Environmental Modelling & Software 77 (2016) 196–220

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Position Paper

Modelling with stakeholders — Next generation

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A R T I C L E I N F O

Article history:
Received 5 May 2015
Received in revised form
16 October 2015
Accepted 24 November 2015
Available online 29 December 2015

Keywords:
Citizen science
Social media
Serious games
Crowdsourcing
Biases
Uncertainty

A B S T R A C T

This paper updates and builds on 'Modelling with Stakeholders' Voinov and Bousquet, 2010 which demonstrated the importance of, and demand for, stakeholder participation in resource and environmental modelling. This position paper returns to the concepts of that publication and reviews the progress made since 2010. A new development is the wide introduction and acceptance of social media and web applications, which dramatically changes the context and scale of stakeholder interactions and participation. Technology advances make it easier to incorporate information in interactive formats via visualization and games to augment participatory experiences. Citizens as stakeholders are increasingly demanding to be engaged in planning decisions that affect them and their communities, at scales from local to global. How people interact with and access models and data is rapidly evolving. In turn, this requires changes in how models are built, packaged, and disseminated: citizens are less in awe of experts and external authorities, and they are increasingly aware of their own capabilities to provide inputs to planning processes, including models. The continued acceleration of environmental degradation and natural resource depletion accompanies these societal changes, even as there is a growing acceptance of the need to transition to alternative, possibly very different, life styles. Substantive transitions cannot occur without significant changes in human behaviour and perceptions. The important and diverse roles that models can play in guiding human behaviour, and in disseminating and increasing societal knowledge, are a feature of stakeholder processes today.

1. Introduction

Since Voinov and Bousquet (2010), over 200 papers have been published in Environmental Modelling and Software (EMS) that refer to stakeholder involvement. In preparing this Virtual Thematic Issue (VTI) Modelling with Stakeholders II, we reviewed articles published in EMS and selected papers that we considered most important in the field. For this position paper, we also considered papers in other journals that advanced the field of participatory modelling (PM) and developed innovative approaches.

Many studies have stressed the benefits, as well as the challenges, of stakeholder participation in environmental modelling (e.g., Carmona et al., 2013; Rockmann et al., 2012; Videira et al., 2009). Experiences with participatory model development have been well documented. However, overview articles and guidance for practitioners are still lacking, particularly regarding the tools, methods, and processes that can be used to meet the challenges of participatory environmental modelling (Videira et al., 2009). This current lack of guidance is, in part, the result of our highly diverse human society that retains a heterogeneous distribution of knowledge and highly localized belief systems. It is also the result

The position paper was initiated at a workshop on 'Modeling With Stakeholders' during IEMSS 2014. Order of authors is the three workshop organizers followed by alphabetical listing of remaining authors. Introductory Articles/Position papers are freely accessible.

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http://dx.doi.org/10.1016/j.envsoft.2015.11.016
1364-8152/

of the expanding multiplicity of opportunities (and accompanying stresses) created by rapid technological developments in an increasingly hyper-connected world. Indeed, participatory modelling and stakeholder engagement are facilitated by innovative communication media and new data acquisition, and processing tools that can be used for local applications, but that are also increasingly provided to a greater, global, community. Concomitantly, planners and policy-makers struggle to reconcile, or arbitrate, increasingly vociferous activist positions: reaching acceptable consensus, or justifiable decisions, is more difficult than ever. Decision-making was perhaps less contested in a more top-down, less transparent, past when the public generally deferred to the authoritative voices of professionals and political leaders.

The human dimensions of PM are why we still believe, just as Voinov and Bousquet (2010) did, that there can be no unique guidance for PM. Instead, PM needs to emphasize a smart adaptability of processes, based on active knowledge of local project specificities, including the identification of appropriate rewards or compensations that enable the meaningful engagement of all needed participants.

The majority of the articles reviewed for this paper describe case studies that involved stakeholders in resource management and environmental planning. Systems involving environmental/natural resource management are inherently complex. They involve multiple sectors, issues and stakeholders. They include a diversity of human-material interactions and they frequently cross administrative boundaries. The complex problems associated with environmental management typically call for an integrated PM approach (Von Korff et al., 2012).

The growing popularity of PM is exemplified by the marked increase in the number of papers published on the topic in recent years (Seidl, 2015). Stakeholder participation in research and decision-making can be traced back to at least the late 1970s and 1980s (Greene, 1987; White, 1979). It derives from (1) a universal drive towards greater decentralisation and ‘people's participation’ (Cohn, 2008; Haklay, 2012; McCall et al., 2015; Silvertown, 2009); (2) a growing ‘grassroots’ demand for public engagement in environmental planning and decision support (e.g., Delgado-Galván et al., 2014; Fulton et al., 2015); (3) a realization by decision-makers that new management or policy recommendations are less likely to be acted on if stakeholders are excluded from the policy development process; (4) a realization by modellers that the public can provide considerable knowledge, labor, and skills, and may even help mobilise funding (Leenhardt et al., 2012; Blackstock et al., 2012); and (5) the fast-growing and easy access to technical capacities that enable quicker and broader public involvement, notably through the internet and Web 2.0.

Distinctions need to be drawn between (a) general citizen involvement or participation – i.e. public involvement in asking or declaring needs, opinions, preferences, constraints, prejudices, etc.; and (b) the involvement of people in the pursuit of technical or scientific knowledge, termed Citizen Science (Cohn, 2008; Silvertown, 2009). For us, public participation in producing knowledge means that people are not just used as passive sensors, but are instead active participants in checking, assessing, or commenting on scientific observations – in addition to declaring their specific interests as citizens. This makes PM a form of Citizen Science because PM engages stakeholders in developing new knowledge, even as it solicits – and carefully examines – public needs, opinions, preferences, and constraints. Many forms of stakeholder and public knowledge can contribute, including so-called “indigenous knowledge”, “traditional ecological knowledge”, or “local spatial knowledge” (Agrawal, 1995; Berkes et al., 2000; Emery, 2000; Raymond et al., 2010).

Amongst some practitioners and modellers, an idealised view appears to exist that stakeholders can, or should, be engaged in most stages of environmental modelling. However, the degree to which stakeholders are engaged in environmental modelling can vary. In the literature on participation there are many examples of “participation ladders” or “levels of engagement”, which purport to distinguish between intensities or depths of participation (Arnstein, 1969; De Kraker et al., 2011; Jankowski, 2009; Lynam et al., 2007; McCall and Peters-Guarin, 2012; Shirk et al., 2012; Voinov and Bousquet, 2010). The most passive participatory process is simply to inform people, which does not involve true engagement of stakeholders. The next level of participation is when local stakeholders (in this case better termed as ‘local experts’) provide data to be used by modellers – this is called “extractive use”. Increasing levels of participation involve the collaboration of stakeholders in various aspects and stages of the modelling activities, such as advising on key indicators or appropriate measurement techniques (IAP2, 2006). The most intense participation occurs when local stakeholders – that is, those affected by the use and outcomes of the model - actually initiate the PM process and are engaged in all its stages: from identification of the problem(s), to model design, parameter selection, data collection, data validation, etc. up to application of the model and to decisions about ‘ownership’ – both ownership of the data inputs (especially confidential or culturally-sensitive material), and ownership of the final products and outputs of the modelling activities. In this ultimate situation, local stakeholders are involved in performing the analyses and modelling as well as the decision-making processes.

A game-changer has been the expansion of the Internet in terms of coverage and functionality. The Internet has become part of mobile telephone services with almost global coverage. This has transformed the ways that people are connected – to each other, to sources of information, and to learning opportunities. However, this connectivity does not resolve the uncertainty in our lives and in the local and societal decisions that have to be made. In many cases, the excess of information and connectedness may even increase the level of uncertainty.

This position paper starts with a review (section 1) of the papers on PM that have been included in the VTI, and also examines trends in the vast literature on PM that we find indicative and promising for the future. After discussing new web services and crowd-sourcing tools and methods that can help PM to move forward (Section 2), we look at how uncertainties are treated in participatory research (Section 3). We then examine possibilities to go beyond current practice in PM, focusing on visualization and communication tools (Section 4). In Section 5 we argue that participants' recognition of their own and other stakeholders' values and biases is an important element in the applications of modelling in policies and projects aiming at a higher degree of participation. Building on the need to identify biases and beliefs to better inform societal decisions and actions, we propose a new framework for organizing PM processes and for making progress on a participatory research and action agenda. We conclude the paper by making some additional suggestions and discussing some principles that we believe will help advance the practice and usefulness of PM.

2. Review

2.1. A classification of components and approaches for participatory modelling

Based on our review of the VTI and other literature on modelling

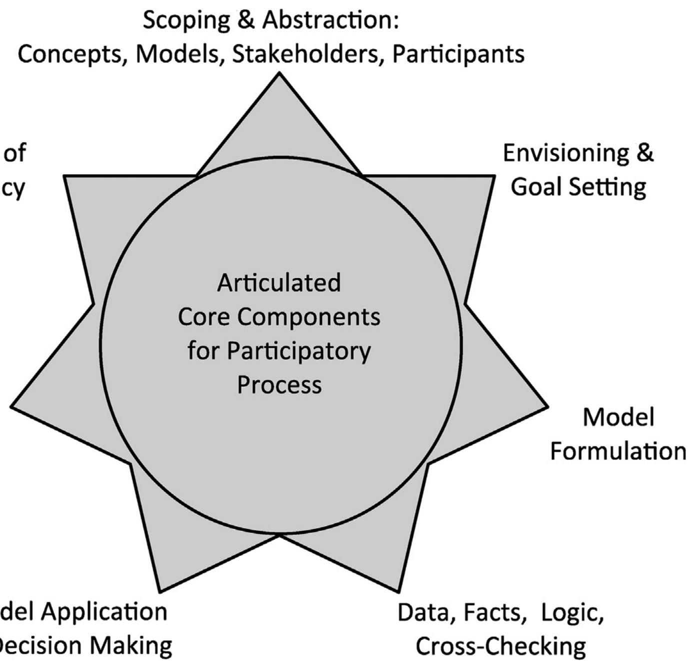

Fig. 1. Components of the PM process. The sequencing of components is adaptable to the evolving needs presented by the issue(s) being investigated (and modelled) and those of the participants and stakeholders. The components are susceptible to being revisited as necessary.

with stakeholders, as well as more general documentation about the design and structure of modelling processes (Chen and Pollino, 2012; Jakeman et al., 2006; Kragt et al., 2013; Robson et al., 2008; Welsh, 2008), we identify seven general domains or "components"[1] in the modelling process, in which stakeholders can engage (Fig. 1). The degree of stakeholder participation in the different components of a project depends on the specifics of the PM process, including: who is involved, what interests they have, their level and type of expertise, legislative requirements and societal expectations, the urgency of the project, constraints or relative freedom in project design, and specific knowledge requirements. We argue that there is no "optimal" level of engagement or predetermined components that people need to participate in; and not all modelling activities should necessarily involve participation in all process components.

At certain stages, the participation may be more virtual than material, meaning that there is an interest or intent to participate, rather than active participation. A PM process should always consider (1) the reasons and intentions of stakeholders in becoming involved as well as (2) the reasons and intentions of modellers (and other professionals) in suggesting and enabling involvement of stakeholders. We have to consider not only why stakeholders may wish to participate, but importantly, also how other powerful stakeholders might permit, facilitate, or encourage other actors to participate, or alternatively, how they might prevent them from participating. Hewitt et al. (2014), Hossard et al. (2013) and Videira et al. (2009) discuss which components of the PM process are most desirable for external authorities to promote.

Stakeholders can – potentially – be involved in any of the seven components of the process, but it is unlikely that any particular stakeholder would be involved in all, and it certainly was not the case in most studies reviewed here. We examine the seven components, discuss their associated opportunities and challenges, and provide an overview of appropriate tools (Table 2). The tools are not unique to specific components; most of them are applicable at a number of stages. The actual sequencing of components or stages in PM (Fig. 1) is adaptable to: (1) the specific issue(s) being investigated and modelled, (2) the various needs of the participants, and (3) the methods being applied. Any components may be revisited as necessary, therefore in Fig. 1 we do not number the components, although it is clear that they may provisionally sequence clockwise and would usually begin with the 'Scoping' component.

Central to Fig. 1, are the core principles adopted for all PM processes. It is expected however that some "core" principles will be adopted for the process. Although those principles may be revisited as the project (and the participants) evolve, they are expected to be more resistant to alteration than the models, perspectives, and transitory evaluations.

We present different options for participation in each of the seven modelling components in Fig. 1 and Table 1, note associated tools and methods that could be used (cf. Table 2), and provide case studies that illustrate the types of participation and tools and methods used (cf. Table 3).

Many of the papers we reviewed provide case studies of stakeholder involvement within the development of specific models. Typically, articles document the development of new tools and methods in a particular case study rather than critically assessing the stakeholder engagement process per se. This is not a trivial issue – the academic rewards system increasingly encourages the development of new tools and methods through their publication in refereed academic journals (c.f. the Economist, October 19, 2013). The same system does not generally reward the extension, adaptation, application, or even the testing, of existing tools and methods. Consequently, meta-studies reviewing tools and techniques to improve the practice of stakeholder participation are comparatively rare in the literature. This paper aims to help fill that void, and we call for more such studies in our Conclusions.

Our review identifies participatory tools and methods that have been used to enhance stakeholder participation in different

[1] We distinguish between the term "stage" - which implies a particular sequencing of a modelling process, and the term "component" - which does not.

Table 1
Participation by stakeholders in components of the modelling process.

	Components of modelling with stakeholders	Tools used (see Table 2)	Studies which address the component (VTI and beyond)
1	Scoping & abstraction: selection of the model or of the topic itself; selection of stakeholders (including self-selection). Stakeholder involvement at this vital formative stage in the modelling process reflects the principle of citizen engagement into the participatory design and analysis. *Identify project goals (V&B 1)* *Identify & invite relevant stakeholders (V&B 2)*	S1-4	Cobb and Thompson, 2012; Hojberg et al., 2013; Hossard et al., 2013; Oliver et al., 2012; Sano et al., 2014; Videira et al., 2010
2	Envisioning & goal-setting: stakeholders can identify the conceptual basis of the model, select the parameters/variables to include in the model, and possibly modify the topic, concepts, critical issues, etc. *Identify project goals (V&B 1)* *Discuss system, Build conceptual model (V&B 5)*	S5-7	Catenacci and Giupponi, 2013; Delgado-Galván et al., 2014; Hewitt et al., 2014; Hojberg et al., 2013; Hossard et al., 2013; Oliver et al., 2012; Sano et al., 2014; Squires and Renn, 2011; Videira et al., 2010
3	Model Formulation: identify the parameters & variables to be used; select model formulation and design methods; select analytical methods and tools. Stakeholder involvement is relatively rare here. *Choose modelling tools (V&B 3)* *Discuss system, Build conceptual model (V&B 5)*	M1-8	Barnaud et al., 2013; Butler et al., 2014; Catenacci and Giupponi, 2013; Fraternali et al., 2012; Hovmand et al., 2012; Knapp et al., 2011
4	Collection of original data and cross-checking of expert data. Stakeholders are involved in this component as citizen scientists. *Collect & process data (V&B 4)*	D1-5	Carmona et al., 2013; Delgado-Galván et al., 2014; Fraternali et al., 2012; Giordano and Liersch, 2012; Hewitt et al., 2014; Hojberg et al., 2013; Lippe et al., 2011; Papathanasiou and Kenward, 2014
5	Apply Model to decision-making. Stakeholders are central to some degree, in this component.	P1, P2, P4 M4	Barnaud et al., 2013; Delgado-Galván et al., 2014; Uusitalo et al., 2015
6a	Evaluation of <u>outputs</u> (or impact evaluation). Stakeholders are often included in this component – participants are asked to evaluate the specific and immediate outputs of a model. This typically involves evaluating technical measures of model performance. *Run the model, Discuss results (V&B 6)* *Analyse model (V&B 8)*	S1-7, P1, P4-5	Butler et al., 2014; Carmona et al., 2013; Delgado-Galván et al., 2014; Fraternali et al., 2012; Fritz et al., 2012; Graveline et al., 2014; Greiner et al., 2014; Groen et al., 2014; Hewitt et al., 2014; Hossard et al., 2013; Lippe et al., 2011; Matthews et al., 2011; Videira et al., 2009
6b	Evaluation of <u>outcomes</u> (or effects evaluation). Stakeholders are often included in this component – stakeholders are asked to evaluate the longer-term, broader-scale results or outcomes following a PM process. *Discuss & define scenarios (V&B 7)* *Analyse model (V&B 8)*		Arciniegas et al., 2013; Barnaud et al., 2013; Bizikova et al., 2011; Carmona et al., 2013; Chen et al., 2013; Cobb and Thompson, 2012; Fraternali et al., 2012; Fritz et al., 2012; Greiner et al., 2014; Labiosa et al., 2013; Matthews et al., 2011; Murray-Rust et al., 2013; Nino-Ruiz et al., 2013; Papathanasiou and Kenward, 2014; Sahin et al., 2016
7	Facilitation of transparency of the process. Public evaluation of the PM process. Stakeholders are central in this component. *Present results to other stakeholders (V&B 9)*	P1-3, S1, D5	Arciniegas et al., 2013; Arnold, 2013; Bijlsma et al., 2011; Martin et al., 2011; Nativi et al., 2013; Nino-Ruiz et al., 2013; Tsouvalis and Waterton, 2012

Notes: Tools and methods used are further detailed in Table 2. The stages of PM presented in Voinov and Bousquet (2010), (Fig. 1) are mentioned in italics (and also reproduced with some modifications later on in Fig. 4). Various terminologies are used in the literature.

components of the PM process (Table 2), and many are also discussed later in the paper. While Table 2 proposes some categories for the various tools used, in reality we often find a hybrid application of tools.

Table 3 analyses the case study articles in the VTI, presenting which of the seven components of stakeholder participation (Table 1) are used or discussed in their associated PM projects. Interestingly, none of the projects reviewed engaged stakeholders in the full complement of PM components (Fig. 1).

2.2. Human dimensions of participatory engagement

For any participatory project or activity there is a set of fundamental questions to be posed, whose answers can improve the design, methods and implementation of the process. Getting the answers involves examining the motivations of various stakeholders, the (mainly) local members of the public who may become engaged, and the (mainly) external planners, policy-makers, modellers, and proponents of PM who enable public engagement and who should follow through on governance.

In this section, we investigate some key questions. For which components of PM have benefits of stakeholder engagement been best recognized and promoted? Who is getting engaged in PM and why? How do certain stakeholders become engaged, and others not? What are the drivers behind engaged participation? What is the centrality of trust and confidence for engagement in PM?

2.2.1. Stakeholder participation is most evident in three salient components of PM

The participatory approach has been most frequently applied in providing data for models and model calibration (Component 4) - engaging the public in identifying, and sometimes measuring or cross-checking, the inputs to models (Fraternali et al., 2012; Giordano and Liersch, 2012; Hewitt et al., 2014; Hojberg et al., 2013; Lippe et al., 2011). Hewitt et al. (2014), for example, present a case study of calibration for modelling land use change in a coastal dune and marshland ecosystem in South West Spain. The Cellular Automata-based modelling framework they employed required the numerical and spatial description of land-use categories, suitability of slope, temperature, rainfall, etc. Stakeholders collected the needed information and model inputs through visual inspection of maps, for both the model calibration and model evaluation stages.

Another component in modelling processes where stakeholders have been much engaged – and encouraged to engage – is during the evaluation of modelling results. Public evaluation of the

Table 2
Tools and methods of Participatory Modelling. See Table 1 for some application examples.

Main components	Tools and methods		References (with focus on papers that describe particular tools)
Scoping, envisioning, etc.	S1	Meetings, workshops, brainstorming, and group facilitation	Almost all
	S2	SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis	Ritzema et al., 2010
	S3	Participatory scenario development	Barnaud et al., 2013; Cobb and Thompson, 2012; Hossard et al., 2013; Labiosa et al., 2013
	S4	Imagineering, visioning and pathways	Barnaud et al., 2013 (integrative negotiation)
	S5	Visualization and graphics, 'rich pictures'	Barnaud et al., 2013 (critique maps)
	S6	Gaming	Fraternali et al., 2012
	S7	Mind mapping	Elsawah et al., 2015
Data	D1	Surveys, interviews, questionnaires	Many
	D2	Mobile applications	Fraternali et al., 2012
	D3	Wikis	Fritz et al., 2012
	D4	Role playing games	Barreteau et al., 2003
	D5	Tools for eliciting expert knowledge	Bastin et al., 2013; Fisher et al., 2012; Morris et al., 2014; Reichert et al., 2013; Scholten et al., 2013
Model development	M1	Agent-based modelling (ABM)	Barnaud et al., 2013; Murray-Rust et al., 2013
	M2	System dynamics	Leys and Vanclay, 2011; Sahin et al., 2016; Wieland and Gutzler, 2014
	M3	Bayesian network models	Catenacci and Giupponi, 2013
	M4	Scenario building	Cobb and Thompson, 2012; Murray-Rust et al., 2013
	M5	Human computation	Fraternali et al., 2012
	M6	Integrated modelling	Giupponi et al., 2013; Knapp et al., 2011
	M7	Conceptual and cognitive modelling (fuzzy cognitive mapping, signed di-graphs, etc.)	Elsawah et al., 2015; Gray et al., 2013; Halbrendt et al., 2014; Nyaki et al., 2014; Dambacher et al., 2009; Fulton et al., 2015.
	M8	Optimization	Kuhn et al., 2016; Gaddis et al., 2010.
	M9	Fuzzy modelling	Wieland and Gutzler. 2014
Presentation	P1	Interactive mapping	Arciniegas et al., 2013
	P2	Visualization, animations, visual analytics	Bizikova et al., 2011; Chen et al., 2013; Nino-Ruiz et al., 2013; Reichert et al., 2013
	P3	Web applications	Bastin et al., 2013; Nino-Ruiz et al., 2013
	P4	Games, role-playing	D'Aquino and Bah, 2013a, 2013b; Fraternali et al., 2012
	P5	Sensitivity analysis	Castelletti et al., 2012; Chen et al., 2013
	P6	Uncertainty analysis	Groen et al., 2014; Uusitalo et al., 2015

processes of stakeholder participation in PM is discussed in Arciniegas et al. (2013), Arnold (2013) and Tsouvalis and Waterton (2012). There are significant differences between inviting or permitting local stakeholders in a PM process to engage in an "evaluation of outputs" (Component 6a) or in a "public evaluation of outcomes" (Component 6b).

The latter case, 'evaluation of outcomes', involves a broader and policy (or society-oriented) assessment of success, and can often elide into Component 7, a meta-evaluation of the whole participatory process itself. For example, Bijlsma et al. (2011) compared stakeholder-based policy development with expert-based policy development and found essentially opposing approaches to stakeholders' handling of uncertainties during policy development. While the experts handled uncertainty by reducing the problem scope, the local stakeholders handled it by broadening the scope to include all their important stakeholder criteria.

2.2.2. How are stakeholders selected to be engaged in PM?

Scoping (Component 1) includes the selection of the stakeholders who will participate in the PM, and is always part of the earliest stage of a PM approach, though in a PM learning process, some new stakeholders may enter later. But, participation can never be all-inclusive. So, are those stakeholders who actually participate, self-selected, or are they invited in by external experts? Do they originate only from 'recognized' civil society like civic organizations, or can anyone join in? Involvement generally is not continuous and is not uniform. Another dilemma in PM, as in other participatory planning, is to identify at what scale the 'group' (family-household/club/neighbourhood/community/interest-action group) should be formed to best represent the 'uniqueness' of interests, needs, priorities and values of the 'group'. Few papers explore this issue; though it is important in upscaling or translating the findings of PM exercises to larger-scale or other situations.

The engagement of stakeholders inevitably involves the balance between "breadth" vs. "depth" of engagement. Not all stakeholders are likely to engage "deeply" — that is, commit to and meet the challenges of more intensive and time-consuming participation, perhaps across multiple stages of a PM process. Can they then form a sufficiently representative constituency of stakeholders? Alternatively, will a PM process that involves a much greater number of participating stakeholders be meaningful, given that there is probably then a more limited depth of engagement, and individual input, from each participant? New mechanisms to encourage engagement are relevant to this, especially the recruitment and participation processes conducted through the web that have allowed much broader public involvement. This parallels the dichotomy between the rich "intensive engagement" of participatory knowledge generation, and, the Web 2.0-enabled "extensive breadth" of crowdsourcing (McCall et al., 2015).

2.2.3. Drivers behind stakeholder engagement

The issue of why participants, local or external, engage or stay engaged in a PM process is complex, the motivations and expectations of stakeholders being key factors. Hewitt et al. (2014), Hossard et al. (2013) and Tsouvalis and Waterton (2012) addressed these general issues of motivation as they apply to different types and intensities of engagement.

'Motivation' provokes questions from two different perspectives. First, what motivates members of the public to participate in what is a difficult and often frustrating process? PM is not to be

Table 3
A classification of sample PM projects (taken from papers included in the current VTI).

Studies	Scoping	Envisioning	Formulating	Data and logic	Application	Evaluation	Transparency	Comments on applications and tools used/discussed
Arciniegas et al., 2013		✓		✓	✓	✓		Land use allocation in a peat-meadow polder in The Netherlands. Stakeholder participation: - Identify land use categories - Prepare maps of current land use - Compare effectiveness of paper maps vs. GIS maps in land use allocation decisions by the stakeholders
Barnaud et al., 2013			✓		✓	✓		Land and forest management conflicts in Northern Thailand using companion modelling approach combining role-playing games and ABM. Stakeholder participation: - Analyse influence of detailed spatial representation and scenario simulation on learning and negotiation among stakeholders
Catenacci and Giupponi, 2013		✓	✓		✓	✓		Adaptation to sea level rise in a lagoon in North-East Italy using Bayesian Decision Network (BDN) modelling combining participatory and probabilistic methods. Stakeholder participation: - Prepare concept map of the system using group brainstorming - Provide conditional probabilities to build a quantitative BDN model - Evaluate alternative adaptation measures to the sea level rise using the model
Cobb and Thompson, 2012	✓					✓		Climate change adaptations in the US National Park Service. Stakeholder participation: - Identify scenarios to be analysed - Use scenario planning for adaptation to climate change
Delgado-Galván et al., 2014		✓		✓	✓	✓		Select most suitable management model for an over-exploited and polluted aquifer in the central-western state of Guanajuato in central Mexico using AHP. Stakeholder participation: - Identify current problems and possible action plans to address them - Identify and rank the criteria and assess the alternative action plans through consensus
Greiner et al., 2014						✓		Pastoral industry in Australia's Northern Territory using mediated modelling. Stakeholder participation: - Build a dynamic systems model based simulator using mediated modelling approach - Evaluate scenarios to improve their learning and planning
Hewitt et al., 2014		✓	✓	✓	✓	✓		Land use changes in a protected area in South West Spain using Cellular Automata (CA) based 'Metronomica' modelling software (Van Delden and Hurkens, 2011). Stakeholder participation: - Identify land use categories, suitable factors for each category and drivers for various land use changes - Calibrate model (together with analytical methods) - Evaluate model by comparing simulated and known land use maps through visual inspection (together with spatial techniques)
Hossard et al. (2013)	✓	✓				✓		Assessment of the effects of different scenarios on management of phoma stem canker in regional case in France. Build quantitative land use scenarios and test them with existing spatially-explicit model built from participatory methods. Stakeholder participation: - Identify stakeholders - Co-build a common vision of the disease behaviour - Collectively design scenarios, and evaluate them
Labiosa et al., 2013						✓		Land use changes in South Florida using a web GIS based DSS (decision support system). Stakeholder participation: - Modify parameters and evaluate scenarios such as sea level rise to understand uncertainty and divergence in their own preferences
Lippe et al., 2011				✓	✓	✓		Land use and land cover changes (LULC) in a mountain watershed in North Western Vietnam using an agent-based spatially explicit LULC model. Stakeholder participation: - Provide qualitative soil fertility data. GIS maps prepared using this data were validated using satellite imagery and used as input to the model. - Make recommendations for increasing soil fertility and evaluate them using the model
Murray-Rust et al., 2013				✓	✓	✓		Land use changes in a municipality of Slovenia using ABM-based scenario analysis. Stakeholder participation:

(continued on next page)

Table 3 (*continued*)

Studies	Scoping	Envisioning	Formulating	Data and logic	Application	Evaluation	Transparency	Comments on applications and tools used/discussed
								- Identify influence of various indicators in terms of their quality of life. - Use scenario analysis to study impact of land use changes on the loss of agricultural land and residential quality-of-life and identify future development hotspots
Nino-Ruiz et al., 2013					✓	✓	✓	Land use allocation in South Western Australia using a web-based land use allocation model. Stakeholder participation: - Steer key variables of the model, visualize potential outcomes and move towards the outcomes that are closer to their interests, instead of the scientists' configuration of the model to present what they consider the most likely outcome. Improves transparency
Papathanasiou and Kenward, 2014		✓	✓	✓	✓			Requirement analysis for environmental DSS at local community level in 8 European countries. Stakeholder participation: - Monitor local resource use in accordance with central policy requirements and continuously update higher levels of government - Map ecological information, in combination with surveys of socio-economic information, community attitudes towards environmental costs and benefits, etc. using a questionnaire
Sahin et al., 2016			✓	✓	✓	✓		Governance of potable water systems in South-east Queensland, Australia using a system dynamics model. Stakeholder participation: - Analyse scenarios using Monte Carlo simulation and select final model
Sano et al., 2014	✓	✓		✓	✓	✓		Prepare a plan for management of the Mediterranean coast of Egypt by capturing mental models of its stakeholders. Stakeholder participation: - Identify causal relationships between key issues - Identify relevance of each issue
Wieland and Gutzler. 2014		✓	✓		✓	✓		Agricultural developments in a German state using a fuzzy system dynamic-based "quick scan" modelling approach. Stakeholder participation: - Provide expert knowledge for preparing "white box" models to save time and improve credibility

entered into lightly by its participants: it is almost always a slow process, individually time-consuming and may not reach any workable conclusions. It is a serious investment of time and energy. This question is examined further in the discussion on crowdsourcing (Section 2). Second, why do planners and policy-makers want public and other stakeholder participation? Why would they encourage it, and how should they try to motivate it? Participation usually slows down decision-making, it has many costs and it can be confrontational and disturb the smooth running of a project. A valid research question is "why do some policy-makers invest so much time in persuading and facilitating the involvement of local stakeholders?"

There are many reasons why external authorities might actively promote participation. Most obviously, there is a recognition that some members of the public can provide important local knowledge (e.g., Hewitt et al., 2014; Lippe et al., 2011), can help fill in key data or information gaps, and offer useful skills. There are sometimes statutory requirements for participation resulting from legislation or policy. Alternatively, a participatory process may help mobilize and justify funding. Finally, there may be the driver of deliberate manipulation or deception for some political goal, that is, to provide a facade and fiction of participation. This leads to the critique that participation may simply be "promoted" to "grease" community acceptance and implementation of pre-existing plans (Arnstein, 1969; McCall and Dunn, 2012). In addition to this, the ability to retain the interest and presence of local stakeholders between the PM stages where they have a more active participation, is important.

Not many of the papers we reviewed addressed these questions. Those that did, mainly identified the motivations of planners and policy makers to be accessing the strengths of local knowledge and experience (e.g., Carmona et al., 2013; Hewitt et al., 2014; Hossard et al., 2013; Lippe et al., 2011; Papathanasiou and Kenward, 2014; Rockmann et al., 2012). Some authors considered that participation may also be promoted as a matter of principle or an ideological commitment to participation, because planners believe that participatory efforts will improve planning and policy-making (e.g., Wassen et al., 2011; Papathanasiou and Kenward, 2014).

The issue of the actual, potential, or relative costs of involving stakeholders in modelling is subject to much debate about how costs vary with or without citizen involvement, and whether these costs (and associated benefits) can be quantitatively measured, for instance whether long-term impacts and their associated costs and benefits are included. The articles we reviewed do not provide much discussion or answers to these questions, apart from the observation that crowdsourcing is often perceived as a means to reduce costs (see Section 2.2).

2.2.4. Human interactions – trust and confidence

Facilitating, encouraging, or more actively generating participation depends heavily on confidence-building and trust, especially between the 'professional modellers' and the local stakeholders.

Trust and acceptance of the PM process by the citizens.

The level of trust that citizens have in the institutions that are introducing a potential project is essential to the success of the participatory activities, and eventually to the project itself. It is difficult to generalize about how ‘trust’ functions, because levels, modalities, and sources of trust vary widely within and between different countries, cultures, and socio-economic groups. There have not been many comparative studies on the effects of inter- and intra-cultural group differences on participatory processes, certainly not in the literature that we examined, and Reed (2008) broad review of stakeholder participation in environmental management did not highlight cultural group differences. However, Enserink et al. (2007) looked at participation in river basin management planning in four countries in Europe, and considered the relationship of practices of participation with some broad inclusive measures of national culture, politics and history. They rightly interpreted “culture” in a very dynamic, adaptive, and innovative frame. Ya and Zhu (2014) examined the significance of some Han Chinese cultural elements and, more specifically, McKinnon (2010) implicitly compared minority Hani (Ho) environmental conservation attitudes and their involvement in participatory research, with those of Han Chinese.

Generally, when intrinsic levels of trust are low, there is a much greater need for the project to build up two-way, shared communications slowly and sensitively. This is most likely to happen through trusted intermediaries. The importance of constructing trusted relationships through slow participatory processes is demonstrated by Wassen et al. (2011) meta-study of 13 projects which concluded that citizens' final acceptance of the modelling studies correlated positively with their degree of participation.

Credibility and validity of the PM process: the professionals' perspective.

The validity and credibility of citizen contributions is a critical issue to be addressed within any participatory process (Fritz et al., 2012; Tsouvalis and Waterton, 2012). Policy-makers who use the results of PM efforts need to be convinced of the credibility and scientific soundness of the inputs and products of local ‘non-professional’ stakeholders (Papathanasiou and Kenward, 2014). Aumann (2011) proposes an approach for constructing credibility by taking into account the mental models of stakeholders and the factors that influence stakeholders to view model results as credible or not.

The need for credibility does not arise only during the PM process, but also, ultimately, when the PM products are presented for implementation. Measuring the ‘acceptability” of a PM process, especially of its final model outputs and their use in decision-making, is a major challenge, requiring relevant qualitative as well as quantitative criteria. Technical criteria need to be used, but so do political-feasibility criteria and concepts of social value. In the context of PM the main interest is not in the criteria for acceptance of model outputs in general. Rather, the focus is on questions such as “what are the criteria?” and “what are the differences in acceptability of models developed with local participation vis-a-vis models developed only by technical experts?”.

Transparency is seen as an essential principle for acceptance. However, similarly to the FPIC (Free, Prior, Informed Consent) principle applied to projects impacting the conditions of local people, transparency is a difficult principle to implement in practice. Transparency should ensure that stakeholders – not only those directly engaged in the modelling process, but all members of the affected public – have a basic understanding about the PM process. Wieland and Gutzler (2014) propose a fuzzy system-dynamics-based “quick scan” modelling approach involving integration of expert and stakeholder knowledge to prepare “white box” models that can be more easily understood by non-expert stakeholders. But there are limits to what can be translated into lay language, and also to the time that people can devote to interpreting and understanding what is being said. The transparency principle has to be seen as an ‘ideal state’ to be aimed at, not as an administrative requirement.

Growing trust through boundary work and learning.

A boundary work approach – boundary objects, concepts, and institutions – has been employed to develop common ground between conflictive stakeholders, especially aimed at the barriers between the discourses of scientist-experts and lay-experts, or between local and indigenous knowledge; although boundary work processes are also applicable to other ‘misunderstandings’. To summarise the approach in PM, boundary objects need be both plastic enough for the specific needs and constraints of the different stakeholders employing them, yet robust enough to maintain a degree of common identity. They are weakly structured in common use, but become strongly structured when applied to specific environmental management issue or conflicts. They hold different meanings for different social actors and epistemic communities, but their structure has commonality enough to make them a recognizable means of translation – examples of boundary objects in PM being maps co-produced by the various conflictive actors (Clark et al., 2011; Hoppe and Wesselink, 2014). Clark et al. (2011) reviewed boundary work applications to natural resource/environmental management from the research programmes of the CGIAR (Consultative Group on International Agricultural Research). Robinson and Wallington (2012) applied the approach to examine contested interactions between scientific and indigenous knowledge systems in the case of feral animal co-management in Australia's Kakadu National Park. The boundary work supported indigenous and non-indigenous managers and rangers in bridging the knowledge divide and ensuring the translation of their knowledges towards co-management. Hahn et al. (2006) specifically examined the value of a bridging organization for trust-building between different stakeholders in terms of generating new knowledge and facilitating adaptive organizations, in a case of co-management of a wetland landscape near Kristianstad, Sweden.

PM processes are often categorized as learning exercises, as exchange and development of knowledge and skills between multiple actors. This is addressed by Martin et al. (2011), Vayssières et al. (2011), Hojberg et al. (2013), Tsouvalis and Waterton (2012), by Arnold (2013) who explore requirements for giving training to PM participants, and by Barnaud et al. (2013) who employ negotiation tools for these learning exercises. When framed in the context of participatory, engaged, planning and modelling, the issues of expertise and training need to extend beyond what is needed for the public to participate effectively. Complementary questions concern the relevant expertise that professionals (e.g., specialist experts, modellers and planners) have in working with and in engaging public participants. Is there a need to train them too? Many experts may not have the social experience, interaction skills or a natural ability to work successfully with local participants. They may not have the abilities to accommodate the complexities and slowness of a PM process, to find and use layperson language, to appreciate and understand the political dimensions of an issue, or to work with diverse personalities. These questions are generally not addressed in the case studies that we reviewed.

Overall, our review recognizes that the human complexities of PM processes – with the uniqueness of local stakeholders and the specificities of external professionals and institutions – forestall drawing generalized conclusions about PM. Yet, that is what this paper attempts to do. We seek patterns and simplifications to help better manage the dynamic and ambiguous complexity of natural and social systems around us, including other human beings and communities.

3. Internet, web services, and crowdsourcing

The promise of using the Internet to facilitate management and decision-making is not new (e.g., Voinov and Costanza, 1999).

However, this concept has only recently been implemented and operationalized in some functional applications (Hämäläinen et al., 2010; Latre et al., 2013). Various web applications and web services are available to interact with models (Walker and Chapra, 2014), to visualize model output (Brooking and Hunter, 2013) and to provide other functionality that can be useful in participatory distributed decision-making (e.g., bringing Multi-Criteria Decision Analysis (MCDA) functionality through a Java-based application that runs in a browser (Mustajoki et al., 2004).

3.1. Web services and tools

In the past, PM efforts had to be limited to relatively small-scale, local or regional applications. An obvious reason was that the main mechanism for participation was workshops that brought together groups of stakeholders. Such groups were constrained by physical accessibility, and to small numbers, to ensure that participants stayed involved and that everybody could be heard.

Web services are a game changer in the world of PM. They enable the vision of "management and decision-making that are disclosed to the public, offering a broad spectrum of views and values, and inviting stakeholders to become participants in a truly democratic process of decision making" (Voinov and Costanza, 1999). With web services, broad participation becomes possible, even on a global scale (Nativi et al., 2013). Participants do not need to all be in one room to 'level the playing field' (Campo et al., 2010) or to learn, provide or share information. This can now be done over the Internet. While most agree that there is no fully satisfactory alternative to face-to-face meetings, attracting stakeholders to attend them is becoming increasingly difficult due to transportation costs, general work stress and lack of time, and the phenomenon of stakeholder fatigue (Reed, 2008). Online meetings and web participation may provide good alternatives because they allow asynchronous, low-cost (in terms of money and time) participation where people can attend and have a voice at the time that is most convenient for them, and with a level of effort that matches their interest.

Quite importantly, modelling itself is becoming increasingly possible with web tools, in many cases right in the browser, with no need to download and install additional software. For example, Systo,[4] an outgrowth of Simile (Muetzelfeldt and Masheder, 2003), allows building and analyzing system dynamics models. Insight Maker[5] is another tool, which is designed to help connect mental models (insights) with quantitative system dynamics and facilitates sharing ideas, models and projects over the web. Similarly much of GIS functionality becomes available through web services, supported by such open source projects as QGIS.[6]

Web services may be used for one-way data collection by higher levels of government, i.e. from members of the public to the government. Such use generally precludes the meaningful involvement of stakeholders in decision-making. This "exploitation" mode of participation, that is, "to acquire information and leave", can be related to crowdsourcing (see below).

Numerous features have been recently added to web services that can advance stakeholder involvement and participation. For example, translation services, such as offered by Google (http://translate.google.com/) and now in Skype, and built in as a standard capability in some web browsers (e.g., Chrome) allow the discovery of web sites in dozens of languages. While not perfect, the translation is usually good enough to convey the meaning. Consequently, we can now engage stakeholders with many different native languages in joint discussions of systems and processes. Such discussions are essential in dealing with large-scale problems that cross political (and linguistic) boundaries. Sun (2013) describes how a traditional client-server-based Environmental Decision Support System (EDSS) can be implemented as a client of cloud-computing services. Google Drive, which is used in this case, provides some basic visual analytics capabilities that increase the collaborative decision-making experience while drastically reducing the cost of small-scale EDSS.

However, using web services and tools does not come without problems (Fung et al., 2013). Many of the advantages brought by the new technology have a backside that may cause additional problems. For example, the asynchronicity of some web communications can tilt the playing field for some participants creating advantages for newcomers joining the conversation at a later stage with more knowledge of what was happening in the meanwhile and therefore less prone to errors in their opinions. At the same time missing some parts of the previous discussions may be disadvantageous to them. Theoretically, anybody with Internet access can participate in a discussion on a pressing issue, such as climate change. However, a Digital Divide (Foster and Dunham, 2015) exists that manifests itself in many ways. For example, Internet access is not equally simple or reliable around the world: it differs greatly across the 'Divide'. Age, education, occupation, income, and life style affect Internet access and use, and especially the differing cultures and traditions of sharing information and of trust in the relevant recipients and suppliers of the information. Authorities may also control, restrict, or manipulate access and use. The great hope of the Internet is that it can give a voice to people who would not otherwise be heard. However, to date, there is little evidence that this has actually happened.

The engagement of citizens in both providing and accessing information suggests that checks and balances would develop that would improve truth in reporting: fraudulent, mistaken, or inadequate information should, theoretically, be quickly spotted, reported, and corrected. In reality, this often does not happen, and there is a proliferation of biased, unchecked, unsourced, or otherwise poorly characterized information. Previously, traditional, "reputable", media outlets had established processes that ensured minimum standards and quality in reporting. Information could be tracked to sources, and usually, was independently confirmed. Biases and misinformation did exist, but were usually better known or easier to uncover. There were also fewer sources of information, less derived information, and just less information published. Today, the sheer deluge of information created by the blogging, tweeting and 'youtubing' culture makes it difficult to hold people accountable for what they report. Quoting out of context, re-blogging and re-twitting of unchecked facts occurs all the time. Rumors can spread at a staggering rate without any substantiation; and it is often impossible to determine sources and evaluate credibility.

In the rapidly expanding pool of text, images and videos, almost any opinion can find justification. As a result, people "cherry-pick" the bits and pieces of information that best match their beliefs, preconceived notions, or mental models. They then add their voices, but make it only harder to sort out the truth. Public perceptions and reporting on the latest developments in Syria or in Ukraine, or on issues such as health-care in the US, offer good examples of the low quality of social media information. The result is often growing polarisation and fading opportunities for reasoned consensus.

[2] A "red team" is an independent entity that aggressively fights "group think" and challenges another group or organization to improve its effectiveness and/or thinking.

[3] Memes are ideas, behaviours, or styles that spread from person to person.

[4] http://www.systo.org/systolite/systolite.html.

[5] https://insightmaker.com/.

[6] http://www.qgis.org/en/site/.

People align themselves with those who think alike: they eagerly exchange false or biased information that matches their expectations and aspirations (Fung et al., 2013).

Facilitation and mediation become ever more important in the world of digitally-enabled participation. The need for a delicate balance between democracy and control remains, but with a different setting. Facilitating a workshop, where all the participants are physically present and can witness all the discussions, is very different from facilitating a web-based discussion, especially if it is happening in an asynchronous mode, when various participants provide their opinion at different times and the facilitator can effectively censor the opinions and information sent to the web portal. What kind of safeguards can be provided to ensure that the results of such discussions really represent the opinions of the participants, and that they are not manipulated in some biased directions?

3.2. Crowdsourcing

Crowdsourcing is a form of volunteering that has gained considerable momentum due to the advent of the Internet. Crowdsourcing is not an entirely new activity. There have been numerous initiatives that involved large numbers of individuals (a crowd) to solve problems or complete tasks, such as the annual Audubon Christmas Bird Count active since 1900 (Audubon, 2013). However, as the preceding section outlines, the technical infrastructure of the Internet greatly facilitates the design and execution of crowdsourcing activities. While there are several definitions of crowdsourcing (Estelles-Arolas and Gonzalez-Ladron-de-Guevara, 2012), its etymology provides a core characteristic: crowdsourcing was coined as a term in 2005 as a portmanteau of crowd and outsourcing (Howe, 2006). Thus, it involves typically two types of actors: those who outsource tasks or problem solving (individuals, organizations, enterprises), and those who complete the tasks or solve the problems (individuals). This is an inherently hierarchical arrangement. The crowdsourced tasks are typically well-defined and the overall problem to be solved either needs or profits from a large number of task executioners. Recent examples include relatively low-level tasks of raw data collection and simple analysis which require advanced cognitive facilities, such as the visual classification of galaxies (www.galaxyzoo.org), land use mapping and classification (Fritz et al., 2012), or the analysis of coastal damage from storms (USGS iCoast program Liu et al., 2014). From a computational perspective, there is a striking similarity with Map-Reduce algorithms (Dean and Ghemawat, 2008) and parallel processing in general: the crowdsourcer maps the tasks to independently working nodes (the individual members of the crowd) and later reduces the results into a coherent output.

Following from the above, we argue that crowdsourcing so far is significantly different from deeper participatory approaches. In general, there are five main types of differences between established approaches to PM and crowdsourcing that relate to: (1) the relations between participants and the tasks, (2) the relations between actors, (3) the richness of the output feedback provided to the participants, (4) the number of participants, and (5) the speed of the process.

In participatory approaches, the participants are usually local stakeholders, meaning that the problem to be solved directly relates to one or more aspects of their quality of life (e.g., work, housing, health, environment, mobility, schooling). Because these local stakeholders are likely to possess some expertise in the problem domain, they can interact with other actors with high confidence and assurance. Additionally, any output generated in the process should be made continuously available to participants in some form (De Kraker et al., 2011). Because of this emphasis on quality, the number of participants is typically rather low, and has an upper boundary due to logistical and communication problems (e.g., Knapp et al., 2011). Crowdsourcing, on the other hand, does not require the participants to be stakeholders. The problem domain can be very distant from their personal daily experiences or quality of life: the outcomes of the study need not directly affect their lives. Following from this, relations between crowd members and crowd sourcers tend to be hierarchical, and the participants might never see the synthesized or processed results of their work (McCall et al., 2015; Craglia et al., 2012). Crowdsourcing emphasizes a high number of participants, in general the more the better, with comparative simplicity of typical tasks and a reliance on Information and Communication Technology (ICT) advances, eliminating any effective upper boundary due to logistical problems. The effective and efficient design of a crowdsourcing interface is a considerable challenge, for example, several factors in user interfaces, such as ‘building vs. buying components’ and ‘satisfier vs. motivator elements’, are currently still under investigation (Prestopnik and Crowston, 2012).

Nonetheless, crowdsourcing is a form of participation, and from a certain viewpoint, participants can be considered as stakeholders: why otherwise would they care to participate and do the tasks, if they had absolutely no interest or ‘stake’ in the problem? Perhaps they are willing to accept that the interpretation or results of the project are beyond their comprehension; and they might still feel good about contributing in some way to solving a problem. Consequently, crowdsourcing is potentially relevant and important for PM. With regards to the conceptual framework adopted in this paper, crowdsourcing in PM focuses on component 4 (see Table 1), i.e. data collection and validation. In practice, the combinations of required domain knowledge, interaction between participants, implied hierarchy between initiator and the crowd, and feedback for the stages of scoping, envisioning, and model formulation will, for the time being, restrict crowdsourcing efforts to data collection and simulation assessment. Such crowdsourcing efforts, however, can be critical in rapid response situations (e.g., earthquakes and other disasters). Indeed, information obtained can be used to create CrowdMaps or can be integrated into the crisis modelling conducted by responding agencies or officials (Liu, 2014).

However, the crowd can potentially participate in more components of the PM process. In a way, the crowd can provide the 'physical mind' or the 'wet-ware' to work in concert with the hard- and software of today to help communicate decisions and shape the behaviour of the masses. Crowdsourcing techniques and platforms can elicit opinions and support discussions that define the scoping and envisioning components (Gray et al., 2012). However, it is yet unclear whether active, reciprocal collaboration or empowerment can emerge from a crowdsourcing approach.

There is reason to assume that the advantages of crowdsourcing (e.g., scalability, reach, numbers) might be helpful for specific problems at advanced components as well. Advances in web technologies offer the tools to make PM available to larger distributed groups of stakeholders, not necessarily confined to one room and one discussion format. Some of the PM characteristics mentioned in Table 3 are likely to change in the future, creating more similarities with crowdsourcing. We briefly discuss some recent studies below that provide evidence for this.

Fraternali et al. (2012) explore how human capabilities can be integrated with computer platforms to enhance the effectiveness of ICT-based Water Resources Management. Crowdsourcing and using Human Sensor Webs (HSW) are some approaches towards such a goal.

One of the major challenges in getting local communities to use existing scientific models is the lack of input data. Crowdsourcing of the data needed, even if it is only qualitative, can help in such situations. For example, Lippe et al. (2011) describe a land-use modelling effort for a mountainous village in North Western Vietnam. The model treated farmers as agents and simulated plot-wise land use. Soil fertility maps for the region were important inputs for the model. Because conventional methods for preparing soil fertility maps were laborious and expensive, a participatory approach was used to collect the desired data. Giordano and Liersch (2012) present a fuzzy GIS-based system that combines local knowledge of experienced farmers with existing technical knowledge to monitor soil salinity. Their work focuses on increasing the reliability and usability of local knowledge, and the proposed approach allows capturing this information in a locally-relevant language. Fuzzy logic is then used to transform the qualitative information into information that is mathematically consistent and tractable for further use by information users, decision makers, and technical experts.

There are other relevant approaches that combine the local knowledge and interests of stakeholders and outside experts in the modelling process (e.g., Chow and Sadler, 2010). Of widespread interest is the rise of public-participation GIS (PPGIS) mapping to supplement data, to better understand local spatial knowledge and to develop scenarios for analysis in PM (e.g., Raymond et al., 2009; Debolini et al., 2013; Swetname et al., 2011; Chingombe et al., 2014).

Crowdsourcing can produce large arrays of spatially and temporally heterogeneous data that may be distributed across numerous servers. These are features of ‘big data’ that require specific methods of treatment and analysis. Even with high numbers of participants, one needs to pay attention to possible systematic bias (Nash, 2014). Depending on the type of data sought, crowdsourcing may be directed towards focusing on places where people live or visit, rather than where they don't.

A temporal bias may occur because people may contribute only at certain times, during certain seasons or days of the week, when they are able to do so. Consequently, there may be a mismatch between (1) locations and timing of data needed for modelling, and (2) actual locations and timing of crowdsourced data, significant examples being in times of stress, such as related to environmental disasters (e.g., De Longueville et al., 2009).

4. Treatment of uncertainties in participatory modelling

The variability and randomness that exist in availability and pricing of resources, data and information for the parameterization of scientific components of models, policies, resource demands, markets, expert and stakeholder opinions and beliefs are referred to as uncertainties. These uncertainties are further exacerbated by subjective decisions on the assumptions, simplifications and interpretations that are used when designing the model. All these factors affect model performance, and need to be characterized and understood. This section reviews advances in evaluation of uncertainties and their propagation through the modelling process and looks at strategies to adapt to this in the context of participatory input elicitation, PM, and participatory decision-making.

Uncertainties are broadly classified as aleatoric and epistemic uncertainties. Aleatoric uncertainty refers to a statistical uncertainty whose quantification does not get better with additional sampling. Epistemic uncertainty refers to the lack of knowledge of the true system, which relates to uncertainties about its mathematical form, applicable parameters, range of parameter values, etc. Bijlsma et al. (2011) further identify three categories of epistemic uncertainty: substantive, strategic and institutional. Each category essentially represents some lack of knowledge. Substantive refers to the substance of policy problems; strategic relates to how actors react; institutional relates to formal competencies, procedures, and conventions. All uncertainties need to be considered, and there are approaches from statistical theory (O'Hagan, 2012) and possibility theory (Page et al., 2012) to handle them. Each approach has its own merits and demerits in a stakeholder driven framework. The choice will depend on the application, type of data, users involved, etc. There have also been recent advances in representing ambiguous knowledge and in using imprecise probabilities (Rinderknecht et al., 2012).

There are three broad phases in PM approaches that relate to the treatment of uncertainties (Fig. 2): (1) their evaluation on the input side, (2) study of their fate and propagation (or generation) through the modelling process and (3) their analysis on the output side. On the input side, there are uncertainties in stakeholder inputs, expert opinions, measured data, and the functional processes represented in the knowledge base and in the construction of the model(s).

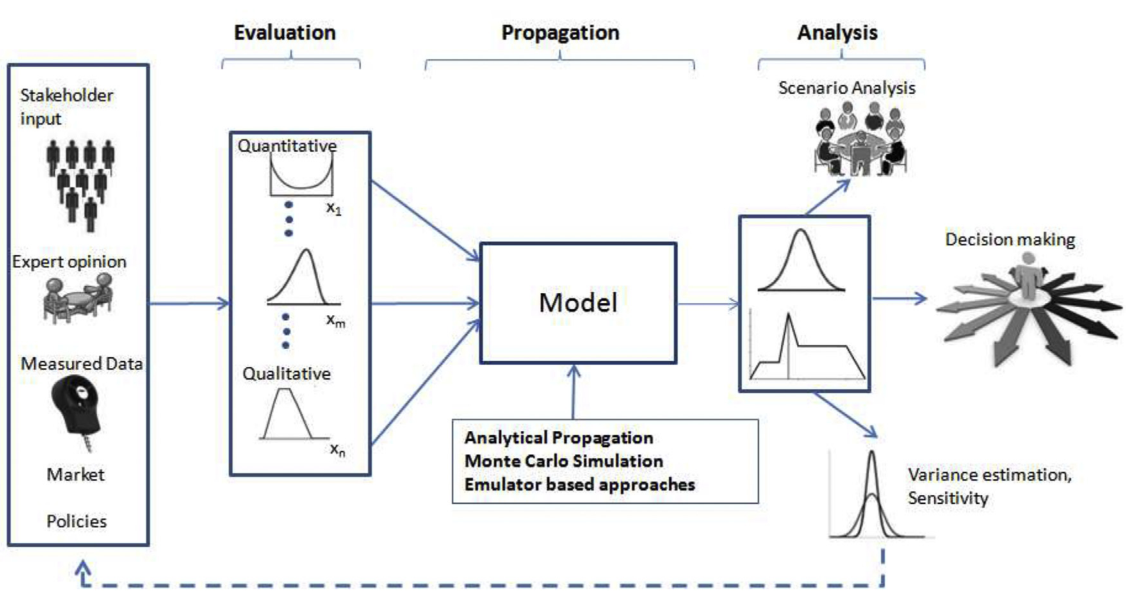

Fig. 2. Different phases in treatment of uncertainties. The statistical distributions presented are for illustration purpose and can take any possible shape. $x_1, x_2 \ldots x_n$ are the inputs.

4.1. Evaluation of input uncertainties

Many environmental models are deterministic, while in reality their outputs are uncertain. Uusitalo et al. (2015) reviews methods such as the use of multiple models, model emulation, and sensitivity analysis, to estimate the uncertainty of such deterministic models. Expert stakeholder assessment can also be used for estimating the variance around parameters and outputs of these models. When stakeholder opinion is sought (Lippe et al., 2011), there can be uncertainties in the knowledge of the stakeholders, as well as in the values of the input parameters which can be quantified using probabilistic approaches. For instance, the variance or quartile of the range of values for a parameter provides information about the level of uncertainty associated with its estimation. If the uncertainty is large, more stakeholder inputs might be needed (Sahin et al., 2016). This in turn supplies additional information that can increase confidence in the estimated uncertainty. Free web-based software tools that aid elicitation of expert knowledge as probability distributions are available (Morris et al., 2014; Fisher et al., 2012).

The elicited information can be aggregated (Krueger et al., 2012), either by using the level of agreement on the uncertainty, or by modelling the disagreement itself as uncertainty. Lippe et al. (2011) assessed uncertainty in the data obtained from stakeholders by examining the extent of disparities amongst them. Since mechanistic models generally show limited ability to model systems with very high uncertainty, Catenacci and Giupponi (2013) use a Bayesian Decision Network (BDN) approach. Inaccuracies resulting from the elicitation process itself, such as misrepresentation of elicitation results and difficulties in expressing individual beliefs, can lead to uncertainties in the probabilistic quantification of knowledge. These types of uncertainties are referred to as ambiguities. Rinderknecht et al. (2012) proposed and used imprecise probability theory to represent ambiguity. In addition, there can be bias in stakeholder elicitation. Scholten et al. (2013) propose a procedure for combining expert knowledge with local data and use a Bayesian approach to account for common cognitive biases. Page et al. (2012) attempt to minimize potential biases by first making participants aware of such biases before the elicitation begins, and then using a fuzzy ranking approach.

4.2. Uncertainty propagation by models

Once uncertainties in the inputs to the model are characterized, they need to be propagated through the model. Simulation approaches like Monte Carlo Simulation (MCS) are widely used for this purpose. Groen et al. (2014) compare MCS and other sampling methods, analytical propagation, and fuzzy approaches, in the context of life cycle assessment. Though robust, MCS is computationally intensive and therefore emulator-based techniques are used to alleviate this issue. Castelletti et al. (2012) provide a detailed introduction to MCS and propose a unified six-step procedure for the application of computationally-efficient dynamic emulation modelling. While many modelling and simulation frameworks exist that support uncertainty propagation, most of them are not exposed as web services and hence are not easy to access. Bastin et al. (2013) describe an architecture developed as part of their 'UncertWeb' project (http://uncertweb.org) to support development of web based tools for analysing uncertainty propagation and for visualizing and communicating the resulting output uncertainties to stakeholders. These tools support a variety of tasks such as: 1) quantifying expert judgements for assessing uncertainties of input data and models, 2) upscaling and downscaling spatio-temporal resolutions of model inputs and outputs, 3) uncertainty and sensitivity analyses, and 4) communication and visualization of results and associated uncertainties.

Wieland and Gutzler (2014) suggest simplifying complex quantitative models to improve the4 credibility of their results with non-expert stakeholders. Such simplified models are faster to develop and can be made more politically relevant by including relevant actors. However, they may fail to give an adequate measure of the uncertainties surrounding their results. Hence, they suggest a fuzzy system-dynamics-based "quick scan" modelling approach to overcome the problem of uncertainties in the results. Hall et al. (2014) also suggest keeping the model simple so that it can be communicated to the stakeholders and thus they can be included in a participatory approach.

It is important to represent uncertainties to provide insights about alternative management interventions. Kelly et al. (2013) review five common approaches that accommodate uncertainty and other considerations and facilitate stakeholder engagement. While system dynamics and agent-based models need substantial testing to understand and interpret data, Bayesian methods can help address uncertainty more easily. When conditions allow the use of multiple models, different modelling strategies may help elicit structural uncertainties that are present, but may not have been considered otherwise (for example uncertainties that extend beyond uncertain parameter values). Such multi-model predictions have often been used in climate modelling and operations research (e.g., Bates and Granger, 1969) and are increasingly used in other domains including soil and unsaturated zone hydrology (e.g., Guber et al., 2009). The downside of using a multi-model approach is the time and resources required to bring in the needed wider range of expertise, and to sufficiently explain the different modelling approaches to stakeholders and interested participants. Among existing modelling methods, Bayesian Networks are an attractive tool to account for uncertainty. They represent uncertainty as probabilities and can account for any type of variable or data. It is still challenging however, to develop Bayesian Networks that can account for dynamic uncertainties. Given that no single method can handle the evaluation of all types of uncertainties, research is needed for hybrid approaches that can handle propagation of multiple types of uncertainties through a model.

4.3. Model outputs and outcomes: uncertainties and adaptive strategies

Making decisions based on the results of a PM process ultimately requires an evaluation of uncertainties that are present not only in the knowledge base and the inputs provided to and propagated through model calculations, but most importantly, in the model outputs and predicted outcomes. These uncertainties cannot be disconnected from each other, especially because constructing, running and analysing the results of models are often an iterative process. We discuss the analysis of uncertainties in model outputs, and then turn to some adaptive strategies for evaluating uncertainties in scenario planning and modelled outcomes.

4.3.1. Output uncertainty analysis

Sometimes, the uncertainties associated with model outputs are large and highly sensitive to model construction and calculation processes. These uncertainties can be handled by making the stakeholders aware of them and by allowing them to manipulate inputs to the model and observe the resulting changes in outputs. Nino-Ruiz et al. (2013) present a 'Spatial Model Steering (SMS)' framework that helps stakeholders visually steer its key variables (e.g., rainfall, carbon tax and market price), manipulate climate change and global warming scenarios, and visualize potential land-use outcomes for various combinations of these key inputs. This allows the users to iterate and steer towards the outcomes that they believe are closer to their interests. Chen et al. (2013) propose a GIS-based methodology for quantitative assessment and spatial visualization of weight sensitivity in multi-criteria decision-making models. GIS-based visualization will assist stakeholders to better understand the extent of sensitivity to differential weighting and to minimize uncertainty. Reichert et al. (2013) propose a set of visualization tools to visualize uncertainty in predictions of the consequences of decision alternatives, and they illustrate the tools with a river-management DSS. Labiosa et al. (2013) demonstrate the use and benefits of exposing existing models to users through a web interface to help them evaluate and understand various scenarios. The users can run various queries and download model outputs, such as predicted land-use plans for the future. They can compare them with known land-use patterns using various statistical and graphical tools.

Expert elicitation can also be used to reduce the set of parameters used in sensitivity and uncertainty analysis of integrated assessment models. This is generally done by carrying out a Sobol sensitivity study. However, Butler et al. (2014) point out the negative consequences associated with using a priori expert elicitation for reducing the set of parameters. Wieland and Gutzler (2014) use system-dynamics methodology along with fast prototyping and easy visualization methods to compute and show changes over time in these variables to stakeholders.

4.3.2. Adaptive strategies for predicted outcomes and scenarios

Formulating adaptive strategies to deal with uncertainties is an emerging strength of PM approaches. Explicit recognition of uncertainty throughout the modelling processes is an important aspect of using models to design for resiliency and support of decisions. So is the interactive development and use of scenarios and the participatory analysis of predicted model outcomes. Graveline et al. (2014) develop a “participative foresight” method, which is a combination of a participatory approach and a consistent hydro-economic model to provide foresight of water demand. They simulated three constructed scenarios and observed that the scenarios differed significantly and concluded it was important to account for the uncertainties in water demand. Comparisons of participatory policy development and expert-based policy development in the face of uncertainties indicate that participatory approaches are more active and tend to increase the quality of the knowledge base, while expert-driven approaches are more passive (Bijlsma et al., 2011). Kalaugher et al. (2013) recommend a dialogue between researchers and farmers to take advantage of the diversity of perspectives and knowledge, thereby gaining an in-depth understanding of the range of adaptation options, the challenges in implementing these options, and the associated management responses.

Scenario planning is an approach that can help deal with uncertainties by encouraging exploratory dialogue about critical uncertainties and risks. Cobb and Thompson (2012) illustrate it with a case study of the US National Park Service (NPS). They explore how decision-makers and scientists in NPS together used scenario planning to understand and find innovative ways to cope with the social and scientific uncertainties associated with climate change. Scenario planning involves a shift from managing for a state of equilibrium to managing for changing states. It is a decision-making tool that is entirely focused on the future. Scenarios are stories based on expert judgement that capture perceptions about alternative future environments. They expand knowledge and reduce uncertainty by exploring trajectories of change leading from the present into a number of alternative futures. Murray-Rust et al. (2013) describe a procedure for interpreting story lines from general qualitative trends to local quantitative parameters by using Agent Based Modelling. Greiner et al. (2014) use a participatory model that was built using a mediated modelling process to deal with environmental, market and institutional uncertainties by carrying out scenario simulations. Transparency of the model facilitated discussion and discourse among the stakeholders and encouraged social learning, leading to improved system understanding and better decision-making under uncertainty. Social learning here refers to a process that uses group interaction and knowledge-sharing methods (De Kraker et al., 2011; Leys and Vanclay, 2011) to seek clarification of understanding and opinion, and convergence of perspectives of various stakeholders with diverse experiences.

While scenarios serve as heuristic tools, it is difficult to meaningfully attach probabilities to them. Bizikova et al. (2011) propose combining predictive, quantitative approaches with narrative-based qualitative methods to explore alternative scenarios, involving both scientists and stakeholders in the scenario-building process. They focus on the use of normative scenarios, or back-casting scenarios, where different futures are chosen, not on the basis of their likelihood, but rather based on their desirability. The participants then work backwards to identify pathways that might lead to them. This results in two-way communication and shared learning, integration of biophysical and socioeconomic aspects, and above all, endorsement from the stakeholders for the results. Game-like simulation tools and three-dimensional (3D) visualization techniques are used that generate and evaluate scenarios, include local knowledge and thus enhance public understanding of various dynamics and trade-offs.

PM processes, and their outcomes and consequent policy actions, depend strongly on how uncertainties are communicated to the stakeholders. The use of new media and methods such as gaming and visualization play a vital role in this process, which is the topic of the next section.

5. Digital and visual media for participatory modelling

The use of various media and formats for communicating in participatory contexts is expanding rapidly. Environmental problems that are often the focal point for convening PM processes tend to require the synthesis of diverse knowledge, data, methods and perspectives resulting in the need to communicate across multiple facets of problems and modelled representations (Hamilton et al., 2015). Graphic and visual media are frequently a core element in communication processes for groups (Gill et al., 2013; Hanzl, 2007). Traditional approaches range from the use of simple tools, such as plans, physical models, sketches or other communication devices (Gill et al., 2013). Beyond simple display of data, information and knowledge about a problem, visualization and other modes for describing systems, problems or ideas are important mechanisms for creating shared understanding. In PM, the shared understanding about complex problems serves as a critical element for driving participant dialogue, deliberation, and social learning (Pierce and Figueroa, 2015). The descriptive and illustrative forms and techniques used to represent important aspects in a PM case can act as artefacts, or boundary objects, that enable communication for bridging understanding among participants (Cash et al., 2003; Rose et al., 2015; Pierce and Figueroa, 2015). Broadly defined, visualization is the process that makes something visible; and the forms or media that are used to convey a visual representation of an idea frequently use digital methods. Visualization techniques are some of the most useful ways to explore and try to understand large sets of information or knowledge (Tufte, 2001; Yau, 2011). Recent advances in digital and communication technologies are leading to new forms of visual media for use in group participatory contexts (Hanzl, 2007). Use of visual media formats provide new avenues and platforms to aid PM across all stages of interaction with participants and stakeholders with descriptions of use cases reported in the PM literature including uses of (1) multi-dimensional graphics from the more common 2-D and 3-D representations through emerging formats in virtual and augmented realities, along with data fusion and interactive formats, (2) participatory planning geographical information systems (PPGIS) and group decision support systems, and (3) gaming technologies and serious game applications.

The following sections give brief and non-comprehensive descriptions of these rapidly evolving areas in application to PM and focus on some of the promising trends. The area is a rich field for research at the case study level. It also lends itself to advanced inquiry in the many fields that could advance generalizable knowledge about PM, for example social learning, conflict resolution, group interaction patterns, digital facilitation, and decision support. Yet, all science-based or model visualizations in PM target improved communication of information, data, and knowledge about issues of relevance to stakeholders.

5.1. Multi-dimensional graphics, data fusion, and interactive formats

Visual communication offers a compelling and, often, persuasive approach for sharing elements of a problem and engaging in a substantive process with stakeholders. Visualization in the form of plans, sections, and physical models has been commonly used for stakeholder communication in the past. Advances in technology allow for increasingly virtual, accessible, and interactive presentations of information. Whether or not the new visualization approaches will replace or complement existing techniques, remains unclear (Gill et al., 2013). Data and information with spatial components, particularly in the case of environmental planning problems, are most often presented in the form of two-dimensional maps (Pettit et al., 2011), though recent advances in hardware and software are leading to three-dimensional graphics and immersive environments (Bizikova et al., 2011). Some authors are reporting advances and improved outcomes in participatory processes using 3D virtual environments. For example, results from a case study of the Yuansantze Flood Diversion project (Lai et al., 2011) indicate that community support for a flood control project in China improved from 50%, before interactions with a 3D virtual environment, to 90% afterwards.

Traditionally, visualizations have been static, but interactive data fusion and dynamic interfaces are emerging as a new modality to deliver visual elements of PM. Recently new forms of visual communication are incorporated into PM case studies, such as mixed-media film-making (Nettley et al., 2014), with observations on the increased credibility and trust generated through the use of snapshots from stakeholders in presentations as well as the iteration of stakeholder involvement through time.

From a functional perspective, all information visualizations in PM target improved communication of information, data, and knowledge about issues of relevance to stakeholders. Yet, many of the tools that are available and used for PM focus primarily on the rudiments of displaying model components and outputs, rather than on model inputs, specifically, empirical observations, participant beliefs and mental models, and more generally, the structured knowledge base used to construct the computer model(s). Computer tools, possibly assisted by trusted human mediators, could greatly improve visualization, exploration and understanding of such a knowledge base: not only the information and beliefs incorporated in the model construct, but also those excluded or initially ignored from consideration (i.e. the negative space of the model construct: mentioned later in section 5.1). Visualization and communication tools (present and future) can have a role not only in understanding and exploring the knowledge base of a model construct, but also in eliciting that knowledge base from PM participants. The AGORA-net Argument Visualization provides one example approach capable of aiding PM processes from initial stages through to culmination (Hoffmann and Borenstein, 2014). A similar approach could be adapted for use in informal PM settings to engage stakeholder groups in substantive dialogues mediated through the use of interactive visuals. As the field of PM advances, improvements in the modes and function of data presentations will be needed.

The uptake of digital and visual media in PM is notable and necessary because of the need to communicate effectively and facilitate the use of disparate information sources. Visualizations can serve as facilitative artifacts, triggers, mechanisms or guides during modelling and stakeholder processes, yet visualizations are not an end in themselves (Pierce and Figueroa, 2014; Pettit et al., 2011). Visualizations are a tool that may augment communication and understanding. While digital media offers a wide and readily observable set of benefits, there are also inherent risks that should be considered in establishing best practices. At a minimum, evaluations of the effectiveness of visualizations should consider three dimensions (Sheppard and Cizek, 2009): understanding, credibility, and fairness (e.g., non-biased presentations). Moreover, accuracy, representativeness, visual clarity, interest, legitimacy, access, and framing (Sheppard and Cizek, 2009) are candidate factors that may be useful considerations for PM processes, particularly for landscape or map-based visualizations.

While visualizations and new media presentations can be compelling, there is a significant risk that the medium of delivery can overshadow the information needed for stakeholder understanding and perception. Recent technological breakthroughs, rapid uptake by the scientific community, and increased public accessibility to interactive mapping, for example, highlight both the benefits and risks of popular visualization interfaces (e.g., Google Earth) or other platforms that may be used in participatory GIS exercises. At the same time, because of rapidly increasing use by the public, applications of interactive mapping (or Web GIS) are an area where collaborative and interactive visualizations are uncovering new understanding: best practice is being determined for the use and dissemination of visual spatial information (Sheppard and Cizek, 2009).

5.2. Participatory GIS and group decision support systems

Spatial collaborative technology systems for creating new knowledge that can be stored, maintained and interactively used, are particularly relevant to PM and decision support in environmental cases: PPGIS (public participation geographical information systems) and its sister, PGIS (participatory GIS), and, GDSS (group decision support systems). Although not all visualizations used in PM are map-based, many recent advances are due to the wide adoption and use of GIS and (P)PGIS technologies.

(P)PGIS is an element included often in spatial decision support systems (SDSS) using deep participatory processes, based on well-developed RRA (rapid rural appraisal) and PRA (participatory rural appraisal) techniques, to incorporate spatial components into a planning problem, thus creating visualizations of the spatial data (e.g. McCall and Dunn, 2012). The driving principles behind PGIS having high significance for PM are that the core intention is to capture people's valuable (but often invisible) spatial knowledge, and utilise it better for functional purposes in planning or management; and beyond this, to privilege these non-authoritative sources of information, that is the knowledge of stakeholder citizens. This is in line with the aims of Citizen Science. Consequently, this promotes stronger feelings and narratives of agency in the public, i.e. citizens feel more included, engaged and valued for their delivery of useful knowledge, and gives them a reason to want to be involved in PM. Finally, not least, (P)PGIS is often considered to garner more (spatial) information for less financial outlay – citizen providers vis-à-vis expensive consultants. The PGIS techniques applied in PM frequently begin with a cognitive (mental) sketch-map on a blank 'no names' map, and marking relevant locations – roughly, without emphasis on high spatial precision. For most PM purposes, these are subsequently transferred to spatial images – aerial photos or remote sensing images (Google Earth is easily accessible) - for geo-referencing and geo tagging, or to participatory 3D models. Depending on the number and types of people participating and the time resources they commit, this is followed by grounded field work for pertinent area and point information such as hot spots and boundaries, employing mobile GIS: iPads, or smart phones with tracking and/or GIS platforms like CyberTracker or ODK. The specifically spatial information is supplemented with other participatory techniques in photography, video, sound recordings. It is important that the maps and spatial images for further public debate and feedback are prepared with appropriate graphics software so as to attempt to represent the ambiguity and implicit uncertainties (section 3.1) in people's perception of spatial phenomena.

Spatial decision support systems (SDSS) integrate operational data with other problem-related data in a GIS format using platforms that enable data collection, analysis, and interpretation of spatial information in a way that is useful for decision-making. SDSS have been used across a number of environmental problems and their primary visualization elements are anchored to spatial or geographic locations. However, in a case of users interacting with a natural user interface, a Touch Table (Arciniegas et al., 2013), the results indicated that, while quantitative GIS maps in these media provided large quantities of information, they did not ultimately produce the most effective results – the cognitive effort needed to process the volume and format of the spatial information seemed to be a critical issue. These results concur with earlier research (Jankowski and Nyerges, 2001) that indicate that maps are useful in early stages of problem formulation, but what remains questionable is the ability of GIS visualization to present the various categories of information in ways that increase both representativeness and efficiency for decision-making. Measuring the effectiveness of such visualization technologies and analyses merits further inquiry.

Tangible formats for displaying spatial data have been used for many years and physical modelling ("maquettes") has been applied in situations of land-use conflicts, scenario development for natural resource management, and other applications. P3DM (participatory 3-dimensional modelling), an approach combining tangible with digital methods, demonstrates that physical modelling can greatly enhance participatory outcomes, especially in terms of the depth and duration of the participatory communication between diverse stakeholders, and the contrasting perspectives that are created for in-depth discussion by jointly viewing a large physical model (perhaps 3 by 2 m or more) of say, a disputed land unit (Cadag and Gaillard, 2012; Gaillard et al., 2013; Hardcastle et al., 2004).

GDSS encompass a moderately larger set of collaborative technology and applications; and generally include interfaces and visualizations that are broader in nature than SDSS, from the perspective of the data types and tools and that are included. GDSS emerged as systems intended to provide computational support to collaborative decision-making processes (DeSanctis and Gallupe, 1987). Important distinctions must be made between the GDSS technology and the engagement process with stakeholders. While the visual and computational interfaces may support bringing complex information into a PM project, the technical interface cannot replace the importance of facilitation and social process management. The technical guidance from GDSS may be useful to a stakeholder group, but understanding the social learning and group interactions (e.g. the human side of any decision support process) that pose the greatest opportunities and challenges to advances in the field of decision support (Adla et al., 2011). Recent advances in GDSS are leading to levels of performance that will enable automation of facilitation tasks, at least partially, and will increase the ability of facilitators (even novices) to monitor and control the meeting process (Adla et al., 2011). A GDSS could also provide indicators to suggest when additional information needs to be presented or integrated into a presentation to a group, and it could make recommendations on mechanisms to help move a group towards agreement (Adla et al., 2011). Interactive and automated GDSS lead to more immersive and automated experiences. In that sense, they share similarities with interactive gaming applications to aid participatory modelling and decision-making.

5.3. Gaming enabled PM processes

Gaming environments show potential for accelerating elements of PM. Already a wide range of visualizations exist in a continuum between conceptual and experiential, and an increasing number of interactive visualization tools in the form of games are used in PM. Gaming environments are reported as a proven approach for teaching decision-making skills (Van der Zee et al., 2012) and for enabling social learning; they may translate to a compelling method for stakeholder engagement as well (e.g., Mayor et al., 2013). Many different types of games can be useful, from logic and strategic games to games with embedded simulations of complex processes (e.g., Van der Zee et al., 2012), and there is also an emerging set of immersive game environments (e.g., Lai et al., 2011; Zhang et al., 2013). In a few cases, PM researchers are leveraging advances from the gaming industry, such as game controllers, stereo glasses, and mobile application marketplaces, to augment and test PM processes and methods (Gill et al., 2013). Interactive gaming environments and platforms increase the allure of PM for stakeholders. Virtual environments (VE), 3D and immersive environments especially, can be expected to introduce a bevy of unexpected benefits and costs, and to also spur further demands for innovation. There is a growing interest in connecting virtual geographic environments with models (Lin et al., 2015). The expectation is that VEs can provide vivid and persuasive tools to present model results, while models can enrich and bring more meaning to some of the processes embedded in the VEs.

Generally, participatory models can be categorized within an approach called 'serious gaming' that has been used on a variety of problems (Djaouti et al., 2011). The field was shaped by Sawyer (2002) who defined a 'serious game' as one that connects a serious purpose to knowledge and technologies from the video game industry. Serious games are computer games designed for a purpose other than pure entertainment – they combine a gaming environment (appealing interface and graphics, intrigue, mystery, etc.) with a serious, problem driven, educational dimension. Serious games often contain a model of an existing reality defined as a system and its interactions (Sauvé et al., 2010). Because of their alignment with real-world problems and data, serious games offer a great opportunity for PM to merge simulations and integrated models within gaming approaches. Other formats that are emerging as game-based approaches for PM include role-playing games (RPGs) and round-based games (RBG's), along with 2-D, 3D, immersive visualization and other technologies. The perspective of a gaming participant can be varied according to a number of factors. RPGs easily lend themselves to multi-stakeholder processes and share a focus on the roles, interactions, states, and traits of entities or characters within the game, while round-based games can encourage social learning, collaboration and interactive dialogue among participants.

Participatory and RPG approaches in the literature have addressed the adaptive nature of systems and community response to uncertainty (D'Aquino and Bah, 2013a, 2013b; Martin et al., 2011). Results from game-based case studies indicate that the methods aid in demonstrating the dynamic nature of systems over time together with the dependency of system responses to decisions made by participants. Gaming environments serve to create shared knowledge spaces where interactive and iterative actions can be tested or 'played out' by participants. Results of a study by D'Aquino and Bah (2013b) indicate that game-based approaches are well situated to enable resilience thinking. In that study, gaming aided indigenous thinking regarding adaptability to uncertainties and improved the potential for adaptive management. Stakeholders were able to model their own perceptions of environmental change in the context of climate-change uncertainties; and the process created an expanded sharing of knowledge among disparate stakeholders and included the incorporation of local indigenous knowledge.

Gaming introduces new fields of subject matter expertise that need to be developed further. Technological challenges are also introduced through the need to connect data and information resources to gaming platforms and frameworks. Modelling frameworks that support game design are typified by five stages; (1) characterization of characters, content, and game operations (e.g., rules), (2) model development to capture key linkages and factors, (3) visual design and styling of the modelling elements, order of gaming operations, and player interactions, (4) game construction, and (5) preparation for game use, such as prototype testing and creation of an instruction manual (Greenblat, 1988; Van der Zee et al., 2012).

6. Participatory judgements, decisions, and informed actions

As discussed above, communications and engagement of stakeholders (including professionals) is affected by human perceptions. In turn, human perceptions, beliefs, and biases (of individuals and groups) influence what projects are chosen, who engages or is engaged, how models are put together, how models are applied, and what decisions and actions are consequently drawn. Our human characteristics and limitations affect all our judgements and decisions. This section presents some of the essential concepts needed to understand, and potentially counteract, some of these characteristics and limitations in a PM process.

Broadening our context, we then seek to address the following questions. How does a PM effort fit in the broader context of good governance (UNDP, 1997; Ribot and Larson, 2005) and enabling well-informed management actions and policy-making, not just for the current benefit of a local community, but sustainably, for the greater good? Can a structured process be developed that helps meet the longer-term, larger-scale opportunities offered by PM and its consequent community decisions and actions while taking into account some of the inherent human dimensions? We attempt to outline such a process.

6.1. Cognizance of human biases and heuristics

Biases affect human judgement and actions. They cause tendencies (1) to believe in, or pay attention to, some ideas (or people) to the detriment of others, or (2) to make decisions or act in some innate ways. Taking cognizance of human biases, and overcoming them when needed, is a major challenge and a necessity for "post–normal" science (Funtowicz and Ravetz, 1993) and for integrated environmental modelling (Glynn, 2014, 2015; Hämäläinen, 2015). Participatory processes need mechanisms to explicitly recognize human biases and heuristics (i.e. mental shortcuts) when they occur, and to resolve them or compensate for them if needed. Well managed groups and participatory processes will avoid the potential traps offered by unwarranted "group think" (overwhelming dominance of a perspective or belief) and/or inappropriate dominance of one or a few individuals. In addition to biases that can negatively affect the dynamics of participatory processes, there are also many other human biases that can negatively influence the way that knowledge and data are put together, how models are constructed, and how model results are interpreted and reacted to.

Confirmation bias, framing biases, steady-state bias, creeping normality, binary bias, cognitive discounting, causality bias, jumping to conclusions (cf. section 5), belief in human exceptionalism and separateness from "nature", are all examples of biases that can negatively affect the pursuit of human knowledge and that need to be considered in PM. Glynn (2014, 2015) discuss these and other biases and make suggestions to take cognizance and compensate for these biases. Approaches include: (1) assessing the negative space of information constructs, (2) assessing the past and the future of situations, not just the present, (3) getting diverse, open, perspectives, (4) red-teaming,[2] (5) using structured, accountable, traceable, transparent processes for information/knowledge gathering, participatory interactions, and decision-making, (6) ensuring adaptive follow-through on any human decisions or actions taken, and (7) following a principle of continuous learning, review and reflection (e.g. Rondinelli, 2013). In his examination of behavioural issues in environmental modelling, Hämäläinen (2015) also considers practical response measures and suggests that "systems thinking" needs to evolve to "systems intelligence". In that context, Critical Systems Heuristics (CSH; Ulrich and Reynolds, 2010) provides a reflective framework and tools that enable exploration of systems, specifically their abstractions and human perspectives, through a set of "boundary questions". These questions test the sources of motivation, knowledge and legitimacy to judge how they are (or ought to be) applied to determine social roles (i.e. types of stakeholders), specific concerns (i.e. types of stakes), and key issues in a system of interest. Answering these questions can help determine system biases and simplifications.

6.2. Behaviours: from individuals to groups to a hyper-connected world

The behavioural and biological sciences have made significant progress over the last 40 years in helping us understand human motivation (e.g., Koltko-Rivera, 2006; Maslow, 1943; Tay and Diener, 2011), human judgement and decision-making (Kahneman and Tversky, 1984; Tversky and Kahneman, 1974) and the sources of human adaptation (Buss, 2004) and learning (Simon, 1990, 1991): the way we think, the way we act, the way we learn and adapt, both as individuals and as groups. Many of our human behaviours and beliefs are understandable in the context of: (1) our evolutionary adaptation, (2) our cultural adaptation, traditions, and rituals, (3) our experiential learning acquired over individual lifetimes; and (4) sometimes (more rarely than we'd like to believe), our capability for conscious, structured, traceable thinking that involves abstraction, deductions, inferences, and logic. Our genes and memes[3] (Dawkins, 2006) have been optimized for their own reproduction and survival (Stanovich, 2005). Their controls of our judgements and actions align best with our human interests when we are faced with situations that have been frequently experienced in the past and that require local, short-term, decisions and outlooks; and conversely, they align badly when trying to handle long-run problems spilling over into faraway places and cultures and future generations. Thus, those same controls do not necessarily prepare us well to manage our natural resources and environments in today's world, which is hyper-connected and which often brings situations that we've never experienced before, at the level of individuals and of entire communities.

Our world is rapidly changing and hyper-connected, not only in a digital sense, but also through the rapid transport or dispersal of physical and biological materials (including ourselves). In today's world, our increasing human population, which is much greater than our evolutionary past, exacerbates the pressures placed on the availability of our resources and the quality of our environments. In today's world, our rate of technology development often exceeds our societal ability to adapt to, and to best use, those same technologies, at least if we consider the longer-term good of the broadest human community. The smartest use of our new technologies and emerging societal processes (including PM) requires that we gain a fundamental understanding of what drives our behaviours, judgements and decision-making. In turn, that understanding, when combined with our new technologies and social constructs, has the potential to transform the way that we acquire and transfer knowledge and best manage our resources and environments. But to be successful in that goal, any approaches that we devise, such as PM, will still require innate 'ownership' by individuals and communities.

6.3. Ownership starts with the local, the present, and the demonstrable

Tsouvalis and Waterton (2012) observe that in the natural and managerial sciences, participatory practices are often portrayed with considerable optimism, especially if they are viewed as potentially able to lead to better decision-making, while in the social and political sciences, such participatory practices have often been characterized as intensely disillusioning (e.g. Cooke and Kothari, 2001). Both of these attitudes can result from a lack of understanding of the science and of the issues relevant to a community's (or participatory group's) desire to better manage their natural resources and environments. Our own view is that reflexive, conscious, transparent, inclusive participatory practices can help communities to learn to take greater ownership of their resources and environments (Irwin, 1995). A PM process that resonates locally in the present and that has clear, timely and demonstrable consequences, will engage its participants. And a community's engagement and ownership is never greater than when the perspectives and recommendations of a PM effort are translated into policy decisions and actions and when community participants are willing to be held accountable for those decisions and actions ('co-learning' and 'co-management'). In turn, the local and historical knowledge of community stakeholders often exceeds that of scientific experts and policy or management professionals (Fischer, 2000) and will generally be critical to the success of a PM process.

6.4. From the madness of herds to the wisdom of crowds: extending PM for a greater good

Consider a cyclic framework for the generation of information, for the declaration and adjustment of beliefs, and for the enabling of decisions and actions that (1) provides structure, (2) addresses the reality that human decisions often have poorly-anticipated consequences, and (3) potentially allows for well-considered corrections, if continuity and accountability can be socially ingrained. Our framework is deliberately idealistic, but offers, at a minimum, a structured perspective for societal progress in the management of natural resources and environments. There is some clear overlap with the PM process components discussed earlier in this paper, but there are also some differences because of the broader context that is being proposed.

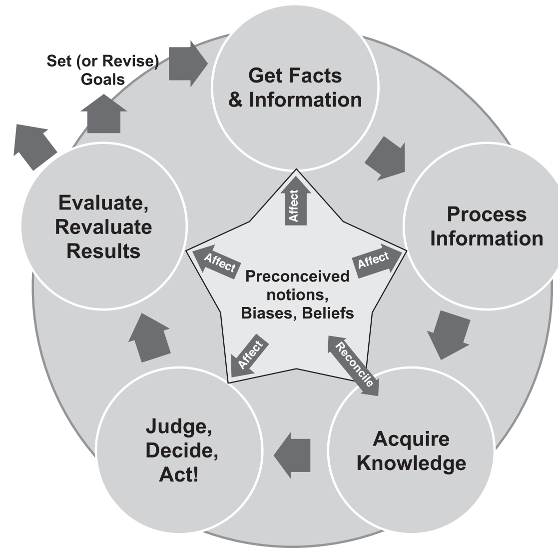

Fig. 3. A human model for science and decision evaluation. The cycle starts with setting goals and ends with evaluation of results. Either end it here or loop back into the cycle.

There is a fundamental, human-driven, cycle to acquiring data, gaining knowledge, building models, and taking actions (Fig. 3). An essential part of our cycle is that it explicitly establishes that a priori knowledge and beliefs are existential elements, rather than peripheral distractions from an otherwise 'rational' process. Once the goals have been set, a possible first step in our cycle can involve getting facts and objective data. Obviously, some conceptual or mental models and a priori knowledge will drive this process. By definition, these are not likely to be "objective". In many cases beliefs can overwhelm knowledge. The individual or group needs to establish the a priori knowledge base (e.g., functional relationships, causalities, effective or likely processes, parameter ranges). It can (1) Trust individual experts or participants to contribute their a priori knowledge base, and/or (2) develop a Joint understanding of the a priori knowledge base. We will call this the Trust and/or Join (TJ) decision and action process. Most likely, the process of establishing a group conceptual model will involve a combination of the two. Next, some understanding will be established of (1) what types of data are critically needed, over what spatial and temporal scales, and (2) what data can be easily, practically, or affordably obtained. Again, the group needs to trust individuals to obtain the data and/or engage in Joint-Fact-Finding, a TJ process.

Interpreting data and facts to develop information. Once the facts, observations and data have been obtained, they need to be interpreted or transformed to develop a coherent information set that can now potentially add to the conceptual model and a priori knowledge base. TJ decisions and actions also must be established.

Internalizing knowledge. Knowledge is commonly defined as the intersection between "facts" and "beliefs". Knowledge differs from information because it requires joining information (interpreted, organized, facts) with the strongly held belief systems that we all have, whether we acknowledge them or not. Those beliefs are acquired through multiple ways, but primarily through our cultural/ritual traditions, experiential learning and also possibly through atavistic (genomic) inheritance. It is well established (e.g., Stanovich, 2005; Heylighen and Chielens, 2008; Fagin and Halpern, 1987; Ariely, 2010; Chabris and Simons, 2011) that people rarely accept facts and highly objective information that should logically encourage them to change their behaviour, unless they can absorb and join the information with their belief and value systems. People rarely change their beliefs through logical argumentation (Anderson, 1983; Anderson et al., 1980). And they will use their beliefs to "cherry pick" explanations and facts that most closely match their beliefs. Consequently, internalizing knowledge at both the level of each participant and at the level of the group is a critical step in developing, and gaining a basic level of trust and acceptance, for any numerical models used as part of a PM process.

Deciding and taking actions based on the constructed model. Human characteristics and limitations become important at this component of the TJ action process, because they affect human judgement, decisions and actions, at both individual and group levels. Human behaviour and political or cultural needs often trump carefully considered/analysed, conscious, and logical behaviour, especially if the needed behaviours and situations have not been experienced iteratively (with appropriate lessons learned) through the actors' lifetimes and/or through human evolutionary adaptation (Glynn, 2014; Stanovich, 2005, 2010, 2013; Stanovich and Stanovich, 2010). Ideally, decisions and actions are taken, on the basis of the model construction and outputs, either by the participatory group and/or by the external entities that it advises (although it is much easier if those entities are engaged participants). Ideally, based on the modelling work conducted, the expected results of the decisions/actions are recorded. Those results should provide an indication of the type and magnitude of impacts, over temporal and spatial scales, of the decisions and actions taken.

Evaluating decision/action outcomes and gaining further understanding through post-audits. This final step in our cycle involves analysis of the decisions made and actions taken based on observations of their consequent impacts. The analysis is also subject to human or societal bias, but it treats the decisions/actions taken, and the consequent observations and post-audits, as the equivalent of a scientific experiment and an opportunity to gain system understanding (cf. Rondinelli, 2013). The understanding then leads to an evaluation or re-evaluation of the models constructed and of their supporting knowledge and information bases. Based on the community's willingness, the cycle may iterate again: acquire data, process information, build and run model(s), declare beliefs and internalize knowledge, take actions, observe and evaluate results.

How does this "knowledge-to-action" cycle compare to the previously discussed PM processes (cf. Figs. 1 and 4)? The cycle as a whole is similar to an adaptive management process and shares all its potential pitfalls (e.g., Argent, 2009; Craig and Ruhl, 2014; Williams and Brown, 2012; McCall and Dunn, 2012; Williams et al., 2009). There are many components of the cycle that have clear links to PM, as has been conducted to date on specific issues and in specific places. However, some of the components differentiate themselves from current and past PM efforts.

This cycle has to first be realized at the level of each individual engaged in the participatory effort, before some group consensus (or compromise) can be achieved on the basis of a "harmonized" community understanding of the cycle. Indeed, ultimately, a broader community outside of the PM group will also need to be engaged in realizing and accepting this "knowledge - to - action" cycle. The process of integrating individual perspectives into a few

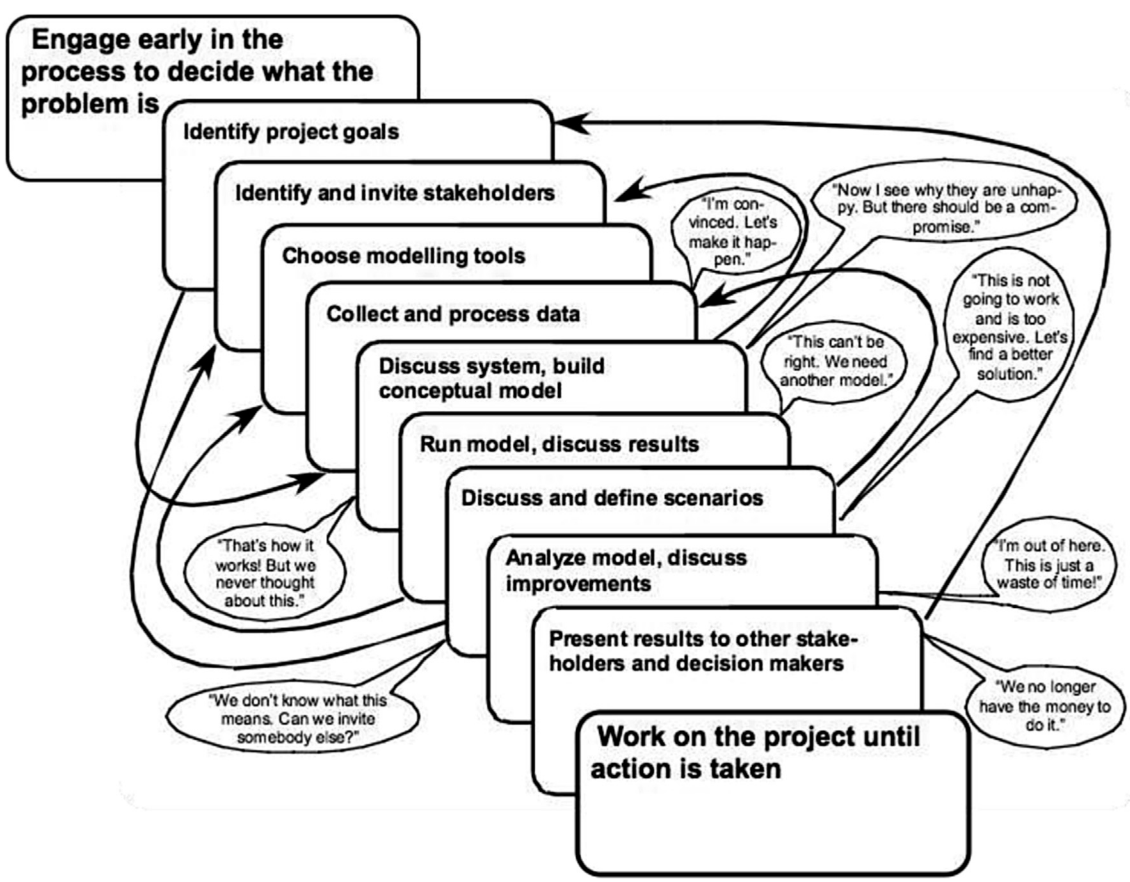

Fig. 4. An extended cycle of PM. Scientists and modellers are expected to take a more proactive role in defining the problems and tasks for scientific inquiry rather than only serve the policy makers in providing answers to questions asked. Eventually, also more participation in the actual action-taking is essential. (Based on Voinov and Bousquet, 2010).

"group perspectives" can be used to help ascertain and engage the external community, assuming that the group has sufficient diversity to represent the external community. That diversity is essential. The perspectives presented, or any consensus achieved or judgements developed, should aim to reflect the best informed, most reflective, diverse, transparent, and structured melding of voices, of sources of information, and of acknowledged beliefs. The wisdom of a "crowd of independent broad-thinking minds" is sought (Surowiecki, 2005), rather than the "madness of a herd" (MacKay, 1841; Petsko, 2008).

One major distinction is that in the PM process there is often a lack of continuity and of a well-defined sequence of events. We have deliberately referred to 'components' rather than 'stages' in Fig. 1. That was to stress that there is no definite order in PM processes. In contrast, the 'knowledge – to – action' cycle assumes a well ordered sequence of events. Perhaps introducing this structure in the PM process would also be beneficial? Perhaps mimicking a 'natural' course of knowledge acquisition could help organizing and conducting the PM process in a more orderly way?

Our comparison also highlights the need for more explicit acknowledgement and discussion of beliefs and preconceived notions in the PM process. The operation of the 'knowledge-to-action' cycle depends on agreement by participants and communities on some core principles (cf. section 1, and the Conclusions below). These should provide the background to establish rules of engagement and of behaviour – non-compliance with which may lead to participants being asked to leave the group modelling effort. Establishing a 'Trust and Join' process implicitly means that documented and defensible "dis-join" may occasionally be needed. Setting rules and 'core principles' early in the PM process is essential.

7. Conclusions and final suggestions

7.1. PM creates value in many different ways

It engages participants in a greater understanding of the tradeoffs between resources needed and the impacts of extraction of those resources. It fosters their cognitive development and, potentially, their acquisition of new tools or capabilities that may be useful to them outside of the modelling effort. If the modelling effort is successful, the results will be translated into better, and more informed management actions and policy decisions. It would be a shame to lose track of the advances made through effective PM efforts and practitioners, and perhaps more importantly, to fail to capitalize on those efforts to help foster future advances in PM, and thus in the improved management of natural resources.

We have three important proposals in this regard:

1) Create a database of participants in PM exercises with some indication of their contributions in specific modelling efforts, and a time-stamped assessment of their technical proficiencies and progress made either externally, or as part of the PM efforts they engaged in. Participant consent would undoubtedly be needed for their inclusion in the database, which means that it would not necessarily be representative of all participants. In addition to technical capabilities, the database might also ideally reflect group (and self-assessment) measures of the (1) critical thinking and (2) collaborative capabilities exhibited by individual participants. There are many sensitivities that would need to be skillfully addressed because each stakeholder or participant invariably brings unique characteristics that can not be easily recognized. However, the aim of this database is (1) to facilitate and support PM, (2) to recognize the contributions of participants, and (3) to support their further development. The database could be hosted through some existing infrastructure, e.g., Orcid - a citizen science research portal (http://orcid.org/). This could help in establishing some cross-project reward/recognition/gaming mechanisms for citizen scientists.
2) Create a database of PM efforts or case studies and their outcomes and aftermaths, specifying at a minimum: (1) the issues addressed and goals of each effort, (2) the technical capabilities used (models and other technological tools), (3) the consensus, majority, and/or minority recommendations made as a result of the PM, (4) the management actions and policy decisions taken as a result of the PM, (5) an assessment of the follow-ups and long-term effects of the PM processes, and (6) an indication of other factors that may have weighed in beyond the recommendations or results of the PM.
3) Prepare, and work towards, a 'Good Practice Guide for Practitioners, Planners, NGOs, Civil Society'. This is not simply an academic exercise nor a journal paper, but a practical guide to potential users about which tools and methods are most appropriate for different components (or stages) of a PM exercise, - real-world experiences, the pitfalls, challenges, handy hints, key moments, etc. It can build on the already established general knowledge of public participation (e.g., Creighton, 2005). It should be written in collaboration with a sympathetic planning or public agency or NGO. There is a plethora of tools and methods that aim at similar objectives and targets, but those rarely refer to each other or attempt to fit in a unified framework. Covering the vast literature on this topic across disciplines would be arduous. Such a Guide would be a major challenge: but we need a comprehensive and critical guide to determine the best ways to use these new tools and methods, preferably in a coordinated, structured manner.

Bringing the three products mentioned above into existence will require putting priority on the needs of modelling practitioners and planners rather than on the needs of contributors who may be primarily driven by a traditional academic reward system. Typical academic reward systems focus on the publication of "exciting" innovative, but theory-framed material, and not on the application or testing of existing tools and methods. Metastudies that work towards ideas (2) and (3) above – studies that review and contest actual grounded PM studies and that critically examine a range of tools and techniques – are rare to find but essential to improve stakeholder participation and PM practice.

Although there is usually a common structure to PM (cf. Fig. 1), the actual processes and sequence of events vary depending on the goals of the modelling, and on the participants involved. PM participants aim to achieve some general consensus on participatory processes, their mediation, and importantly, on a core set of principles to help guide the discussions and processes. There is no set of principles that will always apply; and there certainly will be multiple ways to implement any given set of core principles, because they always depend on the specific issues and participants involved.

An example set of principles is included here:

1. A PM process encourages the traceable, structured pursuit of knowledge. This means that there are mechanisms, procedures and modalities for tracking, determining the origins, and exchanging and sharing information related to the project and modelling process – this is valid for all stakeholders. This does not necessarily mean that all parties will have to accept, use, or weight the sources of information of information in the same way – but there is a mechanism for explicitly sharing and discussing the available information.

2. Because knowledge cannot truly be created without an explicit assertion of beliefs, a PM process includes procedures and modalities to bring credible transparency to individual and institutional beliefs. Political, ideological, ethical or spiritual differences will often occur between different stakeholders or participants in a PM process. Recognizing their sources and respectfully discussing the differences in beliefs will be essential to achieving some form of resolution that will allow the PM process to proceed and have its results accepted.
3. A PM process explicitly recognizes, and when appropriate, possibly compensates for, differences in the power of different constituencies, whether institutionally or individually-sourced.
4. A PM group listens, communicates with, and responds to a great diversity of perspectives. It activates procedures for identifying and responding to a diversity of representatives of the greater community who are impacted as a result of any decisions or actions resulting from the PM. This effort potentially includes representatives (somehow identified) acting in the name of future generations or other absent parties.
5. A PM group has processes to identify potential winners and losers amongst the present and future human constituencies affected by any simulated decisions or actions, and it includes them in appropriate interactive activities.
6. Even if not incorporated into the numerical models developed, the broader impacts of the PM process and its specific issues are taken into consideration. Beyond the immediate resource or environmental issues driving the group's interests, there is an effort to examine other natural or human resources that might be affected, as well as any environmental changes, in the present and the future.
7. The degree of commitment of PM participants is gauged and explicitly expressed. Beyond the many side benefits of PM (e.g., learning), there is a commitment from all participants to the PM process and to its outcomes, for example by seeking follow-up of PM results into meaningful policies and/or community action.
8. Acceptance of PM results and recommended follow-up actions is agreed to in advance, with the understanding that the PM process will be fair, but also probably imperfect. Before initiating or proceeding with a PM process, the participants state whether (or not) they will eventually comply with the outcome of the process, or what further procedures they would require to do so, e.g., a popular referendum, a vote, an approval by a Government agency or a Company Board, etc. This is similar to pre-commitments to accept the result, which can be required in arbitration cases – participants are implicitly accepting that there are likely no perfect solutions to be found for any complex issue, especially if there are multiple objectives: timely actions and decisions with meaningful follow-up commitments are emphasized.
9. The group prepares – and implements (i.e. acts on) – a concrete plan which details actions for follow-up amongst decision/policy makers and the affected public. This implies that a PM approach does not terminate with the end of the specific (investment) project, but has an on-going follow-up with specifically-identified people, and it includes monitoring and evaluation.

Agreement on a set of core principles, such as those listed above, would help establish social norms that can guide PM and contribute to meaningful policy decisions and actions, though they may be hard to achieve and enforce. Most PM activities are voluntary, and therefore it is impractical and infeasible to compel participants to adhere to such social norms, even if they have been explicitly identified early on, or to make them comply with the outcomes or recommendations produced. Nevertheless, the occurrence of subsequent non-compliance, if there had been a previous commitment, would be significant as a pointer to, and critique of, any stakeholders who do not follow the line on consensual social norms and modes of behaviour.

There are a number of practical steps that build on core principles like those stated above, and that can be highly relevant, such as those given by Voinov and Gaddis (2008). Some of those principles overlap with the general heuristics for interdisciplinary modelling projects recommended by Nicolson et al. (2002). However, PM is an evolving field with potentially changing priorities and principles. For example, it becomes increasingly obvious that a requirement of 'neutrality as scientist' may be becoming unrealistic and outdated (Voinov et al., 2014; Mermet, 2011), especially when crucial planetary boundaries are increasingly exceeded or face pressing challenges in environmental protection and resource management (Rockström et al., 2009). While objectivity is certainly something for all scientists (indeed for all PM participants) to strive for, it is unrealistic to expect that scientists and modellers involved in applied science have no beliefs or values of their own. As Glynn (2015) states: "Instead of deluding [themselves] through an 'objectivity frame', [scientists] would be better served to acknowledge that they often make subjective judgements in the pursuit of science. They should strive to discern, examine, and understand their biases and subjectivity, and take appropriate counter-measures if needed." In fact, communicating to the stakeholders in a PM process that scientists also hold values and beliefs can make it easier to build better understanding and trust: people tend to be suspicious of those who claim to have no values (Kahan, 2012).

We increasingly find ourselves in a prosumer information society (Ritzer, 2013; Ritzer, 2013a), meaning that people are becoming both producers and consumers of information, as in the Citizen Science mould. The public is quite content to develop content that drives the business models of Facebook, Twitter and the like, and people eagerly volunteer their time to bring profits and fame to these social media companies, as they do with citizen science projects, and have done for generations in thousands of social and environmental NGOs. There is therefore great potential to engage broad groups of citizens and organizations into knowledge generation and decision-making processes. This is what PM is all about. We believe that a PM project (such as shown in Fig. 4) can provide extensive, innovative, exciting, impactful opportunities for people – planners, policy-makers, activists, local stakeholders – to apply science towards solving some of the most pressing population-resource-space nexus issues of today (Voinov et al., 2014).

The prosumer character of the Internet, the fact that people are getting increasingly engaged with, and also better trained in, using the Internet and its interactive features, opens new promising opportunities to involve the public (1) in discussing problems faced by society, (2) in setting the agenda of scientific research, and (3) in engaging people in actions to implement solutions informed by science. Our claim is supported by the trends that we observe in the rapid expansion of active crowdsourcing and citizen science. As we discussed, there is an avalanche of web tools and apps being developed to support citizen engagement. We expect that PM will capitalize on the increasing use of these tools, thereby helping society move towards more democratic, better distributed, more informed decision-making and environmental management.

Acknowledgements

This paper itself can be seen as an example of web based participatory research. It was entirely written on Google Docs with all co-authors contributing on a more or less regular basis. The authors are grateful to the five anonymous journal reviewers and to

Jack Eggleston and Kevin Breen of the USGS for helping clarify and improve this manuscript.

A. Voinov was supported by the EU-FP7-308601 COMPLEX project. N. Kolagani and P. Ramu were supported by the 5-4/2010-TE project of Department of Land Resources, Ministry of Rural Development, Government of India. Because one of the co-authors of this paper, P.D. Glynn, is an employee of the U.S. Geological Survey, the following statement applies. Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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