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Computational Policy Analysis

Using High-Performance Computing to Support Water Resource Planning

A Workshop Demonstration of Real-Time Analytic Facilitation for the Colorado River Basin

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SUMMARY ■ In recent years, decision support modeling has embraced *deliberation-with-analysis*—an iterative process in which decisionmakers come together with experts to evaluate a complex problem and alternative solutions in a scientifically rigorous and transparent manner. Simulation modeling supports decisionmaking throughout this process; visualizations enable decisionmakers to assess how proposed strategies stand up over time in uncertain conditions. But running these simulation models over standard computers can be slow. This, in turn, can slow the entire decision-making process, interrupting valuable interaction between decisionmakers and analytics.

What if high-performance computers could deliver the analytics decisionmakers need in near real time?

In November 2014, experts from the RAND Corporation and Lawrence Livermore National Laboratory (LLNL) conducted a one-day workshop to explore the impact of high-performance computing (HPC) on the use of Robust Decision Making (RDM) in support of stakeholder deliberations, in particular those regarding resource management decisions. The workshop revisited work RAND conducted on the Colorado River Basin in 2012 and was attended by decisionmakers involved in the original study and others interested in advancing the state of the art in quantitative decision support. During the workshop, high-performance computers were used to stress test five new project portfolios over about 12,000 alternative futures in 45 minutes—a process that would have taken six weeks to complete using traditional computer clusters. This document summarizes workshop results and the observations attendees made about the benefits and challenges associated with using HPC in this context. When asked whether the use of HPC in such analyses as those performed for the the Colorado River Basin Study would change their final decisions, three participants said that HPC would have led them to choose a completely different strategy; six said that they would have chosen a slightly different strategy; and the rest answered “don’t know.” The document also highlights possible ways forward to consider as technology continues to advance the speed of data processing.

INTRODUCTION

In recent years, decision support modeling has embraced a process called deliberation-with-analysis, an iterative process that begins with participants to a decision working together to define its objectives and other parameters, working with experts to generate and interpret decision-relevant information, and then revisiting the objectives and choices based on that information (National Research Council, 2009). This interactive engagement approach has proved successful in many cases, such as RAND's support for the Louisiana Master Plan for a Sustainable Coast (Coastal Protection and Restoration Authority, 2012; Groves et al., 2014) and the U.S. Bureau of Reclamation's Colorado River Basin Water Supply and Demand Study (U.S. Bureau of Reclamation, 2012; Groves, Fischbach, et al., 2013). Deliberation-with-analysis aims to address the shortcomings of the traditional approach, in which scientists and policy analysts would build and run a simulation model and then provide completed results to decisionmakers. Often, this disengaged process would result in analysts answering questions different from those of most interest to the decisionmakers.

Deliberation-with-analysis often proves particularly useful when a diverse group of decisionmakers faces a changing decision environment and has goals and options that emerge from discussion and collaboration. But in such cases, it can also prove useful to run the simulation models many thousands to millions of times to stress test participants' proposed strategies in the face of competing objectives and differing expectations about the future. When informing the decision also involves slow-running simulation models, as is often the case in complex applications, such as water or flood risk management in the face of climate change, this need for many runs of the simulation model can significantly slow down the valuable interaction between decisionmakers and the analytic process. For instance,

RAND's work with the U.S. Bureau of Reclamation on the Colorado Basin involved about a dozen workshops in which decisionmakers debated model results and asked "what if" questions. The time between workshops, about six weeks, was largely driven by the time it took to run the bureau's Colorado River Basin simulation model over 23,000 plausible futures and process the results on cluster computers administered by the Bureau of Reclamation and RAND.

What if we could use HPC to close time gaps, enabling decisionmakers to engage with one another, supported by instantaneous access to customized analysis to guide their deliberations?

RAND and LLNL tested this proposition during a unique workshop. In November 2014, RAND experts partnered with LLNL to explore with participants how HPC capabilities and trends in big data analysis may be able to improve stakeholders' participation in planning studies. Attendees included decisionmakers who had worked with RAND on the U.S. Bureau of Reclamation's 2012 Colorado River Basin Study and others interested in advancing the state of the art in quantitative decision support. During the workshop, participants conducted one iteration of a deliberation-with-analysis engagement, building on the original basin study models and analysis but running the models on a supercomputer. The workshop was designed to examine the potential benefits of applying HPC to real-time decision support, such as reducing the time between iterations, expanding the range of options and futures considered, improving understanding, and facilitating agreement.

This document describes that workshop, summarizes workshop participants' perceptions of the use of the new tool, and looks toward the future by assessing how a deliberation-with-analysis framework, called Robust Decision Making (RDM), may further harness and benefit from similar improvements in HPC technology.

What if high-performance computers could deliver the analytics decisionmakers need in near real time?

PREVIOUS COLORADO RIVER BASIN STUDY

The workshop built on RAND's previous work with the Bureau of Reclamation in developing the 2012 basin study. The Colorado River Basin provides an exceptional challenge for water managers. It supplies water to more than 30 million people in seven states, as well as 22 Native American tribes, four national recreation areas, and 11 national parks. The river supports billions of dollars in economic activity each year and

irrigates 15 percent of all U.S. crops. And demand may only grow; in 2012, for example, the demand for water in the Lower Basin (California, Arizona, and Nevada) had already exceeded the 7.5 million acre-feet volume allocated in the 1922 Colorado River Compact, which is the legal document that determines the allocation of water to the Upper Basin—Colorado, Utah, Wyoming, and New Mexico—and the Lower Basin (U.S. Bureau of Reclamation, 2012). These areas are highlighted in Figure 1. Climate change, coupled with growing demand and other uncertain factors, threatens the successful management of the river.

The basin study used an iterative, quantitative decision support approach called RDM that was designed to improve decisions under conditions of deep uncertainty. Deep uncertainty occurs when the parties to a decision do not know—or agree on—the best model for relating actions to consequences or the likelihood of future events (Lempert, Popper, and Bankes, 2003). The approach has been applied to such areas as flood risk (Lempert et al., 2013; Fischbach, 2010) and water management (Lempert and Groves, 2010; Groves et al., 2008; Groves, Bloom, et al., 2013) in situations where decisionmakers face conditions of deep uncertainty.

RDM rests on a simple concept. Rather than using models, data, and constraining assumptions to describe a best-estimate future, RDM runs models using hundreds to thousands of different sets of assumptions to describe how plans perform in many plausible futures. The approach then uses statistics and visualizations of the resulting large database of model runs to help decisionmakers identify the future conditions under which their plans will perform well and those under which the plans will perform poorly. This information can help decisionmakers

Figure 1. Colorado River Basin Study Area

SOURCE: U.S. Bureau of Reclamation, 2012.

develop plans that are more robust to a wide range of future conditions.

The 2012 Colorado River Basin Water Supply and Demand Study used RDM to guide vulnerability and adaptation planning over a 50-year horizon. The study, supported

How Robust Decision Making Helps Decisionmakers Identify Strategies Together

Traditional decision support analytics often employ an agree-on-assumptions approach, in which all the parties to a decision are asked to agree on a set of assumptions about the future before the analysis can then evaluate and compare the desirability of alternative decisions (Kalra et al., 2014). In contrast, RDM runs the analysis backward, using an agree-on-decisions approach. Analysts begin with one or more strategies under consideration (often a current plan) and then, using potentially the same models and tools, characterize a spectrum of the future conditions, including those in which a strategy fails to meet its goals (is vulnerable). This serves as a stress test of strategies and helps decisionmakers identify “robust” strategies—those that perform reasonably well regardless of what the future brings—and identify the key trade-offs among potential robust strategies. Often, the robust strategies RDM identifies are adaptive, designed to evolve over time in response to new information (Lempert, Popper, and Bankes, 2003; Lempert and Groves, 2010). By embracing many plausible futures, RDM can help reduce overconfidence and the deleterious impacts of surprise, can systematically include imprecise information in the analysis, and can help decisionmakers and stakeholders with differing expectations about the future nonetheless reach consensus on action (Lempert and Popper, 2005; Groves and Lempert, 2007; Hallegatte et al., 2012). But the approach requires many thousands of model runs, and an analysis can in some cases take many hours to weeks.

by the U.S. Bureau of Reclamation and Colorado River Basin states, evaluated future conditions under about 23,000 different futures that each reflected different water needs and climate changes and identified almost 100 different options to reduce supply-and-demand imbalance.

That study provided the first comprehensive look at the vulnerabilities of the Colorado River Basin system to climate change and increasing water needs in the region. Specifically, it identified the key hydrologic conditions under which the Lower Basin and Upper Basin users would experience shortages without additional supplies or demand reduction. For the Lower Basin, these included both conditions similar to those of the recent past and drier conditions. The study also evaluated four portfolios of water management options to reduce the vulnerabilities. By evaluating each portfolio across the 23,000 futures, the study identified the low-regret, high-priority options and the key trade-offs among the strategies.

RDM, by design, offsets miscommunication by supporting interaction between decisionmakers and the scientific analysis process; researchers do not simply pass data on to decisionmakers but instead support a deliberation-with-analysis engagement method. The basin study consisted of a series of monthly meetings in which stakeholders debated implications of previous model runs and raised questions that would take new runs to answer.

WORKSHOP PROCESS

Building on the original basin study, RAND and LLNL teamed up with stakeholders for a workshop to take advantage of LLNL's HPC power and respond to some of the questions raised. The day-long workshop followed the basic structure of a deliberation-with-analysis RDM study, as shown in Figure 2.

Participants gathered in the morning at the High Performance Computing Innovation Center at LLNL in Livermore, California. After some introductory briefings, they were divided into five planning groups, each tasked to develop a proposed management strategy for the river. The groups were asked to represent the following five different interests: Upper Basin, Lower Basin, Southern California, nongovernmental organizations, and Mexico. The groups were given a decision support planning tool, shown in Figure 3, that allowed them to specify attributes, such as reliability, environmental protection, and cost, and to construct a portfolio of actions meeting these objectives. The groups worked independently for about 90

minutes, then each submitted a file with its proposed portfolio to the workshop organizers.

The organizers then sent these files to one of LLNL's supercomputers, which had been reserved for this purpose only for one hour. The supercomputer, "Cab" (LLNL, 2014), is relatively modest by today's standards, with just over 21,000 cores on 1,300 nodes. This supercomputer ran each proposed river management strategy over about 12,000 alternative futures, for a total of 60,000 runs. These calculations, which would have taken about six weeks on the computers used for the original basin study, were completed in about 45 minutes. Each node of Cab ran one instance of the RiverWare-based Colorado River Simulation System model (Zagona et al., 2001; Center for Advanced Decision Support for Water and Environmental Systems, 2015) under Wine (Wine Project, 2015), a Windows compatibility layer. The jobs were managed across Cab's resources with a custom script, written in Python. The outputs of this enormous number of runs were collected and processed using a natively parallel program, written in R, developed by RAND. The workshop organizers then spent about 45 minutes organizing the resulting data into preprepared visualization packages. The visualizations evaluated and compared the vulnerabilities of the strategies each group had proposed, showing the types of futures in which the proposed strategy met its goals and the key characteristics of futures in which the strategy failed to meet its goals. During the short time in which all the simulations

Figure 2. Deliberation-with-Analysis via Robust Decision Making

Figure 3. Example of Workshop Support Planning Tool

and analyses were performed, workshop participants enjoyed sandwiches and heard a lunchtime speaker.

The workshop participants were then shown the results of the vulnerability analyses for each of their strategies. For example, Figure 4 shows the trade-off between the cost of seven portfolios—two of the basin study portfolios and the five from the workshop participants—and their ability to reduce vulnerability in the Lower Basin. Note that the five new portfolios provided results that represent different balances between costs and vulnerabilities.

Figure 5 shows for one of the five new portfolios, the low-regret, high-priority options—those that are needed in more

than 75 percent of futures and those that are needed within five years of being available.

This graphic shows that many options, such as conservation, wastewater reuse, and desalination of the Salton Sea, must be implemented as soon as they are available in order to address system imbalances in most of the 23,000 futures considered. Informed by such visualizations, participants were able to debate the strengths and weaknesses of the proposed strategies, the extent to which they performed as expected, the extent to which they met common goals or pursued conflicting objectives, and how strategies might be made more robust.

Figure 4. Trade-Offs Between Cost and Lower Basin Vulnerability for Two Portfolios from the Basin Study and Five from the Workshop

NOTE: The results for each portfolio show the range in costs (horizontal axis) required to reduce vulnerability to the level shown on the vertical axis.

Figure 5. Low-Regret, High-Priority Options for the Lower Basin Portfolio

NOTE: The results for each portfolio are expressed in terms of the percentage of traces in which the option is implemented (horizontal axis) and the minimum delay (in years) in which each option is implemented (vertical axis). The delay is the difference between the year in which an option is implemented in each simulation and the year in which an option is available for implementation.

WORKSHOP RESULTS

The workshop experience led many participants to suggest that HPC could significantly improve their ability to manage complex systems in the face of uncertain future conditions. At the end of the workshop, we administered a survey and then engaged participants in a structured discussion to evaluate what they learned, liked, and disliked. The survey asked participants to rank 17 potential attributes of the exercise on a scale from 1 to 5, with 5 being the most positive. The attributes are listed on the left in Figure 6. Participants were also given an opportunity to write comments on the surveys. Overall, participants ranked the impact of HPC favorably for all the attributes.

Participants judged that HPC would definitely shorten wait times; lead them to request more analysis; consider more strategies, futures, and trade-offs; and facilitate communication. Participants found HPC less valuable for helping collect more information, improve understanding, improve confidence in results, encourage compromise among participants, and lead to the repetition of fewer tasks.

Regarding its potential to improve the process of deliberation with analysis, one participant remarked that, “HPC could prove to be foundational in integrating, aligning, and bringing together engineers, planners, policy/decision makers, and stakeholders.” As one key goal, decision support endeavors to expand the range of contingencies and options that decisionmakers consider. Workshop participants found that HPC could foster such goals by “enabling a broader spectrum of alternatives to be evaluated in more transparent and expansive ways” and by “increasing the speed of analysis and the number of dimensions and scenarios that can be explored.” Participants also suggested that the ability to conduct the analysis on the spot might help solidify consensus in a workshop by answering questions before participants could return to their offices and backtrack on their agreements.

When asked whether the use of HPC in analyses, such as the basin study, would change their final decision, three participants said that HPC would have led them to choose a completely different strategy; six said that they would have chosen a slightly different strategy; and the rest answered “don’t know.” Of those who reported HPC could have an effect, one suggested that the capability “allows the direct consideration of adaptive strategies in a way that was previously infeasible.” Another offered that HPC “allows us to consider a more robust

Figure 6. Workshop Participant Survey Response

final strategy with a clearer understanding of the trade-offs involved among strategies.”

Participants also mentioned obstacles that could prevent HPC from providing these benefits. Most frequently, participants expressed concern about the potential cost. There was also concern about securing the kind of expertise and time needed for configuring the simulation models and conducting the runs.

Overall, some participants thought HPC offered great potential. “It opens up a new frontier of possibilities,” said one. “Access to such resources would have a transformative effect on the ability to use simulation modeling to support long-term planning under uncertainty,” offered another.

“It opens up a new frontier of possibilities.”

—Workshop participant on the use of HPC for resource management decisionmaking

THE FUTURE OF HIGH-PERFORMANCE COMPUTING AND RESOURCE PLANNING

The workshop demonstration foreshadowed a mode of planning for water and other natural resources in which analytics provide support in real time. No longer will planners need to wait for answers about what would happen under different management choices. This shift from discrete periods of analysis and discussion to more fluid deliberation with analysis can dramatically improve the planning process by better understanding trade-offs through consideration of more options, which can, in turn, lead to better agreements on how to move forward.

Getting to this vision will take some effort, but not too much. Simulation models in some cases may need to be modified to run on high-performance computers. Analysis will need to be scripted and compiled to run on high-performance computers as well. However, with high-speed Internet connecting the world's institutions, water planners can continue to hold their planning workshops in their own local facilities, while partnering with providers of high-speed computing to execute the simulations in real time.

The planning challenges that water and natural resource planners face are only getting greater. Solving these problems will require stakeholders and decisionmakers to come together to consider a wide range of plausible futures and grapple with difficult trade-offs. The use of HPC via a deliberation-with-analysis approach to planning can help ensure that the analytics support, rather than limit, the process.

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