OSS: A Spatial Decision Support System for Optimal Zoning of Marine Protected Areas

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EXTENDED ABSTRACT

We have developed the Optimisation Support System (OSS), a spatial decision support system, to deliver optimal solutions to the problem of identifying comprehensive, adequate and representative locations for conservation planning.

The South Australian Government is committed to establishing a comprehensive, adequate and representative system of 19 marine protected areas (MPAs) by 2010. Each MPA will be the target for detailed investigations into its biophysical, ecological, social, economic and cultural assets. The aim is to use this information to delineate each MPA into a series of zones that offer various levels of protection and use. At the highest level all marine use and extraction activities will be excluded to allow maximum protection of species diversity and habitat. Community consultation and collaboration is therefore critical for successful MPA establishment. A demand exists for the development of a process that allows public participation within a conservation planning environment.

The concept of excluding certain activities, including recreational fishing, has generated much interest in the local media. Recent headlines such as 'Calls to Shelve Marine Parks', 'Anglers Fight For Future of Jetty Fishing' and '330+ Submissions on MPA Proposal' demonstrate the importance of open consultation and the need to provide an inclusive and transparent decision-making process for the design of MPAs. A decision support tool can facilitate decision-making within a negotiating and conflict resolution environment.

We have collated and processed a large database of spatial layers describing the biophysical and human-use features of the marine environment. The biophysical data was then used to identify surrogate ecological regions within the Encounter Pilot MPA. The datasets were categorised into classes describing bathymetry, sea surface temperature, chlorophyll 'a' concentration levels, benthic and coastal habitat types, and shoreline exposure and type. Locations that most efficiently represent these surrogates of biodiversity were selected using a common mathematical integer programming optimisation algorithm.

Established conservation planning principles underpin this research. Inputs into OSS are a suite of environmental, social, cultural and economic datasets. Optimal solutions are found using integer programming algorithms. Implementation is within a Geographic Information System environment (ESRI's ArcGIS) and third-party commercial software (ILOG's CPLEX) provides the optimisation engine. The user interface of OSS can be accessed through a toolbar button and comprises a series of input modules. Fields are quick and easy to populate and in many cases are read directly from an *ArcGIS* map document *Table of Contents*. Solutions are found in less than 1 minute when using datasets described in this paper

This paper briefly demonstrates the application of systematic conservation planning to optimal MPA design and the development of OSS, and explores options for public participation. We demonstrate how OSS and systematic conservation planning can be taken to the wider community to produce on-the-fly outputs. Our novel approach has the potential to build partnerships with community groups and give the community a sense of ownership in the decision-making process. It is more likely that conflicts will be minimised and negotiation hastened for a better MPA zoning outcome for all.

1. INTRODUCTION

The protection of South Australia's marine biodiversity is a high priority. The South Australian State Strategic Plan (Government of South Australia 2003) specifies a target of establishing 19 multiple-use marine protected areas (MPAs) by 2010. MPAs are areas identified as being representative of the different biodiversity systems in South Australian waters. Each MPA will be delineated into a series of zones that offer various levels of protection and use, including limits on use and extraction. The State Government's MPA decision-making and design process aims to be inclusive and consultative to avoid potential public dissent and minimise community backlash.

A systematic and transparent approach to MPA design is called for. Such an approach will allow for the integration of management priorities (e.g. protecting biodiversity) with multiple stakeholder needs (e.g. fishing and recreational use) (Agardy 1997). We present a brief account of our efforts to zone a MPA based on well-established conservation and marine planning principles (Margules and Pressey 2000, Leslie *et al.* 2003). We also demonstrate the development of a decision support tool that can produce rapid solutions to facilitate decision-making and potentially underpin an all-inclusive public participation process.

1.1. Systematic Conservation Planning

Systematic conservation planning (Margules and Pressey 2000) aims to select the areas and environments to protect in order to maximise the chances for conservation. Systematic conservation planning is a complex problem and involves consideration of an established suite of principles such as comprehensiveness, adequacy, representativeness, efficiency and flexibility (Margules and Pressey 2000). Whilst the principles of systematic conservation planning are reasonably well established, the methods for implementing these principles are many and varied.

Many studies have presented methods for conservation planning (e.g. Church *et al.* 1996, Haight *et al.* 2000, ReVelle *et al.* 2002, Rodrigues and Gaston 2002, Leslie *et al* 2003, Haight *et al.* 2005). The methods can be classed according to whether they can guarantee an optimal solution or not. Approaches that do not guarantee an optimal solution include scoring approaches (Pressey and Nicholls 1989), heuristic algorithms, and simulated annealing (Possingham *et al.* 2000, Leslie *et al.* 2003). On the other hand, studies by Rodrigues and Gaston (2002), Önal and Briers (2003), Snyder et al. (2004) and Haight et al. (2005) have demonstrated approaches to conservation planning that guarantee optimal solutions. They all employ integer programming.

Integer programming coupled with a GIS provides the potential to systematically plan using a range of spatial databases. The guaranteed optimality of solutions provides greatest efficiency in MPA design. However, common GIS packages do not include integer programming as a general tool, making it necessary to employ third party software. This lack of integration can hamper decision-making (e.g. Denzer 2005).

1.2. Spatial Decision Support Systems

A spatial decision support system (SDSS) is an intelligent information system that reduces decision making time as well as improving the consistency and quality of the decisions (Cortes *et al.* 2000). A SDSS can be either problem specific or situation and problem specific (Rizzoli and Young 1997). Both are tailored to a specific problem, but the latter is generally limited to one specific spatial location. Amongst Rizzoli and Young's (1997) desirable features of an SDSS is the ability to deal with spatial data and ability to be used effectively for diagnosis, planning, management and optimisation.

1.3. Marine Protected Area Planning in South Australia

The basis for the design of MPAs in South Australia is a 5-level multiple-use zoning system. The aim is to protect coastal, estuarine and marine ecosystems, while also providing for continued ecologically sustainable use of suitable areas. Most activities, including recreational and commercial activities, will continue within a MPA. However, there will be particular zones in which some activities will not be permitted thereby guaranteeing the protection of representative habitats, species and ecological features. At the highest level of protection is the *Restricted Access Zone* in which access and extraction is not generally permitted. While these will generally be the smallest zones, they will include the most important habitat and have the potential to be associated with the greatest conflict. The question that arises is where to best locate core zones for biodiversity conservation that have the support of marine coastal users?

Zoning for the *Restricted Access Zone* in the MPA then becomes a typical environmental decision-making problem because the process includes many stakeholders, uncertainties, multiple, possibly conflicting criteria; and impacts which extend far into the future (French and Geldermann 2005). Public participation, collaboration and consultation in the planning process are then imperatives for attaining a consensual MPA design.

The plan to exclude certain activities, including recreational fishing, has generated much interest in the local media and across the wider community. Recent newspaper headlines, such as 'Calls to Shelve Marine Parks' (Anonymous 2005), 'Anglers Fight For Future of Jetty Fishing' (Austin 2005) and '330+ Submissions on MPA Proposal' (Robinson 2005), further demonstrates the importance of open consultation and the need to provide an inclusive and transparent decision-making process. We suggest that a decision support tool and a systematic approach to planning can facilitate decision-making within a negotiation and conflict resolution environment.

Recognising the need to be inclusive, open and transparent to the public, the State Government has implemented a consultation, collaboration and education program between all spheres of government, industry and community groups with an interest in the marine environment. This includes three on-going committees (*Marine Advisory Committee*; *MPA Consultative Committee*; *Scientific Working Group*), and public workshops and meetings during the draft phase of each MPA design. The potential exists to introduce a spatial decision support tool to the public participation process of MPA design.

2. METHODS

2.1. Study Area

Initial research was applied to the Encounter pilot study area (Figure 1). The region, approximately 80km south of Adelaide and with an area of 2,700 km^2, is high in biodiversity and contains a number of unique coastal and marine environments. High biodiversity values, proximity to numerous coastal towns and ports and high aesthetic values have seen the Encounter region develop into a very popular destination for many recreational and commercial activities. This has placed increased pressure on the environmental stability of the region's marine ecosystems.

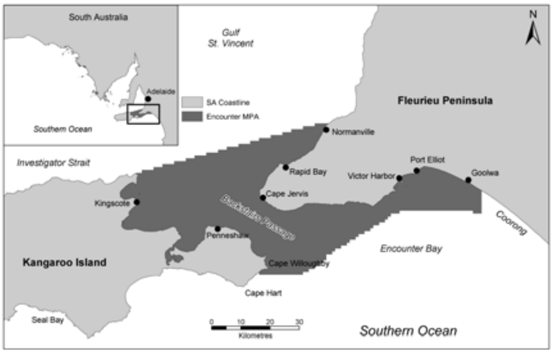

Figure 1. The Encounter MPA, South Australia.

2.2. The Data

We have collated and processed a large database of spatial layers describing the biophysical and human-use features of the marine environment (Table 1). The biophysical data was then used to identify surrogate ecological regions within the Encounter Pilot MPA. The datasets were categorised into classes. Locations that most efficiently represent these surrogates of biodiversity were selected using integer programming. The aim is to minimise an objective function subject to certain constraints. The next section describes the model in more detail.

To add proximity, i.e. spatial realism, we developed three weighting data layers that encourage models to preferably select particular planning units:

- *Environmental variability*: This is an important aspect in determining areas of high value in the design of a system of MPAs. GIS neighbourhood statistics were used to calculate standard deviation across a subset of the biophysical datasets (Table 1), thereby identifying locations of high variability. Areas of high variability (i.e. those that contain steep spatial gradients of each biophysical variable) are more likely to contain greater species diversity and different environment types, and are therefore of greater conservation value (Ferrier *et al.* 2002, Faith *et al.* 2004) and are selected.

- *Social cost*: In an attempt to include recreational and commercial interests, 18 spatial data layers

(Table 1) were classified to encourage the selection of planning units that have a minimum social cost value. This weighting surface is based on a range of biological, social and marine-use data that potentially have social interest value from users of the marine environment (Table 1). Features thought to have a positive contribution to a MPA, i.e. areas that should have lower social cost weighting in the process of selecting areas for MPA selection (e.g. estuary outlets, temperate fish habitats, NZ Fur Seal colonies), are preferably selected. Features thought to have a potentially negative effect on a MPA (e.g. jetties and ports) were assigned high social cost weightings and preferably not selected.

Table 1. Spatial dataset used in the modelling. All data was sourced from the South Australian State Government. Those layers with an * were included in the environmental variability weighting layer.

Biophyisical	Socio-economic
Bathymetry*	Crownland
Benthic habitat	Coastal wetlands
Bioregions	Estuary outlets
Chlorophyll 'a' content*	Temperate fish habitats
(Concentration Levels)	Geological monuments
Shoreline type	Hobart aquatic reserve
Shoreline exposure	Jetties
Sea surface temperature*	Macroalgae
(Summer-Winter range ºC)	Net closures
Sea surface temperature*	NZ Fur Seals
(Summer ºC)	Ports
Sea surface temperature*	Recreational fishing areas
(Winter ºC)	Restricted boating
	Saltmarsh
	Sealion
	Ship wrecks
	Shipping density
	Whale aggregation areas

- *Distance to existing terrestrial/marine reserves*: This layer encourages site selection toward existing marine and terrestrial reserves. Terrestrial reserves were included because many biotic and abiotic processes occur across the terrestrial/marine interface. National Park reserves with marine components were also identified because of their current protection and the common-held conservation goal of expanding existing reserves. The weighting surface was generated using Euclidean distance functions in the GIS.

2.3. Integer Programming

The classic set-covering integer programming model is used in this study to identify the minimum number of planning units required to meet the conservation targets defined by proportional and area constraints. Mathematically, the optimisation techniques attempt to (adapted from Possingham *et al.* 2000):

$$\text{minimise} \sum_{i=1}^{m} l x_i \qquad (1)$$

$$\text{subject to} \sum_{i=1}^{m} a_{ij} x_i \geq c_j \quad \text{for } j = 1 \ldots \text{n} \qquad (2)$$

$$\text{where } a_{ij}, x_i \in \{0,1\}, \; A_j = \sum_{i=1}^{m} a_{ij}$$

$$\text{and } c_j = \begin{cases} pA_j \text{ if } pA_j \geq t \\ \min(A_j, t) \text{ otherwise} \end{cases} \qquad (3)$$

A study area of m planning units contains n classes of physical and environmental data. A m x n matrix **A** is created whose elements a_{ij} are attributed a binary value according to the presence or absence of a class c_j in each planning unit. Planning units are given a value of '1' if they are contain a particular class or '0' otherwise. A solution vector **X** with dimension m is defined such that its elements x_i are given a value of '1' if a planning unit is selected for conservation or '0' if not selected. The set-covering integer programming model strives to minimise the number of planning units to be conserved subject to areal constraints for each class c_j. Areal constraints are a function of the area of the class, the proportional target ((p), the minimum percentage of each class to be restored), and the minimum area target ((t), the minimum number of planning units in each class to be restored). For each class, the areal constraint is equal to the proportional target multiplied by the number of planning units in the class if this value is greater than or equal to the minimum area target. Otherwise, the areal constraint for the class equals the lesser of the total number of planning units in the class or the specified minimum area target.

We have also introduced a further objective into equation (1) that incorporates proximity. A weighting score l was calculated at each planning unit by combining the individual weighting layers in an n-component mixture model:

$$l = w_1 f(1) + \ldots + w_n f(n) \quad (4)$$

where $f(1)\ldots f(n)$ are weighting layers and $w_1\ldots w_n$ are weighting coefficients that are determined by a user. In a similar fashion to multi-criteria decision analysis problems, there is considerable scope for public participation in determining weighting coefficients (e.g. Malczewski 1999, Store and Kangas 2001, Villa *et al.* 2002, Stoms *et al.* 2004, Hill *et al.* 2005). Planning units are selected based not only on their contribution to an optimal solution, but also on their weighting score which is a direct function of location.

2.4. Model Implementation

We employ the commercially available optimiser, *ILOG's CPLEX 9.0* engine (ILOG 2003), to find optimal solutions to our problem. However, *CPLEX* is a stand-alone application and is separate to the GIS, and requires data to be in tabular format. Extracting and pre-processing the data from the GIS is a relatively complex and time-consuming task. The complexity devalues the modelling by making it inefficient and user-*un*friendly. To overcome this problem we designed and tested a spatial decision support system to be used as a tool in conjunction with the GIS to aid in the selection of planning units that meet conservation planning targets. Our SDSS, the Optimised Site Selection (OSS) tool, is available as an extension to *ESRI's ArcGIS 9.0* (ESRI 2004) and allows users to quickly and simply optimise the spatial selection and design of zones within a MPA. We designed OSS to be fully interactive with the GIS and eliminate the need to pre- and post-process spatial layers for input into *CPLEX* and output back to the GIS, respectively.

All input datasets were converted to 1km^2 resolution grids. The number of planning units m in the study area is 2,790. The number of data classes n of biodiversity surrogate (biophysical) data is 44. A presence/absence matrix of 2,790 x 44 is generated as model input. A 2,790 vector of selected and non-selected planning units is generated as output. Existing reserved areas are included in the selected set. All models were run on a Pentium 4, 3.0 GHz PC with 1Gb of RAM.

3. RESULTS

The output example in Figure 2 satisfies a 20% representation target of each dataset. The model also includes the three weighting layers combined using equal weights of 0.33. The optimal set of planning units selected under a pre-defined conservation target is the most efficient set for biodiversity conservation and are of optimal design. Under this solution, 20% of the area of each class of data within each surrogate dataset is identified with maximum efficiency. These could become the core *Restricted Access Zone* zones that offer the highest level of species and habitat protection within the MPA (Figure 2). The 20% target in Figure 2 is only arbitrary. It could be set at 5%, 35%, or any other conservation target as determined by the conservation goals of the State Government.

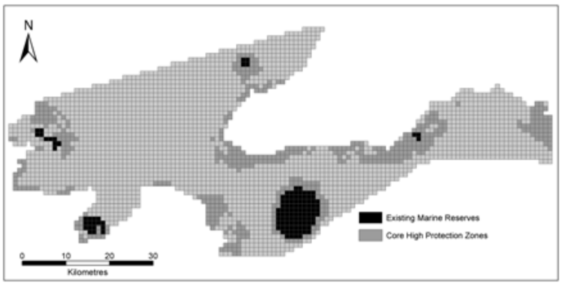

Figure 2. Identifying core high protection zones for marine biodiversity conservation – 20% conservation target and three weighting layers.

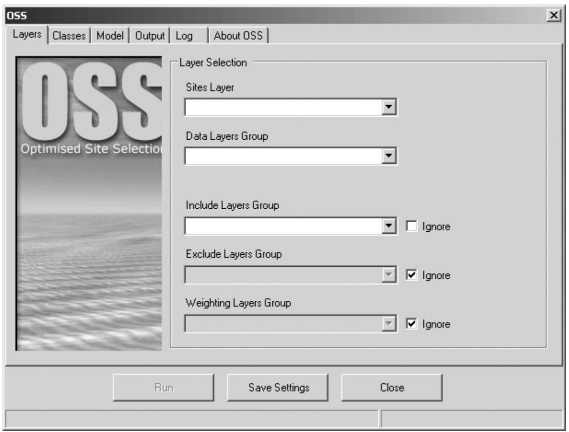

Figure 3: OSS user interface available from an *ESRI ArcMap 9.0* document.

Figure 3 presents the user interface for our spatial decision support system, OSS. The user interface of OSS can be accessed through a toolbar button and comprises a series of input modules. Fields are quick and easy to populate and in many cases are read directly from an *ArcGIS* map document *Table of Contents*. Solutions were found in less than 1 minute when using datasets in this paper. This includes all pre-processing, solving of the integer programming model, and returning a solution to the GIS. The value of OSS lies in the high level of interactivity with the GIS. Spatial layers in the GIS can be instantly modified by the user and input into OSS.

4. DISCUSSION AND CONCLUSION

The integer programming optimisation models implemented in this study were successful in finding efficient and representative combinations of planning units for protection given the specified parameters. OSS facilitated and simplified the modelling procedure by providing a user-friendly interface to find optimal solutions. Our methodology can be applied across any study area and any scale to solve user-selected optimisation constraints for MPA design.

OSS has other advantages on top of the increased simplicity and speed for finding solutions, namely repeatability and interactivity. The views of other decision makers beyond the researcher and GIS user can be easily incorporated. The GIS-user can use the GIS to make any changes to the input data and repeat the modelling as often as they like, recording the effect on solutions as they go. For example, new data layers can be included or existing layers excluded, specific planning units can be explicitly included or excluded, dataset class boundaries can be redefined, new weighting layers can developed that meet the goals of the MPA planner, and weighting layer weights can be adjusted. Any conservation target can be entered into OSS and solutions instantly examined. Outputs from a previous model run, such as those in figure 2, can be included as an additional constraint that is then built on to by new solutions. The expanded solutions are also maximally efficient representations of habitat and meet the constraints and goals defined by the MPA planner.

The State Government of South Australia is investigating methods that may enhance the MPA design process. They consider that the selection of priority planning units for dedicated conservation and high-level protection is a critical intermediate step in zoning a MPA. These priority units would be best identified using a community consultation approach in conjunction with modelling. The automated modelling processes we present rapidly generates alternative arrangements of planning units based upon differing criteria, thereby providing additional material for discussion between decision-makers and community representatives. However, if these models are to be effective, they must be able to be constrained by specific conservation targets. OSS includes features that allow such constraints to be applied, and uses an analytical model that guarantees fast and optimal solutions. The use of GIS and spatial optimisation is therefore of value to the State Government and can be used in conjunction with traditional methods to aid the process of MPA selection and zoning.

We recommend that future community consultation, whether it is through the formal *Marine Advisory Committee* or *MPA Consultative Committee*, or through more *ad hoc* and open public/community meetings, provide the opportunity for audiences to contribute directly to MPA design. A potential approach would be to take a laptop loaded with OSS, *ArcGIS* and *CPLEX* into these community forums and produce on-the-fly optimal solutions that meet conservation targets as well opportunity for instant public participation. It is more likely that conflicts will be minimised and negotiation hastened for a better MPA zoning outcome for all.

5. ACKNOWLEDGEMENTS

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