Environmental Modelling & Software 80 (2016) 113–121

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Best practices for conceptual modelling in environmental planning and management

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A R T I C L E   I N F O

Article history:
Received 3 July 2015
Received in revised form
16 February 2016
Accepted 16 February 2016
Available online 1 March 2016

Keywords:
Conceptual modelling
Participatory modelling
Model formalism
Model representation

A B S T R A C T

Conceptual modelling is used in many fields with a varying degree of formality. In environmental applications, conceptual models are used to express relationships, explore and test ideas, check inference and causality, identify knowledge and data gaps, synchronize mental models and build consensus, and to highlight key or dominant processes. Due to their sometimes apparent simplicity, development and use of a conceptual model is often an attractive option when tackling an environmental problem situation. However, we have experienced many examples where conceptual modelling has failed to effectively assist in the resolution of environmental problems. This paper explores development and application of conceptual modelling to environmental problems, and identifies a range of best practices for environmental scientists and managers that include considerations of stakeholder participation and trust, model development and representation, integration of different and disparate conceptual models, model maturation, testing, and transition to application within the problem situation.

1. Introduction

There is a frequent need in addressing environmental problem situations to meld science and management, and there are many good reasons for stronger relationships between science and policy making, including overall improvements in science-policy communication and the ambition to make the outcomes of research efforts more useful for our society. A useful step in melding science, management and policy is to develop models (Clark and Schmitz, 2001). Indeed, modelling is one of the core components of many integrated approaches to addressing environmental challenges, including the well-known integrated assessment and modelling (IAM) techniques and methodologies (e.g. Hamilton et al., 2015) and optimization (e.g. Maier et al., 2014).

Models that describe the problem situation, and which allow exploration of the system of interest under a range of interventions, support the application of science to serve management. This can include incorporating hypotheses into an adaptive management framework (e.g. Argent, 2009; Holling, 1978; Walters, 1986; Williams and Brown, 2012) for even greater transparency and exploration, and to address the mistrust of models that sometimes occurs within policy and management circles. We promote developing conceptual models as the first step in any such endeavour. This is especially true when developing decision support systems, which require accurate identification, formalisation and communication of the elements involved in the decisions to be taken, all of which can be part of the conceptual modelling process (Sojda et al., 2012).

1.1. Conceptual modelling in practice

Conceptual (mental) models capture our current understanding about the structure and workings of a system (Gupta et al., 2012)

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http://dx.doi.org/10.1016/j.envsoft.2016.02.023
1364-8152/

and are usually produced as a group exercise to engage stakeholders, reach consensus, and/or as a first step of a quantitative modelling exercise (Elsawah et al., 2015; Gupta et al., 2012; Gupta and Nearing, 2014; Voinov, 2008). They are also quite often needed as a preliminary step in those processes where multiple disciplinary experts are involved who need to develop a common platform for mutual understanding and learning.

The process of building models (rules), as well as the formalism used (syntax) can be different from one case to another. There is no decided standard for conceptual modelling, although conceptual frameworks such as DPSIR (Driving forces, Pressures, States, Impact and Responses) can provide structure and guidance (Giupponi, 2014). In most cases, the rules and the syntax are discussed and defined in the process of building them. As a result, it may be quite difficult to reuse, reconnect, maintain or update conceptual models that have been previously developed, or that have been proposed or developed by different contributors. One of the problems is that the notion of a "concept" is exceptionally wide and appears to be quite different when different approaches are used.

Conceptual modelling is a part of many approaches used in explaining, understanding and exploring different kinds of systems. The practice of conceptual modelling can vary from completely informal (e.g., "hand-waving" or rich pictures on a flip chart) to highly ordered and structured (e.g., systems dynamics formalism). For example, qualitative analysis (Levins, 1974) uses the sign (+, −, 0) of ecological interactions to indicate system behaviours, with 'loop analysis' (e.g. Dambacher et al., 2003) carrying this further to assess system stability and predictability. Systems thinking and soft systems methodologies often utilise diagramming approaches to capture specific concepts, to separate these concepts logically, and to represent relationships between the concepts (noting, however, that the connecting relationship between two concepts also represents a separate concept).

In "multi-methodology" approaches to conceptual modelling, the initially simple illustration of concepts and relationships can be taken through steps of increasing formalisation and structuring that consequently provides increased capacity to explore, explain and solve problems. Relevant examples are found in the:

- conceptual diagramming of the Integration and Application Network group at University of Maryland (http://ian.umces.edu/learn/conceptual_diagrams/)
- templates for the development of conceptual models at the National Centre for Postsecondary Improvement (http://web.stanford.edu/group/ncpi/unspecified/student_assess_toolkit/conceptualModels.html)
- a web-based interactive tool to draw diagrams and then convert them into dynamic models - Insight maker (https://insightmaker.com/insight/)
- conceptual mapping tools and web resources at the Florida Institute for Human & Machine Cognition (IHMC; http://cmap.ihmc.us/)

In many problem situations, conceptual models are considered to be clearly separate from the formally coded operational model used by management to support decisions. Knowledge engineering (Scott, 1991), a subfield in computer science, is one discipline in which conceptual modelling is particularly well developed and allows for separating the conceptual modelling process from that of constructing the model in computer code. Likewise, Jensen (2001) was one of the first to describe the use and value of Bayesian belief networks for such conceptual modelling due to their inherent nature of being able to represent and reason with causal relationships. Conceptual modelling was also strongly advocated as part of the early development of system dynamics (Forrester, 1973). An historical example can be found in the World 2 model developed by Jay Forrester in the early 1970s and utilised as the modelling tool for simulating evolution scenarios of the Planet Earth until the end of the 21st century, in Meadows et al.'s (1972) 'The Limits to Growth'.

There are many identified 'methods' for explaining and exploring systems, most of which contain conceptual modelling elements, and many of which are relevant to the environmental problem domain. A methodological framework for conceptual modelling could, for example, take advantage of Cognitive Mapping (Axelrod, 1976) techniques applied in dedicated workshops with researchers and stakeholders. Cognitive mapping techniques then have a crucial role to play in ensuring that the emerging external model(s) (i.e. the shared model(s) emerging from mutual learning) are an accurate representation of internal structures and beliefs. However, the emerging model(s) must also demonstrate a consensus view of the problem under discussion, thus representing a fundamental intermediate step of participatory modelling and decision making (Giupponi and Sgobbi, 2008). Fuzzy Cognitive Mapping (Kok, 2009; Kosko, 1986; Özesmi and Özesmi, 2004) can provide further developments for integrated modelling and scenario analysis including both quantitative and qualitative approaches. System Dynamics further develops upon visual representations of systems provided by Cognitive Mapping and provides a functional formalization of the system, by means of a compact series of symbols (stocks, flows, variables, connectors), which are immediately related to mathematical concepts (e.g., stocks corresponding to integrals) and can thus provide the basis to move from cognitive, to operational mathematical models for implementing simulations of system behaviour.

Many attempts to apply environmental analysis and modelling techniques over the past 30 years have failed to effectively assist in the resolution of environmental problems (see examples in Allan and Stankey, 2009; Walters, 1986). Reasons for this are as diverse as poor stakeholder engagement, lack of transparency in analysis and modelling, over-complicated modelling, insufficient skills or resources, or lack of relevant data or knowledge.

Rather than produce yet another conceptual modelling method or a multi-method combinational framework, this paper presents the eight fundamental elements (or principles) of a best practice approach to conceptual modelling in support of environmental model development:

1. Use an open and transparent model development process
2. Encapsulate and communicate concepts effectively
3. Establish and maintain elegant models
4. Create robust and adaptable models
5. Use a formal approach to model representation
6. Test and re-test the models
7. Explore model behaviour through scenarios
8. Ensure the model can be converted into an operational form

The order of these elements follows a logical progression of the conceptual modelling process, although in practice many of these are parallelised, iterative and intermingled. The following sections describe the eight fundamental elements.

2. The eight fundamentals of conceptual modelling as best practice

Overall, the best practice approach is founded upon the importance of *process*, especially processes that i) include relevant stakeholders (including knowledge holders), ii) have clear structure, and iii) create a useable and useful output. Advantages of such processes include enhanced communication, reduced transaction costs, clearer outcomes and increased likelihood of success.

However, practitioners need to be wary of the extremes of process-based practice. At one end it may be that the solution is perceived to be obvious and easy to achieve and that a defined process is unnecessary, despite, for example, disagreement amongst key stakeholders or lack of political support for the 'obvious' solution. At the other extreme, the process is viewed as the 'divine ruler' and followed doggedly, even when the activity is heading for failure due, for example, to insufficient resources or higher priorities for stakeholders.

2.1. Open and transparent model development process

The first principle in conceptual model development is adoption of an open and transparent process throughout. Openness implies not only that stakeholders are able to participate, but also that the process is open to considering and accepting input (e.g., data, observations, concepts, pre-conceptions, beliefs, process understanding) from *all* stakeholders. An open conceptual modelling approach often involves one or more workshops where people and ideas come together to produce consensus-based outputs. In some cases the process (building consensus) may be even more important than the product (the model) (Voinov and Bousquet, 2010).

In forming a conceptual model through an open process, there is also a need for transparency. Conceptual model formation necessarily involves encapsulation, manipulation and representation of concepts, and doing this transparently is the only way to ensure that the original concept and its associated meaning are not lost.

2.2. Effective encapsulation and communication of concepts

When analysing the relationships between local socio-ecological systems and exogenous drivers within an environmental problem situation, communication between stakeholders is a crucial issue. Stakeholders, including, e.g., on-the-ground wildlife habitat and population managers, economic players, policy makers, disciplinary experts, local knowledge holders, consumers and users, bring with them significantly different concepts and worldviews. A shared vision about the problem and the purpose of the modelling is a prerequisite for mutual understanding and learning, and developing conceptual models through a participative process provides a communication language and a vehicle to facilitate fruitful interactions, and the crossing of disciplinary, cultural, and other barriers. Development of this shared vision and purpose also requires clear articulation of model context and limitations, including specification of system boundaries in time and space, model inputs and outputs, state variables, governing physical and behavioural laws, temporal and spatial resolution, uncertainties to be included and simplifying assumptions to be made (Gupta et al., 2012).

Approaches to environmental problem situations are expanding to include more and more mental models (internal, subjective representation of reality, owned for instance by policy makers) and to combine these with scientific models (based on mathematical simulation). To do this, means of communication are needed to make the different mental models explicit (i.e., "external"), such as cognitive maps (Doyle and Ford, 1998). In conceptual modelling, a variety of diagramming and graphical approaches are used to represent a diverse range of concepts. It is essential that the concepts that are encapsulated by the modelling process actually fit the concepts expressed by the stakeholders. Common concepts include entities, processes, stores, funds and stocks, flows, causes and responses, and explicit and implicit relationships.

Clearly encapsulating and communicating these common concepts provides a valuable communication interface. This value is assured, firstly, through conceptual and graphical representation of the main elements of the socio-ecological system and their causal connections. Using a language and a format that are understandable across disciplines and by users and stakeholders then adds further value.

As an example, this was done recently in modelling the effects of a changing climate on greater sage-grouse (*Centrocercus urophasianus*) demography in Northern Montana, USA (Fig. 1). In this figure, there are many relevant concepts, encapsulated in both shapes (e.g., predation) and links (e.g., a relationship between sage height and winter survival). In this domain the effects of local weather conditions on grouse habitat use and demographics are not well understood. Also, there is considerable uncertainty about future climate drivers and their effects. Such uncertainties underscore the requirement for each concept to be clearly encapsulated and communicated.

In our experience with the greater sage-grouse model, we found that collaborators were more able and willing to contribute new ideas and critique older ones as the conceptual model progressed. It seems that the process of delineating the relevant concepts and causal relationships was important to them. It did not seem problematic that these relationships were not definitive, and were surrounded by uncertainties. The natural resource managers with whom we worked embraced a view that 'it is more important to ask the right questions than spend your entire life searching for an answer' (Zar, 2010). Conceptual modelling is a critical step in helping natural resource managers develop useful management-focussed products.

A conceptual model should present not just the structure of the system, which is usually what is captured by the cognitive diagrams or flow charts, but also deal with issues of time and space (Voinov, 2008). For example, some or all of the following may need to be considered: What is the specific time span of the system? Are we looking at it over years, days, or seconds? How fast are the processes? Which processes are so slow that they may be considered constant, and which other processes are so fast that they may be considered at equilibrium? If the system is evolving, how does it change from one state to another? Is it a continuous process or does it come in discrete, instantaneous events? Is the next state of the system totally defined by its current one, or is it a stochastic process, where future states occur spontaneously with certain probability? What is the specific size of the system that we are analysing? Is there some hierarchy associated with the system and in which level of that hierarchy is our system embedded? How far spatially does that system extend? What are the boundaries? What will be the spatial resolution of the processes that we need to consider? How does the system evolve in space? Is it static, like a map, or dynamic, like a movie or animation?

Whenever conceptual models can be developed upon, or made consistent with, widely adopted frameworks, the process of communication, understanding, shared vision and mutual learning can be facilitated. For example, the DPSIR framework (Fig. 2) is adopted by some researchers as a reference for approaching and communicating environmental issues as it is relatively easy to use and is adopted in many official documents and reports (e.g., for indicator-based state of the environment reports) and thus it is usually familiar to policy makers.

Some decision support tools have adopted such simplified frameworks as reference conceptual models to organise and communicate information throughout the process. The example in Fig. 2 shows how broad categories of water management strategies (4 Responses) were analysed in a participatory process in Nepal, with the support of quantitative indicators allocated to the DPSI nodes (Ceccato et al., 2011). The potential 'supply' of knowledge offered by researchers (i.e., whole lists of indicators) was screened by stakeholders, and the indicators most relevant for the local

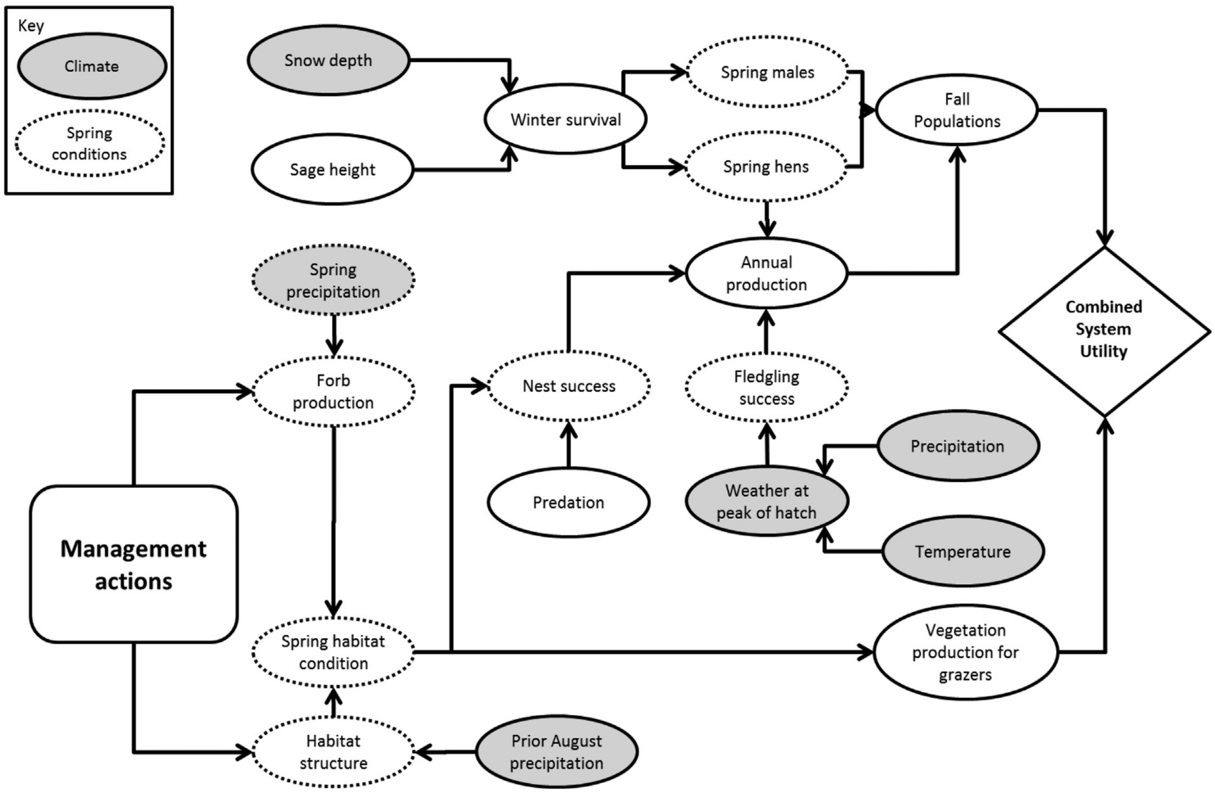

Fig. 1. A conceptual model of primary interactions of greater sage-grouse demographics. Arrows show logical causal direction. This depicts how management actions (e.g. cattle grazing intensity), govern Fall population sage-grouse numbers, including habitat and demographic interactions influenced by climate change, with all then reflected in "combined system utility". Spring conditions are emphasized because grouse biologists expected that these drive Fall numbers. This model provides a framework for assessing such hypotheses.

process (marked in blue) were further considered for the analysis of alternative strategies.

2.3. Elegant modelling

Elegance is a key goal of the conceptual modelling process, ensuring that only essential and important elements of the system are included in the model and, ideally, that the model can eventually be validated. One of the characteristics found in some failures of the conceptual modelling approach is over-complicatedness, resulting in an excess of knowledge gaps and unknowns that leave the process at a standstill, with a long research agenda that provides no relevant information to support current management decisions. Practitioners should keep in mind that ALL models are wrong, but some are useful (Box and Draper, 1987)! While elegance is certainly subjective and can vary from one application and one stakeholder group to another, there are still certain principles of model design that distinguish a more useful model from a less useful one.

These model design principles include:

- aligning the model with the goals of the study – what does success look like (Sojda, 2007)?
- ensuring the model is within the defined scope and boundaries of the study;
- ensuring the model covers the system or systems under consideration, and includes the system 'levers' available to managers;
- being parsimonious (Box, 1976);
- defining the entities of the model and their meaning – ideally using formal means such as ontological references, definitions of terms, and using a clear legend of utilised symbols; and
- considering if, and how, any resulting numerical model will be evaluated.

The quest for elegance raises a challenge in almost all modelling processes of determining what to keep in and what to remove. In an open participative process, best practice takes a wider and more open view of the 'important' elements (including potentially unorthodox ideas), and uses testing and scenario exploration to determine what is actually important. The goal for the model should be for it to be *simple enough to be usable* but *complicated enough to be useful,* whilst holding to the parsimonious principle of Ockham's razor. This process also serves a larger purpose of creating a shared understanding amongst participants of the systems and its behaviour.

2.4. Robust and adaptable models

The requirement to be able to add or remove concepts, to link or integrate the conceptual model with other existing models, or to apply the model to alternative policy options and management scenarios, creates a requirement for the model to be robust and adaptable. In the early stages, when the model development process is largely 'whiteboarding' this is relatively easy due to the lack of formality. As the model matures, representing more investment in thought and exploration, the more difficult it becomes to adapt.

Adapting models becomes more challenging when mixing conceptual representations. For example, it is unclear how to connect a Fuzzy Cognitive Map (FCM) (Kosko, 1986) type of a model

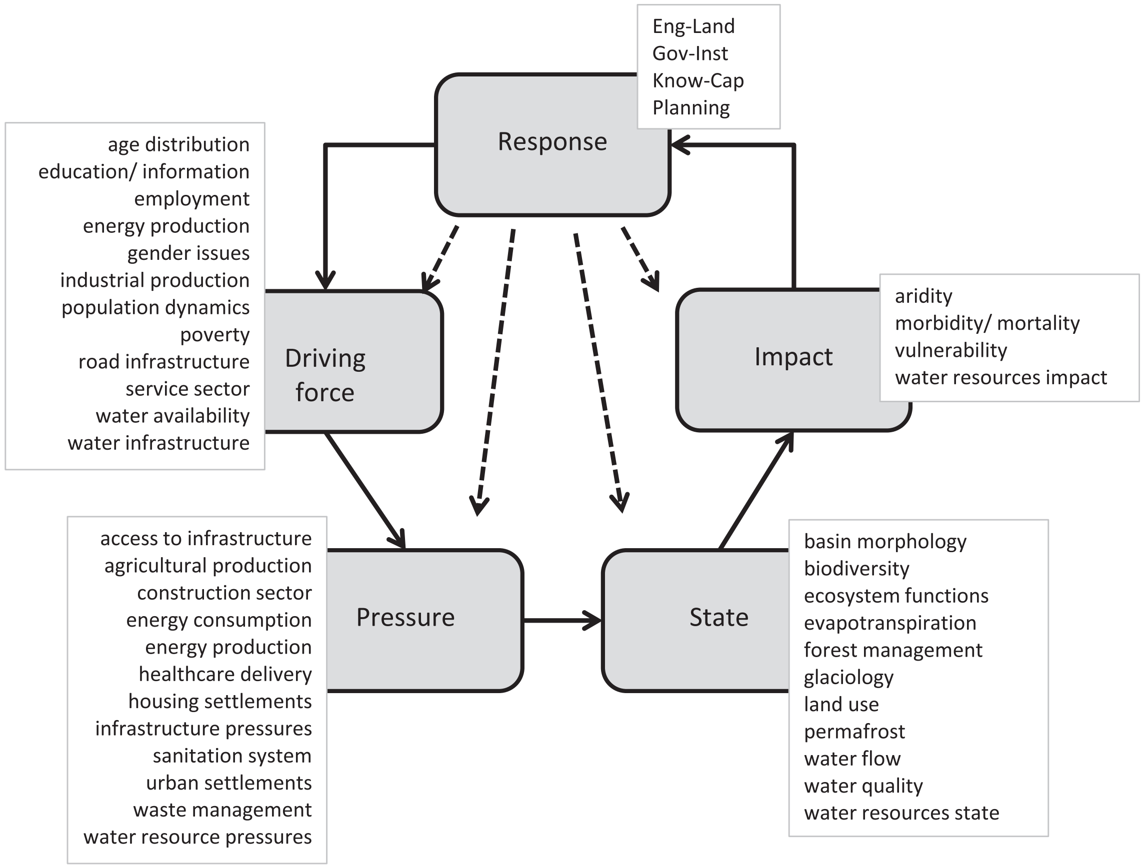

Fig. 2. Conceptual model of water related socio-ecological systems in Nepal framed within the DPSIR framework.

(Fig. 3) to a diagram developed using a system dynamics tool such as Stella®, especially including relationships with different strengths of causality. In FCMs, almost anything can be considered as a concept, with no restrictions or rules. In Stella, a stocks-and-flows formalism is assumed. Therefore, adaptability of any selected model representation method must be tested. 'Hard wired' connection between models (or sub-models) is desirable but not essential. In cases where 'hard wired' connection is difficult the models can be loosely coupled, requiring development of clearly defined interfaces between models.

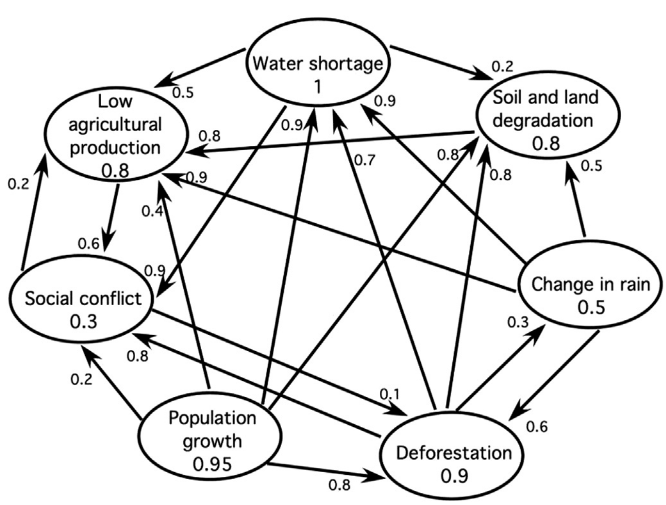

Fig. 3. An FCM type model developed for describing drought in Tanzania.

Modularity and object-oriented approaches help with presenting complex relationships while retaining overall simplicity, thereby increasing adaptability. In this case other tools for concept mapping, such as the Florida Institute for Human & Machine Cognition's Cmap (http://cmap.ihmc.us), could be even more efficient. System dynamics interfaces, however, still provide the functionality for further formalizing the model and integrating concepts into quantitative representations or declarative modelling standards that are supported by other system dynamics interfaces, such as Simile® or Vensim®.

2.5. Formalising the model

The feature of flexibility, which is a huge advantage of the conceptual modelling approach, can become a drawback by limiting the communicative power of an *ad hoc* conceptual model beyond the particular group or case study where it was developed. Limitations to communication arise due to the need to continually explain the meaning of each element and concept in the *ad-hoc* model, and the misunderstandings likely to arise from this. This problem can be only alleviated if certain standards are agreed upon and followed as the conceptual model develops. However imposing standards also raises the risk of limiting flexibility.

Most likely the use of conceptual models will unfold in two stages. First a model will be drafted without much adherence to any standards and prerequisites, taking advantage of the flexibility of on-the-spot discussions and agreements about 'what we mean by what'. Then, in the second stage the draft model will be translated and redesigned according to the standards and requirements of a specific framework. This is often the routine used in stakeholder workshops, where a flipchart or a simple software package with shapes and connectors (e.g., Excel/PowerPoint, Cmap or web-based Insight Maker or Systo) is first used simply to sketch the concepts and their relationships. In a later effort, where the conceptual model is considered to be mature and to represent a reasonable consensus, these diagrams are re-constructed to adhere to a formalism (using e.g., Stella, Powersim, Vensim, netlogo, Mason, Repast) while still maintaining the overall set of concepts. Some modelling tools are used for sketching purposes without necessarily implying the modelling formalism involved. For example, Muetzelfeldt (2010) shows application of the Simile® system dynamics tool to create conceptual diagrams for a variety of agricultural projects with no direct connection to system dynamics, while giving more formality (and thus standardisation) to the diagram itself and also offering the potential to develop operational simulation models.

From the point of view of interoperability, integration, testing and consistency, more standards and semantic order should be considered in conceptual modelling. At the same time, changes in people's thoughts or beliefs are often slow, and potentially lag behind efforts to identify and define standards. It is yet to be seen whether collective thinking and reasoning, which seem to be developing in the era of social media and web applications, will result in wider acceptance of standards for conceptual modelling. One clear advantage of collective development of standards is in building shared understanding between stakeholder groups as they participate in the joint learning and standards development process.

2.6. Testing the model

Once a conceptual model is tied to a certain formalism, testing for inconsistencies and logic becomes possible and essential. The model should be subject to testing of:

- Scope – ensuring that all important processes and their linkages have been captured and that the agreed key questions (e.g. policy or process-oriented) are able to be answered with the aid of the model.
- Logic – ensuring that the concepts in the model make sense to the people involved in development and, ideally, to others external to the process.
- Connections – ensuring that the concept associated with each connection is sound, and that it is relevant to the concept at each end of the connector.
- Flow and sequence – for areas of the conceptual model where there are logical sequences of concepts, testing the flow of logic and associated information.
- Limits, thresholds and conditionals – considering the conditions under which each of the concepts are relevant and where they fail or are irrelevant, and the alternative paths of logic when a particular condition is not met. In an example from Fig. 1, consider when and how 'winter survival' is influenced strongly by factors other than snow depth and sage height, such as winter predator assemblages and buffer prey numbers, and let Ockham's razor determine if these are included.

As conceptual models can be thought of as representing alternative hypotheses of the structure and functioning of the modelled system (Gupta et al., 2012), there is value in testing these hypotheses. Although not able to be done formally, sensitivity analysis can be used to gain a better understanding of the impact various modelling components have on model outputs and modelled system behaviour. Qualitative analysis can be similarly applied. For example, a level of testing can be achieved by simply "greying out" some of the components of the conceptual model and investigating the impact this has under a range of plausible conditions. In this way, less sensitive components can be identified, which could potentially be excluded from the conceptual model for the sake of parsimony.

As the model matures from concepts to causal or numerical relationships (e.g. a decrease in x gives rise to an increase in y), further testing should occur to check if fundamental quantitative outputs (e.g. mass balances) make sense, before too much additional effort is expended on more detailed model development. Some software packages have built-in functionality that can be helpful in testing, such as tracking of causalities in Vensim.

2.7. Able to support exploration and scenarios

When applying models to systems that evolve over time under the effects of multiple exogenous drivers, scientists typically approach uncertainty about the future with a scenario approach. Scenarios "provide a dynamic view of the future by exploring various trajectories of change that lead to a broadening range of plausible alternative futures", enabling "… a creative and flexible approach to preparing for an uncertain future" (Mahmoud et al., 2009). In particular, uncertainty surrounds the limited capacity of models to provide future projections, and thus simulations are run with consideration of multiple plausible future states of the world and of the case considered.

In a less formal sense, scenario exploration can simply be considered as 'gaming' with the model by stakeholders – considering a range of past management actions and drivers and testing if the model behaviour reflects the experience of different stakeholders. Then, considering and exploring the conceptual model behaviour under potential future management actions and exogenous drivers.

Formal techniques are available to include scenario development and analysis in the participatory modelling and decision making process to deal with uncertainty. Examples are Robust Decision Making (Bryant and Lempert, 2010; Lempert et al., 2003; Popper et al., 2005), Scenario Planning (Schoemaker, 1995), Info-Gap (Ben-Haim, 2001), Real Options Analysis (Woodward et al., 2011), management strategy evaluation (e.g. Sainsbury et al., 2000) and structured decision making (e.g. Gregory et al., 2012). Multi-Criteria Analysis (MCA) may also support analysis of alternative scenarios and policy options in a decision support context (Figueira et al., 2005). Policy makers and other stakeholders can find support in the vast MCA methods literature for organising and synthesising complex and conflicting multidimensional features of the issue analysed (Belton and Stewart, 2002), thus improving their ability to explore and assess trade-offs between alternative options and stakeholders' preferences (Mysiak et al., 2005). In the context in which multiple actors are involved in the decision process, MCA methods can significantly contribute by making explicit conflicting values and individual preferences, thus facilitating decision makers to interactively examine the trade-offs between objectives and to aggregate individual preferences. However, care needs to be taken to ensure uncertainty in stakeholder weights and performance values are considered as part of the MCA process, possibly including formalisation of weighting procedures, to ensure transparency and to not disenfranchise certain stakeholder groups (Hyde et al., 2005; Hyde and Maier, 2006).

2.8. Convertible into operational modelling form

A common final step in putting a conceptual model to use on an ongoing basis is to convert it to an operational environmental software system that supports system exploration and, ideally, supports decision making. There are many tools, models, methods and modelling frameworks that can be used in this process (Kelly et al., 2013). As explained, many of the fundamental elements of the conceptual modelling process operate iteratively and in parallel. In this context, many conceptual modelling activities introduce software development early in the process, which has the advantage of ensuring that a formalism is followed from the start.

The range of methods and tools available include manual 'paper-based' approaches, spreadsheets, bespoke models coded in a variety of languages, research-standard modelling frameworks and platforms, and off-the-shelf applications. Examples of systems software such as Stella, Simile, Vensim, Powersim, Hugin, and Genie have been used in ecological applications, while Garp3 and DynaLearn have been used for education. Research directions in modelling software development are exploring the use of service-based approaches the incorporate international standards, such as from World Wide Web Consortium and the Open Geospatial Consortium.

As one example, Fig. 4 shows the approach developed in a participatory process to explore the potential for implementing conservation tillage techniques in Morocco (Bonzanigo et al., 2016 (in press)). In this case, the lack of precise quantitative data vis a vis the availability of extensive expert knowledge, suggested the evolution of the conceptual model - cognitive maps developed with local and international experts in the IHMC Cmap software - into a Bayesian decision network, implemented in the Genie software. Cognitive maps made of a combination of simple and clear concepts linked by causal links allowed for building an effective interface between experts. The same structure was adopted to build the Bayesian decision network model, thus moving from concepts to an operational tool exploring the conditional probabilities of adoption of conservation tillage techniques, under different environmental, socio-economic and policy circumstances.

3. Conclusion and recommendations

Only by accepting the challenge of approaching the internal components of models in a participatory context to construct their external counterparts, can we expect to harness the full potential of modelling complex environmental issues. In our recent experience, this has rarely been the case. Even the potential role of modelling, itself, has been questioned, with decision makers often viewing models (including DSS) as "black boxes" which cannot be fully understood and trusted.

In some environmental problem situations, there is a perception that modelling remains an academic exercise with very strong – and usually hidden – components of subjectivity and uncertainties. This seems particularly true of scenario models for future ecological projections. This may not be a problem whenever the modelling serves an individual's, or a group's, efforts to explore the functioning of complex systems, but it may result in a crucial limitation when the exercise is aimed at supporting decision or policy making.

As such, we have experienced that the results of models sometimes are not fully trusted, as they are incorrectly seen to be subject to manipulation by experts, policy makers, or interested groups. Perspectives for the solution of such problems are offered by post–normal science (Funtowicz and Ravetz, 1993) which

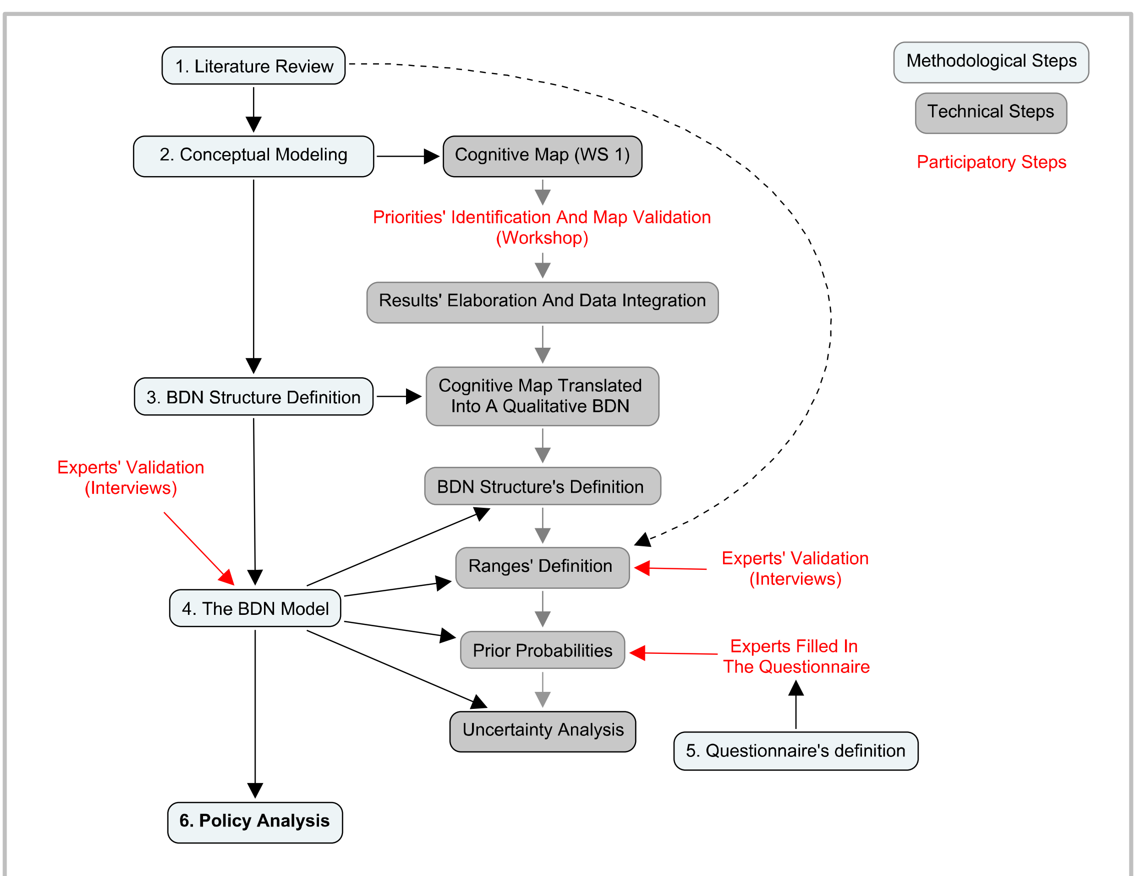

Fig. 4. The modelling process adopted to analyse the potential for conservation tillage in Morocco (adapted from Bonzanigo et al., 2016 (in press)).

recognises that scientific and technical discourse should be opened to non-experts (stakeholders and the general public). By embracing open and transparent modelling processes and following the best practice principles of conceptual modelling presented here, via:

1. Use of an open and transparent model development process
2. Encapsulating and communicating concepts effectively
3. Establishing and maintaining elegant models
4. Creating robust and adaptable models
5. Using a formal approach to model representation
6. Testing and re-testing the models
7. Exploring model behaviour through scenarios
8. Ensuring the model can be converted into an operational form,
   - it is hoped that modellers can continue to increase the acceptance, adoption and effectiveness of our endeavours to understand, inform and improve the management of socio-ecological systems.

Participatory modelling (Voinov and Bousquet, 2010) has been consistently seen as a way to open up the modelling process and to make it available for stakeholders and decision makers. Conceptual modelling has been a key component of participatory modelling and of successful application of adaptive management to natural resource problems. Williams and Brown (2012) provide an excellent compendium of how such system modelling must proceed through the deliberative 'conceptual' phase of model identification we have described here, before being able to proceed through the subsequent iterative phases of "decision making, monitoring, assessment, and learning". We could not agree more. The expansion of social media and Internet connectivity bears the promise of some conversion between participatory modelling and a relatively new phenomenon known as 'citizen science' (eVoinov et al., 2016). This will inevitably have further implications for how conceptual models will be developed and shared over networks to enhance the joint learning and understanding experience for various participants in the process.

Acknowledgements

The authors gratefully acknowledge input to this manuscript provided by participants in the workshop 'Conceptual Models and Getting Feedback on DSS and Modeling Research in its Early Stages', held at the 2014 iEMSs International Congress on Environmental Modelling and Software. A. Voinov was in part supported by the EU-FP7-308601 COMPLEX project.

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