3-5-2021

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Recommended Citation

Cuihong Song, Natallia Leuchanka Diessner, Catherine M. Ashcraft, Weiwei Mo, Can science-informed, consensus-based stakeholder negotiations achieve optimal dam decision outcomes?, Environmental Development, Volume 37, 2021, 100602, ISSN 2211-4645, https://doi.org/10.1016/j.envdev.2020.100602.

Can science-informed, consensus-based stakeholder negotiations achieve optimal dam decision outcomes?

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Abstract

Integrating science and decision-making in dam management is needed to address complex tradeoffs among environmental, economic, and social outcomes across varied geographic scales and diverse stakeholder interests. In this study, we introduce an approach that integrates system dynamics modeling (SDM) and role-play simulation (RPS) to facilitate use of the best available knowledge in dam decision-making. Using a hypothetical dam decision context in the New England region of the United States, this research investigates: (1) How do science-informed, negotiated outcomes compare to Pareto-optimal outcomes produced by a scientific model that balance selected system performance tradeoffs?; and (2) How do science-informed, negotiated outcomes compare to the status quo outcome? To our knowledge, this research is the first effort to combine SDM and RPS to support dam decisions and compare science-informed, consensus-based outcomes and optimized system outcomes. Our analyses show Pareto-optimal solutions usually involve a multi-dam management approach with diversified management options. Although all negotiated outcomes produced a net loss compared with at least one of the Pareto-optimal solutions balanced across tradeoffs, some yielded benefits close to or better than specific Pareto-optimal solutions. All negotiated outcomes yielded improvements over the status quo outcome. Our findings highlight the potential for science-informed, stakeholder-engaged approaches to inform decision-making and improve environmental and economic outcomes.

Keywords:
Sustainable dam management; participatory system dynamics modeling; science-informed role-play simulation; Pareto-optimal solutions; hydropower-fish-cost tradeoffs; environmental dispute resolution and negotiation

1 Introduction

Dam management is a challenging planning problem (Graham et al., 2017; Hurford et al., 2014), which typically involves complex environmental, economic, and social tradeoffs that are closely linked to specific dam characteristics (e.g., type, spatial location, and functions) (Almeida et al., 2019; Ziv et al., 2012). Dam management also requires building consensus among a diverse range of stakeholders with different interests (Baish et al., 2002; McCartney, 2007). Improving the use of science in dam decisions, and natural resource management decisions in general, is important for more sustainable decision-making (Dilling, 2007; Löschner et al., 2016). However, the best available knowledge is not always used to inform dam decisions. For instance, dam management typically follows a piecemeal approach, focusing on determining a management strategy for a single dam at a time (Baish et al., 2002; The Heinz Center, 2002). In contrast, research suggests that multi-dam or even multi-basin scale management approaches can produce solutions with greater benefits to meet a broader range of interests (Almeida et al., 2019; Opperman et al., 2011; Roy et al., 2018; Song et al., 2019). On the other hand, the effectiveness of consensus-based, stakeholder-engaged approaches in improving sustainability outcomes is not fully understood. In fact, a common criticism of such approaches is that consensus-based decisions do not always lead to strong environmental outcomes, especially at the larger landscape scale (Layzer, 2008; Poloni-Staudinger, 2008). It has been argued that consensus-based decisions tend to produce "lowest-common-denominator" outcomes, which largely maintain the status quo (Layzer, 2008; Susskind and Ali, 2014).

This research aims to foster the use of science in dam decision-making and to examine the effectiveness of consensus-based approaches in improving system outcomes. A novel approach that integrates system dynamics modeling (SDM) and role-play simulation (RPS) was developed to achieve this goal. SDM is a computer-aided methodology developed to understand dynamic interactions within and among complex systems under external disturbances (Ford, 2000; Forrester, 1997). This modeling tool has been previously used to evaluate system performance related to dam management, including hydropower production (Bosona and Gebresenbet, 2010; Sharifi et al., 2013), diadromous fish population potential (Barber et al., 2018; Ford, 2000), and tradeoffs among hydropower, fish population, and economic cost (Song and Mo, 2019; Song et al., 2020; Song et al., 2019).

RPS provides a forum to engage participants in a hypothetical, yet realistic policy decision-making scenario in which they reconsider the usual way of making decisions and explore innovative solutions (Rumore et al., 2016; Stokes and Selin, 2016). RPS can integrate socio-economic and biophysical data, and is therefore well suited to facilitate deliberation for policy innovation, education, and research purposes (Mayer, 2009). The hypothetical decision-making scenario is designed to be contextually similar to illustrate challenges participants experience in practice, but also abstracted enough to immerse participants in a safe space free from their usual pressures to explore change, without being distracted by arguments over how individuals perceive the specifics of the case (Crampton and Manwaring, 2014; Gordon et al., 2011). RPS participants typically assume a role different from their own, which is intended to interrupt behavior patterns, relieve anxieties related to embarrassment or concerns about revealing one's strategy, and provide insights into other stakeholders' perspectives, interests, and constraints (Crampton and Manwaring, 2014; Rumore et al., 2016). RPS has been used in diverse environmental public policy and natural resource management contexts, including climate change, mercury pollution, payment for hydrological services, and sustainable development of rivers (Rumore et al., 2016; Shafiqul et al., 2012; Stokes and Selin, 2016).

Combining SDM and RPS provides an opportunity to link science and decision-making. SDM can be used to simulate the complete range of possible outcomes across quantifiable performance variables under stakeholder-defined dam management alternatives. SDM is also an ideal approach to facilitate communication and negotiation, as well as to assist stakeholders and decision-makers in considering basin-scale tradeoffs and building consensus (Stave, 2010; Van den Belt, 2004). The RPS provides a forum to convene diverse stakeholders to discuss the results of the SDM, along with a range of non-quantified social values defined within the RPS scenario.

Several notable efforts have previously combined RPS and SDM to enhance linkage of science and decision-making of various environmental issues, such as climate change (Sterman et al., 2015) and coastal protection planning (Deegan et al., 2014). However, this approach is rarely used specifically in dam decision-making even though the sustainable development of dams is a topic of global importance (O'Connor et al., 2015; Pittock et al., 2017). In addition, previous studies mainly applied combined SDM-RPS approaches to assist learning about the science of a specific environmental issue or the specific economic, social, and political barriers to consensus-based agreements (Sterman et al., 2015). To our knowledge, the effectiveness of the SDM-RPS approach in promoting system outcomes has not been examined. Therefore, this research investigates two research questions: (1) How do stakeholder negotiated outcomes compare to Pareto-optimal solutions produced by a scientific model?, and (2) How do negotiated outcomes compare to the most likely outcome in the absence of successful negotiations (i.e., the status quo)?

2 Research Design and Methods

To research these questions, the authors developed the Pearl River Negotiation Simulation, an integrated SDM-RPS about hypothetical, but realistic, dam decisions, and implemented the Simulation in two workshops with stakeholders engaged in dam decisions (Diessner et al., 2020). The SDM used in the RPS was adapted from an SDM developed for part of the Penobscot River in Maine, U.S.A. to simulate different dam management options (Song and Mo, 2019; Song et al., 2020; Song et al., 2019). Adaptations to the model, the design of the Pearl River decision-scenario, and the participant roles were based on a stakeholder assessment, which included interviews with 36 individuals engaged in dam-related work in New England, focusing on New Hampshire (Diessner and Ashcraft, 2019). The negotiated decisions analyzed here are the outcomes from four groups that negotiated during the two Pearl River Negotiation Simulation workshops. The performance of the negotiated, Pareto-optimal, and status quo outcomes were analyzed using six environmental and economic indicators modeled by the SDM: spawner population potential for four sea-run fish species, annual hydropower generation, and project cost. These six system performance indicators were not intended to be comprehensive and, instead, were selected to illustrate important issues for stakeholders engaged in dam decisions in New England for which adequate quantitative data exist to inform model development. The SDM-RPS approach developed in this study can be tailored to include other quantifiable indicators important in other contexts, such as flood control and water supply, and scales relevant to stakeholders' interests.

The sections below detail (1) the Pearl River Negotiation Simulation; (2) the Pearl River energy-fish-cost SDM; (3) the Pareto-optimal dam management solutions; (4) the status quo and negotiated decisions from the Pearl River Negotiation Simulation workshops, and (5) methods for comparing Pareto-optimal, negotiated, and status quo outcomes.

2.1 The Pearl River Negotiation Simulation

The Pearl River basin is a hypothetical coastal river basin, the features of which resemble a simplified, yet realistic New England dammed landscape. The Pearl River and its main tributary, Mill Creek, drain an area of approximately 518 km^2. There are five dams in the basin: three run-of-river hydropower dams on the mainstem of Pearl River (Dams 1, 2, and 3) and two non-hydropower dams (Dams A and B) on its tributary, Mill Creek (Figure 1, see Section A in supporting information (SI) for detailed information of the five dams). The Pearl River basin is home to four sea-run fish species: alewife (*Alosa pseudoharengus*), American shad (*Alosa sapidissima*), Atlantic salmon (*Salmo salar*), and sea lamprey (*Petromyzon marinus*), which provide important recreational, commercial, and ecological value to the local communities. However, fish populations have declined significantly over the past few decades despite installation of fish passage structures (hereafter called fishways) on the three mainstem hydropower dams.

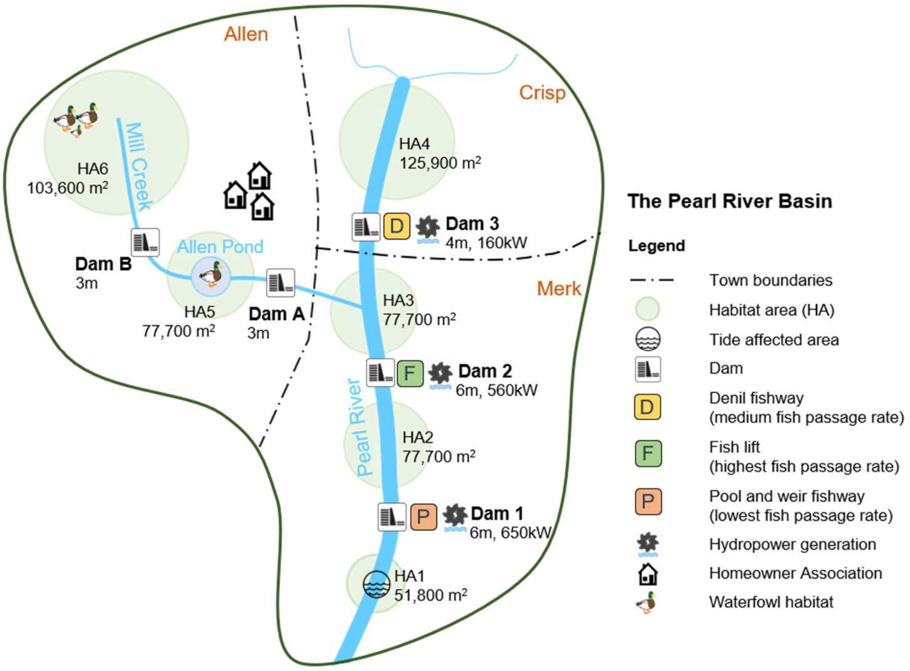

Figure 1. The Pearl River basin map showing the location and current condition of five dams. The five dams divide the basin into six habitat areas.

In the RPS scenario, the State Water Resources Division (State WRD) has convened a Pearl River Basin Working Group to explore a more comprehensive approach to making decisions about the dams on the Pearl River. Two common catalysts for changes to dam management in New England, public safety and hydropower relicensing, have led to this opportunity. The State WRD recently notified the Town of Allen that Dam A on the Mill Creek poses a threat to public safety, which needs to be addressed to comply with state safety requirements. Some town residents want to repair the dam, while others want to remove the dam to restore ecosystem functions. At the same time, the three hydropower dams on the mainstem of the Pearl River (Dams 1, 2, and 3) are about to come up for federal relicensing.

Representatives from seven stakeholder groups are participating in the Working Group meeting: State WRD, the Federal Agency of Natural Resources (Federal ANR), the Historic Preservation Agency of the State (State Historic), HydroEnergy, LLC. (owner and operator of Dams 1, 2, and 3), the Allen Pond Homeowner Association (Allen HOA), Rivers-R-Us (an environmental nongovernmental organization (NGO)), and the Town of Allen (owner of Dams A and B). The seven stakeholder groups and their priorities, interests, and constraints were identified through a stakeholder assessment including 36 stakeholder interviews in the New England region of the United States (Table 1). In the meeting, the Working Group participants need to reach three decisions to develop a Work Plan: 1) Which dams should be included and, for each dam, which management options should be considered?; 2) Who is responsible for implementing the Work Plan?; and 3) Who pays to implement the Work Plan?

Each negotiator received "General Instructions", which include information known by all negotiators. The General Instructions describe the negotiation context, the three decisions for the Working Group, and the alternatives for each decision. The General Instructions state that, if the negotiations fail, the most likely outcome will be that the Town of Allen decides on its own what to do about Dam A. Each negotiator also received "Confidential Instructions" with information specific to their role about their interests and priorities (Table 1), their preferred alternatives, and the constraints within which they can accept an agreement. It is up to each negotiator to decide how much of their confidential information they want to share during the negotiation. Different negotiators will interpret their role and instructions differently and use different negotiation strategies to advance their interests. The negotiators are able to craft new alternatives for the decisions, as long as the alternatives fit within the constraints of their roles. The General and Confidential instructions were informed by a stakeholder analysis (Diessner and Ashcraft, 2019). For the complete General and Confidential Instructions, see (Diessner et al., 2020).

Table 1. The Pearl River Negotiation Simulation stakeholder roles and their main interests.

Stakeholder Role	Interests
Federal Agency of Natural Resources (Federal ANR)	• Improve fish populations • Improve ecosystem health and resilience (e.g. open up-river miles, improve upstream habitat quality) • Build community support for proposed projects
State Water Resources Division (State WRD)	• Improve safety of Dam A • Improve fish populations • Improve ecosystem health & resilience (e.g. open up-river miles, improve upstream habitat quality)
Rivers-R-Us (Environmental NGO)	• Improve fish populations • Improve ecosystem health and resilience (e.g. open up-river miles, improve upstream habitat quality) • Improve river-based recreation
Historic Preservation Agency of the State (State Historic)	• Preserve historic resources • Early involvement of historic interests in the decision-making process

Town of Allen Municipal Official (Owner of Dams A, B)	• Improve safety of Dam A • Foster economic vitality • Build community support for decision
Allen Pond Homeowner Association (Allen HOA)	• Maintain property values • Maintain or improve pond-based recreation • Maintain waterfowl habitat
HydroEnergy, LLC (Owner of Dams 1, 2, 3)	• Generate hydroelectricity • Reduce uncertainty & costs related to the upcoming relicensing process

During the negotiation, participants used the information in their instructions and a web-based SDM application to inform their decisions. The SDM application is a user-friendly interface that displays system outcomes for Decision 1 regarding six performance indicators, which are described in the next section. The SDM application includes a table page where users can select different dam management options for each dam and a results page. The design and characteristics of the web application were first developed by the authors of this paper in collaboration with the Data Discovery Center at the University of New Hampshire, tested with discipline-specific experts and workshop participants, and then refined based on user experiences and feedback. The SDM application is open-sourced and can be accessed at: https://ddc.unh.edu/dam-system-dynamics/.

2.2 Development of the Pearl River energy-fish-cost SDM

An integrated SDM model, consisting of age-structured fish population models, energy models, and cost models, was built in Vensim® DSS on a daily time step and applied to simulate spawner population potential for four sea-run fish species, annual hydropower generation, and project cost. This model was adapted from existing models in (Song and Mo, 2019; Song et al., 2020; Song et al., 2019). A Vensim® file that contains the complete model is provided in the SI.

The age-structured fish population models simulate spawner population potentials for the four anadromous fish species by tracking their growth, mortality, maturity, iteroparity (reproductive strategy), timing and routes of migration at each life stage throughout the whole life span. The stabilized fish population potential was used in the analysis. To ensure stabilization, we ran the model over a 150-year time horizon. The detailed relationships, equations, parameter values, and assumptions associated with the fish population models are provided in Section B of the SI.

The energy models simulate daily hydropower generation at each hydropower dam, under the assumptions that river discharge is constant and equal to bankfull discharge, as shown in Equation 1 (Adeva Bustos et al., 2017; Singh and Singal, 2017).

$$E = Q \times H \times t \times \eta \times \rho \times g \times 10^{-6} \qquad \text{Equation 1}$$

where E is daily hydropower generation at each hydropower dam, MWh; Q is daily turbine release, m^3/s; H is rated head, a measure of the vertical drop, meters; t is daily turbine operation period, hours; η is plant overall efficiency, assumed to be 0.85; ρ is water density, equaling 1000 kg/m^3; and g is gravitational acceleration, 9.8 m/s^2.

Turbine release at each dam site equals 30% of bankfull discharge (Naito and Parker, 2016, 2019). The calculations of bankfull discharge, values of daily turbine release, and rated head are provided in Section A of the SI. To reduce fish mortality, we assumed all hydroelectric dams shut down turbine operations during the peak juvenile and adult downstream migration periods of the four fish species (see Section A of the SI for the turbine shutdown period). The annual hydropower generation for all hydropower dams (MWh/y) was calculated by summing the daily hydropower generation over a one-year period.

The cost models calculate total project costs for dam repair, removal, and installation of fishways and hydropower.

- The cost of dam repair applies only to Dam A, which is the only dam requiring a decision in the RPS scenario. The repair cost for Dam A was assumed to be a one-time cost of US$ 0.5 million (CIP Board, 2020).
- Dam removal cost was simulated as a one-time cost by multiplying dam height by the unit cost of dam removal, US$ 0.384 million/meter. The unit cost of dam removal is the average dam removal cost per vertical meter rise of dam height and was calculated based on removal costs from (Maclin and Sicchio, 1999) and from 37 removal projects in the New England region provided by collaborators from the National Oceanic and Atmospheric Administration (NOAA) Restoration Center.
- The fishway installation cost was calculated as the sum of capital investment and operation and maintenance (O&M) costs over a 30-year planning horizon to be consistent with the Federal Energy Regulatory Commission (FERC) license period for non-federally owned hydroelectric dams (Madani, 2011). Capital investment of fishway installation was predicted as a product of dam height and the unit capital cost per vertical meter rise of dam height (Table B2 of the SI). The annual O&M cost was estimated to be 2% of the capital cost (Nieminen et al., 2017).
- Turbine installation cost only applies to Dam A and Dam B. We calculated the cost of upgrading each non-powered dam to a hydroelectric dam by multiplying the potential hydropower capacity at each site by the average unit cost per hydropower capacity (US$ 5,000/kW) (O'Connor et al., 2015).

2.3 Modeling and identification of the Pareto-optimal dam management scenarios

We modeled the six system performance indicators under 33,856 different combinations of management alternatives for the five dams in the Pearl River basin. One combination is hereafter referred to as a dam management scenario. The current, or baseline, dam management in the Pearl River basin is:

- Three hydropower dams on the mainstem of the Pearl River: Dams 1, 2, and 3, with an installed pool-and-weir fishway, fish lift, and Denil fishway, respectively;
- Two non-powered dams on the tributary: Dams A and B, with no installed fishways.

Fishways vary substantially in how well they facilitate upstream fish passage depending on the type and number of fishways installed and on the type of fish species (Bunt et al., 2012; Noonan et al., 2012). This model includes four common types of fishways: pool-and-weir fishway, Denil fishway, fish lift, and nature-like fishway. Each of these fishways provides greater passage benefits for Atlantic salmon, relative to the other three fish species modeled (see Table B2 in the SI). We assume that up to two fishways can be installed at each dam and the two fishways must be different types. Some options are not possible, such as installing a nature-like fishway on the three mainstem dams because nature-like fishways are rarely used on higher dams. The available management alternatives for each individual dam are provided in Table C1 in the SI.

In the fish-energy-cost optimization, dam management scenarios that dominate others are considered preferable. For example, scenario x_1 dominates scenario x_2 if x_1 is no worse than x_2 in all objectives, and x_1 is preferable to x_2 for at least one performance measure, such as x_1 resulting in more of one fish species, equal numbers of the other fish species, equal hydropower, and equal cost (Marler and Arora, 2004). The Pareto-optimal solutions are a set of all solutions that are not dominated by any other solution. From among the possible dam management scenarios, we determined Pareto-optimal solutions using the *nondominated_points()* function from the 'emoa' package in R.

2.4 Pearl River Negotiation Simulation status quo and negotiated outcomes

To analyze whether negotiated agreements yield benefits over the status quo outcome, we compared the six system performance measures for each outcome. For the Pearl River Negotiation Simulation, the status quo outcome is that the Town of Allen decides to repair Dam A and no action is taken on the other dams. For aging, smaller dams in New England, dam repair is a common outcome in the absence of successful negotiations to fund removal. The financial cost of repairing Dam A is relatively low in the Pearl River Negotiation Simulation, which is another reason repairing Dam A is a likely outcome in the absence of a negotiated alternative. The negotiated decisions used were outcomes from four groups of stakeholders (hereafter Groups 1-4) that negotiated during two Pearl River Negotiation Simulation workshops. Each of the four negotiating groups included representatives from at least three different types of stakeholder groups engaged in dam issues in New England, including representatives from federal and state agencies, municipal government, homeowners who abut a dammed pond, environmental NGOs, and hydropower businesses. During the workshops, participants assumed a role different from their actual role in dam issues.

2.5 Outcome analysis and comparison

2.5.1. Analysis of system performance measures

To make it easier to compare the negotiated, modeled, and status quo outcomes across the different units of the six system performance indicators (e.g. US$, MWh/y, number of spawners), we normalized the indicator values using Equation 2 (Arora, 2017).

$$Normalized\ value_j = \frac{Numerical\ value_j - Least\ preferred\ numerical\ value}{Most\ preferred\ numerical\ value - Least\ preferred\ numerical\ value} \qquad \text{Equation 2}$$

where j represents one of the 33,856 modeled scenarios. *Normalized value*$_j$ and *Numerical value*$_j$ represent the normalized value and actual value of a specific indicator (e.g., alewife), respectively, generated by a dam management scenario j. *Normalized value*$_j$ for any indicators ranges from 0 to 1 and numbers close to 1 are preferred. *Numerical value*$_j$ for any indicators ranges from the *Least preferred numerical value* to the *Most preferred numerical value*. The *Least (or Most) preferred numerical value* differs depending on the system performance indicator.

- For the fish and energy indicators, more is better, and the lowest number produced by any dam management scenario is the *Least preferred numerical value*. The highest number of fish population (or energy) generated by a dam management scenario is the *Most preferred numerical value*.

- For cost, less is better, and the highest project cost produced by any dam management scenario is the *Least preferred numerical value*. The lowest project cost is the *Most preferred numerical value*.

A parallel coordinates plot and radar charts were developed to illustrate the system performance of the various dam management scenarios. These two types of visualization techniques are ideal for comparing multiple variables and analyzing the relationships between them (Siirtola et al., 2009). The parallel coordinates plot depicts the outcomes of all possible dam management scenarios using normalized values for the six system performance indicators (Figure 2), allowing for comparison of each scenario's performance profile. The parallel coordinates plot was plotted using the *ggparcoord()* function from the 'GGally' package in R. The radar charts also illustrate the outcomes according to normalized values for the six performance indicators and are used here to compare the negotiated decisions, the Pareto-optimal solutions, and the status quo solution. The radar charts were plotted using the *radarchart()* function from the 'fmsb' package in R.

2.5.2. Performance of negotiated decisions vs. Pareto-optimal solutions

To analyze differences between negotiated decisions and Pareto-optimal solutions in terms of the six system performance measures, the indicator "net gain/loss" was created and calculated using Equation 3.

$$Net\ gain/loss_{n,p} = \sum_{i=1}^{6}(Normalized\ value_{i,n} - Normalized\ value_{i,p}) \qquad \text{Equation 3}$$

where n indicates one of the four negotiated outcomes, such as Group 1's outcome in Table 2, and p indicates one of the Pareto-optimal outcomes, such as P-2 in Table 3. $Normalized\ value_{i,n}$ refers to the performance of a specific negotiated outcome, according to an indicator, i, such as cost. $Normalized\ value_{i,p}$ refers to the performance of a Pareto-optimal outcome according to indicator i. The differences between the normalized values for the negotiated and Pareto-optimal outcomes for each indicator are calculated and then summed to generate the $Net\ gain/loss_{n,p}$, which compares the overall performance of a negotiated decision, n, to a Pareto-optimal solution, p. If the value of $Net\ gain/loss_{n,p}$ is positive, negotiated decision n yields an overall gain compared to Pareto-optimal solution p. If $Net\ gain/loss_{n,p}$ is negative, negotiated decision n yields an overall loss relative to Pareto-optimal solution p. Importantly, the Pareto-optimal solutions give equal weight to each of the six performance measures, but it is unknown how individual negotiators weighted the performance measures in practice. This analysis therefore compares the negotiated and modeled Pareto-optimal outcomes according only to the system performance measures and does not consider the benefits different outcomes provide from the perspective of the negotiator.

2.5.3. Performance of negotiated decisions vs. the status quo outcome

We also analyzed net gain/loss between negotiated decisions and the status quo outcome, which is repairing Dam A in this study (Equation 4).

$$Net\ gain/loss_{n,s} = \sum_{i=1}^{6}(Normalized\ value_{i,n} - Normalized\ value_{i,s}) \qquad \text{Equation 4}$$

where *Net gain/loss*$_{n,s}$ is net gain/loss of negotiated decision *n* as compared to the status quo solution. As in Equation 3, *n* indicates one of the four negotiated outcomes and *Normalized value*$_{i,n}$ refers to the performance of a specific negotiated outcome according to a particular indicator. *Normalized value*$_{i,s}$ is the normalized value of system performance indicator *i* for the status quo solution, *s*. The differences between the normalized values for the negotiated and status quo outcomes are calculated for each indicator and then summed to generate the *Net gain/loss*$_{n,s}$. If *Net gain/loss*$_{n,s}$ is positive, negotiated decision *n* yields an overall gain compared to the status quo solution. If negative, negotiated decision *n* yields an overall loss.

3 Results and Discussion

3.1 Modeled fish-energy-cost tradeoffs from the SDM

Under all possible dam management scenarios in the Pearl River system, normalized values indicating the performance of the six system indicators are shown in Figure 2. As a reminder, in the parallel coordinates plot, 0 indicates the least preferred outcome and 1 indicates the most preferred outcome for all indicators, even though lower values are preferred for cost while higher values are preferred for fish spawners and hydropower generation. For the baseline condition (black polyline in Figure 2), the normalized value of energy generation is 0.84, the normalized values of the spawner population potential of the four fish species are zero, and the normalized value of cost is 1. Based on the performance of the six system indicators, we divided the remaining dam management scenarios into two groups. 661 out of the 33,856 dam management scenarios were identified as Pareto-optimal solutions, and the rest as suboptimal.

We then divided the Pareto-optimal solutions into five subgroups: (1) solutions that maximize energy generation (Pareto_MaxE, green polylines in Figure 2), (2) solutions that minimize project cost (Pareto_MinC, red polyline in Figure 2), (3) solutions that maximize spawner population of the four fish species (Pareto_MaxF, blue polyline in Figure 2), (4) solutions that balance across fish-energy-cost tradeoffs (Pareto_Balanced, purple polylines in Figure 2), and (5) other Pareto-optimal solutions (Pareto_Others, yellow polylines in Figure 2). For the solutions that maximize a single indicator, there are strong conflicts between energy generation, project cost, and fish populations, which is consistent with findings from previous studies (Song et al., 2020). Energy generation is highest when hydropower is installed at both Dam A and Dam B and none of the mainstem dams are removed (Pareto_MaxE). Under this condition, a strong tradeoff exists between fish and cost. The decision to only repair Dam A (also the status quo solution) results in the outcome with the lowest project cost (Pareto_MinC), but also the lowest fish populations. Removing all five dams is the best outcome for fish population potential (Pareto_MaxF), but the worst outcome for energy generation and results in a relatively high project cost at around 75% of its maximum value.

Six Pareto-optimal solutions were identified, shown as Pareto_Balanced in Figure 2, which achieve threshold benefits for all system performance indicators (for information about the details of the dam management solutions and their normalized values, refer to Section D in the SI). The thresholds are: (1) the populations of four types of fish species are greater than 50% of the maximum value the river can support, (2) energy generation is greater than 60% of its maximum, and (3) project cost is less than 40% of its maximum. These thresholds were identified through a systematic variation of upper bounds of preferred values for energy, fish, and cost indicators (Arora, 2017) (refer to Section D in the SI for the detailed process). We defined these six solutions as balanced Pareto-optimal solutions. Any of the balanced Pareto-optimal solutions can be achieved only by diversifying management options (e.g., combining dam removal, and fishway and hydropower installation) across multiple dams, which is a realistic condition as reported by previous studies (Opperman et al., 2011; Song et al., 2020).

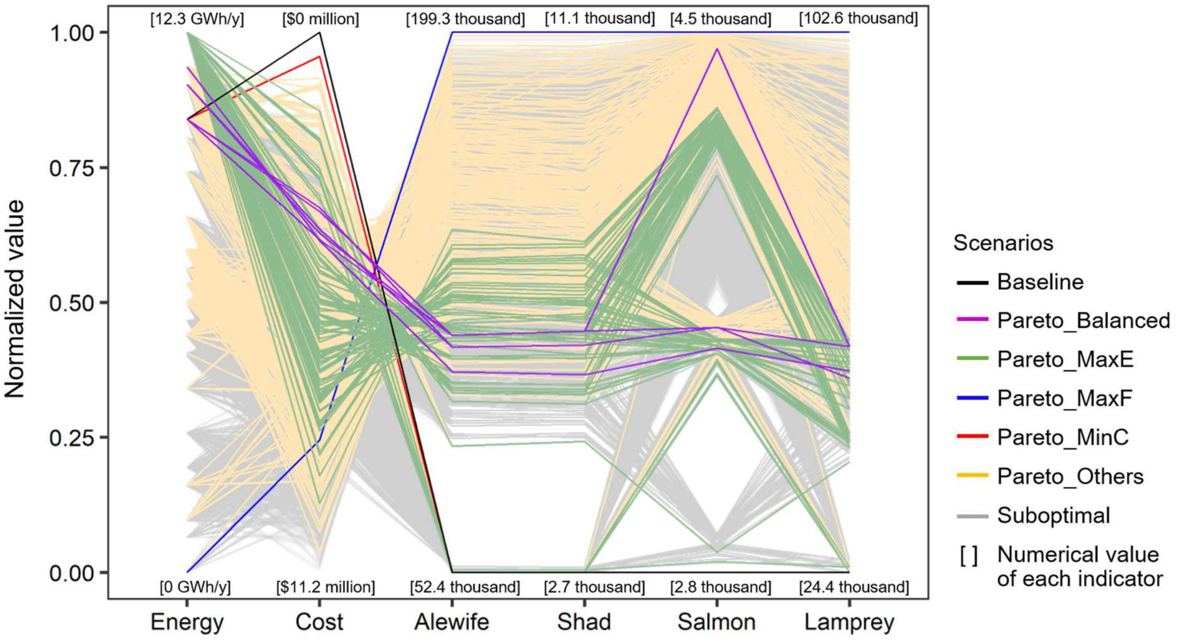

Figure 2. Parallel coordinates plot illustrates tradeoffs among hydropower generation, project cost, and population potential of four sea-run fish species for all possible dam management scenarios in the Pearl River basin. Each vertical axis represents one of the six system performance indicators. Each polyline represents one of the 33,856 possible dam management scenarios. Each scenario's performance is evaluated according to the points at which the polyline intersects each vertical axis. Within a given scenario, the steepness of the diagonal lines between two adjacent axes displays the degree of conflict between the two objectives. For all variables 0 indicates the least preferred condition and 1 indicates the most preferred condition.

3.2 Negotiated decisions

The four negotiated decisions are provided in Table 2. Like the balanced Pareto-optimal solutions, all four negotiated decisions diversify management options across multiple dams. The performance of the six system indicators vary across the negotiated decisions as shown in Figure 3 (A). Out of the four negotiated agreements, Group 1's decision results in the lowest level of salmon population potential. Group 1's decision was the only outcome that did not include installing fish passage at Dam A, and therefore continues to block salmon from reaching habitat upstream of Dam A on the tributary. Group 4's decision also results in a relatively low level of salmon population potential, as compared to Group 2 and 3's outcomes. Group 4 provided fish passage at Dam A, but took no action at Dam B, which prevented salmon from reaching habitat upstream of Dam B. Group 2's decision results in the highest cost because Group 2 removed Dam 3 and installed both hydropower and a nature-like fishway at Dam B. Operating and maintaining the fishway over 30 years is more expensive than removing Dam B, which two other groups decided to remove. The decisions of Groups 2 and 3 result in a relatively high level of salmon potential because both decisions provide fish passage beyond both Dams A and B and the nature-like fishway installed at Dam A provides greater fish passage benefits for salmon as compared to the other fish species.

All four negotiated decisions preserve a high level of energy generation, demonstrating that it can be difficult for stakeholders to agree on removing functional hydropower dams to restore healthy ecosystem. This finding is consistent with a study of public preferences for different dam tradeoffs in New Hampshire, which found that, in general, people prefer to keep dams for hydropower, as compared to removing them to benefit fish and wildlife (Diessner et al., In press). Group 2 did decide to remove one of the hydropower dams on the mainstem but offset the hydropower loss by installing hydropower at both Dams A and B on the tributary.

Table 2. Four consensus-based negotiated decisions

Negotiating	**Negotiated dam management options at each dam**				
groups	**Dam 1**	**Dam 2**	**Dam 3**	**Dam A**	**Dam B**
Group 1	Install fish lift	No action	No action	Repair	Remove
Group 2	Install Denil	No action	Remove	Repair, install hydropower and nature-like fishway	Install hydropower and nature-like fishway
Group 3	Install Denil	No action	No action	Repair, install nature-like fishway	Remove
Group 4	Install Denil	No action	No action	Repair, install hydropower and nature-like fishway	No action

3.3 Negotiated decisions vs. balanced Pareto-optimal solutions

A comparison of the radar charts for the four negotiated decisions (Figure 3 (A)) and the six balanced Pareto-optimal solutions (Figure 3 (B)) reveals a general similarity. We compared the overall net gain/loss of each negotiated decision to each of the six balanced Pareto-optimal solutions ($T_{n,o}$) (Table 3). Group 3's decision (highlighted in green in Table 3) results in a net gain ($T_{n,o} > 0$), as compared to five of the six balanced Pareto-optimal solutions. Relative to the other negotiated outcomes, Group 3's decision results in either the greatest gains or lowest losses when compared to each of the six balanced Pareto-optimal solutions, and can therefore be considered preferable over the others. Group 2's decision performs similarly, resulting in smaller gains and slightly larger losses as compared to Group 3's decision. This finding suggests that negotiators informed by scientific information about the impact of their decisions can reach decisions that yield as much or more benefit than modeled Pareto-optimal solutions that balance tradeoffs between energy generation, diadromous fish populations, and cost. However, the decisions reached by Group 1 and 4 show this is not always the case. Group 1's decision and, to a lesser extent, Group 4's decision consistently result in a net loss ($T_{n,o} < 0$) as compared to any of the balanced Pareto-optimal solutions, and can therefore be considered less preferable than the others. The net loss for the Group 1 and 4 decisions may be due to the relatively low performance of fish population potential. When summed across the four types of fish species, the relative loss outweighs any relative gains from increased energy or lower cost.

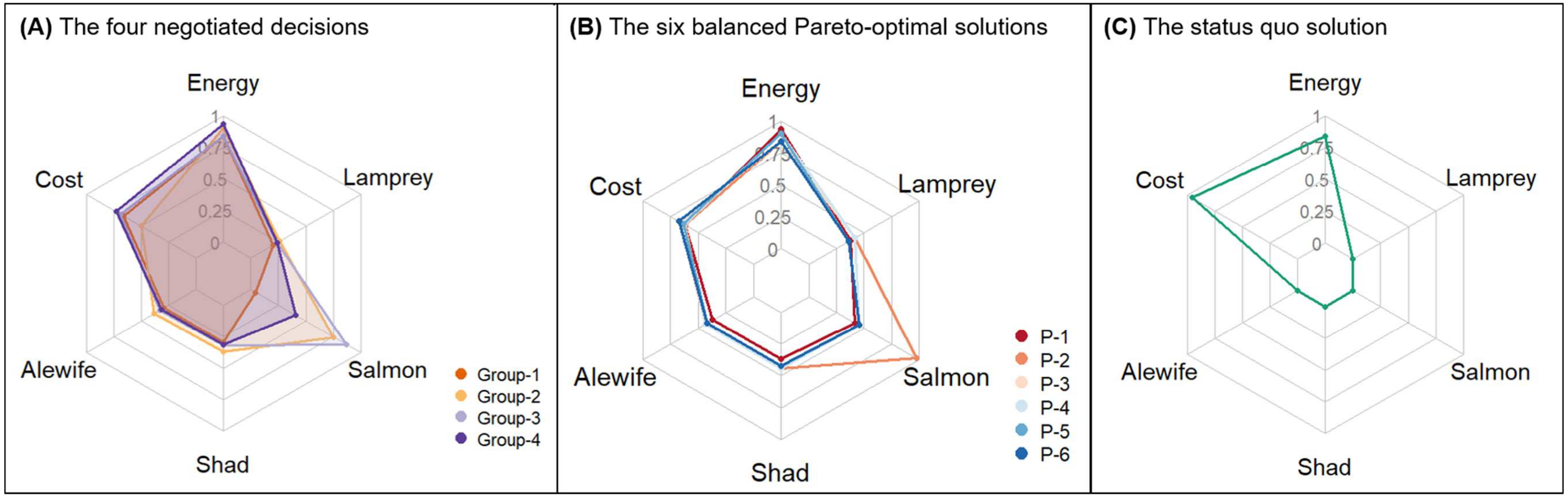

Figure 3. Radar charts showing the performance of energy, cost, and population potential of four fish species for the four negotiated decisions (A), the six balanced Pareto-optimal solutions (B), and the status quo solution (C).

Table 3. Net gain/loss of the four negotiated decisions, as compared to the six balanced Pareto-optimal solutions (P-1~6) and the status quo solution. Group 3 (highlighted) is considered preferable over the others as its decision results in either the greatest gains or lowest losses when compared to each of the six balanced Pareto-optimal solutions.

Negotiating groups	Net gain/loss compared with balanced Pareto-optimal solutions ($T_{n,o}$)							Net gain/loss compared with status quo ($T_{n,s}$)
	P-1	P-2	P-3	P-4	P-5	P-6	Average value	
Group 1	−0.74	−1.40	−0.93	−0.95	−0.86	−0.83	−0.95	0.54
Group 2	0.09	−0.56	−0.09	−0.12	−0.02	0	−0.12	1.37
Group 3	0.21	−0.44	0.03	0	0.1	0.12	0.02	1.49
Group 4	−0.14	−0.79	−0.33	−0.35	−0.25	−0.23	−0.35	1.14

3.4 Negotiated decisions vs. the status quo outcome

Outcomes for the six system indicators for the status quo solution are displayed in Figure 3 (C). As compared to the negotiated solutions, the status quo solution yields no benefits for the spawner population potential of the four fish species, costs less, and generates either comparable or less hydropower. The net gain/loss between negotiated decision *n* and the status quo solution ($T_{n,s}$) is provided in Table 3. Group 3's decision gains the most and Group 1's decision gains the least as compared to the status quo solution. In addition, all four negotiated decisions yield a gain ($T_{n,s} > 0$) and can therefore be considered preferable to the likely outcome in the absence of successful negotiations. This finding suggests collaborative governance can produce decisions supported by key stakeholders that result in improvements over the status quo for both the environment and for financial cost.

4 Conclusions

This study applied an integrated SDM-RPS approach to explore the effectiveness of science-informed, consensus-based negotiations in promoting system outcomes. We find that negotiated decisions tend to manage dams on a basin scale and use diversified dam management options, which maximize the selected socio-environmental outcomes of dam management with limited financial resources (Opperman et al., 2011; Roy et al., 2018; Song et al., 2020; Ziv et al., 2012). Indeed, negotiated decisions yielded benefits close to or better than specific Pareto-optimal solutions obtained from the scientific model. Critics of the negotiated outcomes might point out that the Pareto_Max F outcome, in which all dams are removed, yields significantly greater benefits for the four fish populations. Advocates for the negotiated agreement could respond by pointing out the improbability of an outcome in which all dams on the river are removed and the relative feasibility and desirability of implementing an agreement with support from all major stakeholders that provides improvements over the status quo.

Although negotiators do not know what the balanced Pareto-optimal solutions are, the outcomes suggest the negotiators incorporated the SDM results into their negotiations to develop innovative solutions that considered multiple dams at the basin scale and yielded system performance improvements over the status quo solution. These findings illustrate the potential of the SDM-RPS approach to inform actual decision-making to achieve outcomes that balance multiple tradeoffs, including environmental protection. The results analyzed here focus on the interests quantified and incorporated into the system dynamics model to compare different outcomes across specific performance indicators. However, the RPS roles incorporate other interests, some of which like recreation can be quantified, and others, such as historic preservation, are more qualitative. The ways in which negotiators interpreted the information provided and incorporated considerations about non-modeled interests into decisions, may explain some of the differences we find between the negotiated and the Pareto-optimal solutions. Our findings raise interesting opportunities for future research, such as explaining the variation across the different negotiating groups' outcomes, the application of a similar methodology to compare the benefits provided by the negotiated outcomes to each negotiator relative to the Pareto-optimal and status quo outcomes, and experimental approaches investigating the effect of education sessions on the performance of negotiated outcomes. While this integrated SDM-RPS approach is simplified to avoid overwhelming participants with information, it is flexible and future research could tailor the approach to include other quantifiable indicators, such as flood control, water supply, and recreational activities, and different spatial and temporal scales of analysis relevant to stakeholders and decision-makers. Using a similar evaluation methodology, future research could expand on our findings about the performance of consensus-based decisions relative to optimized system performance decisions. Based on our findings, people engaged in dam decisions will find integrating SDM with RPS a useful approach to convene diverse stakeholders to discuss biophysical and socio-economic data and foster consensus-based deliberations about the tradeoffs between different management options. This approach will also be useful to stakeholders early in dam decision processes who wish to encourage systems thinking across scales and across tradeoffs to foster integrative alternatives to the opportunistic, piecemeal approach to making dam decisions.

Acknowledgement

We would like to acknowledge the U.S. National Science Foundation's support via the Research Infrastructure Improvement Award (NSF #IIA-1539071). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We would also like to thank William Winslow and Michael Routhier from the Data Discovery Center at University of New Hampshire (UNH) for their assistance in developing and maintaining the web-based SDM application. We would like to thank all the Pearl River Negotiation Simulation workshop participants, the Future of Dams project team, members of the UNH Environmental Policy, Planning, and Sustainability Lab, as well as Kelly Addy, Charlie French, Clayton Mitchell, Casey Porter, Nick Anderson, and Mingcheng Ren for their assistance with the workshops.

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