DRAFT (DO NOT CITE)

Date: March 16, 2026

To: Delta Stewardship Council

From: Delta Independent Science Board

Subject: Highlights from the Emerging Climate Science Symposium

Table of Contents

As global climate change intensifies, landscapes around the world are facing increasing stressors and shocks that threaten their stability and functionality. The Delta Independent Science Board (ISB) seeks to stay informed on pressing and important topics affecting the Sacramento-San Joaquin Delta system to meet its legislative mandate to provide scientific oversight that supports adaptive management. The Delta ISB hosted a hybrid symposium on September 16 and 17, 2025, at UC Davis that brought together over 250 scientists, practitioners, and decision-makers to assess the latest climate science and its implications.

The symposium highlighted the shift from the current practice of using historical climatic data in modeling efforts toward approaches that consider evolving future conditions. Presentations and panels examined the latest knowledge regarding climate-driven stressors, such as droughts, floods, atmospheric rivers, wildfires, and sea-level rise, and explored how these hazards impact hydrology, ecosystems, and infrastructure. The symposium highlighted uncertainties in projections, extreme events, and their cascading impacts. As a Board of ten scientists from across the

United States and spanning different disciplines, we have experience working across many regions, including large systems outside of California such as the Chesapeake Bay and the Everglades. We bring a national perspective to the many issues facing the Delta region and we leverage this perspective in sharing some highlights from the symposium. These highlights are discussed as it relates to current understanding surrounding the state of climate science, how climate science has evolved over the past decade, major uncertainties, adaptation strategies, and approaches that could be employed in the Delta. This summary is not a comprehensive review by the Delta ISB on the topic, but is intended to help facilitate discussion on the latest climate science and help inform organizations working in the Delta on the discussion at the symposium.

State of Science

Keynotes and panel presentations summarized the current state of climate science for the Delta region, including observed and projected changes in key stressors and hazards under climate change. Presenters highlighted the growing risks from compounding and sequential events, including but not limited to extreme precipitation from atmospheric rivers; rapid snowmelt; increasing drought frequency; sea level rise; low-snow conditions; wildfires; and, flooding, all of which are amplified by rising temperatures.

California is undergoing fast-moving environmental changes as the state's climate continues to shift. During the symposium, experts outlined several emerging trends with important implications for water management, public safety, community resilience, and long-term planning. The summary below distills the key themes of the symposium from both presentations and group discussions, focusing on issues relevant to state and regional agencies. The section on the state of science is broken out into three parts:

1. What do we know?
2. How has science advanced in the past decade?
3. What are the major uncertainties?

What do we know?

Warming Trends in California and Globally

Current global temperatures have risen 1.3 to 1.5°C relative to the pre-industrial baseline, and California has warmed at least as quickly as the planet overall. According to the California Environmental Protection Agency (CalEPA), statewide average air temperatures increased by about 1.4°C and average summer temperatures in California increased by approximately 1.8 C between by 1895 and 2025. In a future world that is projected to be 3°C warmer, California's average warming may exceed the global average by up to 1°C.

However, there is significant spatial and seasonal variation in warming, with the most pronounced changes occurring in inland valleys and higher-elevation watersheds, where warming has accelerated since the 1980s. Inland and mountain regions (including the Central Valley, Sierra Nevada, and desert areas) are warming up to 1.5 times faster than the statewide average. In contrast, coastal areas, moderated by the Pacific Ocean, may warm up to 1°C more slowly than inland regions.

Rising temperatures are altering fundamental atmospheric and hydrologic processes in nonlinear ways. Warmer air can hold more moisture, which, in turn, influences storm intensity. The atmosphere's moisture-holding capacity increases by roughly 7% per degree centigrade of warming, leading to greater precipitation rates during storms, particularly over short durations.

These changes underscore an emerging theme: California's climate future will be shaped less by gradual shifts in average conditions and more by growing variability and volatility. Despite some uncertainties, current science clearly points to a hotter, drier climate punctuated by increasingly intense wet events.

Increasing Hydroclimate Variability

California has always experienced large swings in precipitation, but new scientific assessments show that these swings are becoming more pronounced. As the air warms, it essentially acts like an "expanding atmospheric sponge," soaking up more moisture during dry periods and releasing more rainfall during storm events.

Storms such as atmospheric rivers may become less frequent overall, but when they do arrive, they are expected to be stronger and occur in clusters. At the same time, rising evaporative demand is setting the stage for more severe droughts. These opposing forces are increasing the likelihood of rapid transitions from flooding to drought, a pattern often described as “hydroclimate whiplash.”

These shifts are happening faster than in the past, with sharper transitions between wet and dry periods that affect reservoir management, ecosystems, flood risk, and drought preparedness. As this variability grows, it is becoming increasingly clear that relying solely on historical hydrology is no longer sufficient for water planning in the state.

Changing Extremes: Droughts and Floods

Droughts

Recent droughts show how warmer air temperatures can amplify water shortages. Hotter conditions dry out soils, reduce runoff efficiency, and increase water demand. The frequency and severity of droughts are rising due to increased evaporative demand driven by higher temperatures, even in the absence of major changes in annual precipitation totals. Warmer conditions reduce runoff efficiency and prolong water deficits. Recent multi-year droughts demonstrate how temperature-driven aridity can overshadow modest precipitation declines.

Floods

On the other extreme, the most intense atmospheric rivers are becoming stronger, leading to intense floods. Updated modeling work suggests that the probability of large, statewide flooding events occurring is becoming more likely. Extreme precipitation and subsequent flooding are also projected to intensify. The strongest atmospheric rivers, California’s primary sources of major winter storms, are expected to strengthen as the climate warms. Modeling shows that the likelihood of catastrophic events comparable to the Great Flood of 1862, which is the largest recorded flood in the Western United States, could double. The ARkStorm 2.0 framework updates previous mega-flood estimates with new climate data, indicating higher risks of extremes under continued warming trajectories.

Together, these trends reveal a future in which both severe droughts and extreme floods become more likely, often occurring within the same decade.

Loss of Snowpack and Shifts in Runoff

California's mountain snowpack, historically the state's largest natural water reservoir, is diminishing. Warmer winters increase the fraction of precipitation falling as rain rather than snow, leading to earlier, more concentrated runoff. Up to 1.5 million acre-feet of snowpack could be lost by midcentury and, as a consequence, the midwinter runoff would be decreased by about that much.

The shift toward flashier, earlier runoff reduces natural storage capacity and increases winter flood risk. Combined with rising evaporative demand, these changes transform California's seasonal water balance and challenge traditional storage systems designed around historical patterns of snow accumulation and melt.

Emerging Hazards: Storm Clustering and Rain-on-Snow

Storm sequencing is changing while annual storm counts may decrease. The remaining storms are becoming more intense and more closely spaced. Clusters of strong atmospheric rivers can overwhelm reservoirs, rivers, and levee systems.

Rain-on-snow events, warm storms depositing heavy rainfall on existing snowpacks, are particularly dangerous. Rain-on-snow events produce rapid melt, extreme runoff, and destructive floods. As mid-elevation regions warm, the frequency and magnitude of rain-on-snow-driven flood events are projected to increase.

Accelerating Sea Level Rise

Rates of global sea level rise have roughly doubled over the last 30 years due to thermal expansion and melting ice sheets. For the San Francisco Bay–Delta, additional local factors, such as gravitational effects related to Antarctic ice mass loss, may lead to higher-than-average relative sea level rise.

Rising seas increase the risks of:

- Levee overtopping and failure
- Salinity intrusion into the Delta
- Amplified storm surge impacts
- Chronic tidal flooding in coastal communities

These changes heighten stress on critical water conveyance systems and low-lying infrastructure throughout the region.

Fire, Watersheds, and Ecosystem Impacts

Climate-driven increases in wildfire frequency and intensity are reshaping California's hydrology. Burned watersheds exhibit greater runoff, reduced canopy interception, increased sediment loads, and degraded water quality. Post-fire flooding and debris flows pose additional hazards to reservoirs, water treatment facilities, and downstream communities. These interactions create compounding challenges for water supply reliability, ecosystem function, and public safety.

How has the science advanced?

Over the past decade, scientific research has advanced understanding of how climate variability and change are shaping extreme events, water availability, and system-wide risks. In particular, progress in sub-seasonal forecasting, improved characterization of rare high-impact events, growing recognition of rapid-onset hazards such as flash droughts and hydroclimate "whiplash," advances in climate modeling (including the use of artificial intelligence [AI]), and clearer insights into the timing of transitions to low-to-no-snow conditions are transforming the basis for climate-informed planning and decision-making. Together, these advances provide more actionable information for managing water resources, reducing risk, and preparing for a future marked by greater climate variability and more extreme weather events.

Improved sub-seasonal forecasting (near-term, 2–3 weeks) for extreme events

One important area of development is the substantial advances in sub-seasonal climate forecasting, particularly at lead times of approximately two to three weeks for extreme events, such as atmospheric rivers. Forecasting at these timescales has improved markedly, providing decision-makers with actionable information well beyond traditional weather forecasts. This extended lead time is especially critical for water and reservoir management, as it allows operators to distinguish between upcoming dry periods when retaining water is advantageous, and periods when additional storm activity may require pre-emptive releases to reduce flood risk. Improved sub-seasonal forecasts also enhance emergency preparedness for heatwaves, heavy rainfall, and storms, enabling earlier coordination among agencies and more effective risk reduction strategies. **These scientific gains highlight the growing importance of translating forecast information into operational decisions through improved communication, partnerships, and co-production between scientists and practitioners.**

Better understanding of rare events (e.g., atmospheric rivers) driving system-wide changes

Scientific understanding of rare, high-impact atmospheric events has improved considerably, revealing their critical role in shaping long-term hydroclimatic conditions. Research increasingly shows that the rarest events such as extreme atmospheric rivers, can dominate cumulative precipitation totals, drive flooding, and strongly influence water availability over decadal timescales. These events serve as a critical bridge between short-term weather variability and long-term climate change, linking episodic extremes to persistent system-wide changes. Improved characterization of the frequency, intensity, and drivers of atmospheric rivers has clarified their contributions to water resources as well as their associated flood hazards. This growing body of work underscores that long-term planning cannot rely solely on historical averages, but must explicitly account for low-probability, high-consequence events that disproportionately shape regional hydroclimate outcomes.

Recognition of flash droughts, hydroclimate "whiplash," and wildfire connections

Flash droughts, defined by their rapid onset and intensification, have emerged as a critical but challenging hazard because they unfold faster than most existing decision-making and management cycles. Unlike traditional droughts, flash droughts can develop within weeks, leaving little time for mitigation or response. Recent scientific advances have improved recognition of these events and begun to clarify their underlying mechanisms, including land–atmosphere feedbacks and anomalous temperature-driven evaporative demand. Importantly, researchers are now exploring strong linkages between flash droughts, hydroclimate "whiplash" (rapid transitions between wet and dry extremes), and heightened wildfire risk. These cascading interactions pose compounding threats to water supplies, ecosystems, and public safety, emphasizing the need for integrated monitoring systems and predictive tools that can anticipate rapid climate transitions before impacts fully materialize.

Enhanced climate model reliability and assessment, including the potential benefits of artificial intelligence

Climate modeling capabilities have advanced significantly, leading to a clearer understanding of where models perform well and where uncertainties remain. Notable improvements have been made in representing regional and local-scale processes, which are essential for translating large-scale climate change impacts into actionable regional implications. At the same time, discrepancies between modeled and observed climate behavior, such as differences in projected versus observed Pacific Ocean trends, have highlighted the need for continued model evaluation and refinement. Emerging approaches that integrate AI offer promising opportunities to enhance model performance, identify patterns in complex datasets, and improve representation of poorly resolved processes. While AI is not a replacement for physical understanding, its integration into climate science is increasingly viewed as a complementary tool that can accelerate insight, reduce uncertainty, and support more reliable climate assessments for planning and decision-making. In addition, physics-informed machine learning and AI models provide an approach for leveraging some of the benefits of AI while still incorporating physical understanding.

Understanding the timing of transition to low-to-no-snow conditions

Recent research has substantially improved constraints on the timing of transitions to low-to-no-snow conditions in mountain regions, a shift with implications for water resources, ecosystems, and downstream communities. The southern hemisphere indicates what this shift may look like for California because studies show that low-to-no-snow emergence is occurring approximately 20 years earlier in the southern hemisphere and at lower levels of local warming compared to the northern hemisphere. These transitions reflect shifts in a mix of changing atmospheric dynamics, regional warming, and topographic influences that result in reduced runoff efficiency, even in wet years. While projections of the timing of snowpack loss have become more robust, uncertainties remain in the spatial patterns of these changes and their post-threshold impacts. The most significant consequences are expected after mid-century, particularly if global warming exceeds approximately +2.5 °C.

What are the major uncertainties?

Despite the notable scientific advances described above, substantial uncertainties remain in the understanding of how climate change will manifest across California and the Delta. While the broad direction of change is clear, these uncertainties complicate the task of translating climate projections into precise planning and operational guidance. Symposium discussions identified six areas where scientific understanding remains materially incomplete and emerging research is actively reshaping the basis for regional planning:

- Pacific Decadal Oscillation and ENSO Behavior Under Warming
- Dynamic Versus Thermodynamic Drivers of Precipitation Change
- Recurrence Potential of Medieval-Scale Megadroughts
- Infrastructure Vulnerability to Compounding and Sequential Hazards
- Ecosystem Tipping Points and Post-Transition Consequences
- Limits of models and decision frameworks

These six areas are described in depth in the sections below.

Pacific Decadal Oscillation and ENSO Behavior Under Warming

One of the most consequential uncertainties discussed at the symposium concerns how large-scale Pacific Ocean circulation patterns, specifically El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), will evolve as greenhouse gas concentrations continue to rise. For decades, the prevailing expectation from global climate models was that warming would produce an El Niño-like mean state in the tropical Pacific, implying greater warming in the eastern tropical Pacific relative to the west. However, observed Pacific sea surface temperature trends through 2025 have displayed the opposite signal, with a persistent La Niña-like pattern characterized by anomalously cool eastern Pacific waters. This represents a significant discrepancy between model projections and observations, with direct implications for California's precipitation.

A recent study revealed that existing models have underestimated the sensitivity of regional ocean–atmosphere patterns to external forcing, including the cooling effects of aerosols transported from South and East Asia. This implies that current climate models may also be underestimating the persistence and magnitude of future drought risk in California if greenhouse gas emissions continue unabated, since the PDO could remain locked in a negative phase for several more decades. As discussed at the symposium, if this interpretation is confirmed by subsequent research, future drought risk may have been systematically underestimated in regional planning frameworks that rely on those models.

Dynamic Versus Thermodynamic Drivers of Precipitation Change

A related and long-standing uncertainty concerns the relative contributions of thermodynamic and dynamic processes to future precipitation change. The thermodynamic component, which is driven by the well-understood Clausius-Clapeyron relationship, whereby warmer air holds roughly 7% more moisture per degree centigrade of warming, provides a physically robust basis for projecting increases in precipitation intensity during storm events, as well as greater atmospheric evaporative demand during dry periods. This thermodynamic signal is consistent across models and observations and underlies high confidence in projections of more intense extremes at both wet and dry ends of the distribution.

By contrast, the dynamic component remains far more uncertain. This component includes changes in the large-scale atmospheric circulation patterns that govern storm tracks, the position of the jet stream, and the frequency and duration of blocking events. As discussed during the symposium, current climate models show little agreement on the direction or magnitude of dynamic changes over California, including shifts in the position of the North Pacific High, changes in the intertropical convergence zone, and variations in the vertical distribution of moisture that influence how much precipitation falls west of the Sierra Nevada versus how much passes over the range undelivered. These dynamical uncertainties make it difficult to project long-term mean precipitation totals with confidence, even as confidence in the sign and magnitude of extreme event changes grows. At the symposium, panelists acknowledged that the overall mean precipitation signal for California remains statistically indistinguishable from zero across the current generation of downscaled projections. However, there is also a clear signal toward more frequent extreme wet years, a pattern consistent with intensification of atmospheric river events.

Recurrence Potential of Medieval-Scale Megadroughts

Paleoclimate evidence from tree ring chronologies, including submerged conifer stumps documented in Tenaya Lake and other Sierra Nevada areas, confirms that droughts of multi-decade duration occurred in California during the Medieval period. These drought events represent severe and persistent dry spells far exceeding anything in the modern instrumental record. What remains poorly understood is the precise atmospheric and ocean–atmosphere mechanism that sustained such droughts for 60 to 70 years or more. These durations far exceed the typical interannual or even decadal oscillations of ENSO and the PDO. As discussed at the symposium, the lesson ordinarily drawn from the Holocene record is that California's hydroclimate is ultimately capable of recovery from extended dry periods, driven by the same variability that produces wet anomalies. However, the emerging evidence that PDO phase may now be partly externally forced raises the possibility that the boundary conditions governing drought persistence have changed. Current climate models cannot fully explain the mechanisms that sustained Medieval megadroughts, which limits confidence in assessments of whether anthropogenic forcing could increase the likelihood of their recurrence.

Infrastructure Vulnerability to Compounding and Sequential Hazards

Significant uncertainty surrounds the vulnerability of the Delta's aging and complex infrastructure to compounding and sequential hazards. While individual stressors (e.g., sea level rise, extreme flooding, land subsidence, seismic activity) can each be assessed in isolation, the difficulty lies in characterizing the joint probability and cascading consequences of multiple stressors occurring in close temporal proximity. For example, as discussed by symposium participants, an earthquake that weakens levee foundations need not coincide with a major flood to cause widespread failure; a significant storm event within 18 months of a seismic event could exploit compromised infrastructure before repairs are completed. Locally, variable vertical land motion or subsidence, which ranges from 2 to 13 millimeters per year across the Delta, further complicates vulnerability assessment by creating highly location-specific differences in relative sea level exposure that are poorly captured in regional-scale models. Developing assessment frameworks that incorporate these compound and sequential risks remains a critical scientific and engineering need.

Ecosystem Tipping Points and Post-Transition Consequences

Finally, considerable uncertainty surrounds the timing, nature, and downstream consequences of ecosystem regime shifts under continued warming. Evidence presented at the symposium indicates that by approximately mid-century, the forests of the Sierra Nevada will be exposed to a climate regime more characteristic of present-day Southern California chaparral and shrublands. The transition from conifer-dominated forest to shrub-dominated landscape is expected to occur rapidly and discontinuously, most likely triggered by a large-scale wildfire event, bark beetle infestation, or a combination of stressors acting in succession. While the direction of this transition is projected with reasonable confidence, the consequences for watershed hydrology, sediment delivery, carbon stocks, water quality, and downstream Delta conditions remain insufficiently studied. As noted during symposium discussion, the scientific community has devoted considerable attention to documenting the approach to this tipping point, but comparatively little work has examined what the system will look like after it is crossed. Given the nonlinear nature of ecosystem transitions and the long lead times required for management responses, this represents a gap with important consequences for long-term Delta planning.

Limits of models and decision frameworks

Finally, there are important uncertainties related not only to the climate system but also to the models and decision frameworks used to translate climate information into operational guidance. Hydrologic and water-operations models often rely on historically-based sequences that are modified to approximate climate change, an approach that can underrepresent unprecedented combinations of events, such as extreme storm clustering with high antecedent soil moisture or simultaneous drought and heat extremes. While high-resolution downscaling, large ensemble simulations, and emerging AI tools are improving representation of regional processes, they cannot fully eliminate uncertainty stemming from structural model limitations or from deep uncertainty in future socio-economic pathways.

There is still limited understanding of how best to couple physical projections with social, institutional, and economic dynamics that shape real-world adaptation. Existing planning cycles, permitting timelines, and funding mechanisms can be substantially longer than the time required for new science to alter risk assessments, creating potential misalignments between evolving knowledge and risk mitigation implementation. These institutional uncertainties interact with physical uncertainties to influence which adaptation pathways are feasible, when, and for whom. As several symposium participants emphasized during breakout discussions, the presence of deep uncertainty does not preclude action, but it does underscore the need for flexible, scenario-based, and stress-testing approaches that explicitly acknowledge what we do not yet know while still moving forward with no-regrets, multi-benefit interventions.

Taken together, these uncertainties underscore the importance of embracing adaptive, scenario-based planning frameworks rather than point-estimate forecasts. They also reinforce the need for continued investment in observational networks, model development, and targeted process studies to narrow the range of plausible futures and support more robust, risk-informed decision-making across the region.

How can we use the science to adapt?

Several themes arose during presentations and discussion about how emerging climate science can be incorporated into adaptive management. Foremost, the increasing volatility of California's hydroclimate, often characterized as "hydroclimate whiplash," suggests the need to increase attention on managing for extreme conditions, rather than average conditions based on historical trends. The hydroclimate changes include increased aridity, the amplification of the winter high precipitation season, and the expectation of disproportionately larger impacts due to non-linearities. The potential adaptive management responses to those challenges included flexible and forward-looking planning, tighter links between mid-term climate forecasts and management models, and restoring natural processes in the upper watershed to mitigate risk.

The symposium participants discussed some of the federal, state, and local agencies that are already using current climate science to inform planning and operations. Nonetheless, many participants saw opportunities for improvement in ensuring that the best available science was being used across diverse agencies and programs. Further, they wanted to see climate science result in management actions and for affected communities to be engaged in generating and evaluating adaptations and responses before crises occurred. Participants emphasized that, while there remain important scientific uncertainties, these should not preclude action on improving system resilience. It was acknowledged that not all future harms can be avoided but that adaptive management can lessen impacts, promote faster recovery from adverse events, and create a more resilient socio-ecological system.

Flexible and forward-looking planning

Under the theme of flexible and forward-looking planning, approaches were raised that leveraged new data, modeling, and decision support tools. A major idea was to use scenario planning and scenario-neutral stress-testing for major decisions. Scenario planning leverages alternative futures for comparison, making it an effective tool for addressing concerns about non-stationarity and compounding events. Stress testing, in contrast, involves systematically varying system variables and evaluating performance metrics to define acceptable and unacceptable performance across a wide range of future conditions. The decision scaling approach being used by the Department of Water Resources (DWR) is an example of this method. DWR creates and tests scenarios by systematically varying precipitation and temperature and then examines how reliably key water supply and ecological indicators stay within ranges defined as acceptable or desirable. Participants emphasized that stress tests should include performance evaluation over a change in low flows rather than only mean or high flows. A specific technique mentioned was the use of synthetic stochastic weather generators and adjusted historical records to incorporate variability and climate change impacts. Broadening the range of conditions used in hydrologic models and addressing the issue of under-sampling of extreme events would advance traditional probabilistic approaches.

Other approaches were discussed that included the use of evidence-based adaptive management and dynamic adaptive planning. Both approaches involve identifying adaptation strategies and testing them against acceptable thresholds of system behavior. Testing occurs through monitoring or modeling system changes and identifying management triggers for specific actions or changes in management strategies. The two approaches differ in that dynamic adaptive planning generally encourages aligning major decisions with long-term goals (e.g., 20-year time horizons are used by DWR), while adaptive management may have short or long cycles and incorporate triggers for minor and major decisions. In dynamic planning, a planner has a strategic vision of the future, commits to short-term actions, and establishes a framework to guide long-term actions. Such approaches may require more resources to plan, conduct, and model, but often do not require additional data or fundamentally different models. Because some adaptation measures take decades to plan and build, participants recommended looking out to long-time horizons (such as the end of the century). Climate trends remain relatively modest through mid-century, but impacts are expected to accelerate sharply afterward, making long-range planning essential.

Several examples of new science that could serve as management triggers were presented in the symposium presentations. One was the Evaporative Demand Drought Index (EDDI), which is a robust measure of drought and can serve as an early warning for late-summer low flows, flash droughts, and enhanced fire risk. Flash droughts were defined as phenomena that occur "too fast for [the] decision cycle" of management, but developing methods for early prediction and recognition can help mitigate associated negative impacts.

Linking improved near-term forecasts to management models

An example mentioned by multiple presenters at the symposium was Forecast Informed Reservoir Operations (FIRO). FIRO was cited multiple times as a "big advance" that integrates improved mid-term weather and water forecasts (particularly of atmospheric rivers) into dam operations to more flexibly balance water management, informing whether to store water or release it for drought and flood control. This approach leverages advances in the resolution of climatic process monitoring, which can be used to inform mitigation strategies. Weather forecasting for projections of just over two weeks has improved substantially, enabling better planning for extreme events. Symposium participants also raised the idea of using advances in deep learning (AI tools that extract patterns from data) and large-sample hydrology (big data statistical exploration) to conduct streamflow forecasting and other short-term forecasts. They suggested that new tools should be considered since deep learning models sometimes outperform traditional models that use equations to mimic physical processes or fit statistical models based on current hypotheses of system behavior.

Flood-Managed Aquifer Recharge (FloodMAR) was also identified as a key resilience strategy that aims to increase groundwater as a rainfall reservoir (“groundwater banking") by capturing floodwater for groundwater recharge. This approach has been linked to FIRO, as FIRO offers similar flood risk mitigation by retaining more water in reservoirs. It has broad benefits of reducing the mismatch between water demand and supply during dry periods, and can potentially serve as a cold-water input to create fish refugia. Both FIRO and FloodMAR provide adaptive capacity for a future that receives more rainfall in extreme storms including atmospheric river events and experiences diminished snowpack. The idea of groundwater banking as a complement to surface reservoirs offers additional water security benefits, as underground storage is not influenced by the higher rates of evaporative loss that may be expected in a warmer future.

Multi-benefit risk mitigation approaches

Another theme that resonated with many symposium participants was increasing the attention paid to mitigation options that provide multiple benefits, referred to as win-win interventions. A key element of the discussion was to seek climate-informed mitigation that would create benefits regardless of the specific future climate. Wetland restoration was a primary example of a positive approach (including stream-wetland complexes with beaver dams), which, when implemented in the upper watershed or headwaters, can mitigate flood risk while also creating ecosystem benefits (e.g., habitat for smelt and salmon) and promoting carbon sequestration. Similar projects were discussed that enhance levees for flood control while also creating habitat on the water side and increasing protection and recreational aspects. In addition, wildfire mitigation tools like Pyrecast can help manage fire risk during dry periods, which offers potential co-benefits to water supply, habitat, and carbon stocks. Practices to reduce or reverse Delta subsidence, including rice farming and wetland restoration, were discussed as projects which can preserve peat soils, stop or reverse soil carbon emissions, and increase levee resilience against sea level rise and extreme events (if sited appropriately).

A related discussion was to examine ecosystem transitions that may negate or enhance adaptation benefits. Evidence was presented that tree ecosystems could transition to shrubs due to climate change. This change has many uncertain effects on the system that will require more research to understand adaptation needs and whether current approaches could be maladaptive.

Institutional and Collaborative Strategies

A key discussion point, particularly among the modelers present at the symposium, was the potential benefit of shared resources or improved communication among researchers and decision makers. Strengthening partnerships between academia and government was seen as a path to making the best available science actionable and usable by agencies and organizations, including water management districts. Agency scientists were interested in learning from each other, and some have interest in using the same or similar climate change scenarios to better understand related risks.

Another point that was discussed was that, in order to tighten the adaptive management cycle, decision makers should consider expanding monitoring networks and the use of remote sensing observations to measure the success of adaptations and perform after-action reviews of actions and model performance. An example was how monitoring vertical land motion, or subsidence, is essential because subsidence is a significant hazard that often exceeds the rate of sea level rise. Locally, variable vertical land motion drastically affects the relative sea level rise signal in the Delta, with measurements showing a range of 2 to 13 millimeters per year. Any improved monitoring or other science investments will require long-term funding streams.

What can be done differently?

Symposium presentations and breakout discussions highlighted meaningful ongoing activities within the Delta and California to incorporate climate science into planning and management. The Delta Stewardship Council developed Delta Adapts, a climate change initiative that includes a vulnerability assessment and an adaptation plan focusing on four thematic areas: flood risk reduction, ecosystems, agriculture, and water supply. The State of California is also advancing its adaptation strategy through the Fifth Climate Change Assessment, which provides a scientific foundation for understanding risks and vulnerabilities across the state and is designed to inform planning and investments at all scales. Some key strengths of those Delta-focused and statewide efforts were adoption of formal, structured decision-making approaches to manage uncertainty and the use of scenario-based planning.

To complement established management efforts, participants offered ideas for changes in planning and adaptation strategies. The themes of the proposed changes were to shift towards flexible, data-driven, and integrated adaptive management to handle extreme hydroclimatic variability. Participants also noted the need for future discussions about the many social dimensions of climate change. In a modeling context, those efforts could include how models are used and implemented at multiple levels of governance. Beyond modeling, participants noted a need to engage with communities to design adaptive pathways and create incentives for forward-looking planning.

Table 1 summarizes the suggestions made during the symposium for potential changes to concerns and uncertainties raised. Several of the suggestions highlight tools developed to enable climate-informed management. A lesson from these projects was that creating shared resources and tools with an end-user focus could build upon these examples. These suggested new directions collectively represent the core principles of the adaptive management cycle, requiring enhanced monitoring efforts, measuring the success of adaptations, and performing "after-action reviews" to refine future strategies. A dynamic approach to managing uncertainty was seen as crucial because the trends and impacts, though relatively flat until 2050, are expected to rapidly increase thereafter.

Table 1. Existing Management Efforts and Suggested Adaptation Strategies. This was based of presentations, plenary discussion, and breakout groups at the symposium.

Existing Management Effort	Suggested Adaptation Strategy
Traditional Climate Planning (Reliance on Averages): Planning often relies on historical averages ("the mean") or limited realizations of different scenarios, resulting in insufficient evaluation of extreme events and preparation for non-stationary conditions.	**Embrace Extremes and Scenario-Neutrality: Avoid using the average for management** as **extreme events are the new normal.** Implement **scenario-neutral approaches** (bottom-up stress tests) to define acceptable and unacceptable system performance across the policy-relevant state space, focusing on changes in **low flows** rather than mean flows.

Existing Management Effort	Suggested Adaptation Strategy
Water Operations Modeling (CalSIM3) As implemented by the Bureau of Reclamation's, CalSIM3 (a water resource planning model), currently relies on a historical time series that is "perturbated" to adjust for climate, a method acknowledged to poorly represent extreme events like " hydroclimate whiplash."	**Decouple and Advance Modeling.** Gain the ability to decouple CalSIM from the historical record and explore alternative hydrology. Use techniques such as synthetic stochastic generators or adjusted historical records to better capture variability. Furthermore, improve efficiency by adopting better coding alternatives (e.g., rewriting older macro-based inputs).
Traditional Reservoir Operations Dam operations traditionally rely solely on fixed historical data and rules to balance flood control and water supply.	**Integrate Real-Time Forecasting.** Given the enhanced skill of advanced weather forecasts (particularly atmospheric rivers), there are opportunities to align management with forecasts such as FIRO to make dam operations more flexible and adaptable.
Flood Control and Water Storage Efforts focus on localized control and storage, but struggle with the "mismatch between demand and supply" during extremes.	**Develop Multi-Benefit Storage Solutions.** Some participants indicated that new storage is needed to replace the loss of snowpack as a major water reservoir. FloodMAR was an example of an integrated strategy that combines flood control with groundwater recharge, capturing high-flow water for drought preparedness.
Localized Restoration Agencies are investing in restoring freshwater-managed wetlands for the dual purpose of subsidence reversal and carbon sequestration but may not be achieving maximum benefits.	**Quantify and Optimize Benefits of Nature Based Solutions.** Conduct research to better understand benefits of environmental restoration approaches including wetland restoration in headwaters, and reducing methane emissions from wetland systems to maximize net carbon sequestration. Science is needed for accurately projecting the degree to which subsidence can be

Existing Management Effort	Suggested Adaptation Strategy
	halted or reversed with different land use practices.
Insufficient Data on Water Use There is an acknowledged gap in understanding how much water is being taken out of the system by people, including evaporative loss.	**Adopt Advanced Monitoring and Data Tools.** Better quantify water consumption, particularly Evaporative Transpiration (ET). Specific suggestions were to scale up efforts like OpenET to the watershed scale for comparisons across regions. Use tools like EDDI for early warning of drought and low flows.
Siloed Planning and Inconsistent Funding Funding for multi-benefit projects is often inconsistent (bond-based funding) and planning operates in "silos," struggling to integrate models for multi-objective management.	**Improve Coordination and Institutional Frameworks**. De-silo studies and practices to share resources and design for multiple project benefits. Improve cross-agency coordination to integrate model results in a way that is informative for multi-objective management. Secure ongoing, long-term funding streams to support monitoring and maintenance, moving beyond inconsistent bond-based funding.
Science-to-Operations Disconnect Science and modeling efforts often suffer from a disconnect with operational practices. This disconnect results in climate tools and model outputs that lack an end-user focus or provide data that is not easily accessible, interoperable, or usable by practitioners	**Improve Access and Relevance for End Users.** Improve access to and transparency for modeling efforts, making it easier for end users to learn about and understand these resources. Tools would be created with an end-user focus, ensuring the outputs of models are configured to be the inputs that end users require. Strengthening partnerships between academia and practitioners could improve science-to-operations knowledge transfer. Using storytelling can make the science personal and actionable for communities and decision-makers
Reactive and Limited Scope Planning	**Expand Scope and Integrate Risks.**

Existing Management Effort	Suggested Adaptation Strategy
Decisions often ignore compounding risks (e.g., climate + seismic + subsidence), rely on a limited local scope, and lack preparation for "sudden transitions."	Integrate compounding risks into assessment to improve mitigation strategies. Incorporate upstream watershed management (e.g., mountain meadow restoration) as a fundamental part of Delta solutions, recognizing that headwaters directly influence downstream water flow, quality, and timing.

What is next?

In summary, the symposium highlighted how California's climate future will be shaped by extremes rather than historical averages. State and local agencies will need flexible, adaptive approaches that account for greater uncertainty and faster hydrologic transitions.

Across all scientific assessments, a clear message emerges: the "average" water year is disappearing. California's future will be marked by heightened extremes, hotter temperatures, deeper droughts, more intense storms, greater flood potential, and rising seas. Even amid uncertainties in precipitation projections, the direction of change is unequivocal: a hotter and more variable climate is becoming the new norm.

The challenge for California and the Delta lies not only in understanding these risks but in embracing adaptive, flexible, and forward-looking strategies that account for the accelerating pace of change. With improved scientific tools, regional collaboration, and integrated water management strategies, California and the Delta can enhance its resilience against a climate future increasingly defined by volatility.

Over the coming months, Maven's Notebook will be preparing proceedings from the symposium and the Delta ISB will continue to synthesize what was learned from the symposium. While proceedings are being prepared, you can view the recordings, PowerPoint presentations and other materials prepared during the symposium (see Appendix). As a follow up to the symposium, the Delta ISB will be investigating what more can be done with the science, how to facilitate thinking more at a system level, and how science is absorbed and integrated into practice. Based on how this follow up goes, the Delta ISB may work on a perspective piece for peer review publication.

Appendix – Materials from the Symposium

- **Meeting Notice/Agenda**
- **Recordings**
- **Presentation Slides**
- **Science Gap Priority Matrix**
  These were the top 3 science gaps or needs identified by the five breakout groups. This is also presented in table view here.
- **Survey Results**
  See what participants said they learned during the symposium.
- **AI Generated Summary of Select Documents: Overview of Climate Science in the Sacramento-San Joaquin Delta**
  This document was created using NoteBookLM to summarize what is known about climate change prior to the symposium.
- **Panelist and Speaker Profiles**

Further Reading

State of Bay-Delta Science: This is an ongoing synthesis and communication effort led by the Delta Science Program. The 2025 edition features seven articles exploring extreme climate and weather events and their impacts on the Bay-Delta and its watershed. Individual chapters address heatwaves, droughts, atmospheric rivers, wildfires, and related governance and climate adaptation considerations. Many of the presenters at the symposium authored these articles.

California's Fifth Climate Change Assessment: The fifth assessment is in development, and will contribute to the scientific foundation for understanding climate-related vulnerability throughout California. The latest edition will include a report focused on the Delta, prepared by the Delta Stewardship Council, Delta Protection Commission, and the Sacramento-San Joaquin Delta Conservancy.

Delta Adapts: Since 2018, the Delta Stewardship Council has led a two-part climate initiative called "Delta Adapts," which takes a comprehensive, regional approach to climate resiliency that cuts across regional boundaries and commits to collaboration across state, local, and regional levels.

Article: Human emissions drive recent trends in North Pacific climate variations: This article by Jermey Klavans et al. (2025) highlights how climate models have historically suggested an El Niño-like trend in the tropical Pacific under climate change, meaning they predicted greater warming in the eastern tropical Pacific compared to the west. However, real-world observations through 2025 have shown a La Niña-like trend, which is the opposite of what many models predicted. This discrepancy raises significant uncertainty about future atmospheric circulation change.

Useful articles on approaches to reduce uncertainty:

- Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world by Marjolijn Haasnoot et al. (2013)
- Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum, and Precautionary Approaches by Robert J. Lempert and Myles T. Collins (2007)