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Publication Date

2018-04-01

DOI

10.1016/j.envsci.2018.01.022

Peer reviewed

Collaborative Model Development Increases Trust in and Use of Scientific Information in Environmental Decision-Making

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This is the accepted version of a manuscript published in *Environmental Science & Policy* on 8 February 2018.

The full citation is Ulibarri, N., 2018. Collaborative model development increases trust in and use of scientific information in environmental decision-making. Environmental Science & Policy 82, 136–142. https://doi.org/10.1016/j.envsci.2018.01.022.

Abstract

While science matters for environmental management, creating science that is credible, salient to decision-makers, and deemed legitimate by stakeholders is challenging. Collaborative modeling is an increasingly-used approach to enable effective science-based decision-making. This work evaluates the modeling process conducted for two hydropower dam licensing negotiations, to explore how differences in the collaborative development of hydrological models affected differences in their use in subsequent decision-making. In one case, the model was developed iteratively through deliberation with stakeholders. Consequently, stakeholders understood the model and its limitations and trusted the model and modelers; the model itself was also better designed to evaluate resource managers' questions. The collaboratively-developed model became the focal point for subsequent negotiations and enabled creative group problem-solving. Conversely, in the case with less engagement during model development, the model was not used subsequently by decision-makers. These differences are argued to result from trust built during the modeling process, applicability of the model to test real management scenarios, and

the broader social context in which the models were used.

1. Introduction

Science matters for managing the environment. A strong understanding of a problem's causes and impacts leads to more effective and durable policies and programs (Connick and Innes, 2003; Foley et al., 2013; Frame et al., 2004). However, creating science that is useful for decision-making—science that is technically credible, salient to decision-makers, and deemed legitimate by stakeholders—is challenging (Cash, 2001; Cash et al., 2003). The science surrounding many environmental challenges is often uncertain, meaning that there is not a clear "solution" for decision-makers to use (Polasky et al., 2011). In some instances, this uncertainty can lead to adversarial situations where competing experts interpret information to support their side (Doremus and Tarlock, 2008; Ozawa, 1996). The science produced by research entities may not directly address the needs and concerns of decision-makers, creating the need for boundary organizations to translate science for policy and communicate the needs of decision-makers to scientists (Dilling and Lemos, 2011; Guston, 2001). Finally, even if the science suggests a single "best" solution, decision-makers still have to address the complex tradeoffs between multiple and equally legitimate societal values (Balint et al., 2011; Lach et al., 2005).

The environmental governance literature holds that we can promote better use of scientific information in decision-making by incorporating stakeholder collaboration into the scientific process (Arkema et al., 2015; Cash et al., 2003; Peterson and Freeman, 2016). In collaborative governance, diverse organizations, including federal, state, and local government agencies, community groups, non-governmental organizations (NGOs), and businesses work together in a deliberative process to decide jointly how to manage the environment (Ansell and Gash, 2008; Emerson et al., 2012; Emerson and Nabatchi, 2015). A subset of these collaborative approaches orient around the use of computer-based decision-support tools, including simulation models (Cravens, 2014). Called collaborative or participatory modeling, in these approaches scientists work with stakeholders to identify issues of concern, and then use these concerns to develop simulation models (Belt, 2004; Bourget, 2011; Michaud, 2013; Palmer et al., 2013). The models are then used to frame the conversation in planning processes, multiparty negotiations, and other decision-making fora. The collaborative modeling approach entails developing a single shared body of science around which conversations and negotiations take place; as a single data source, the model thus highlights and enables dialogue about tradeoffs (Arkema et al., 2015; Cravens, 2016; Slotterback et al., 2016), an important requirement for enabling collaborative dialogue (Jacobs et al., 2016). Collaborative modeling also helps decision-makers understand the parameters that affect a system and how varying those parameters affects their interests (Cravens, 2016), improving their intuition about how complex social-environmental systems work.

A critical gap in understanding the impact of collaborative modeling is whether the ways models are developed affects their subsequent influence on the process. Many existing evaluations of collaborative modeling focus primarily on technical details of the modeling approach (e.g., Arkema et al., 2015; Peterson and Freeman, 2016) and therefore do not illuminate whether and how the modeling process influences stakeholder interactions and decision-making. Studies that evaluate social processes around collaborative model use are generally simulations not tied directly to real management decisions (Hedelin et al., 2017; Reitsma et al., 1996) and/or case studies that lack a counterfactual of what would have happened absent stakeholder engagement (Beall King and Thornton, 2016; Cravens, 2016; Jacobs et al., 2016; Morisette et al., 2017; Schenk et al., 2016; Slotterback et al., 2016). Finally, most studies—whether technically or socially oriented—focus on the collaborative *use* of models, overlooking the social dynamics surrounding the way a model was *built* (excepting perhaps a scoping session with stakeholders to inform model parameters).

However, we know that different ways of interacting with stakeholders—whether a process is collaborative or consultative—affect the overall quality and outcomes of that process (Ulibarri, 2015a, 2015b). Consultation and collaboration can be thought of as two nodes on a spectrum of participation (Arnstein, 1969). In consultation, a plan or program is developed by the lead decision-maker, who then seeks input from other organizations and individuals on their proposal. In collaboration, the project owner develops the program jointly with other stakeholders through face-to-face dialogue, deliberation, and trust building (Emerson and Nabatchi, 2015; Innes and Booher, 2010). While both collaboration and consultation "engage" the public, collaboration is more effective at building trust, enabling creative decision-making, and ensuring that stakeholders' interests make it into a final decision. Thus, whether a model was developed unilaterally or with regular stakeholder interactions could affect the models' credibility, salience, and legitimacy, and therefore its use in subsequent decision-making.

The work presented here assesses how the collaborative development of simulation models affects the use of science in decision-making, using a comparative ethnographic study of two processes to develop operating licenses for hydropower dams in California. It explores whether collaborative modeling affects the credibility, salience, and legitimacy of technical data; the use of data by stakeholders; and other dimensions of the decision-making process. By evaluating the collaborative modeling process, this work will advance the practice of science-based governance by evaluating whether proposed approaches perform as intended and uncovering process design features that can enhance the use of science in collaborative decision-making.

2. Materials and Methods

2.1. Case Study: Collaborative Modeling in FERC Hydropower Licensing

Hydroelectricity is an important component of a resilient energy portfolio. It is renewable, emits low greenhouse gas amounts, and with storage dams can be turned on quickly to meet peaking demand and balance temporally variable wind and solar sources. However, hydropower projects interact with numerous other resources. Many projects are managed not just to produce electricity, but also to provide water supply storage and/or control against floods. For projects that store water behind a dam, generating electricity alters the natural flow regime, affecting water quality, temperature, erosion rates, and the types of species that can survive in and near the river (Poff et al., 2007, 1997). Hydropower projects also provide recreational opportunities (e.g., fishing, boating, and camping) at the reservoir, yet negatively impact river-based recreation such as whitewater boating and fishing (Hooker, 2014).

The United States Federal Energy Regulatory Commission's (FERC) process for licensing hydropower facilities seeks to balance power generation with non-power considerations when determining whether to issue a license and what operating regime to require (DeShazo and Freeman, 2005; Moore et al., 2001). To achieve the required balance and reduce conflicts, FERC has structured its licensing process to encourage stakeholder participation. At a minimum, utilities must consult with federal, state, and local agencies, tribes, NGOs, and the public throughout the process. However, some utilities choose a more collaborative approach, actively engaging stakeholders in developing technical studies to quantify the project's impacts, collecting and analyzing data, and crafting the license application (Ulibarri, 2015b, 2015a). Thus, FERC relicensing processes vary from consultation to collaboration, particularly in how they aggregate technical information, providing an excellent case to compare differing approaches to collaborative modeling.

This study focuses on two ongoing hydropower relicensings[1] in California's Central Valley: Golden Dam and Platinum Dam[2]. Table 1 provides an overview of similarities and differences between the two cases. Both are run by publicly-owned regional water utilities, have sizeable generating capacities (over 150 MW), and are authorized for multiple uses beyond hydropower. Both have downstream rim dams that block upstream passage of anadromous fish. Both operate under California water and energy legal frameworks and used the same consulting firm to run the relicensing process. The relicensings had similar organizations participating, with several individuals who participated in both. However, the two cases differed substantially in their approach to collaborative engagement in and out of the modeling process: one was collaborative, while the other was consultative.

Table 1 provides a summary of the two cases. "Collaborative dynamics" are necessary interacting components of a collaborative process (Emerson and Nabatchi, 2015). *Principled engagement* emphasizes the use of deliberation and interest-based negotiation to reach decisions made jointly by the full stakeholder group. *Shared motivation* refers to how participants view the collaborative process, including whether they trust one another and feel that the process meets their interests. *Capacity for joint action* is the structure, resources, and leadership necessary to maintain collaboration over time. (For more details, see Emerson and Nabatchi (2015) or Ulibarri (2015a) for more extensive application to FERC relicensings.) As the table shows, Golden was generally more complete qualitatively along each dimension of collaboration, with the exception of shared motivation.

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[1] *Re*licensing means that these are reauthorizations for existing (rather newly built) facilities.
[2] Pseudonyms are used to protect the identity of individuals involved in the relicensings.

Table 1. Case Summaries

	Golden	Platinum
Project characteristics		
Owner	County Water Agency	County Irrigation District
Generating capacity	>300 MW	>150 MW
Authorized uses	Hydropower, flood control, water supply, recreation	Hydropower, flood control, water supply, recreation
Relicensing characteristics		
Lead consulting firm	HDR	HDR
Total meetings held	>400	~75
Facilitator	3rd-party mediator	Lead engineering consultant
Main participants	Utility, federal and state wildlife agencies, US Forest Service, CA State Water Board, environment NGOs, recreation NGO	Utility, federal and state wildlife agencies, CA State Water Board, upstream dam owner, environment NGOs, recreation NGO
Collaborative dynamics		
Principled engagement	Moderate deliberation, but with frequent caucuses to meet first with more likeminded individuals. The group aimed to reach consensus on major decisions but was not always successful.	Minimal deliberation. One meeting was highly deliberative, but all others were framed as consultant presentations followed by audience question. Minimal evidence of joint decision-making, with most decisions made by the utility or consulting team.
Shared motivation	No explicit statements of trust or distrust. Several concurrent lawsuits.	No explicit statements of trust or distrust. Several concurrent lawsuits.
Capacity for joint action	Numerous meetings, facilitated by third-party mediator. Process team made of diverse organizations to coordinate schedules and manage agendas.	Less frequent meetings, with minimal coordination of schedules. Leadership was primarily from the utility and consultants.
Modeling approach	Highly collaborative (iterative, two-way exchange)	General consultation (mostly one-way exchange)

While many different models were developed during each relicensing, this study compares the development and use of the *project operations model* in the two relicensings. The operations model, which depicts how water moves through the stream reach where the project is located, is used to estimate power generation, reservoir volume, river flows, and irrigation deliveries. Because understanding where water is at what times forms the crux of a relicensing, operations models are foundational tools for hydropower negotiations and are increasingly common in relicensing processes. The operations model is first used to develop a "base case" that depicts water's distribution under historical operations at the dam. Then, by altering input parameters in the operations model, stakeholders can test the impact of altered management regimes on water-related resources, including river flow, reservoir surface level, power generation, and water temperature; these water parameters translate into things stakeholders care about, such as whether a boat ramp reaches the reservoir or how much fish habitat is available.

2.2. Data and Analysis

A comparative qualitative case study, which relies on observed patterns of similarity and difference to infer the causes and consequences of phenomena (Mill, 1970; Yin, 2009), was used to evaluate the effects of collaborative model development. The two cases are remarkably similar along most variables (e.g., project location, size, socio-political demographics, see Table 1) except in the extent to which the relicensing used collaboration in and out of the modeling process. The comparative approach uses this pattern to infer that observed differences in outcomes, including the contents of the models and how they were used in decision-making, were influenced by differences in the model development approach.

Data were collected using an ethnographic approach—pairing participant observation with interviews—to capture decision-making *in situ* (Hoch et al., 2015). Between May 2012 and August 2016, I observed 71 meetings (totaling 323 hours) for the two relicensing processes; 60 were for Golden and 11 were for Platinum. At each meeting, fieldnotes captured meeting dialogue (who said what, mostly paraphrased), informal conversations, and nonverbal interactions and cues about emotions (e.g., laughter or raised voices). Observations focused on the process by which models were developed and used, how decisions about modeling were made, and whether they were made unilaterally by the modeling team or with input from other stakeholders.

To capture decisions that took place outside of group meetings and understand how individual participants experienced the process, I conducted interviews with 27 key personnel involved in each process.[3] These included representatives of the hydropower utilities (n=3), consulting firms including the lead modelers (n=6), federal agencies (e.g., US Forest Service, National Marine Fisheries Service, n=6), state agencies (e.g., California Department of Fish & Wildlife, State Water Resources Control Board, n=6), and NGOs (n=6); several interviewees were involved in both relicensings, providing an opportunity for comparison. Interviewees were selected from individuals who attended relicensing meetings regularly and focused on individuals who were either a lead negotiator or a key technical staff member for their organization. Interviews took place in spring 2016. Questions included how individuals were involved in each modeling process; whether, how, and why they had used the models in their own decision-making; and broader reflections on the relicensing process as a whole.

These data, described in detail in the results, revealed distinct differences in how the models were developed and used: the collaboratively developed Golden model became a central hub through which most decisions were negotiated, while there was no evidence the consultation-based Platinum model was ever used. To understand why these differences occurred, I use a modified grounded theory approach (Corbin and Strauss, 2007), an iterative theory building approach of using data to develop a theory of why something happened, then collecting additional data to update and refine the underlying theory. The fieldnotes, interview transcripts, and other documents accumulated during the process (e.g., powerpoint slides, technical reports, and comment letters) were analyzed using NVivo version 10, a qualitative analysis software. Open coding approach was used to identify emergent themes relating to how participants talked about the models and when and where the models were used. Codes and themes were then compared between the two relicensings to identify similarities and differences in model use and the circumstances that supported or hindered that use.

[3] Given how infrequently meetings were held and therefore how much less observational data were available, the interviews were especially important for Platinum.

3. Results

3.1. Collaborative Approach, Constant Model Use; Consultative Approach, No Model Use

The Golden Dam relicensing represented collaborative model development nested in a highly collaborative decision-making process. The Golden project operations model was built using an iterative, transparent process with substantial two-way interaction. Two engineering consultants developed the computer code for the model. While they developed the code, semi-monthly meetings were held with relicensing participants to share model updates, test assumptions, and discuss data accuracy. The consultants regularly changed the model in response to participant comments, for instance updating the approach used to estimate overland flows. Moreover, the model was built to be usable and changeable. The code used Visual Basic and Excel, both fairly easy-to-learn platforms. The consultants tried "to make [the model] as dynamic as possible" by including few numbers directly in the code, instead providing Graphical User Interfaces for stakeholders to create and test scenarios themselves by entering different values for model input parameters.

The collaboratively-built Golden model became the central hub for negotiating potential management regimes, as almost every decision relating to water use went through the model. This included brainstorming ideas to bracket the range of potential operating regimes, refining the nuances of a specific potential operating regime, and comparing competing proposals. While some ideas tested through the model had broad support among the stakeholders and others were controversial, almost all ideas went through the model. The general format was that the utility or the agency/NGO caucus developed a proposal, the consultants modeled that proposal, and then the group met to discuss the model results. For instance, the resource agencies, drawing on other studies conducted during the relicensing, identified springtime snowmelt as strongly influencing riparian habitat in the upper river. To bracket the range of possible management approaches, they requested a model run that stopped all springtime diversions so all spring runoff stayed in the river. After viewing the impact of that "extreme" approach, the group refined the proposal to target specific resources when they were most critical (e.g., to have adequate flows while fish were spawning) and minimize impacts on power generation and water supply.

The Platinum Dam relicensing represented a consultative approach to model development. Like Golden Dam, an engineering consultant built the Platinum operations model. The model was built in Excel for accessibility and distributed to stakeholders on a CD. However, model development entailed far less two-way interaction. The utility held four public meetings during model development and two training sessions on running the model. At these meetings, the consulting team shared the status of the model and the data underlying it, but stakeholder feedback did not lead to changes in the model. There also was minimal dialogue leading to mutual understanding about topics stakeholders and the modeling team disagreed on (which was strikingly different from the Golden case).

In Platinum, there was no evidence that the models were used since they were completed. As of this writing, consultants had not received requests to run the model, nor did stakeholders report using them. The model therefore has not influenced either individual or collaborative decision-making.

It is impossible to confirm whether the collaborative model development process was the primary cause of these extreme differences in the models' use during each process—one in which the model is a central tool for decision-making and the second where it plays no role. However, there are few plausible reasons why stakeholders in Platinum would not use the model beyond their not trusting the data or not believing it to be useful. Platinum stakeholders had to make the same types of decisions as stakeholders in Golden, were equally technically sophisticated (both groups include trained hydrologists, engineers, and biologists), and equally reliant on "science." One would therefore expect people to have used the model since it was designed to provide information they needed—the fact that they did not is surprising.[4]

Why were the two models used so differently? In the following sections, I argue that it revolves around the models' salience and credibility, which were built through the collaborative modeling process and the broader collaborative context in which the models were used.

3.2. Collaborative Development Enabled Trust in the Models and Trust in the Modelers

Trust is a likely factor underlying the collaborative model's frequent use. In Golden, participants trusted the model and the modelers. No one questioned the fundamental assumptions or results provided by the model, nor did they question the intentions or integrity of the modelers. As one NGO participant stated, "It's amazing how much less effort it is for me because I know that they're going to do a good job. It's going to be good information that I can trust. That makes a huge difference." In other words, the model was held to be an "authoritative data source" by all stakeholders (Cravens and Ardoin, 2016).

To get to this level of trust required a slow, iterative process for all stakeholders to learn about the model. Sometimes the Golden model changed because of these efforts, for instance when stakeholders observed that the model was consistently underestimating high temperatures. At other times the group's dialogue would settle that a change was unnecessary—but the stakeholders needed to deliberate for everyone to understand that decision. The modelers in Golden came to understand that they needed this slow process to ensure that everyone was on board with the assumptions (i.e., to maintain the model's credibility). As one modeler said,

> "The relicensing participants seemed to scrutinize [the input hydrology data] closer than we expected. Again, maybe part of that was on our side having gone through it before and … we in real-time operations planning had reviewed the hydrology pretty closely. We had a pretty good idea of, okay, well, this is a as-

[4] This could also reflect the differences in overall collaborative dynamics between the two cases. The pattern of one-way exchange that led to the more consultation-driven model development could have also influence the lack of model use.

> good-as-it's-gonna-get data set. Once we crossed we were pretty satisfied with that. Then it took a lot more convincing to get everyone else onboard with this… The relicensing participants actually went in and were tweaking on a monthly basis some of the scaling factors for different watersheds… Going through that was—that surprised me they did that. I don't blame the relicensing participants for wanting to feel comfortable with the data itself. One of the big challenges and benefits in the modeling is that in a lot of ways once you establish that both the model itself is doing what people want and that the inputs are correct then you stop talking about that. Now you got your focus on the output."

In Platinum, the lead modeler also understood the importance of trust: "I take my role as trying to be trustworthy, a fair broker to everyone on the thing… [T]o me, the most important thing is people to have trust that the person is putting this together, and that there should not be a mystery of the modeling." Despite this recognition, the stakeholders never indicated the same level of trust as in Golden. For instance, a state agency representative questioned the consultant's approach to validating the model, noting that he would prefer to see that the base cases matched the complete project history, rather than a limited subset of years. The consultant replied that he chose the approach because the project operators changed their decision rules in recent years, so "history" was no longer representative of current operations—a valid point. However, instead of working to make sure everyone was comfortable with the assumption, the consultant continued, "We're not going to debate what the base case is… This is the base case that the districts accept as depicting operations," shutting down further dialogue. In this example, the agency representative clearly had a sense of unease with the model assumptions, but the consultant did nothing to assuage this; he instead 'built trust' by claiming expert status.

The difference between these two cases – one where stakeholders fundamentally trusted the model and another with less buy-in – was the dialogue process and slow iteration for stakeholders to understand and therefore accept the model and underlying data.

3.3. Collaboratively-Built Model Was Designed to Directly Test Management Questions

Golden's collaboratively-built model was also more directly useful for addressing management questions surrounding the hydropower project's operation compared to Platinum's. While both models were highly tailored to the specific hydrological and hydraulic setting—the consultants in both cases had worked in those watersheds for many years prior to the relicensing process—the dialogue during Golden's model development meant the operations model was more tailored to address the specific management questions stakeholders wanted to explore. In the Golden operations model, most operating assumptions were coded as parameters, providing a dial to test different management approaches. When a factor was initially hard coded but a stakeholder had an idea that would change that parameter, the modelers would update the model and soft-code the parameter. For instance, when the utility decided to investigate installing a new lower level flood control outlet on the dam, the modelers created a new model parameter enabling outflow at the proposed height of the outlet. The modelers also created many flexible visualization capacities, making it easy to compare results across different management regimes. For instance, they created a flag for different operating rules so stakeholders could see what rule (e.g., a minimum flow requirement, a recession ramp down, or natural inflow) was driving flows at any given time.

The Golden model was thus extremely salient (Cash et al., 2003) and directly supported decisions resource managers were making. In meetings, stakeholders repeatedly thanked the consultants for how useful the model was for understanding the implications of their decisions. Agencies called the model "a great tool," and an NGO participant, who had engaged in dozens of relicensings over his career, said the operations model was "the most versatile, most sophisticated" of any models he's seen in a relicensing.

The lead modeler liked having built such a salient tool:

> Using the tools we have to evaluate the different processes … has been very illustrative of some of the operational challenges that go on with real-time operations. Conversely, it's been very rewarding to see that the modeling tools we developed have been robust enough to hold up and be able to support a lot of

> those types of analyses. Not to say that there aren't tweaks we have to do to make this, but that the base tenets, the models are still there.

Indeed, the modeling team would have used different visualizations given their training, but altered how they presented information to suit the stakeholders' preference: "More often than not we don't do a whole lot of prep other than at this point [than] just looking at the [time series]… That seems to be what people are comfortable with."

In contrast, the stakeholders felt the Platinum model's logic did not intuitively match management decisions they would like to test. They felt it was "complicated" and had too many output parameters—they just wanted reservoir storage, flow, and power generation (much like the Golden model). Moreover, many parameters were hard coded into the model, making it much harder to test out management ideas that fundamentally changed the project or its operations. For example, at a meeting designed to train stakeholders on using the model, the lead modeler demonstrated how to test higher instream flows. However, just changing the flow requirements "broke" the model, as it drew down the reservoir too quickly. The modeler then took water from many other sources (e.g., reducing canal diversions, increasing inflows from upstream) to make the model run. Thus, the model could not easily compare a single operational change (low vs. high instream flow requirements). Finally, there were only four "knobs" to adjust soft-coded parameters; the modeler said he could "translate other requests [beyond those parameters] into those knobs," but that made it more difficult to decipher the direct effect of an operational change. These all made the model less intuitive to test management options.

3.4. Stakeholders Perceived Many Benefits of Collaborative Model Use for Decision-Making

A final factor underlying the Golden model's frequent use is the many benefits stakeholders reported from collaborative modeling. The stakeholders in Golden saw the benefit of using the model as the basis of negotiations, as it helped the group to identify points of controversy:

> "the modeling I think helps a lot and [the group has] been really pretty good at identifying where their real difficult points are so that we could just—we didn't have this whole thing we could just kind of focus on these little pieces and try to resolve those." (USFS1)

Identifying what people's interests are and where they diverge is an important steps in enabling interest-based negotiation (Fisher et al., 2011) and principled engagement (Emerson and Nabatchi, 2015), as it allows stakeholders to build more mutually beneficial decisions and to prioritize where to focus energy in negotiations.

The models also allowed stakeholders to have a joint mental framework to compare different proposals. The model "facts" were agreed upon and shared among the group—for example, everyone could see that a given approach reduced power generation by a certain percentage. As one agency participant noted:

> "[O]verall the collaboration from the technical aspect, refining the studies, has been pretty beneficial. Even with the results that are being presented. You have that exchange of here's what we saw in the data, then you can get, through the collaboration process, other people can come forward and say, "Did you look at the data this way? Because this is what we're seeing." (State2)

For this participant, viewing the model results as a group enabled dialogue about how to manage the system. The model results thus were the baseline from which they could negotiate the individual values associated with tradeoffs they were making, e.g., whether this much loss of power is worth this much gain in fish habitat.[5]

The Golden model also enabled *what if* thinking, not just the testing of concrete management options. Brainstorming enables people to come up with better alternatives of management options (Cravens, 2016; Jakeman et al., 2006; Morisette et al., 2017). The Golden model was built for brainstorming and wild-idea thinking because there were few fixed constraints build into the model. Only boundary conditions like inflow to the system and external

[5] It's important to note that this reliance on the model as a shared framework for negotiation relies strongly on the trust developed through the collaborative modeling process. See Cravens and Ardoin (2016) for a similar discussion on the interplay between trust and shared use of a model.

temperature—things that people cannot not manage—were fixed as hard codes. Everything else was on the table to be tweaked, from altering water supply deliveries to completely re-operating the dam and tunnels, because it was soft-coded as a parameter. The hard-coding of the Platinum model, in contrast, limited generative thinking (had it been used in a group context) and signified a fixed view of how the dam should operate and of the range of possible management approaches.

Interestingly, the Platinum stakeholders demonstrated that they had the potential for creative group decision-making early in their approach to developing a fish population model (not the operations model). The consulting firm developed a broad conceptual model of factors affecting each life stage of steelhead and fall-run Chinook, which they then brought to the group for confirmation. The consultants had been unable to locate information detailing how many of the parameters affected salmonid survival, so the consultation meeting functioned as a group literature review. The head consultant would ask about the effects of water temperature on Chinook spawning (for example), and agency and NGO biologists would share relevant citations and what they knew about each piece. Stakeholders also took the opportunity to suggest parameters they thought were missing from the model. The consultants then compiled this information into an expanded conceptual model, distributed to participants via email.

However, this was a one-off meeting. All future engagements around developing the fish model followed the unidirectional flow of information like that in the operations model, and like the operations model, the fish population model had not been used or requested by any stakeholders as of this writing.

4. Discussion

This study has assessed the collaborative development of decision-support models in water resources management. Comparison of a collaboratively-built model with a consultant-built model with consultation reveals that the collaboratively-developed model was perceived as more credible and salient by decision-makers. As a trustworthy, "authoritative" data source, it served as the basis for most decisions negotiated by the collaborative group. It was salient, as the collaborative design process meant it directly addressed the questions and concerns held by resource managers and other stakeholders. Thus, the collaborative development of water management models appears to support enhanced use of science by decision-makers.

This study suggests a strong interplay between a model's salience and credibility. The process of designing and tweaking the Golden model, including dialogue to bring everyone onto the same page and adapting the model to address what stakeholders wanted, helped build the stakeholders' trust in the data. At the same time, trust in the model was necessary for stakeholders to use the model as centrally in testing management regimes. In other words, building salience helped build credibility, and credibility was necessary for salience to matter.

Because the two cases varied substantially both in overall collaboration and collaborative model development, it is hard to disentangle what collaborative model development was responsible for versus collaboration overall. However, given the centrality of the Golden operations model for most decisions compared to the complete non-use in Platinum, it's hard to conclude that collaborative model development has no effect. Developing the Golden model collaboratively—along with the broader context supporting that collaboration—helped the modelers adapt the model to answer real management question and build trust in the data and understanding of the model's assumptions and limitations in a way that the Golden process did not.

While a full analysis of why the two cases were so different is beyond the scope of this paper, these cases highlight the importance of the modelers in supporting collaboration. In both cases the modelers were embedded in the process, with more direct engagement than a hired consultant or modeler that creates an entire package for decision-makers to consume. However, in Golden, the lead consultants regularly adjusted the models in response to stakeholder needs or questions and developed visualizations and ways for people to understand the models; in Platinum, the exchange was one way, with the modeler telling people how the model worked but not adjusting the model or tools to visualize outputs in response to feedback. Interestingly, the modelers in both cases *said* they were doing collaboration, as in interviews, both used the term "collaborative modeling" without prompting from the interviewer. However, the Platinum modeler saw his job as education—"I think our process has been very much open to any training they need, anytime. I enjoy teaching, or sharing, whatever you wanna call it… helping people understand what is in my side of the equation or my tools."—a more unidirectional activity. The lead Golden modeler recognized that it would be more of a "dynamic" process with two-way exchange; the model had gone through over 50 iterations during its development and use by the stakeholders, and they built the model to be small and easy-to-update knowing that it would go through these changes.

The modelers also needed support of the utilities and the other stakeholders. In Golden, individuals on both the consulting team and the stakeholder group had substantial experience in traditional modeling approaches and found that it was not useful, leading to their desire to develop models collaboratively. In Platinum, the modeling process started with debate over whether to even build the model. The utility did not originally propose to build an operations model, but it was requested by numerous conservation groups, state and federal agencies, and a local farm bureau, so the utility added it to the final study proposal. Stakeholders then requested many changes to the utility's proposed model, including the model platform: agencies and NGOs wanted to use HEC-ResSim, a frequently used platform, because it was more "sophisticated" than the utility's proposed Excel. The CDFW and multiple conservation NGOs participating in the Platinum relicensing also requested an open process to develop the hydrology database, with more consultation than the utility proposed. In response, the utility wrote,

> "*The [Dam Owners] are not certain what CDFW intends by the phrase 'collaborative process'*…. The study plan specifically provides for ongoing cooperation and consultation… It is the belief of the [Owners] that it is more efficient for the [Owners] to develop the initial packages of hydrology and model logic… prior to meeting with RPs [Relicensing Participants]." (emphasis added)

This and many other stakeholder requests were not incorporated into the final study plan. This dialogue suggests that the parties lacked agreement about what kind of model development process the relicensing would entail, and that the utility saw collaborative model development as an obstruction—not aid—to decision-making. Thus, prior experience and the willingness of the utility (the convener of the relicensing) were key factors leading to more engaged collaborative modeling.

This analysis also offers insights into when and where collaborative model development is likely to be most effective. First, in both cases, the stakeholder group was highly technically trained, with most participants (both resource agencies and NGOs) having graduate training in either hydrology, ecology, or economics. In a setting with less technically-oriented participants, collaborative model development could be substantially more challenging as it would take more support to educate stakeholders to where they could understand the model. Second, this process entailed a concrete management decision, rather than ongoing operations. The challenge of sustaining engagement in collaborative processes over time has long been recognized in the collaboration literature (Weber, 2009), so having a discrete task is perhaps easier than constantly using and adapting these models over the lifespan of a license. Finally, many of the benefits of collaborative development appear to have come from active participation in the development process. In a longer term process, stakeholders drop out over time and/or are replaced by others from their organization. While the model would still be salient for decision-makers, bringing new participants on board to trust the model could be difficult.

By focusing on the development (rather than just the use) of a collaborative decision-support model, this research reframes modeling as iterative process rather than the model as the end result. Much existing research on collaborative and participatory modeling for sustainability brackets the process: stakeholders help frame what they want the model to do, and then modelers build the model, and then stakeholders use the model with support from the modelers for decision-making (Arkema et al., 2015). In Golden, model development was an ongoing process. The model structure, input data, and verification was developed iteratively with stakeholders, and even after the model was "done" it was continually evolving to meet stakeholder needs. This suggests that for truly effective collaborative science, interaction between scientists and decision makers needs to be ongoing.

Acknowledgements

The author wishes to thank the participants in the Golden and Platinum relicensings for sharing their time, expertise, and generosity in letting me observe their interactions for so many years; R. Matthew, R. Nelson, and A. Siders for thoughtful feedback on the manuscript; and A. Cravens for so many insights in the many iterations of this project. Research travel was supported by grants from the Stanford Center for International Conflict and Negotiation, the School of Earth, Energy, & Environmental Sciences, and the Emmett Interdisciplinary Program in Environment and Resources at Stanford University. Interview transcription was funded by the School of Social Ecology at UC Irvine.

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