Article

What do users really want? Participatory development of decision support tools for environmental management based on outcomes.

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Abstract: There is increasing demand from stakeholders for tools to support outcome-based approaches in environmental management. For such tools to be useful, understanding user requirements is key. In Scotland, UK, stakeholders were engaged in the development of an Environmental Decision Support System (EDSS) to support the management of land and freshwater resources for multiple policy outcomes. A structured participatory engagement process was employed to determine stakeholder requirements, establish development principles to fulfil these requirements and road-test prototypes. The EDSS specification that emerged from this bottom-up process was spatially-explicit, free at the point of use, and touch and mobile device compatible. This application, which is under development, does not closely resemble most existing published EDSS. We suggest that there is a mismatch between the way scientists typically conceptualise EDSS and the kinds of applications that are likely to be useful to decision-makers on the ground. Interactive mobile and web-based geospatial information services have become ubiquitous in our daily lives, but their importance is not reflected in current literature on EDSS. The current focus in environmental management on adaptive, stakeholder-centred strategies based on outcomes offers an opportunity to make better use of these new technologies to aid decision-making processes.

Keywords: Environmental decision support systems; applications; outcome-based approach; adaptive management; user requirements; environmental management; participatory land planning

1. Introduction

Research in environmental science is often undertaken under the premise that scientific information and knowledge is necessary to inform environmental policy and management. This has led to the widespread development of computerized tools to bridge the divide between scientific analysis of the state of the environment (e.g. water quality, biodiversity, land use change) and environmental policy (e.g. European directives on freshwater quality and terrestrial biodiversity conservation measures). These tools fall approximately into two types, though in practice there is a great deal of overlap. Decision Support Systems (DSS) are typically targeted at supporting policy implementation in a specific context, while Policy Support Systems or (PoSS) have broader aims, including policy formulation and strategy [1]. In the context of environmental management, we follow [2], and refer to both of these two types as Environmental Decision Support Systems (EDSS).

43   In theory, the relationship between science and policy is close and direct [3]. In practice, this is not
44   always the case, especially when science throws up wicked problems [4] to which policy makers or
45   environmental managers are unable to respond in conventional normative ways. Consensus is
46   beginning to emerge around the need for integrative, adaptive approaches to environmental
47   management as a means to tackle these kinds of intractable problems [5, 6]. Adaptive environmental
48   management seeks to integrate project design, management, and monitoring, to provide a
49   framework to systematically test assumptions, promote learning, and supply timely information for
50   management decisions (e.g. [7]). Involvement of stakeholders is essential to facilitate the processes of
51   generating and sharing knowledge to improve understanding of the effectiveness of management
52   actions. Policy makers and land managers require better access to the results of scientific analysis,
53   while scientific stakeholders need to better understand other stakeholders' needs in order to
54   structure and focus their studies (e.g. [8]). Private sector stakeholders, like land-based businesses,
55   are increasingly interested in easy to use web-based dashboard 'business intelligence' tools to better
56   manage their holdings, creating new demands and opportunities to bridge the relationship between
57   policy and management, and the supply and provision of scientific analysis. A need is therefore
58   emerging for new software tools and applications to respond to these demands, bringing new ways
59   of working. Modellers can play a key role in structuring integrative projects to meet these needs
60   whilst overcoming technical, knowledge and team-related challenges [9].

61   In this paper, we discuss our recent progress in responding to the challenge of providing
62   web-based digital tools that meet user needs for their adaptive management of natural resources.
63   The paper is structured as follows. In the next section, we describe some of the most important
64   limitations of EDSS as currently conceived from an adaptive management perspective.
65   Subsequently, we show how we have tried to address these issues by engaging policy stakeholders,
66   regulators and resource managers to co-develop an environmental decision-support application for
67   understanding the effectiveness of environmental policy interventions in river catchments in
68   Scotland. We present the results of this process and finish with a general discussion summarizing
69   key points, lessons learnt. Finally we offer some brief recommendations for future development of
70   EDSS.

71   **2. Background**

72   The work presented here forms part of a long-term Scottish Government Strategic Research
73   Programme (SRP) project which aims to understand and improve the management of Scotland's
74   land and freshwater resources for multiple policy and management outcomes. In Scotland, the Land
75   Use Strategy aims to take a more integrated approach to management of natural capital to deliver
76   multiple benefits [10]. Since 2007 Scottish Government policy objectives have been framed as a set of
77   national level outcomes to guide all policy, management and applied research [11]. This emphasis
78   on outcomes stems from the increasing interest across research, policy and management
79   communities to improve not only how we plan individual and multiple landscape management
80   actions, but also how we evaluate and learn from their successes and failures (see e.g. [12]). In
81   Scotland, as elsewhere in Europe, land managers are eligible for grants in return for implementing
82   environmental improvement measures under Pillar 2 of the Common Agricultural Policy (CAP). A
83   wide range of options are available relating to livestock, croplands and vegetation, among others
84   (see, e.g.
85   https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/agri-environment-climate-sch
86   eme/management-options-and-capital-items/#32412). Choosing the most appropriate measure for a
87   given land holding is a complex problem involving multiple choices, actors and possible outcomes.

88   The application of computerized tools to these kinds of problems has a long history (see e.g. [13,
89   14, 15]). The use of computer modelling to facilitate adaptive environmental management was
90   advocated by [16]. Early DSS (see e.g. [17, 18]) were conceived as computerized tools to manage
91   operational decisions where either the decision formulation or the solution, or both, were arguable

or directly contested [2]. While the involvement of end-users is clearly a key aspect of such a system, this does not necessarily imply the democratisation of knowledge and decision-making that lies at the heart of stakeholder-centred approaches to environmental management, i.e. in participatory, collaborative or mediated modelling (e.g. [19, 20, 21]). An EDSS designed under the conventional paradigm of DSS is a tool to help the competent authorities solve environmental problems, but does not necessarily emphasise sharing and co-construction of knowledge with stakeholders or social learning (*sensu* [22]) as a strategy for managing disagreement resulting from the diverse perspectives and requirements of multiple stakeholders. This means that frequently, such systems are not targeted at stakeholder needs [23]. From an adaptive management point of view, in which it is often desirable or even essential to share knowledge effectively amongst diverse stakeholder groups, this is problematic. Recently, digital catchment observatories have been suggested as a means to improve knowledge sharing and co-construction with stakeholders [24].

At the same time, many EDSS, ostensibly intended for non-scientific stakeholders to pick up and apply to their specific problems or needs, do not end up being used for that purpose [25], [2]. While the reasons for the lack of uptake by intended end users are diverse [2], lack of stakeholder involvement at the design stage is clearly a significant factor. [23], in their analysis of four EDSS in landscape and catchment management contexts, concluded that "the appropriate and methodological stakeholder interaction and the definition of 'what end-users really need and want' have been documented as general shortcomings of all four examples of DSS." Understanding and managing the diverse requirements a software application needs to meet – the requirements problem - is recognised as a major challenge in software development generally [26]. Responding to this challenge by improving the integration of the end user in the development process is a key underlying motivation of the User-Centred Systems Design (UCSD) paradigm [27,28]. However, while user-centred approaches have become mainstream in software development circles, they still lack general application in an EDSS context.

Further, since publication of [2], the role of software in supporting decisions of various kinds in everyday life has grown substantially. Mobile and web-based applications have become ubiquitous in all kinds of contexts, e.g. purchasing or contracting goods and services, banking, navigation, social networking etc. Typically these tools are web based, designed for mobile devices, built on Free and Open Source Software (FOSS), and optimised for touch-based interactions. Yet EDSS for the most part, remain some way behind the innovation curve. Most EDSS are still stand-alone systems, many require expensive proprietary software and frequently are not optimised or not available, or not optimised, for touch screens. In agriculture, a new generation of decision-support tools has begun to emerge, in the form of Farm Management Information Systems [29, 20, 31], allowing farm managers to adapt their operations to variables like temperature and precipitation, market prices or policy measures. However, there remains a substantial mismatch between the computationally intensive and conceptually challenging modelling approaches typically used by the scientific community (e.g. [1. 32]), and the lightweight, web and mobile-based and touch-screen-friendly applications for smart devices that we all use in our daily lives.

Finally, a key limitation of conventional EDSS from our point of view relates to the difficulty of applying them in the context of outcomes-based approaches. The likely result, in terms of environmental improvement or otherwise of a particular measure, should be a determining factor in the choice of measure. This requires us to understand not only the potential spatial distribution of particular environmental variables in the landscape, in order to suggest locations for management measures and interventions, but also the causal logic that connects these measures to the desired outcomes. Conventional EDSS approaches have emphasised the former, while approaches like logic modelling (also known as results chain logic modelling) are frequently applied to the latter [33, 34]. Logic modelling, which has its origins in program theory [35] is widely used for planning and evaluation of environmental and agricultural policy measures in the UK and elsewhere [36]. At present, however, we are unaware of any EDSS software or framework that successfully integrates

142   the aspatial process-based approaches found in logic modelling software like Miradi with the
143   spatial, Geographical Information Systems (GIS)-type approach found in EDSS for rural planning at
144   the level of the management unit (e.g. [14].)

145   In the following paper, we argue that a reappraisal of the process of development of software for
146   EDSS is necessary in the light of the need for adaptive management and outcome–based approaches
147   to environmental decision-making and the wide range of new smart applications. To this end, we
148   address the following three key research questions (RQs):

149   1.   How can we develop decision-support tools that align better with adaptive management and
150   outcome-based approaches to environmental management: what are the key requirements of such a
151   system?

152   2.   How can we make better use of well-established mobile and touch-based devices and software
153   for supporting environmental decisions?

154   3.   How can we involve key stakeholders like scientists, regulators and land managers to better
155   understand these requirements?

156   **3. Methods**

157   In order to respond to these three RQs, we conducted research and stakeholder engagement
158   activities in two phases where Phase 1 addressed RQ 1 and RQ2 and Phase 2 addressed RQ3. The
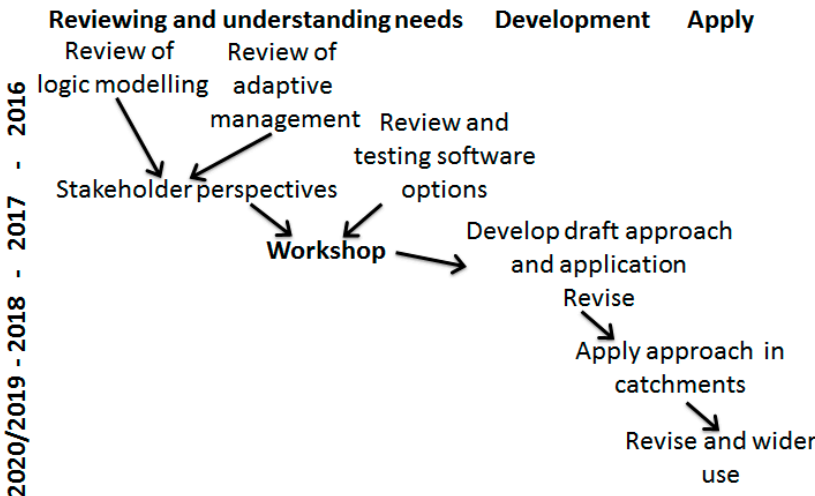159   conceptual design of the process is shown in Figure 1.
160

163   **Figure 1.** Conceptual process design for stakeholder-driven development of an outcome-based
164   EDSS.

168   *3.1 Ethical statement*

170   All stakeholders gave their informed consent for inclusion before they participated in the study.
171   The study was conducted in accordance with the Declaration of Helsinki, and the protocol was
172   approved by the Scottish government rural and environment science and analytical services division
173   (RESAS).
174

3.2   Phase 1: Stakeholder engagement and review of software options

Following production of a review of outcome-based logic modelling [34], meetings were held with policy stakeholders in Scottish Government to discuss how logic modelling could support their outcome-based approach in the National Performance Framework [11]. To start the co-construction of an outcome-based logic modelling approach to aid decisions about landscape interventions to deliver multiple benefits e.g. water quality, terrestrial biodiversity and land manager income, a series of interviews were carried out with 13 national and regional level stakeholders about adaptive management and outcome-based approaches [37]. The results of this work are extensive and lie beyond the scope of this paper, but provided a useful starting point for understanding the rationales behind the outcome-based approach.

Using initial insights from stakeholders of their needs to be addressed, experiences from colleagues involved in participatory GIS projects and our expertise in integrative modelling with stakeholders we started to narrow down the wide range of software options. Potential software options were selected for their potential to meet seven initial requirements which formed our screening criteria (Table 1). Review of existing software options for supporting outcome-based environmental management was undertaken from published, unpublished and internet sources. Where possible, we downloaded software and experimented with it in order to better inform our review. A short list of software options was then explored with the aim of developing an interactive prototype. A set of additional requirements were used to guide this development. One aim was to develop a prototype to be demonstrated to stakeholders in the second phase.

3.3   Phase 2: Participatory workshop

In Phase 2, we organised a half-day workshop with stakeholders with expertise in outcome-based environmental management, in order to deepen understanding of requirements and begin a process of co-development. The workshop was attended by six participants representing key domains in land and water management in Scotland, comprising representatives from the Cairngorm National Park Authority, Scottish Natural Heritage and Scottish Environmental Protection Agency and three researchers with >50 years collective experience of developing practical tools to support land and water management for multiple benefits.

The workshop was based around a series of linked activities. In the first activity the participants were asked to rate a list of 17 "needs" identified during the earlier interviews and were given an opportunity to add their own perspectives on the needs we are addressing The second activity involved working in pairs, of researcher and a practitioner, the participants were invited to provide suggestions for the key principles that our approach would use to address the identified needs. The idea of "principles" is central to UCSD (see e.g. [38, 28]) and is distinct from user requirements or needs in that it specifies how a system should be developed, not what the system aims to do.

A sheet of existing principles from related approaches or applications was provided to the participants as a guide. As we were interested to see what principles the participants would come up with independently, we did not share our draft list. Principles suggested by the participants were discussed by the whole group, and at the end of the activity, the participants were invited to comment on the draft list of principles we had developed ourselves prior to the workshop.

The third activity included an overview of hands-on advanced testing of software options, development of an interactive digital prototype, and facilitated discussion around an interactive prototype on a large touch table.

4. Results

4.1   Phase 1

225   The stakeholder interviews confirmed the need for tools that supported an outcome-based
226   approach with a central role for facilitation in place based studies. There is a wide range of software
227   tools and applications that are or could be used to aid facilitated discussions of place based studies.
228   Using the list of screening criteria (Table 1) we reduced a long list of 19 software options to seven
229   options for further hands-on testing and development. The long list of software options were
230   classified into four broad groups. These were: existing adaptive management logic modelling
231   applications e.g. Miradi[1], existing desktop participatory modelling applications e.g. QUICKScan[2],
232   GIS applications e.g. QGIS[3], and a range of software packages for developing web based
233   applications e.g. R Shinydashboard[4]. In order to review these options in a structured way, we
234   developed a set of seven criteria. These criteria were informed by our own previous work in this
235   area, the interviews with stakeholders [37] and conversations with colleagues. These criteria were as
236   follows:
237
238   The tool/software:
239
240   1.   *Should be free at the point of use.* This is an essential pre-requisite of the outcome-based approach,
241   which requires transparency and effective exchange of knowledge and data between stakeholders at
242   all points in the process chain. Commercially licensed software is typically not free to use or share
243   and thus cannot meet this basic requirement.
244
245   2.   *Should work on touch devices like mobile phones, tablets and larger touch tables since touch-enabled*
246   *devices are now widely used.* Many applications that have potential for use as EDSS (e.g. QGIS) are not
247   designed for touch screen use. Again, to ensure that any application can be widely shared, it should
248   function on a range of devices, not just on standard desk-based PCs. Outdoor workers, e.g. in
249   forestry or agriculture, are likely to prefer an application which can run on portable devices like
250   smartphones or tablets.
251
252   3.   *Should have map-based functionality for users to interact with spatial information e.g. information on*
253   *fields and other features related to land and water management.* The focus on spatial information is crucial,
254   since nearly all environmental decision-makers use maps as a means of communicating information
255   about interventions in the landscape. At the same time, to establish a genuine process of knowledge
256   exchange, information needs to flow in both directions, so some form of user interaction is
257   necessary, either in terms of allowing the user to pull data from the system, or in actually offering
258   the possibility to upload and work with users' own data.
259
260   4.   *Should include functionality for outcome-based logic models i.e. linking land management to a range of*
261   *outcomes.* This apparently very specific requirement can be seen to have broader implications for
262   environmental decision-support. The software needs to be able to link the information provided to
263   the user to desirable or required outcomes in a dynamic way. In this way it is possible to understand
264   the implications of different interventions – e.g. for example, by adding a connection between land
265   use type in a holding and sediment or nutrient run-off, a user would potentially be able to evaluate
266   the likely outcomes of land use changes in terms of water quality and other policy and management
267   objectives.
268
269   5.   *Should allow developers and end-users to develop and extend the software/existing application.* The
270   ability to modify and extend the software to add or change functionality was thought to be

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[1] https://www.miradi.org/

[2] http://www.quickscan.pro/

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

[4] https://rstudio.github.io/shinydashboard/

important, since environmental management is a dynamic sphere of action in which new datasets, plans and policies and strategies are frequently emerging. It should be clarified that we did not anticipate that all users should want or need to do this, but that it should in principle be possible for the development team.

6.   *Should have potential for scientific innovation.* This is a constraint that may have little interest from the point of view of an end-user, but is important for researchers in today's competitive science environment. A tool or approach that cannot show some potential to advance scientific practice or understanding cannot be expected to hold the interest of the scientific community, and makes it more difficult to obtain funding. It should be emphasized that we are not necessarily talking about technological innovation - finding new ways for stakeholder groups to interact around a problem would also be a worthwhile scientific innovation.

7.   *Should be actively maintained, preferably through a large, open user community.* Given the previously mentioned interest in software that is free (at least at the point of use), it is important to distinguish between projects that are no longer actively maintained and those that are, preferable with a large or active user community. This is an important factor in ensuring the ability to modify or extend the software in the future – changes in PC hardware or software over time mean that software needs to be actively maintained. The multi-purpose software environment R and the popular free GIS package QGIS, for example, are actively maintained, with vibrant user communities, whereas the GIS software ILWIS, while still maintained, seems to be less actively developed and the user community, by comparison, is small.

Using these screening criteria we selected seven potential software options for more detailed hands on testing (see Table 1). Six of these seven options were software packages and applications for developing web-based applications. The other option was ROAM which is QGIS application designed to aid field-based collection of data using touch devices. Our proposed principles for development of a digital application meeting these seven criteria are shown in Figure 2.
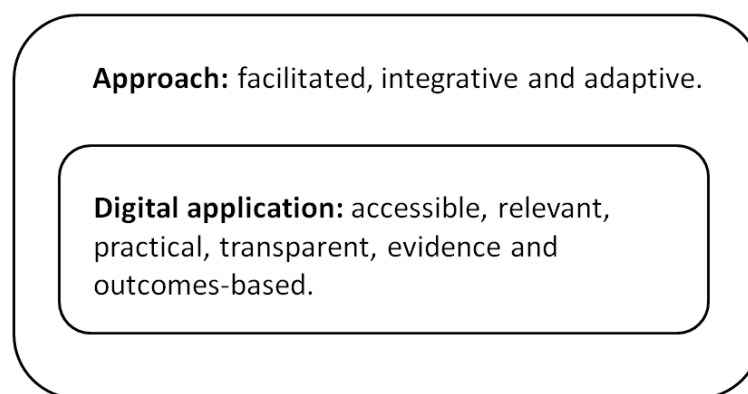

Approach: facilitated, integrative and adaptive.

Digital application: accessible, relevant, practical, transparent, evidence and outcomes-based.

Figure 2. Draft principles produced by the workshop organisers.

Software options were classified in four broad groups (Table 1), which are discussed as follows.

4.1.1.   Existing adaptive management logic model applications

The only software known to the authors in this group is Miradi, a software application intended to help adaptive management of conservation projects. This was included as the only software explicitly designed to facilitate the logic modelling outcome-based approach. Logic chain modelling is explicitly implemented through a flowchart view, and other functionality to assist work planning and budgeting and assessment of viability of targets. At present the software has no spatial

312   component, but stated future plans for the software include development of a spatial mapping
313   capability. But as at presently non-spatial, proprietary, and non-modifiable software this was not
314   included in our selection.
315
316
317   4.1.2.   Existing standalone participatory modelling applications
318
319   This group comprises a small selection from the large range of modelling applications currently
320   in existence that include explicit participatory modelling functionality or that have been used in
321   participatory processes and is not intended to be representative or comprehensive (see e.g. [39, 40]
322   for more detailed reviews of participatory modelling software options and approaches). QUICKScan
323   is a well-known commercial software application developed by Alterra, at Wageningen
324   Netherlands, which is widely applied, including in Scottish cases [41]. It offers a rule-based
325   approach to help stakeholders negotiate trade-offs in resource management contexts, and is
326   explicitly spatial. This seemed quite appropriate for our case, but as a non-modifiable and non-free
327   software, could not be included in our selection. Metronamica is another software application with
328   20 years + development behind it, very popular in the land-use modelling community. Though it
329   does not offer specific participatory functionality, it is frequently used in decision-support contexts
330   (e.g. [1]), and for working with stakeholders [42, 32], even if its complexity means that stakeholders
331   rarely use the model themselves.
332
333   4.1.3.   GIS modelling applications
334
335   This group includes very well-known commercial applications like ArcMap as well as the
336   popular open source application QGIS. These have been included because there are many spatial
337   decision support applications built around these platforms, see e.g. for ArcMap [43, 44] and for QGIS
338   [45,46], but unfortunately, we found both of these to be poorly adapted to touchscreen
339   environments, both in terms of operation (sluggish and buggy) and in terms of the user interface
340   (tiny buttons, missing right mouse button functionality). The 3D Community Viz Public
341   Participation GIS plugin for ArcMap was unusable on our touch table. The ROAM application,
342   which provided a touch-screen friendly interface for QGIS was much more promising, and was
343   selected for further investigation.
344
345   4.1.4.   Software packages and applications for developing web-based applications
346
347   This last group stood apart from the other three software groups in that all of the tools reviewed
348   in this group were web-based. Though these tools have the potential disadvantage of requiring
349   adequate internet and mobile coverage, they can be designed to work off-line. They represent a
350   significant innovation in terms of user interaction and inter-platform flexibility. For all of the other
351   groups, non-windows operating system users are disadvantaged (with the notable exception of
352   QGIS), and mobile device support is nearly non-existent. This group of applications stood out as
353   addressing much more closely stakeholder needs, e.g. mobile, touch-enabled and Free-and-Open
354   source (FOSS). With these applications a clear trade-off could be identified between being able to use
355   "as-is" and customizability – in many cases there seemed to be good potential to flexibly incorporate
356   and link maps, tables and charts, but we lacked the programming skill to do this effectively. One
357   application in particular, Rshiny, and its dashboard extension, Rshinydashboard, was very
358   promising in this regard, since these tools are part of the well-known FOSS environment "R", which
359   is very popular with scientific users and has a large and active user community. For this reason, the
360   advanced prototype was developed in Rshiny.

361 **Table 1.** Assessment of software options for tool development.

362

Options	Criteria								Links/notes
	Free to use[1]	Use on touch devices[2]	Interact spatially[3]	Logic model[4]	Develop/ extend[5]	Innovation[6]	Status[7]	Selected: yes or no	
Existing adaptive management logic model applications									
Miradi	100-999	No	No	Yes	No	Low	Active	No	https://www.miradi.org/
Mobile version	Maybe[8]	Yes	Maybe	Yes	Maybe	Maybe	Active	No	Not available.
Existing standalone participatory modelling applications									
Quickscan	100-999	No	Yes	Maybe	No	Low-med	Active	No	http://www.quickscan.pro/products
Metronamica	>10000	No	Yes	Maybe	No	Low-med	Active	No	http://www.metronamica.nl/
Geodesign	0	Maybe	Yes	Maybe	Maybe	Med-high	Active	No	https://www.geodesignhub.com/, Limited to the existing geodesign process.
GIS modelling applications									
Community Viz ArcMap plugin	100-999	No	Yes	No	Yes	Med	Active	No	http://placeways.com/communityviz/index.html
MCDA4ArcMap	0[9]	Maybe	Yes	No	Yes	Med	Active	No	https://mcda4arcmap.codeplex.com/
EMDS (US EPA)	0	Maybe	Yes	Maybe	Maybe	Low-med	Active	No	http://1726-4482.el-alt.com/aboutemds Not freely available.
Standard ArcMap	100-999	No	Yes	No	Yes	Low-med	Active	No	http://www.arcgis.com/
Standard QGIS	0	Yes with plugin	Yes	Yes	Yes	Med	Active	No	http://www.qgis.org/en/site/ Issue about large move from version 2 to 3.
ROAM (QGIS app)	0	Yes	Yes	Maybe	Yes	Med-high	Active	Yes	https://github.com/DMS-Aus/Roam
Software packages and applications for developing web-based applications									
Python back-end	0	Yes	Yes	Yes	Yes	High	Active	Yes	Meets many criteria, will take more

Options	Criteria								Links/notes
	Free to use[1]	Use on touch devices[2]	Interact spatially[3]	Logic model[4]	Develop/ extend[5]	Innovation[6]	Status[7]	Selected: yes or no	
based Leaflet applications e.g. Django or Flask									effort to develop https://www.djangoproject.com/ http://flask.pocoo.org/
Javascript back-end based Leaflet applications using Node	0	Yes	Yes	Yes	Yes	High	Active	Yes	https://nodejs.org/en/
Kivy	0	No[10]	Yes	Yes	Yes	High	Active	No	https://kivy.org/#home
RShiny, RShinydashboard	0	Yes	Yes	Yes	Yes	High	Active	Yes	https://shiny.rstudio.com/ https://rstudio.github.io/shinydashboard/
Jupyter dashboard	0	Maybe	Yes	Yes	Yes	High	Active	Yes	https://github.com/jupyter/dashboards
Tableau	0	Yes	Yes	Yes	Yes	Med-high	Active	Yes	https://www.tableau.com/ Not sure if it can be used off line.
Spotfire	1000-9999	Yes	Yes	Yes	Yes	Med-high	Active	No	http://spotfire.tibco.com/
Plotly (Dash)	0	Yes	Yes	Yes	Yes	Med-high	Active	Yes	https://plot.ly/products/dash/

363
364 1 Approximate cost (£): 0, 1-99, 100-999, 1000-9999, and >10000; 2 Is the user interface designed for non-expert/group touch screen i.e. is the navigation easy to
365 use: yes or no; 3 Is there part of the screen that includes a map: yes or no; 4 Can logic models potentially be viewed and edited: yes or no; 5 Can the project team
366 with their Python, R and JavaScript expertise develop the application and extend it: yes or no; 6 What is the potential for scientific innovation: low=old
367 application and widely used, med=established application but not widely used, high=new application; 7 Is it still being supported: inactive= little evidence of
368 activity over the past year, active= evidence of activity over the past year; 8 A 'maybe' indicates that information was not available to judge against these
369 criteria; 9 ArcMap not free to use; 10 Not on Windows devices.
370

Table 2. Workshop participants' 12 principles related to stakeholder requirements (centre) and our own list of 7 proposed criteria (right). The number in superscript in the middle column denotes the number of times this requirement was listed. In some cases the same requirement appears more than once for a single principle, because this requirement was selected by more than one of the three groups.

No.	Principle	What stakeholder requirement does this relate to?	Which of the seven criteria does this relate to?
1	Updateability	None	2. Work on touch devices 5. Allow users to develop and extend 6. Potential for scientific innovation 7. Actively maintained
2	Agile development. Multiple versions	• Dashboard format • Support/ incentives and regulation	1. Free at the point of use. 5. Allow users to develop and extend 7. Actively maintained
3	Provides cost-benefits of options	• Helps indicate areas to 'invest' in interventions	3. Map-based functionality for users to interact with spatial information 4. Include functionality for outcome-based logic models i.e. linking land management to a range of outcomes
4	Clarity of objective: public interest, land manager, community	• Policy and on the ground connections	3. Map-based functionality for users to interact with spatial information. 4. Include functionality for outcome-based logic models i.e. linking land management to a range of outcomes
5	Iterative: exploration of multiple scenarios and consequences	• Iterative evaluation of options	4. Should include functionality for outcome-based logic models i.e. linking land management to a range of outcomes
6	Credible/transparent	• Provide evidence of benefits • Information needs to be provided in a digestible format	1. Free at the point of use. 2. Work on touch devices 3. Map-based functionality for users to interact with spatial information.
7	Credible and trustworthy	• Information needs to be provided in a digestible format[2]	4. Should include functionality for outcome-based logic models i.e. linking land management to a range of outcomes
8	Practical - relates to users experience and needs	• Provide evidence of benefits[2] • Spatial location of interventions	3. Map-based functionality for users to interact with spatial information.

			4. Include functionality for outcome-based logic models i.e. linking land management to a range of outcomes
9	Accessible/easy to use	• Information needs to be provided in a digestible format[3] • Place-based • Information needs to be provided in a digestible format[4] • Spatial location of interventions[2]	1. Free at the point of use. 2. Work on touch devices 3. Map-based functionality for users to interact with spatial information.
10	Clear on operational scale	• Integrated approach for incentives, regulation and voluntary measures/ balance is key	3. Map-based functionality for users to interact with spatial information.
11	Dealing honestly with uncertainty: avoid large-scale uniformity of outcome, diversity manage via incentives/regulations	• Tools should promote diverse outcomes, even to similar places and objectives	4. Should include functionality for outcome-based logic models i.e. linking land management to a range of outcomes 5. Allow users to develop and extend
12	Limited need for time-consuming tool. Must not take ages to develop	• Spatial location of interventions[3] • Information needs to be provided in a digestible format[5] • Tools should promote diverse outcomes, even to similar places and objectives[2] • Information needs to be provided in a digestible format[6]	2. Work on touch devices 3. Map-based functionality for users to interact with spatial information. 5. Allow users to develop and extend

375 *4.2   Phase 2*
376
377 4.2.1.   Stakeholders' principles for EDSS
378
379   Workshop participants identified 12 principles for development of a software application for
380 supporting environmental decision-making to improve the management of land and freshwater
381 resources in Scotland. These are shown in Table 2. The key points that emerged from this activity
382 and the subsequent discussion are described as follows.
383
384 4.2.1.1.   Updateability: This was regarded as very important due to the rapidly evolving nature of
385 environmental policy and the need to be adaptable and responsive. Participants emphasized the
386 highly changeable nature of both the policy context and the data (Principle 1, Table 2).
387
388 4.2.1.2.   Practicability and usefulness: It was agreed that the tool should be both practical and
389 useful. Since usefulness is subjective and therefore dependent on the end-user, involving end-users
390 in the development process seemed like a good way to achieve this, e.g. through AGILE
391 development principles [47] (Principle 2, Table 2).
392
393 4.2.1.3.   Clarity of purpose and objectives: Participants highlighted the need for clarity about the
394 intended purpose and objective of the application. This is likely to depend on specific end users,
395 further highlighting the need for a flexible, AGILE-type approach (see above)
396
397 4.1.2.4.   Uncertainty, credibility and trustworthiness: Participants emphasized the need to deal
398 honestly with uncertainty, both of data and of model/application outputs. This was regarded as
399 having important implications for the credibility and trustworthiness of the information provided
400 by the decision-support application (Principle no. 6, Table 2). It was suggested that data should be
401 filtered before providing it, since users may lack the knowledge to appreciate uncertainty. However,
402 it was also appreciated that absolute certainty was not attainable, since scientists themselves
403 frequently disagree about the trustworthiness of data or the reliability of the results. However, this
404 was regarded as an important development principle even if it is not achievable in practice.
405
406 4.1.2.5.   Openness about limitations/transparency: It was regarded as important to be transparent
407 about what a tool can and cannot do. Transparency of the tool and of the decision-making process
408 was a key principle (Principle no. 6, Table 2). This is somewhat related to the issue of trust and
409 credibility (above).
410
411 4.1.2.6.   Specify intended scale of data and operation: In an issue related to the need for openness
412 about uncertainty, participants raised the need to be clear about the intended cartographic scale of
413 operation for the application. This can be partially addressed in practice by ensuring that datasets do
414 not display at zoom levels that exceed their nominal scale.
415
416 4.1.2.7.   Cost-benefit estimates for policy interventions: The need to provide cost-benefit
417 information was highlighted by one of the participants, but others disagreed. One argument that
418 was made against this idea was that it would be difficult to determine which actors would be best
419 placed to make the cost-benefit assessment, since each actor would require a different cost-benefit
420 analysis to suit their land/circumstances.
421
422 4.1.2.8.   Diversity vs commonality: Although there was a high level of agreement about some
423 aspects, for example, the importance of credibility (Principles 6 and 7; Table 2) and accessibility
424 (Principle 9; Table 2), there was disagreement about others, e.g. appropriateness of cost-benefit

425 analysis. This reminds us that end users are likely to have widely varying objectives in mind, and
426 that it will be difficult to please all of them with a single application.
427
428 4.1.2.9.   Decision support, not decision automation: Participants were keen to emphasise the need
429 to be clear that the tool supports decisions, but does not actually make them.
430
431   In discussion, our own, more generalized principles (Figure 2) found general agreement.
432 Several of our own suggested principles were also included by the participants, e.g. transparent,
433 accessible and practical. However, participants observed that more clarity could be provided by
434 setting them out as sentences (rather than single words). Following the workshop, we drew up a
435 revised set of general principles incorporating the principles suggested by stakeholders and
436 following their advice (Table 3). This is intended as a synthesis, not a replacement, of the detailed
437 principles set down in Table 2.

438   **Table 3.** Integrated general principles for application development.

Approach
The approach will help **facilitate** decisions about land and water resources.
It will aim to be **integrative** through considering a range of environmental and financial outcomes.
It will aim to support **adaptive** management though clarity of objectives/outcomes, and linking with evidence that supports exploration of those options to achieve those objectives/outcomes.
The approach will be designed to be **easy to use** and **efficient**.
Digital application
It will be **accessible** for anyone to use.
It will be **relevant** and **practical** for land managers.
It will aim to be **credible**, with **transparency** in the information and methods used.
It will be designed to be **updateable** with new information as it comes available.

439
440 4.2.2.   Facilitated discussion around the prototype application
441
442   The prototype application (Figure 3), as we had hoped, since we had developed it in response to
443 stakeholder criteria, was well-received. Though the application meets many of these requirements,
444 being FOSS, optimised for touch-table use and multi-platform, it does depend on the R software
445 environment, which is not currently supported as standard on mobile phones, though it does appear
446 to be possible to run it[5]. Stakeholders particularly appreciated the smooth map scrolling provided by
447 the leaflet application, a GIS map server package available under R. The users appreciated the
448 dashboard format, with a large map window occupying most of the screen and user controls and a
449 linked chart output in a box to the right. The application was tested with land use data (Land Cover
450 Map 2007[6]), which it allowed users to interact with (enquiry of land use type, clipping out a polygon
451 and querying land use area in the polygon area). The land use data generated an interesting
452 discussion, and stakeholders highlighted the importance of providing scale information, clearly
453 naming the source of the land use data, and adequately informing about its known limitations.
454 Participants were not widely agreed about the reliability of the land use dataset, which led to a
455 detailed discussion around reliability and trustworthiness of information presented.
456
457
458

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[5] http://tteoh.com/technology/2016/10/20/r-rstudio-mobile-android/

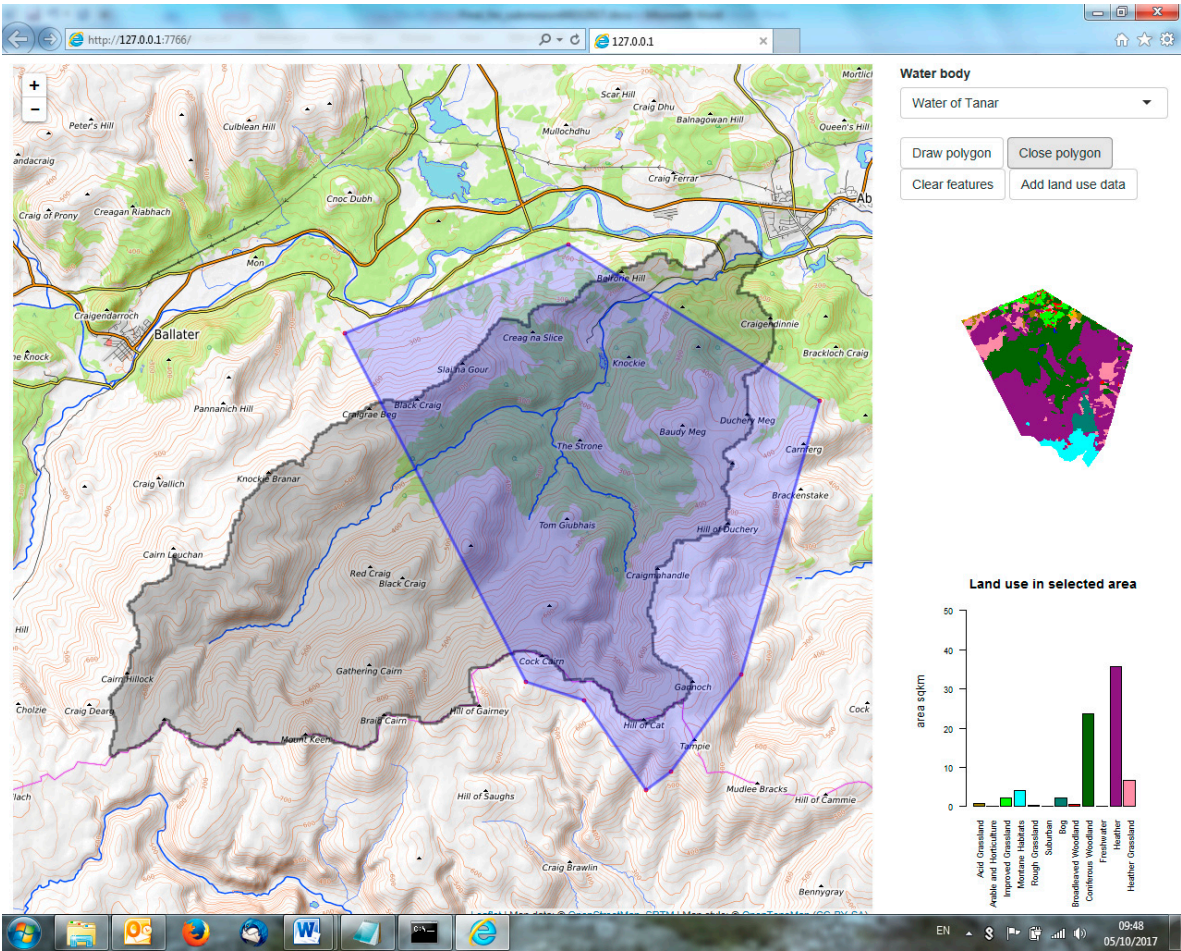[6] https://www.ceh.ac.uk/services/land-cover-map-2007

459
460

Figure 1. Prototype application running on Windows. The screen capture shows the Water of Tanar
sub-catchment of the river Dee in Aberdeenshire, Scotland. The user has drawn a polygon, which has
been clipped out of the land use base map (LCM2007) and is displayed in the box to the right of the
map window. Below it, the area of each land use in the polygon is displayed as a histogram.

5. Discussion

5.1.   Outcome-based environmental management: what do users really want?

There is an increased need from stakeholders for integrative approaches and tools to address
outcome-based approaches in environmental management. The new breed of web-based tools offers
new opportunities for application development, but at the same time, to develop software systems
effectively it is necessary to understand user requirements. This lies at the heart of producing useful
software and is an established principle in software development that developers of EDSS could
learn from. In order to understand user requirements, structured participatory processes like the one
we have presented in this paper are necessary. The process of co-construction of an application
typically passes through a series of key steps relating to facilitated participatory activities.
Stakeholders can analyse their needs as environmental decision-makers, identify key development
principles for a software application designed to address them and road–test an advanced prototype
application.

We discovered that the tool our stakeholders wanted does not much resemble most published
examples of EDSS used by the scientific community (see, e.g. [48]). Our application should be free to
use, touch and mobile-device enabled, part of an existing active development chain or community

482 and be clearly oriented to understanding and evaluating environmental policy options in terms of
483 outcomes, e.g. showing how a riparian buffer strip can improve water quality in a given location, or
484 showing how land use change may influence diffuse pollution. It will be intended for use, probably
485 in the field, by land managers and regulators, e.g. farmers, protected area managers or utilities
486 operators.

487 One possible reason why the EDSS that has been conceptualised by our stakeholder group is so
488 different to existing EDSS found in the literature is because of the specific requirements of our study
489 and its context, e.g. catchment management in Scotland, adaptive management framework, and
490 emphasis on understanding effectiveness of interventions through outcomes. But since these aspects
491 are also recognised as important in environmental management further afield; though adaptive
492 management has some well-recognised limitations (see, e.g. [49]) it is still widely regarded, at least
493 in modified guise of adaptive co-management (ACM) as a playing a valuable role in good
494 environmental governance [50]. At the same time, outcome-based approaches are increasingly seen
495 as best practice in environmental assessment, decision-making and stakeholder engagement [51].
496 Therefore the apparent absence of appropriate tools probably does indicate a real need.

497 In fact, there seems to be a genuine mismatch between what environmental decision-makers
498 like our stakeholders want, and what EDSS developers, who are typically scientists, tend to produce
499 (Table 4).

500 **Table 4.** The mismatch between EDSS that scientists have tended to develop, and EDSS that
501 environmental decision-makers typically want.

EDSS that scientists have tended to develop	EDSS that decision-makers want
Platform	
Micro-computer oriented, Windows operating system	Mobile device oriented, multi-platform
Cost model	
Proprietary	Free and Open-Source
Application type	
Stand-alone, out of the box solution that the user cannot easily modify	Flexible, integrated (web-based), easily customizable
Purpose	
Understanding a complex problem	Deciding from a range of options
Exploring future scenarios	Evaluating cost-benefit
Predicting tendencies	Linking science and policy to show clear outcomes
	Synthesizing complex information into a digestible message
Implicit role of scientist	
Selling knowledge systems	Facilitator and provider of free, open advice
External expert	Participant and stakeholder

502

503

504

505   There are four key reasons for this mismatch in general terms

506   1.   *Problem-solving stage.* The kinds of EDSS that help stakeholders understand complex
507   interactions, explore future scenarios, or predict existing tendencies are generally not suitable, or
508   really intended, for use directly by practitioners, but are rather intended to supply information to
509   them in the form of reports and briefings based on model results. Generally, practitioners do not
510   need or want to run land use simulations for 2050 or experiment with the effect of different types of
511   forcing mechanisms on climate. An EDSS that a farmer might hold in their hand to allow them to
512   explore a range of options for managing a river catchment belongs to a different part of the process
513   at a later stage in the chain. This kind of EDSS operates under the assumption that first type
514   described is already embedded in the policy-making process. This type of EDSS belongs to a
515   different problem-solving stage, where, in the words of [52], "we agree to stop worrying about
516   generalities and focus instead on impacts, mitigation, compensation, and accommodation". There is
517   a fundamental need to better understand the requirements of users at the policy implementation
518   stage.

519   2.   *Type of decision-maker and level of action*. A related question is the type of decision-maker and the
520   level of action at which they are typically operating. The hypothetical farmer referred to above is
521   making decisions at the scale of the land parcel, unlike, say, an agriculture minister, who is
522   interested to know, in broader terms, about land use in general to inform land use policy more
523   broadly. Many EDSS found in the scientific literature are concerned with these higher level decisions
524   and EDSS directed at the scale of the land parcel tend to be under-represented in the scientific
525   literature (though see, e.g. [14]). One of the most important priorities for our stakeholder group was
526   the provision of reliable scientific information in an accessible and digestible format, rather than
527   solution of complex analytical problems, or estimations of long-term tendencies.

528   3.   *Technological development time-lag*. The significant time lag between submitting research
529   proposals and the award of funding, and between development of a model or system and
530   publishing it in a journal means that the most recently published EDSS are based on
531   conceptualisations of technology (if not actual availability) from 3 or 4 years ago. Given the pace of
532   change in information systems development, there is a significant likelihood that EDSS of the kind
533   that emerged from our participatory process are currently being developed but are poorly
534   represented in literature. An interesting review of this topic in the context of rural development can
535   be found in [53].

536   4.   *Change in the role of the scientist*. As can be appreciated from Table 4, the type of EDSS
537   conceptualised on the right requires the scientist to play a different, perhaps less glamorous role,
538   than that of aloof, objective expert of popular imagination. To help achieve sustainability objectives
539   in land and water management scientific stakeholders should focus on facilitation and knowledge
540   transfer at the level of implementation of concrete actions, as well as knowledge production
541   activities higher up the chain.

542   Designers of EDSS need to move away from developing tools for standard desktop software
543   and systems and make full use of mobile and touch-based technologies which people are becoming
544   increasingly familiar. Web dashboards, already popular as 'business intelligence' tools, provide the
545   user with a range of integrated graphical outputs, e.g. a map, a histogram and a data table and offer
546   an idea of how such applications might look. FOSS tools like Rshiny and Rshiny dashboard which
547   facilitate web-development from inside widely supported scientific software environments with
548   active user communities (in this case, R), seems like a promising direction of travel.

549   Providing complex information under high uncertainty in an easily digestible format is a major
550   challenge. Our stakeholders were clear that the limitations and level of uncertainty in complex

551 scientific information needed to be clearly explained in any application, and that great care should
552 be taken not to provide information out of context or at inappropriate spatial scales.

553 **6. Conclusions**

554   Developing software applications to support land managers decisions under outcomes-based
555 approaches to adaptive environmental management requires better stakeholder engagement
556 practices to understand their needs and development requirements, and a stronger focus on new
557 digital tools and open software and data. We have presented an example of a stakeholder-centred
558 process to develop one such tool. By focussing on understanding and managing outcomes of
559 environmental improvement measures, a preliminary review based on initial requirements led to
560 the rejection of a large range of currently available tools and software as unsuitable. Many do not
561 run effectively on the mobile and touch-based devices that land managers typically use, and most
562 are proprietary systems that require an upfront financial outlay and do not allow users to modify the
563 source code or customize the application to suit their own needs. These aspects restrict their use to
564 mostly scientific stakeholders and do little to facilitate environmental decision-making at the scale of
565 the land parcel. What stakeholders really need are mobile, web-based, touch devices that are free at
566 the point of use and flexible enough to be easily adapted to meet changing requirements and
567 different user needs.

568   Under the late nineties and early noughties "out-of-the-box toolkit" paradigm, scientists sought
569 to package their knowledge into marketable products and systems under the assumption that clients
570 would materialize with fully-formed problems requiring solutions. Since then, the world has moved
571 on. Scientists now understand that this kind of hands-off back-office knowledge delivery is
572 ineffective; these kinds of tools are rarely used. Not only do land-managers not want to use a
573 complex computational model, they need software that answers specific questions like "how much
574 will it cost to build a riparian buffer strip along the river that bounds my land, and to what extent
575 will this reduce surface run-off from my arable fields?", or "what specific interventions would be
576 most appropriate in this part of the catchment, and what incentives and regulations are likely to be
577 relevant?" To provide better answers to these questions, scientific stakeholders need to play strong
578 facilitation roles at all points in the development process, including problem-framing, stakeholder
579 engagement, application development and use.

580

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