



Position paper

Environmental decision support systems (EDSS) development – Challenges and best practices[☆]

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ABSTRACT

Despite the perceived value of DSS in informing environmental and natural resource management, DSS tools often fail to be adopted by intended end users. By drawing together the experience of a global group of EDSS developers, we have identified and assessed key challenges in EDSS development and offer recommendations to resolve them. Challenges related to engaging end users in EDSS development emphasise the need for a participatory process that embraces end users and stakeholders throughout the design and development process. Adoption challenges concerned with individual and organisational capacities to use EDSS and the match between EDSS and organisational goals can be overcome through the use of an internal champion to promote the EDSS at different levels of a target organisation; co-ordinate and build capacity within the organisation, and; ensure that developers maintain focus on developing EDSS which are relatively easy and inexpensive to use and update (and which are perceived as such by the target users). Significant challenges exist in relation to ensuring EDSS longevity and financial sustainability. Such business challenges may be met through planning and design that considers the long-term costs of training, support, and maintenance; revenue generation and licensing by instituting processes which support communication and interactions; and by employing software technology which enables easy model expansion and re use to gain an economy of scale and reduce development costs. A final group of perhaps more problematic challenges relate to how the success of EDSS ought to be

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evaluated. Whilst success can be framed relatively easily in terms of interactions with end users, difficulties of definition and measurability emerge in relation to the extent to which EDSS achieve intended outcomes. To tackle the challenges described, the authors provide a set of best practice recommendations concerned with promoting design for ease of use, design for usefulness, establishing trust and credibility, promoting EDSS acceptance, and starting simple and small in functionality terms. Following these recommendations should enhance the achievement of successful EDSS adoption, but more importantly, help facilitate the achievement of desirable social and environmental outcomes.

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1. Environmental DSS (EDSS) – premise and promise

The environmental and social challenges of the late twentieth and early twenty-first centuries are complex and intertwined by nature, and global in extent. Responding to such contemporary environmental and social challenges requires change – change in patterns of consumption, processes of production, methods of resource management, and ways that we value other species and future generations. Faced with such drivers for change, scientific rationality has emerged as a prominent force in environmental policy and management worldwide. The need to formulate new policy objectives and implementation options, and to change the way in which we manage our environment and resource-using activities on the basis of robust analysis and evidence, has become well accepted. In conjunction with this rise of rationality, there has been a global growth in the supply of suitable tools and technologies to support policy assessment in various ways, accompanied by a similar but variable growth in demand for different types of decision support tools (Nilsson et al., 2008).

It is within the necessity to do things differently created by contemporary drivers of environmental change that the concept of the Decision Support System (DSS) fits, as technology to assist in the comparative assessment and selection of options for change. More specifically, the effort to develop technologies that inform environmental policy and management organisations in the search for solutions to complex problems has resulted in the development of what has been termed environmental DSS or EDSS (Guariso and Werthner, 1989; Rizzoli and Young, 1997). It is not our objective to provide a comprehensive review of the history of DSS development, but rather, in line with the recognised focus of this journal (Casagrandi and Guariso, 2009), to push forward our understanding of EDSS use and potential. The history of DSS can be found elsewhere in both extended (McCown, 2002a) and more succinct (Courtney, 2001) forms. However, before we begin to characterise, dissect, and re-formulate practices appropriate for remedying current challenges in EDSS development and use, it is important that the reader appreciate the initial intentions (the premise and promise) of DSS technology which first emerged almost four decades ago. As a leading journal in the field, further information on EDSS can be found in *Environmental Modelling and Software*.

The concept of the DSS was developed by Gorry and Morton (1971) by building on the work of Herbert Simon (1960) whose work focused on organisational decision-making. Simon (1960) distinguished three main phases of organisational decision-making (what we will term ‘decision phases’) – (i) the gathering of “intelligence” for the purpose of identifying the need for change (called “agenda setting” by Rogers, 2003); (ii) “design” or the development of alternative strategies, plans, or options for solving the problem identified during the intelligence gathering phase, and (iii) the process of evaluating alternatives and “choosing”. As described by Courtney (2001), Gorry and Morton’s (1971) original innovation was to distinguish between structured, semi-structured, and unstructured decision contexts, and then to define DSS as computer-aided systems that help to deal with decision-making where at least one phase (intelligence, design or choice) was semi- or unstructured.

So what constitutes a semi- or unstructured decision context? Pidd (2003) elaborates decisions into three categories along a continuum of structured to unstructured – from puzzles (with agreeable formulations and solutions) through problems (with agreeable formulations and arguable solutions) to messes (with arguable formulations and solutions) (see McIntosh et al., 2005 or Oliver and Twery, 1999). The distinction between categories makes explicit the fact that decisions involve problem formulation as well as solution generation and selection, and that both dimensions may be contested. Contested decision formulations exist where the nature of the problem is disagreed, e.g. is water scarcity a consequence of poor water infrastructure, poor resource management or profligate demand behaviour? Contested solutions are where different views exist on which option (or set of options with differing emphases) is the best to solve a given problem e.g. should water demand be reduced by pricing, conservation education, water use bans, or providing grants for xeriscaping gardens? Taking these distinctions, DSS were originally intended to be computer-aided systems to support one or more phases of decision-making where either the decision formulation was agreeable but the solution arguable (semi-structured), or the formulation and solution were both arguable (unstructured).

In addition to helping the process of structuring and resolving what action to take when knowledge about the nature and impact of problems (and how best to tackle them) is uncertain and contested, DSS and more specifically EDSS are meant to improve the transparency of decision formulation and solution. Transparent because rational explanations can be provided to support decisions, and because the user/stakeholder/citizen can reproduce the decision procedure, play with the weights, and perform sensitivity analysis to assess decision strength and robustness. However, as is well documented elsewhere, there are significant concerns about the uptake and actual use of EDSS and related technologies (Diez and McIntosh, 2009, 2011; Lautenbach et al., 2009; Oxley et al., 2004; Elmahdi et al., 2006). A brief sampling of existing literature on EDSS reveals various case studies on designing and building real-world EDSS (e.g. Cortés et al., 2000; Poch et al., 2004; Twery et al., 2005; Argent et al., 2009; Elmahdi and McFarlane, 2009), and a more limited literature on evaluating EDSS (e.g. Inman et al., 2011).

In general, the literature does not provide a guide for EDSS researchers/developers, stakeholders, and policy makers that: (i) describes the problems and challenges faced by EDSS developers (as opposed to information systems, or IS, developers more generally), and (ii) offers good system development practice recommendations that can help to overcome these difficulties and complications. The ‘ten iterative step’ model of Jakeman et al. (2006) goes some way towards providing such a guide but deliberately does not examine user interfacing, usability or the embedding of models into decision support systems – the primary concerns here.

The aim of this paper is to fill these two gaps; to improve EDSS development practice through collating and critically assessing the professional experience of a global group of EDSS developers (the authors) from academia, government, and business. This will be achieved by:

1. Characterising EDSS in terms of their intention, structure, function and use;
2. Characterising contemporary challenges to EDSS development and use; and
3. Presenting a set of best practice recommendations (essential do's and don'ts) and critically assessing how each recommendation might help avoid the problems and meet the challenges previously identified.

There are clear connections between the emphasis on users and use within this agenda and participatory or collaborative modelling, which focuses on bringing together multiple stakeholders to learn from each other and to jointly assess policy or management option impacts (see [Voinov and Bousquet, 2010](#)). The focus of DSS and EDSS work is on understanding how to develop more useful and usable systems for environmental policy and management organisation decision-making tasks. Sometimes such tasks might require a participatory modelling approach for purposes of, for example, policy formulation, but not always. Rather, the underlying ambition in DSS and EDSS work is to develop systems which are able to support a broader range of strategic (e.g. policy) and operational (e.g. planning) decision-making processes in organisations. This paper consequently explores a broader range of intended system end-uses than that explored within participatory modelling.

Further, the intellectual roots of the ambition to more closely involve users in the development of DSS/EDSS lie within (i) the soft systems side of operations research ([Checkland and Holwell, 1999](#); [McCown, 2002a](#)), which frames information systems (incl. DSS) as mixed human-technology systems and demands that information systems be jointly developed with changes to the human (i.e. organisational process) systems, and; (ii) user-centred and interaction design (see for example [Cooper et al., 2007](#); [Moggridge, 2007](#)) which demand that products (incl. DSS) be designed on the basis of a good understanding of user expectations, needs and behaviours and evaluated with regards their specific utility and benefits to different users, which themselves are mediated by the roles that users have within organisations and the roles that those organisations have. The intellectual roots differ from those of participatory modelling which stem from the desire to achieve wider social change through the democratisation of decision-making.

To proceed, the paper first reviews a number of EDSS, organised according to their intended use context (target decision phase, structure of decision context). Contemporary development and use challenges experienced by EDSS development professionals are then characterised and assessed before a set of best practice recommendations are discussed with respect to their potential to resolve the types of challenges experienced by EDSS development professionals.

2. Characterising EDSS – intention, structure and use

[Rizzoli and Young \(1997\)](#) define EDSS as DSS developed for use in environmental domains that ‘integrate models, or databases, or other decision aids, and package them in a way that decision-makers can use’. [Cortés et al. \(2000\)](#) define an EDSS as “an intelligent information system that ameliorates the time in which decisions can be made as well as the consistency and the quality of decisions, expressed in characteristic quantities of the field of application”. They further state that EDSS play an important role in helping to reduce the risks resulting from the interaction of human societies and their natural environments. A recent definition presented in [Elmahdi and McFarlane \(2009\)](#) describes an EDSS as “an intelligent analysis and information system that pulls together in

a structured but easy-to-understand platform (i.e. DSS) the different key aspects of the problem and system: hydrological, hydraulic, environmental, socio-economic, finance-economic, institutional and political-strategic”, i.e. that EDSS should combine database engineering and modelling, and facilitate or be used with a participatory decision framework.

Numerous EDSS have been developed spanning a broad range of modelling and software approaches and technologies, and utilising a wide range of implicit or explicit definitions of decision support. Beyond general concerns about adoption problems, what do we specifically know about EDSS as a class of technology? What kinds of decisions are EDSS designed to support? What kinds of model information management and decision support tools do they employ? What do we know about how they have been used in practice? [Table 1](#) presents the characteristics of a range of EDSS chosen to represent a variety of land and water related decision contexts. The EDSS have been organised according to the two dimensions of decisions described in [Section 1](#):

- Decision phase (*sensu* [Simon, 1960](#)); and
- Structure of decision context (*sensu* [Gorry and Morton, 1971](#); [Pidd, 2003](#)).

The reader should note that we have deliberately avoided using a single detailed process model of organisational decision-making to structure the analysis in [Table 1](#) due to the contested nature of the subject. Radically different views of decision-making process in organisations exist, from the conventional and linear ‘recognise problem – define problem – generate alternatives – analyse alternatives – choose from alternatives’ model ([Courtney, 2001](#)) through anarchical, sequential, sequential interrupted by events, convergence and inspirational models ([Langley et al., 1995](#)) to models which describe processes for sharing and contesting meaning in organisations like the Process for Organisational Meaning (POM) model of [Checkland and Holwell \(1999\)](#). The differences stem from fundamental differences in how organisations as social processes are conceptualised. To avoid the complications of the various arguments involved we have chosen to frame organisational decision-making simply and coarsely using Simon’s model (intelligence gathering – designing alternatives – choosing alternatives), and in relation to decision context structure.

With regards the review in [Table 1](#), EDSS focused on supporting the intelligence gathering phase are presented first, and those focused on supporting the choice phase last. EDSS focused on supporting multiple phases are presented in the middle. Within each phase, EDSS are presented in order of those focused on supporting structured through semi-structured to unstructured target decision contexts. Within this categorisation, the characteristics of EDSS presented are:

- Name of the EDSS and developers/authors;
- Types of models, technologies, and techniques used in the EDSS;
- Stated purpose of the EDSS; and
- Details of reported use of the EDSS.

Most of the EDSS reviewed were targeted at providing support across the intelligence, design and choice phases within unstructured decision contexts ([Table 1](#)). In other words, more than half of the EDSS reviewed (12 out of 19) were developed to provide what might be framed as ‘complete’ (i.e. all phases) decision support in the least structured, most messy of contexts. Only seven out of 19 EDSS mentioned in [Table 1](#) were focused on design and choice phases alone, and none exclusively on the intelligence phase alone. Four out of seven design and choice phase EDSS were targeted at

Table 1

Review of the EDSS target uses and users (see Section 1 for an explanation of 'decision phases' and 'structure of decision contexts').

Target decision phase	Structure of target decision context	Name of tool and references	Type of tool	Stated purpose	Target end users and reported use
	Semi-structured	MedAction PSS—Van Delden et al. (2007)	Integrated assessment model (IAM) composed of numerical and rule-based sub-models	"PSS is best geared towards policy makers and planners at the regional level to provide assistance in the following: 1. Understanding the important processes and their linkages shaping the region; 2. Identifying and anticipating current and future problems in the region; 3. Designing policy measures to mitigate the problems and assessing their effectiveness; 4. Evaluating different alternatives and selecting a candidate for implementation"	Presented to and discussed stakeholders, but not operationally used by them.
	Unstructured and semi-structured	Participatory Integrated Planning (PIP) — Castelletti and Soncini-Sessa (2006, 2007)	Procedure to structure the process of jointly deciding on objectives (the problem), and; designing, evaluating and negotiating options in river basin management	"... a Participatory and Integrated Planning (PIP) procedure that constitutes a first attempt to bridge the ... gap". "... of a methodological approach (procedure) to be adopted to address the decision-making process".	Developed within and used by a range of stakeholders within the Lake Maggiore management project, other uses mentioned but not described in detail.
	Unstructured	MODULUS—Oxley et al. (2004)	Integrated assessment model (IAM) composed of numerical and rule-based sub-models	"to enable end users to understand the processes causing and caused by land degradation, and to provide appropriate tools for the design and evaluation of policy options"	Presented to and discussed with local government and other stakeholders, but not operationally used by them.
		mDSS—Mysiak et al. (2005)	Hydrological models, mathematical decision models, multiple criteria analysis	"mDSS has been developed with the aim of guiding users through the identification of the main driving forces and pressures on water status and to help them explore and evaluate the possible measures"	Presented to users from water authorities after a training stage but no follow-up has been made to check on the operational use.
		CLAM—Ticehurst et al. (2008)	DSS	"Users are encouraged to use the CLAM to think critically about the (social, economic and ecological) trade-offs involved in managing their coastal lake systems, and to evaluate the model results and questioning their validity"	Intended end users including local government, trained in how to use and update. Some evidence of tools being updated, but not overwhelming evidence that they are operational.
		NED-2 — Twery et al. (2005)	DSS with data management, artificial intelligence, and simulation models	"to improve project-level planning and decision-making... by integrating treatment prescriptions, growth simulation, and alternative comparisons with evaluations of multiple resources"	Used primarily by private consulting foresters to manage clients' forest lands, but also by public land managers to evaluate alternatives for large holdings.
		CAPER —Kelly and Merritt (2010)	DSS	"developed to explore likely ecological response to changes in catchment exports of nutrients and suspended solids resulting from changed management of the lakes and their catchments. "	Used to negotiate and develop components of the Great Lakes water quality improvement plan (WQIP; Great Lakes Council, 2009) and the draft WQIP for the Botany Bay (Sydney Metropolitan Catchment Management Authority, 2010).
		IBIS—Merritt et al. (2009, 2010)	DSS	"explore the likely outcomes of catchment water planning scenarios on the ecological characteristics of the inland wetland systems in NSW Australia to improve the capacity of organisations to plan and manage environmental flows at valley and wetland scales"	DSS application in early development stage for the Darwin Harbour water quality protection plan (WQPP). Not yet operationally used by the Department of Environment Climate Change and Water. Has been used to explore possible impacts of climate change and water delivery scenarios defined in accordance with the proposed Murray Darling Basin Plan.
		Groundwater Decision Support System (GWDSS)—Pierce (2006)	System dynamics models, Tabu search optimization algorithm, GIS	"to address the complexities associated with determining an acceptable groundwater allocation policy"	Presented to a group of stakeholders to help define strategies for sustainable aquifer yield.

Design and choice	Not explicitly mentioned	Gnangara Decision Support Tool (GDST)—Elmahdi and McFarlane (2009)	System dynamics models, Modflow	"The purpose of the DSS is to provide quantitative assessments of land and water management options recommended by the Gnangara taskforce at the local area level"	Used by stakeholders "to readily set up scenarios in the DSS and analyse their impacts on Gnangara groundwater system and its values". No evidence in literature that the GDST has been used operationally. Delivered to relevant authorities to support basin management, and by the German Hydrological Institute for strategic planning.
		Elbe-DSS—de Kok et al. (2009), Lautenbach et al. (2009), Matthies et al. (2006)	Rainfall-runoff model, river network model, water quality model	"the principal objective of the Elbe-DSS is to demonstrate the capability to support management tasks related to problems in the fields of: water quality, flood risk, river navigation, and increasing the ecological value of the riverscape". "for defining water use policies by assessing the economic and environmental impacts within a single multi-criteria/multipurpose decision-making simulator"	Delivered to relevant authorities to support irrigation planning.
		GESMO project DSS—Recio (2005)	Modflow, statistical econometric models	"An integrated assessment model that highlights the interconnections between different air quality problems, the interactions between pollutants in the atmosphere, and the interdependencies between emission controls across pollutants and source categories... this approach provides a practical tool to identify cost-effective emission control strategies to improve air quality at least cost by considering these interactions"	International policy negotiations on air emissions reduction. Decisions makers participating in the Convention on Long Range Transboundary Air Pollution were involved in developing GAINS. The predecessor model, RAINS, received extensive use, but no documented use of GAINS yet.
		GAINS — Amann et al. (2011)	Integrated assessment model (IAM) providing both simulation and optimization functionalities	"A decision support system to assist cage aquaculture managers ... to perform four essential tasks: (i) site classification, (ii) site selection, (iii) holding capacity determination, and (iv) economic appraisal of an aquaculture farm at a given site."	Aquaculture managers for design of new aquaculture facilities. No reported use.
	Semi-structured	SMOM (Simplified Modelling — On Growing — Monitoring) — Halide et al. (2009)	Multi-module tool, with modules to perform different aspects of aquaculture facility design, using a mixture of classification, multi-criteria decision analysis (MCDA), simulation and	"Optimizing areas for habitat restoration requires that the landscape be assessed for suitable habitat while considering costs and socio-economic constraints. ... Together with extant native vegetation and land use information, our approach attempts to find optimal solutions to satisfy species requirements, while considering budget constraints."	Habitat and land conservation managers for designing habitat restoration schemes. No reported use beyond test case study.
		OPRAH (Optimal Restoration of Altered Habitats) — Lethbridge et al. (2010)	Spatial optimisation based tool employing a simulated annealing algorithm	"StockPlan is both a workshop and a software package to assist cattle, sheepmeat, and wool producers make management decisions either before and during seasonal dry spells or in the early stages of drought."	Targeted at farmers. Developed by Government Department. No reported use.
		StockPlan—McPhee et al. (2010)	4 tool system employing a mixture of age structure analysis, financial analysis and economic analysis	"provides integrated decision support for environmental evaluation and planning at multiple spatial scales"	Used by several management and education organisations for forest and landscape management. Used to analyse a set of scenarios by the authors only.
		Ecosystem Management Decision Support (EMDS)—Reynolds (2005)	GIS, multiple criteria analysis, rule-based reasoning engine	"to implement the Integrated Coastal Zone Management (ICZM) in Taiwan."	Updated and used by users from the Sardinian (Italy) water authority.
Design and choice	Not explicitly mentioned	DSS for sustainable coral reef management—Chang et al. (2008)	A set of system dynamics models	"modelling of complex multi-reservoir and multi-use water systems based on Trophic State Index with additional consideration on algal composition in the reservoirs"	
		Water Resources Aided by Graphical Interface — Quality model (WARGI-QUAL) — Sulis et al. (2011)	DSS		

semi-structured decision contexts, whilst only 1 of the EDSS designed for intelligence, design and choice phases was. Nine of the 12 intelligence, design and choice phase targeted EDSS were designed for unstructured contexts as opposed to none of the purely design and choice phase EDSS.

Denzer (2005) suggests four main technologies that can be found in an EDSS including approaches for numerical calculation (models), geographical representation (GIS), artificial intelligence (optimisation and decision analysis), and data management and networking (data management systems). From the review presented in Table 1, a variety of structures, tools and technologies are employed in EDSS. Five out of the 19 reviewed employ some form of optimisation technique (e.g. Tabu search, MCDA) whilst the majority employed a variety of simulation and scenario-driven modelling approaches. The extent to which the various EDSS have been used operationally by intended users is variable and not always clear. There appear to be four main categories of use:

- 'Delivered', 'presented to', 'discussed', 'involved in development' but not actually used, e.g., *mDSS*;
- Users trained but limited evidence of use, e.g. CLAM;
- Used for one-off or infrequent strategic purposes, e.g., water quality improvement plan development as per CAPER and GDST; and
- Frequent, routine use by trained stakeholders to the extent it becomes a recognised job function, e.g. NED-2

Although the set of EDSS reviewed is not complete, no clear relationship is evident between the extent/success of use and the characteristics of the EDSS (purpose or tools employed), or the intended use in terms of targeted decision phase or context. At least one system, the NED-2 forest management DSS, has been widely adopted in part because it simplifies activities which users already need to do. Whilst the limited review sample means that conclusions are tentative, the lack of correlatory pattern might indicate that the source of variability in the use of developed EDSS is linked more to development process than the end product or targeted use. Focussing on development process rather than technological characteristics as the locus for adoption and use problems ties with what is known empirically about the factors which influence IS and EDSS design, adoption, and use outcomes. In the next section, mindful of this proposition, we shall examine the challenges faced by EDSS developers.

3. Characterising challenges in EDSS development

Challenges that EDSS developers have to face and development approaches to choose from are manifold. During the iEMSs 2010 meeting (Swayne et al., 2010) in Ottawa, Canada, a group of 24 EDSS development professionals (the authors) from across the globe met to discuss and share good and bad practice points during a facilitated workshop (W15). The intention was to bring together EDSS professionals with a broad range of experience in terms of problem domains (e.g. farm management, flooding and climate change, water resources, natural resources, land degradation, etc.) and employment context (e.g. government, academia, business) to discuss and identify key challenges. In doing so the aim was to capture and disseminate significant and broadly applicable insight based on experience in designing and developing EDSS, particularly in relation to comparing successfully used and unused EDSS. The challenges identified during the workshop were grouped into four main areas:

1. *Engagement challenges* related to the quantity, quality, and appropriateness of end user involvement in the development of the EDSS.
2. *Adoption challenges* stemming from a failure to take up and use the EDSS as a consequence of a range of factors from lack of capacity to the characteristics of the system.
3. *Business, cost and technology challenges* related to making the EDSS sustainable in the long-term through understanding costs and using appropriate software technology.
4. *Evaluation challenges* concerned with defining and measuring how the success of EDSS can be assessed.

3.1. Engagement challenges

The first category of problems and challenges relates to the quantity and quality of end user and, where relevant, broader stakeholder involvement. The reader should note that these problems are not unique to EDSS, but rather are widespread across a range of IS and within participatory modelling (Voinov and Bousquet, 2010). For example, Diez and McIntosh (2009) demonstrate that 'user participation' is the best predictor of pre-implementation (design) phase outcomes for IS. Whilst 'user participation' itself is only a potential predictor of implementation phase outcomes, 'behavioural intention' and 'perceived usefulness' are best predictors at individual scale for the same outcomes, and are themselves a function of user engagement.

Although stakeholders and end users can be one and the same, they can also be different entities with different expectations of an EDSS. Stakeholders are typically those who have an interest in both the problem that is being addressed by developing of an EDSS and the solution to the problem (e.g. a Government or funding agency). However, a stakeholder may not necessarily be an end user of the EDSS but simply someone with a stake in the outcome of the decision. The challenge to effective EDSS development to serve both the end user and stakeholder communities are threefold:

(1) EDSS developers often lack a strategy, and sometimes funding, to engage in sufficient end user or broader stakeholder engagement processes during EDSS development. Diez and McIntosh (2009) and Quinn (2010) both emphasise the necessity to understand end user needs and to work collaboratively with this group of people. Whether broader stakeholder engagement matters materially to the success of the EDSS endeavour depends on the purpose and intended role of the EDSS. Newham et al. (2007) found that not clearly defining the scope and extent of the participatory activities at the beginning of the project was a major constraint to successful EDSS development outcomes, in that continued participation by the broader set of stakeholders requires considerable investment which, while potentially very worthwhile, can drain resources from other parts of a funding-limited project, and damage success.

To avoid pitfalls during EDSS implementation resulting from unforeseen end user or stakeholder issues, the developer should maintain a well-established and permanent contact office. An embedded representative or champion in the targeted organisation(s) can help ensure responsiveness and improve the probability of adoption and satisfactory use, particularly if located in both the management and technical functions (Sieber et al., 2010a, 2010b). Elmahdi and McFarlane (in press) present a method for developing EDSS with embedded representatives from multiple agencies/organisations to develop a strategy for groundwater resources.

(2) There are two obvious challenges in identifying the specific end users of an EDSS. First, many EDSS projects are funded by international or large national research foundations, but implemented by private companies or academic researchers, with funding often granted independently of the direct involvement of potential or targeted end users (Quinn, 2010). Separating fund granting from the process of capturing and responding to specific

user needs in this way creates a systemically problematic context for EDSS developers, who must meet two separate and potentially competing or at least non-overlapping sets of demands. It is challenging for developers in receipt of such funds to identify and engage with specific end users who have requirements sufficiently similar to the focus of the EDSS required by the funding agency.

Volk et al. (2010) present the example of the MedAction EDSS (Van Delden et al., 2007) that was funded by the EU independently of specific end user needs. End users were identified later in the project, which led to time wastage and EDSS ineffectiveness. Once identified, end users were reluctant to contribute to the development of the MedAction EDSS because there was no requirement for their organisations to use the system once it had been completed and turned over to them. It would be better if end-using organisations were involved in specifying the call for EDSS development and potentially also paying for it.

Another development experience with difficulties rooted in the funding system occurred with the EU project PLUREL (<http://www.plurel.net>; Haase et al., 2010), where, unlike MedAction, prospective users were involved in the initial development of the integrated Impact Assessment Tool (iIAT). Development activities included both conceptualisation and design of final EDSS content. However, because the iIAT covered the entire EU (as required by the funders), the database and the supporting GUI did not provide regional detail and many end user organisations did not see how the system could help them directly and so became less engaged. End users need to be able to recognise themselves and their tasks in the EDSS: too much context and the end user can become quickly overwhelmed and discouraged, too little content and the end user can become frustrated and start questioning the utility of the tool to make meaningful decisions (Quinn, 2010).

A more positive experience comes from the United States where a DSS that was developed to assist resource managers to accomplish specific tasks (NED-2), such as designing forest management projects on specific tracts of land, served a second purpose by also providing other stakeholders a means of influencing resource policy (Twery et al., 2005). In that effort, both potential field-level users of the EDSS and decision-makers higher in the organisations had regular opportunities to influence development.

In contrast, Volk et al. (2010) report that although it was possible to obtain feedback from management for the Elbe-DSS, contact with the technical and analytical staff who were actually supposed to use the EDSS was much harder to establish (see Lautenbach et al., 2009; Berlekamp et al., 2007; and Matthies et al., 2006 for descriptions of the Elbe-DSS). Because policy analysts and their assistants are among the people who should be using an EDSS, it is critical to include their requirements and address their needs during the design of the system.

(3) At the practical scale, once end users have been identified and engaged, the process of how to go about successfully eliciting relevant information from them to develop a useful and robust EDSS rarely receives adequate attention from developers (Burstein and Holsapple, 2008), and almost certainly contributes EDSS failure. End users can have difficulty articulating the decisions they are called upon to make and may not be able to precisely describe the bounds of the decision space within which they operate (Quinn, 2010). Readers familiar with the lack of detail regarding how to actually carry out the first (and perhaps most fundamental), 'problem definition' stage in DSS development as specified in many texts will recognise this difficulty.

Consequently there is a need for improvement in both methods for eliciting decision requirements and professional practice in applying those methods. Some approaches do exist such as Contextual Design (Beyer and Holtzblatt, 1997) and Goal-Directed Design (Cooper et al., 2007) but these have not yet received

documented environmental application. Elmahdi and McFarlane (in press) created MAF (Multi-Agency Framework) as an approach to support environmental participatory processes, and in particular to structure inter-agency dialogue to avoid a situation where the planning decision of one agency constrained the ability of another agency to achieve its own objectives. The MAF process involves stakeholders in the conceptualisation, specification, and synthesis of knowledge and experiences to address a complex problem. Also, it distinguishes between factors that influence the system, indicators that can help to assess the system, any conflicts between the stakeholders, and outcomes on the scale of interest. In doing MAF provides a way of exploring the links from drivers and factors to outcomes via decision-making processes and behaviour.

3.2. Adoption challenges

Following the process of engaging with users to understand and reflect needs, the next set of challenges facing EDSS developers are with respect to how to enhance the prospect of positive adoption outcomes. Of course, successful engagement with users during the design phase of EDSS development lays the foundation for successful adoption or implementation, but this is not the whole story.

McIntosh et al. (2008) distinguish between three potential modes of organisational use which an EDSS can be designed to support:

1. Existing forms of action through providing currently used information in a new way;
2. Existing forms of action through providing new information in such a way that either the effectiveness or efficiency of that action will be improved; or
3. Alternative forms of organisational action through providing new information, potentially in new ways.

Volk et al. (2010) claim that the best chance for EDSS adoption in an organisation is through providing a tool that enables that organisation to face new challenges and deal with problems not encountered previously (mode 3). This was the case for the Elbe-DSS (Lautenbach et al., 2009), the Gngara-DSS (Elmahdi and McFarlane, 2009) and for FLUMAGIS (Volk et al., 2007, 2008). The analysis of agricultural DSS use by McCown (2002b) showed the same situation to be true – farmers tended to adopt DSS to learn about and understand how to adapt to changing economic, environmental or other conditions, and then discard the DSS once learning was complete.

In contrast both Oliver and Twery (1999) and Rauscher (1999) found that adoption of an EDSS is more likely if it focuses on accomplishing a task that a potential user is already required to do and also makes the task easier (mode 1 or 2). The addition of analysis capability to an EDSS can increase chances of adoption, but again only if the user sees the EDSS as a means of making the required work more manageable (Oliver and Twery, 1999). IS adoption research reinforces this feature – users must perceive the system to be easy to use and to materially contribute to making their work easier (perceived usefulness) (Venkatesh et al., 2003).

Regardless of which mode of use is most likely to result in successful adoption, what is clear is that if the development of the EDSS is not end user-driven, a substantial and costly effort in promotion, demonstration, and documentation will be required. Elmahdi and McFarlane (in press) documented early feedback from the Gngara Mound EDSS development that suggested the following actions would assist adoption:

1. The EDSS not requiring a level of expertise or knowledge that end users do not possess.

2. The tools being flexible enough to meet end users' requirements to use them in ways that suit them personally and organisationally.
3. The tools being presented in a simple fashion to the end user to reduce complexity.
4. The tools only being transferred to end users after they have undergone and passed rigorous review in order to earn end user confidence (it doesn't take much to discourage new users).
5. The tools being well documented with adequate help resources available online. Over-reliance on EDSS developers for technical support being unwise.

Another important challenge for adoption can be the operational status of the EDSS when presented to end users and stakeholders. EDSS developers face the risk of developing "mock-up" prototypes which do not meet expectations. In particular, prototype systems can have difficulties coping with:

1. spatial, temporal, and thematic integration;
2. technical performance and promised system advances; and
3. quality assurance features, promised data integration, and model results.

Conversely, prototype "mock-ups" can sometimes demonstrate planned features that cannot subsequently be implemented in the functional system, thus over-promising system capability and eventually disappointing end users. A fully functional EDSS prototype for demonstration is a key strategy for advertising operational performance to end users, and for engaging potential users effectively in the design process. The new system should convince potential users through the use of relevant applications that the innovation is clearly superior to its predecessor. However, confronting the end users with a nearly final prototype implies that end user feedback on the system design can no longer be incorporated since many EDSS design features cannot be changed close to completion. Following an iterative or evolutionary development approach (e.g. Van Delden et al., 2011) instead of a waterfall approach offers the advantage of being able to incorporate end user needs in the EDSS instead of relying on software developer and scientist assumptions. In the long-run such approaches should lower costs by avoiding mis-specifications and poor adoption outcomes.

Credibility and reliability also have a significant impact on EDSS adoption in terms of trust between user and developer, and in terms of the attributes of the information provided by the system (certainty, relevance, completeness, reliability) as shown by Diez and McIntosh (2011) in relation to adoption by desertification policy and management organisations. Conversely, the argument of EDSS not being reliable enough can be made by those who refuse to employ rational, analytical decision aids. Setting standards and requirements that cannot be met is a potential defense by vested interests when faced with rigorous analysis. The EDSS may be "good enough" in the sense of technically and with regards user relevance but still not accepted or adopted. Some authors have argued that before DSS are accepted and used, decision-making organisations and key decision-makers must be convinced that there is a need to change decision strategy (Chenoweth et al., 2004). Change in decision strategy is a necessary pre-condition to adoption.

The extent to which the inclusion of uncertainty in EDSS inputs, processing and outputs is necessary or an important determinant of adoption or use success is not clear. Based on the experience of Volk et al. (2010), it was found that improvements are needed in EDSS regarding the treatment of uncertainty due to sparse data availability, the coupling of different models and tools; spatial

heterogeneity in variables and parameters, and calibration procedures. Other authors (e.g. Refsgaard et al., 2007) have positioned uncertainty representation as central to environmental modelling activities and something to be focussed on from the outset. Voinov and Bousquet (2010) argue that understanding scientific uncertainty is important and best achieved through participation in modelling activities.

However, integrated assessment modelling workshop evidence suggests that decision-makers are not particularly interested in uncertainty *per se* (UNECE, 2002). Rather, they are interested in knowing whether particular decision strategies are robust across a range of possibilities. Amann et al. (2011) interpreted this finding by assessing options against the worst case, most conservative conditions, rather than against a range of conditions. Further, evidence suggests that humans are able to make quick, robust decisions under information poor conditions using simple heuristics (Todd, 2007), so whilst uncertainty communication may play a role in engendering trust across science-stakeholder boundaries (Voinov and Bousquet, 2010), it is less clear the extent to which detailed model/DSS uncertainty representations are necessary.

3.3. Business, cost and technology challenges

Ensuring EDSS reflect user needs and are eventually used satisfactorily is not however without cost, and the resources needed are easily underestimated during EDSS development planning, with risks to the longevity of the EDSS. For example, in addition to the stakeholder or user engagement costs involved in requirements analyses, high transaction costs may be incurred internally among developers. Discussions to agree on terminology and priority setting for requirements should be carefully managed to avoid their becoming unproductive.

The challenge of EDSS longevity should be ensured by a developing business plan that explicitly defines expected costs and outcomes over the lifetime of the product, and shows how revenue will be generated or funding secured to cover those costs. Important factors for ensuring longevity and business viability include the characteristics of the organisation(s) producing the EDSS, the licensing arrangements, and the software structure and approach.

Will the EDSS developer be able to ensure long-term maintenance and support for the product? How will the developer be influenced by personnel changes? Until the 1990s, EDSS were often created by scientists and engineers who also built the mathematical models underpinning them. Today, successful EDSS require teams including mathematical model builders, professional software engineers, domain experts, and ergonomic and interaction design specialists. When an EDSS depends on one or a few charismatic developers for ongoing maintenance, it is less resilient to personnel changes. Larger, more established organisations or groups have an advantage in being better able to guarantee long-term maintenance and support, and the necessary competences. They may also be able to achieve the economies of scale in reuse of software components to further assist in overcoming the significant up-front development costs associated with developing an EDSS from scratch.

Within this arena, software licensing plays an important role by providing a contractual description of the user-creator relationship and the basis for generating a viable business plan for the EDSS. Further, because licensing fosters longer-term thinking, it can be an important factor in determining ultimate software and EDSS sustainability and success. Licensing options include open-source, freeware, and proprietary licenses.

Proprietary systems link software to livelihoods in the sense that developers within companies have a very strong financial incentive to ensure their products are successful, which is a positive influence on long-term quality. The evidence for this is strong – many

successful EDSS involve software and consulting services by one or more contractors, often linked to training services. Recognised research institutions may also license proprietary EDSS. An emerging alternative is EDSS development by international consortia of researchers working on open-source projects. These groups use online code management systems to organise code contributions into a licensed software or library. For example, HydroPlatform (Harou et al., 2010) allows network-based environmental management models to connect to a shared open-source user interface and database. A third model for long-term software success is for a government agency to recognise the utility of the EDSS and commit at a high level to providing ongoing support (Reynolds, 2005; Twery et al., 2005; Havis and Crookston, 2008).

Finally, software structure may be a factor in determining EDSS business success, i.e. how easy and cost-effective is the code to maintain, expand and link to other codes? EDSS are complex and success requires professional software development practices. Several software approaches are available including dedicated decision support systems, modelling frameworks, commercial modelling systems, and stand-alone software (reviewed by Harou et al., 2010). The boundaries between these approaches sometimes overlap but they reflect the wide range of options. Expanding an EDSS built with a modelling framework or interface standard (Argent, 2004; Rizzoli and Argent, 2006; Gregersen et al., 2007) is likely simpler and cheaper than expanding a single purpose or stand-alone EDSS not designed for modularity, although no literature data on the comparative costs of doing so is available beyond the qualitative assessment of effort presented by Oxley et al. (2004).

3.4. Evaluation challenges

Whilst quantifying costs in advance is difficult, more challenging disagreements can arise over how to define and measure EDSS success (see Matthews et al., 2011). Following Goeller (1988), we can judge the success of using an EDSS to support policy and management through three sets of criteria:

- *Analysis* – analysis success reflects how the EDSS analysis was performed and presented to the users. The analysts must take care of user (client) satisfaction, but success based only on this measure will be transitory. Indeed, users may be not satisfied because they are being presented with results they do not want to accept.
- *Application* – application success is concerned with how the EDSS was used in the decision-making process and by whom. A good indicator of application success is the extent to which information from the EDSS influences the decision-making process (although this raises a set of further measurement questions – how does one assess information influence in relation to decision-making processes?). Further, application success can be identified by whether the EDSS can support the framing of problems to better identify those worthy of resolution (Hermans, 2005).
- *Outcome* – outcome success provides information on how the use of analytic results from the EDSS affects policy, planning and management and if action informed by EDSS use ameliorates the problem it purports to address. As described below however, this evaluation is problematic.

Outcomes evaluation assesses on the one hand the relationship between environmental change and EDSS use in policy and management processes, and on the other the effects of EDSS use on attitudes, behaviours and learning in the context of decision-making processes. In the latter situation, evaluation of EDSS outcomes should recognise five important caveats:

1. The intangibility of many outcomes can lead to evaluations that just measure what is easily quantifiable rather than more important outcomes that are difficult or costly to measure. An example of an intangible outcome is that the social capital built up between individuals may be strengthened through stakeholder direct participation in the EDSS development phase, which may in turn enhance adaptive capacity far more than the outputs from the EDSS itself (Burton et al., 2007; Kaljonen, 2006).
2. The use of EDSS may provide educational benefits in terms of changing mental conceptualisations of real-world systems (Kolkman, 2005), and in terms of providing a tool to learn about and adapt to environmental changes (McCown, 2002b). However linking such educational benefits to action is difficult and in fact, as Matthews et al. (2011) found, users of models may learn but choose not to change their behaviour. Educational success is no guarantee that any particular outcome will be achieved any better. Organisational learning in particular is complex and may be difficult to influence (Courtney, 2001).
3. The long-term and cumulative nature of change (individual or organisational) may also be incompatible with short-term, project-based evaluation of outcomes. For example, the project team may have moved on to a new research area long before the outcomes can be measured, thereby complicating the process of understanding the EDSS intervention and its consequences (Blackstock et al., 2007).
4. Even where outcomes can be measured, one cannot be sure that success is an outcome of using the EDSS. Establishing causality is very difficult when processes and participants cannot be directly replicated or controlled (Robson, 1993). This difficulty is compounded for interventions in the complex, coupled social-ecological systems that are the typical focus of EDSS (Bellamy et al., 2001). However, attribution of perception that a change was stimulated by an intervention is possible.
5. Even where outcomes can be distinguished with clear causality, there may be considerable disagreement between stakeholders and the interested public on the relative importance of individual outcomes (particularly when these outcomes are non-commensurable). Outcomes other than those expected (or even desired) by the EDSS funder will be discounted in favour of those that “fit the expectations” (Fischer, 2000).
6. There needs to be an increased recognition of the limits on the influence that science generated “expert” outputs can have within a plurality of expertise derived in different ways (Stilgoe et al., 2006). Research-based tools such as EDSS are only one source of influence and usually not one of the more important (Solebury, 2001).

Drawing from the challenges outlined across Section 3, Table 2 presents a set of criteria for evaluating the success of EDSS in terms of their ability to support policy and management processes, in terms of scientific and engineering analytical capabilities, and in terms of software capabilities. Uncertainty has been listed as a key success factor for science and engineering analysis applications because quantitative precision is critical. Uncertainty has not been listed as a critical success factor for policy or management process support because the evidence regarding the benefits of including uncertainty representations in EDSS for robustness in decision-making are unclear and contested (see discussion under Section 3.2).

4. Recommendations

Given the range of challenges described, what recommendations can be made in relation to EDSS development practice? What constitutes good, or even best practice, and what should be avoided (beyond that which has already been mentioned)?

Table 2

Summary of success criteria for different EDSS roles.

EDSS capacity	Success criteria	
To support policy and management decision-making	Analysis	1. Ability to produce understandable results 2. Ability to support the analyst to produce such results 3. Ability to produce results addressing end user questions
	Application	1. Tool used by the intended end users for the intended purpose 2. Tool used at all 3. Number of users 4. Number of organisations using the tool
	Outcome	1. Impact of the tool in changing attitudes, behaviours and on-the-ground outcomes
To support science and engineering analysis	1. Validation of model result against data 2. Representation of uncertainty in results	
Underlying software capacities	1. Transferability and extendibility	
	2. Ease of system maintenance (fix and update)	

The following recommendations are a compilation of the knowledge and experience accumulated by the authors and others from many attempts to develop EDSS, some of which have been more successful than others. None of the recommendations will be universally applicable, but they will all have times and places in which they are important. The context and focus of the development effort of any EDSS will dictate which of these will be most applicable.

4.1. Recommendations related to improving EDSS end user and stakeholder involvement

Perhaps the most critical task in the design, development, and deployment of EDSS is to make sure that they will actually be used in some capacity by the targeted end users. Consequently it is worth exploring what steps can be taken to improve the efficacy of end user and stakeholder participation. To this end, the following recommendations are made for involving users in the development of decision and information support tools:

- *Understand roles and responsibilities* – at the beginning of the EDSS development process, clearly identify end users, stakeholder, clients, etc. and the responsibilities of each party. This will help avoid fundamental misunderstandings and disagreements in the future.
- *Dedicate time and resources for a requirements analysis or a usability survey* to better understand the organisational context within which the end users, stakeholders and EDSS developers operate together (Elmahdi and McFarlane, in press). There are various methods from the IS development community for user modelling and work flow modelling like Contextual Development (Beyer and Holtzblatt, 1997), and usability assessment (Tullis and Albert, 2008) that could be borrowed.
- *Work with end users and stakeholders to clearly define what constitutes project success* – consider the cost-effectiveness of an EDSS versus other means of achieving the outcomes. Identify an exit strategy for the end user/stakeholder participation process.
- *Provide stakeholders the opportunity to contribute to and challenge model assumptions* before results are reported – this helps to create a sense of ownership during the EDSS development process (McIntosh et al., 2008).
- *EDSS design should strive to include and effectively communicate model-based uncertainties to users.* This should be accomplished without confusing or intimidating the end user or causing the stakeholders to lose confidence in the EDSS (Quinn, 2010).

- *User groups often feel irrelevant or ignored because they do not receive feedback* concerning their suggestions/ideas and do not see them incorporated in the final EDSS (van Delden et al., 2011). Therefore, discussing development timelines with users and providing feedback on their input is crucial in building ongoing trust and commitment. Often creativity and a facilitator's experience and time resources are required in the development of analogues and prototypes to provide early end user feedback on the EDSS architecture.
- *Recognise that eliciting information from the EDSS end user is an active not a passive process* and in many cases is the hardest part of effective EDSS design (Quinn, 2010). Consider including social scientists and computer scientists with user interface and interaction design (Moggridge, 2007) experience in development teams to provide better understanding of the human factors involved in EDSS design.

4.2. Recommendations related to improving EDSS adoption

Little empirical evidence exists concerning the organisational use of EDSS and, with few exceptions (e.g., Borowski and Hare, 2006; Diez and McIntosh, 2011; Inman et al., 2011), the literature does not report examples of quantitative EDSS evaluations based on end user observations. However, there have been systematic analyses of adoption and use conducted in other information science fields. McCown (2002a, 2002b) reviewed the usage of agricultural DSS and found that adoption had sharply decreased (after initial interest) or was simply non-existent. He surmised that farmers often cease to need computerised decision aids once a decision becomes routine. In addition, he concluded that options for external guidance of farmer actions using information systems had increased to include not only intervention to aid better choice of actions, but also intervention to facilitate learning and modification of the decision process (thus somewhat obviating the need for an agricultural DSS). On the other hand, EDSS for natural resource management activities are sufficiently complex that those who adopt an EDSS typically continue to use it and only discontinue use if a better EDSS comes along (Twery et al., 2005).

Diez and McIntosh (2009) reviewed how different organisational factors influence design, adoption, and use of decision and information support tools. They found that the most relevant implementation factors included user participation, computer experience, perceived effectiveness, system quality, management support, and user support/training. van Delden et al., 2011 advocate the use of champions (i.e., power users who actively motivate the adoption of the system) at different levels of the organization. However, they note that the presence of a champion in the early

phases of the development and implementation is no guarantee for adoption or long-term use; rather, embedding the system in a wider group of people in user organisation(s) during the implementation phase is of more importance to facilitate long-term use.

Since the use of EDSS in many areas (e.g., planning and policy making) is still very novel, it is expected that implementation will become easier once a critical mass of users has been reached (van Delden et al., 2011). This may especially be true as EDSS become more user-friendly and learning curves for most systems decrease, thus enabling a greater number of end users and stakeholders to participate in the decision-making process. Building on the work by McIntosh et al. (2008), specific recommendations related to EDSS adoption challenges include:

- *Find a champion in the user organisation* to promote the EDSS beyond the technical staff to the policy staff (van Delden et al., 2011).
- *Create a plan for continuity of EDSS support* including planning for the transition from the development team to stakeholders and clients for adoption.
- *Actively build capacity* (through the use of open-source and collaborative software tools) within the end user and stakeholder community to help promote adoption and ensure an ongoing commitment from the user base.
- *Do not oversell* the EDSS by using “flashy” system technologies (e.g., within graphical user interface or visualisation tools), as this can lead to unrealistic stakeholder expectations. During the development process, be open and honest with the end users and stakeholders about system weaknesses and what needs to be improved. This will help to boost credibility.
- *Minimise costs* – agree on clear EDSS objectives and functionalities then implement strategies to ensure that EDSS fulfil those, are easier and less costly to use, and that required information and databases can be easily updated.
- *Reduce the requirement for expensive training* i.e. rely on simpler tool design and the distribution of adequate documentation to make EDSS easier to use independently.
- *Design usable interfaces based on eliciting and characterising user needs* in the context of their role and tasks, their navigation strategies, vocabulary and expectations. Follow the general recommendations from HCI for designing user interfaces (Shneiderman, 1998), e.g. strive for consistency, provide permanent and instructive feedback, minimise opportunities for input errors, and minimise the users’ mental overload. It is important to accomplish this without overburdening potential users.

4.3. Recommendations related to improving the EDSS development process

In the past three decades or so, the literature regarding development of DSS (and EDSS) has migrated from a focus on the technical to decision-making to model integration to the participatory and collaborative aspects of system development. For example, Sage (1991) concentrated on the technical aspects of DSS development, proposing definitions of a database, model-base, and a dialogue generation system as principal components of a DSS. Sprague (1980) was more concerned about the decision analysis aspects of DSS development, recommending that DSS support for decision-making should handle a variety of decisions (e.g., structured vs. semi-structured and interdependent vs. dependent) and include all phases of the decision-making process. The question of how different EDSS tools could be integrated in a generic manner was investigated by Denzer (2005). Recently, the importance of

increased communication and interaction between involved EDSS groups has been highlighted (e.g. Volk et al., 2010; van Delden et al., 2011). Many of the above EDSS development aspects are included in development flow chart diagrams for DSS and EDSS development as for example presented by Poch et al. (2004) and more recently by van Delden et al. (2011). Important EDSS development steps as outlined in the flow charts include problem analysis or defining the scope, model selection and integration, collecting data/knowledge acquisition, and graphical user interface design and development. Specific recommendations that encapsulate many of the above steps include the following:

- *Create a business plan to explicitly define expected costs and outcomes.* Do not underestimate resources needed, i.e., consider long-term costs of training, support, and maintenance.
- *Develop and maintain scoping documents* that can help in specifying the issues raised and decisions made and in communicating the information to all involved development parties (Elmahdi and McFarlane, in press).
- *Design an EDSS that can be used to solve a number of environmental problems over a period of several years* rather than one that can only be used for one singular problem. Identification of outcomes should include the effects of EDSS use on values, attitudes, and behaviours.
- *Develop EDSS tools incrementally using known technology* – avoid high risk innovation or the use of unproven technology. In addition, use iterative processes, allowing refinement of functionality and user interface design based on feedback obtained during development.
- *Develop a systematic way to ensure the accuracy of raw data*, i.e., carefully monitor both the data values and the manner in which the data was generated.
- *Develop efficient ways of extracting and combining data and/or develop simple or more highly aggregated models.* Make an effort to generate the data or estimate it (provided the necessary data does not exist).

5. Conclusions

Most of the EDSS reviewed (in Section 2) were developed to provide support across all three phases of the decision-making process (i.e., intelligence, design and choice phases) within unstructured decision contexts. Several were not operationally used by the intended users, however the extent and success of use was not always clear. Although limited, the review did not reveal any patterns between reported use and the structure/function of the EDSS, indicating that success of use was more related to the development process than end product. As discussed in Section 4, the success of an EDSS can be judged from three perspectives. As a policy and decision tool, EDSS success relates to how results from the tool affects the planning and management of the real-world system, and whether the EDSS has helped to ameliorate the target problem. As a scientific and engineering tool, EDSS success is based on whether the tool adequately represents the real-world system and its processes, including model calibration and validation. Conversely, EDSS success as a software tool is related to factors such as the institutions producing the EDSS, licensing arrangements, and software structure and approach. It is therefore clear that evaluating the EDSS success is a multifaceted quest that considers a combination of institutional, technical, and human factors.

The manifold challenges in EDSS development were characterised into four groups related to: 1) engagement; 2) adoption challenges; 3) business, cost and technology; and 4) evaluation. The

Table 3

Best practice recommendations for EDSS development to help ensure success of use.

	Best Practice Recommendations
Design for ease of use	• Design user-friendly interfaces based on elucidating the user's needs and capabilities • User interface should be adaptable to different types of users, based on their knowledge/expertise • Tools should be well-documented with adequate help facilities
Design for usefulness	• At the beginning, clearly identify end users and stakeholders and their roles, responsibilities, needs and capabilities • Dedicate time and resources for a requirements analysis or usability survey • Consider including social scientists to provide input regarding human factors involved in EDSS design • Focus on overall system – what problems are to be solved? Who will use the EDSS? What added value does it bring? • Work with end users and stakeholders to define what project success is, including considering its cost-effectiveness vs. other means of achieving outcomes • Base model selection on spatial and temporal scale and level of complexity required for problems, and to fit with end user decision strategies
Establishing trust and credibility	• Be open and honest about system weaknesses and areas in need of improvement, including model uncertainties and assumptions • Discuss development timelines with users and provide feedback on their suggestions/ideas • Provide stakeholders the opportunity to meaningfully contribute during development • Regular collaboration between all parties to understand each other's requirements and share expertise • Don't use 'flashy' system technologies to oversell the EDSS
Promoting EDSS for acceptance	• Develop and maintain scoping documents (including issues raised, decisions made) • Find a champion to promote the EDSS at different levels of the organisation • Actively build capacity within end user and stakeholder community • Implement strategies to ensure that EDSS are easy and inexpensive to use
Plan for longevity	• Plan for continuity of EDSS support • Ensure required information and databases can be easily updated • Create a business plan to explicitly define expected costs and outcomes
Starting simple and small	• Design a EDSS that can be used to solve multiple environmental problems • Develop tools incrementally using known technology • Avoid undue model complexity • Use a modular approach to modelling or environmental modelling frameworks

best practices suggested to overcome the challenges are summarised in Table 3 and can be grouped according to recommendations related to:

- Designing for ease of use;
- Designing for usefulness;
- Establishing trust and credibility;
- Promoting the EDSS for acceptance; and
- Starting simple and small.

Some of these recommendations reiterate points from the good practice guidelines for involving users in the development of decision and information support tools presented in McIntosh et al. (2008). The guidelines stress the importance of understanding user needs, being clear about the purpose of the tool, developers working collaboratively with practitioners and stakeholders, and building and maintaining credibility and trust. This paper extends these guidelines to include insights into other aspects of EDSS development and adoption.

The likelihood of EDSS adoption can be increased by using a champion to promote EDSS use beyond technical staff to policy staff, and actively building capacity in a wide group of people in the user organisation. More effort is required in promoting and demonstrating the EDSS, especially if it is not developed in a directly end user-driven manner. In such cases the end user must be convinced of the effectiveness and value of the tool. However, if the EDSS does not bring added value to the decision-making process or is not cost-effective compared to other means of achieving the same outcome, the need to develop the EDSS must be questioned. Such assessments should be conducted in the early stages of development, along with a requirements analysis or usability survey – we should not be in the business of pushing inappropriate technology.

Planning in the early stages should consider the long-term use of the tool, including provision for support and the adaptability of the EDSS to incorporate new data and information or to be applied to new problems. It is also recommended that the EDSS incorporate known technologies and only models that serve stakeholder requirements, thus avoiding undue complexity. Model development can be a costly exercise; therefore model integration using a modular approach or environmental modelling frameworks is encouraged.

Finally, these best practice recommendations have emerged from the insights of a large group of experienced EDSS developers, who endeavour to improve EDSS development practice so that future tools are more useable and utilitarian in supporting environmental management and therefore more likely to be adopted and used.

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