Teaching top-down modeling to bottom-up thinkers: A report from the initial phase of a collaborative watershed-modeling project

Melanie Thornton, Liz Allen, and Allyson Beall
Washington State University

Abstract: Conducting environmental research that is relevant to the needs of decision makers is an increasingly important goal for academic institutions. There is great potential to develop decision-relevant outputs by integrating process-based watershed models with local expertise in collaborative system dynamics models. This paper reports on a workshop held to teach process-based modelers working on an interdisciplinary regional modeling project about the potential for representing hydrologic and socioeconomic conditions using a system dynamics model. A revised version of the Idagon, a classic watershed system dynamics model, was employed to demonstrate to researchers how collaborative watershed modeling with stakeholders will be carried out. We collected information about technical modelers' perceptions of system dynamics before and after the workshop. We found that even scientists who have a passing familiarity with system dynamics approaches benefited from a refresher training session and thoughtful discussion of the applications and limitations of system dynamics modeling. Process-based modelers' most prevalent concern about collaborative modeling was related to how uncertainty can be captured and communicated. On the basis of questionnaire responses and group discussion during the system dynamics training, we make recommendations for future efforts to increase collaboration and mutual understanding among process-based (bottom-up) and system dynamics (top-down) modelers.

Key words: Water quality, water quantity, collaborative modeling, process-based modeling, water resource management

1. Introduction:

In environmental management contexts, tools for understanding systems that are accessible to the public are critically important because diverse stakeholder perspectives must be incorporated in decisions about natural resource management (Beall and Ford, 2011). Collaborative modeling, or CM, is a methodology based on developing a common language to integrate technical scientific information with local knowledge and expertise in simulation models (van den Belt, 2004). Models can play an important role in problem definition and evaluation of potential management practices or policy alternatives. The process of building a collaborative model helps stakeholders clarify their own mental models and gain a better understanding of relationships and interconnections in a system.

System dynamics modeling promotes exploration of connections and feedbacks, as opposed to studying discrete components of a system from within the confines of traditional disciplinary boundaries (Forrester, 1961). Using system dynamics in collaborative modeling processes has been shown to be effective for developing policy scenarios (van den Belt, 2004; Vennix, 1996; Beall and Ford, 2011). Models may create a space for identifying consensus-based solutions to environmental problems. Collaborative processes rely upon shared information for the purposes of problem identification, education, increased trust and buy-in from local stakeholders (Cormick et al., 1996; Beierle and Konisky, 2000; Brick, 2001; Beall, 2004).

While integrated process-based models are valuable from a technical academic research perspective, they are limited in terms of their utility for education and exploration of potential impacts of management decisions. Process-based models are too computationally demanding to use in a collaborative modeling context, where models are run during public meetings with scenarios generated by stakeholders. System dynamics modelers and process-based modelers typically approach scientific questions and problems in very different manners. Process-based models are based on understanding the physical, chemical, geological, and biological events using mathematical descriptions and equations. System dynamics models take a top-down perspective, focusing on feedbacks and connections between components while process-based models are built from the bottom-up and mechanistic in their representation of system components. For example, the process-based model MODFLOW[1] is used to simulate the flow of groundwater through aquifers, and NEWS[2] is a spatially explicit, global nutrient export model that simulates how nutrients are transported in rivers. Exploring and understanding the differences between system dynamics and process-based modeling approaches will support improved interdisciplinary collaboration and development of collaborative models that are relevant to the needs of stakeholders.

2. Background:

2.1 WISDM

Watershed Integrated System Dynamics Modeling (WISDM) is a USDA funded grant that integrates existing widely applied process-based models such as MODFLOW and NEWS, described above, into an interdisciplinary framework to address issues related to water resource sustainability. The WISDM project involves hydrologists, environmental engineers specializing in process-based modeling, environmental scientists, atmospheric chemists and economists. WISDM will apply technical information from an integrated computationally intensive process-based model, called BioEarth, into a user-friendly system dynamics model within a collaborative modeling framework. The collaborative modeling process will work iteratively with a diverse group of stakeholders, including agency representatives, policy decision-makers and biophysical scientists, to create web-based simulation models of issues relevant to urban and agricultural systems. Scenarios will be designed with stakeholders to ensure that information is relevant to their specific needs and questions. The CM process will feed stakeholders' scenarios, needs and questions back to BioEarth to further refine the linked model.

There are numerous potential challenges associated with carrying out a project that brings together modelers who have diverse training and expertise. Process-based modelers typically use an already existing model to answer a specific scientific question (bottom-up), where as system dynamics modelers develop a model to better understand

---

[1] MODFLOW stands for Modular Three-Dimensional Finite-Difference Groundwater Flow Model

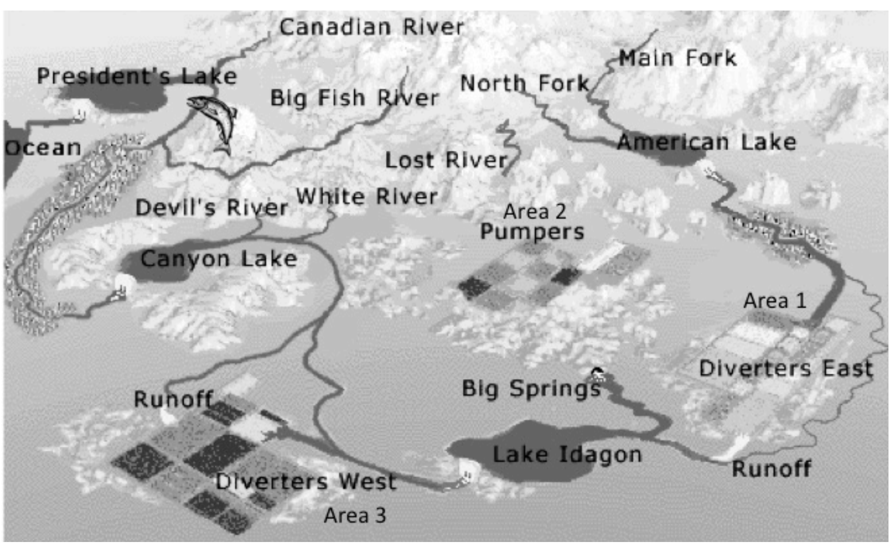
[2] NEWS stands for Nutrient Export from Watersheds

and represent the system of the scientific question (top-down). Despite potential challenges, this is a much-needed area of research. In order to make better resource management decisions, system dynamics models that integrate information from complex technical models are essential (Weaver et al., 2013)

IDAGON

The Idagon[3] is a system dynamics model of an invented watershed, similar to the Snake River basin in the Northwest region of the United States (Figure 1). The model simulates the annual flows in the Snake River at key points of interest to agricultural producers, environmental groups and the electric power industry (Ford, 1996). The model represents issues associated with junior water rights, declining water tables and low in-stream flows at points in the river where high flows are important for wildlife. The Idagon was designed to allow individuals to experiment with different policies related to reservoir operation, land development, land fallowing, and irrigation efficiency. Ford's classic model was developed in partnership with Idaho National Lab and the Rocky Mountain Water Research Institute. The Idagon can be thought of as natural resource science's version of the Beer Game (Ford, 1996).

We presented the Idagon model to a group of process-based modelers, economic modelers and environmental engineering graduate students with the goal of initiating a conversation about how process-based models can be used within a system dynamics framework. The goal of the training session was to increase mutual understanding of how biogeochemical and economic models could be integrated into collaborative modeling framework. The system dynamics training session also served as a forum for process-based modelers to communicate about any uncertainties or hesitations they felt related to using a system dynamics platform in the WISDM project.



[3] More information about the Idagon can be found at http://public.wsu.edu/~forda/AAIda.html. The Idagon model is available to download at http://public.wsu.edu/~forda/downida.html.

Figure 1: Schematic of the Idagon watershed. Areas 1-3 are agricultural regions. Hydropower stations are located at the outflows of American Lake, Lake Idagon, Canyon Lake, and President's Lake.

3. Running Simulations and Capturing "Ah-ha" Moments

In order to educate process-based modelers about system dynamics models and assess their perceptions about the utility of watershed models that take a systems approach, we carried out a brief (1.5 hour) training session about the capabilities of the Idagon system dynamics model. We conducted a survey before and after the training session (Appendix A). Detailed notes on the discussion among scientists and graduate students from process-based modeling backgrounds and system dynamics modeling backgrounds were recorded. During the meeting, we presented decision-making simulations to achieve management objectives in the Idagon watershed and demonstrated how delays and complex feedback processes can be visualized using system dynamics software.

3.1 Pre-Training Questionnaire

Among the 12 training participants, 9 people reported being familiar with system dynamics, another 3 stated that they were "a little bit" familiar. In the anonymous pre-meeting survey, participants were asked to describe system dynamics in a few words (Appendix B). The definitions supplied by participants reflect general familiarity with the concept of stocks and flows, and a perception that the strength of system dynamics modeling lies in it's ability to reflect interconnections between components of a system and feedback loops. A number of participants expanded on their initial definition of system dynamics, adding text to their questionnaires during the training session. This suggests that by listening to a description of system dynamics meeting participants acquired new information and developed a deeper understanding of the field.

3.2 Simulations

Following an overview of how system dynamics models may be applied, the steps in building a system dynamics model, and applications of collaborative modeling for water planning and management, the training session transitioned to focus on the Idagon watershed model. Simulations were run to explore how policy decisions seeking to increase regional economic productivity could lead to changes in long-term water availability. In the first simulation, participants were asked to imagine their primary goal was to increase agricultural productivity and maintain instream flows for fish habitat. We modeled a scenario of lining agricultural canals to increase irrigation efficiency. In the short term, this management practice allowed more land to be irrigated for agriculture and in-stream water availability was maintained. However, over a 40-year simulation groundwater levels declined due to reduced leakage from the irrigation canals. In this simulation, the model shows significantly reduced outflow at the groundwater-fed Big Springs, thus decreasing the water level in Lake Idagon (Figure 2).

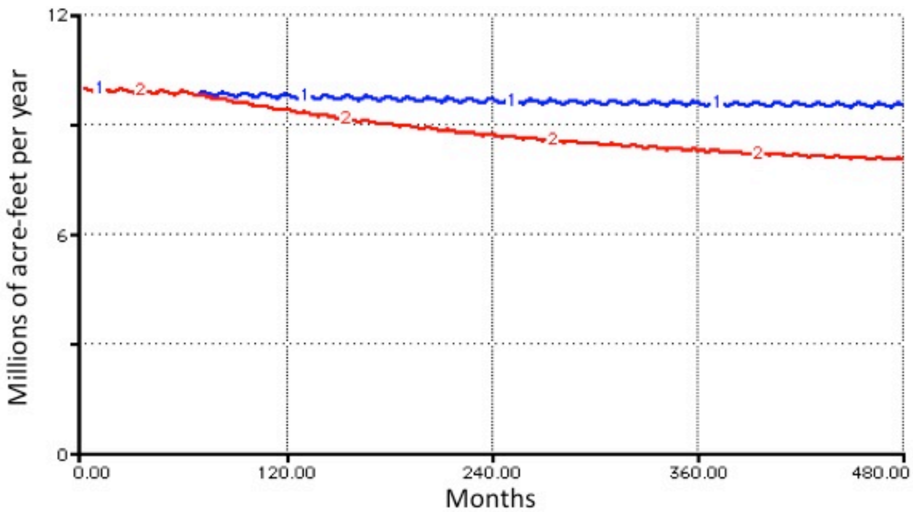


Figure 2: Groundwater discharge at Big Springs. Line 1 (blue) represents Big Springs discharge with no modifications to the model. Line 2 (red) represents Big Springs discharge when increased efficiency of irrigation canals is simulated.

In the second simulation, participants were asked to suppose their primary goal was to increase the total economic productivity in the Idagon River watershed; this is based on combined income from agricultural areas and hydroelectric power generation. We modeled a decision to increase the amount of irrigated land by 30% for 10 years. This management change increased crop revenues and hydropower generation, but caused a sudden decline in Lake Idagon storage. Then we simulated a new policy to maintain some of the gains in economic productivity without jeopardizing Lake Idagon. A policy to fallow 10% of the land each year conserves some water and allows soil moisture and nutrients to accumulate (Figure 3). Running the fallowing policy for 10 years was sufficient to restore water levels in Lake Idagon and increase total economic product from the initial "business as usual" scenario.

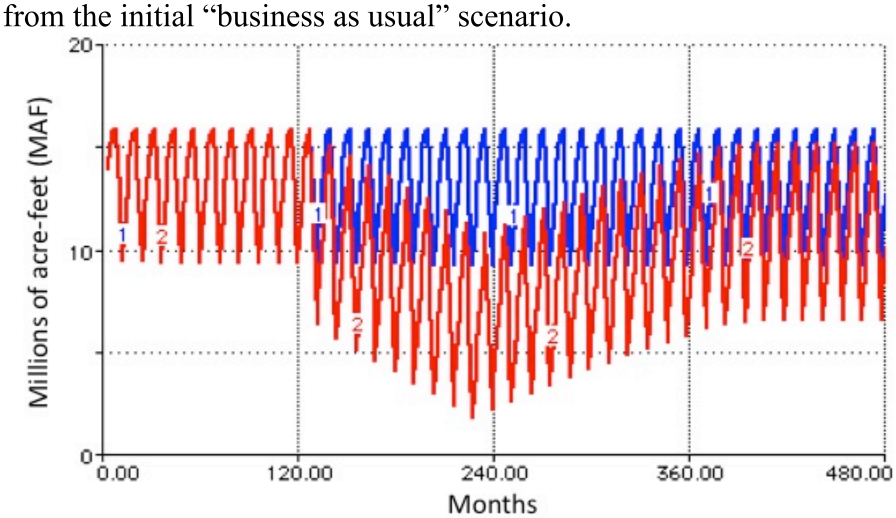


Figure 3: Water stored in Lake Idagon. Line 1 (blue) represents Lake Idagon water levels with no modifications to the model. Line 2 (red) represents Lake Idagon water levels with an increase in agricultural land and a fallowing policy simulated.

3.3 "Ah-ha" Moments

Looking at the modeled Lake Idagon water level, a hydrologist from the research team asked where inputs to the lake were coming from and how certain modelers could be that those modeled inputs were plausible in the real world. In the simulation, water in Lake Idagon was declining because agricultural production had expanded. To the scientist who asked the question and other process-based modelers in the room, these flows seemed arbitrary; they had to be reminded that although the model is a "cartoon" of the Snake River basin, it is not an invented or imaginary system. Real-world relationships between percolation and groundwater are being modeled in the Idagon. For example, groundwater discharge at Big Springs in the model matched the real-world hydrograph at Thousand Springs on the Snake River.

One environmental engineer at the training initially remarked, "Participants should think about entering an avatar world when using a system dynamics model". According to this perception, using a system dynamics model would be a chance to enter an alternate reality and freely experiment with ideas. This view of system dynamics' capabilities assumes a model built from a top-down perspective cannot be a perfect scale model of the world, and that model developers should not make the claim that it provides information about real world conditions. This perception, however, does not acknowledge that system dynamics models like the Idagon can in fact be based on empirical data and or recreate real world behavior.

The fact that the Idagon system dynamics model has its foundation in empirical data raised new questions for the group. Several process-based modelers asked how we could determine whether this model was a good representation of all the interactions in the Snake River basin. They expressed concern that perhaps a model like this might seem prescriptive to stakeholders, but that it is at best an approximate representation of the system not fine-tuned enough to serve as a decision support tool. At this point in the discussion, top-down modelers explained that it was true that a model like the Idagon alone is not a viable decision-support tool, but explained that interacting with a system dynamics model such as this allows people to learn about the system and see possible relationships between actions in one area and outcomes in another part of the system. They also agreed that no one makes resource management decisions on the basis of a model alone, and decision-makers are always synthesizing different sources of information and motives for action.

The discussion about how a watershed model would be used in decision-making highlights a difference in how system dynamics modelers and modelers trained as engineers think of their work. Environmental engineers who develop hydrological models may think their primary objective is to match a model to a real-world process detail-for-detail. Often, model development comes first, and then the developer begins to think about what science question could potentially be explored with their process-based model. System dynamics modelers typically think about what problem or scenario they want to understand in more depth, then look for information about the system at the level of detail necessary to answer the question at hand.

Viewing this simulation, one of the workshop participants remarked that there does seem to be a lot of potential to look at unintended consequences, for example of fallowing 20% as opposed to 30% of an agricultural region; the emphasis on positive and negative feedbacks is educational. The researcher noted that there must be sensitive thresholds at which point a positive or negative feedback loop becomes dominant, which would have dramatic effects for the system. The question that followed was whether adding more exogenous variables to the model would create a model that is a better fit with real-world conditions. At this point system dynamics modelers explained that a principle of system dynamics modeling is that we don't try to force the model with exogenous variables; the relationships of stocks and flows connected within the system should be adequate to simulate the system being studied.

3.4 Post-Training Questionnaire

Following the presentation, we asked participating scientists to reflect on the critical distinctions between system dynamics models and process-based models (Appendix C). Asked if they learned something new about system dynamics or if there was information that was surprising or interesting, 3 people left the space blank, several others noted that there were not any radical changes in their understanding of system dynamics models and their possible applications, but mentioned that having a refresher on key concepts and open ended discussion about applications and limitations was fruitful. Other reactions included surprise at the level of detail in hydrological process that could be represented with system dynamics, the fast processing time and low computational requirements of this modeling framework, and the widespread application of system dynamics models in decision support contexts.

During the discussion, the most prevalent questions and concerns expressed revolved around dealing with uncertainty in models. Participants asked: What if the model gets wrongly applied? How can stakeholders trust a model? And, how can researchers validate a system dynamics model? System dynamics modelers noted that there are different kinds of uncertainty; uncertainty about what may or may not happen, and uncertainty about how well the model fits reality. Dealing with the first type of model uncertainty, future change, is a challenge in process-based and system dynamics models alike. The second kind of uncertainty, fit of the model to the real world, depends on the uncertainty of the inputs. System dynamics models are validated as they are built; there is continual checking for internal consistency of relationships between components. In collaborative modeling, the goal is not to make a model so good it fits the real system exactly, but to be sufficiently accurate to test assumptions about how the system works. The model itself is only one tool for increasing system understanding in the CM process; new knowledge of the system also comes from hearing about other actors' concerns and how they see the big picture.

The final question in the post-training questionnaire asked participants to reflect on what they would like to know moving forward in the WISDM collaborative modeling project (Appendix D). Process-based modelers felt that they need more training about system dynamics and CM to understand what the interface between system dynamics and process-based modelers will look like and how this interaction can benefit stakeholders in the real world. An economist in the group asked if there are instances when a collaborative modeling approach could exacerbate conflict between different interest groups. This reflects a general interest in the research group concerning when collaborative system dynamics modeling should be used. Researchers were concerned with ethical questions inherent in the relationship between academic research and stakeholders, namely, how will participants in the collaborative modeling process interpret information and results from the model and use knowledge gained from the modeling process for resource management decision-making?

3.5 Follow-Up Interviews and Discussion

Individual meetings with four of the WISDM researchers who participated in the initial system dynamics training session were held two months after the training. These meetings provided an opportunity for process-based modelers and researchers who primarily work with empirical data collection to share their concerns about the CM process and the utility and limitations of system dynamics models with graduate student interviewers in an informal, relaxed context. The unstructured interviews provided additional insights into how process-based modelers view challenges associated with integration of process-based and system dynamics models and interdisciplinary collaboration. Goals and expected outcomes of the CM process within WISDM were discussed.

Models are essentially simplifications of reality, and due to the inherent uncertainty and complexity of real systems, it is impossible to create a completely accurate model. One researcher pointed out that our ability to model, or to think about the future in the context of previous observations and expectations, is one of the defining characteristics of our humanity. Researchers frequently explore the relative strengths and limitations of process-based models and system dynamics models in decision-making contexts. One environmental engineer expressed that while system dynamics models have great value as learning tools, they should not be used as stand alone models for decision-making, and thus should not be introduced to stakeholder groups as a "decision support tool". Others were less cautious in their use of the term "decision support tool". In general there was agreement that it would be unwise to use any model as the only tool for making a resource management decision, as models are primarily used to improve people's understanding of the system and evaluate the long-term effects of management decisions and policies. A hydrologist engaged in the project articulated that participating in the model development process and learning about the system facilitates science-based decision-making and better management choices; thus a model can be a valuable tool for decision support, so long as it is combined with other sources of information.

Academic process-based modelers engaged in the WISDM project are hesitant to share model outputs with stakeholders who may have the power to apply information from the model in the real world; this cautious stance is due to close attention to and awareness of model uncertainty on the part of researchers. One atmospheric modeler went so far as to say that it would be more comfortable to do research if there could be assurance that their research would not be used to make decisions with societal implications. They acknowledged that it was important to make science-based decisions, but felt that the uncertainty of atmospheric models is often too great to rely upon for a policy decision. Thus, hesitation to share modeling tools with stakeholders arises because of awareness of model limitations and concern that the end-user may make a decision or base a management strategy on the outputs of the model that is inaccurate. In some respects modelers' caution is justified and prudent, but ultimately it is valuable for academic researchers to recognize that agencies, companies, and governing bodies are always acting on incomplete and imperfect information; and so long as there is transparency about model uncertainty and limitations, increasing the scientific data available to those decision makers will lead to enhanced understanding of systems and better-informed decisions. System dynamics modeling represents a substantial improvement on resource managers' mental models; people cannot do multi-step calculations and think about multiple feedback processes in their heads, but a model makes those elements visual and traceable, allowing consideration of complex relationships.

Researchers who were interviewed agreed that it is necessary to revisit and explore the issue of model uncertainty throughout the project to ensure that assumptions and limitations of both the process-based and system dynamics components of the model are made explicit and well understood by the interdisciplinary research team and participating stakeholders alike. Clear communication about research goals and expected applications of the system dynamics model and the CM process is imperative. While acknowledging that models should be combined with other tools for decision making, there is room for more training to educate the research team about how system dynamics modeling and systems learning can promote evidence-based decision-making and collaboration.

4. Recommendations for further collaboration among bottom-up and top-down modelers

Our interdisciplinary collaboration faces many challenges. Our goal is to create a salient suite of models that compliment and ultimately improve one another and that can be used to help address real world problems faced by our stakeholder group. The WISDM modeling team is made of individuals with very different approaches to research and modeling. Although there is agreement that the primary reason that anyone builds a model is to better understand the world, our process-based modelers and system dynamics modelers frequently have different perceptions about the purpose and goals of modeling. System dynamics modelers begin by looking at the system holistically seeking to see behaviors created by the structure of the system whereas process-based modelers generally utilize first principals to build the world piece by piece from the bottom up. System dynamicists prefer to build new models for each situation whereas process modelers look to apply, improve and link the models they have already developed. All of that being said, the strength of the collaboration is based on the recognition that while there are many opportunities for technical science to inform decision-making, better integration of biophysical research with socioeconomic scenarios is needed to produce decision-relevant model outputs.

Teaching technical modelers about system dynamics is essential for our interdisciplinary research teams. The full research team must have a solid understanding of project goals and how stakeholders will be engaged. Focusing on model strengths throughout the CM process is advised to prevent modelers and stakeholders from becoming overwhelmed by details of model structure and questions of validity to the point that they become distrustful of the process (Winz and Brierley, 2007). Continued system dynamics training is critical for researchers involved in collaborative modeling projects so that they can increase their comfort level with regard to representing uncertainty in system dynamics models. Further training and close collaboration between top-down and bottom-up modelers will yield better incorporation of technical information from process-based models into a system dynamics framework. Use of the Idagon watershed model as a "straw man model" proved to be a useful training tool to demonstrate the capabilities of system dynamics models to fellow researchers and to enter into a discussion about the goals of modeling, how to represent uncertainty, the role of stakeholder engagement, and application of models in decision-making contexts.

As top-down modelers, we will continue to communicate about how uncertainty is represented in system dynamics. Many bottom-up modelers expressed concern about models being inappropriately applied as predictive tools. It is our assessment that if opportunities for process-based modelers to learn about system dynamics are increased, those researchers will develop more confidence in collaborative modeling as a tool to enhance stakeholders' understanding of social and environmental systems. It is also important to communicate that models do not necessarily have to be complex in order to be useful and achieve desired outcomes. A shared language must be developed for modelers from different backgrounds to understand one another's perspectives on concepts such as uncertainty, validity and prediction. Ultimately, close collaboration of stakeholders and researchers from different backgrounds will lead to better models and resource management decisions because the interactions of whole systems and feedback processes are taken into account.

Appendix A. Pre and Post Training Questionnaire

BEFORE THE PRESENTATION:
1) Are you familiar with system dynamics modeling? (YES/NO)
2) In a few words, how would you define system dynamics?

AFTER THE PRESENTATION:
3) Did you learn something new about system dynamics? What, if anything, surprised or interested you?
4) From your perspective, what is the critical distinction between system dynamics models and process-based models?
5) Did this presentation raise any new questions for you? What else would you like to know after seeing the overview of the Idagon watershed model?

Appendix B. Answers from Pre-Training Questionnaire: Question 2

In a few words, how would you define system dynamics?
A tool for modeling dynamics of physics, behavior, etc. Assuming the physical behaviors can be represented by first order differential equations
All components effect system which is always changing, effected by and can affect others
A process that involves intensive interactions among different subsystems
Modeling to understand processes, not predict results
A conceptual framework of stocks and flows that allow the user to link elements and look at relationships/feedbacks
The components in the model have dynamic feedbacks with each other over time
Tool to understand the dynamics of a system by developing stocks, flows and it's interactions
Feedback for individuals to understand system feedbacks and processes
A type of modeling structure that works with stocks and flows and takes into account feedbacks and positive/negative loops
System based stock and flow to answer a set of questions
Stocks and flows as influenced by decisions
A way of modeling systems that captures all of the feedbacks in the system, simple, not very process based, efficient

Appendix C. Answers from Post-Training Questionnaire: Question 4

System Dynamics Models	Process-based Models

User-friendly interface, used to apply basic science and evaluate implications	Used more for basic science
Model must be renewable for all new conditions	
Emphasizes the interactions and feedbacks between subsystems and it's dynamics with time	Emphasizes the process within each sub-model
The end goal is process understanding	The end goal is making predictions or mimicking results from experimental data
Focus on feedbacks	Focus on mechanisms
Involvement of policy, management dynamically	
Feedback lops show connected components	Models addresses just one of the dynamics of a stock at a time
Often presented as hypothetical and not an exact representation of a particular system	
Better for understanding the general themes of the system structure	Used as a predictive tool
Teaching power of the model is important	Getting the process right is important
Focus on decisions/ policies, stakeholder involvement and critique of the model	
Simpler, help run multiple scenarios faster? Maybe they help identify processes that the process based models should focus on modeling better, so a better communication tool	

Appendix D. Answers from Post-Training Questionnaire: Question 5

Did this presentation raise any new questions for you? What else would you like to know after seeing the overview of the Idagon watershed model?
Would like to see more applications of system dynamics modeling, would like know about circumstances in which system dynamics should not be used
Discussion during meeting was fruitful, water-soil quality and economics relationship would be better modeled with this framework
Want to know if the Idagon model can easily be applied in other places and it's flexibility to add new processes
How does building the model work when in a live setting?
New questions about uncertainty
How are the results verified/ validated for historical data?
Explain more about the built in physical dynamics that run behind the model, so that people will understand and credit the backbone of the model
How can you get stakeholders involved when the system is hypothetical?
Uncertainty and how it is dealt with
When does collaborative modeling or system dynamics modeling get used inappropriately? Do they get taken and used to do things (prediction?) they were not meant to do?
What are the interactions between mechanistic models and system dynamics models?
You mention the mass balance check with historical data. The distribution between mass balance components could change over time, which a process based model could capture. So I am wondering how system dynamics captures this for say a future simulation. Is it not assuming the same relative mass balance components as historical?

References

Beall, A. (2004). A Sense of Place: Ecological Values, Ethics and Collaborative Problem Solving in the American West. Masters Thesis. Washington State University, Pullman Washington.

Beall, A. M., & Ford, A. (2010). Reports from the Field: Assessing the Art and Science of Participatory Environmental Modeling. *International Journal of Information Systems and Social Change (IJISSC)*, *1*(2), 72-89.

Beierle, T., and Konisky, D.M. (2000). Values, Conflict and Trust in Participatory Environmental Planning. Journal of Policy Analysis and Management, Vol. 19, No. 4, 587-602.

Brick, P., Snow, D., & Van De Wetering, S. (Eds.). (2001). Across the Great Divide: Explorations in Collaborative Conservation and the American West. Island Press. Washington, D.C., Covelo, California.

Cormick, G., Dale, N., Emond, P., Sigurdson, G., & Stuart, B. (1996). *Building Consensus for a Sustainable Future: Putting Principles into Practice.* National Round Table on the Environment and the Economy. Ottawa, Ontario.

Ford, Andy. (1996). Testing the Snake River Explorer. *System Dynamics Review, 12*(4), 305-329.

Forrester, J. (1961). *Industrial Dynamics*. Pegasus Communications. Waltham, MA.

van den Belt, M. (2000). Mediated Modeling: A collaborative approach for the development of shared understanding and evaluation of environmental policy scenarios, with case studies in the Fox, River, Wisconsin and the Ria Formosa, Portugal. Ph.D. Dissertation, University of Maryland.

Vennix, J. A. M. (1996). *Group Model Building. Facilitating Team Learning Using System Dynamics*. John Wiley and Sons. New York.

Weaver, C. P., Lempert, R. J., Brown, C., Hall, J. A., Revell, D., & Sarewitz, D. (2013). Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews: Climate Change*, *4*(1), 39-60.

Winz, I., & Brierley, G. (2007). The use of system dynamics simulation in integrated water resources management. In *Proceedings of the 25th International Conference of the System Dynamics Society, Boston, Massachusetts, USA, August.*