Decision support systems: experiences, lessons and recommendations

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Abstract

Integrated assessment (IA) models and Decision Support Systems (DSS) offer a framework for capturing, storing, and synthesising available knowledge and data to support effective management of complex environmental problems. The nature of DSS projects and the features and functionality of the delivered product vary according to the problem focus and selected modelling methodologies as well as the make-up of DSS development teams and stakeholder groups. Despite this, understanding both the positive outcomes and challenges from past environmental DSS projects can provide learnings for future DSS development. This paper draws on the experience of the authors in developing several DSS for environmental and stakeholder issues to provide recommendations for developing high quality and effective DSS.

Introduction

Decision Support Systems (DSS), and the inherent metadiscipline of Integrated Assessment (IA) and modelling, and are increasingly recognised as essential tools for understanding and managing complex environmental and resource management problems (McIntosh et al. 2011). These tools provide a framework for capturing, storing, and synthesising available knowledge and data for purposes like: strategic planning, impact assessment, and more generally for generating insights into management alternatives. Often DSS development projects constitute a large investment, typically involving a team of researchers, software developers, and end users. Each DSS project has a unique character, in terms of development purpose, modelling components and techniques, implementation platforms, the degree and extent of stakeholder involvement and needs, and the form and functionality of the final product. Yet, there are useful lessons that both researchers and users can learn from sharing and openly reflecting on development experiences. Whereas the DSS literature often focuses on documenting the DSS components and results, there is little attention given to reflecting on these projects, and what lessons can be gained from them. The aim of this paper is to articulate the role of DSS for supporting environmental management and to describe, and bring together, some general modelling experiences from several DSS developed by the authors for stakeholder problems. The types of DSS that we discuss here are ones that necessarily employ model-based techniques to address environmental problems that require improved system understanding and entail difficult decisions around the need to make multiple trade-offs, usually of a conflicting nature, between socioeconomic and environmental objectives.

In the next section we describe the philosophy of integrated assessment and modelling inherent in the proper design of environmental DSS and follow this with a definition of DSS and the stages in their development. We then present an overview of a number of DSS to outline their type, problem focus, purpose, range of disciplines and models included, stakeholders involved and breadth or depth of issues. The paper draws on the results from this analysis to shed light on some of the key lessons, and their implications for future development and use of DSS in coastal management.

The nature of integrated assessment and modelling

Integrated assessment is a ‘whole of system’ approach which provides a framework for linking the complex, interacting processes that occur within a system. It recognizes both the individual components as well as the linkages between them, and that a disturbance at one point in the system might be translated to other parts of the system. It also recognizes that there can be multiple stakeholders with different (and often conflicting) aims. In particular, trade-offs between economic, social and environmental outcomes must be considered to improve the sustainability of catchment systems. These types of complex interactions lend themselves to consideration by modelling approaches. In particular, integrated models are required to describe the links between economic, social and environmental system outcomes under various management and climatic regimes. The development and application of these models can enhance communication and interaction between different disciplinary teams and stakeholders. They can also provide a clearer perspective on the integrated nature of the problem.

The development and use of models is a major activity of integrated assessment. This is because people think and communicate in terms of models as simplifications of reality. The types of models used include:

- Data-driven models which represent measurements and experiments;
- Qualitative conceptual models which describe systems and processes;
- Quantitative numerical models that formalise qualitative models;
- Decision making models that transform the values and knowledge into action.

Modelling can also provide a focus for capacity building through training and the development of training materials. This focus can have the benefit of exposing catchment managers, local stakeholders and researchers from more narrowly focused perspectives, to other ways of thinking about change in the system. In this way it can enhance the integrated system understanding.

What is a DSS?

Decision support systems (DSS) are computer-based tools designed to support decision making and planning processes that can offer a way of capturing and testing assumptions about complex system behaviour and/or examining alternative solutions to the way we manage resources. Numerous environmental DSS (eDSS) have been developed for application to complex environmental and natural resource management (NRM) issues. DSS are largely a product of an Integrated Assessment process. They can provide many benefits including: a way of interconnecting different knowledge bases (disciplinary, qualitative and quantitative); libraries of databases, models, methods, visualization and other tools; a focus for integration and engagement across researchers and stakeholders; a guide to the relative priority of filling different knowledge gaps in further research; and training and education tools.

DSS can help structure and explore complex environmental problems as well as provide information for analysing and assessing decision options. They have been developed and used by research and other organisations for a range of purposes, including predictive modelling, optimisation modelling, exploratory or scenario modelling and, increasingly, participatory modelling and facilitation.

Overview of iCAM decision support systems

The Integrated Catchment Assessment and Management (iCAM) Centre at ANU has been delivering decision support tools for more than a decade. A development timeline for a selection of DSS and integrated models is shown in Figure 1. These tools are broadly classified by the theme or issue they were developed to address and their modelling approach. Four of the DSS considered in this paper were developed to consider issues around the management of coastal catchments and/or their estuaries: CAPER, CATCMODS, CLAM, and the Landscape Logic Tasmanian DSS. DSS addressing non-coastal issues have been included in this paper as they provide useful lessons for development of environmental DSS.

The Coastal Lake Assessment and Management (CLAM) tool was developed in 2004 in a research project for the (then) NSW Department of Infrastructure, Planning and Natural Resources (DIPNR) to investigate issues around the sustainability of coastal catchments and their estuaries. CLAM uses a Bayesian Network (BN) approach (Chen and Pollino, 2013) to integrate best available knowledge (scientific or expert elicited) about the relationships between management inputs and environmental and social consequences. Users can explore the impacts of pre-defined scenarios on a broad range of indicators including water quality, sea level rise, land use and management, terrestrial and aquatic ecology, economic, social value and amenity variables. Between 2004 and 2008, 27 applications were developed for coastal systems in NSW. The level of engagement of the clients was high with DIPNR co-developing the CLAM methodology and NRCMA heavily involved in the scoping and management of the roll-out phase. Engagement with representatives from industry, local government, environmental and community groups was more targeted and involved their participation during the scoping and evaluation phases for each coastal system, and follow-up with individuals as required. The CLAM methodology, case studies and reflections on the evolution of the approach have been published in Ticehurst et al. (2007, 2008) and Ticehurst (2008).

The Tasmanian Aquatic Condition DSS (Merritt et al. 2010) was developed to synthesise information from the Landscape Logic research project under the Commonwealth Environmental Research Facilities program. The intention of the Landscape Logic research undertaken in Tasmania was to improve the information available to environmental managers and policy makers investing in water quality improvement. The DSS can be used to explore likely response in the aquatic health of rivers and estuaries to changes in land use and other scenarios. It incorporates BNs for estuary water quality and health (Pollino, 2010) and river health (Magierowski et al. 2010) and a water quality model that simulates annual loads of total nitrogen and phosphorus as well as flow and turbidity. Capacity building was a key component of Landscape Logic, particularly in the use and development of BNs by partner NRM agencies. However, the involvement of stakeholders in the development of other parts of the DSS was limited; the DSS was developed mainly to integrate research outcomes from component projects and act (in part) as a repository for method and models.

The EXploring CLimAte Impacts on Management (EXCLAIM) DSS was commissioned by the Central West CMA to investigate the impacts of climate change on natural resources in the Macquarie Marshes in inland NSW (Fu et al. in review). Five climate scenarios from the Murray Darling Basin Sustainable Yields project were input to the IQQM hydrology model and a simple inundation model of the Macquarie Marshes. Ecological response models for key vegetation, waterbird and fish species were developed using the BN approach. Expert/stakeholder input on system conceptualisation and the scope of the model were elicited during workshops, with representation from the CMA, state government agencies, local council, industry groups. The EXCLAIM DSS framework, and ecological response models, formed a precursor to the development of the IBIS DSS, which has an emphasis on environmental flow management as well as climate change.

IBIS was commissioned by the (then) NSW Department of Environment, Climate Change and Water (DECCW). It has three applications: Narran Lakes, Gwydir Wetlands and Macquarie Marshes. Unlike EXCLAIM, IBIS integrates a dynamic, spatially distributed hydrology model with BN ecological response models (Fu et al. 2011). This hybrid model allows spatial and temporal representation of hydrology whilst utilising the strengths of BNs, namely: explicit representation of uncertainty and the capacity to use a range of data types to populate the network. The DSS was designed to explore the likely outcomes of water planning scenarios on ecological characteristics of the wetland system and was intended to improve the capacity of DECCW to plan and manage environmental flows at wetland and valley scales particularly at medium to long term (decadal) planning scales. It was not intended as a tool to support short term (annual) planning activities of local water managers. Stakeholder engagement was mostly constrained to the science division of the funding agency.

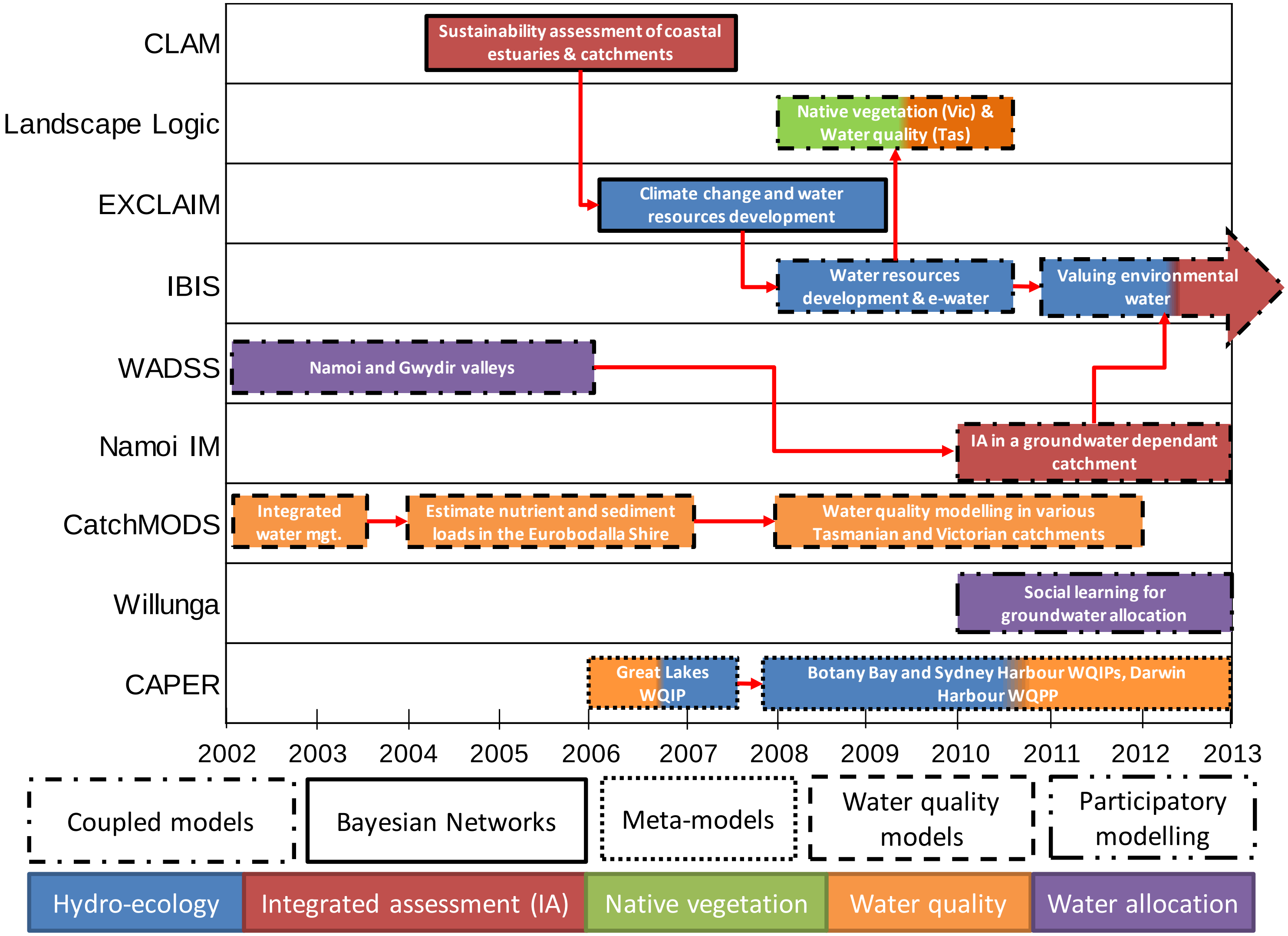

Figure 1: Development timeline for nine DSS and integrated models developed at iCAM. The focal theme(s) and the primary modelling approach of the tools are shown by the colour and outline of the box, respectively. Relationships between development of the tools are indicated by the red arrows.

The Water Allocation Decision Support System (WAdss) was developed in the early 2000s to integrate scientifically sound and accepted information on the socioeconomic trade-offs likely to result from changes in access, allocation and pricing across a water system (Letcher et al. 2004). The DSS links several spatio-temporal models within a coupled component framework, including rainfall-runoff and routing, regulated river, crop yield and water use and farmer decision models. WAdss was developed to be used in a workshop situation, either by allowing the analysis of pre-run scenarios, the sharing of scenarios between users, or the live development of scenarios in meetings and workshops (Letcher, 2005).

WAdss was used as a basis for the Namoi Integrated Model that aims to identify the trade-offs associated with various policy and climate change scenarios for a groundwater region (Jakeman et al. 2012). This research involves a collaborative team of research scientists from social, economic, ecological, hydrological, legal and institutional disciplines and is funded by the Cotton CRC and the National Centre for Groundwater Research and Training (NCGRT). The integrated model uses the output from the likely behaviours and adoption of various actions by landholders from the social model, the water allocation levels and the crop yields and water use, to input into the farm decision model and determine farm profitability. It also estimates the ecological impacts of the surface and groundwater flows following farmer decisions.

The Catchment Scale Management of Diffuse Sources (CatchMODS) tool was designed to simulate the effects of management activities on the water quality at catchment scales. The tool was developed to integrate hydrologic, economic, sediment and nutrient export models to allow evaluation of the impact of user-defined management scenarios aimed at reducing nutrient and sediment delivery to the Ben Chifley Dam in NSW (Newham et al. 2007). Since its development, the tool has been applied to catchments in the Eurobodalla Shire, linked with field-scale models to look at field scale phosphorus exports in the landscape context in northern Victoria (Vigiak et al. 2012) and integrated with economic valuation tools in the Georges Bay catchment in Tasmania.

The objective of Willunga project was to develop and evaluate a participatory modelling methodology to be used for promoting social learning about the future of groundwater allocation and management policies in the Willunga Basin, South Australia. Initial scoping involved interviews and workshops using conceptual models to describe current perceptions of groundwater management, future drivers and impacts of concern and responses of interest (El Sawah et al. 2011). This helped stakeholders better understand each other's needs and create relationships to work on groundwater issues. It was considered that personal experience with the policy could be improved by understanding how each individual's actions affected the operation of the system as a whole. To this end, interviews with catchment managers, policy makers, NGO, and landholders were used to construct 'cognitive maps' (Eden and Ackermann, 1998) describing their respective mental models of how their actions are influenced by and impact on the management of the groundwater system. A coupled modelling framework is being used to allow these actions to be represented in agent based models (ABM) and linked with system dynamic (SD) models to explore how how water allocation policies and farmer's decisions interact and influence groundwater and groundwater dependent economic and ecological systems (Guillaume & El Sawah, In review).

The Catchment Planning and Estuary Response (CAPER) DSS was initially developed for the Australian Government Coastal Catchment project in the Great Lakes region of New South Wales (Kelly and Merritt, 2010). The DSS was developed and used to support the negotiation of a Water Quality Improvement Plan (WQIP) by allowing users to develop rural and urban water quality scenarios and explore likely impacts of catchment exports on estuary water quality and a limited set of ecological indicators. The DSS employed a meta-modelling approach whereby 'simplified' models were developed based on the outputs of more complex agricultural and urban catchment water quality models and estuary mixing models. This allowed model developers and users to develop and run catchment land management scenarios within a workshop environment. The DSS has proved to be translatable to other coastal catchments and estuaries with applications developed for Botany Bay, Darwin Harbour and Sydney Harbour. These projects have been led by Dr Rebecca Kelly at isNRM Pty Ltd who has refined the meta-modelling approach such that new applications for the CAPER DSS are more cost-effective and increasingly tailored to the planning environment. CAPER has been (or is currently being) used to directly inform and support the negotiation of recommendations in water quality improvement (or protection) plans in each of the four application areas (e.g. GLC, 2009; SMCMA, 2011).

Experiences and lessons from developing the DSS

The development of a DSS project can provide a useful focus for organisations to address relevant management and policy questions, and go beyond business-as-usual scenarios. They do require a strong commitment and work ethic from both the DSS developers and clients or partner organisations in order to develop effective tools that achieve the outcomes they were intended to. This section summarises some key experiences and lessons gained from our various projects.

The importance of ongoing engagement and participatory processes, especially in the very early stages of the project, cannot be over-emphasised. Whilst participatory approaches can be time and energy consuming (for all involved) and on-going process will help ensure all parties are on the same page and develop mutual trust and effective relationships. Developers should work with clients to scope the level of engagement required within the project and how to manage expectations. An example where we could have done this better was in the development of the IBIS applications. On advice from the client, IBIS was intended to inform medium to longer term strategic planning activities and as such was not designed for local water planners who are responsible for operational planning which operates from real-time to short-term planning scales. Subsequently local water planners were not heavily engaged throughout the development process. This led to some confusion from them about the purpose of the tool and how it would support their planning processes. Engaging these people throughout the process may have allayed these concerns and managed expectations more effectively.

There is often a compromise that needs to be made between the breadth of issues and the depth to which they can be considered within a DSS. For example, CLAM was developed to assess social, economic and environmental trade-offs associated with development, remediation and use options for coastal lakes and estuaries. The tool can and has been tailored to look at many types of issues. However, given the breadth of issues represented in these models, users are constrained to examining the likely impact of pre-defined scenarios on variables of interest. To include new scenarios in a CLAM requires model developers to scope the scenario options and define relationships between the scenario options and connected variables. In contrast, the CAPER DSS has a much tighter focus than CLAM, capturing the relationship between catchment management and nutrient and sediment inputs to estuaries and the response of the estuary to these catchment inputs. However, CAPER offers users a greater capacity to develop urban and rural land use and management scenarios across the subcatchments and local government areas.

Although the CLAM and CAPER DSS have very different design and functionality there are similarities in the philosophies of the two approaches. Both tools were developed to be used in a workshop environment to support group learning and NRM planning. This requires modelling tools that are computationally efficient and which can be run in a matter of minutes (or less). CAPER achieves this through the meta-modelling approach whereby the outputs from more complex catchment and estuary mixing models are 'summarised' into simpler models that are incorporated in the DSS and which are used to model scenarios linking catchment management to estuary response. In CLAM, the representation of relationships using Bayesian probability theory allows almost instantaneous computation of the user-selected combinations of the pre-defined scenarios. For all DSS developed within our group, we have steered away from incorporating highly complex and over-parameterised models for which there is typically insufficient data to support their use and which are much more computationally demanding. Such models are generally not suited to use in a workshop environment.

To be effective and useful to a specific end-user, a DSS needs to improve the efficiency of decisions currently made by that organisation, or support existing or new actions through provision of new information (Diez & McIntosh, 2009). In our experience, client commissioned tools are often the ones with greater longevity or multiple applications (e.g. CAPER, IBIS). CAPER is most closely aligned with planning and benefited from a statutory requirement on water quality which require the development of tools and DSS to support negotiation of water quality impvement or protection plans. Other DSS have been used more for developing system understanding than any formal role in planning activities. The value of researcher driven tools such as WAdss and the Namoi and Willunga integrated models is that they are an investment in knowledge. They capture science to put into decision making framework and may lay the foundation for future client commissioned DSS projects.

The design and implementation phase of the development of a DSS will often be an iterative process whereby prototype or pilot projects are used to develop the methodologies and preliminary models which are tested collaboratively with the stakeholders. This approach was taken with the CLAM, EXCLAIM and IBIS DSS. For the CAPER and CATCHMODS tools, the design of the interface and functionality of the models were refined progressively with subsequent applications to catchments as the developers of the tool learned what approaches and features worked best with planning processes or were more intuitive to users of the tools. Similarly, learnings and features of models or interfaces from DSS projects inform the development of subsequent DSS (e.g. CLAM influenced EXCLAIM which in turn influenced IBIS).

The limited adoption of DSS has been widely reported in the literature (Diez & McIntosh, 2011). However, adoption is not the sole measure of a successful DSS project. For example, WAdss is one of the more complicated DSS discussed in this paper. It was a product before its time, being one of the first examples of an integrated modelling approach to real-world water allocation problems. More than a decade later, only now is its potential for decision support being realised. Similarly, the Murray Flow Assessment Tool (Young et al., 2003) was criticised at the time of its development. However, it is now more popular and has been used widely to consider the impacts of water resources management on water dependant vegetation and fauna species. The lesson here is that none of the DSS are a success or failure at a single point of time. Even if the tool is not adopted the learning from its development can inform the development of future tools.

The crucial nature of the capacity building and facilitation role is not always recognised by both DSS developers and funders. Capacity building is a critical phase if the DSS is to be adopted and used by organisations to improve their decision making activities. Often, potential users exhibit a range of technical skills and capacity or want to use the tool for different purposes and it is crucial that training activities be targeted to users depending on these factors. We have tended to develop separate training modules for users who may not need to understand the technical details and technical users who are anticipated to use and maintain the DSS outside of the organisation or develop future application. The role of a model facilitator may need to be considered by developers and clients. Model facilitators present the model and its results including the possibilities, limitations, underlying assumptions and associated uncertainties. This includes frankly discussing when results are reliable and can support decisions and when the results are not reliable or are uncertain. This approach has been used successfully using the CAPER DSS to develop WQIP and WQPP and was a key intention of training local consultants to develop CLAM applications (Ticehurst, 2008).

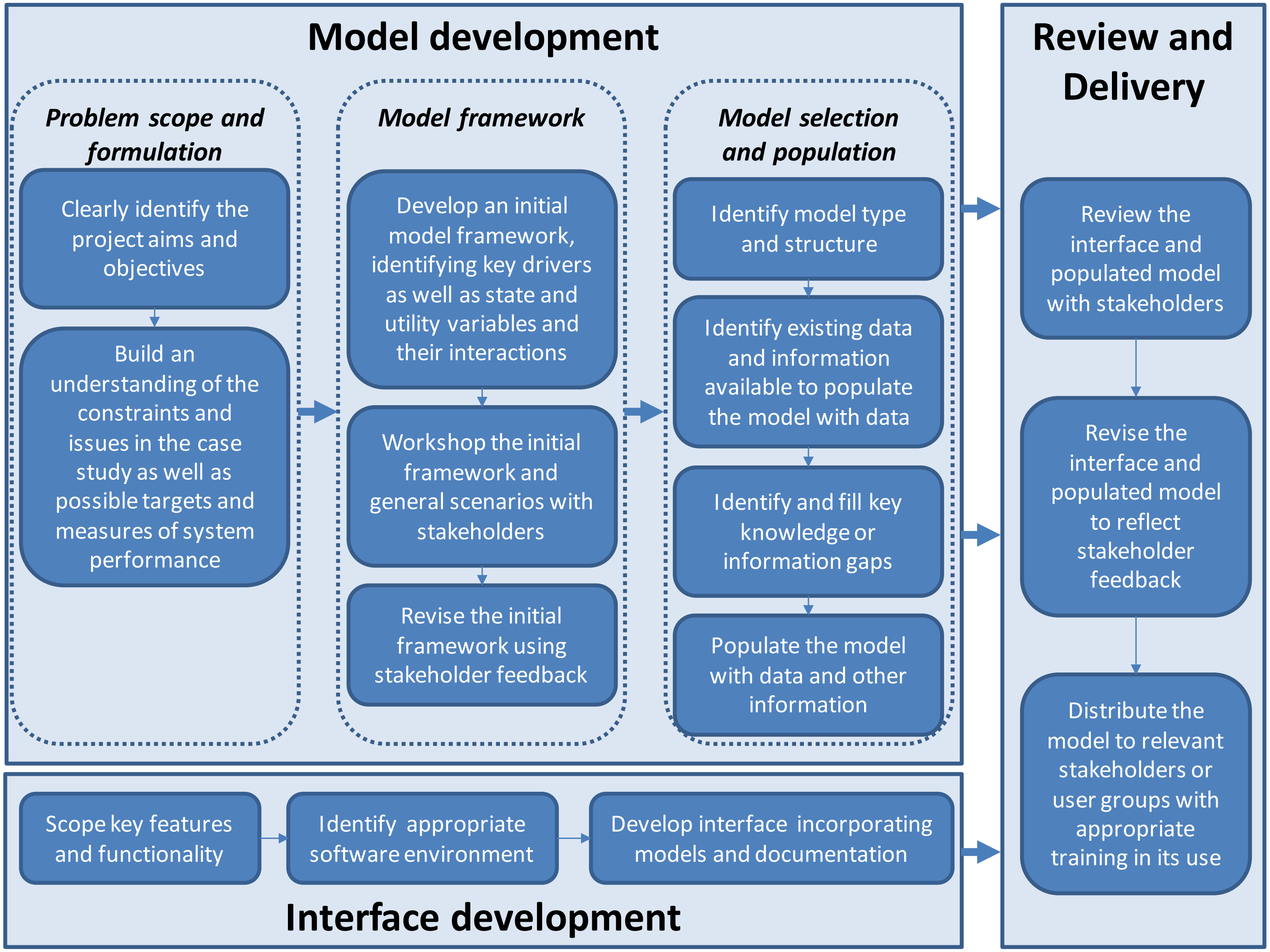

Figure 2: Recommended steps for a participatory approach to Integrated Modelling and Decision Support.

Recommended DSS development steps

The IA and DSS projects described previously have crystallized a basic set of steps we recommend should be followed when developing integrated models and DSS (Figure 2). The steps fall within three phases: model development, interface development and the review and delivery of the DSS.

The model development phase comprises the definition of problem scope, development of a (conceptual) model framework, model selection and population of the model with data. The project aims and objectives need to be clearly defined in order to define the scope of the DSS project including spatial and temporal scales, constraints and issues in the case study as well as identify key criteria or model components and measures of system performance. This can be achieved by reviewing existing information on the case study area including management reports, previous studies and other ‘grey literature’ information and consultation activities. The problem focus needs to be firmly developed before any model development is undertaken and should include substantial stakeholder collaboration. Particular consideration needs to be given to which stakeholders should be involved in all steps of the DSS project as well as who will use the model, how they will use it, what they will potentially use it for and how results need to be presented for different audiences. A broad consultation with many different stakeholder groups that seeks discussion across social, economic and environmental issues may help distil both the specific scenarios to be considered in the model and the states that would be most usefully demonstrate impacts on nodes.

Using outcomes from the project scoping steps, a model framework should be developed which explicitly shows the main drivers (e.g. climate or management levers), outputs (e.g. indicators of assets) and the processes connecting them. Model frameworks can help to clarify current understanding of system, including knowledge gaps and priorities. Often, they are developed in-house by DSS developers using information sourced from reports and other available information with input from a few key stakeholders. Developing frameworks collaboratively with stakeholders can help to ensure all parties are talking about the same system (or parts of the system) and promote co-development of the DSS and a sense of ownership over the finished product. The initial framework should be workshopped with stakeholders and revised accordingly. At this stage, the working version of the model framework should identify specific scenarios and key impacts to be considered by the model.

The revised model framework guides the selection of appropriate model type and structure. The DSS projects outlined above have used a number of modelling approaches to integrate the knowledge base. For example, BNs were adopted for all or part of the modelling where several issues were of concern and the knowledge had to be drawn from various sources types that were at times qualitative, uncertain and/or derived from expert elicitation (e.g. CLAM, EXCLAIM, IBIS and the Landscape Logic DSS). For WAdss, the coupled component model approach was selected because of the need to cascade water allocation decisions and socioeconomic and environmental impacts through zones of a catchment system. Similarly, models in CAPER are used to generate estimates of pollutant exports by subcatchment and/or local government area. ABM and SD models are being used to support participatory modelling in the Willunga project because ABM facilitates detailed discussion of how individual landholder decision making behaviour fits within its broader context and SD models help express system processes in simple terms. Our experiences with DSS and IA projects, including those outlined in this paper, led to a recently published journal article by Kelly (Letcher) et al. (2013) which provides a framework for choosing an appropriate modelling approach considering spatial and temporal scales required, reliance on qualitative data, characterisation of uncertainty, and the purpose for which the model is being developed.

Once the model type and structure have been specified, the working model framework should be reviewed to identify processes, links and variables for which no or very limited information exists. These links and variables could be filled with information sourced from monitoring or expert elicitation, for example. However it is critical to provide feedback to the stakeholder community on the limitation of data used and factors not able to be included in the DSS so as to manage expectations of the model capabilities.

The data population step of model development is time consuming and usually the primary focus of both traditional model building practice (usually the prime focus in budgets as well!). This step should involve a comprehensive evaluation of the effect of alternate assumptions on model behaviour and results, using sensitivity or uncertainty analyses.

The development of the interface can occur concurrently with model development. Key features and functionality of the DSS interface will be guided by the outcomes of the scoping and model framework steps. The selection of software should be sensitive to the capacity of end-users to use, understand and analyse the system, consider technologies and related software currently used within user organisations which may use outputs from (or provide input to) the DSS and be cognisant of any fiscal constraints to purchasing particular software. The design of the interface should allow non-technical users' to gain insight into the workings of the model through supporting documentation that can be viewed within the DSS and to provide ease of access to model runs and results.

Once the models have been populated with data, rigorously tested and implemented in the interface, the DSS developers need to seek feedback from key stakeholders on the usability of the system, the clarity of supporting documentation in the interface and the results provided by the model. The DSS model and interface are then revised to reflect stakeholder feedback. Once finalised, the tool needs to be distributed appropriately, including the software system, model documentation and training materials. This is often done through workshops run with people identified as key users by the client or through the project scoping activities.

Conclusion

This paper has drawn on experience gained from over 10 years integrated model and DSS development to provide recommendations on steps to develop effective DSS which can support management of complex and contentious NRM issues. Well-designed DSS can help help advance scientific, societal and stakeholder understanding. However, this paper has highlighted the importance of context and purpose on design of the tool and the need for involving stakeholders to ensure needs are met.

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