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Key Points:
- Reported are future directions in participatory modeling as decided by a group of experts
- This paper discusses broad questions of practice, participation, and innovation that can be addressed by researchers from many fields

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Twelve Questions for the Participatory Modeling Community

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Abstract Participatory modeling engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality and has evolved into a field of study as well as a practice. Participatory modeling researchers and practitioners who focus specifically on environmental resources met at the National Socio-Environmental Synthesis Center (SESYNC) in Annapolis, Maryland, over the course of 2 years to discuss the state of the field and future directions for participatory modeling. What follows is a description of 12 overarching groups of questions that could guide future inquiry.

1. Introduction

In this paper, we draw on our collective experience in this area (each person with over 10 years and some up to 30+ years in practice and study) to offer a dozen critical questions that we argue can—and should—guide the continued growth of environmental participatory modeling (hereafter PM) practice and research. Among these dozen queries are context-specific questions, which can guide modelers as they conduct environmental PM interventions, as well as difficult to address, outstanding issues that work in the field has not answered.

Our goal is to establish a research agenda for guiding the future of environmental PM. PM, both a field of study and practice, has grown to integrate the social, natural, and environmental sciences into shared modeling endeavors. This paper represents a call to action for both those seeking to engage the public in earth science research and those seeking to spread the use of PM; addressing these questions will be essential to further developing PM as a useful and mature practice.

Participatory approaches to resource management must involve those who are affected by the decisions that stem from environmental management decisions (Reed et al., 2009). Environmental resource management often requires a combination of descriptive and normative knowledges as well as local capacity for action (and inaction). Because resource users have such knowledge and capacity, local engagement is crucial in PM. However, there are imbricated layers of power between researchers and locals—often with researchers holding the balance of power due to their increased access to social goods such as money, formal education, and prestige. Regardless of researcher intention, this can create cultures of oppression and subversion that are at odds with productive, equitable decision making (Steel & Whyte, 2012). Many participation scholars have highlighted such power struggles (e.g., Cooke & Kothari, 2001; Freire, 2018; Whyte & Crease, 2010). At minimum best practices in participatory research involve researchers virtuously conducting their work with, not on, participants akin to participatory inquiry (Ferkany & Whyte, 2011; Reason, 1994).

Participating scholars have developed several approaches for involving stakeholders in environmental research and decision-making (e.g., participatory rural appraisal, Henman & Chambers, 2001; Participatory Action Research Bryant & White, 1984; or soft systems modeling Checkland, 1999). PM can greatly benefit from these approaches as one way of developing explicit, shared models along the way. Models are abstractions representing the system, and they come in many types; this paper mentions at least physical, mathematical, simulative, and mental models. Models are valuable in environmental governance not only because they are central to science (Magnani et al., 1999) but also because, as some would argue, models are central to human reasoning in general (Johnson-Laird, 1983). Representing ideas through models affords individuals a structured means of explaining not only how we think about the world but also how we make decisions. Explicit, shared models can bridge power dynamics by providing many complementary entry points for epistemic and logistical participation. In this function, models operate as boundary objects facilitating collaboration (Star & Griesemer, 1989). Developing explicit, shared models together through PM can enhance this benefit. Indeed, recent study has shown an increase in the inclusion of those who do not typically externalize models into the scholarly practice of environmental modeling and decision making (Voinov & Bousquet, 2010).

However, including models in participatory resource management can present considerable challenges to participatory approaches because the creation of models as tools for thinking may require certain kinds of technical expertise (Gray et al., 2018). Not only can such expertise be hard to obtain but also, once obtained, it can actually inhibit participation by oppressing other kinds of expertise; the threat of technocracy is ever present (Whyte et al., 2017). PM, therefore, as a field, faces a number of challenges in articulating and implementing best practices. We must engage these challenges not only within the field of PM but also in the geosciences at large. Studies about approaches and tools that facilitate learning, communication, and outcomes of PM are at the core of this field. Recently, the National Socio-Environmental Synthesis Center (SESYNC) funded an interdisciplinary team of biophysical scientists, social scientists, software developers, and PM practitioners to meet and address the process, products, and outcomes associated with PM and its different approaches. Here we focus and reflect on the critical questions that arose and guided our discussions throughout two 3-day meetings.

At the first meeting, all participants were asked through an online survey to name only one question they felt the field of participatory modelers and practitioners needed to consider. These questions were then grouped by a small team and reviewed at the second meeting. Those who did not attend the first meeting were asked to generate additional questions. In total, about 20 individuals contributed to the question list. We chose to take this list and elaborate on these questions. We used a participatory approach to developing this manuscript. We drafted ideas using an online open editing portal where all participants (see list below) were given a set amount of time to contribute. From there, a small team integrated the ideas into this publication.

To begin, we define PM as a purposeful learning process for action that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality. In this process, the participants cocreate the problem statement and use modeling practices to define the descriptions, solutions, and decision-making actions of the group (see Falconi & Palmer, 2017; Voinov & Gaddis, 2008 for examples) PM is often used in environmental management contexts (see Table 1 for hypothetical examples and for a preview of the questions listed below).

We generated 12 groups of questions that the field of PM needs to address. These 12 sets are broken into major categories:

1. Goals and potential synergies and trade-offs;
2. Learning;
3. Translation of the process into action, communication, and accessibility;
4. Broader issues of participation;
5. Scaling.

Table 1
Barriers to PM

Barrier	Description
Spatial/Quantitative reasoning ability is limiting.	A generalized move in U.S. National education away from quantitative, spatial, and complex systems reasoning. Even in relation to GIS, which enjoys widespread use in planning and decision-making circles, its use is often relegated to illustration and description rather than sophisticated spatial analysis (Göçmen & Ventura, 2010; Göçmen, 2013). Emphasis is misplaced on software use, rather than in spatial reasoning with the tool.
Modeling takes time and effort.	The effective use of modeling tools is labor intensive and requires training and sustained effort. All forms of modeling require proper conceptualization (Zellner and Campbell 2015): problem definition, formulation of guiding question, meaningful abstraction, verified coding (when applicable), and relevant testing.
PM is a long-term and iterative process.	A culture of rapid answers and fixes (Hoch et al. 2015; Zellner and Campbell 2015). Participatory modeling is a desirable approach to complex problems, where there are no final answers, and our best hope is for iterative innovation and adaptation. This open-endedness clashes with the impatience of most political settings, and the misplaced expectation that the future is predictable and easily fixable, if only we had enough precise data, accurate models, and enough resources to develop both. We are discouraged from failing because it is not efficient. “One cannot be an efficient innovator; one can be an effective innovator if allowed to fail and try again” (Zellner and Campbell 2015). This, however, takes more time than many communities are willing to wait. Paradoxically, rapid fixes are in most cases superficial and derail communities from a more desirable trajectory. Slowing down can help communities see and make decisions toward such trajectories. At the same time, with global change that affects climate, biodiversity, and numerous resources that are crucial for the Earth life-support system, in some cases we run out of options for a truly democratic and all-inclusive process. Certain decisions should be made quickly and it is not always obvious that an expert driven decision is inferior to a democratic, stakeholder backed process.

Note. PM = participatory modeling.

Below, we briefly discuss our perspectives on the state of the art in PM, highlighting possible future directions for the field and practice of PM. We conclude with a call to action for current and future PM researchers and practitioners.

2. Twelve Questions

2.1. Goals and Synergies

1. What are current and emerging goals of PM? Why are we engaging in PM? With these goals in mind, how can we improve PM? Furthermore, how can we better communicate with stakeholders in an effort to create more innovation in PM?

The popularity of environmental modeling with stakeholders has grown considerably in recent years. It has been spurred by the assumption that including stakeholders and a wide variety of scientific perspectives is required to improve our understanding of social-ecological systems and current environmental problems. As Voinov and Bousquet (2010) point out, “Stakeholder engagement, collaboration, or participation, shared learning or fact-finding, have become buzzwords and hardly any environmental assessment or modeling effort today can be presented without some kind of reference to stakeholders and their involvement in the process” (p. 1268). They go on to identify two major objectives that drive environmental modeling with stakeholders: (1) to increase and share knowledge and understanding of a system and its dynamics under various conditions, and (2) to identify and clarify the impacts of solutions to a given problem. With these objectives, however, come more questions and contexts, which require us to consider goals and opportunities in greater detail.

Currently, a wide range of stakeholder-centered modeling programs and practices exist, which all essentially aim to provide facilitation in participatory management contexts and ultimately support for decision making. Other goals may also be relevant. For example, as the field of PM becomes more mainstream, important questions arise such as: who is communicating what, why are they doing that, and who is expected to learn or change a decision because of a model. These questions are not easily answered and are rarely explicitly reported in the literature. As technology rapidly develops, new areas become available for PM applications. For example, it is still unclear how social media can be best used to expand and improve the PM experience. As we grapple with the questions below, defining goals and benefits of PM and of each PM application is essential.

2. How do you facilitate movement and synergy of ideas across different types of models? And where does this fit in the transdisciplinary continuum? How do we accommodate the mechanisms that vary at different social and biophysical scales and how can these mechanisms work across scales?

There are numerous modeling methods applied in the process of PM. Many tools and approaches have been developed to meet particular needs within the PM process (Voinov et al., 2016), and the perspectives engendered and outcomes generated may differ as a result of the applied methodologies. The technical complexity of the systems being modeled, the complexity of the tools and approaches used, and the complexities of the human and technological interactions in the PM processes may negatively affect PM outcomes. Complexity may affect the process at least in two ways. First, some of the easier to use modeling methods (e.g., Fuzzy Cognitive Mapping) may not handle the level of complexity necessary for a particular problem, making it necessary to turn to other tools (e.g., integrated models) (Giabbanelli, 2014). However, when trying to integrate models created for subsystems, managing complexity over the entire system is more difficult, especially when we have to deal with models built at different spatiotemporal and complexity scales (Voinov & Shugart, 2013). Second, models may represent well some types of information or dimensions of reality, but do poorly for others. This has often been explored in the domain of information representation: for example, how to connect different models operating on different clocks (e.g., a time step in one model stands for 5 days whereas it represents 7 days in another model). With this, additional sensitivity issues may arise, because now the results are impacted by the frequency and type of information exchange between the component models (Belete & Voinov, 2016). In contrast, however, there has not been much work conducted on how to connect, reconcile, and integrate the use and outputs of radically different PM approaches, qualitative and quantitative, for dimensions specific to the PM process and its users. For example, if a modeling tool was found supportive of learning by stakeholders, and another one provided well-calibrated and accurate simulation results but was not transparent and hard to communicate to stakeholders, how can these two tools and processes be integrated so that they best support each other and the ultimate goals of the PM process?

Further, besides integration of computer models, we may often require integration of mental models (i.e., cognitive representations) of individuals, often from multiple disciplines (Lavin et al., 2018). This integration requires that stakeholders not only discuss the issues but also work to find means of knowledge generation and communication that is transdisciplinary and that involves stakeholders from outside of academia. Exchanges between heterogeneous groups of stakeholders can take several forms (Choi & Pak, 2006) ranging from multidisciplinary (where knowledge is shared but stakeholders stay within their boundaries) to transdisciplinary (where the synthesis of knowledge transcends traditional boundaries). The selection of modeling types thus impacts our positioning in the transdisciplinary continuum. Efforts to facilitate synthesis and manage uncertainty could greatly improve researcher and stakeholder ability to use models across broader applications.

2.2. Learning

3. How can we better measure learning in and through the PM process, and how is learning diffused throughout the community/organization or other stakeholders? With this, how is evidence of learning measured and reported?

Learning is an essential outcome of PM exercises. A number of PM studies have attempted to assess the learning that took place throughout the modeling process using surveys, interviews, discourse analysis, and mental model elicitation (Jones et al., 2009; Radinsky et al., 2016). However, tracking learning over the long-term postmodeling process is extraordinarily difficult because of the many confounding factors that affect the ways in which participants conceptualize and reason about a problem. In addition, tracking the diffusion of learning through groups of people who did not take part in the PM exercise, but who may use the output from these exercises or work with those who did, has for the most part not been attempted. There is also a delay factor in appreciating learning: it might take some time to actually realize what was learned. Moreover, how does learning translate into acceptance of what was learned and into action based on what was learned? In spite of these unanswered questions, PM has been demonstrated to help participants understand multiple perspectives on a complex problem, to promote systems thinking, and to improve relationships among participants, which is conducive to future social learning (Hoch et al., 2015; Radinsky et al., 2016; Zellner et al., 2012). Given this potential for additional learning outcomes to be measured and tracked over the course of a PM exercise (and possibly beyond the initial effort), more study is warranted. Such studies could take the form of mental or cultural model assessments (Doyle et al., 1998), as well as research on impacts of PM on beliefs, biases, heuristics, and values (Glynn et al., 2017). The impacts of these learning gains, however, are extremely difficult to ascertain. If there are changes in management practices or policies, can those be traced back to specific instances of learning?

4. How do internal ideas about system processes and functions move to external representations within an individual and among groups? How are the models generated and used during the PM process representative of individual mental and shared cultural models? How do they impact learning; that is, do they cause changes of mental or cultural models during the PM process?

Mental models are internal representations of reality that allow humans to recognize patterns, predict the outcomes of decisions/behaviors, and plan actions without being overcome by the complexity of the real world. They are internally held simplifications of reality that result from lifelong, individual-level learning as people modify their understanding of the world (Jones et al., 2011) and are shaped by, among others, knowledge, first-hand experiences, cultural values, and access to resources. Mental models are held by individuals and are unique and incomplete representations of reality that consist of beliefs and subjective knowledge, rather than objective truths on system realities. Mental models, however, can contain certain system realities because data, process information, and realistic tacit knowledge can be integrated into subjective mental models, albeit often in a simplified manner.

While mental models are deeply personal, groups of people often have partially overlapping mental models as a result of having similar cultural backgrounds and interests, having had similar experiences, or frequently exchanging knowledge and interpretations of data. This, for example, occurs in social groups and among people who collaborate in the workplace. Research on the functioning of teams, including managerial decision teams, show that this partial alignment is important for group decision making and action taking (Johnson-Laird, 1983; Klimoski & Mohammed, 1994; Mohammed et al., 2010). To function well, teams need to share mental models of the task at hand, as well as of the team and its abilities, resources, and division of labor. Similar principles likely also apply to participants in PM projects, though we currently lack a deep understanding about what mental model aspects need to be aligned, and to what extent, to achieve the project's objectives. In particular, we do not know how much disagreement on how the system under study functions can persist without making it impossible for a group to agree on a course of action. We also do not know when joint, collaborative thinking, which can be quite helpful for group dynamics, becomes *group thinking* (Glynn et al., 2018) and turns into an obstacle for critical thinking and effective decision making.

5. What are the major interpretation and communication issues in PM? Are there best practices to address these issues?

Approaches to PM in general are gaining popularity (Gray et al., 2018). However, there is little explicit information or understanding about the interpretation and communication processes that occur as modelers and communities move from narrative descriptions of events into model formalizations, functions, parameters, and back to narrative descriptions. The researcher/facilitator often works to ensure that participants' stories and comments are correctly integrated into the model. This is done through a series of questions, beginning with concept/problem identification, through model formulation and parameterization, and ending with model validation and scenario analysis. Participants are often engaged throughout this process, but how can we improve on these steps to ensure better interpretation and communication throughout the team?

The second issue involves communicating the shared model developed through the PM process and model output back to the participants and to others who might use the model for decision making or policy making. This sort of communication is entirely dependent on the receiving audience. We have found that showing modeling participants the model using the same modeling language used to create it made communication easier. In this manner, participating stakeholders are able to see their personal narratives translated into the model and their personalized narrative structures, which do not need to be elicited in the same manner as the modeler might use. For example, ideas from participants could be derived through art, songs, dance, and other creative forms of communication that might be more appealing to the participants. Such modeling language, however, may be a barrier to communication with others who were not part of the process but are interested in using the results of the PM process.

A communication challenge for modelers using quantitative or other complex models can be knowing to what extent to unpack the *black box*, which is composed of the formalized equations and parameters underlying the model. In our experience, there is a range of desire on the part of stakeholders to *peek* inside this black box. Some have no desire to do so, while others want to question model assumptions and parameters in detail. Participants can become frustrated if the models are not easily comprehensible. User interfaces, model guides, and diagrams depicting model structure and order of operations can help communicate the model to collaborators without a scientific or modeling background. In addition, modelers can collaborate with colleagues from design, science communication, and human-computer interaction fields to better design these elements.

2.3. Translation of the Process into Action, Communication, and Accessibility

6. How can we make PM more accessible to a range of communities? What are the barriers to entry and how can they be lowered?

Despite the promise of empowerment brought by engaging communities in PM, there is a relatively low adoption rate of PM approaches. The costs and time required for PM processes may be compared unfavorably to the costs, time, and effort of outsourcing the analysis to consultants external to the decision-making process (Zellner & Campbell, 2015). We also suspect that the modeling tools present theoretical, methodological, and usability barriers for widespread community use, and contribute to the low adoption rate. Examples of these barriers can be found in Table 1. The goal of community empowerment may not be possible without including technical experts as part of the constituency. This is related to the way that we communicate across expertise, backgrounds, disciplines, and interests. It also requires certain changes in the goals and attitudes of participating modelers and researchers, who may have more responsibility in generating actionable results and more continuity in supporting the stakeholder processes beyond the duration of the initial studies (Voinov et al., 2014; Table 2).

2.4. Broader Issues of Participation

7. How does PM address how a community handles power, advocacy, equity, justice, ethics, and knowledge exploitation? Where do the vulnerabilities exist? Will the PM facilitator (consciously or unconsciously) manipulate the participants to orient the collective decision? How are power asymmetries of different constituencies and participants handled and recorded?

PM seeks to empower a wide range of stakeholders to take part in the decision-making processes that will shape their communities. While there is a set of best practices for participatory planning processes (e.g., Forester, 2012) and a set for modeling (e.g., Jakeman et al., 2006), there are no formal community best practice standards to facilitate PM processes in a fair, transparent, and scientifically sound manner (though efforts are beginning, e.g., Voinov et al., 2014). Thus, these issues are generally handled by the respective group within the institutional guidelines of the organizing party. For example, if the PM project is initiated and run out of a U.S. academic or governmental institution, then the process is subject to the institutional review board (IRB) that is charged to assure that appropriate steps are taken to protect the rights and welfare of humans participating as subjects in a research study. Similarly, if research is funded by the European Commission, it will have to follow the EU's guidelines on gender mainstreaming, ethics guidelines, and data sharing. How these practices are handled varies between countries and institutions, and each PM process and modeling group follows their own rules ideally agreed on at the beginning of the PM process. Clearly within these formal and informal agreements there is considerable variation, with many potential problems to avoid, and different strategies to best deal with emergent issues. There are numerous case studies and a few PM review articles that have been investigating these issues, but these have not been systematically reviewed. Problems that were frequently mentioned by our group include cultural barriers relating to indigenous people, gender discrimination, exclusion from the process or within the process, dominant behavior and views creating biases, groupthink, manipulation, hostility, and unskilled facilitation (Hoch et al., 2015). Best practice recommendations on how to deal with these issues through structured and community-driven facilitation (Hovmand, 2014) are just now emerging based on comparative case study analyses when drawing from the wider literature on participatory environmental research (e.g., de Vente et al., 2016). Applying those best practices, however, puts those that design or facilitate PM in the difficult position of maintaining equity while still taking on the responsibility of guiding the process forward (Barnaud & Van Paassen, 2013). These issues warrant consideration within PM.

Table 2
Twelve Questions Illustrated Through Two PM Examples

Question	Example 1.	Example 2.
Goals and Synergies		
1. What are current and emerging goals of participatory modeling (PM)? Why are we engaging in PM? With these goals in mind, how can we improve PM? Furthermore, how can we better communicate with stakeholders in an effort to create more innovation in PM?	Excess nutrient overload (also known as, eutrophication) in area inlets has caused individuals living in the area to seek assistance from management officials. One of the officials has decided to convene a group to create a simple dynamic model using agent-based modeling software. The official will create this model with input from each individual involved in the process.	An environmental studies professor is asked to facilitate the discussions among multiple stakeholders engaged in a regional watershed conference. The goal of this conference is to generate multiple plausible outcomes based on a finite set of decisions. The professor decides to use a Fuzzy Cognitive Mapping (FCM) approach that solicits inputs from the stakeholders.
2. How do you facilitate movement and synergy of ideas across different types of models? And where does this fit in the transdisciplinary continuum? How do we accommodate the mechanisms that vary at different social and biophysical scales, and how can these mechanisms work across scales?	The official calls together a number of stakeholders and decides to hold meetings every week during evening hours for a month. Some complain because those who work evenings cannot attend. From there, the official plans to share this model with community members via town halls or similar events.	FCM requires that each stakeholder or stakeholder groups create individual conceptual models with a small set of heuristics. Individuals are asked to generate this model at the beginning of the meeting.
Learning		
3. How can we better measure learning in and through the PM process, and how is learning diffused throughout the community/organization or to other stakeholders? With this, how is evidence of learning measured and reported?	During meetings, individuals are encouraged to ask questions. A student doing an internship with the management agency is asked to keep track of the questions in an effort to follow up with participants.	The professor gets permission to record sessions to conduct a discourse analysis on conversations throughout the conference. She intends to measure differences in how individuals describe challenges in management.
4. How do internal ideas about system processes and functions move to external representations within an individual and among groups? How are the models generated by and used during the PM process representative of individual mental and shared cultural models? How do they impact learning; that is, do they cause changes of mental or cultural models during the PM process?	The official is challenged with the task of both helping the modeling group and later the broader community understands the model tools and representations. This involves determining how the representation will be shared and other tools that might be used.	All models are merged into a common model through a discussion of each term in each model, and connections are drawn between model elements. From there using fuzzy set theory and neural network math, scenarios are developed.
5. What are the major interpretation and communication issues in PM? Are there best practices to address these issues?	During this PM process a number of group members become confused as to how the science, the policy, and the multiple plausible decisions intersect.	Some of those at the conference are confused about the math used to create the scenarios.
Translation of the process into action, communication, and accessibility		
6. How can we make PM more accessible to a range of communities? What are the barriers to entry and how can they be lowered?	The final representation is shared with local decision-makers but no further action is taken.	Most at the conference feel that the final representation is inclusive of their views, but they are unsure how to share the final representations with others.
Broader issues of participation		
7. How does PM address how a community handles power, advocacy, equity, justice, ethics, and knowledge exploitation? Where are the vulnerabilities? Will the PM facilitator (consciously or unconsciously) manipulate the participants to orient the collective decision? How are power asymmetries of different constituencies and participants handled and recorded?	A number of those in the town hall meetings are concerned that they were not consulted in the process. A few of those in the initial modeling group are concerned that only a few dominant voices are reflected in the model.	Some individuals arrive at the meeting feeling a bit offended that they were not invited. They learned about the conference from colleagues. Therefore, while they participate in discussion, they were unable to create an initial model.
8. How does PM recognize and possibly counter biases or accommodate differences in beliefs and values among stakeholders?	A few members of the original group feel that the use of the shared model and suitable facilitation processes enabled them to provide their individual ideas in a way that they may have not if only the official created the model. In addition, groupthink and biases are possibly minimized through explicit articulation of possible biases, followed by video training and	Two researchers converse about how uncomfortable they are with a process that relies on qualitative models of expert opinion rather than hard quantitative data. They feel this is not scientific.

Table 2 *(continued)*

Question	Example 1.	Example 2.
	other bias-countering techniques. Participants are asked to explicitly consider what may be missing from their mental constructs and what may be improperly assumed.	
9. How can we harness the capacity of multiple publics to address the needs of an issue or problem? Is there a place for citizen science, for example, as a means to bring members of the public together? What are other means of harnessing the capacities and perspectives of multiple publics?	The creation of the model resulted in some change in management practices, but the official fears it may not be enough. This individual then decides to convene a group of citizen scientists to measure certain changes in water quality.	During the conference, many ask, "Who is not present and why not?" How can they ensure that others join?
Scaling the process and results		
10. How do we scale participation in the modeling process to accommodate multiple goals, and connect multiple scales and sectors of governance, to ultimately impact broader society?	Other communities in the area are facing similar challenges. Some wonder if they could use a similar approach.	At the end of the conference, many realize that they may have the ability to work with their local groups. They ask the professor for tools to share their ideas and models with the government agencies and local volunteer watershed groups that are helping manage watersheds in their region (s).
11. How does PM support planning and decision-making that connect multiple scales and sectors of governance? How can a PM process support the coordination of the activities recommended by the process, with the activities planned by authorities and actors that are not part of the PM process? How can institutional learning be integrated into PM?	While the process resulted in modest local changes to the watershed around the inlet, little has changed in the part of regional policy.	When advocating for improved watershed management within governance structures, the expertise of those who created the model gets called into question.
12. What are key roles and processes involved with PM? What are the constituent elements for best practices in PM? When is social friction productive?	The official who led the process engages in some reflection about how much she directed the process versus allowed the stakeholders to lead. She notes changes to her personal practice for the future.	The professor published the results of the social learning processes that occurred but wonders what else can be done to encourage buy-in to the participatory process.

8. How does PM recognize and possibly counter biases or accommodate differences in beliefs and values among stakeholders?

There are a number of tools to elicit and recognize bias, beliefs, heuristics, and values: especially in qualitative modeling but also in building quantitative models. There are also some tools, such as video or other instruction, and gaming technologies (Barton et al., 2016) that can help researchers recognize biases. Many of the PM tools are formalized to elicit ideas about the decision being made. How can the field of PM pair these formalizations with means to elicit and possibly learn from biases and beliefs? Do measures such as art, role playing, sensory translations, and embodied ways of knowing help? How can conflict be framed to encourage recognition of particular strengths? Furthermore, what is the relationship between individual biases and group/community biases? Understanding these relationships would go a long way toward mitigating issues with translation and may encourage greater public adoption of PM approaches.

9. How can we harness the capacity of multiple publics to meet needs of the issue or problem under consideration? Is there a place for citizen science, for example, as a means to bring members of the public together? What are other means of harnessing the capacity of the public?

One area that has gained recent attention with respect to public action is citizen science. Defined in many ways, we refer here to citizen science as endeavors where persons who do not consider themselves scientific experts work with those who do consider themselves experts to address an authentic research issue or question, or to work on a scientific study. This can be done through hypothesis testing, observation, and model testing, to name a few approaches. PM is one area that may be ripe for a citizen science approach, as modeling is essential to the process of science in that conceptions of reality are posed and tested as a matter of course. Public engagement in modeling could also include citizen science because the engagement of varied publics in the scientific process is part and parcel to citizen science. In this manner, citizen science endeavors might provide an ideal context for stakeholders to not only represent but also test ideas that result in authentic research. The notion of participation has been thoughtfully considered in citizen science (see Bonney et al., 2009; Shirk et al., 2012). While many may have top-down or scientist-driven notions of citizen science, a number of projects embody a more collaborative and, in some cases cocreated, process. In these projects, such volunteers are seen as collaborators or even drivers of the research question, data collection and idea representation, data analysis and conclusions, and decision making. Could this serve as a model for PM? (See Jordan & Gray, 2017). Could lay persons drive or be equal collaborators in the PM process?

2.5. Scaling the Process and Results

10. How do we scale participation in the modeling process to accommodate multiple goals, and connect multiple scales and sectors of governance, to ultimately impact the broader society?

Considering the strengths and potentials of PM and the urgent need for new governance approaches to support sustainable transitions, implementation and scaling up the impact of PM in society is a fundamental question for the PM research community to engage in. One of the weaknesses of a PM approach is that participation tends to be limited to a select group of people—typically between 10 and 30—as a result of the intensively interactive process. Limited participation means that many stakeholders who have an interest in the problem being discussed are not involved. Moreover, if PM is an especially powerful learning process, can those who are not directly included benefit from the insights that occur while they are not part of the in-room conversation? Stakeholders who participated in building the model and accept its output and the conclusions drawn from that output may be challenged to communicate their trust in the model to those who were not involved in constructing it. This is especially difficult because it is usually academic researchers who drive the PM process, and who are likely tied to the mechanisms that fund these efforts. Scaling up PM may require reducing the driving role of the researchers and transitioning to community leadership. Public officials, community leaders, and/or technical managers may then emerge as drivers of the process, and may need to learn some of the technical and procedural aspects of PM.

Various methods and tools have been developed to address these issues. Some modeling approaches rely less on formal modeling expertise (e.g., Rich Pictures, Role-Playing Games, Fuzzy Cognitive Mapping), while other more sophisticated tools can be added to the process if warranted, and with additional levels of expert support. The methods and level of support needed for each type of tool remains to be systematically studied. Various means of including a broader group of stakeholders in the PM process include putting a model online for the public to interact with and comment on; assembling a larger than typical group of participants and collecting their input using clicker technology; or replicating the experience with different small groups. Questions to explore includethe following: what affordances should internet interfaces have for meaningful, scientifically valid, and lasting engagement of stakeholders? How is such information to be used for decision making? What kinds of interfaces and facilitation strategies help build on and synthesize the insights and conclusion of different group exercises?

11. How does PM support planning and decision making that connect multiple scales and sectors of governance? How can a PM process support the coordination of the activities recommended by the process, with the activities planned by authorities and actors that are not part of the PM process? How can institutional learning be integrated into PM?

The governing of society has led to the organization of government into local, regional, and national scales and the division of administration into sectors, such as water and sewage, planning, building, traffic, healthcare, and education. This compartmentalization is a practical implication of the large number and range of issues and decisions that modern society needs to address. In a democracy, it is a well-established principle that those who are affected by a decision should have a part in the decision-making process (Dahl, 2008); and the related subsidiarity principle says that political issues, if possible, should be dealt with at the most immediate (or local) level that is consistent with their resolution.

As our understanding of socio-ecological systems expands, however, and as problems such as resource depletion, pollution, and extinction of species become increasingly urgent, the reconnection of geographical and administrative scales and sectors is recognized as a key challenge for establishing sustainable modes of governance (Milz, 2015). Two general strategies have been posited. The first is a reorganization of government entities. A current example is the reorganization of water policy in Europe according to river basins (European Water Framework Commission, 2000). There are many arguments for making decisions on water resources according to river basins and for taking an ecosystem approach. Large difficulties of integrating this new way of organization into the existing national institutional systems of the member states have been observed. Examples include increased institutional system complexity, less transparent decision making, more expert-based decision making and difficulties to coordinate decisions across administrative scales and sectors (Hedelin & Lindh, 2008; Jager et al., 2016; Koontz & Newig, 2014).

The second strategy is to develop processes that can connect geographical and administrative scales and sectors. PM has a number of attributes that make it useful with respect to these processes. For example: (1) PM tools can systematically capture and handle the complexities of social-ecological systems of different and connected scales, both knowledge-wise and value-wise; (2) PM tools and processes can support learning; (3) PM tools are often computer based, and can therefore be used and shared at a distance; (4) PM tools often bring together data that actors within different sectors and at different scales own, for example, local and national authorities; and (5) PM tools can support transparency, democracy, and handling of power (e.g., by structured and documented deliberation and by electronic voting procedures).

Currently, a typical PM study is performed at either the local or the regional scale, whereas studies of national scales are rare. PM studies generally are set up based on complex problems, such as river basin management, forest management, and urban planning. This kind of setup would be excellent for studying the linkage of sectors, because complex problems generally span several different sectors (and scales). Nevertheless, few PM studies explicitly engage in the issue of linking scales and sectors. Sectors are often linked implicitly, by involving persons from different authorities. Explicit, systematic, and theory-based or theory-generating studies of cross-sector issues, however, are lacking. Such studies would be necessary for developing the knowledge needed for the inherent potentials of cross-sectoral PM.

12. What are key roles and processes involved with PM? What are the constituent elements for the best practices in PM? When is friction productive?

The PM literature is dominated by empirical studies, specifically by case studies where different PM approaches are being developed and applied. We have identified over 200 PM case studies published in scientific journals from 2000 to 2017. In some cases, the PM processes and methods are systematically analyzed and evaluated against predefined criteria, but in many cases, evaluation is lacking or is not based on transparent and systematic methodological approaches. If one could effectively capture the knowledge and experiences generated and contained within the whole collection of published PM case studies, it would be valuable in providing answers to many of the questions raised in this paper. There is, however, a lack of a common set of theories and concepts in the field, making it difficult to compare cases and draw theoretical knowledge from this empirical and contextualized knowledge. Such theories and concepts could then act both to support the design of new PM processes (cases) and to structure analysis and evaluation of past cases. A major task for the PM community is therefore to develop a common set of useful concepts and theories.

2.6. Conclusions

Above we articulate 12 sets of questions related to important areas of PM research that warrant deeper consideration. We argue that these areas are essential to advance the field and encourage broader use of PM approaches especially with focus on environmental issues. We suggest that conceptual studies, studies that develop interdisciplinary theoretical frameworks, and review case studies, are necessary to complement the decision-making case studies currently reported as using PM. While a number of the questions posed relate to philosophical issues facing those who primarily study PM processes, there are also a number of practical questions that will greatly enable facilitators to better engage stakeholders in environmental modeling and can help modelers to produce more relevant and actionable products. Finally, there are a number of considerations for those seeking to engage the public in environmental management and decision making.

All this is critical to ensuring the public's investment into effective environmental management. We, therefore, conclude this manuscript with a call to action to (1) conduct systematic review and reporting on the issues raised above, and (2) focus research on participatory processes, modeling methods, computer interfaces, and collaborative tools that can advance participation in environmental and earth science issues facing the public as well as the PM process itself. There is a growing need for better exchange of best practices in PM and collective shared efforts to answer some of the pressing questions listed in this paper. We have established and are using a web portal (participatorymodeling.org) where we hope to foster more interactions and cross pollination of ideas on PM. Please join us!

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