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# A simulation interface designed for improved user interaction and learning in water quality modelling software

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ABSTRACT

Traditional simulation software that supports management decisions is configured and run by experienced scientists. However, it is often criticised for its lack of interactivity, not only in the application of decisions but also in the display of results. This paper presents the simulation interface of software with management strategy evaluation capabilities and its capacity to enable resource managers to learn about water quality management as evaluated in a workshop setting. The software 'MSE Tool' is not intended to produce definitive real-world advice but provides a test-bed for managers to interactively design strategies and explore the complexities inherent to water quality management using a simple, yet effective, user interface. MSE Tool has been used in a pilot application that simulated the effects of management strategies applied in catchments and their effects on riverine, estuarine and marine water quality in South East Queensland, Australia. The approach and the software are suitable for reuse in other management strategy evaluation projects.



**Software and availability**

| | |
|---|---|
| Name of software | MSE Tool Simulation Interface (MTSI) |
| Version | 2.1 |
| Target system requirements | Microsoft Windows XP, Microsoft.NET Framework 3.5 |
| Development environment | Microsoft Visual Studio 2008 (C# and VB.NET) |
| Third party libraries | SharpMap version 0.9, Catfood Shapefile 1.0, CenterSpace NMath 4.0, Syncfusion 8.103 |
| Developers | CSIRO Marine and Atmospheric Research, Ecosciences Precinct, Dutton Park, Queensland, Australia |
| Customer | Healthy Waterways Inc. |
| Availability | Restricted. Contact CSIRO Oceans and Atmosphere Flagship for details. |

## 1. Introduction

Management strategy evaluation (MSE) is an approach which is well established in the management of natural resources, where it

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is used to support decision-makers assess the trade-offs associated with alternative management and policy options (Smith, 1994). MSE employs computer models to simulate each part of the system using an adaptive management framework (Smith and Walters, 1981; Walters, 1986) and allows managers to test policies and familiarise themselves with alternative outcomes in a safe computer environment (Butterworth et al., 2010; Dichmont et al., 2006; Smith et al., 2007). Key components of an MSE are the simulation of the adaptive management loop, a description of the system under control (monitoring, assessment and decision) and the biological and human response to the determined actions. MSE is grounded around adaptive management (Smith et al., 1999; Walters, 1986)—a key element of natural resource management, and is a type of decision support system (DSS) and, more specifically, an environmental decision support system (EDSS).

MSE has been used for many purposes and case studies; for example, in fisheries (Butterworth and Punt, 1999; Dichmont et al., 2008; Smith et al., 1999), coastal zone management (Jones et al., 2011; McDonald et al., 2008), multiple use management (Fulton et al., 2011b), biosecurity (Dunstan and Bax, 2008) and conservation (Bunnefeld et al., 2011; Milner-Gulland et al., 2010). Several generic tools have been developed for MSE in these different fields, most notably FLR (Fisheries Library for R) (Kell et al., 2007), Atlantis (Fulton et al., 2011a,b) and InVitro (Fulton et al., 2011b; McDonald et al., 2008). Most MSE models have been built for individual examples in a programming language familiar to the scientist.

In its traditional form, MSE relies on an experienced team of scientists and model developers to construct and run the simulation tools in complex software environments that provide model outputs in response to specific requests from decision-makers. Decision-makers are usually consulted on the selection of indicators that reflect the desired objectives, and on reference values for these indicators. The increasing use of computer-assisted simulation to support policy-making in the management of natural resources and environmental issues has seen a growing tendency for managers to also be involved in the model building and model running exercises (Argyris and Schön, 1978, 1996; Boschetti et al., 2010; Brugnach, 2010; Fulton et al., 2013; Jakeman et al., 2008) and has hence created a need for software with less complexity and parameterization but improved user interaction. This is partly a result of progress in computing leading to faster modelling capabilities that allow interactive, stakeholder-driven models to be built more easily. In turn this progress has led to a research stream focused on using participatory modelling in natural resource management (Sandker et al., 2010; Worrapimphong et al., 2010), and to a growing number of applications in which stakeholders and managers themselves can test their ideas. Economic and social models are often integrated within such applications. Results derived from these models, which are based on a limited set of parameters, are not intended to replace the comprehensive advice from an expert team of modellers and scientists. Rather, the results allow the managers to more easily explore the constraints that are imposed by the interactions of their management actions.

Several interactive tools are available for general use under popular operating systems such as Microsoft Windows and Mac OS (e.g. Stella—http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx), as well as in specific applications such as for ecosystems (e.g. EcoPath with EcoSim—http://www.ecopath.org), coastal zone management (e.g. Jones et al., 2011), land use (e.g. CommunityViz—http://www.ebmtools.org/about_ebm_tools.html; ALCES—http://www.alces.ca) and freshwater systems (e.g. SedNet—http://www.toolkit.net.au/tools/SedNet). Selection between these products depends on availability, cost, level of interactivity and relevance to the case study.

The MSE Tool software, which was developed for this project, is an interactive desktop modelling software package for stakeholders and decision makers. Consequently, the approach to modelling used in the MSE Tool occupies a different space in water management modelling, especially in terms of complexity and accuracy. Generally, the MSE Tool is different to a hydrological and hydrodynamic process model in that:

- its primary objective is to engage the user in an interactive, near real-time simulation that conveys a general understanding of the effects of water-quality altering actions on catchments, including the size of change brought about by actions, the time required for actions to take full effect and the economic and social implications of such actions—it is not intended as a tactical tool for determining a single, prescriptive management plan;
- its model outputs are not required to have the same accuracy since they are used to support learning by users rather than for predictive applications;
- its simulation runs are faster and easier to interpret; pre-calculated runs are not necessary since the simulations are designed to respond to a selected, specific suite of parameters and processes—accuracy is traded for responsiveness;
- the application is constrained to a number of pre-defined simulated management actions, but additional actions can be added by the developer with little effort.

### 1.1. Simulating water quality management at a regional level

The MSE Tool's Simulation Interface (referred to as MTSI in the following) is here set in the context of an MSE for use in catchment-to-coast water quality management in South East Queensland (SEQ), Australia (Dutra et al., 2010). The waterways of SEQ comprise 14 large river catchments, and many associated sub-catchments, which flow into Moreton Bay. Together they form an overall catchment area of 21 220 km$^2$, with complex spatial and ecological interactions (Dutra et al., 2010). The wetlands of Moreton Bay are Ramsar listed (Ramsar Secretariat of the Convention on Wetlands, 2014) and home to a very diverse mix of species (Wetlands International, 1995). The SEQ region includes the major urban centres Brisbane and the Gold Coast, and its population is projected to double from three million in 2010 to approximately six million in 2026 (Office of Economic and Statistical Research, 2011). With this population growth comes increased demand on water resources (Abal et al., 2005) and the threat of contamination due to human development such as sewage, industrial pollution and increased use of fertilisers in agriculture (Moreton Bay Waterways and Catchments Partnership, 2002).

The South East Queensland Healthy Waterways Partnership is a collaboration between government, industry, researchers and the community. It was formed to ensure healthy waterway and catchment ecosystems for SEQ (Moreton Bay Waterways and Catchments Partnership, 2004). To assess the condition of SEQ waterways from catchments to the coast, the partnership established an ecosystem health monitoring program at 19 freshwater catchments, which flow into 18 estuarine areas and 9 marine areas (Smith and Storey, 2001) (Fig. 1). Water quality data is collected twice per year at 135 freshwater sites and monthly at 254 estuarine and marine monitoring sites (South East Queensland Healthy Waterways Partnership, 2009a,b). The partnership produces an annual report card (Fig. 1)—a yearly assessment of the health of each of the waterways using a variety of ecological indicators. Grades are calculated for each of the catchments, estuaries and marine areas by comparing the results of a site to regional

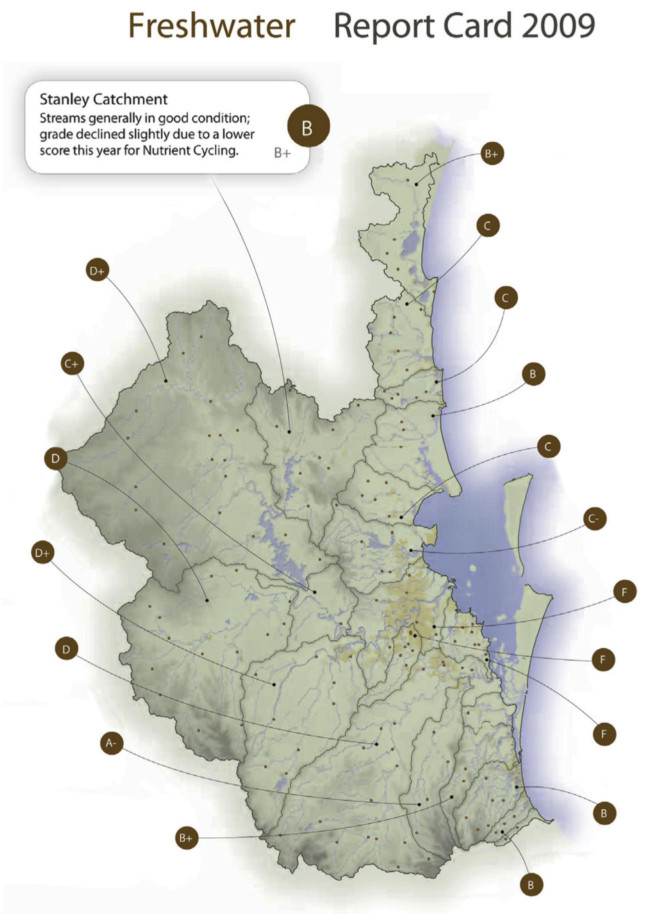


**Fig. 1.** Healthy Waterways Freshwater Report Card 2009 (South East Queensland Healthy Waterways Partnership, 2009a,b) with waterway health rating based on a variety of ecological indicators. Modified from original with focus on the Stanley catchment to illustrate score text box (score text boxes have been deleted for all catchments except Stanley to improve legibility). Ecosystem Health Monitoring Program monitoring stations are marked with red dots. Copyright© Healthy Waterways Limited, 2009 Ecosystem Health Report Card. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Ecosystem Health Guidelines and Water Quality Guidelines (Healthy Waterways Partnership, 2011).

The rest of this article is structured as follows. Section 2 examines the benefits and risks of interactive simulation software and how this applies to the MTSI. Section 3 explains the software design. Section 4 presents the modelling approach used to capture the interactions between management action simulations, biophysical processes and the ensuing changes in ecological, economic and social indicators. Section 5 describes the MTSI's graphical user interface which allows stakeholders to interact with the simulation. Section 6 discusses the lessons learned from the use of the software in a workshop setting.

## 2. Learning with interactive simulation software

Well-known concepts in simulation software, which have been previously described in literature, are the *virtual world* (Schön, 1983) and *microworlds* (Gonzalez et al., 2005). The MTSI is representative of a virtual world since the user is provided the opportunity to observe at leisure, to apply action at one's own pace, to create outcomes immediately, to engage in the process of discovery, to reverse moves and to construct and manipulate with little risk (Schön, 1983). The MTSI also falls in the domain of microworlds which represent complex simulations that utilize Dynamic Decision Making in real time (Gonzalez et al., 2005). The process is comparable to driving a car since the present environment is determined by past decision sequences and future outcomes are limited by the present position and its possible choices.

MTSI provides an interactive and engaging simulation experience for the user whilst fulfilling the requirement for an environment in which learning to manage water quality in SEQ is the main objective. Of primary importance during the development were the speed with which underlying models produced output and a user-friendly interface. Interactive modelling environments with user-friendly interfaces have been shown to motivate users and increase their understanding of complex systems (Sawicka and Campbell, 2001).

However, while interactive computing delivers a richer and more powerful environment than rule-based algorithms (Wegner, 1997), as the complexity of choices and feedback in simulation systems increase, users are less able to make expedient choices and consequently their capacity to learn decreases. In complex dynamic decision-making environments, users increased the number of expert-like decisions and were able to reach predicted outcomes after a learning phase with the system although they did not appear to have a better representation of the system (Broadbent and Aston, 1978; Tabacaru et al., 2009). Likewise, subjects failed to improve their management of complex dynamic environments as they gained experience—mostly because they relied to a lesser degree on the feedback of outcomes (Paich and Sterman, 1993).

Much of the problem in the management of complex systems seems to be caused by the surprisingly small amount of human immediate memory recall (Miller, 1956) which imposes a limit to the analysis of complex feedback. In complex tasks, such as those with many interacting processes, human working memory can be consumed by cognitive load, which disrupts learning (Gary and Wood, 2007). We therefore aimed to reduce this cognitive load by presenting the model output in an efficient, logical and consistent manner, thus helping to free the memory capacity of users so they are able to learn more effectively.

Highly interactive simulation software also bears the risk of the user learning to manage the simulation (game mastering) rather than acquiring knowledge. This was demonstrated by Sterman (1994) who showed that as the complexity of variables in a management flight simulator increased, subjects showed significantly worse decision performance as indicated by faster choices, less analysis and less responsiveness to critical variables. Subjects showed little understanding of processes and causes.

We have implemented several design features in the software and provided user instructions to reduce the described problems: 1) Set-up of management actions is limited to two steps: i) the user chooses a management action and applies it to grid cells with a single mouse click, and ii) the user chooses the duration to the next management intervention by selecting a value from the time-step drop-down box. These simple steps reduce the number of settings which the user is required to make. As a result, users are able to create management scenarios within minutes. 2) Intermediate and final output of simulation runs is well-structured, easy to interpret and uses similar elements throughout. 3) The software provides functions to store and retrieve simulation runs, their parameters and results for later analysis. Results from our workshops, where participants were given clearly defined goals (Appendix A), were encouraging and showed that all areas – report card grades, social perception and cost effectiveness (as described in the following section) – improved when managed by user-defined strategies.

In the literature we found few examples of water quality simulation software with emphasis on improved interactivity. One such system was presented by Newham et al. (2004), who designed a desktop–based water, sediment and nutrient modelling framework where management actions are applied at catchment–scale. Newham used a hydrological model compared to MTSI's empirical water distribution model which, in our case, was a choice dictated by responsiveness, given the small scale at which actions were applied.

## 3. Software design

MTSI and its parent application, the MSE Tool, were developed for the Microsoft Windows operating system using Microsoft Studio.NET 2008 with Microsoft Framework 3.5. Since MTSI was designed as a stand-alone component of the MSE Tool, it is reusable in other MSE applications and provides a complete user interface for simulating water quality management actions. The initial concept was developed by CSIRO (Pantus et al., 2008) and expanded in 2009 and 2010. The model includes a component which lists the typical management actions that can be adopted to improve the quality of water in both rural and urban areas in the region. When running a scenario, the software simulates calculation of report card grades, based on the same catchments and time periods as the existing Healthy Waterways report card system.

The MTSI consists of a number of software modules which were designed as stand-alone entities and constructed, to a large extent, in the same units as those of the models (Fig. 2). Separation between the software modules within the application was a primary concern since it allows upgrade of existing and integration of new components in the future.

At the software architecture level we chose to keep implementation-specific program parts separate from the rest of the code. Code providing the functionality of the general aspects of an MSE is contained in the "MSE Framework"; whereas code dedicated and configured to the real-world application is found in the "Domain Model". Both were developed with standard interface definitions which allow either part to be replaced. In the application presented here, the Domain Model was configured for the South-East Queensland catchments and for output which simulates the Healthy Waterways report card.

Two execution modes are available in MTSI. In interactive mode, simulations are run in background threads and allow the user interface to stay responsive and to deliver an interactive experience. In closed-loop mode, simulations can be executed a defined number of times using user input that has been captured in a previous interactive session. This allows management actions to be tested over the range of variation of the underlying stochastic models.

## 4. Modelling approach

### 4.1. Biophysical model

At the centre of the MTSI is the biophysical model with components for catchment, estuary and bay water modelling. The biophysical model (Fig. 2) in MTSI makes use of an empirical system model based on historical water quality observations as described in de la Mare et al. (2012). This approach replicates the Ecosystem Health Monitoring Program (EHMP) implemented by the SEQ councils (Smith and Storey, 2001) and uses the same framework and timing. The scale at which actions cause changes and the environmental indicators that are simulated were also simply determined by the EHMP (refer to Volk et al. (2010) for examples of scale and indicators in other DSS and to Junier and Mostert (2014) on the difficulties when different user groups require different scale levels). Simulated runs can produce rapid output since data is modelled only for EHMP locations. MTSI estimates the relationships between water quality parameters at different monitoring stations and consequently allows prediction of changes in these parameters under new, simulated conditions.

In the upper catchment we used the historical monitoring data to create a generalized linear mixed-effects statistical model relating the site health score to known quantities in the cells flowing to the site (area of non-urban use, medium vegetation and stream buffers with high density vegetation—all positively correlated to health score) and capturing variability (such as rainfall) implicitly as site- and year-specific random effects. In the simulation model, the management actions (e.g. riparian vegetation) influenced the health score by increasing the area of the densely vegetated stream buffers. The catchment-level report card score was then computed from the individual site health scores (Dutra et al., 2010; Healthy Waterways Partnership, 2011).

In the estuaries we modelled the water quality variables (total nitrogen (TN), total phosphorous, light penetration, dissolved oxygen, turbidity and chlorophyll) directly by capturing their mean and covariance structure in the monitoring data using a site-specific multivariate lognormal distribution. The relationship between log TN at a site (e.g. S3 in Fig. 3) and the six variables at the immediate upstream sites (S2 and S4), or sites in the case of a confluence, was found by backwards stepwise regression. The water quality variables were simulated in a cascading way through the estuarine network by sampling from each site's multivariate lognormal distribution, with mean determined through the regression on the values at the upstream sites (or historical mean for sites at the top of the network, e.g. site S1 in Fig. 3). Local effects due to management actions were implemented as reductions in TN

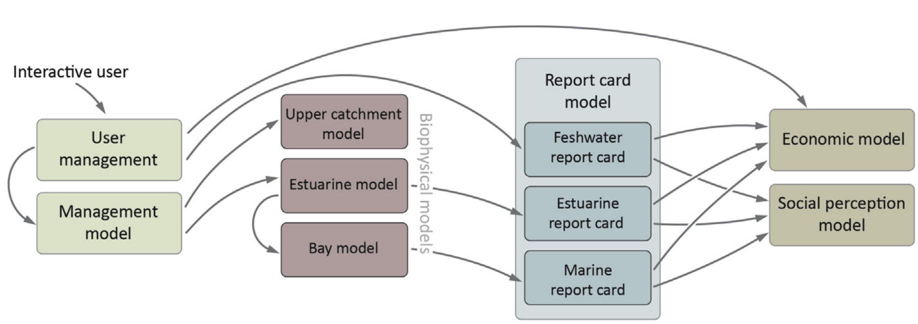


**Fig. 2.** MTSI models, software components and their linkages. Users implement management actions (strategies) which are used by the Biophysical model to calculate changes to estuarine and marine variables. These are used to produce estuarine and marine report cards. Freshwater report card scores are determined directly from the user's choice of actions in the upper catchments. The report cards provide input to the social impact and economic models.

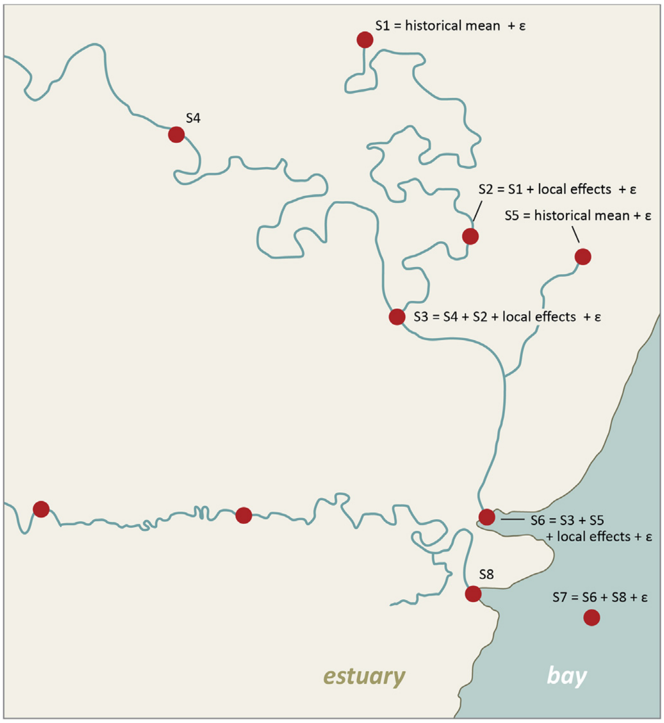


**Fig. 3.** Biophysical model. Each site represents an EHMP monitoring station. Site S1 is an uppermost estuarine station in a catchment. Site S2 is affected by S1, but also by local management actions. Further downstream at the river mouth, site S6 is affected by several sites (S3 and S5) as well as local effects. In the bay, sites, such as S7, are influenced in some way by sites at the mouths of the estuaries. At each EHMP station, the effects from local management actions and changes from upstream stations are propagated with consequential cumulative effects across the network (Dutra et al., 2010). A random component ε is introduced at all sites to represent the variability seen in the historical data. Locations and densities of EHMP stations in this example are fictitious.

and turbidity, by an amount dependent on the degree of abatement (the reduction in TN or turbidity in a cell) of each action, the timing and the number of cells the action was applied to.

The bay water quality model is also an empirical model built from the historical monitoring data in the same way as the estuarine model. As in the estuarine model, the correlation structure among the six variables is faithfully represented. However, the expected mean at each site now depends on the water quality variables at the river mouths; the generalized linear regression is replaced by a random forest model (Breiman, 2001) in order to account for nonlinear relationships. During simulation, management actions do not affect the bay sites directly, but rather indirectly through their effect on water quality at the river mouths via the estuarine model. For both the bay and estuarine models, the report card score is calculated directly from the average degree of compliance of the six water quality variables over sites, where compliance means the variable falls within certain thresholds (Healthy Waterways Partnership, 2011). See de la Mare et al. (2012) for a more complete description of the bay and estuarine models.

### 4.2. Management model

We decided that a realistic and engaging simulation should allow the user to have fine control of actions applied in a catchment, both spatially and temporally. A 1 × 1 km grid was superimposed over the Healthy Waterways report card region; it covers the SEQ council boundaries and is made up of 23 144 cells, each of which can have actions applied to it. This resolution was deemed acceptable since the model's purpose, to simulate certain predefined processes in near-real-time, did not require a finer scale.

Each cell in the grid was assigned a set of properties derived from its location. These are used to restrict which actions may be applied to the cell, and what effect those actions have on the simulated biophysical model of the region. The cell properties included the watershed to which the cell belongs, its land-use category, vegetation density, length of river or stream that passes through the cell, percentage of riverbank vegetation, and whether the cell contains a sewage treatment plant.

Watersheds for cells in the upper catchments were created from a digital elevation model with 250 m resolution (Geoscience Australia, 2009). Vegetation cover was determined using the Vegetation Cover of Queensland shape file (Queensland Herbarium, 2009). Broad Vegetation Group values were converted to a 250 × 250 m raster of simple density values consisting of thick vegetation (rainforests, scrubs, moist to dry woodlands dominated by *Eucalyptus*), medium vegetation (open forest to woodlands, shrublands and heaths) and sparse vegetation (grasslands, wetlands, mangroves and all other values). This vegetation-category raster was sampled at the centre point of each cell to determine the category assigned to that cell. We also derived the amount of riverbank vegetation for each cell from this source. The default land-use category for each cell was assigned as 'natural'. An urban footprint coverage (Geoscience Australia, 1998) was then superimposed on the vegetation density map, so that cells having their centre in an urban area were classified as 'urban'. To determine whether a cell was predominantly in a rural area, we used the 1999 Land Use Map of Queensland (Witte et al., 1999). The amount of riverbank vegetation for each cell was calculated using the Vegetation Cover of Queensland shape file (Queensland Herbarium, 2009).

We identified the management actions that have the purpose of improving water quality in SEQ from interviews with eight key experts and from a review of the literature (Dutra et al., 2010). Actions were defined for each of the land-use types (Table 1). The response to the selected actions is simulated by the biophysical model which determines the changes in water quality indicators at each of the estuarine and bay nodes in the network of EHMP monitoring stations. Fig. 3 is a schematic representation of this hydrological network. The model produces values within seconds in response to various scenarios.

In the models, the effects of simulated actions were assumed to propagate in the same direction as net water flow. At each time step there is a set of actions which are associated with some cells. Depending on the type of action, there may be a delay before the action has any effect on the simulated environment and a further delay until the maximum effect of the action is reached (e.g. installing infrastructure takes time to implement and planted vegetation requires time to grow). An action, once applied, cannot be undone and remains in force for all future time-steps. It is possible to specify that multiple actions should be applied to the same cell. It is also possible to duplicate an action on a cell (except for 'sewerage treatment plant upgrade'); in this case the further effects of the action diminish with each new application. The interventions affecting a cell at a particular time are often due to actions applied over several previous management periods. The model calculates the combined effects of these actions on water quality in the cells and aggregates these effects over each monitoring station's watershed. The effect of actions on water quality indicators is a complex process involving interactions with topography, hydrography and soil biogeochemistry. The model uses a simplification of these processes based on White et al. (1992).

**Table 1**
Management actions for the literature-based and expert-based parameter configurations.

| Action code | Management action | Land use | Source | Detailed actions | Reference |
|---|---|---|---|---|---|
| 0 | No action | Any | – | – | – |
| 1 | Riparian revegetation | Any | Literature/Expert | Vegetation used to stabilise gullies/banks (riparian buffer area is 1 km long and within 100 m from both sides of the river margins) | (Alam et al., 2006b) |
| 2 | Sewage treatment plant upgrade | Any | Literature/Expert | Deliver TN concentrations of 2 mg/L (expert) or <2 mg/L (literature) in the outfall | (BDA Group, 2005) |
| 3 | Rural Stormwater | Rural | Literature | Stormwater quality improvement device | (pers. comm. Sqid Pty Ltd, 19 July 2010) |
| 4 | Gully/Channel rehabilitation | Rural | Expert | Water troughs, porous weirs, fencing | (Olley et al., 2009) |
| 5 | Best Farming Practices | Rural | Literature | Fencing | (Rolfe et al., 2004) |
| 6 | Best Farming Practices | Rural | Expert | Minimum tillage | [a] |
| 7 | Best Urban Design | Urban | Literature | Water sensitive urban design (rainwater tanks and double reticulation) | (Water by Design, 2010) |
| 8 | Best Urban Design | Urban | Expert | Water sensitive urban design | (Water by Design, 2010) |
| 9 | Urban Stormwater | Urban | Literature | Grassed riparian buffer | (Alam et al., 2006a) |
| 10 | Urban Stormwater | Urban | Expert | Grassed riparian buffer | (Alam et al., 2006a) |

Notes
[a] Interviews with experts were conducted under ethical constraints; therefore these experts cannot be identified.

### 4.3. Economic model

Costs that are associated with actions are calculated in MTSI's economic model, which was calibrated on actual data and uses a cost-effectiveness approach (CEA) based on the output of the report card model. A piecewise function was used to capture the change in global water quality that is associated with a change from one grade to another. Output of the economic module forms part of a triple-bottom-line assessment in which users compare alternative strategies. When applying actions, both establishment costs and annual maintenance costs are taken into account. These costs were determined from average values in published studies (Alam et al., 2006b; BDA Group, 2005; Olley et al., 2009; Rolfe et al., 2004; Water by Design, 2009). We assumed that there is an average improvement in water quality scores as grades improve.

### 4.4. Social perception model

An assessment of possible social perception changes is performed by the social perception model. Experts were provided with a definition of the report card grades and asked to score a range of social value indicators associated with each grade on a scale of −4 to 4 (most positive) from the point of view of individuals from a range of social groups. The social groups included residents, business owners, fishers, indigenous and interest groups. Indicators encompassed the categories of water, health, biodiversity, ecosystem services and social capital. The resulting S-shaped curves of value against report-card grade were stored in a look-up table. In the course of the simulation the social value could then be simply determined from the report card grade.

## 5. User interface

The graphical user interface built for MTSI enables the user to interactively construct management strategies at the beginning of a simulation, to change these when a simulation run displays intermediate results, and then to explore the resulting biophysical, social and economic consequences on the whole SEQ region. A high-level overview of the program's features and outputs follows. A trial run of the software demonstrating its capabilities is presented in Appendix A from Dutra et al. (2010).

When defining a new strategy, the user is initially required to choose one of the available strategies, either based on literature or expert opinion. The user then chooses a ‘scenario’, a set of initialisation parameters for the simulated environment, for an interactive simulation run. For MTSI, two scenarios were provided, one of effective governance which assumes actions to always be as effective as possible, and one of weak governance which assumes actions to be implemented less effectively as time passes.

Before the simulation begins, and at configurable intervals during the simulation, the program displays the Actions window that provides the actions that can be applied to cells in the region they wish to manage in the next time step. Fig. 4 shows the Actions window with an example of actions selected for a specific estuary. The user can select a management action from the buttons on the left side of the screen. Once an action is selected, the cells to which that action can be applied remain coloured, while invalid cells are dimmed. In this example the ‘Best Farming Practices’ and ‘Water Sensitive Urban Design’ actions have been selected in the Caboolture estuary. All other cells in this region are shown in grey. The user chooses where the selected action is to be applied by clicking on any active cell or by clicking and dragging a selection box around multiple cells, which will apply the action to all cells within the boundary. Financial costs of all applied actions are shown on the right side, in this case for the first year of a 30-year run. These costs are grouped by action type and whether the cost is incurred in the current time step (an upfront cost of implementing the action) or in future time-steps (a committed cost for system maintenance or similar). This allows the user to track projected expenditures against a hypothetical budget before committing to a further set of actions.

When the user has completed a set of actions, a time interval for evaluating the effectiveness of those actions is chosen: after one year, two years or five years of simulation or at the end of the run. We chose these as an approximation of the intervals at which the stakeholders for the pilot project are accustomed to planning new actions in the real world. The simulation is executed for the selected duration and then paused to allow the user to examine the results. The software displays the results within a few seconds, which is necessary for the application to feel responsive to a user. These results include:

- an interactive map of catchment, estuarine and marine Healthy Waterways report card regions where each EHMP station can be clicked and indicator values — nitrogen, phosphate (only estuarine), light penetration, dissolved oxygen, turbidity and chlorophyll A — are displayed;

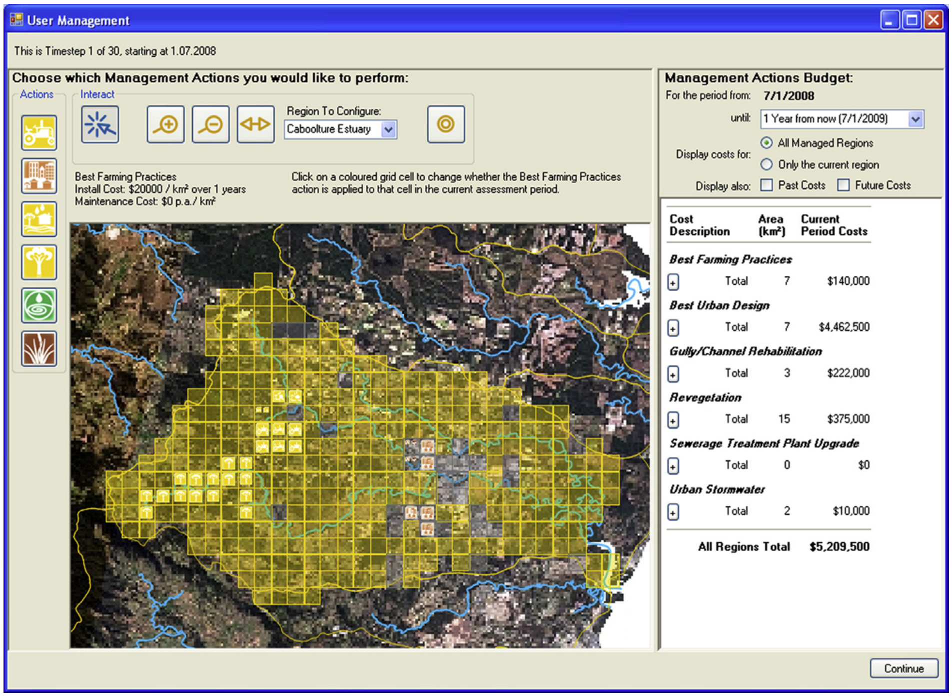


**Fig. 4.** Actions window with actions selected. The 1 × 1 km grid of cells is displayed as a transparent overlay over a geo-referenced satellite image, and colour coded according to the land-use type (green for natural, yellow for rural, brown for urban). The catchment boundaries and stream networks are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- a graph showing indicator values at the EHMP stations of each catchment, estuarine region or Moreton Bay EHMP site (Fig. 5);
- report card grades over elapsed time for each of the catchment regions, estuarine and bay regions presented as a graph, as grades on a map (using the same visualisation as the Healthy Waterways report card, Fig. 6) or in table form;
- a linear graph of social perception indices by region and social values (such as 'aesthetics' or 'cultural') and by social group (such as 'boaters' or 'tourists');

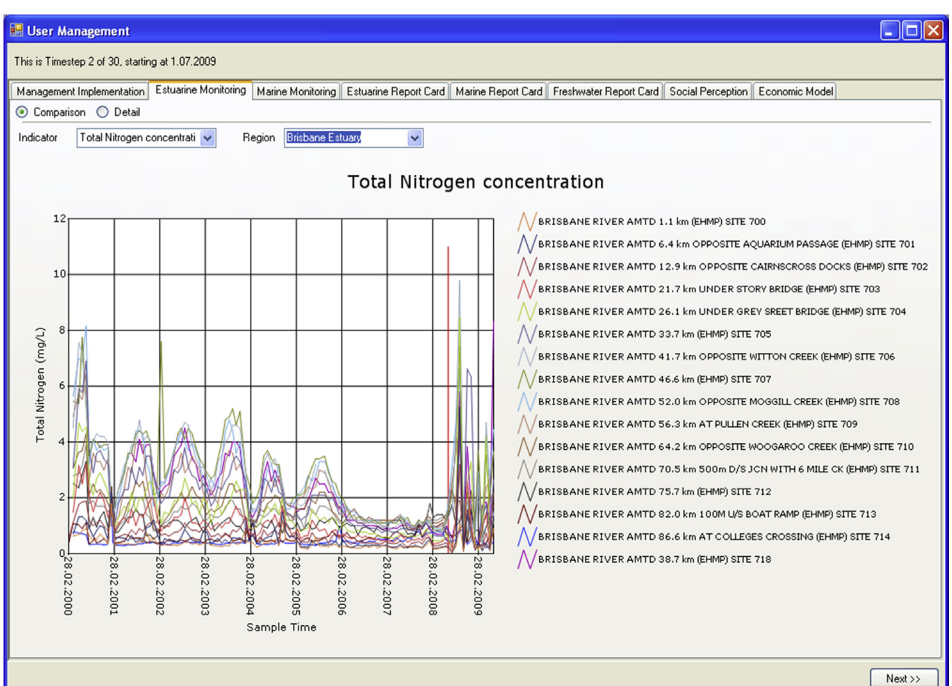


**Fig. 5.** Results from a strategy run showing changes in predicted total nitrogen concentration at EHMP monitoring sites in the Brisbane River catchment over a period of nine years.

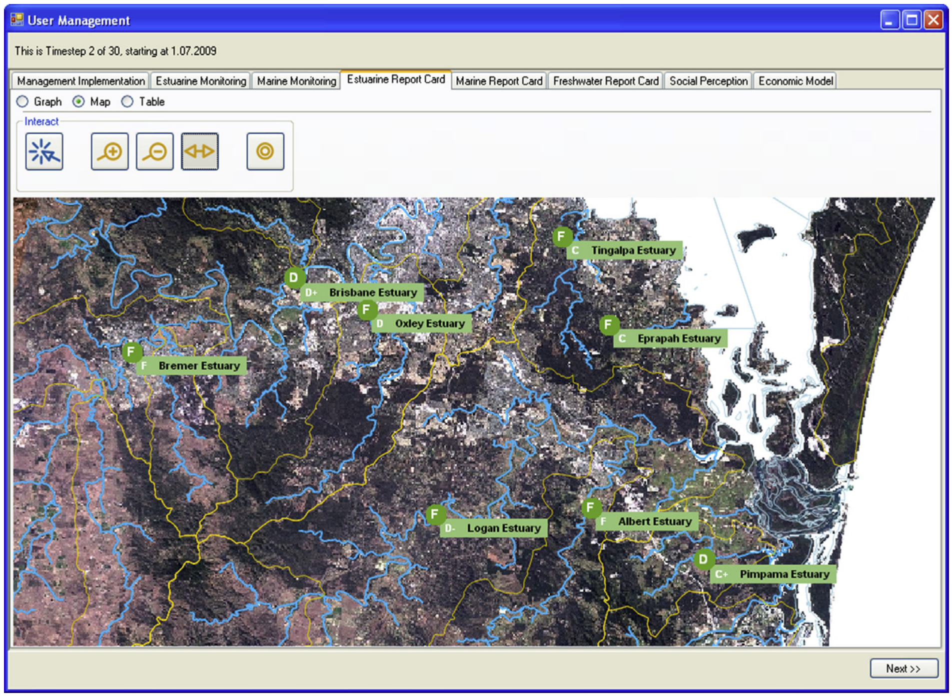


**Fig. 6.** Results from a strategy run showing a map view of predicted report card grades (in darker green circles) for several estuaries. Report card grades from the previous period are displayed to the left of the catchment name. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- costs of the management actions, benefits and cost effectiveness.

After examining the consequences and evaluating the effectiveness of the chosen strategy, the user can choose to add new actions before the simulation resumes. This cycle continues for the entire 30-year span of the simulation. When the interactive simulation ends, the user can examine the full set of results, and choose to save the new strategy for further testing.

Once a strategy has been defined and saved, the range of possible responses to that strategy can be determined by running multiple replicates of the simulation in a non-interactive and significantly faster mode. Our method of fitting the biophysical model to historical data required the introduction of a random effect. Consequently, each replicate triggers a slightly different result from the stochastic biophysical response model, which in turn may result in a range of possible social and economic impacts for the same set of actions. The envelope of results from multiple replicates is shown on all output (for example Strategies 1.2 and 1.3 in Fig. 7) and should, therefore, be used when assessing whether any particular strategy is likely to be effective.

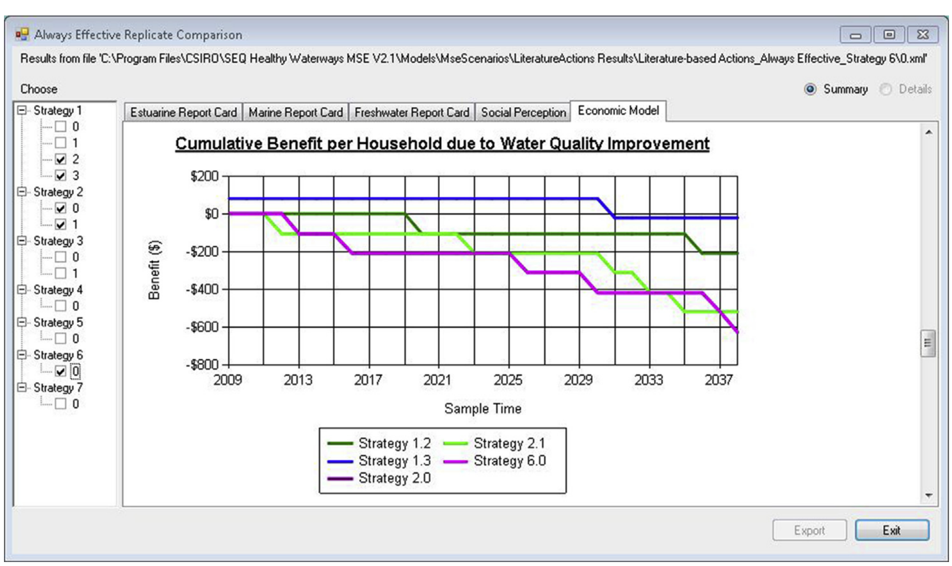


**Fig. 7.** Result of the economic model's cumulative monetary benefit per household due to water quality improvement. The screen allows comparison of results from several previous strategy runs.

MTSI allows combined visualisation of the results of multiple replicates from multiple strategies and thus enables the performance of different strategies to be compared and contrasted across the biophysical, social and economic dimensions (Fig. 7).

## 6. Discussion and conclusion

MSE software requires flexible approaches to modelling, visualisation and interactivity, which depend both on the context of its application (e.g. conservation, fisheries, catchment-to-coast management) and its intended use. In our case the context was water quality management and the client specified that mid-level managers were the targeted users. The MTSI was developed according to these specifications.

Despite the many EDSS software developments and journal articles on the subject, a thorough review showed that EDSS are used less often in real-world natural resource management than expected. McIntosh et al. (2011) compared 19 EDSS developments and found that only four of these had progressed beyond the development and presentation stages and appeared to be in operational use. Van Delden et al. (2011) attributes the failures to bring such software to productive use in “a lack of transparency, inflexibility and a focus on technical capabilities rather than on real planning problems” and finds that it is crucial for an EDSS system to replicate the perceptions, experiences and operational procedures of the policy makers. In such positive circumstances the system will enhance policy practice rather than replace it. Hence, there is evidence that EDSS can be of value in the management of natural resources beyond a learning environment — but achieving this is a complex process. Based on an analysis of the failures in EDSS development, McIntosh et al. (2011) also provided valuable recommendations for an improvement in the development process. In a specific software example, which failed to gain acceptance with the users in its first version, Junier and Mostert (2014) found that over-promising had raised user expectations to unfulfillable levels and the vagaries of the real world had changed the product so that it did not suit the purpose of any user group.

One of the key results from our own case study is that developing flexible software requires an investment in the development of reusable software modules so they can be added or subtracted as is necessary for each MSE application. This is important because modules can be used in different contexts and with other MSE software. The code for the MTSI allows it to connect to software written in a variety of programming languages and using different software tools, making it adaptable to various requirements. However, it is critical that software engineers and developers, who are not traditionally included in scientific teams developing MSEs, are involved in the development of MSEs in the early stages.

The development of the tool involved interviews and meetings with resource managers. At each interaction with managers and other stakeholders the team communicated the advantages but also the limitations of the modelling approach to avoid false expectations in the final product.

Although we did not assess the validity of MTSI's outputs, there were promising results from two experiments conducted in a workshop where regional water quality managers tested the MTSI to improve water quality in a specific catchment in SEQ. The main objective was to assess the extent to which the MTSI could be used in supporting learning in an adaptive management context. The experiments focused on the water quality management in a single catchment where water quality managers were asked to assess their strategy by comparing final outcomes after a simulated 3-year period to initial expectations. Objectives and actions taken by each participant were recorded, along with their expenditure profile, how their actions affected social, economic and biophysical indicators, and how each of these affected the way in which participants made decisions (Myers et al., 2012).

The analysis of results of the first experiment showed that the MTSI worked effectively as a ‘virtual world’ (Schön, 1983) or ‘microworld’ (Gonzalez et al., 2005). Results from the workshops show three distinct groups clustered by their behaviour (for details refer to Myers et al., 2012). The first group quickly learned that limited spending would be sufficient to achieve improvement in water quality. This group explored the effects of the actions in the initial steps of the runs and quickly learned which actions were more effective in improving water quality. The second group continued to use the maximum allowable expenditure and experimented with different combinations of management actions per period. This was an explicit attempt to learn from the MTSI about the relative performance of alternative management actions, despite the fact that these did not lead to further improvements in water quality. The third group was cautious in their expenditure and combination of actions in the early stages of the experiment.

Results from the second experiment demonstrated that the same participants learned by using the MTSI in the first experiment. Participants learned that better outcomes were achieved when applying management actions at the early stages of the experiment. As a result, water quality objectives were achieved more quickly and cost-effectively than in the first experiment (Myers et al., 2012). The software therefore helped participants to learn about the effectiveness of their actions and also promoted dialogue and engagement between the managers from various councils and other managers involved in the participatory modelling experiments.

Most simulation software is computationally intensive and run time is long, often measured in hours, days, and even months. In principle MTSI can be used in these models, but their long run times mean that in practice they cannot be used interactively to facilitate learning and experimentation by users who do not require the system solely for its accuracy. In order to reduce run times, a compromise in accuracy and full representativeness of the system is required. This means that the focus of quick simulation models should be different: to facilitate the development of management strategies that can be trialled and refined quickly, thus promoting learning. When developed and refined by managers, such strategies can then be tested with more complex modelling tools, providing results that are more aligned with the manager's needs. In the workshop this aspect was fully explained to the managers, but the tool is vulnerable to the risk of managers using it for management advice, which is not its intended design. In reality, several tools are required in natural resource management (Fulton et al., 2011a; Smith et al., 1999). The MTSI application fills a valuable gap between detailed spatiotemporal catchment (e.g. BC2C—http://www.toolkit.net.au/tools/BC2C) and receiving water models (e.g. Healthy Waterways RWQM— http://www.healthywaterways.org/ScienceandInnovation/Modelling/ReceivingWaterQualityModel.aspx) and complex, full-scale ecosystem MSE process models such as Atlantis and InVitro by combining a rapid modelling component with robust interaction and visualisation tools.

In a workshop setting we found that the MTSI facilitated learning and may therefore fill a gap in MSE modelling capabilities. For the SEQ, such a tool can provide additional information to the report cards and assist in decision-making by providing psychological, relational, and political aspects. The tool can help communicate such specific information in a way that managers and other stakeholders will easily understand. The MTSI could play a key role in linking information and decision-making by 1) facilitating learning and experimentation with the water quality management system and therefore the development of management strategies that can be tested in predictive modelling tools, and 2) by improving dialogue and engagement between regional managers in workshop.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2015.04.006

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