needs of the larger Bay-Delta Science community. Following that feedback, future agendas will be developed on a 3-5 year cycle.

The IEP *Science Strategy* and the Delta Science Program's *Science Action Agenda* are intended to be synergistic. The IEP *Science Strategy* will be integrated into the Delta Science Program's (DSP) *Science Action Agenda* and will guide the development of *IEP Annual Work Plans,* as well as provide a basis for longer-term IEP budget and program planning. The integration of these agendas is a key component of achieving the goals of IEP and the Delta Science Plan and will be facilitated through coordination between the IEP Lead Scientist and the Delta Science Program Lead Scientist.

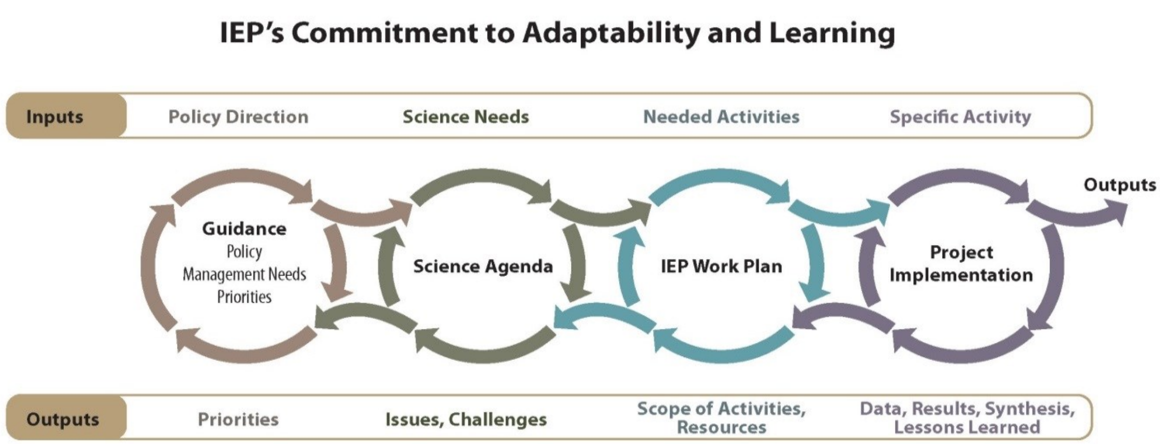

Figure 1: Adaptability and Learning.

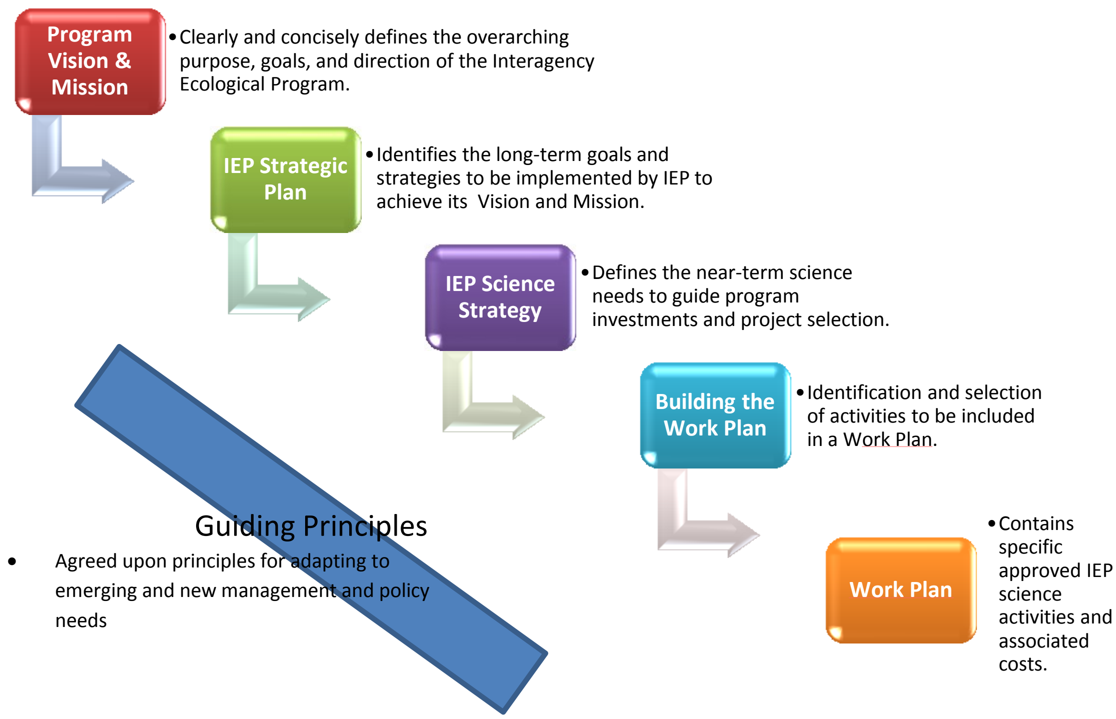

Figure 2: Integration of Strategic Planning.

Development of the IEP *Science Strategy*

The development of the IEP *Science Strategy* is part of a collaborative, iterative process that integrates management, regulatory, and science needs into a cohesive strategy (Figure 1 and Figure **2**). The IEP *Science Strategy* provides focus for near-term science planning (ultimately executed through *Annual Work Plans*), and articulates thematic, recurrent, and emerging management challenges and solutions.

Creation of the *Science Strategy* was initiated by the IEP Coordinators and Lead Scientist in 2015 and provides the link between the IEP *Strategic Plan* (approved by the IEP Directors in December 2014) and the annual IEP *Work Plans* (Figure 1). Using the IEP *Strategic Plan* as a guide, feedback on policy and management priorities were received from the IEP Directors, as well as input from the IEP Science Advisory Group (SAG), the Stakeholder Advisory Group, the IEP Resource and Regulatory Advisory Group, IEP Project Work Teams, IEP member agency staff, as well as the DSP *Science Action Agenda* and the research goals of the larger Delta science community (Figure 3). The solicited feedback produced more than 125 suggestions for research questions and priorities for study and program action (Appendix A), which were used to identify and determine the best methods for addressing near-term science priorities.

A conceptual model (Figure 4) was used to develop general organizing themes and facilitate a consistent approach to analyzing the science needs for each theme. The conceptual model approach is consistent with previous IEP activities, including development of IEP *Annual Work Plans* and synthesis reports (e.g., IEP POD 2010, IEP MAST 2015). The *Science Strategy* conceptual model is a tool for characterizing, summarizing, and displaying the primary IEP science research needs and themes, and how they relate to resource management. The model draws heavily from environmental factors described in the Delta Smelt Synthesis Report (IEP MAST 2015), expanded here to include multiple target species. To ensure the *Science Strategy* will be responsive to management needs, the conceptual model includes a specific list of management drivers which can influence, and be influenced by, the other main tiers of the model (Landscape Attributes, Environmental Drivers, Habitat Attributes, and Target Species, Figure 4).

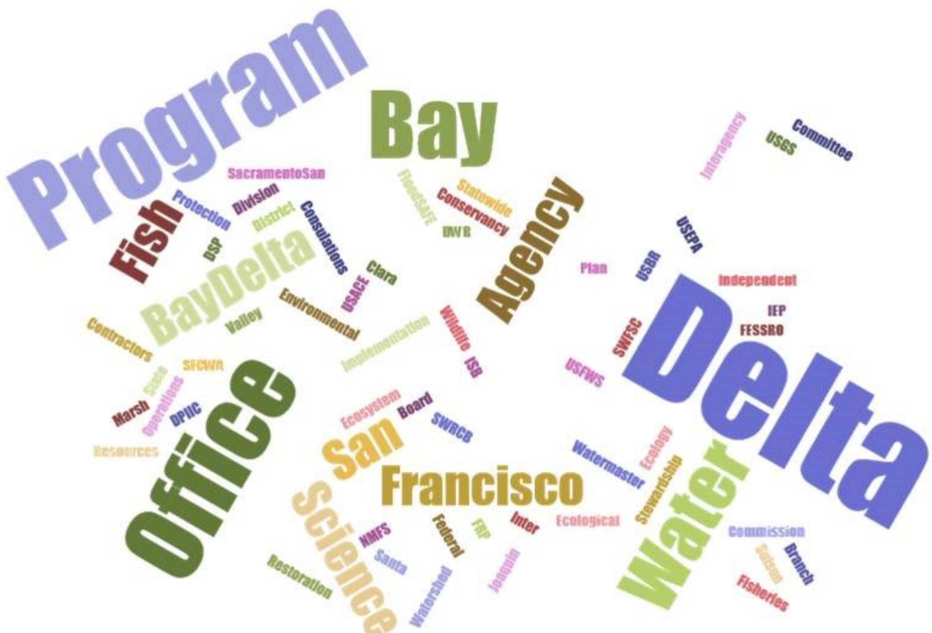

Figure 3: A word cloud of the Delta science and stakeholder community.

Use of the IEP *Science Strategy*

IEP Work Plan Development: The primary purpose of the IEP *Science Strategy* is to guide the development of the IEP *Annual Work Plans* (

Figure **2**). As noted previously, the current *Science Strategy* is intended to provide an overview of science priorities that address management questions over the next two years. However, the IEP *Science Strategy* is not meant to be the only set of guidelines in the development of the *Annual Work Plans*, which also consider many other similarly important factors, including budget, feasibility, CESA/FESA take, logistics, personnel, contracts, and investigator qualifications. In addition to informing the IEP *Annual Work Plans*, we expect the *Science Strategy* will be used by IEP member agencies and the Delta science community in several ways.

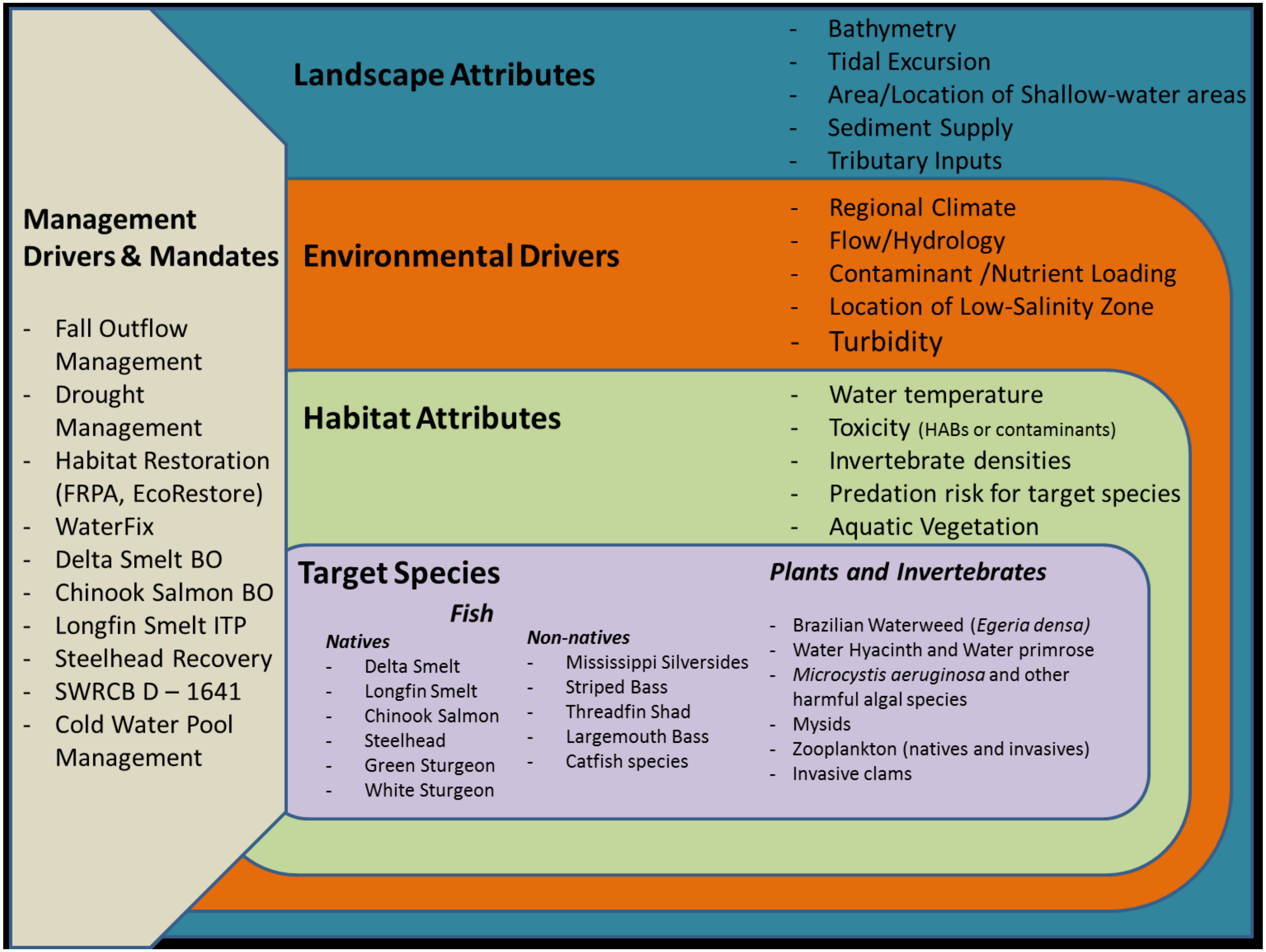

Figure 4: Conceptual model diagram used to organize *Science Strategy* items into general categories.

Planning for Investment in Science (Long-Term Budgets). Agencies and partners need a tool to help inform fiscal planning and allow investments in science without impacting current obligations. Agencies must not only manage today's budget as efficiently and effectively as possible, but must also develop visions and budgets for 3-5 years or more in order to ensure resources are available to answer tomorrow's questions. IEP *Science Strategies* can be used to help agencies project needs and costs consistent with their unique mission and responsibilities, while simultaneously considering input from others, to work toward a set of common priorities.

Capitalizing on Opportunities (Short-Term Funding). The *Science Strategy* acts as a guide for quickly and effectively leveraging shorter-term funding or staffing opportunities in a way that recognizes overall priorities. As an example, special funding to address specific management issues, such as drought or habitat restoration, could be employed in a manner that also addresses broader questions at little or no extra cost.

Focusing Research (Proposal Solicitations). The development of Requests for Proposals for IEP and its member agencies can be focused upon those areas identified in the *Science Strategy* that inform management questions in a thoughtful and holistic way to ensure the science derived from limited funds will be maximized.

Outreach to the Scientific Community: Lastly, we intend for the IEP *Science Strategy* to share and coordinate our near-term priorities with the broader scientific community. The integration of the IEP *Science Strategy* into the broader science community will be achieved by the participation of stakeholders in the development of IEP Science Strategies every 3-5 years, by sharing the near-term science priorities of multiple agencies working in the Delta, and by complementing the broader scope of the DSP *Science Action Agenda,* as described in the *Delta Science Plan.* The IEP *Science Strategy* will be a useful tool for members of the academic community and stakeholders interested in developing or funding Delta science projects with management significance. Sharing this information with the broader scientific community will be a key tool to reduce redundancy, identify knowledge gaps, and maximize the efficiency of study efforts. The priorities identified the IEP *Science Strategy* cannot be accomplished by the IEP alone, and the IEP is committed to coordinating with the greater Delta science community to accomplish the coequal goals of ecosystem restoration and reliable water supply.

Detailing the Themes in the *Science Strategy*

The following themes were selected for the 2016 IEP *Science Strategy*:

- Effects of Climate Change and Extreme Events
- Understanding Estuary Food Webs
- Ecological Contributions of Restored Areas
- Restoring Native Species and Communities
- Impacts of Non-Native Species

Specific information needs for management were identified within each category; these needs were listed as management-related questions and were developed with explicit consideration of the interactions between tiers in the conceptual model. Because of the complexity of the Bay-Delta system, a multi-faceted approach is suggested to improve our understanding of ecosystem dynamics at multiple spatial and temporal scales. This multi-faceted approach uses three strategies: 1) monitoring; 2) focused studies and 3) synthesis.

The themes are intentionally broad and are not ranked, and the IEP recognizes that there is substantial overlap in the fundamental ecology and management needs among the five themes, reflecting the complex ecology of the Delta. As such, readers will notice this overlap in the science needs highlighted for each theme, but to help minimize redundancy in the text, the *Science Strategy* does not discuss overlapping science needs in detail for each relevant theme.

Effects of Climate Change and Extreme Events

While drought has long been of concern to IEP agencies because of its effects on water management and species of concern (e.g., Chinook Salmon), the focus on climate change emerged more recently. Shifting environmental regimes due to global climate change have been well-documented in mountain and forest ecosystems (e.g., Cayan et al. 2001, Westerling et al. 2006), and evidence is emerging that such shifts are also occurring in aquatic environments (Rieman and Isaak 2010; Poff et al. 2015). Climate change has, and will, fundamentally affect a multitude of resources in California (Staudinger et al. 2012), with models suggesting that climate change induced changes in sea level rise and air temperature will have profound changes on Bay-Delta habitats and fishes of concern (Cloern et al. 2011, Feyrer et al. 2010, Brown et al. 2013, 2016), and climate change scenarios suggesting there will be changes in the timing and magnitude of precipitation in the Sierra Nevada mountains (Dettinger et al. 2015). These and other changes in future weather patterns affecting the Bay-Delta watershed are likely to result in a transition to a distinctly different "normal" with alternating periods of more intense drought and flooding (Dettinger and Cayan 2014). The combination of altered timing and magnitude of precipitation and changing frequencies of floods and droughts will influence environmental factors, such as the location and extent of shallow water habitat, flows and hydrology (Cloern et al. 2011), water temperature (Brown et al. 2016), and location of the low salinity zone (Feyrer et al. 2010, Brown et al. 2013, Feyrer et al. 2015), all of which have implications for the quantity and quality of water available for export (USBR 2014) and Bay-Delta ecosystem management (Brown et al. 2013, Brown et al. 2016).

Evaluation of climate adaptation has been identified by the Secretary of Interior as a high priority to provide context for and to assess vulnerability of Bay-Delta resources (USBR 2014). Similarly, the State of California has adopted a statewide Climate Adaptation Strategy that includes the sectors of Water and Biodiversity and Habitat, among others (http://www.climatechange.ca.gov/adaptation/strategy/index.html). Thus, understanding the effects of climate change and developing management actions for adaptation are high priorities for federal and State agencies. The IEP *Science Strategy* includes assessing the impact of climate change on the Bay-Delta and identifying potential adaptation responses in coordination with existing State and Department of the Interior (DOI) programs, such as the USFWS Landscape Conservation Cooperative activities (http://lccnetwork.org/lcc/california) and the USGS CASCADE effort (http://cascade.wr.usgs.gov/). Studies of habitat vulnerability to climate change have immediate application to the activities outlined within the non-native species and restoration project categories of this *Science Strategy*.

Priority Science Questions to Inform Management

1. How will physical, chemical, and biological conditions in the estuary change as climate change occurs?

   Importance: Choice of management strategies depends on a thorough understanding of the responses of the ecosystem to extreme climate events, such as drought and flood, and to more gradual changes, such as changes in water temperatures and salinity regime. Data needs for management include a complete description of physical, chemical, and biological responses to climate change. At a minimum, baseline conditions should be documented and impacts to existing Bay-Delta resources should be outlined.

2. Is the Bay-Delta water and fish management system resilient to climate change?

   Importance: Initial studies by the IEP Drought MAST team suggest that drought events result in major ecosystem changes. Moreover, recent assessments of the current drought's impact in the Bay-Delta provide a preliminary picture of the increasing likelihood of such events into the future (Dettinger and Cayan 2014). When wet conditions return, continued ecosystem assessments can provide an indication of ecosystem resilience to possible climate shifts. The FLaSH studies (Brown et al. 2014) provided an indication of such resilience but a more sustained effort is needed to fully understand ecosystem response. Recent reviews of CVP/SWP operations have suggested that recent dry years offer the chance to articulate a new set of management strategies for extended droughts and to test the effective management of water releases to protect species of interest (IRP 2013, 2014). Assessments like the Drought MAST and CVP/SWP review provide information regarding the effectiveness of management actions and identify ecosystems or specific habitats that may be less resilient to climate change. Ultimately, these assessments and related studies allow resource managers to make reasonable projections for adapting to changes in water supply and to understand future wildlife management needs in response to climate change.

   Research in similar systems outside California has highlighted the importance of refuge areas during extreme climatic events, such as drought (Lake, 2003). Refuge areas allow certain species to survive that otherwise would not during extreme conditions, which can facilitate population recovery when extreme conditions subside. An increased understanding of areas that act as refugia for species of concern during extreme conditions, particularly drought, will also support informed management decisions and priorities during extreme climate events.

What additional science tools are needed?

Monitoring:

System-Wide Responses. A general theme for all the topics in the *Science Strategy* is that more information is essential for calibration and validation of planning and water operation tools. Climate change is likely to create conditions that will challenge these models (e.g. CALSIM, DSM2), and an evaluation of these models in light of recent drought years and potential future flood years would be prudent. Observations during the recent drought, continuing through subsequent wetter conditions, provide an excellent opportunity to observe how different components of the ecosystem respond to changing hydrology. Supplemental sampling (i.e. Drought Monitoring) was added to IEP's core monitoring program to provide a way to evaluate changes to habitats caused by our on-going drought. However, such event-triggered and relatively short-term monitoring does not provide the consistent baseline data needed to assess the effects of long-term climate change. To increase effectiveness and interpretability of future climate-related (or drought/flood-related) assessments, hydrologic, water quality, productivity, and habitat occupancy monitoring will be needed in areas not currently monitored, and more frequent monitoring of some variables might be needed. As an example, the extent of submerged and floating vegetation is a topic of concern but there are no regularly scheduled aerial overflights to provide system-wide assessments of increases and decreases in vegetation extent. Such increased monitoring efforts, in turn, can be used to develop and improve physical and biological models for assessment of climate-based changes in the Bay-Delta ecosystem. In addition to enhanced routine monitoring, IEP agencies should prepare rapid environmental response monitoring capabilities in preparation for new or infrequent hydro-meteorological conditions that can deploy physical and biological monitoring to capture the information required for better models and more informed planning.

Hydrologic Monitoring. Hydrologic monitoring in the Bay-Delta is necessary to support improvement of existing models or development of new models to provide information at appropriate time scales (sub-daily to hourly) and geographic scales (entire region to sub-regions, such as North Delta). As scientists assess changes in these seasonal and decadal patterns, refinement to DSM2, CALSIM and SCHISM models (among others) will be necessary to use these tools to plan future environmental and species regulatory needs, flood system responses, and temperature management operations. Refining these models and applying them to answer management questions requires expanded investment in monitoring. For example, collecting data on physical attributes (e.g. water temperature, velocity, DO, nutrients, and turbidity) while also collecting data on biological attributes (e.g. plankton abundance, chlorophyll concentrations, and fish abundance) allows scientists to make connections between the physical and biological parts of the ecosystem.

Adaptive Monitoring. Focused studies associated with proposed management activities associated with drought and flood management in the near future will need an adaptive monitoring component. Examples include water management, induced flow changes, construction of barriers (e.g. drought barriers), in-channel construction, and levee improvements. The ability to rapidly expand monitoring infrastructure and perform experiments will be needed.

Focused Studies:

Developing special studies for unpredictable episodic events (floods and droughts) or gradual long-term change is difficult. One approach might be to develop specific study plans that function much as adaptive monitoring was described above. Another approach is modeling studies involving a large component of data integration and synthesis. However, the possibility of focused studies should not be dismissed because innovative approaches are likely possible.

Synthesis:

Continued synthesis efforts (e.g. FLaSH, Smelt MAST, Drought MAST) provide a strong foundation for understanding ecosystem changes in response to Bay-Delta climate change. After an extreme event, it is important to continue the evaluations for a minimum of one year to adequately assess the resilience and potential recovery of the estuary. We expect that synthesis and evaluation efforts will continue to include the use of conceptual models, and incorporate emerging and enhanced versions of more complex hydrologic (e.g. UnTRIM) and population models (e.g. Newman, 1998).

Population Response Modeling. Models exist for evaluating population level response of species of interest to climate change (Brown et al. 2016), and the IEP should take advantage of existing vulnerability assessment tools and efforts to evaluate Bay-Delta resource vulnerability to climate change (USBR 2014a, USBR 2015, IEP 2015, pending reports by SAIL and CAMT). These assessment tools and associated agency efforts will identify changes in environmental attributes that are likely to require modifications to existing management strategies to protect high risk species and increase their populations. While approaches exist for evaluating reduced growth of populations due to low abundance, they have not been widely used to evaluate Central Valley species when considering climate change. These approaches are useful for determining when additional innovative management actions (e.g. reintroductions and translocations) are needed for preserving and recovering endangered species in light of climate change. The IEP Project Work Teams can serve as a forum for interagency discussion and synthesis of information from efforts using these approaches.

Effects of Exceptional Management Efforts During Extreme Climate Conditions. Water management and infrastructure often change during extreme climatic events. For example, during the current drought (2013 – current year), there were many changes to water management in the Delta, including installation of the False River Emergency Drought Barrier and changes to the operation of the Delta Cross Channel to preserve water quality conditions in the interior Delta. In some cases, multiple special studies or enhanced monitoring activities are conducted to understand the impacts of these modified operations. As the extreme drought or other climate conditions that motivate these modified operations are likely to recur, it is imperative to determine the effects of modified operations on the ecosystem parameters of interest, such as water quality or species distributions, and time for staff to analyze these operations must be planned in advance. The IEP recommends that these synthesis efforts be based on specific management questions and conceptual models for expected effects of modified operations.

Water Quality Modeling. Recent advances in water quality modeling suggest this is an area that will likely see increased innovation in the near term. Water quality modeling will be important under climate change as droughts and floods expose contaminants, intensify contaminants, and modify concentrations of these constituents.

Hydrologic Modeling. Predictions of Sierra Nevada precipitation under climate change scenarios include changes to timing and magnitude of regional precipitation. New opportunities may arise to divert exported water earlier in more intensive rainfall seasons, and allow ecosystem use of water resources later as intense runoff events move through the Bay-Delta system. Accurate understanding of climate change-related variations in individual year hydrographs will aid in our scenario planning for water deliveries and beneficial uses. The development of models to predict the probability of cold water pools and projections of accessible cold water pool capacity will be critical to fisheries protection strategies in the future (IRP, 2015).

Coordination:

Formation of a PWT dedicated to climate change topics would facilitate focused studies and synthesis of data on this topic. Additional community members with parallel interests include DSP, SFCWA, CWQMC and CWEMF.

Understanding Estuary Food Webs

Lower trophic food web processes are poorly understood in the San Francisco Estuary. For example, the effects of changes in detrital input and nutrient flows on plankton, macrophytes, and algae should be investigated. In recent decades, dramatic changes in the lower food web have resulted in food limitation being a major factor in the decline of pelagic fish in the estuary (Kimmerer 2002, Hammock et al. 2015). Phytoplankton, the historical base of the pelagic food web, has declined substantially in the estuary, and historic spring and summer phytoplankton blooms in Suisun Bay have decreased in frequency and magnitude following invasion of an introduced clam (*Potamocorbula amurensis*) in 1987 (Kimmerer et al. 1994). In addition to the significant impact of clam grazing on the availability and size classes of phytoplankton (Kimmerer and Thompson 2014, Lucas et al. 2016), there are questions regarding the relative roles ammonium and light limitation play in inhibition of phytoplankton (e.g., Dugdale et al. 2007, Glibert et al. 2011, Cloern et al. 2015). Species composition is also an important aspect of the pelagic food web, and recent localized increases in phytoplankton biomass have not been accompanied by increases in pelagic zooplankton or fish. Phytoplankton taxa vary in food quality – diatoms and cryptomonads are considered “good food” for zooplankton, whereas flagellates and cyanobacteria (blue-green algae, *Microcystis* spp.) are considered of poor quality, and possibly toxic. Factors influencing species composition and biomass include environmental conditions, new species introductions, and nutrients. Little is known about how contaminants, such as herbicides, interact when they co-occur or how interactions with available substances may increase or decrease their toxicity.

The questions below are driven by a need to understand the interaction between habitat, hydrodynamics (including water quality and quantity) and biology.

Priority Science Questions to Inform Management

1. Habitat: What is the contribution of different habitat types (open water, floodplain, tidal marsh, benthic, floating aquatic vegetation, submerged aquatic vegetation, etc.) to the food web in the estuary?

   Importance: Different habitats within the estuary are likely to have varying contributions to the Delta food web; therefore understanding the role of each habitat type is needed to design management actions to support different components of the ecosystem. The importance of comparing productivity between habitat types is discussed further in the section below on the Ecological Importance of Restored Areas.

2. Hydrodynamics: How do hydrodynamics, including stratification and mixing, influence the transport and flux of nutrients, and variability in primary and secondary productivity among habitat types (pelagic/near-shore/tidal marsh)?

   Importance: Habitat specific food webs warrant investigation into how they link and interact at various scales. For example, there is increased interest in productivity subsidies that might result from the flux of productivity between tidal marshes and open water habitats as well as the transport of phytoplankton and zooplankton from upstream areas of high densities (North and Central Delta) to downstream areas of lower densities (Suisun Bay) (Kimmerer and Thompson 2014). In addition, food webs also warrant consideration of where in the estuary they are located based on environmental conditions, for example zooplankton species vary among salinities (Delta freshwater, low salinity zone, higher salinity areas). This has implications for identifying restoration activities that might influence productivity.

3. Biology: Which producers (e.g., phytoplankton, benthic algae, macrophytes) make up the base of the food web in the estuary?

   Importance: Understanding the basic composition of the food web is an important first step in designing management actions to increase productivity of the pelagic food web in the estuary. In particular, there is an urgent need to understand the sources of productivity for species of interest such as Smelts, Salmon, and Sturgeon.

4. Biology: What factors currently limit pelagic productivity?

Importance: Low pelagic productivity appears to be one of the major stressors in the ecosystem. In turn, an understanding of the timing and magnitude of factors that limit pelagic productivity is critical to the development of management actions. Examples of limiting factors include impacts from harmful algal blooms, FAV/SAV, nutrients, and clam grazing.

5. Biology: What are the acute and cumulative effects of contaminants on primary and secondary producers and species of concern?

   Importance: Contaminant interactions are complex and can have antagonistic or synergistic impacts when present, inhibiting primary and secondary production. Pesticides and herbicides are used heavily both upstream and within the Delta. Concentrations vary seasonally and have different affects based on the life stages of the organism.

6. Biology: How do shifts in the food web affect target species at higher trophic levels?

   Importance: It is important to understand how changing environmental conditions and species introductions have impacted the quantity and quality of primary and secondary production and linkages to higher trophic levels) and the "top-down" effects that fish predation can have on zooplankton abundance.

What additional science tools are needed?

Monitoring:

Expansion of existing IEP long-term monitoring studies into under-sampled areas and habitats, such as the North Delta, would fill a gap in IEP's current data collection efforts. Considerable efforts in tidal restoration are planned in the North Delta, yet this area is underrepresented in water quality, zooplankton, and benthic sampling. This is a critical area for understanding differences in production among habitat types, as discussed in the section, "Ecological Contribution of Restored Areas."

Focused Studies:

Special Field and Lab Studies on Productivity. Identifying high productivity areas of the Bay-Delta and the factors and mechanisms responsible for high productivity will require targeted field sampling at finer spatial and temporal scales than have generally been applied in current monitoring programs (i.e., more monitoring stations and high frequency sampling). Laboratory studies will also be needed to quantify the individual and interactive effects of contaminants on species of interest across a range of species and life stages.
Factors that should be studied in lab and field studies include:

- Water quality (e.g.: temperature, salinity/conductivity, O_2, pH, turbidity and organic carbon)
- Nutrients and stoichiometry
- Phytoplankton community composition
- Zooplankton community composition
- Contaminants (herbicides, pesticides, ammonium, etc.)

Special Field and Lab Studies Examining Incorporation of Marsh Detritus into the Pelagic Food Web. There is uncertainty as to whether tidal marsh materials will benefit the pelagic food web. This is discussed further in the section "Ecological Contribution of Restored Areas."

Synthesis:

Apply Updated Food Web Conceptual Models for Developing Hypotheses in Evaluating Food Production. Efforts are needed to understand the linkage of other habitats and restoration activities to primary and secondary production throughout the estuary. These efforts should consider scale of restoration footprint and the temporal and spatial scales of benefits along with the life stage of the target organism.

Apply Hydrologic Models. UnTRIM, RMA11 and others are needed to examine flows and transfer of nutrients, primary production, and secondary production from upstream areas to downstream areas.

Coordination:

Several focused studies within the IEP umbrella currently investigate hydrodynamic, water quality, as well as food web dynamics in specific Delta areas, including Suisun Marsh, Ryer Island, and Little Holland Tract. Continued focused studies and synthesis on this topic would benefit from coordination with additional community members with parallel interests, including DSP, SFCWA, CWQMC, RegionalSan, and CWEMF as well as the Estuarine Ecology and Tidal Wetland Monitoring PWT's.

Ecological Contribution of Restored Areas

The Biological Opinions for both Delta Smelt and Chinook Salmon, and their associated recovery plans, call for the restoration of habitat in the Bay-Delta (USFWS 2008). Current restoration plans call for the restoration of 9,000 acres of tidal wetlands and at least 17,500 acres of floodplain habitat, particularly in the Yolo Bypass. The wide geographic coverage and large size of planned restoration sites will result in substantial changes to the overall Bay-Delta landscape and its hydrodynamic and physical processes (Herbold et al. 2014). Although these changes are intended to increase the area of suitable habitat as a means of increasing populations of native fish species, there is considerable uncertainty regarding the outcomes of restoration. In addition to targeted species (i.e., those protected by the FESA and CESA - mainly Delta Smelt, Longfin Smelt, Winter-run Chinook Salmon), habitat restoration may help non-listed fishes, such as Sacramento Blackfish, Sacramento Pikeminnow, and Tule Perch. This section of the IEP *Science Strategy* lists specific questions regarding the ecological contribution and potential benefits of restored areas to target species, and outlines some near-term studies that would provide baseline information to facilitate the evaluation of restoration projects as they proceed.

This list builds on the IEP Tidal Wetlands Project Work Team's suite of conceptual models outlining hypotheses for the mechanisms behind tidal wetland function.

Priority Science Questions to Inform Management

1. How does large-scale tidal wetland and floodplain restoration affect the range of tidal excursion, bathymetry, X2, and sediment dynamics in the estuary?

   Importance: By design, habitat restoration is intended to substantially affect specific regions, as well as the broader ecosystem. Restoration of tidal wetlands and floodplain areas are likely to affect several key physical characteristics and processes, such as sediment dynamics, bathymetry, tidal range, and the position of the salt field (X2). Such changes have the potential to affect habitat conditions for species like Delta Smelt and other management issues including water project operations, entrainment, and water quality.

2. At a local scale, how do tidal wetland and floodplain restoration affect tidal dynamics?

   Importance: Locally, tides move material (food items, nutrients, contaminants) in and out of restored areas and affect the accessibility of restored areas to target species. A better understanding of hydrodynamics (e.g., fluctuations in flow and full "tidal footprint" of restored areas) is critical to understanding the mechanisms behind restoration outcomes for the local food web and target species benefit.

3. How will habitat connectivity change when current habitat restoration plans are implemented? Are there other strategically located sites that could be restored to fill important gaps in the habitat?

   Importance: A key benefit of restored areas for target species is the ability to access sites from existing habitat areas and migration corridors. In addition, connectivity among restored areas may enhance their collective benefit. To our knowledge, habitat connectivity in the Delta has yet to be assessed at a landscape-scale. Such an assessment would require the consideration of physical processes (e.g., flow paths and tidal stage) and behavior (e.g., migration corridors of salmonids) and distribution of species of concern.

4. How do floodplain and tidal wetland restoration influence the mobilization of contaminants, such as mercury and pesticides?

   Importance: Floodplain restoration will likely result in the rewetting of areas of ground that have not experienced regular floods in decades. Mobilization of stored sediment, which may contain mercury, and potentially increased input of agricultural run-off containing pesticide-based contaminants may have unanticipated ecological effects. Understanding the changes in the concentrations of these contaminants will help evaluate the effects on the local food web and target species.

5. Is water quality in restored areas suitable for target species?

   Importance: It is necessary to describe basic water quality conditions in order to evaluate whether restored areas provide suitable habitat for target fishes. For example, researchers should compare water quality in restored areas to that of existing known habitat in adjacent or nearby channels, and to existing wetland and floodplain areas. It will also be informative to evaluate the effect of restoration on water quality in proximate areas. Water quality dynamics in adjacent sites may influence the ability of target species to access restored areas, or their ability to do so.

6. Do restored areas produce invertebrate prey for target fish species (e.g., zooplankton, aquatic insects)?

   Importance: Although there is evidence that tidal wetland and floodplain areas can be valuable producers of invertebrate prey for target fish species (Sommer et al. 2001; Howe and Simenstad 2007; Durand 2015), the degree of the food web benefit is uncertain because invasive species, (e.g., clams and some introduced fishes) may reduce the benefits of such production to species of concern (Lucas and Thompson 2012, Kimmerer and Thompson 2014). In order to evaluate the success of restored areas, it is critical to measure food densities and compare them to densities in existing habitat, both in proximately located channels and wetland areas.

7. What is the predation risk between restored areas, compared to existing habitat (e.g., channels)?

   Importance: Increased predation by non-native predators in restored habitats is a key concern, and the degree to which this limits the benefit for target species. To evaluate this risk, it is necessary to compare predator densities and target species survival between restored areas and existing habitat.

8. Is there evidence that target fish species benefit from restored areas?

   Importance: Habitat restoration is planned based on the assumption that there will be benefits to target species, such as salmonids and Smelts. Therefore, a high priority is to determine whether the target species use restored habitat, and whether they receive benefits (e.g. faster growth, improved survival, more life history diversity). This is discussed further in the section, "Restoring Native Species and Communities."

9. What is the response of non-native species to restored areas?

   Importance: One of the greatest challenges to restoration in the Bay-Delta is the establishment and effects of non-native species. Therefore, a key question for restoration is to what degree are restored areas colonized by non-native species, particularly clams, aquatic vegetation such as water hyacinth and Brazilian Waterweed, and predators of target species such as Mississippi Silversides, Largemouth Bass, Striped Bass, and Channel Catfish. Furthermore, it will be necessary to evaluate whether and to what degree the presence of invaders in restored areas affects potential benefits to target fishes.

What additional science tools are needed?

Monitoring:

Cohesive Estuary-Wide Monitoring Strategy. Many of the above science needs can be accomplished by implementing a monitoring plan with standardized protocols across sites. The IEP Tidal Wetlands Project Work Team and Fish Restoration Program staff are in the process of developing a template for a monitoring plan for tidal marshes. This group is testing various data collection methods for invertebrates and fishes in shallow-water areas, and developing decision-making tools to aid in the design of monitoring programs for specific sites.

Collection of Baseline Data. Most restoration projects in the Bay-Delta are still in the planning stages; however, many of the above management questions call for comparing data collected from restored areas to existing habitat conditions. To do this, it is critical for IEP to develop a database of "pre-project" habitat conditions, including native species presence/condition, water quality, and current food and predator densities. In addition to existing tidal wetlands, it is necessary to document conditions in channel habitats that are near sites planned for restoration, as these areas make up the majority of existing habitat. This effort may combine expanding current routine monitoring to include strategic areas that are adjacent to those planned for restoration with compiling existing data that will be useful for comparison. It is critical that pre-project habitat monitoring proceed in a coordinated fashion, such that habitat conditions can be compared between sites and over time.

Focused Studies:

Restoration Projects. As restoration projects are implemented, focused studies will be useful for evaluating specific hypotheses regarding tidal wetland function. It will not be possible for regional monitoring efforts to address all mechanisms behind food web structure, function and outcomes for target species. For this reason, the IEP *Science Strategy* encourages focused studies that address the ecosystem function of restored areas. Specific topic areas that deserve emphasis are: (1) Hydrodynamic effects of increasing the area of shallow-water habitat and resulting flux of nutrients, plankton, and aquatic insect prey; (2) Habitat use of target species in shallow-water habitat; and (3) Evaluation of how diet or carbon sources change for target fishes as restoration projects proceed. Where possible, we recommend adaptive management studies to examine responses to different actions. For example, IEP and partners will continue to study how different land use and hydrologic changes to floodplain habitat affects food web and fish responses (e.g. Experimental Agricultural Floodplain Studies in the Yolo Bypass).

Synthesis:

Predictive Models for Restoration Outcomes. To facilitate later evaluations of project success, IEP should develop models to predict the effects of restoration on hydrodynamics and habitats (e.g., turbidity), and these models may also be useful for designing new restoration projects. For example, hydrodynamic models have been used to evaluate alternative designs for planned tidal wetland restoration at Prospect Island and other sites. At a landscape scale, predictive modeling can be used to address several of the questions listed above, including how habitat connectivity will change with planned restoration projects, and how the X2- low salinity zone habitat area relationship will change. Quantitative predictions for these questions will facilitate informed planning for new restoration projects and help managers think about how current management practices may need to be adapted once landscape-scale changes to the estuary have taken place.

Coordination:

The IEP Tidal Wetlands PWT is an active group that engages scientists from numerous state and federal agencies, and is functioning as a productive forum for guiding focused research and developing a template for a tidal wetland monitoring program that can be applied regionally. This group is an ideal platform for increased coordination of future focused studies and synthesis efforts.

Restoring Native Species and Communities

Native species have been in a long-term decline in the Bay-Delta, which has resulted in several fishes being listed as endangered or threatened under California and federal endangered species acts (ESA). These species include, but are not limited to, Delta Smelt, Longfin Smelt, Winter- and Spring-run Chinook Salmon, Steelhead, and Green Sturgeon. ESA listed species' extinction risks have increased due to the recent multiyear drought, and the increasingly low abundance of these species has intensified the scrutiny related to regulatory compliance, fish population recovery, and preservation-oriented management of Delta resources. During Water Year 2015, IEP continued to improve understanding of threats to Delta Smelt, Longfin Smelt, Chinook Salmon, Steelhead and White and Green Sturgeon, and helped identify gaps in the understanding of species ecology and management. Beyond the listed species emphasized here, other native fishes (e.g. Sacramento Blackfish, Hitch, Tule Perch, Lamprey) deserve consideration in our research and monitoring portfolios. As part of its *Science Strategy* and

Work Plan development, the IEP will continue its broader baseline monitoring efforts in response to emerging challenges. However, this section focuses on ESA-listed fishes because of the specific regulatory demands for these species.

A major threat to Bay-Delta native fishes is the reduction of the quantity and quality of habitat. Although the existing IEP long-term monitoring surveys provide much of the data about status and trends of native species, along with environmental conditions, in the Bay-Delta, many of these surveys were not designed to yield all of the management-relevant information desired by managers. In addition to these surveys, IEP scientists and partners need to design targeted laboratory and field studies to investigate factors and mechanisms impacting native species. The Delta Smelt MAST effort and the current SAIL effort have developed and are using species conceptual models for Delta Smelt, Winter-run Chinook Salmon, and Green and White Sturgeon to identify high-priority science and monitoring improvements for inclusion in the IEP *Science Strategy*. Some of the recommended science actions include the expansion and refinement of existing IEP monitoring to better assess species status and needs and the management of aquatic resources, including the protection of spawning habitat, migration corridors, and estuarine tidal habitats of rare and endangered species.

Delta Smelt

Delta Smelt is one of the highest profile species for Bay-Delta management and operations. There are requirements under the Smelt Biological Opinion (USFWS 2008) to modify operations and implement Reasonable and Prudent Alternatives as part of water project operations to avoid jeopardy under the Endangered Species Act. For the purposes of the 2016 IEP *Science Strategy*, Delta Smelt will continue to be a primary target for research and monitoring. The overall approach is guided by the recent Delta Smelt MAST effort (IEP MAST 2015) which provides the most comprehensive conceptual model regarding Delta Smelt biology, habitat drivers, and population responses.

Priority Science Questions to Inform Management

1. How can monitoring be improved to determine the distribution, abundance, and health of Delta Smelt?

   Importance: Historic IEP monitoring is not sufficient to fully determine the distribution and abundance of Delta Smelt, and these data gaps make it difficult to reliably optimize water management actions for the benefit of Delta Smelt. For example, refining our survey methods can improve our ability to determine when and where fish are vulnerable to entrainment and water project operations. This can also inform models that quantify the population level effects of entrainment or other critical habitat alteration.

2. What are the habitat needs of Delta Smelt?

   Importance: Information is needed about Delta Smelt habitat needs in order to guide habitat restoration, inform key operational issues (http://www.fws.gov/sfbaydelta/cvp-swp/cvp-swp.cfm), and identify potential approaches to adapt to climate change. There continue to be fundamental gaps in our understanding of Delta Smelt, including effects of harmful algal blooms, importance of predation, and characteristics of suitable spawning habitat.

3. Does restoration increase Delta Smelt habitat and provide greater food web support?

   Importance: Work is needed to determine if tidal wetlands restoration improves habitat conditions for Delta Smelt, and to guide adaptive management for future restoration efforts. The potential food web benefits of restoration are discussed in greater detail in the section on "Ecological Contribution of Restored Areas."

4. How do operational changes (e.g. flows, pumping, barriers) and fluctuating environmental drivers (flows, air temperature, food, salinity, turbidity) affect Delta Smelt?

   Importance: Resource managers need information about the effects of different management actions on Delta Smelt in order to inform decisions. Modeling and synthesis are needed to understand how changes in different environmental conditions affect Delta Smelt.

What additional science tools are needed?

Monitoring:

Improvements to Monitoring Technologies. An ongoing priority is to make targeted refinements to surveys tasked with describing the distribution and abundance of Delta Smelt in the upper estuary. For example, testing the efficiency of survey gear types will help refine estimates of fish densities, and sampling in previously un-sampled or under-sampled locations will help define distributions of fish. Field efforts will also include testing the SmeltCAM, the efficacy of environmental DNA (eDNA) as a method for detecting the presence of Delta Smelt, and establishing protocols for making effective population size measurements as a supplement to the existing population index. Work supported by SWCFA is investigating the potential for using telemetry tagging technologies in tracking smelt movement.

Additional Health and Life History Metrics. Recent work by researchers at UC Davis has shown that the application of new histological and clinical performance tools can provide insight into Delta Smelt life history and health. Further analysis should be done on collected Delta Smelt for health indicators, such as growth, origin (using otoliths), body condition, fish pathogens, and disease.

Focused Studies:

Data Gaps. IEP MAST 2015 identified a suite of data gaps for Delta Smelt, including the effects of contaminants, predation, harmful algal blooms, and Delta Smelt physiological responses to changing habitat conditions. For example, habitat conditions that trigger or facilitate spawning have not yet been identified in the field.

Restoration Projects. Shallow water habitats (e.g., tidal marsh networks) are not well-sampled by existing IEP methods, and targeted studies are needed to examine the degree to which these habitats are occupied by Delta Smelt, and whether they provide food resources to Delta Smelt in adjacent channels and shoals.

Synthesis:

Modeling. As noted by several review panels (SWRCB, IEP SAG, DSP) and by the IEP SMT itself, one of the highest priorities for the Delta Science community is to develop life cycle models to support Delta Smelt research and management. Models are needed to synthesize data from multiple sources and to explore effects of possible management scenarios on the various life stages of Delta Smelt. Therefore it is a high priority to continue efforts to develop life cycle models for Delta Smelt that have predictive capabilities for testing population outcomes of potential strategies for management (e.g. water project operations).

Longfin Smelt

Much like Delta Smelt, there is concern about declines in Longfin Smelt abundance; however, knowledge of the ecology of Longfin Smelt lags behind that of Delta Smelt. It is likely that investigations providing information that is useful for the management of Delta Smelt will also provide information relevant to Longfin Smelt. This section draws on issues relevant to both species, as well as input from the Longfin Smelt Technical Team. This team was organized in response to litigation settlement agreements requiring State, municipal and agricultural water collaboration on future research studies. Currently, Longfin Smelt abundance and its relationship to outflow (or X2) remain an important basis for management. Criteria in the State Water Project's Incidental Take Permit for Longfin Smelt are linked to flow and the Longfin Smelt represents the flow-related species for which the habitat protection outflows (X2 days at Chipps and Ryer Islands) were promulgated in the Bay-Delta Standards, D-1641. An alternate hypothesis for recovering Longfin Smelt suggests that shallow water habitat restoration will benefit the population and increase abundance.

Priority Science Questions to Inform Management

1. What hydrological, ecological or biological mechanisms (or combination thereof) underlie the relationship between Longfin Smelt abundance and outflow (or X2)?

   Importance: Longfin Smelt abundance continues to decline, and outflow during the winter and spring remains a strong driver for abundance. Knowledge of the underlying mechanism(s) could provide insight into the importance of flow itself or other potential mechanisms that might be activated independently to benefit Longfin Smelt abundance in the absence of increased flows.

2. What habitats are used by each life stage? Within these habitats, how do changes in habitat characteristics influence abundance of Longfin Smelt, both locally and at the population level?

   Importance: Developing conceptual and analytical models that describe the influence of factors on the abundance and survival of each life stage of Longfin Smelt are among the first steps towards understanding how management decisions affect Longfin Smelt.

3. What life-stage specific survival most influences recruitment or adult abundance?

   Importance: Knowledge of critical survival periods in the life history of a species can help deduce the factors that most strongly influence success. Our current inability to calculate accurate abundance indices (or population estimates) for early life stages of Longfin Smelt hinders our ability to investigate stage to stage survival, and identifying which life stage transitions offer the best opportunity for improving abundance through management actions, such as habitat restoration.

4. What timing, magnitude and duration of outflow (or X2) are needed for strong recruitment of Longfin Smelt?

   Importance: As Longfin Smelt abundance continues to decline and as drought becomes the norm rather than a passing phase, the questions above become critical for managing the water that remains in the system. If outflow itself proves necessary for successful Longfin Smelt recruitment, then optimizing its use will be necessary. The autocorrelation of flows through the water year render statistical analyses unhelpful, so other approaches need to be developed based on the timing and habitat needs of Longfin Smelt during its critical period(s).

5. Does shallow water habitat restoration provide growth or survival benefits that result in increases in Longfin Smelt abundance?

   Importance: Shallow water habitat restoration is identified as the mitigation measure in the Longfin Smelt Incidental Take Permit for the combined operation of the State Water Project and the Central Valley projects. Habitat restoration is hypothesized as an alternative means for increasing Longfin Smelt abundance and verifying the benefits and the magnitude of effect on Longfin Smelt abundance will be important steps to support this premise.

What additional science tools are needed?

Monitoring:

Improvements to Monitoring. Core IEP monitoring activities provide important abundance and distribution information for older juvenile and adult fish (e.g., Fall Midwater Trawl, Bay Study Midwater and Otter Trawl), while other monitoring surveys provide upstream distribution information for larvae and small juveniles (e.g., Smelt Larvae Survey, 20-mm Survey) used to assess the risk of entrainment in south Delta exports. However, current surveys do not cover the distribution of larvae and small juveniles during moderate and high outflow conditions, which is when we expect improved recruitment and abundance. Periodic (monthly or twice monthly), enhanced larval and early juvenile sampling (i.e., Smelt Larva Survey and 20-mm Survey) extending throughout San Pablo Bay would provide the density and distribution data needed, as well as fish samples for diet, condition, and otolith growth to help elucidate factors contributing to improved recruitment. Adding sampling of tidal marshes in the lower estuary to current monitoring programs would provide data on spawning and rearing. Such enhancements would complement sampling and research currently funded to investigate Bay tributary contributions to the population and proposed sampling for open water in San Pablo Bay, and expanding surveys to cover the distribution of early life stages will allow for more accurate abundance and stage-to-stage survival calculations.

Focused Studies:

Benefits of Culture and Tolerance Testing. Our knowledge of Delta Smelt reproductive biology and ecology benefitted greatly from developing culture methods and a cultured population. Availability of cultured fish provided for important new avenues of investigation, such as environmental and contaminant tolerance testing, age and growth, metabolic demand measurements, etc. Continued and enhanced support for the culture of Longfin Smelt is necessary to address similar questions.

Directed Investigations of Habitat Use. In addition to rearing in small marsh channels and large Delta and river channels in the San Francisco estuary, Longfin Smelt have been observed spawning and rearing in small tributaries of Lake Washington, Washington state (Harza, 1994). Longfin Smelt larvae hatch during winter and spring when outflow can be high, providing extensive freshwater and low salinity rearing habitat (young larvae are not tolerant of mesohaline or polyhaline waters). Outflows (net currents) at all levels transport buoyant early stage larvae downstream toward higher salinities, potentially reducing survival if larvae encounter salinity levels they have not yet developed to tolerate. This highlights the influence of habitat complexity on currents, slowing transport, and increasing residence time as potentially important factors to enhancing recruitment success. Currently, one funded project seeks to use direct sampling and otolith chemistry to detect tributary spawning and determine if tributary rearing results in distinctive otolith chemical signatures. If so, natal signatures of recruited juveniles or adults may help distinguish important rearing habitats. Salinity history derived from otolith chemistry has already shown the importance of low salinity rearing habitat (Hobbs et al. 2010).

Data Gaps. Surveys targeting fish larvae and juveniles do not cover the geographic distributions of these life stages for Longfin Smelt. In moderate and high outflow years, sizable fractions of the larval population rear and recruit in San Pablo Bay. Such indices and the survey data supporting them will be important in identifying when and where year class strength is determined. Subsequently, we can use abundance by life stage information for developing first approximations for survival and for identifying important periods and habitats for determining recruitment.

Restoration. The Longfin Smelt Incidental Take Permit for the combined operation of the State Water Project and the Central Valley projects identifies 800 acres of restored habitat to be created as mitigation, in addition to the much larger values for Delta Smelt. Habitat restoration is expected to provide substantial benefits for Longfin Smelt and lead to regional changes in the landscape of the upper estuary over the next couple of decades, however, such benefits need to be investigated, documented and measured. Such habitat benefits will need to change the abundance trajectory of Longfin Smelt to positive prior to additional water export. Furthermore, continued funding by the Fish Restoration Program Agreement is needed for scientific personnel to develop methods for addressing the question of habitat restoration benefits for mitigation restoration.

Synthesis:

Modeling. The current conceptual model for Longfin Smelt (IEP 2010) provides only modest detail to direct current and future work. Next steps involve the development of a detailed conceptual model comparable to that for Delta Smelt (IEP MAST 2015) that can incorporate potentially important landscape attributes (e.g., shallows with long residence times), environmental drivers (e.g., increased outflow sufficient to shift low salinity habitat into San Pablo Bay) and habitat attributes (e.g., suitable temperature and turbidity).

Chinook Salmon and Central Valley Steelhead

Understanding salmonids in the Bay-Delta and tributaries is critical to the operation of reservoirs and large-scale water diversion and export facilities, ESA-listed species recovery planning, and regulation of state and federally managed commercial and sport fisheries. A robust monitoring program that provides information on the timing, abundance, life history diversity, and condition of salmon stocks at critical life stages and geographic locations is fundamental to the management of the fisheries and associated water resources. Central Valley salmon stocks differ in their ESA listing status and can mix as juveniles in the main-stem Sacramento River and Delta (NMFS 2011). The timing of riverine and Delta management requirements differ for each salmon run. Yet, in the majority of our salmon monitoring network, it is unclear whether a juvenile salmon sampled at a particular location and time is from a stock that is of conservation concern (winter, spring, late-fall) or intended to be commercially harvested as adults (fall). It is important to have quantitative stock-specific abundance and distribution estimates for salmon and steelhead generated from monitoring programs to make more accurate decisions on water project operations to protect listed runs, provide an early warning for the abundance and timing of each salmon and steelhead stock leaving the freshwater each year, and increase the management value of monitoring to support life cycle modeling efforts to manage salmon, steelhead and water resources in the Central Valley and Bay-Delta.

Priority Science Questions to Inform Management

1. What modifications to current monitoring are needed to accurately identify salmon stocks?

Importance: The inaccuracy in stock identification of the current "length-at-date" approach compromises the management value of the long-term data collected in monitoring programs (IEP SAG 2013). Inaccurate stock identification data are used reluctantly by technical staff to inform water project operations and otherwise valuable monitoring datasets are omitted from some quantitative synthesis analyses due to the fundamental uncertainty in inferring patterns specific to stocks.

2. What modifications to current monitoring are needed to generate salmon abundance estimates in key geographic locations?

   Importance: We need to know how many salmon from each stock are entering and leaving the freshwater Delta to provide an early warning for the abundance of salmon leaving the freshwater each year and the extent to which Delta survival objectives are met (NMFS 2014).

3. What environmental factors influence the timing of salmon movement, route selection, and survival?

   Importance: Integrating how habitat and hydrodynamics influence fish movement and survival is critical to our understanding on how to improve water projects operations for salmon protection (NMFS 2014; CAMT SST Draft Gap Analysis Report).

4. What is the spatial distribution and abundance of ESA-listed salmon in real-time?

   Importance: Knowing the location and the proportion of the population that are in upper and middle river regions and the tidal Bay-Delta influences the ability to make informed and timely management decisions to facilitate salmon survival, growth, and habitat availability during critical window for rearing, migration, and spawning.

5. What is the role of Delta-rearing and migration to support healthy, diverse and resilient salmon populations?

   Importance: Juvenile Chinook salmon migrate from their natal rivers at different times and sizes with the majority of salmon leaving at sizes requiring non-natal rearing prior to being sea-ready. This baseline information is needed to inform the extent to which Delta salmon habitat restoration is increasing the success of this life history strategy.

What additional science tools are needed?

Monitoring:

Accurate Salmon Stock Identification in Monitoring. Recent studies have identified that current length-at-date (LAD) methods for stock identification of juvenile salmonids (Fisher 1992) used in the salmon monitoring network vary in the accuracy of true genetic identity (Harvey and Stroble 2013; Pyper et al. 2013). IEP will prioritize the collection of genetic tissues and otoliths in strategic locations of scientific and management value to inform water project operations and begin to develop a robust database necessary to support synthesis work, status and trend evaluation, and life cycle models for the diversity of salmon stocks in the Central Valley.

Stock-Specific Juvenile Abundance Estimates. A lack of comparable abundance estimates for individual salmon stocks precludes the effective use of monitoring data to detect population-level effects of many management actions on the juvenile life stage (water operations, restoration, hatchery release practices) or use in quantitative analyses, such as life cycle modeling efforts. The IEP will continue to prioritize improvements to our sampling program through the use of new technologies to generate abundance (and/or survival) estimates of individual stocks at key life stages and geographic locations like the Red Bluff Diversion Dam (RBDD).

Focused Studies:

Understanding Salmon and Steelhead Mortality Through Integration of Biological and Physical Factors. There is general recognition that system-wide changes to the ecosystem have likely influenced Central Valley predator and prey species complexes, which likely impact juvenile salmon distribution and abundance. Recent CAMT and SAIL technical teams working on South Delta salmonid survival and life cycle mechanisms, respectively, highlight that little is known about what ecological mechanisms are impacting salmon migration behavior and survival directly. Linking measurements of flow characteristics (velocity, turbidity, temperature) with fish behavior and survival measurements is essential for understanding how managers can accelerate salmon recovery efforts, monitor effectiveness at habitat restoration sites, and inform ecosystem based adaptive management solutions for native species viability. The IEP will continue to prioritize the use of technology (e.g. acoustic and PIT tag telemetry) to expand survival monitoring of both hatchery and natural-origin stocks including those with ESA and harvest relevance to better represent the migration success of a broader temporal diversity of juvenile outmigration behaviors.

Health, Life History Diversity and Delta Rearing. Chinook salmon exhibit significant diversity in juvenile rearing strategies with the majority of fish leaving their natal rivers at sizes requiring non-natal rearing downstream prior to ocean entry. The extent to which salmon successfully use the Delta for rearing and contribute to adult returns remains largely unknown. Recent work by NOAA Fisheries and UC Davis has shown that additional tools can provide valuable insight into salmon life history diversity such as quantify Delta rearing by juvenile salmon using otoliths (Miller et al 2010; Sturrock et al 2015). Samples can provide indicators such as fish age, habitat-specific growth rates, migration behavior, duration spent in different rearing habitats, and use of the Delta. Additional biomarkers can be used to assess fish condition and exposure to contaminants, pathogens, and diseases.

Salmon artificial propagation practices designed to bypass mortality risks associated with migrating through the Delta result in high rates of straying of returning adults (Palmer-Zwahlen and Kormos 2015). The resulting high level of gene flow limits the ability of stocks to maintain local adaptation, compromising genetic and life history diversity as well as potentially reducing physiological capacity to withstand high temperatures or flows at critical life stages (Eliason et al 2011; Satterthwaite and Carlson 2015).

It should be noted, that in addition to studies in the Bay-Delta, related studies within the watershed should seek to understand more about how gene flow from hatchery fish may be influencing fitness in natural populations (e.g., hatchery impact/influence), such as measuring aerobic scope capacity of all stocks to evaluate stock specific ability to withstand increasingly variable changes in temperature and flow associated with habitat alterations, diversions and climate change.

Restoration Projects. Habitat restoration is likely to be one of the major regional changes in the Bay/Delta landscape over the next decade. Floodplain and shallow water habitats, such as tidal marshes, are not well-sampled by historical IEP methods, so targeted studies are needed to examine if the predicted benefits and risks of these actions influence on Chinook salmon populations. The IEP will continue to lead efforts to monitor the effectiveness of restoration on Chinook salmon, yet greater collaboration outside of IEP will be necessary for understanding the critical role of these habitats in salmon recovery. Coordination among IEP regulatory and science planning monitoring programs requires additional planning to maximize the synergies between these elements. These projects have the potential to increase adult returns, reducing the need for mitigating artificial propagation practices with negative impacts to natural production.

Synthesis:

Planning and Tactical Operation Models. Development of better models to integrate fish and water quality monitoring data to report, simulate, and forecast the distribution of salmon runs in time and space is essential to rapidly provide insight to decision makers on fish and water management in the Estuary in-season. Technological improvements to estimating Chinook Salmon survival within days to weeks has increased the desire to use this metric for rapid integration to inform decisions on water project operations. Development of models should be coordinated with tagging studies and other monitoring data to provide an accurate and consistent interpretation of the information to support decision makers. Life cycle models are under development by many groups including NMFS, DSP, and CVPIA to evaluate near –term and long-term benefits and risks of actions to salmon and steelhead recovery and the IEP SMT and work teams are well-positioned to coordinate and improve how research and operational monitoring can be used by these tools.

Comparative and Synthesis Studies. Many efforts have focused on conceptual model development (e.g., SAIL and IEP MAST) and lay a foundation for better data integration for understanding Chinook salmon in the Delta. For example, assessment of the effects of drought on Chinook salmon has not occurred regularly. An interagency team assembled results regarding Chinook salmon and drought in Water Year (WY) 2014, and a similar, if not greater, effort should be undertaken for the more recent drought years. New information is available about cohorts that were impacted during early freshwater life stages and a full life cycle accounting for observed impacts will be very informative.

Green and White Sturgeon

Like salmon, understanding sturgeon in the Bay-Delta and tributaries is critical to the operation of reservoirs and large-scale water diversion and export facilities, ESA-listed species recovery planning, and regulation of state and federally managed commercial and sport fisheries. Managing Sturgeon is particularly challenging compared with other target native species for the following reasons:

- Sturgeon populations are relatively small;
- young individuals (e.g., age-0 through age-5) are difficult to capture and monitor;
- Sturgeon are late maturing (e.g., 15+ years) and long-lived (50+years);
- Sturgeon from the San Francisco Estuary may spend substantial time in estuarine areas outside the state of California, and
- Sturgeon achieve large size and support popular legal (White Sturgeon only) and lucrative illegal fisheries.

There are currently only two long-term monitoring studies used in estimating and forecasting abundance in sturgeon (primarily White Sturgeon): the IEP Estuarine and marine fish abundance and distribution study (Bay Study) and the IEP White Sturgeon population study (adult sturgeon population estimates).

No demographic measures (i.e., abundance, recruitment, and survival) are currently available for Green Sturgeon. As a consequence, information necessary to evaluate the relationship between water operations and fisheries regulations and Green Sturgeon abundance and recruitment does not exist, and it is uncertain if the population is following general patterns observed during major environmental stress (e.g., the current drought). Green Sturgeon adult spawner abundance (escapement) has been estimated in the last few years, but population models necessary to generate overall abundance from these estimates require further development. Synthesis of existing long-term data sets (including from IEP Work Plan Elements) is underway but requires further support and development.

Priority Science Questions to Inform Management

1. What is the influence of water operations, major environmental stress, and fisheries regulations on White and Green Sturgeon abundance and recruitment?
   Importance: Understanding major drivers or limiting factors in White and Green Sturgeon abundance and recruitment is necessary to identify critical life stages and habitats, prioritize resources, and focus management actions. For example, episodic White Sturgeon recruitment in the Bay-Delta has been correlated with wet years and sustained high winter and spring flows (and inundation of the Yolo Bypass). White Sturgeon abundance, survival, and harvest estimates also provide key information for managing the sport fishery. However, these estimates may not be sufficient to establish mechanisms for large-scale recruitment trends and assess the potential influence of water operations on White Sturgeon abundance and recruitment because current surveys were not designed for this purpose.

2. What is the year-class strength or recruitment of Green Sturgeon?

   Importance: Current monitoring is not sufficient to estimate abundance and recruitment in Green Sturgeon.

3. Can current (or improved) methods for estimating demographics in White Sturgeon be modified and applied to Green Sturgeon?

   Importance: Demographic estimates in White Sturgeon involve synthesis and quantitative modeling of long-term data sets from IEP and CDFW programs. These long-term data sets could be used to estimate demographics of Green Sturgeon.

4. What is the annual distribution and relative abundance of early life-stages of White and Green Sturgeon?

   Importance: Egg and larval collection is necessary to verify spawning and estimate spawning distribution. Verification of spawning habitats and distribution can be used to evaluate recruitment mechanisms and identify critical life stages and habitats for sturgeon. Electronic tag technologies can be applied as fish grow to juvenile stages.

What additional science tools are needed?

Monitoring:

Improved Demographic Monitoring and Programmatic Surveys. The long term IEP surveys have provided key information on status and trends of sturgeon; however, additional tools are needed to expand and improve these estimates. For example, current long-term sampling does not include a Year Class Index (YCI) survey for Green Sturgeon, and IEP surveys associated with the White Sturgeon YCI (Bay Study) should be reviewed and expanded to improve confidence surrounding population estimates.

The long-term fish surveys remain the core of IEP's work but expanding and refining these surveys is necessary. For example, age, genetic, and mark/recapture should be added to existing surveys where appropriate. Methods have been established to sample nearly all life stages (eggs, larvae, juveniles, and adults) of sturgeon in the Bay/Delta and tributaries. We recommend monitoring all life stages of sturgeon at some level by way of long-term IEP surveys to improve our understanding of the effects of water management on individual life stages.

Focused Studies:

Landscape Changes and Restoration Projects. Establishing mechanisms for recruitment in sturgeon will improve our ability to predict the potential effects to sturgeon populations of large-scale changes to the Delta landscape and hydrology, such as the proposed California Water Fix and restoration of flood plain areas in the Yolo Bypass.

Synthesis:

Modeling. Monitoring and focused studies are critical in collecting data on life history, distribution, and diversity. Quantitative models are also necessary to synthesize these data into more pertinent metrics for management, such as status trends of sturgeon. We recommend an integrated approach using conceptual and quantitative modeling. Several such tools are under development (e.g. SAIL; CDFW White Sturgeon brood-year modelling) that may be able to support integrated analyses.

Comparative Studies and Technical Review. Assessment of sturgeon populations is generally challenging because of their broad distribution and life history diversity, and associated difficulty in sampling and development of quantitative population models. Given these limitations, technical review of existing quantitative models and comparison with other regions involved in similar sturgeon monitoring and management (e.g., Columbia River basin White Sturgeon) can be informative.

Coordination:

Many of the recommendations above have been identified as high priority by IEP Agency Directors, IEP PWTs, IEP MTs, IEP SAG, CSAMP/CAMT SST, Delta Smelt MAST, California Hatchery Scientific Review Group and/or Salmon and Sturgeon SAIL. Focused studies and synthesis on this topic would benefit from coordination with additional community members with parallel interests including DSP, SFCWA, SFEI, Universities, FRPA as well as the multiple IEP PWT's focused on these species.

Impacts of Non-Native Species

Non-native species continue to threaten Bay-Delta ecosystem services, posing a number of challenging resource management issues. Invaders include phytoplankton, macrophytes, invertebrates, and fishes. These invasions have disrupted the food web dynamics and biogeochemistry of the estuary, its underlying water quality and chemistry, and have changed interactions among species. Ballast water, the aquarium trade, recreational boating, and intentional releases have been implicated as avenues for introductions.

Beginning in the late 1860's, the reclamation process that transformed wetlands to agricultural fields created disturbances that increased the Bay-Delta's susceptibility to invasions. This physical transformation was fairly complete by the 1930's (Thompson 1957). Changes in patterns of flow and physical alteration of habitats in the Bay-Delta may no longer reflect the habitats in which native species evolved, and these shifted habitat characteristics may be more favorable to non-native species, helping them outcompete native species. Examples of impacts from invasive species include:

Harmful Algal Blooms: Adverse effects on human health; reduced water supply reliability; habitat degradation; toxicity to fish, mammals, and invertebrates.

Aquatic Weeds: Reduction of open-water habitat; water quality effects (e.g., increased water temperatures, clearing of suspended sediments, increased variability in dissolved oxygen and pH); fouling of infrastructure (e.g., trash wracks at diversion structures); promotion of alien species; boating hazards, need for expensive treatment methods.

Benthic Invertebrates: Fouling of infrastructure; declines in pelagic food resources; contaminant biomagnification; loss of native fauna.

Pelagic Invertebrates: Shifts in the aquatic food web.

Fishes: Predation and competition

Priority Science Questions to Inform Management

1. Where and when are new invaders arriving in the estuary?

   Importance: Early detection of invasions improves the effectiveness of management and/or control measures.

2. What are the characteristics of species, communities and habitats that provide resilience or vulnerability to invasions?

   Importance: Understanding which species, communities, and habitats are resilient or vulnerable to invasions is a key step toward developing appropriate and effective management and control measures. Habitat characteristics associated with the presence of invaders can inform models that allow managers to predict which areas are most susceptible to invaders. This information can in turn be used to prioritize resources for effective detection and control.

3. What are the ecological consequences of invasions?

   Importance: Assessing the effects of specific invasions on Bay-Delta habitats will provide insight into the mechanisms driving trends in species abundance and community structure and will help identify possible management approaches.

4. What are environmental effects of non-native control measures?

   Importance: Key approaches to the management of non-native species include chemical treatment and physical removal. Information is needed about how these treatment approaches may affect desirable native species, such as Delta Smelt or Chinook Salmon. Additionally, information is needed on whether such control measures can be used to reset an ecological balance that favors native communities, rather than requiring perpetual effort to maintain an ecosystem in an unsteady state.

5. How do different management actions (e.g., restoration, operations) affect the risk of species invasions or spread?

> *Importance:* Information about the degree to which different operations or habitat changes (e.g., restoration) promote or suppress the establishment and/or spread of non-native species is necessary to developing effective management and restoration plans.

What additional science tools are needed?

Monitoring:

Detection and Identification of New Algae, Macrophytes, Invertebrates, and Fishes. The long term IEP surveys have, to date, provided key information about new invertebrates and fishes. However, additional tools are needed to detect and identify new harmful algal blooms, macrophytes, invertebrates, and fishes. For example, current long-term sampling does not adequately evaluate surface-oriented algal blooms (e.g., *Microcystis*), the biota of inshore habitats (e.g., epibenthic fauna), or the proliferation of aquatic weeds. Some of these gaps can be addressed by expanding current surveys, but there is an increasing need to develop novel tools such as, eDNA and aerial imagery (e.g., from drones, satellites).

Long-Term Programmatic Surveys. The long-term fish and invertebrate surveys remain the core of IEP's work. We anticipate that the major sampling programs would continue to provide the basis for detection of many new species, and for evaluations of the effects of non-native species. Capacity for laboratory identification of new species caught in existing or additional surveys will need to be expanded to speed up processing of collected samples.

Focused Studies:

Restoration Projects. Habitat restoration is a potential major change in the Bay-Delta landscape over the next few decades, and targeted shallow water studies are needed to determine whether the potential presence of non-native species will interfere with providing benefits to species of concern. Moreover, because most of these habitat projects will be engineered, there will be opportunities to design specific experiments to test the effects of different restoration approaches on the proliferation of non-native species.

Adaptive Management. Focused studies associated with proposed management activities will need to consider non-native species. Examples include water management induced flow changes, construction of barriers (e.g., drought barriers), in-channel construction, and levee improvements. Management approaches to minimize the effects of our scientific operations on species introductions will also receive attention as IEP develops *Annual Work Plans*.

Synthesis:

Modeling. An integrated approach using conceptual and quantitative modeling would facilitate assessing and characterizing the spread and effects of non-native species. Several such tools are under development (e.g., SAIL, NMFS Salmon Life Cycle Model) that may serve as a model for developing integrated analyses of invasive species, and support for these emerging tools will be timely and critical to the success of these efforts.

Comparative Studies. Assessing the effects of non-native species is generally challenging because of the complex ecological interactions, and because pre-invasion data is often limited. In order to overcome the limitations inherent to descriptive studies, careful comparisons with other regions and their invasions can be informative.

Coordination:

Coordination with existing detection and prevention programs will supplement current IEP monitoring efforts, and facilitate the detection of potential invaders. Focused studies and synthesis on this topic would benefit from formation of a PWT (IEP Project Work Team) dedicated to non-native species topics. Additional community members with parallel interests include DSP, SFCWA, SFEI, FRPA, CSAMP, USDA, CA Division of Boating and Waterways, CA Department of Pesticide Regulation and Universities.

Future Directions

The 2016 IEP *Science Strategy* is a pilot effort with a two year timeframe to allow for adaptive management of the agenda development process and the adjustment of science priorities. The program will review the utility and effectiveness of this pilot prior to beginning the development of the next full agenda revision, which will cover a 3-5 year timeframe.

The authors recognize that management questions cannot be adequately addressed with ecological research alone, and we encourage the investment of resources and efforts into examining the socio-ecological interactions that are impacting the health of the Bay-Delta ecosystem. Although outside the scope of IEP, we recognize the importance of policy, economy, land use, and human behavior on management decisions and the complex interactions of those processes on our aquatic resources. It is our hope that additional research on multi-disciplinary approaches to ecosystem restoration and water management will be supported throughout the Delta, and we look forward to the opportunity to collaborate on these endeavors in the future.

As the *Science Strategy* is used, we anticipate that it will increase dialog on critical topics, and help guide and increase the effectiveness of the program with clearer science questions, timely studies, synthesis, and partnerships.

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Appendix

Priority Topic	Management Priorities and Science Tools	Input Link[1]
Impacts of non-native species		
	Detection and identification of new invasions	ROAG, SMT/CT
	Detailed assessments of the impacts of invaders	Directors, Stakeholder, Biotelemetry, Sturgeon, SMT/CT
	Ecosystem resilience to invasion	SMT/CT
	Long-term monitoring and new surveys (e.g. *Microcystis*, aquatic weeds)	Directors, ROAG, Stakeholder, SMT/CT
	Focused studies on effects of restoration and adaptive management	ROAG, SMT/CT
	Comparative studies with other regions	ROAG, SMT/CT
Effects of climate change and extreme events		
	Hydro-meteorological characteristics associated with climate change	Directors, SMT/CT
	Ecosystem resilience to climate change	SMT/CT
	Long-term hydrologic monitoring	Directors, ROAG, SMT/CT
	Productivity estimation and prediction (floodplains, tidal habitats)	SMT/CT
	Population response modeling (climate and operations simulation)	Directors, ROAG, SMT/CT
	Water quality modeling	Directors, SMT/CT
Restoring native species and communities		
	Habitat needs of native fishes	Directors, Steelhead, Sturgeon, Juvenile Salmon, Genetics, SMT/CT
	Ability of restored areas to support native fishes	Directors, Steelhead, SMT/CT
	Resilience to operational changes	Directors, ROAG, Steelhead, SMT/CT

	Population level effects of different environmental drivers	Directors, Stakeholder, Biotelemetry, Steelhead, Sturgeon, Juvenile Salmon, Winter-Run, SMT/CT
	Improved knowledge of species identification, demographics, and distribution	Directors, Stakeholder, Biotelemetry, Steelhead, Sturgeon, Juvenile Salmon, Winter-Run, SMT/CT
	Fish movement and migration	Directors, Biotelemetry, Steelhead, Sturgeon, Juvenile Salmon, Winter-Run, SMT/CT
	Long-term monitoring with expanded tool-set (e.g. SmeltCam)	Directors, ROAG, Stakeholder, Biotelemetry, Sturgeon, Genetics, Winter-Run, SMT/CT
	Focused studies on benefits of restoration projects	SMT/CT
	Addressing monitoring data gaps (early life stages, genetic stock identification)	Directors, Stakeholder, Sturgeon, Juvenile Salmon, Genetics, Winter-Run, SMT/CT
	Culture and tolerance testing (*Longfin Smelt*)	Directors, SMT/CT
	Modeling (life cycle, statistical)	Directors, Sturgeon, Winter-Run, SMT/CT
	Comparative and synthesis studies	Directors, ROAG, Tidal Wetland, SMT/CT
Understanding estuary food webs		
	Contribution and type of producers	Directors, SMT/CT
	Which habitat types support increased productivity	SMT/CT
	Influence of hydrodynamics on productivity	SMT/CT
	Nutrient and contaminant effects	Stakeholder, Sturgeon, SMT/CT
	Environmental factors limiting productivity	SMT/CT
	Interactions between trophic levels	Stakeholder, Genetics, SMT/CT
	Long-term monitoring and new surveys (integrated food web sampling)	SMT/CT

	High-frequency spatial sampling	SMT/CT
	Synthesis to integrate data sources and identify gaps	Directors, ROAG, SMT/CT
	Focused studies to evaluate habitat restoration contribution	Directors, SMT/CT
	Field and lab manipulations (carbon flow, nutrient loading)	SMT/CT
Ecological contributions of restored areas		
	Effects of restored tidal wetlands on tidal dynamics	Tidal Wetland, SMT/CT
	Impact of restoration on habitat connectivity	SMT/CT
	Influence of restored areas on sediments, predation, productivity, and contaminants	Directors, Tidal Wetland, SMT/CT
	Impact of restoration on water quality parameters	SMT/CT
	Impact of restored areas on native and invasive species	Directors, SMT/CT
	Consistent estuary-wide monitoring	SMT/CT
	Development of baseline data (restoration and adjacent sites)	Directors, SMT/CT
	Predictive modeling (hydrodynamics, turbidity)	SMT/CT
	Habitat use and diet of target species	Directors, SMT/CT

[1]**Regulatory and Operations Advisory Group (ROAG); Science Management Team and Coordinators (SMT/CT); PWTs (Biotelemetry, Steelhead, Sturgeon, Juvenile Salmon, Genetics, Tidal Wetland, Winter-Run)**