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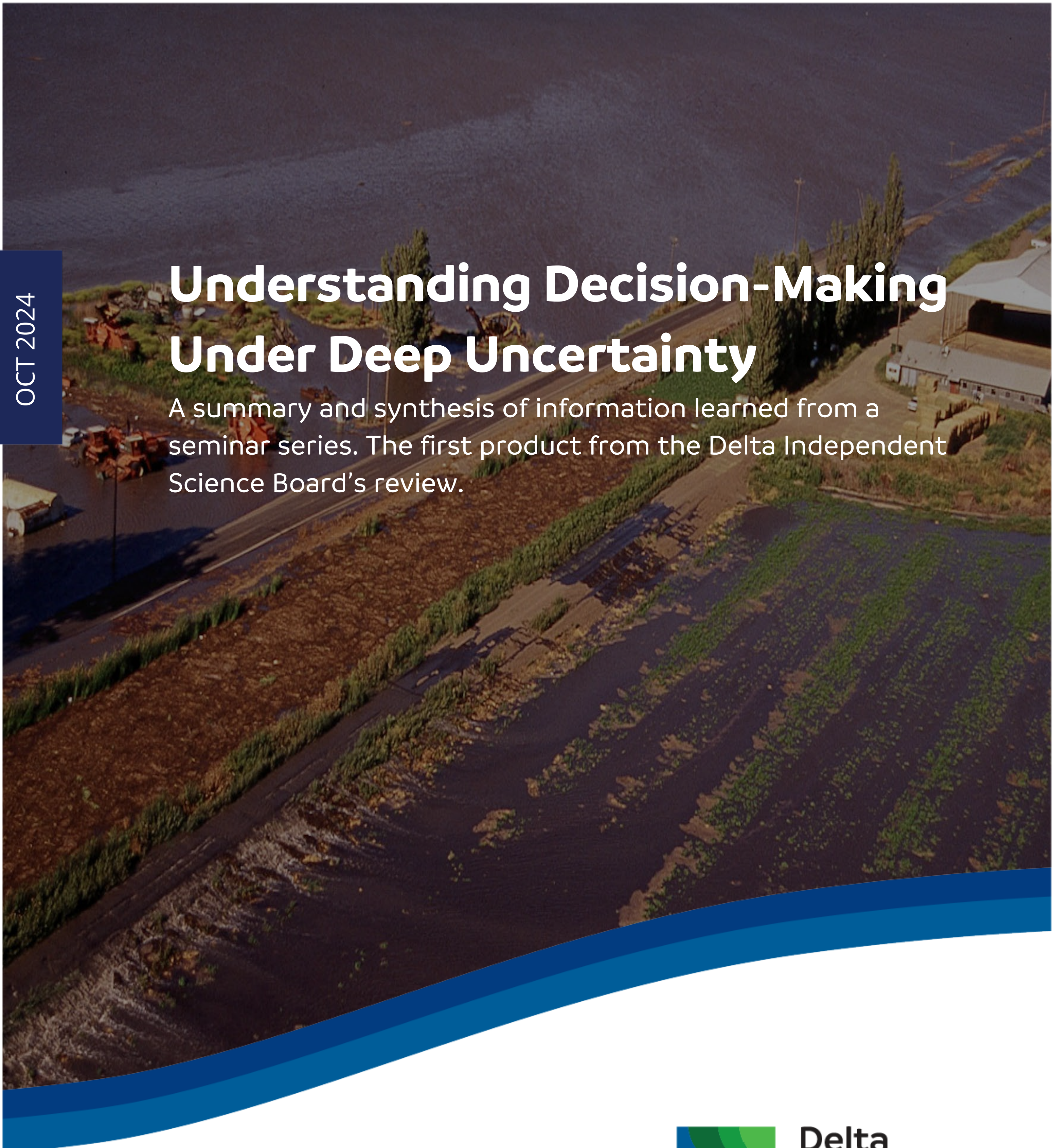

Understanding Decision-Making Under Deep Uncertainty

A summary and synthesis of information learned from a seminar series. The first product from the Delta Independent Science Board's review.

Delta Independent Science Board
DELTA STEWARDSHIP COUNCIL

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Created by the Delta Reform Act of 2009 and appointed by the Delta Stewardship Council, the Delta Independent Science Board is a standing board of nationally and internationally prominent scientists that provide oversight of the scientific research, monitoring, and assessment programs that support adaptive management of the Sacramento-San Joaquin Delta through periodic reviews.

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Summary

The Delta Independent Science Board (Delta ISB) has reviewed the scientific tools and concepts that can increase the capacity to anticipate and adapt to growing uncertainty of future conditions in the Bay-Delta system. These tools and concepts are often classified as "decision-making under deep uncertainty" (DMDU). Over the past year, the Delta ISB has organized five seminars to introduce DMDU to the broader community. *Deep Uncertainty* is defined here as unpredictable events or system variability that cannot be well characterized with existing data, models, and understanding. Often, there is little or no agreement among interested parties on how systems are likely to behave or the probabilities of occurrence of such events, including the duration, sequence, and co-occurrence of events.

The tools of DMDU are meant to push the boundaries of typical ways of thinking to address a wide variety of risks and uncertainties, including potential unpredictable sequencing or compounding of events. By providing tools to explore uncertainty when probabilities of future events are uncertain, DMDU can refocus some effort on seeking creative solutions, rather than devoting all resources to prediction. While many DMDU practices are resource-intensive to apply, a key concept learned from the seminar series was that DMDU is not an "all or nothing" approach, and users can often gain substantial insight from using initial approaches or subsets of practices, even when a full-scale comprehensive approach is not applied.

Key takeaways from the seminar series include:

1. **Practical Applications of DMDU**
    - The Delta region has challenges in preparing for multiple sources of uncertainty and could benefit from the implementation of DMDU tools, as revealed from applications in similar systems. Some agencies, such as the California Department of Water Resources, are already implementing aspects of DMDU into their decision making.
    - DMDU tools can support better planning for the future to avoid unanticipated costs that are associated with being underprepared for an event.
    - DMDU tools can be applied using methods with varying levels of analytic demand. Qualitative and quantitative tools are used depending on resource availability.

- Not all decisions will benefit from the use of DMDU tools, but the effort can be worthwhile for decisions that are complex, difficult to reverse, and costly.

2. **Understanding the Benefits of DMDU**
    - DMDU aims to promote systematic and deliberative exploration of possible futures for management application that could reduce the potential for unanticipated and unintended consequences.
    - DMDU opens up a space for conversations about what the future might look like and how different decisions will fare under those conditions, ultimately leading to more informed choices.
    - Tools are designed to select the decision that addresses risks using criteria consistent with stakeholder preferences and financial feasibility.
    - Reframing uncertainty as opportunity can be a powerful tool to encourage decision-makers to embrace uncertainty rather than ignore it.
    - Minimizing biases that limit which uncertainties are explored will promote decisions that are robust to future variability and reduce regret.
    - DMDU techniques promote inclusion of interested community members in decision analysis through co-design of scenarios, knowledge sharing, and collaborative interpretation, which can broaden support for a management plan or decision.

3. **Adoption of DMDU Tools**
    - DMDU can take time to implement, but decision analysts and policy makers can start with simple approaches. For example, low effort stress-testing can be applied after a preferred plan is selected to assess performance under extreme scenarios. This analysis can help identify when a preferred plan might create unintended vulnerabilities and can provide insights on how to avoid regret, despite uncertainty.
    - The decision of an organization, business, or institution to use DMDU tools is sometimes triggered by having a single ‘change-agent’ who understands the method and the potential benefits from its use. One passionate person might be enough to build momentum and support for a DMDU tool.

Introduction

Uncertainty surrounding future environmental, social, and economic conditions has significant impacts on the ways in which decisions are made and how well those decisions hold up over time. Decisions made without sufficient information on how changing factors will impact a system can lead to under-preparedness and vulnerability to shocks. Rapidly changing conditions and increasing uncertainty of future projections associated with climate change highlight how extreme and hard-to-predict conditions challenge effective management of the greater Bay-Delta system, including its watersheds. Similarly, changing social, policy, and economic conditions can alter resource use and desirable management approaches, sometimes substantially. When conditions change rapidly and unexpectedly, managers are forced to prioritize some goals at the expense of others and may not have time to consider all management options or elicit preferences from interested parties.

Scientific analysis can reduce some types of uncertainty to improve the accuracy and the time and space scales of those predictions, typically using well-calibrated simulation models. However, other types of change have unknown or unknowable likelihoods of occurrence and research cannot substantially improve predictability. For example, new research may not increase our ability to predict global pandemics, collapses in fish populations, or novel species invasions far in advance.

These conditions exhibit *Deep Uncertainty,* which is defined here as unpredictable events or system variability that cannot be well characterized with existing data, models, and understanding. Often, there is little or no agreement among interested parties on how systems are likely to behave or the probabilities of occurrence of such events, including the duration, sequence, and co-occurrence of events (Haasnoot et al. 2013; Hallegatte et al. 2012). These types of uncertainties include extreme, novel, and compounding events and conditions that are important for the Bay-Delta system.

To build an understanding of scientific tools and concepts that can increase the capacity to anticipate and adapt to growing uncertainty of future conditions in the Bay-Delta system, the Delta Independent Science Board (Delta ISB) began a review of decision-making under deep uncertainty (DMDU) in the spring of 2023. This review explores the techniques and recommendations that could be applied to the Delta to better characterize and prepare for uncertainty and improve the decision-making processes. As part of this review effort, a five-part seminar series hosted by the Delta ISB, with support from the Delta Science Program, introduced concepts from the decision sciences to the broader Delta community. This is the first report of the DMDU review, providing an introduction to key concepts and a synthesis of seminar presentations on DMDU. A subsequent report, including findings and recommendations from the full review, will be released early next year.

Screen shot from the first seminar series with speaker Alice Hill (Council on Foreign Relations)

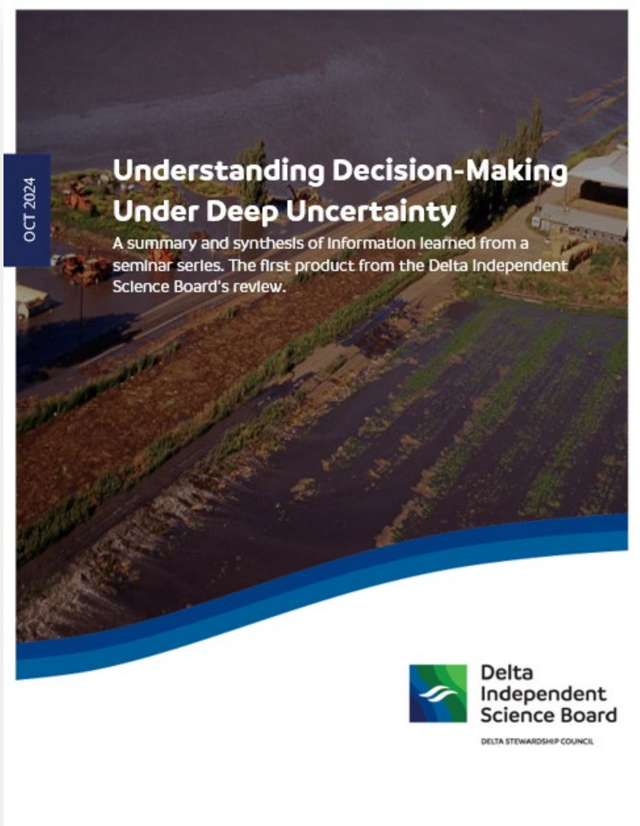
What did the seminar series feature?

The seminar series featured experts speaking on the science of DMDU, scenario development methods, opportunities for expanding the use of DMDU tools, and current efforts to address regional sources of deep uncertainty. The seminars brought together a wide range of audience members, including state and local agencies, academia, NGOs, and private businesses. An overview of the seminar series, including links and detailed summaries from Maven's Notebook to each seminar, can be found in Table 1.

Table 1: Overview of the Seminar Series. Appendix A provides a summary of the main points and key takeaways from each seminar. Archive views are current as of the publication of this report.

Topic	Date	Speakers	Links	Attendance
Introduction to Deep Uncertainty and its Benefits	April 26, 2023	Alice Hill, *Council on Foreign Relations* With intro by Lisa Wainger, *Delta ISB* Laurel Larsen, *Delta Science Program*	YouTube Recording Flyer Maven's Notebook Summary	Live: 80 Archive: 273
Available Tools in DMDU and their Applications in California	June 14, 2023	Robert Lempert, *RAND Corporation* Andrew Schwarz, *DWR*	YouTube Recording Flyer Maven's Notebook Summary	Live: 68 Archive: 168
Cognitive Biases and Scenario Development	August 17, 2023	Andrew Parker, *RAND Corporation* Jody Wong, *RAND Corporation*	YouTube Recording Flyer Maven's Notebook Summary	Live: 63 Archive: 307
Scenario Development Methods	September 14, 2023	Brett Milligan, UC Davis	YouTube Recording Flyer Maven's Notebook Summary	Live: 35 Archive: 194
Dynamic Adaptive Policy Pathways	January 18, 2024	Marjolijn Haasnoot, *Deltares and Utrecht* Andrew Warren, *Deltares*	YouTube Recording Flyer Maven's Notebook Summary	Live: 70 Archive: 249

What is in this report?



This report synthesizes what was learned during the seminar series to reflect how different speakers understand and use DMDU, including the challenges faced and their insights. However, many aspects of DMDU were not covered and numerous experts and practitioners were not included in the seminar series. Therefore, this partial synthesis of DMDU is meant as an initial step towards understanding DMDU, rather than a comprehensive description.

The report is broken out into four sections:

1) What is DMDU?
2) What are the tools available?
3) What are the challenges and limitations?
4) What are the opportunities and benefits of DMDU?

Each section features information and examples from experts from the seminar series, supported by additional literature. After reading this report, one should have a basic understanding of DMDU tools and principles, and a familiarity with several concrete examples of its successful implementation.

What is DMDU?

Dr. Lisa Wainger of Delta ISB introduced the concepts underlying DMDU during the first seminar. DMDU encompasses a set of tools for community engagement, anticipatory planning, and forecasting. Multiple approaches may be used to identify and evaluate a wide range of possible futures and pathways, assess the robustness of potential decisions under each scenario, and select the decision that addresses risks using criteria consistent with preferences of interested parties and financial feasibility. Risk may be defined in multiple ways and evaluated from multiple perspectives.

Instead of planning for a single “best guess” future, DMDU approaches evaluate varied conditions under which a policy or plan might fail, in order to understand if an alternative approach may be more robust to uncertainty and/or develop recovery strategies. The goal of DMDU is not to design projects that eliminate risk at inordinate and unsupportable costs. Rather, DMDU approaches are more likely to emphasize adaptive planning in which management actions are modified in response to decision triggers or tipping points. The result is that risk mitigation efforts can be sequenced in time to promote cost-effective and responsive management (e.g., Haasnoot et al. 2013).

These tools can be applied to manage the risk associated with low probability-high consequence events that impact flood protection, water supplies, ecosystems, and human well-being. Those events include extreme droughts, extreme floods, or wildfires that have some predictability but may not be captured well in management due to their perceived low probability of occurrence or the expectation that risk mitigation will be cost-prohibitive. Further, extreme events could occur in combination with less predictable events, particularly those unrelated to climate change such as earthquakes, tsunamis, or sudden mass human migration, which compound effects and management challenges. These events are included here to recognize that probabilities of future events that are based on historic conditions may no longer provide accurate assessments of the variability of future conditions.

What are the tools available?

DMDU tools broadly aim to find robust policy actions that enable decisionmakers to move forward despite uncertainties, rather than waiting for improved predictions. When plans are subjected to uncertainty analysis, it is possible for a robust decision to emerge where net benefits persist under a wide variety of plausible future outcomes. In some cases, the preferred plan chosen for the most probable future may also be a plan that is robust to alternative outcomes.

Many DMDU tools use a process of co-development that can involve community input and/or a transdisciplinary team. Transdisciplinary approaches are those that deeply engage interested parties in problem identification, analysis choices, and plan selection. A key motivation for using a transdisciplinary approach is that the higher the complexity and the higher the stakes of the decision, the more important it is to involve extensive community engagement from the beginning to promote useful and actionable outcomes (Wibeck et al. 2022).

When dealing with uncertain future conditions, incorporating input and collaboration between a variety of interested parties can lead to more robust results and broad support.

Multiple DMDU tools were presented during the seminar series, including scenario planning, vulnerability analysis and dynamic adaptive policy pathways, which will be summarized in the sections below. This report does not describe all DMDU tools. For a more comprehensive look at the current array of DMDU tools, see Kwakkel and Haasnoot (2019).

Scenario Planning

As described by Dr. Andrew Parker (RAND Corporation) during his seminar, a scenario is a set of future states of the world presented to decision makers as plausible and worthy of consideration, but without initially assigning likelihood. In some cases, scenario planning can underdeliver in terms of providing useful insights about managing future uncertainty. One of the reasons that scenario planning is not always useful for managing future risk is that people have cognitive biases that can cause them to disregard some types of uncertainty.

Using a wide range of scenarios that are developed to overcome cognitive biases and that may not have assigned probabilities, is a common tool of DMDU for thoroughly exploring decision outcomes under uncertainty, as described by Dr. Lisa Wainger in her seminar. Many normal human cognitive biases can affect scenario choices including *Normalcy* bias and *Optimism* bias. Normalcy bias reflects a well-documented tendency to think that the present is relatively stable and the future will be a linear continuation of the present, disregarding the potential for significant changes or disruptions, despite historic precedents. Optimism bias reflects our tendency to overestimate the probability of positive outcomes and underestimate the likelihood of negative events, which also causes us to ignore low-probability events. A classic example of the effects of both Normalcy bias and Optimism bias on decision-making around water resources is the Colorado River Compact (Ge et al., 2023; See Box 1).

Box 1. The Colorado River Compact: A Historical Case Study of Normalcy and Optimism Bias in Water Resource Management

When the Colorado River Compact was negotiated, estimates used for allocating water across the basin's seven states were around 16-17 million acre-feet of average streamflow in the basin (Reisner 1993). The decision-making, however, was overly optimistic. In fact, at the time of negotiations, a United States Geological Survey hydrologist had estimated that average flows were closer to 15 million acre-feet based on early 20th century evidence (Kuhn and Fleck 2019). More recent data from paleoclimate proxies and tree-ring analysis confirm that the Colorado River's average flows are significantly lower on average than the compact negotiators believed, which has led to more water being allocated in the basin than is available. The costs of the 1922 decision, and the biases that contributed to it, include decades of interstate and inter-sectoral conflicts over how to effectively meet compact obligations. Additionally, water managers, Tribes, and interested actors have also faced extensive negotiation costs in trying to identify alternative plans for managing the basin under very different conditions.

Even if decision-makers in 1922 had been able to check their Optimism bias, Normalcy bias would have made it difficult to imagine how both water supply and demand conditions in the Colorado River basin would change 100 years later. We now know that the past is not necessarily a good predictor of the Colorado River's hydrologic future, particularly due to climate change (Milly et al. 2008; Udall and Overpeck 2017). Colorado River experts have recognized the need to overcome biases from reliance on past normalcy assumptions and understand a broader range of sources of uncertainty under different future conditions (Garrick et al. 2008). In addition to climate change, there are uncertainties around compounding multi-year droughts and changes to management priorities (e.g., emerging environmental and Tribal water issues, new industrial and urban demands, shifting agricultural practices, etc.), that can be difficult to plan for. Given such uncertainties, both water managers and academics have begun to explore the applicability of DMDU tools for decision support in the Colorado River basin (Gerlak et al. 2021; Smith et al. 2022; Bonham et al. 2024). The goal has been to help decision-makers assess the robustness of different reservoir management alternatives given uncertain futures.

Under DMDU, developers promote the creation of diverse scenarios that encompass extreme cases, unexpected events, and various combinations of uncertainties to navigate complex decision landscapes (Figure 1). Scenarios should stretch decision-makers' thinking and challenge assumptions to go beyond the probable and into plausible or wild card conditions. Developing plausible scenarios requires creativity to go beyond a single vision of the future. Scenario development also involves creating qualitative narratives and quantitative projections that envision what the future could look like.

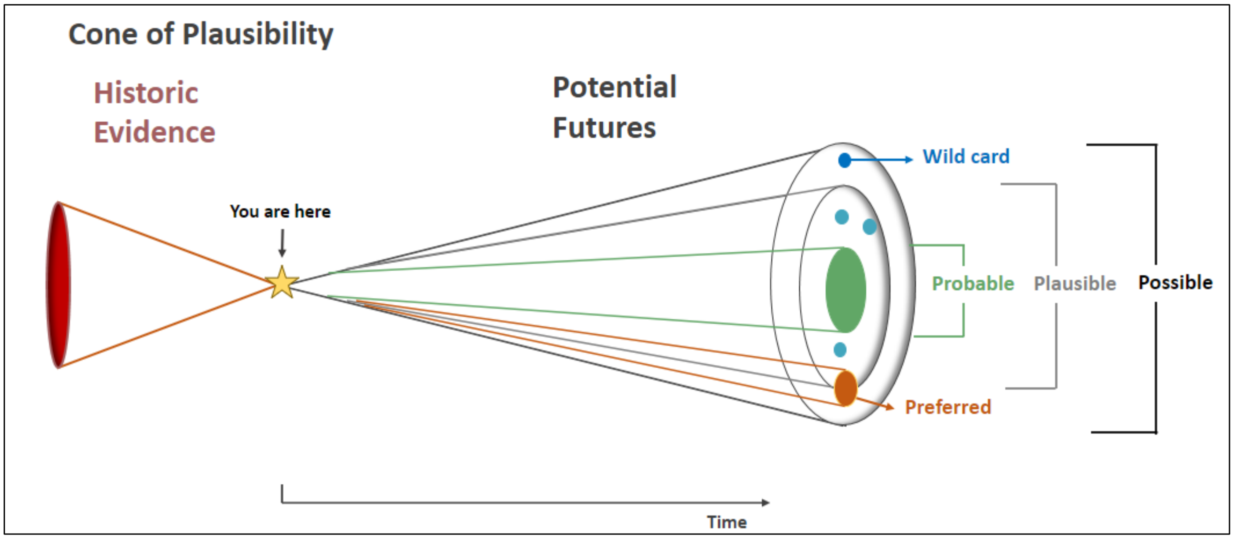


Figure 1. DMDU Cone of Possibilities. The concentric cones on the right represent projections into the future, with uncertainty increasing over time. The future uncertainty is larger than the historic variability that is captured with historical data and is shown as the cone to the left of the star that represents the current day. DMDU scenario planning aims to look beyond what is probable, to evaluate what would happen if an improbable or wild card type of event were to occur and how it might impact the type of plan that should be implemented.

Diverse scenarios help decision-makers explore alternative future adaptation pathways and identify strategies that perform well under alternative strategies (see Box 2 for example). The number of scenarios needed to explore potential future conditions can be minimized by using scenarios with uncorrelated drivers and outcomes. For example, if a salinity increase outcome is a major concern, it may not be necessary to have scenarios with alternative drivers of salinity increases to explore the solution space. In addition to biophysical stressors, scenarios can include human behavioral responses that may ameliorate or exacerbate problems, either in scenario design or in scenario evaluation. Ultimately, the goal is to recognize that the world is dynamic and uncertain and strategic planning is likely to require flexibility and adaptability.

The science of scenario development uses data-informed approaches to understand evidence of change and incorporates *Horizon-scanning* activities that identify how the system may be changing in the future. In a broad sense, scenarios are an integral part of *Stress Testing*, where a management or infrastructure plan is evaluated for its performance over a range of diverse future conditions (e.g., Lempert et al. 2004). Scenarios provide the plausible future conditions over which plans are compared using multiple metrics. Results can lead to new insights about which plans have superior performance across diverse conditions.

Box 2. Exploring the Benefits and Limitations of Scenario Planning for Extreme Events: Insights from ARkStorm

An example of DMDU scenario planning that is already being applied in the Delta region is the United States Geological Survey's (USGS) ARkStorm scenario (Porter et al. 2011), which was presented by Dr. Laurel Larsen during the seminar series. ARkStorm was created to inform a strategy to respond to a series of severe atmospheric rivers and flooding, using the extreme historical event of a storm that occurred during the winter of 1861-1862. The scenario included a large storm followed by an examination of secondary hazards such as landslides and flooding, physical damages to the built environment, and social and economic consequences. The simulated storm was estimated to produce precipitation that exceeds levels only experienced on average once every 500 to 1,000 years. California agencies who participated in that exercise reported using results to improve preparations (Kaplan 2023), and to evaluate opportunities to consider using greener approaches to stormwater management (Smith 2022).

However, ARkStorm also shows the limits of forecasting based on historic data since climate change is expected to intensify extreme weather events (e.g., Espinoza et al. 2018). To address this limitation, researchers have already updated the historic data to create ARkStorm 2.0, which represents how storm intensity could increase in a future climate era. The study found that climate change has already increased the risk of a mega flood scenario in California, and that future climate warming will likely bring about even sharper risk increases (Huang and Swain 2022). The results from ArKStorm 2.0 suggest a growing urgency of planning for and mitigating hazards from catastrophic floods in California under a warming climate (Huang and Swain 2022). Scenarios such as these show the impacts of being underprepared for extreme or compounding events and can offer opportunities to identify management changes that improve disaster preparation and response.

Vulnerability Analysis

Another overarching category that DMDU components can fall into is vulnerability analysis, which is a systematic examination of the conditions under which policies or projects are likely to fail. Vulnerability assessments can be used to find tipping points that can lead to planning failures, and to identify plans that perform well under a variety of plausible conditions. Diverse scenarios are often used to evaluate the influence of uncertainty on the success or failure of the policy options (Kwakkel and Haasnoot 2019).

Robust Decision-making (RDM) leverages concepts, processes, and computational tools, not for improving predictions, but for enhancing decision-making in situations of deep uncertainty. It is a framework that integrates *Decision Analysis*, *Assumption-Based Planning*, scenarios, and *Exploratory Modeling* to test strategies against many possible future scenarios. The goal is to identify key policy scenarios and adaptive strategies that remain effective across varying futures. RDM also fosters community engagement and consensus through a decision-making process called "deliberation with analysis," encouraging learning and collaboration (Marchau et al. 2019).

Dr. Robert Lempert (RAND Corporation) explained during the seminar series that in the case of RDM, the approach is to use models to thoroughly *stress test* proposed decisions against a wide range of plausible futures. The results are analyzed to identify key features that distinguish those futures in which proposed plans either meet or miss the objective. This information ultimately helps decisionmakers identify, frame, evaluate, modify, and choose robust strategies that meet multiple objectives over many different possible futures (Lempert 2019; see Box 3 for example).

Box 3. Stress Testing Water Quality Plans: Addressing Climate Change Vulnerabilities in Los Angeles

The city of Los Angeles had created the Enhanced Watershed Management Plan (EWMP), a Total Maximum Daily Load Implementation Plan, for the Tujunga Wash, the largest subwatershed of the Los Angeles River. The city's plan used hydrological and optimization models to determine best management practices but had uncertainties around land use and altered precipitation patterns from climate change. Dr. Lempert explained during the seminar that his team took the same models they used for the original management plan and conducted a study using Robust Decision-making methods to stress test the plan over a range of land use scenarios and 24-hour rainfall events. The results showed over one hundred different futures in which the plan did or did not meet its water quality goals, illuminating the vulnerabilities. Once these data were created, they could be visualized and separated based on failed or successful plans. Lempert explained that this analysis results in two policy-relevant scenarios with clear definitions, which became a powerful tool to use in policy discussions.

Some agencies working in the Delta region have incorporated vulnerability assessment DMDU approaches into their management planning efforts. Andrew Schwarz, Climate Action Manager at the California Department of Water Resources (DWR), spoke at the June 2023 seminar about how DWR has used these kinds of DMDU tools in his work at the state level. He explained that some of the key uncertainties that DWR is concerned with are changes in precipitation patterns and flood risk. Schwarz stated that DWR is using DMDU approaches to understand the range of outcomes that DWR defines as plausible, which will help lead DWR to adaptation strategies to key vulnerabilities even if they do not address the most extreme events. One approach that DWR is using is *Decision-Scaling,* a method that is somewhat similar to RDM (see Box 4 for example; Ray et al. 2020).

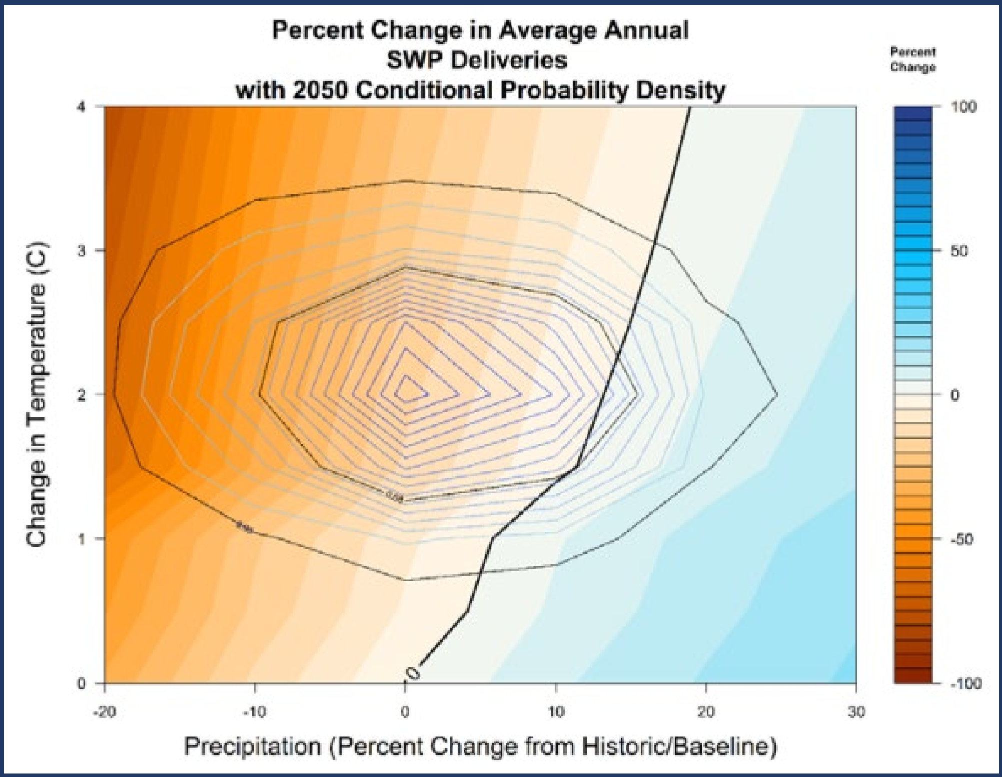
Decision-Scaling, a method that was largely used for understanding implications of different climate futures, is designed to assess uncertainties and identify key factors that could lead to system "failure" based on pre-determined criteria. As described in Marchau et al. 2019, the method involves three main parts: *Decision Framing*, *Climate Stress Testing*, and *Estimating Climate-Informed Risks*. In the Decision Framing step, objectives and metrics are established, and decision-relevant uncertainty factors are identified, such as future climate conditions. This step also includes selecting the models or functional relationships needed to represent the system and considering potential adaptation alternatives.

The second step of Climate Stress Testing is a multidimensional sensitivity analysis to determine the vulnerabilities to climate changes and other uncertainties, which identifies climate conditions that pose challenges. The third step, Estimating Climate-Informed Risks, involves using the identified climate information, often applied as downscaled climate projections, to assess the level of concern associated with these conditions.

Box 4. Assessing Climate Vulnerabilities and Projecting Future System Performance: A Decision-Scaling Approach for California's State Water Project

In 2019, the California Department of Water Resources (DWR) released its Climate Change Vulnerability Assessment, which describes, evaluates, and quantifies the vulnerabilities of its facilities and operations (DWR 2019). DWR operates the State Water Project, which supplies water to an almost 27 million Californians and irrigates 750,000 acres of farmland. DWR's vulnerability of assessment of hydrologic impacts used Decision-Scaling to explore system performance over a range of temperature and precipitation changes for various metrics, including average annual Oroville storage levels, net Delta outflow, State Water Project deliveries, and system shortages.

Probabilistic risk estimates for metrics like the average annual State Water Project delivery in 2050 are developed by combining the results of modeling the State Water Project's sensitivity to climate changes with the mid-century general circulation model(GCM)-informed *probability density function,* which is a graph that shows the probabilities of all possible outcomes, for future Central Valley watershed climate conditions. This approach provides a graphical representation of the probabilistic range of future system performance relative to selected metrics.



Box 4. Continued

The response surface in the figure above illustrates expected system performance for different combinations of changes in precipitation, warming, and sea level rise. The point at 0 degrees warming and 0 change in precipitation reflects historical conditions. A black line extends upward and to the left from this line, representing system performance that exceeds a desired impact level. The circular polygons illustrate the probabilistic extents of future conditions (temperature and precipitation) for 2050 as indicated by the GCMs. The response surface for average annual State Water Project deliveries demonstrates the system's sensitivity to changes in temperature, precipitation, and sea-level rise. Each color band on the surface represents a 5% change in system performance. The bands become narrower as precipitation decreases (to the left) and wider as precipitation increases (to the right), indicating that State Water Project deliveries are more sensitive to reductions in precipitation than to increases.

The Decision-Scaling approach enabled the evaluation of sensitivity to numerous potential future climate conditions, the estimation of the likelihood of specific outcomes in comparison to desired performance levels, which allows DWR and other interested parties to assess future risks and develop proactive adaptation strategies

Dynamic Adaptive Policy Pathway

The *Dynamic Adaptive Policy Pathways (DAPP)* approach, which was presented in a seminar by Dr. Marjolijn Haasnoot and Andrew Warren of Deltares, includes decision making over time in response to how the future unfolds. The approach reveals the usefulness of identifying and testing both short-term actions and long-term options (Marchau et al. 2019). DAPP embeds concepts that future conditions are uncertain and that policies must adapt over time to remain effective. Key components include adaptive planning, adaptation pathways, and tipping points, where policies may need to shift to maintain resilience in the face of changing environmental conditions (such as sea level rise).

Dr. Haasnoot developed the DAPP method and described it as breaking adaptation into manageable steps, linking the short term to the long term. The approach suggests that certain policies or measures have a design life after which they may no longer achieve desired objectives, due to evolving conditions. Before reaching a tipping point where current actions are no longer effective, decision-makers using the method would identify options and identify conditions under which they would shift to alternative policy pathways.

Alternative actions or policies are visualized as parallel horizontal lines in pathways maps and opportunities to shift among actions are represented as vertical colored lines that occur at thresholds of future conditions (Haasnoot et al. 2013; Figure 2). With DAPP, actions can be adjusted depending on how the future unfolds and as new information is gained, with the goal of avoiding maladaptation or path-dependency from locking into a single strategy.

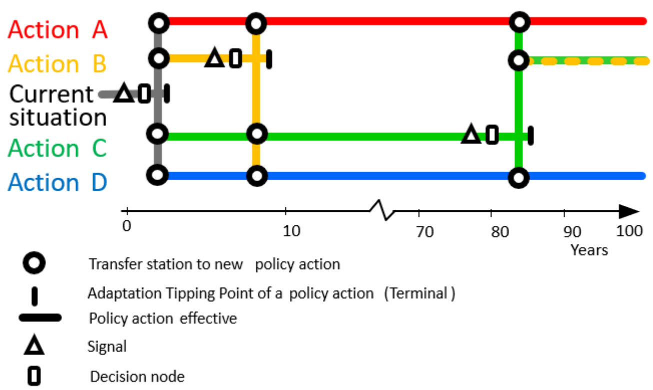


Figure 2: Adaptation Pathways Map, taken from Haasnoot et al. (2013).

The map shows different possible sequences of decisions to achieve the decided objectives. Key thresholds or triggers (vertical solid lines) signal when it's time to start switching pathways within the map to avoid under preparedness or decision lock-in. Haasnoot described DAPP as best used in situations when there is potential for long lifetime or societal impacts, high sensitivity to uncertain changes, risk of path-dependency (where the decision you take now influences the decisions you can make in the future), high investment costs, or potential for high regret. Haasnoot explained this with the caveat that the DAPP method is not a silver bullet for everything, but it’s one approach to deal with uncertainty and long-term impact.

The DAPP approach enables policymakers to plan dynamically, ensuring that decisions made now do not lock them into ineffective long-term strategies. It encourages proactive decision-making before critical thresholds are crossed, thereby maintaining flexibility and resilience in policy responses. Warren presented multiple case studies of the DAPP method being applied to different systems around the world (see Box 5 for an example). Warren emphasized that one of the greatest benefits of using the DAPP method is raising awareness and having the community and decisionmakers thinking broadly about the potential challenges for the future.

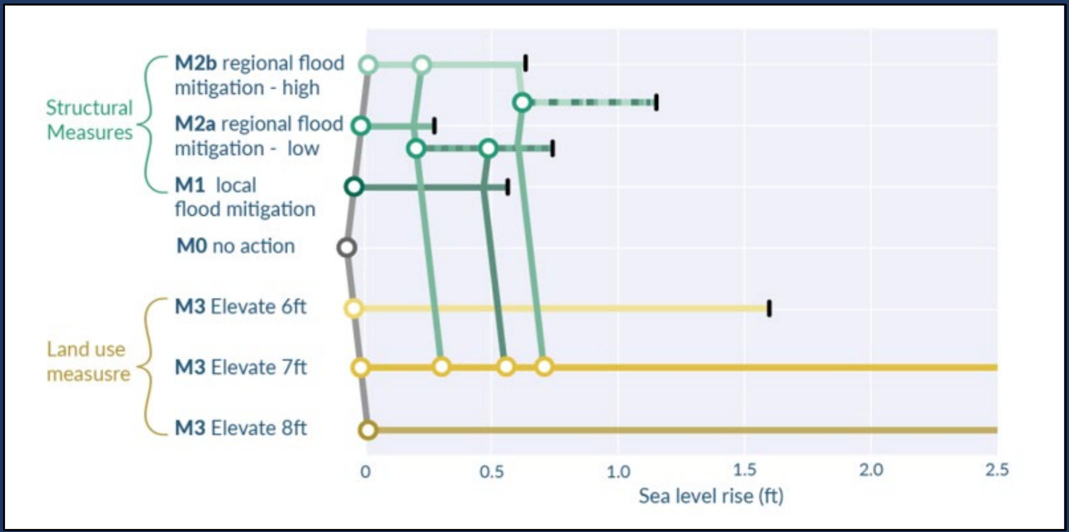
Building a dynamic policy pathway was said to be most effective when completed in a phased approach involving multiple iterations of the plan, with a gradual increase in terms of level of analysis. Dr. Haasnoot concluded the seminar by stating that, given the new climate reality, pathways can be used to link urgent actions to long-term adaptation needs and identify pivotal decisions.

Box 5. Adaptation to Sea Level Rise in the Little River Basin, Miami, Florida using DAPP

Planning for flood protection in Miami-Dade County, particularly in the highly urbanized C-7 basin, must address the compounding effects of sea level rise, rising groundwater levels, and extreme rainfall. The C-7 basin, also known as the Little River Basin, covers 32 square miles and serves 254,000 residents. The basin's primary canal, the C-7 canal, is critical for flood protection and maintaining groundwater levels to prevent saltwater intrusion, but its performance is hindered during intense rainfall and high sea levels due to gravity-only drainage.

Three adaptation strategies were evaluated for the C-7 basin: local flood mitigation (M1), regional flood mitigation (M2), and land-use mitigation (M3). M1 and M2 options, which include structural measures like flood walls and pumps, effectively reduce flood risk under moderate sea-level rise but are less effective under extreme scenarios. In contrast, M3, involving the elevation of buildings and roads, offers long-term protection, particularly when raised to 7 or 8 feet, making it the only strategy capable of maintaining or reducing current flood risk under significant sea-level rise.

The pathways analysis shows that, given the high uncertainty and potential severe consequences of sea-level rise in this area, raising properties, buildings, and transport infrastructure, including roads, is the most viable long-term option to manage future flood risk and increase flood resilience. The application of the DAPP approach suggested a reasonable set of pathways may include (a) local and regional pumps in the near term; (b) raising properties and infrastructure for the longer term; and (c) initiating the measures in (b) now, as their implementation may take a long time.



Adaptation pathways map for the entire basin, based on the simulated expected annual damage for the current sea level and the two possible future sea level rise. See Bouwer et al. (2017) for full case study.

Hybridizing the Approach

Several seminar speakers mentioned that DMDU approaches can be modified or hybridized to better fit the management need at hand. Andrew Warren explained that when using a Dynamic Adaptive Policy Pathways approach, decision makers can choose the level of complexity that they require for their system. He described DAPP as having 3 main levels of complexity: (1) creating qualitative pathway narratives (typically takes less than a day, workshop based), (2) adding quantitative design of pathways by bringing in reports and previous studies (including calculating tipping points), and (3) a full assessment of pathways where multiple pathways are modeled. Warren emphasized that sometimes decision makers only need a level 1 analysis to figure out next steps and identify a path forward. The level 2 and 3 analyses are only applied if needed and are not necessary for less complex issues.

Andrew Schwarz touched on the idea of hybridizing DMDU tools in his seminar presentation. In his work at DWR, he has used multiple DMDU tools to plan for the future adaptively, including system stress testing of climate change models, decision scaling, and Robust Decision Making (see Box 4 for decision-scaling example). Schwarz shared that moving forward, DWR will be hybridizing traditional scenario analysis with DMDU methods for their State Water Project Delivery Capability Report. Their plan is to use a limited array of scenarios, each linked with a probabilistic level of concern. Schwarz said that those levels of concern give decision makers a sense of how extreme the scenario is relative to the others, and how much risk is involved in using that scenario for planning purposes.

Broadly, DMDU tools are meant to push the boundaries of typical ways of thinking to address a wide variety of risks and uncertainties, including potential unpredictable sequencing or compounding of events. Dr. Robert Lempert explained that DMDU tools can create a robust strategy that is often designed to adapt over time in response to new information, meaning that decision makers can be empowered to identify low-regret, adaptive and diversified solutions. DMDU is not an “all or nothing” approach, and users can find substantial insight from these methods even when a full-scale comprehensive approach is not applied.

What are the challenges and limitations?

As we heard from Dr. Marjolijn Haasnoot, a seminar speaker, “DMDU is not a silver bullet.” There are challenges to implementing DMDU methods that either prevent its use or diminish its effectiveness, as well as limitations where DMDU may not be an appropriate use of resources. This section aims to acknowledge what these limitations and challenges are, and if there are any opportunities to work with or around them.

Cognitive biases

Cognitive biases come up daily in our lives and have significant impacts on the way we perceive the world and make decisions. Cognitive biases are systematic errors or deviations from rationality in perception, cognitions, or judgement that are often unconscious and result in the use of heuristics, or mental shortcuts (Schirrmeister et al. 2020). They are not inherently bad, as they allow for mental efficiency. But they can lead to the creation of highly subjective views of reality, which have an impact on decision making.

Alice Hill touched on cognitive biases in her seminar presentation and explained that these biases often arise from not being accustomed to assessing a risk that is unfamiliar or ignoring risks that we don’t recognize. In addition to normalcy bias and optimism bias described earlier in this report, Dr. Andrew Parker listed several different biases in his seminar that impact decisions such as confirmation bias (people are more likely to believe or to put more weight on outcomes that match prior beliefs), overconfidence increasing with task difficulty (lower knowledge leads to higher confidence), “production blocking” (a few ideas become dominant during brainstorming), and loss aversion (experiencing losses as more severe than equivalent gains).

These biases ultimately can lead to systematic errors in decisions such as choosing suboptimal policies, from a cost-benefit perspective (see Box 2 for an example on the Colorado River Basin). Scenarios have a complex relationship with cognitive biases because they can both be affected by biases and help to minimize them. Dr. Parker explained that when creating scenarios, group brainstorming can lead to production blocking where the group comes up with fewer ideas than they would have separately. Scenarios also often involve a conjunction of details, which can lead to the conjunction fallacy. This occurs when a conjunction of events (A and B) are perceived as more likely than either constituent (A or B).

On the other hand, Dr. Parker lists the outcomes of using scenarios as (1) consideration of multiple rather than single futures, (2) focusing on possibility rather than likelihood, (3) increasing concreteness, (4) focusing on policy options rather than expectations, and (5) presenting uncertainty across, rather than within, scenarios. Similar sentiments are found in the literature. Bradfield (2008) claims that scenarios force individuals to scan their perceptions, stretch their mental models, and develop a shared view of uncertainty, all leading to better confidence in decision making. Moving people beyond the typical business-as-usual thinking is a difficult task but can result in organizational learning (Bradfield 2008).

Cognitive biases become more difficult to avoid when uncertainty is deep and can result in systematic errors when they continuously go undetected. Low-probability events can easily be dismissed or overemphasized, creating a false sense of accuracy (Erdmann et al. 2015). In some cases, DMDU principles can help lessen cognitive bias. Andrew Schwarz noted in his seminar that working with communities and planners to widen their perspectives on possible future scenarios is key to lessening cognitive bias. Dr. Robert Lempert added that at the very least, DMDU can provide the framework to interested parties, communities, and agencies to understand potential risks and risk mitigation options more clearly.

Dr. Jody Wong in her seminar stated that using DMDU tools like scenarios can extend cognition, create shared knowledge, and shape beliefs. In DMDU, decisions about the future are motivated less by accurate anticipation and risk assessments than collectively held narratives. Because environmental decision-making grapples with uncertainty, it gives psychological agency to narratives, which highlight certain contingencies, responsibilities, priorities, and pathways over others.

Socio-political issues

The socio-political landscape can create obstacles that prevent the use of DMDU tools from being adopted on a wider scale. Apart from DMDU tools being relatively new and therefore foreign to most decision makers and managers, current government structures naturally deter some of these future-thinking methods. The so-called 'tragedy of the horizon' comes into play, where the long-term impacts of uncertain change take place in a timeline that extends further out than what concerns most businesses, politicians, or investors (Frame and Cradock-Henry 2022). Dr. Robert Lempert explained in his seminar that you sometimes see groups pushing back against the idea of an adaptive strategy because they have the political capital right now to lock things in, and they may be afraid that they won't have it down the line. Short-term needs and returns are of higher priority than accommodating for longer-term planning, and the current system of limited term decision makers can restrict what those leaders are able to prioritize.

Additionally, the pressure of avoiding the wrong decision is higher when dealing with systems that exhibit deep uncertainty and can lead to decision paralysis (Hallegatte 2014). Encouraging managers or decision makers to direct resources and time to a new technique that might not have any previous case studies within the system can be difficult. Typical political aversion to making mistakes can limit flexibility or willingness to experiment with new methods of decision making. Furthermore, high turnover of people with differing opinions and ideas can be hard to balance while implementing an unfamiliar tool.

Andrew Warren, in his seminar, walked through several examples of successfully implemented management plans that included Dynamic Adaptive Policy Pathways (see Box 5). He stated that often what's needed is a “change agent”, or someone who sees the need to address the uncertainty that lies ahead and who wants to drive the adoption of DMDU methods within their organization, agency, business, etc. Warren explained that this “change agent” does not need to be higher up in the chain of command, as long as they have good connections to those that can influence the decision-making process. These people can open the door to conversations about the benefits of these tools and start to lay the groundwork for eventual adoption. Dr. Andrew Parker also spoke about how DMDU might overcome socio-political obstacles, and he argued that because scenarios focus on the possibility rather than the likelihood, it can be less psychologically threatening and therefore allow us to address inconvenient or difficult futures.

Limitations

There are times when the use of DMDU techniques may not be appropriate for the scale, complexity, or resource limitations that a system may have. Dr. Robert Lempert explained that in some situations it may not be worth the additional time and effort to conduct engagement and modeling, such as for small projects. In contrast, large projects with existing integrated modeling are better able to incorporate DMDU tools. DMDU is also more useful when there is a sufficiently rich decision space in which robust plans can be determined, and realistic options are available to choose from (Lempert and Collins 2007). Lempert, in his seminar, added that you can use a screening process to see if it's necessary and beneficial to use DMDU tools within a project or plan.

Andrew Schwarz, in his June seminar presentation, argued that there is a problem when DMDU is presented as needing to have infrastructure that is fully adapted to a potential “black swan” event. Black swan events lie outside of the regular realm of possibility, often not having any comparable historical events, and bring an extreme impact (Callahan 2008). Schwarz explains that the price tag on preventative preparation for those kinds of events is huge, and that though we should still have a response ready, it should not necessarily be built into the infrastructure.

The literature on this topic suggests some solutions to this cost and feasibility limitation. In a 2018 report from the Climate-Safe Infrastructure Working Group to the California State Legislature and the Strategic Growth Council, the concept of using adaptive pathways within infrastructure plans is explored. The report recognizes the need for improved infrastructure to withstand the changing future conditions, within the limitations of what can be feasibly funded and built. They suggest using adaptive planning to create a ‘Climate-Safe Path’ that rejects the need for a single step-change in favor of change in multiple stages. This means having a long-term goal for adapted infrastructure that is realized through a variety of strategies in multiple stages over the course of decades. For example, infrastructure can be designed to be built in stages, as risks increase over time.

The report further emphasizes a resilience strategy that involves developing plans for situations where an extreme event exceeds the capacity of the infrastructure. This is aimed at improving and quickening response and recovery. It also highlights an adaptability strategy, which involves creating plans and integrating features into the infrastructure design now that would allow projects to be adapted to a higher level of protection if necessary over time (CSIWG 2018). While this ‘Climate-Safe Path’ roadmap involves substantial investments, resources, and research to fill knowledge gaps, it provides a plan for low-probability, high-impact events in the short-term and a guide to improve infrastructure in the long-term. Many DMDU approaches don’t aim for management plans to be fully prepared for a black swan event, but rather open up the conversation to think about how the current plan holds up under these rare conditions and if there are any cost-effective ways to avoid under-preparedness moving forward.

In addition, Dr. Parker mentioned some cautions with scenarios. The narrative nature of scenarios may make it easier to recall or imagine those scenarios, which, in turn, may increase perceived likelihood. Hence, they should be chosen carefully. In particular, they may legitimize multiple viewpoints. While some rare cases may be worth consideration, creating a false sense of equal likelihood may be one potential harm. Narrative scenarios often involve a conjunction of details, each adding realism, and may implicitly take advantage of the conjunction fallacy, which is when the conjunction of events feels more likely than either of the events themselves.

Ultimately, DMDU is not an appropriate tool for all types of decisions and choosing whether or not to use its techniques and/or results should be based on thorough discussion. Using DMDU approaches imposes a cost, but the payout is largest when contextual uncertainties are deep, policy options are many, decisions are difficult to reverse and costly, and system complexity is high (Marchau et al 2019). In cases without these characteristics, traditional predict-then-act approaches may suffice.

What are the opportunities and benefits of DMDU?

Widening perspectives

Alice Hill said that using DMDU tools opens the door for looking at various possible futures and facing risks that we otherwise may fail to identify. Dr. Robert Lempert echoed that idea explaining that DMDU tools can expand decision makers' view of how the world works by looking at scenarios that otherwise might be dismissed or ignored. Using scenarios can also help decision makers form new mental models of the situation they are facing and lead them to consider flexible options that work across multiple futures, rather than designing solutions for a single future, according to Dr. Andrew Parker in his seminar.

Structure for anticipating and managing uncertainty

Dr. Rob Lembert explained that DMDU allows you to creatively plan, even if you don't have exact probabilities or predictions of the future. Instead of possibly delaying decisions due to lack of information or ignoring key uncertainties in decisions because their probability is unknown, DMDU tools can offer ways to make adaptable plans that work with uncertainty. In some cases, uncertainty can even be reframed as an opportunity to think about what kind of future is preferrable and how to take steps today to move towards it. Dr. Lempert emphasized that the quest for prediction can distract from the main task of seeking creative solutions, and that DMDU can refocus time and resources onto the latter.

Cost saving

Alice Hill explained multiple benefits of managing uncertainty during her presentation at the April DMDU seminar. She stated that planning for uncertain futures can be costly, but if you are reducing future risk, you will see a significant payoff by saving money in the long term. Hill added that cost-benefit analysis with uncertainty can improve future planning to avoid much larger costs that are associated with being underprepared for an extreme event.

Collaboration and knowledge sharing

Using DMDU practices can also help with collaboration, knowledge sharing, and community acceptance of necessary change. Some DMDU tools, such as exploratory scenarios, can create opportunities for co-design between the design team, decisionmakers, agencies, and community members that leads to more highly supported plans. Brett Milligan in his seminar explained that in his own work, he found that scenario development that involves stakeholders and decision makers can help generate new ideas and identify commonalities in what people want that can be used to choose management plans (see Box 6 for details on Milligan's work with Franks Tract Futures).

Box 6. Franks Tract Futures: Leveraging Participatory Scenario Design to Transform Community Perspectives and Enhance Community Collaboration

Franks Tract Futures was a project to find a preferred proposal to redesign and enhance a 3,000-acre flooded island in the Delta. Franks Tract is used for recreation and fishing, contributes to the local economy, contains both native and invasive plants and fishes, and is susceptible to saltwater intrusion from the ocean into waterways that convey freshwater to cities and agriculture throughout California (CDFW 2020).

As described by Brett Milligan during his seminar, stakeholder participation can improve both scenario design and community approval. Milligan used public surveys with local residents that asked which areas of the tract most needed improvement and how the community currently uses the different areas. Milligan explained that the initial survey results showed most residents did not want any changes to be made to Franks Tract, but that after the participatory scenario planning process was finished, most participants chose a design that featured significant changes to the tract.

The process of co-design was described as collaboration between the design team, state agencies, and locals to share ideas and knowledge leading to a more dynamic and supported plan. It is an iterative process in which initial scenarios are designed, interested parties are invited to provide feedback, and the designs are adjusted to reflect the preferences expressed to the team. Milligan concluded that participatory scenario design can help get people on board with a project or policy when they may have been initially against it. Additionally, using surveys and other methods can help identify commonalities in what interested parties want, which can be incorporated into the scenarios and management plans. The outcome of this community participation is that the capacity of interested parties to anticipate and respond to unprecedented change is increased (Butler et al. 2020).

Better preparation and avoiding regret

The conversations and knowledge sharing that take place during the process of using a DMDU approach can lead to better preparation during unpredicted events as well as clearer roles and responsibilities for action. So-called black swan events that are outside the regular realm of possibility, such as extreme flooding or compounding of events, are often ignored in planning due to the cost of preparing for such events. But DMDU methods can create space to think about these kinds of worst-case scenarios, that can lead to ways to mitigate risk, define which agencies or groups will take responsibility for different responses, and provide time for stakeholders to weigh in on which tradeoffs are more or less acceptable during emergency response. Such activities might not result in changing infrastructure design for unlikely events, but rather maps out what could happen and allows for the creation of a plan to deal with the impacts to reduce damage or increase response effectiveness.

The context in which DMDU is most useful

DMDU will not be useful in all situations but has the greatest potential to produce benefits when multiple uncertainties are present, many policy choices are available, choices are difficult to reverse, and major investment is being proposed. In these situations, DMDU may reveal opportunities for lower cost solutions, such as staged construction, and may prevent harm by avoiding infrastructure investments that perform well under typical conditions but increase risk under extreme events with historic precedence. While the traditional decision-making method of “predict-then-act” is effective in simple systems with lower uncertainty, complex systems with decision freedom and deep uncertainty can benefit greatly from the “monitor and adapt” method found in DMDU, which recognizes the need for flexible long-term developments.

What is next?

The seminar series has helped introduce concepts of DMDU. Over the course of this year, the Delta ISB will continue to work on this review, which will include a dedicated effort to review the scenario-planning methods being used within the Delta or in regions relevant to the Delta. After evaluating the methods in use, the review will explore potential benefits and concerns of applying structured scenario development methods from DMDU or related disciplines. The ultimate goal of this Delta ISB review is to support planning and management of events that are largely unpredictable or of greater magnitude in outcomes than are typically prepared for in current management practices (e.g., long-term average conditions).

Appendix A. Seminar Summaries

The five seminars are summarized below. An overview of the seminar topics covered follow, which include a summary of the main points and key topics covered.

Seminar 1: April 26, 2023 – Alice Hill

On April 26, Alice Hill, the David M. Rubenstein senior fellow for energy and the environment at the Council on Foreign Relations, provided an introduction to deep uncertainty and its benefits. She presented an overview of the challenges and benefits of planning for extreme events related to climate change and gave examples from her own work. She also spoke about ways to organize government entities around these issues and how anyone in any sector can get involved in advocating for improved planning for extreme events. Some of the key points Hill raised are that the California state government can provide leadership in preparing for climate change and its associated uncertainties, risk mitigation efforts can be highly cost-effective when compared to being under-prepared, and that exploring a range of risks is valuable for building relationships across agencies that enhance the response to extreme events.

- YouTube recording
- Maven's Notebook Summary

Seminar 2: June 14, 2023 – Robert Lempert and Andrew Schwarz

The second seminar focused on available tools in DMDU and their applications in California. Dr. Robert Lempert, principal researcher at the RAND Corporation and director of the Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition, presented what DMDU is, why it should be used in certain situations, and how it can be applied. Lempert gave several examples of projects that have applied DMDU tools and how it created a more robust plan. Andrew Schwarz, the State Water Project climate action coordinator for the California Department of Water Resources, then presented on how DMDU is being applied within different projects at the California Department of Water Resources. Many of the projects he spoke on focused on climate adaptation in the Delta and how to use DMDU to best plan for an uncertain climatic future.

- YouTube Recording
- Maven's Notebook Summary

Seminar 3: August 17, 2023 – Andrew Parker and Jody Wong

The third seminar had a thematic focus on cognitive biases in scenario development and how they can be minimized. Dr. Andrew Parker, senior behavioral and social scientist and professor at the Pardee RAND Graduate School, discussed the benefits of using scenarios and when they can be useful. He explained the various cognitive biases that can affect scenarios and the ways in which we perceive the scenarios. Dr. Jody Wong, associate policy researcher at the RAND Corporation, presented case studies and examples to show how scenarios can serve as communication tools that help to develop a shared understanding of uncertainties and decision options. Dr. Wong discussed how scenarios are essentially narratives or stories about how the world works, what the future will look like, and what our own role in this process is. She explained the ways in which scenarios, or narratives, can be potent drivers that propel people to act despite uncertainty.

- YouTube Recording
- Maven's Notebook Summary

Seminar 4: September 14, 2023 – Brett Milligan

The fourth seminar featured a presentation by Brett Milligan of UC Davis' Department of Human Ecology, titled "Testing and Making Futures – Participatory Scenario Planning in California's Delta". The seminar explored the various drivers of scenarios, and how scenarios can be developed with stakeholder participation. Milligan used several examples from his work to demonstrate how using participatory scenario planning can improve outcomes and build community. Milligan spoke first about Franks Tract Futures and the process of learning how involving stakeholder input can improve scenario design and build community buy-in. Milligan also discussed his upcoming project, Just Transitions, which he described as a scaled-up version of Franks Tract Futures. Just Transitions will also involve in-depth stakeholder participation and allow those normally left out of the conversation to add their values and needs to the scenario design process.

- YouTube Recording
- Maven's Notebook Summary

Seminar 5: January 18, 2024 – Marjolijn Haasnoot and Andrew Warren

The fifth and final seminar focused on Dynamic Adaptive Policy Pathways (DAPP) and the potential applications of the tool to the Delta region. Dr. Marjolijn Haasnoot, associate professor at Utrecht University and climate change adaptation researcher at Deltares, and Andrew Warren, researcher at Deltares, presented on DAPP methods and their application. Several practical examples of using Dynamic Adaptive Planning were presented to show when it is most effective and how it can be used to reframe uncertainty as opportunity. Warren explained that one of the greatest benefits of using the DAPP method is raising awareness and having stakeholders and decisionmakers think broadly about the potential challenges in the future. Dr. Haasnoot emphasized that given the new climate reality, DAPP can be used to link urgent short-term actions to long-term adaptation needs and identify pivotal decisions.

- YouTube Recording
- Maven's Notebook Summary

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