Decision-Making Under Deep Uncertainty: Seminar Series Appendix

A summary and synthesis of information learned from seminar speakers

Delta Independent Science Board

Draft - Do Not Cite (March 22, 2024)

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All links in this document have been created with meaningful text. If you have a printed copy of this review, you can find the electronic version of this report on the Delta ISB's meetings webpage for the April 22, 2024 meeting: https://deltacouncil.ca.gov/delta-isb/meetings.

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Introduction

Uncertainty around 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 risk leading to under-preparedness and vulnerability to shocks. The Delta Independent Science Board (Delta ISB) is completing a thematic review on decision-making under deep uncertainty (DMDU) in the San-Joaquin Sacramento Delta (Delta) region to build an understanding of the scientific tools and concepts that can bolster the ability to anticipate and adapt to

increasing uncertainty of future conditions, specifically in the Bay-Delta system (DMDU Prospectus). This review will explore 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 engage stakeholders, rights holders, and other interested and affected parties. See the "Seminar Summaries" section below for an overview of the content covered in each seminar.

Approach of the seminar series

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 were an opportunity to explore social science research that evaluates community responses and reactions to future scenarios, and potential approaches to mitigate concerns. See Table 1 for summary information on the five seminars.

The goal of the series was to hear from a variety of speakers that have experience with DMDU tools in different contexts, and who could share their insights and guidance with the Delta ISB and the public through this formal seminar series. From researchers to consultants to policy makers, multiple perspectives were heard on the topic. Seminars featured one to two speakers who presented examples from their area of expertise and then took questions from ISB members and the public audience. The seminars brought together a wide range of audience members, including state and local agencies, academia, NGOs, and private businesses.

Table 1: Summary of seminar information

Topic	Date	Speakers	Links	Attendance
Introduction to Deep Uncertainty and its Benefits	April 26, 2023	Alice Hill, *Council on Foreign Relations* Lisa Wainger, *Delta ISB & University of Maryland Center for Environmental Science*	YouTube recording Flyer Maven's Notebook	Live: 80 Archive: 237

Topic	Date	Speakers	Links	Attendance
		Laurel Larsen, *Delta Science Program & UC Berkeley*		
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	Live: 68 Archive: 111
Cognitive Biases and Scenario Development	August 17, 2023	Andrew Parker, *RAND Corporation* Jody Wong, *RAND Coporation*	YouTube recording Flyer Maven's Notebook	Live: 63 Archive: 198
Scenario Development Methods	September 14, 2023	Brett Milligan, UC Davis	YouTube recording Flyer	Live: 35 Archive: 132
Dynamic Adaptive Policy Pathways	January 18, 2024	Marjolijn Haasnoot, *Deltares and Utrecht* Andrew Warren, *Deltares*	YouTube recording Flyer	Live: 70 Archive: 124

Goal of the appendix

The goal of this appendix is to summarize and analyze the information learned from the seminar series supplemented with prominent literature on the topic to understand how DMDU tools could be applied in the Delta region to improve decision making and to identify current areas of opportunity to apply these techniques. This document synthesizes how the different seminar speakers understand and use DMDU, including the challenges they face. This is not meant to act as a comprehensive review of DMDU topics, but rather a focused look at potential applications to the Bay-Delta region along with best practices. For a more complete and in depth look at DMDU tools and principles, see Marchau et al. (2019).

Approach for synthesizing seminar information

The approach for analyzing the information heard during the seminars was to synthesize how different speakers understand and use DMDU, including the challenges they face. Insights were derived and organized by topic below. When dealing with uncertain future conditions, incorporating input and collaboration

among a variety of stakeholders can lead to more robust results and improved support. Thus, this report aimed to integrate information from a diverse knowledge base to ensure multiple perspectives on the topic were included. Given that this is a limited look at DMDU topics, mainly focusing on the applications to the Delta region, there are aspects of DMDU that are not mentioned and numerous experts and practitioners who were not able to be a part of the seminar series. The Delta ISB acknowledges this limitation but still aims to present and synthesize the breadth of knowledge that was presented throughout the seminar series.

Overview of what you will find in this appendix

This document is organized into four main sections: 1) how the seminar speakers characterized DMDU, 2) how they use DMDU tools with practical examples, 3) the challenges and limitations faced, 4) and the areas of opportunity and benefits of the approach. Each section features information and examples from these experts, supported by additional literature. A summary of key takeaways can be found in the final section. After reading this appendix, one should have a basic understanding of DMDU tools and principles, and a familiarity with several concrete examples of its successful implementation.

How do experts characterize DMDU?

In the first seminar of the series, Delta ISB Chair Lisa Wainger, introduced the topic of DMDU and described deep uncertainty as being generally understood as unpredictability, with the likelihood of future events and outcomes unable to be well-characterized with existing data and models. Wainger stated that this uncertainty cannot be easily reduced and that stakeholders may disagree on the consequences of different actions. There are different opinions on what constitutes ‘deep uncertainty’, but for the purposes of this Delta ISB review, it is defined as **unpredictable events or system variability that cannot be well characterized with existing data, models, and understanding** (DMDU Prospectus). These types of uncertainties include extreme, novel, and compounding events (DMDU Prospectus).

Decision-making under deep uncertainty, or DMDU, is a set of decision support tools that can help evaluate unpredictable and often ignored potential future events. Wainger described it as an umbrella term for a variety of tools that can be used in both small and more time-intensive and comprehensive ways. Wainger listed a few examples of DMDU tools such as scenario development, vulnerability assessments, and adaptive planning, which will be discussed more in-depth in

following sections. Wainger emphasized that these tools are underpinned by strong stakeholder engagement and deliberative approaches to incorporate and navigate the different perspectives on what the future might look like.

The use of scenarios is one of the more prominent DMDU tools, and it involves creating qualitative narratives that envision what the future could look like (Figure 1). In Figure 1 the concentric cones on the right represent projections in time (with uncertainty increasing as you move outwards from the center cone and further into the future), and the cone on the left represents historical evidence limited by what has happened in the past. This type of DMDU scenario planning aims to look beyond what is just probable, moving towards what is plausible or even possible, to see what would happen if a wild card type of event were to occur and how it might impact the type of plan that should be implemented.

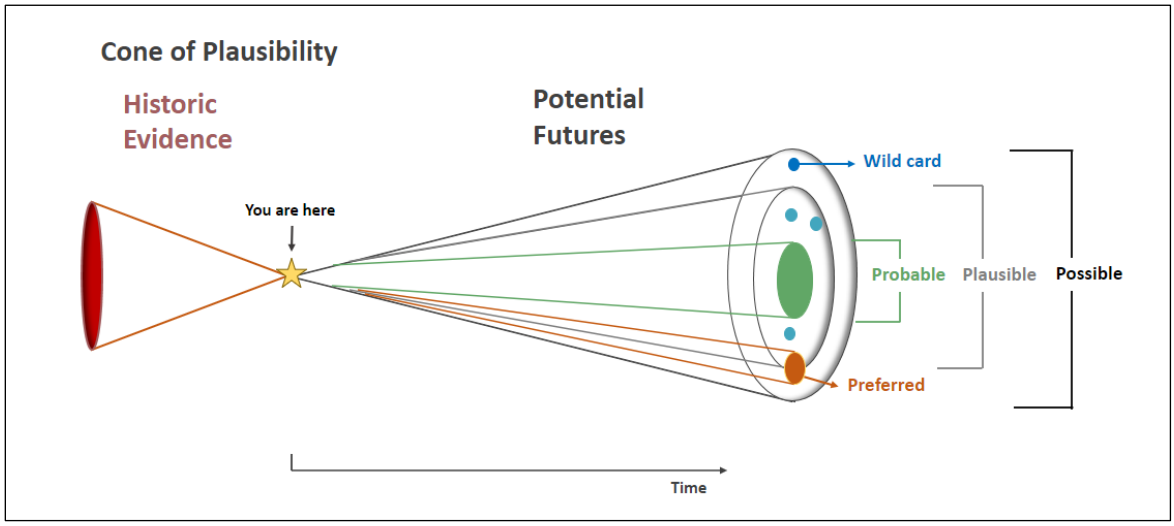

Figure 1: DMDU Cone of Possibilities

One example of this type of DMDU scenario planning is the United States Geological Survey's (USGS) ARkStorm scenario (Porter et al. 2011). Laurel Larsen, previous Delta Lead Scientist at the Delta Stewardship Council, gave an overview of this scenario at the first seminar. Larsen offered ARkStorm as an example of how DMDU is already being done to a certain extent in California. ARkStorm was created to figure out a strategy to respond to a series of severe atmospheric rivers and flooding, similar to what was estimated to have occurred during the winter of 1861-1862. The scenario included this large meteorological event 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. Larsen explained that as a result of coming together and figuring out how they would deal with such a scenario, many state and local agencies expressed that they felt much more prepared to deal with extreme rainfall situations.

Researchers have already designed ARkStorm 2.0, an updated storm scenario that was reimagined for the new climate change 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). It was concluded, based on the results from ArKStorm 2.0, that there is a growing urgency of planning for and mitigating hazards from catastrophic floods in California under a new warming climate (Huang et al. 2022). Scenarios such as these show the impacts of being underprepared for extreme or compounding events and can influence decision makers to alter management plans for better future flood protection.

How to implement a DMDU approach

There are a variety of DMDU tools, varying from simple to complex, which are used to improve the decision-making process by better identifying potential sources of uncertainty, assessing their potential risks, and finding possible pathways to mitigate or adapt to them. This section won't attempt to list or explain each and every one of them, but rather look at the common features of these tools and provide examples from the seminar speakers. For a more comprehensive look at the current array of DMDU tools, see Kwakkel and Haasnoot (2019). DMDU tools broadly aim to find robust policy actions that allow decisionmakers to move forward without ignoring uncertainty around future conditions or becoming stuck on improving predictions. In this case, a robust decision is one where expected performance is only weakly affected by the actual future states that emerge and can generally hold up under a wide variety of plausible outcomes. DMDU methods don't aim to find the 'correct' path forward, but rather one that works well under a myriad of conditions.

The current array of DMDU tools have mostly been developed in the last decade. Many use a process of co-development that can involve community input and/or a transdisciplinary team. One of the key rationales behind using a transdisciplinary approach is that the higher the complexity and the higher the stakes, the more important it is to involve extensive community engagement from the very beginning to ensure useful and actionable outcomes (Wibeck et al. 2022). When dealing with uncertain future conditions, incorporating input and collaboration

between a variety of stakeholders can lead to more robust results and improved support.

Kwakkel and Haasnoot 2019 offered five broad categories which make up the various components of DMDU approaches. For the purposes of this appendix, only categories that were discussed in the seminar series will be examined further below.

Scenario Generation

One of the five broad categories of DMDU components offered by Kwakkel and Haasnoot (2019) is generation of scenarios, which involves systematically exploring the consequences of different uncertainties, using "what-if" thinking. Scenario development is a means for thinking about possible threats and opportunities that the future might hold and their impacts on an organization, business, or system (Kwakkel and Haasnoot 2019). Jody Wong, August seminar speaker and associate policy researcher at the RAND Corporation, described scenarios as essentially stories about how the world works, what the future will look like, and what our own role in the process is.

Brett Milligan, associate professor at UC Davis' Department of Human Ecology and the September seminar speaker, is experienced in designing scenarios, specifically with community participation. He presented several of his past scenario development projects, one of which is called Franks Tract Futures. 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).

Milligan explained the process for scenario development that was used for Franks Tract Futures, and how 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, stakeholders 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 stakeholders want, which can be incorporated into the scenarios and management plans. The outcome of this stakeholder participation is that the capacity of stakeholders to anticipate and respond to unprecedented change is increased (Butler et al. 2020).

Vulnerability Analysis

Another overarching category that DMDU components can fall into is vulnerability analysis, which includes sensitivity analysis, stress testing, and vulnerability assessments. Vulnerability assessments can be used to identify tipping points where plans fail and to find common features in the plans that succeed. This method is often combined with generation of scenarios, in which alternative policies are evaluated over the scenarios, using vulnerability analysis to detect the influence of uncertainty on the success or failure of the policy options (Kwakkel and Haasnoot 2019).

Within this category, we heard from 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, about how he has used Robust Decision Making (RDM), stress testing, and modeling to identify robust strategies that meet objectives over a wide variety of futures. Lempert explained that in the case of Robust Decision Making, the approach is to use models to 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 which meet multiple objectives over many different possible futures (Lempert 2019).

Lempert also presented examples of using stress testing to see what conditions may cause a plan to fail. One example looked at a water quality implementation plan for a sub-watershed of the Los Angeles River. The city of Los Angeles had created a plan to meet the federal water quality requirements that did not include impacts from climate change. 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. Lempert

explained that his team took the same models they used to come up with the original management plan and stress tested them 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 this mass of data was created, it could be visualized and separated based on failed or successful plans. Lempert explains that this analysis results in two policy-relevant scenarios with clear definitions, which become a powerful tool to use in policy discussions. Ultimately the outcomes of stress testing focus stakeholders' attention on the characteristics of their policy options and not on predictions of the future.

Some agencies local to 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 seminar about how he has utilized 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 they are using DMDU approaches to understand the full range of plausible outcomes, which will allow them to assess the level of concern they should have and discern the solutions that should be invested in.

One example of a DWR project that used aspects of DMDU vulnerability assessment tools was the Central Valley Flood Protection Plan, which acts as California's strategic blueprint to improve flood risk management in the Central Valley (Central Valley Flood Protection Plan 2022). Schwarz explained how they projected climate impacts on the region using three future projections (a low, medium, and high warming) with a 50-year planning horizon. They also ran a suite of models to estimate the impacts of climate projections on expected annual damage and expected annual life loss with and without investments. The outcomes showed that with investment into adaptation, the impacts were significantly less. Schwarz noted though that even with adaptation we won't be able to maintain current performance, but we may be able to manage the new conditions more effectively.

Dynamic adaptivity

Kwakkel and Haasnoot (2019) also listed policy architecture as one of the five key DMDU categories, which covers the various ways in which adaptive policies can be structured. Dynamic adaptivity lies within this broader policy architecture category and is described as a series of actions whose implementation coevolves with how

the future unfolds (Kwakkel and Haasnoot 2019). Dynamic Adaptive Policy Pathways (DAPP) is one example of a DMDU tool in this dynamic adaptivity sub-category that can be utilized to move forward with management plans without ignoring uncertainty about future conditions. Marjolijn Haasnoot and Andrew Warren of Deltares, a Dutch knowledge institute for water and the subsurface, presented at the January seminar on their experience using DAPP and the different applications of the tool. Haasnoot developed the DAPP method to support decision making under uncertain change and described it as breaking adaptation into manageable steps, linking the short term to the long term. With DAPP, you can adjust actions depending on how the future unfolds, with the goal of avoiding maladaptation or path-dependency. Haasnoot showed what different policy pathways can look like, with a 'metro-map' style being the most common (see Figure 2).

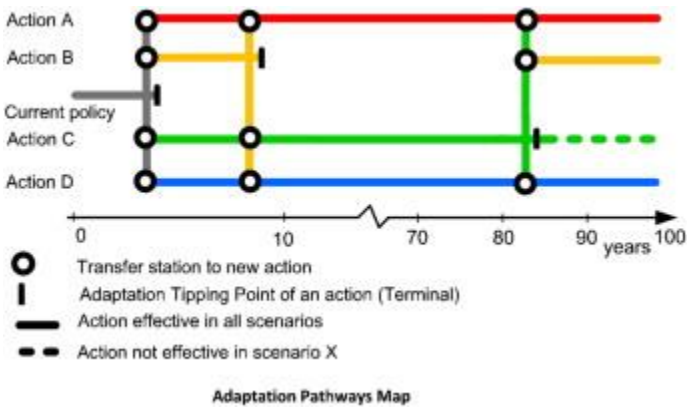

Figure 2: Adaptation Pathways Map, taken from Marjolijn Haasnoot and Andrew Warren January DMDU seminar presentation slides

The map shows different possible sequences of decisions to achieve the decided objectives. Key thresholds or triggers 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.

Warren presented multiple case studies of the DAPP method being applied to different systems around the world. One example was a flood risk scoping assessment in the Miami region. The study aimed to hypothesize what the future

might look like under different sea level rise scenarios, and what the potential paths forward were. Warren described the study as starting with a conversation with stakeholders around a table with hand-drawn adaptation pathway maps to think about the risks, vulnerabilities, and existing flood impacts. Next, a more quantitative analysis took place where tipping points were calculated, and modeling was used to add quantitative details to the initial qualitative narrative driven pathways. Finally, the full adaptation pathway plan was mapped, and it showed that land measures, such as raising the land, were needed in the end but that earlier measures, such as installing pumps, would buy some time. See Figure 3 for the adaptive pathways plan that was created in the process. Warren emphasized that one of the greatest benefits of using the DAPP method is raising awareness and having stakeholders and decisionmakers thinking broadly about the potential challenges in 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 gradually increasing level of analysis. 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.

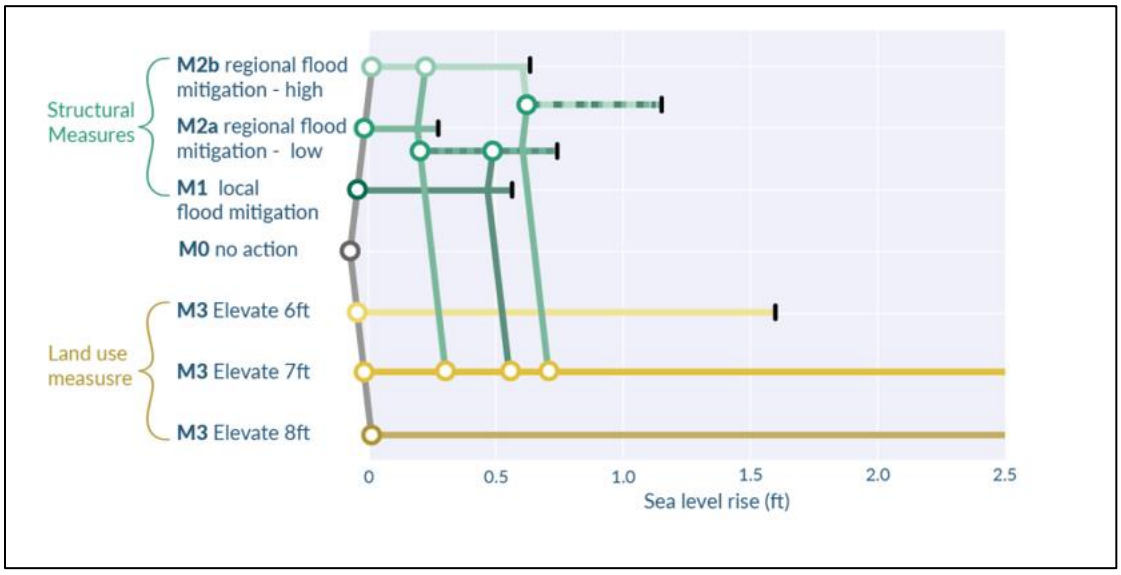

Figure 3: Adaptation Pathways map for the entire basin, based on the simulated expected annual damage for the current sea level and the two possible future SLR. See Bauwer et al. (2017).

Hybridizing the approach

Several seminar speakers mentioned that DMDU approaches can be modified, simplified, 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 own 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. 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 potential unpredictable sequencing or compounding of events. Rob Lempert, the June seminar speaker and principal researcher at RAND, 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 January seminar speaker, Marjolijn Haasnoot, “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. Andrew Parker, August seminar speaker and senior behavioral and social scientist and professor at the Pardee RAND Graduate School, listed several different biases that impact decisions such as confirmation bias (prior beliefs favor processing of alternatives), overconfidence increasing with task difficulty, brainstorming in groups leading to "production blocking", and loss aversion (experiencing losses as more severe than equivalent gains). These biases ultimately can lead to systematic errors in decisions and become more prevalent in systems with deep uncertainty.

Scenarios have a complex relationship with cognitive biases because they can both be affected by biases and help to minimize them. 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: a conjunction of events (A and B) are perceived as more likely than either constituent (A or B) (Andrew Parker seminar). On the other hand, 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 et al. 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 principals can help lessen cognitive bias. Andrew Schwarz noted in his June seminar presentation that working with communities and planners to widen their perspectives on possible future scenarios is key to lessening cognitive bias. Robert Lempert added that at the very least, DMDU can provide the framework to stakeholders, communities, and agencies to understand what they are doing more clearly. Jody Wong, June seminar speaker, stated that using DMDU tools like scenarios can extend cognition, create shared knowledge, and shape beliefs.

Socio-political issues

There are obstacles that our current socio-political landscape creates that can 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). Robert Lempert explained in his June seminar presentation 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). Trying to convince 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 January seminar presentation, walked through several examples of successfully implemented management plans that included Dynamic

Adaptive Policy Pathways. 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, so long as they have good connections to those that can influence the decision-making process. This can open the door to conversations about the benefits of these tools and start to lay the groundwork for eventual adoption. Andrew Parker also spoke about how DMDU might overcome socio-political obstacles, and he argued that because scenarios focus on possibility rather than 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. Robert Lempert explained that there are some situations where it may not be worth the additional time and effort, such as when it is too computationally demanding for a smaller project or a larger project with a high amount of integrated modeling. There also needs to be 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 presentation, 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 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. They emphasize a resilience strategy which involves developing plans for the possibility of a situation when an extreme event exceeds the capacity of the infrastructure, in order to improve and quicken response and recovery, as well as an adaptability strategy where you develop plans and integrate 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.

Ultimately, DMDU is not an appropriate tool for all types of decisions and choosing whether or not to utilize 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 have more degrees of freedom, and when 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

Hill touched on this topic, saying that using DMDU tools opens the door for looking at various possible futures and facing risks that we otherwise may ignore or fail to identify. 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 multiple futures rather than a single future, according to Andrew Parker, August seminar speaker.

Structure for anticipating and managing uncertainty

Lempert 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,

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. 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 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 favors better planning for the future to avoid much larger costs that are associated with being underprepared for an extreme event. The USGS ARkStorm scenario that Laurel Larsen presented at the introductory seminar estimated that such a series of heavy rainfall events could lead to over $725 billion in economic impacts from both property repair costs and business interruption costs (Wing at al. 2016).

Collaboration and knowledge sharing

Using DMDU practices can also help with collaboration, knowledge sharing, and stakeholder engagement. 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 a more dynamic and supported plan. Brett Milligan, September seminar speaker, explained that in his own work he found that scenario development that involves stakeholders and decision makers can help identify commonalities in what people want across the board and incorporate that into management plans. This process of co-development and collaboration increases the capacity of stakeholders to anticipate and respond to unprecedented change (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 allow for the consideration of high-impact, low-probability occurrences. By creating space to think about these kinds of worst-case scenarios, decisionmakers can improve communication and come up with management strategies that are more robust to deep uncertainty. This might not

manifest itself in bolstering infrastructure for unlikely events, but rather maps out what could happen and allows for the creation of a plan to deal with the impacts efficiently.

The context in which DMDU is most useful

Certain systems will experience these benefits more than others. Situations in which there are multiple uncertainties present, multiple policy choices available, difficulty of reversibility of choice, and major investment involved in the ultimate choice will see the most benefit relative to cost. While the traditional decision-making method of "predict-then-act" is effective in more simple systems with less 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.

Certain management decisions specific to the Delta region might benefit in particular from applying DMDU tools. The complexity of the system, the varying agencies that have authority, and future impacts from sea level rise and climate change all combine to create a rich decision space that fits the criteria for using DMDU. Based off the seminars, the Delta ISB identified a few examples where DMDU could be applied, which could be further investigated. For example, levee protection in the Delta will have to consider future impacts on levee stability from sea level rise and further subsidence of islands' peat soil, both contributing to higher stress on the levee walls. Salinity management, also impacted by sea level rise, must balance the ecological water needs of the system, agricultural requirements, and the need to release water to flush out intruding salinity. Reservoir operations in the region are further complicated by having to manage water storage under a changing climate with unreliable precipitation patterns. These examples all exhibit characteristics of a system that would benefit from a DMDU approach to different extents due to the high-stakes nature, complexity and presence of tradeoffs, numerous decision options, uncertain probabilities, and stakeholder disagreement.

Other Benefits

There are many more benefits that could be discussed. Cork et al. (2023) summarized the key aspects, such as uncovering a spectrum of values, sharing diverse knowledge and worldviews, facilitating social learning, increasing awareness of multiple interpretations of reality, uncovering socio-ecological systems not typically included in current modeling, creating space for innovation, and mitigating conflicts through social learning and collaboration.

Key takeaways

- Acknowledging biases and using methods to minimize them will lead to more rational and robust decisions.
- Including stakeholder participation in the DMDU process can improve scenario design, knowledge sharing, collaboration, and community support for a management plan or decision.
- Cost-benefit favors better planning for the future to avoid much larger costs that are associated with being under prepared for an event.
- Not all systems require the use of DMDU tools, and it is not always realistic that they can be implemented given time and resource constraints.
- DMDU tools can be modified to better fit a system by hybridizing them with non-DMDU tools or 'cherry-picking' aspects of multiple DMDU methods and combining them.
- Getting an organization, business, or institution on board with using DMDU tools is sometimes a matter of having a single 'change-agent' who believes in the method and the potential benefits from its use in the system. One passionate person might be enough to build momentum and support for a DMDU tool.
- The Delta region has multiple sources of uncertainty that could benefit from the implementation of DMDU tools, and examples exist of similar systems using DMDU to create management plans. Some agencies, such as DWR, are already implementing aspects of DMDU into their decision making.
- DMDU does not aim to reduce uncertainty or come up with the "correct" plan, but rather open up a space for conversation about what the future might look like and how different decisions will fare under those conditions, ultimately leading to a more informed choice.
- Reframing uncertainty as opportunity can be a powerful tool and can encourage decision makers to embrace uncertainty rather than ignore it.

Seminar Summaries

The five seminars are summarized below. See Table 1 for a chronological summary of the seminar topics, dates, speakers, attendance numbers, and links to the YouTube recordings. An overview of the seminar topics covered follow, which include a summary of the main points and key topics covered.

Seminar 1: April 26 – 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.

Seminar 2: June 14 – Robert Lempert and Andrew Schwarz

The second seminar focused on available tools in DMDU and their applications in California. 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.

Seminar 3: August 17 – Andrew Parker and Jody Wong

The third seminar had a thematic focus on cognitive biases in scenario development. 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 themselves and the ways in which we perceive the scenarios. 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. 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.

Seminar 4: September 14 – 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.

Seminar 5: January 18 – 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. Marjolijn Haasnoot, associate professor at Utrecht University and climate change adaptation researcher at Deltares, and Andrew Warren, researcher at Deltares, presented on what DAPP is and how the process of using the method works. 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. 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.

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