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An overview of the system dynamics process for integrated modelling of socio-ecological systems: Lessons on good modelling practice from five case studies

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ABSTRACT

Similar to other modelling methodologies, the potential of system dynamics to contribute to system understanding and decision making depends upon the practices applied by the modeller. However lessons about many of these practices are often unreported. This paper contributes to the methodology of system dynamics modelling of socio-ecological systems by 1) examining issues modellers face during the modelling process, and 2) providing guidance on how to effectively design and implement system dynamics modelling. This is achieved through an investigation of five case studies, drawing on lessons from these experiences. This is complemented by a literature review of system dynamics applied within the context of integrated modelling and environmental DSS. The case studies cover a variety of environmental issues and system dynamics modelling methods and tools. Although we used system dynamics as the common lens from which lessons are drawn, many of these insights transcend to other integrated modelling approaches.

1. Background

Modelling, and Integrated assessment and modelling (IAM) in particular, provides tools and techniques that can promote dialogue among stakeholders about how a system operates, as well as facilitate policy assessment to identify acceptable interventions or strategies for change (Parker et al., 2002; Jakeman and Letcher, 2003; Van Delden et al., 2011; Hamilton et al., 2015). The modelling process is valuable despite the fact that models, both conceptual and numerical, are approximations or simplified representations of the system of interest (Jakeman et al., 2006). A wide range of modelling techniques is used to develop integrated models that combine socio-economic, ecological and other biophysical elements, with efforts increasingly revolving around environmental decision support tools (Laniak et al., 2013). Examples of common integrated modelling approaches include system dynamics (SD), knowledge-based models, Bayesian networks, coupled models and agent-based models (Croke et al., 2007; Kelly et al., 2013). Modelling approaches vary in their capacity to represent elements of complexity and uncertainty in the modelled system. Many factors determine the suitability of a modelling approach to a particular situation such as model purpose, availability of data and the functional form of the interactions of interest (Jakeman et al., 2006;

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Chen et al., 2008; Kelly et al., 2013). In this article, we focus on the application of SD for IAM and environmental modelling in general.

1.1. System dynamics

System dynamics (SD) was developed in the late 1950s by Jay Forrester and a group of researchers from the Massachusetts Institute of Technology under the name of “industrial dynamics” (Forrester, 1961). Forrester (1969) extended SD applications to include large socio-economic problems, such as urban modelling. Later, Meadows et al. (1972) presented the revolutionary best-seller “Limits to growth” for which they made use of systems thinking and SD concepts to explain how short-term development policies can lead to “overshoot and collapse” behaviour of socio-ecological systems. “Limits to growth” has exemplified the potential of SD as a tool to help understand complex socio-ecological systems, and is still regarded as a valuable resource for thinking about sustainable futures (e.g. Turner, 2012).

Grounded in control theory and systems thinking (Richardson, 1999), SD provides a set of conceptual and quantitative methods that can be used to represent, explore and simulate the complex feedback and non-linear interactions among system elements, management actions, and performance measures. In SD, a problem is represented as a network of cause-effect and feedback loops, with state variables represented by ‘stocks’ and rate of change in stocks represented by ‘flows’. SD models are generally not used to search for steady-state solutions like many other modelling paradigms, but instead are used to simulate dynamic behaviour through time. They (re)create dynamic behaviour by tracking the change in the values of stocks and flows over time, and explicitly mapping information transfers among stocks and flows to model feedback interactions (Sterman, 2000). This explicit representation of the causal relationships that derive the problem behaviour (i.e. known as problem structure) makes SD particularly well suited to improving system understanding and exploring the unexpected effects that may play out when these causal relationships run their course.

1.2. SD in the context of environmental modelling and IAM

There have been an increasing number of studies using SD for environmental modelling and IAM. These studies can be categorised according to their main problem focus (Simonovic, 2009; Winz et al., 2009) and the approach for the SD application (Mirchi et al., 2012). Thus, SD has been applied to a wide range of problems including: urban water planning (Qi and Chang, 2011; Zhang et al., 2017), water-groundwater interactions (Safavi et al., 2015), climate change vulnerability assessment (Sahin and Mohamed, 2014), regional analysis (e.g. Guo et al., 2001), trans-border water issues (e.g. Duran-Encalada et al., 2017), and more recently water-energy-food nexus issues (e.g. Akhtar et al., 2013). In general, there are three approaches for applying SD in the context of environmental modelling and decision support (Mirchi et al., 2012). First is the use of SD models as predictive tools to simulate the biophysical processes within an environmental system. For example, Venkatesan et al. (2011a, 2011b) develop an SD model of the processes of water use, water quality, and hydrology in order to forecast salinity loads in return flows. The second approach is the use of SD as a holistic framework to examine the feedback interactions among several biophysical and socio-economic systems. The purpose of these models is usually to support integrated assessment of policies by examining the broad and long term decision outcomes. For example, Gastélum et al. (2009) and Ahmad and Prashar (2010) develop basin-scale models which integrate hydrological, agricultural, economic, and ecological subsystems to examine the long term socio-economic and ecological impacts of water allocation policies. The third approach is the use of SD as a platform for participatory modelling in order to engage stakeholders and build a shared systems understanding. This approach includes studies reported in the areas of mediated modelling (van den Belt, 2004), participatory SD (Antunes et al., 2015), SD learning laboratories (Bosch et al., 2013), and Group Model Building (Chen et al., 2014). For example, Vugteveen et al. (2015) use SD to help stakeholders build consensus on the important socio-ecological indicators for managing the coastal region.

The complex nature of environmental problems and decision-making needs presents a series of challenges for using SD as a modelling methodology of environmental modelling, and in particular IAM. First IAM of socio-ecological systems requires input from a wide range of sources and types of knowledge (Jakeman et al., 2006). This includes qualitative and quantitative data from various stakeholder groups, including scientists, policy makers, and community members. To collect, synthesise and use these data in useful ways, IAM needs to utilise and combine different methods (i.e. conceptual, numerical, and participatory) in appropriate methodological designs that best fit the project's context, objectives, and constraints, in the latter case including resource availability (Kelly et al., 2013).

SD offers a portfolio of methods that can be used to support data collection (Luna-Reyes and Andersen, 2003), problem conceptualization (Lane, 2008), systems thinking and learning (Sterman, 2001), and stakeholder participation (Hovmand et al., 2012). The variety of options leads to questions around the best mix of methods to use in an SD modelling process while considering the problem context (Howick and Ackermann, 2011). Part of this challenge facing modellers is associated with the choice of SD simulation software to use given the variety available in the market place. Nabavi et al. (2017) argue that modellers' judgments on methodologies (i.e. methods and tools) for developing SD models is crucial not only for the quality of the model's results, but also to determine if the method has been used in an ethical manner by considering possible interests, decision options, and impacts.

Secondly, IAM promises to offer an integrated view of systems and processes that cause the problem. Depending on the model's purpose, these processes can be modelled with different representations and levels of aggregation (Kelly et al., 2013). This may require coupling SD with other modelling techniques and computational algorithms. Chen and Wei (2014) reviewed the applications of SD in water security applications, and concluded that there is still limited progress in integrating SD with other modelling techniques. Thirdly, IAM deals with spatially distributed biophysical and socio-economic systems, where spatial heterogeneity significantly affects system behaviour, and therefore how they respond to decision making (Hamilton et al., 2015). BenDor and Kaza (2012) reviewed how the spatial dimension has been incorporated in SD models, and found that little work has been done into rigorously selecting and implementing approaches to build spatial SD models.

Finally, given the complex nature of problems addressed, the modelling process of IAM projects tends to be non-trivial (Jakeman and Letcher, 2003), particularly for those projects with a strong social component. Developing a reliable SD model is time and resource consuming, requiring intensive engagement with users and stakeholders as well as expertise in SD modelling and facilitation. There have been efforts, however, towards developing more efficient and leaner SD modelling processes (Warren, 2014) by utilizing reusable modelling components which can help in problem structuring by focusing on the key feedback loops, and expediting the model development by providing ready-to-use validated components.

While many arguments can be correctly made about the need