Lewis A, Slegers S, Lowe D, Muller L, Fernandes L, Day J. Use of Spatial Analysis and GIS techniques to Re-Zone the Great Barrier Reef Marine Park. *Coastal GIS Workshop*, July 7-8 2003, University of Wollongong, Australia.

Use of Spatial Analysis and GIS techniques to Re-Zone the Great Barrier Reef Marine Park.

Adam Lewis[1]*, Suzanne Slegers[1], Dave Lowe[1], Leath Muller[1], Leanne Fernandes[1], Jon Day[1]

[1]Great Barrier Reef Marine Park Authority, Townsville, Australia. *
***contact author: a.lewis@gbrmpa.gov.au**

Abstract

Coastal GIS Workshop, July 7-8 2003, Wollongong

On June 2, 2003 a Draft Zoning Plan for the Great Barrier Reef Marine Park was released for public comment. The Draft Zoning Plan (DZP) proposes important increases in marine sanctuaries (no-take zones) to better protect biodiversity within the Great Barrier Reef. The DZP is the culmination of more than 3 years work, incorporating biophysical, economic and social information. Development of the DZP, the accompanying map series, and the schedules describing the proposed new zone boundaries, have been critically dependent on spatial analysis and GIS, which have assisted the Great Barrier Reef Marine Park Authority (GBRMPA) to: incorporate thousands of map-based submissions into an analytical process; progress seamlessly from computer-based reserve selection tools (based on best available data) to human decision-making (based on informal knowledge); progress from final DZP boundaries to publication-quality maps in a matter of weeks; and to rapidly generate detailed legal boundary descriptions directly from GIS datasets. Finally, we have used GIS methods to demonstrate to key stakeholder groups the transparency and objectivity of the process, and that biophysical and social/economic principles publicly stated prior to the development of the DZP have indeed guided the outcome.

Introduction

The Great Barrier Reef Marine Park (the Marine Park) and World Heritage Area extends nearly 2000 km along the Australia's north-eastern coast. It includes roughly 2900 individual reefs, and other habitats ranging from shallow, muddy in-shore waters, to submerged reefs, steep continental slopes and waters 3000m deep. The Marine Park, declared in

1975, now covers 345,400 km^2, an area exactly five times the size of Tasmania.

The Great Barrier Reef Marine Park Authority (GBRMPA) uses a system of zoning to moderate use of the Park. Although the entire Park is a marine protected area, different zones provide different levels of protection, and it is the no-take zones (locally known as green zones) which prohibit take, and which essentially represent 'marine sanctuaries' within the Marine Park. Currently only 4.5% of the Marine Park is in no-take zones protected from all types of extractive activities including commercial and recreational fishing/collecting.

One of the issues facing the Marine Park is the need to better protect biodiversity. To address this the GBRMPA developed the Representative Areas Programme, or RAP (Day et al. 2002, Day et al., in press). Since 1999 the GBRMPA has developed a proposal, in the form of a Draft Zoning Plan (DZP) to increase the network of green zones in the Marine Park. The DZP was released for public comment on 2 June 2003.

RAP has aimed to develop a comprehensive, adequate and representative network of marine protected areas for the Marine Park. This has included mapping of biodiversity into 70 bioregions, extensive use of external expertise, development of biophysical, and social, economic and cultural, principles to guide the process, informal consultation with key informants, and formal consultation as required under law. In the first stage of formal consultation an unprecedented 10,190 submissions were received, including thousands of maps (Day et al. in press).

This paper describes some of the ways in which GIS and spatial analysis methods have been critical to the RAP process so far. These include a GIS-infrastructure to support the use of reserve design software, processing of thousands of map-based submissions, a seamless progression from computer-based reserve selection tools (based on best available data) to human decision-making (based on expert knowledge), publication of maps and legal boundary descriptions directly from GIS datasets, and communication with key stakeholder groups.

The re-zoning problem

The Representative Areas approach is largely defined by the need to include examples of all 70 bioregions (figure 1) in a network of green zones, so that at least 20%, of each bioregion is included, and in several parts. See Day et al. (2002) for the complete set of biophysical principles advised by the Scientific Steering Committee for the RAP. In essence, this is a spatial reserve design problem. However, in addition to the biophysical principles the RAP problem is guided by a set of social/economic/cultural/management (SEC) principles (Day et al. 2002). These specify that, as far as possible, impacts on current users should be minimised, the approach should be equitable, and the resulting Zoning Plan should be practical for users and managers.

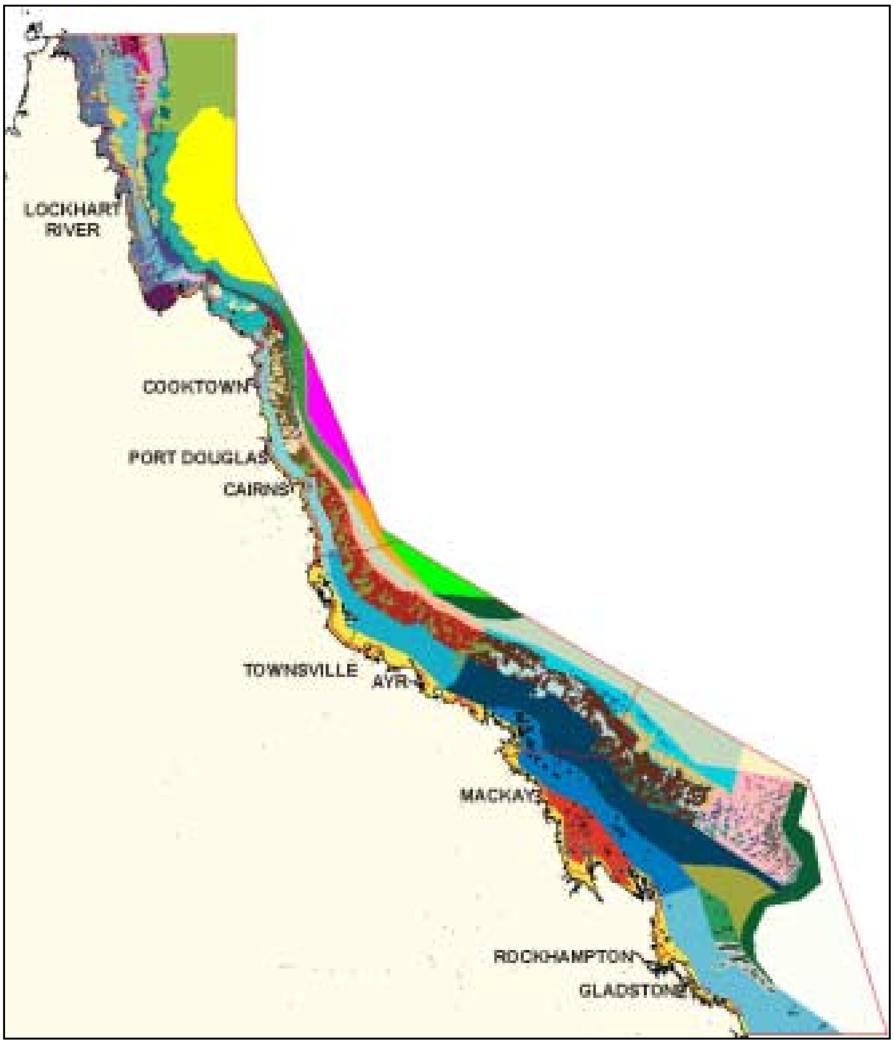


Figure 1. Bioregions of the Great Barrier Reef Marine Park and World Heritage area. 30 reef bioregions and 40 non-reef bioregions are identified, reflecting variations in the biological and physical environments within the Marine Park. Changes in depth, water quality, substrate type, tidal range, wave energy, and latitude are some of the characteristics that are clearly reflected in the pattern of the bioregions.

In 2000 the GBRMPA chose the SpExAn (Spatially Explicit Annealing) reserve design software as its preferred reserve selection tool (RST), with modifications to the software to more directly reflect the detail of the biophysical principles. These modifications gave rise to MarXan (Ball and Possingham 2000). MarXan was chosen for its perceived ability to quickly find near-optimal solutions (Pressey et al., 1996).

MarXan includes several algorithms for reserve selection but primarily uses simulated annealing – a randomisation method that seeks a minimum value of an objective function. The objective function is formulated to represent the reserve selection problem. In the taxonomy of reserve selection methods, MarXan falls somewhere between the full optimisation offered by integer linear programming and the stepwise progress toward a sound result offered by spatially explicit heuristic algorithms (eg., Lewis et al. 1994, Walmsely et al. 1999). The limitations and advantages of heuristics are argued by Underhill (1994) and Pressey et al. (1996).

The RAP team also considered, and pursued to some extent, three alternatives to MarXan: manual identification of green zones; interactive building of a network of green zones using ReST (Reserve Selection Tool, Taplin 2000, pers. comm.) and; TRADER, a method based on randomisation combined with multivariate regression trees (De'ath 2002, pers. comm.). Alternatives were considered important for several reasons, including risk management, performance of MarXan when the complexity of the objective function was increased, and the likelihood that, at some stage, 'human' choices must be facilitated.

The RAP problem is computationally complex. If the Marine Park is divided into small 'planning units' (ours averaged 2000 hectares) then a selection of roughly 20% can be achieved in something like 10^{1000} ways. This is an unthinkable number of possibilities, the full range of which could never be explored by any computer. For a problem of this size processing times can be limiting, even with efficient near-optimal methods such as simulated annealing.

The MarXan algorithm

MarXan attempts to find the lowest value of an objective function by exploring different configurations for the network. Typically, the algorithm starts with nothing and adds sites until a specified set of conservation objectives are met. The choice of which site to add is random, but poor choices can be rejected. Sites can also be dropped, so bad choices can be rejected later. As the algorithm proceeds, there is an increasingly strong incentive to accept only good choices. 'Good' and ‘bad’ are defined by the objective function, which will either increase (bad), or decrease (good) with each choice.

The objective function is given as:

$$OF(t) = BLM \times Boundary(t) + \sum \left(Penalty[i] \right) + Cost(t)$$

where

t is time, as the algorithm progresses

BLM is a constant reflecting the importance of the boundary

$Boundary(t)$ is the length of the outer boundary of the selected sites at time t

$Penalty[i]$ is the penalty, for conservation objective i at time t.

This will be zero when the required amount of feature i is included in the network

$Cost(t)$ is the 'cost' value of all the sites included in the network at time t

(Ball and Possingham, 2000)

The objective function will reach a minimum when the necessary amounts of all conservation features are included in a small, compact, network of sites. Although the algorithm seeks the lowest value of the objective function (the optimum), in practice near-optimum values are found, and repeated runs on the same problem will generate a scatter of solutions, each of which is near-optimum.

An analytical, GIS, framework for applied reserve design

The focus of conservation biology regarding reserve selection tends to be the choice of algorithm or software used in a particular case, or the merits of one approach over another in general – optimisation versus heuristics, richness versus rarity. We found that there are other important practical issues including the need:

- to revise data constantly – new data on commercial fisheries were received only shortly ahead of important deadlines;
- to constantly include new issues – the best analytical approach to dugong habitat was not decided until late in the process;
- to be independent of the reserve selection algorithm used – allowing humans to make decisions if necessary; and
- to structure the data to represent the problem – spatial relationships such as adjacency to terrestrial conservation reserves can only be considered if the spatial database is designed appropriately.

Ultimately, given these other needs, the reserve selection software was a small part of a complex GIS-based analytical framework.

The spatial analysis and GIS framework therefore consisted of processes to:

- Build planning units for the reserve selection tool;
- Store and maintain source data and meta-data;
- Process community submissions / maps into spatial data;
- Prepare inputs for MarXan, call MarXan, and convert outputs to GIS datasets;
- Progress smoothly from analytical reserve design to human decision-making;
- implement simple, coordinate-based, boundaries;
- report on the success of the selected reserve in meeting objectives;
- produce maps for publication;
- produce legal descriptions from GIS datasets; and
- communicate the process to interested parties.

These steps, and some of the issues confronted, are described below. Although MarXan was not the only reserve selection tool we applied (see above) it was the primary tool and its data requirements and terminology are sufficiently generic for this paper to use them henceforth.

Building planning units

Planning units are a way of dividing up the area of interest into small units that can be added together to build a reserve. It is common to use regular grid cells or hexagons to generate planning units, however it is also logical for these units to reflect the spatial scale of management, existing administrative boundaries, and physical boundaries that are also logical management boundaries, for example Lewis et al. (1991, 1993), working in Tasmania, used catchments and sub-catchment boundaries. Smaller planning units allow a more detailed representation, and may facilitate more optimal solutions at the cost of increased execution time – smaller units means more units. For the Marine Park problem we developed a complex hybrid of all of these considerations. We used large hexagons ($30km^2$) in off shore areas where the spatial scales of environmental change are broad, and where there are no reefs. We used smaller hexagons ($10km^2$) closer to the coastline in non-reef areas. In reef areas we used reefs, and the areas around reefs. We also used the existing zone boundaries, the boundary of the Marine Park, the coastline and, in some places, bioregion boundaries (Figure 1). For rigour, repeatability and as a record of process, the planning units dataset was built using AML procedures in ArcInfo, including routines that generated hexagon meshes, used Theissen polygon analysis to find mid-lines between reefs, ran overlays and applied simplification rules.

Planning units are often regarded as a static input to the reserve design process, in which case repeatability is not important. However during the course of the RAP we revised the planning units several times for a range of reasons, including changes to the boundary of the Great Barrier Reef Marine Park itself. Furthermore, we found it useful to constrain MarXan by running solutions on larger planning units, and feeding the results into progressively smaller units. To facilitate this we developed a quadtree indexing system on planning units to allow rapid aggregation to larger units in a spatially-nested hierarchy.

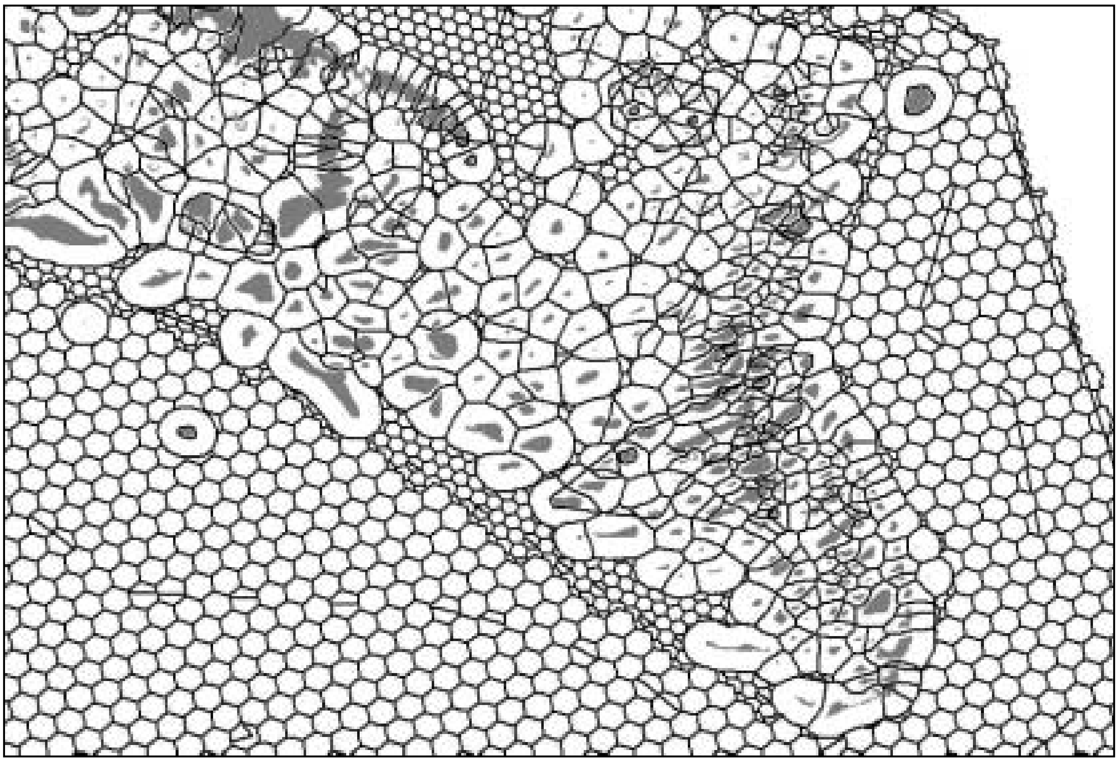


Figure 2. Over 17,000 'planning units' were developed for the reserve design process. Boundaries consist of hexagons, mid-lines between reefs, off-sets from reef edges, administrative boundaries and bioregion boundaries. A series of AML programs derived the planning units from source datasets. We used a spatial index to aggregate to larger units when necessary. The length of the side of the larger hexagons is 3 kilometres. The example is from the Swain Reef area, in the south east of the Marine Park.

Storage, maintenance and transformation of source data

The RAP drew on a large number of datasets. We used ArcInfo coverage formats to represent data, and data administration processes to manage updates and revisions.

Spatial analyses were generally necessary to manipulate raw data into information more directly relevant to the RAP problem. For example, boat ramp data were processed into a density surface extending 20km from the nearest boat ramp. The integral of the surface within each planning unit became the value of ‘boat ramps’ within the planning unit. (For interpretation, this relative value could be approximately related to the distance to the nearest boatramps.) The density surface was produced using ArcInfo GRID through repeated application of a filtering kernel, using a 1 km grid resolution. The analysis ensured that planning units were ‘aware’ of any boat ramps within 20km, rather than just the boatramps that fell within the planning unit. Indeed, as many boatramps fall outside of but immediately adjacent to the Marine Park, the latter approach would have failed to represent the information correctly.

Commercial fisheries data, a critical input to the RAP, also required careful pre-processing. These data are reported in commercial fisher’s log-books on a daily basis, and keyed to a database by the Queensland Fisheries Service. Following discussions with officers of the Queensland Fisheries Service and other sources of expertise on each commercial fishery, in particular Dr. Bruce Mapstone of the Cooperative Research Centre for the Great Barrier Reef, we processed the commercial fishing log-book data through three generic steps:

1. Aggregation of several years of data to ensure that the outputs were not skewed by short-term changes in patterns of reporting, management, or fishing behaviour driven by market or natural forces. In general, data were aggregated over all years for which there was reliable reporting.
2. A choice of units to represent the fishery, in practice either Gross Value of Product in standardised dollars, or days of fishing effort.
3. Spatial allocation. While commercial fishers report on grid cells of 6 or 30 minutes (6 minutes is roughly 11 kilometers or 6 nautical miles) for some fisheries it is possible to spatially refine data by assuming that the fishing activity does not occur either where it is not permitted nor where the physical environment is unsuited. Thus trawling effort was

allocated to areas other than reefs, and line fishing catch value was allocated, where possible, to reefs.

Figure 3 illustrates fishing data after processing.

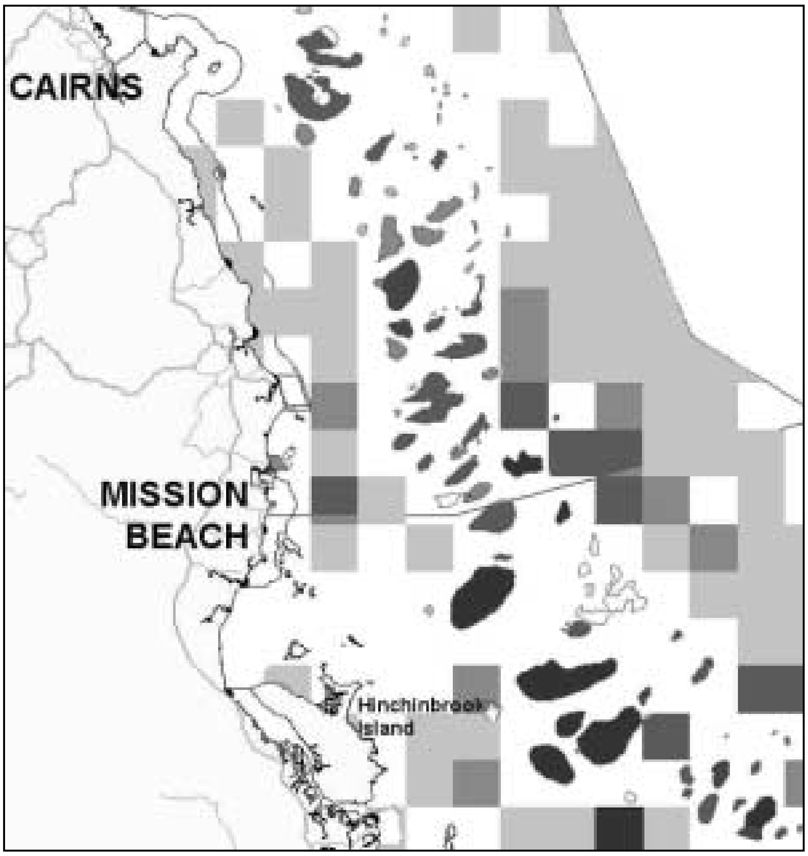


Figure 3. The estimated distribution of fishing value between Cairns and Hinchinbrook Island. Darker colours represent increasing gross value of product, averaged over all reports from 1996 to 2001. Data are reported on 6 minute grid cells, but, where possible, are allocated to reefs according to the estimated length of reef perimeter within the grid. No value is allocated to reefs that are already closed to the industry. Different analysis methods were needed for each major fishery; in each case the analysis was designed to best represent the fishery.

Processing community maps into spatial data

Over 10,000 submissions were received during the first formal community participation stage of the RAP (which ended in August 2002). During the consultation GBRMPA provided standard maps (1:250,000 scale) on which participants were encouraged to indicate their preferred locations for highly protected areas. Several thousand maps resulted. These were automated by laying a transparent film over each map and noting, from the overlay film, those spatial units referred to in the map. These numbers were then keyed into the submissions database using standard data entry methods, and linked to the remainder of the submission. Highly detailed maps, with clear and specific boundaries, were digitised.

Producing input files for the MarXan

The data inputs for MarXan, the main reserve selection tool, are simple and reasonably generic (Table 1). They consist of a *targets* file, which specifies how much (regardless of units) of each ‘conservation feature’ or ‘species’ is sought in the reserve network; a *planning units* file, which specifies the ‘cost’ should a particular planning unit be selected and the availability of that planning unit for selection (its ‘status’); an *amounts* file, which details how much of each conservation feature is to be found in each planning unit; and a *boundary* file. The boundary file specifies the adjacency of planning units, and the ‘length’ of the boundary between any two adjacent units. For more detail see Ball and Possingham (2000).

Table 1a. Part of a ‘targets’ file for MarXan. Columns indicate a unique identifier for the ‘conservation feature’, a text label, the relative importance of reaching the target, and the actual target. In this case the labels refer to Bioregions, and the target value is 20% of the bioregion area, expressed in km^{2}m. Our complete targets file had 370 entries drawn from several datasets. Other ‘targets’ are also possible (Ball and Possingham 2000).

id	name	spf	target
48	'NA1'	5	450
49	'NA3A'	5	2599.5
46	'NA3B'	5	900
47	'NA4'	5	1888.2
52	'NB1'	5	2657.55
53	'NB3'	5	2214.15
..	..	..	..

Table 1b . Part of a ‘planning units’ file for MarXan. Columns indicate the planning unit number (the number reflects our quad-tree indexing system referred to in the text), the availability of the planning unit for selection during the process (0 = available, 1 = selected already, 2 = selected and must remain selected, 3 = cannot be selected) and the ‘cost’ incurred should the unit be selected. Our complete planning units file had 17,858 records.

id	status	cost
1010103	3	19.080174
1010110	3	16.490159
1010111	3	14.860650
1010112	0	63.118766
1010113	0	77.171795
1010121	3	4.035053
1010130	1	55.939535
1010131	1	95.776667

Table 1c . Part of an ‘amounts’ file for MarXan. Columns indicate the ‘conservation feature id’ (matches the id column in Table 1a), the planning unit number (matches the number in Table 1b), and the amount of the conservation feature to be found within the planning unit. In this case, 61.99 km^2 of bioregion ‘NA4’ is found in planning unit 1212212. Our complete amounts file, which had 67,135 entries, was generated through a series of spatial overlays.

species	pu	amount
47	1212212	61.998476
47	1212213	60.294226
47	1212230	65.530962
47	1212231	1.943146
47	1212300	69.884150
47	1212301	58.423905
47	1212302	18.947580
47	1212310	6.147783
48	2223113	13.424997
48	2232020	17.785773
48	2232022	17.075131
48	2232023	0.447442
48	2232201	12.506497
48	2232203	4.915908

Table 1d . Part of a ‘boundary’ file for MarXan. Columns indicate the left and right planning unit numbers (matches the column in Table 1b), and the ‘length’ of the shared boundary between this pair. Our complete boundary file, produced through a series of spatial analysis operations, contained 50,216 records.

id1	id2	boundary
1010103	1010103	14000
1010110	1010110	10994
1010111	1010111	15230
1010121	1010121	4000
1010130	1010130	5999
1010132	1010132	13981
1010233	1010233	16000
1010303	1010303	5999
1010310	1010310	11999

Each MarXan input file is conceptually simple and is prepared as an ASCII list (Table 1). However, the logical relationships between the files are all important, and changes to the files are necessary when the parameters defining the problem change. For instance:

- Introducing a new conservation issue,
- Deciding how the current zoning should be used (should the new network be built on existing green zones?) , and
- Changing the emphasis on adjacent land use (the importance of terrestrial National Parks, or port areas).

In the RAP analysis we considered over 370 conservation features, represented by roughly 20 distinct spatial datasets. Social and economic considerations, such as boatramps and commercial fishing values, were represented by another 30 datasets. Anticipating that data would be revised during the RAP process as more up-to-date advice or information became available, we developed procedures using the ESRI Arc Macro Language (AML) to generate the input files for MarXan from source GIS datasets. This involved well over 20 distinct programs and many thousands of lines of AML code. However, given the number of distinct steps to produce the MarXan input files, human error is almost inevitable if the process is not automated. With a problem of the scale of the Great Barrier Reef, errors in the input files are difficult to detect, and could lead either to failure of the process, or to undetected errors in results. Our investment in AML programming was thus fully justified.

Calling the reserve selection tool

The MarXan reserve selection tool reads a command file of parameters at execution time, including data file names and paths for that ‘run’. Rather than run MarXan interactively we used AML routines to produce the command file and to call MarXan. This allowed us to fully track each run by consistently generating a new date-stamped directory for the inputs to and products from each run. All data and program components required to repeat the process were included in this directory, giving an important element of reliability and repeatability.

We also found it valuable to constrain the MarXan process spatially, by solving the selection problem firstly at broad scales, and then at increasingly fine scales (Figure 4). Effectively MarXan was run several times for each result, with slightly different inputs each time. Automating the MarXan calls within a GIS environment allowed the necessary spatial pre-processing without additional user-input. These processes also automated the conversion of MarXan results into GIS datasets for further display and analysis.

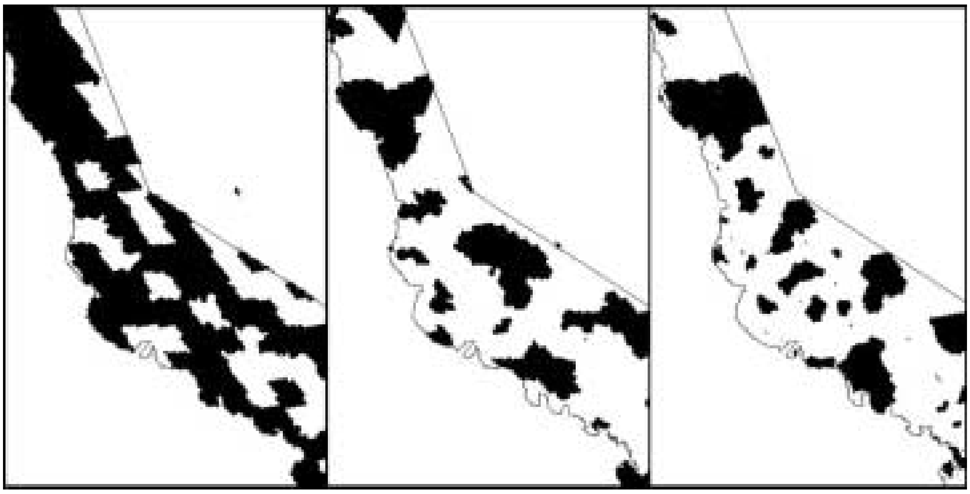


Figure 4. Progressive, spatially constrained MarXan solutions. The MarXan reserve selection tool produces a solution at a broad scale (left). This solution becomes the input for the next finest resolution (middle), which in turn is the start point for the finest resolution (right). A substantial GIS infrastructure is necessary to use MarXan in this way, as input files and annealing parameters must be generated in real time. The example shown is one of a myriad of possible solutions and bears no relationship to the DZP.

Progressing from analytical reserve design to human decision-making, and simple, coordinate-based boundaries

A major achievement for the GIS approach was the smooth progression from automated reserve-design to human decision making (Figure 5). Once the most up-to-date and reliable spatial data were included in the reserve selection process we progressed rapidly to solutions that, on the basis of this ‘formal’ knowledge, appeared to be sound. A series of analytical planning meetings was then used to gather and include expertise and ‘informal’ corporate knowledge. This knowledge was typically revealed in response to each proposed marine sanctuary, rather than as ‘data’. The continuity from automated reserve-design to expert-guided choices ensured that the most was made of both formal data and expert knowledge.

The analytical planning meetings used ArcView to project the results of the ‘latest’ analysis onto a screen for consideration of the meeting. Participants represented the range of expertise available within the Marine Park Authority, including marine park planners with responsibility for reading and synthesising public submissions, fisheries specialists, conservation planners, tourism managers, and staff with responsibilities in enforcement, shipping management, water quality, indigenous liaison and policy development. Others brought specific knowledge acquired during the development of previous zoning plans, or specialist expertise including social scientists, researchers and resource information specialists.

At each meeting the results of the previous meeting were scanned in detail, moving consistently through the Marine Park. Proposals that gained general approval from the meeting were returned to the subsequent meeting. Conversely, proposals that were clear and unacceptable clashes with current uses and the expectations of local communities were removed. We encouraged the analytical process to take on board meeting recommendations firstly by adjusting the ‘cost’ of planning units – to make them more or less attractive to the selection process – and secondly by altering the status of the planning units to specify that certain units must be ‘in’ or ‘out’.

As the configuration of green zones stabilised we stopped using the reserve selection tool and began a process of revision that relied on human knowledge. We also implemented a process of boundary simplification to implement ‘coordinate-based boundaries’. This replaced the irregular boundaries formed by planning units, with straight-line boundaries that could be defined in terms of a relatively small set of coordinates. We were able to partially automate this process using an algorithm, developed by the first author, that built a partially convex hull around each polygon shape. However, within the time available we were not able to develop this to address the complex topology of multiple interlocking zone types. The conversion to coordinate-based zones was therefore completed in the ArcEdit environment using multiple resolution back-ground grids as ‘snap features’. In this final stage each coordinate was resolved to no more than two decimal places of a minute, with preference for coordinates consistent with commercial fishing reporting methods, and for north-south / east-west lines.

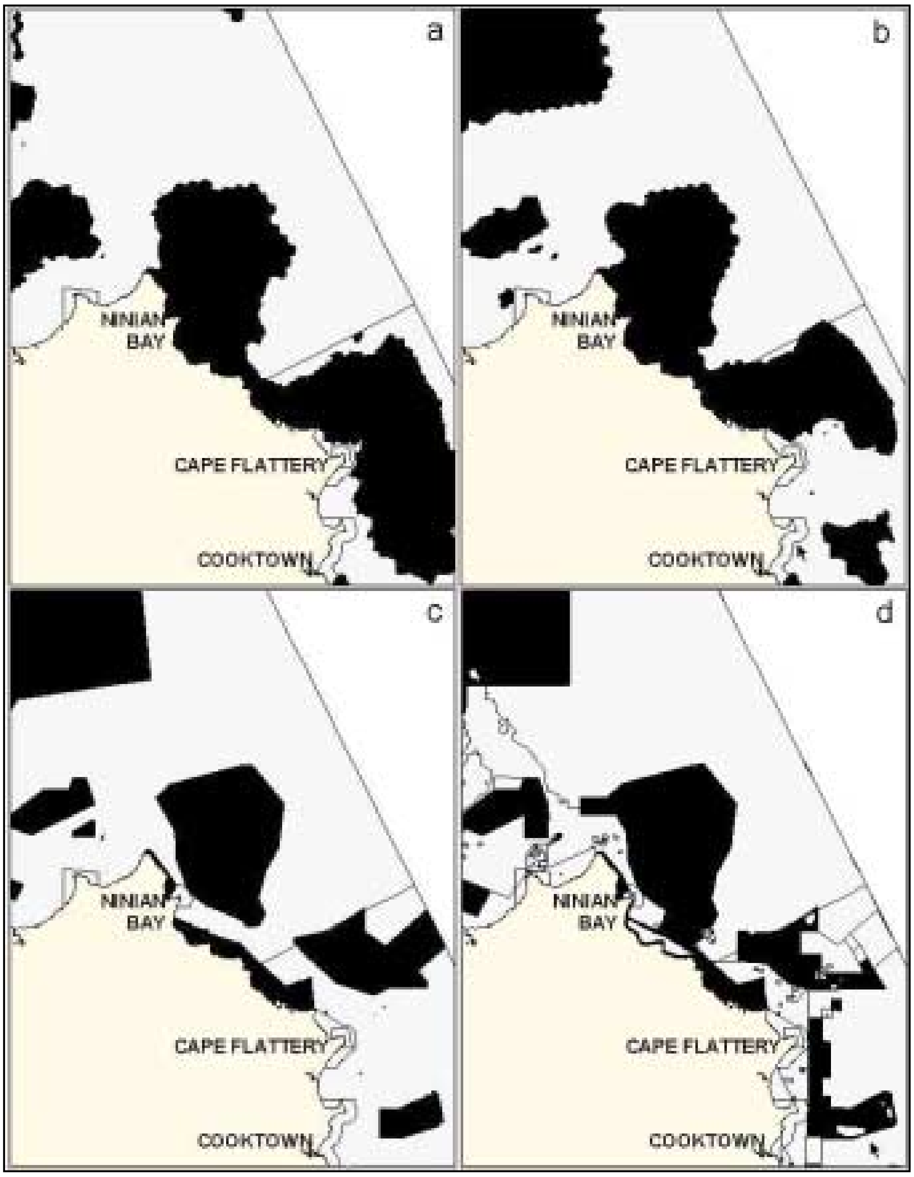


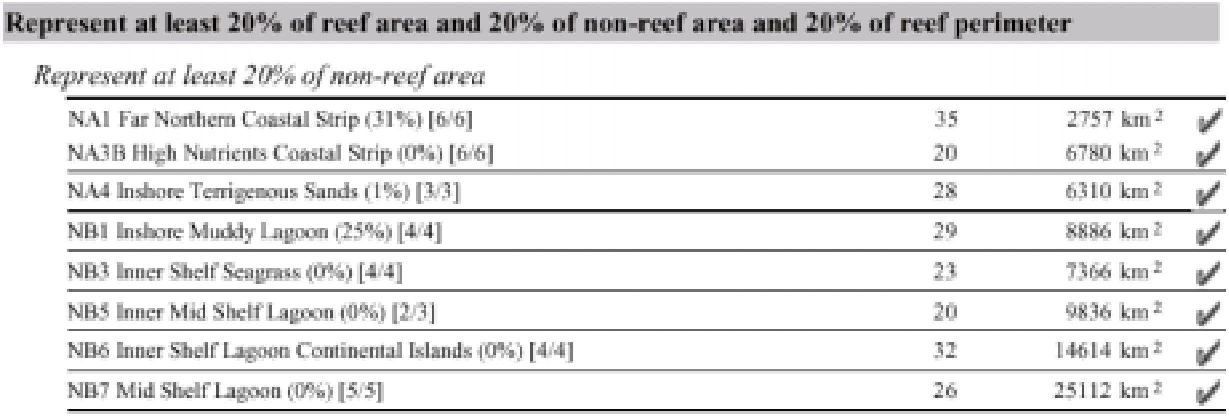
Figure 5. Progression from analytical results to DZP boundaries. Frames a and b are analytical results based on increasing amounts of formal information – frame b includes economic data as well as biophysical. In frame c, informal data including knowledge gained from public submissions has been included, and boundaries have been partially simplified. Frame d is the final draft green zones, with additional line-work showing the boundaries of other zone types in the DZP.

Reporting on the selected reserve

The MarXan reserve selection tool can report only on values used in the selection process, and only by planning unit. We anticipated that our needs would go beyond this, to report on information that was not part of the actual selection process, in formats other then those used in the analytical process, on modified boundaries produced by the coordinate conversion described above, and even on reserve network options generated independently, for instance by purely manual processes or independently by stakeholder groups, as happened with Cairns-based recreational fishers (Cairns Post, Thursday 19th June 2003).

To allow comprehensive and flexible reporting we developed a suite of overlay procedures to overlay each theme of information with any reserve network and produce summary tables. As before, these procedures were developed in AML, and the products were ArcInfo tables subsequently exported as .dbf files. The resulting information included the area, proportion and frequency of replication of each bioregion within the candidate network, and other statistics relevant to the biophysical principles underpinning the RAP.

To progress from the tables generated in the *post-hoc* overlays, to a cohesive and readable report in a standard format, we developed a Microsoft® Access database which imported and normalised the tabular data, and generated reports either for the candidate network as a whole, or for individual polygons within the candidate network (Figure 6). These reports were vital as the reserve design process moved from an automated to a manual process. While the reserve selection tool maintained fidelity to biophysical principles to ensure that conservation targets were met, and to other data to ensure that impacts were minimised across many user groups, manual adjustments were less omniscient. Accurate reports generated on a daily basis as the candidate network was revised ensured that critical targets were achieved.



Represent at least 20% of reef area and 20% of non-reef area and 20% of reef perimeter

Represent at least 20% of non-reef area

NA1 Far Northern Coastal Strip (31%) [6/6]	35	2757 km²	✓
NA3B High Nutrients Coastal Strip (0%) [6/6]	20	6780 km²	✓
NA4 Inshore Terrigenous Sands (1%) [3/3]	28	6310 km²	✓
NB1 Inshore Muddy Lagoon (25%) [4/4]	29	8886 km²	✓
NB3 Inner Shelf Seagrass (0%) [4/4]	23	7366 km²	✓
NB5 Inner Mid Shelf Lagoon (0%) [2/3]	20	9836 km²	✓
NB6 Inner Shelf Lagoon Continental Islands (0%) [4/4]	32	14614 km²	✓
NB7 Mid Shelf Lagoon (0%) [5/5]	26	25112 km²	✓

Figure 6. Part of a 'post-hoc' report on a candidate network of green zones, stating the extent to which biophysical objectives are achieved. The report includes the percentage of the bioregion currently protected (in brackets), the number of replicates within the bioregion [in square brackets], the percentage included in the candidate network, and the total area of the bioregion. These reports were independent of the method used to select the network and were not limited to the planning units or themes of information used in the reserve selection tool.

Maps for publication

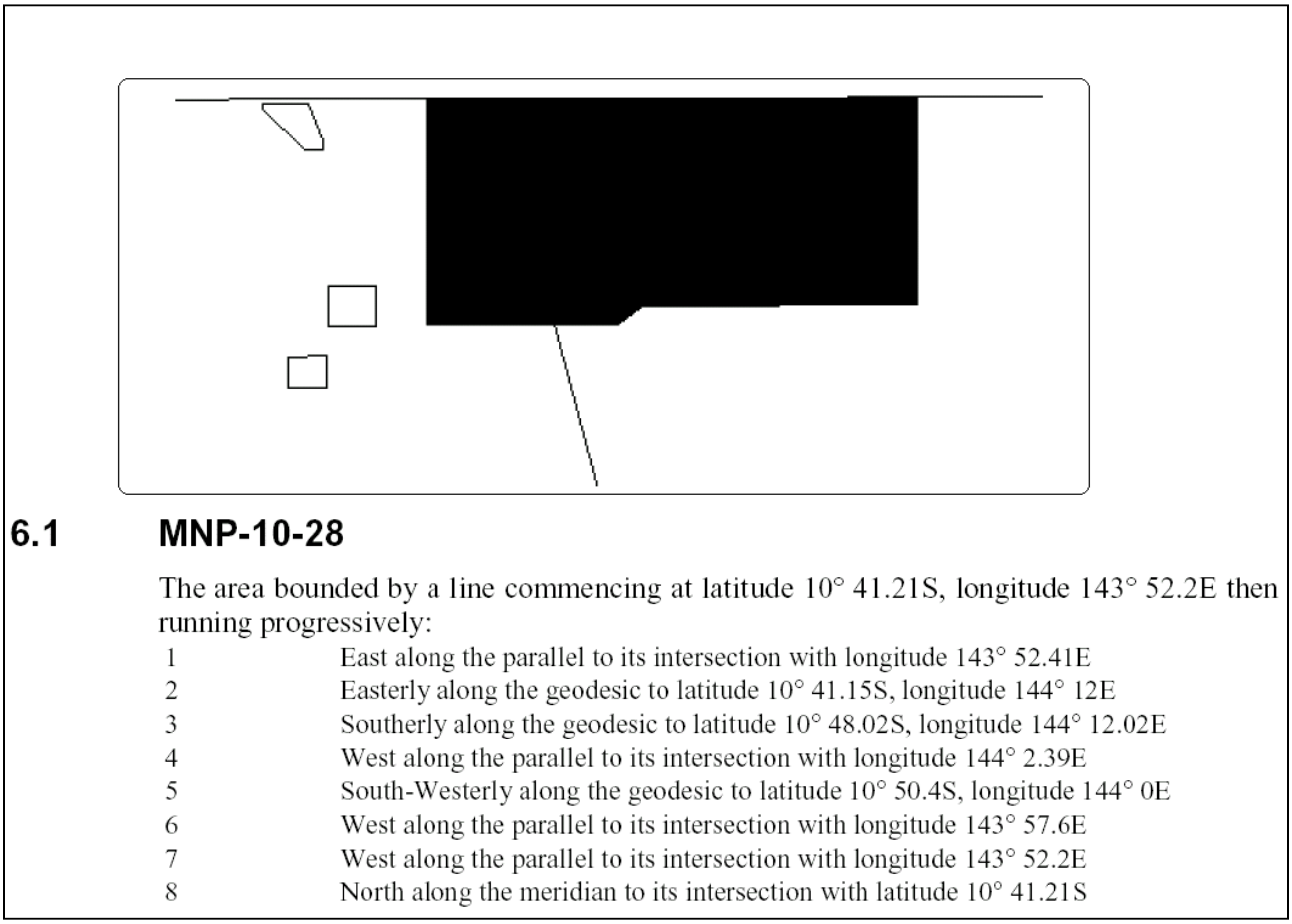
As the process of building boundaries of the DZP drew to a close, so too did the dead-lines for publication quality maps. All those who made submissions in the first formal community participation stage were to receive a copy of four 1:1,000,000 maps illustrating the boundaries of the DZP. Furthermore, a series of 18 1:250,000 ‘detailed’ maps was necessary for public information points such as libraries, community halls, council offices, boat and tackle shops, and dive shops. Eighteen working days were available between internal agreement on the draft boundaries for green zones, and publication deadlines.

To meet these deadlines we used previously developed AML programs for map production, modified to support the publication of the DZP. The use of AML to live-link source datasets to the map series ensured that the map depiction reflected the most recent data, and even very late changes in the Draft would be accurately reflected in the maps. (In contrast the map annotation, which was not linked to feature attributes, led to a number of errors). Publication was via “PDF” format files produced from encapsulated postscript files.

Legal boundary descriptions

Legal boundaries are defined very differently in the DZP compared to previous plans. In previous plans, boundaries defined in reference to geographical features, often using offsets from reef edges and the coastline to define notional lines such as a ‘reef 500 metre line’ (GBRMPA 2002). Because ‘the reef edge’ is itself uncertain, this has led to difficulty in enforcement of zone boundaries. The DZP, in contrast, defines boundaries as a series of coordinates, specified in degrees and decimal minutes, referenced to the GDA94 datum (ICSM 1999).

A boundary description based only on coordinates could not be developed manually without human error. Furthermore, there is no tolerance for error because the boundary description, not the map, is the legal definition of each boundary. To overcome this we automated the process and generated a boundary description schedule directly from the spatial features within the GIS coverage. As the GIS coverage lay at the root of both the maps and the schedule, we could be confident that the two were correct and consistent. Coordinate sequences were generated from features in the GIS dataset of the zoning using VBA programming in ArcMap.



6.1 MNP-10-28

The area bounded by a line commencing at latitude 10° 41.21S, longitude 143° 52.2E then running progressively:

1 East along the parallel to its intersection with longitude 143° 52.41E
2 Easterly along the geodesic to latitude 10° 41.15S, longitude 144° 12E
3 Southerly along the geodesic to latitude 10° 48.02S, longitude 144° 12.02E
4 West along the parallel to its intersection with longitude 144° 2.39E
5 South-Westerly along the geodesic to latitude 10° 50.4S, longitude 144° 0E
6 West along the parallel to its intersection with longitude 143° 57.6E
7 West along the parallel to its intersection with longitude 143° 52.2E
8 North along the meridian to its intersection with latitude 10° 41.21S

Figure 7. A polygon depicting a green zone and the automatically generated boundary description in the schedule of the DZP.

Communicating the process to interested parties

A major and unexpected contribution of GIS has been to communicate the process of developing the DZP. We used ArcView to progress through layers illustrating the environmental, economic and social datasets used in the process, and then through the evolution of the DZP boundaries. Projection of data onto a screen using ArcView enabled a variety of presentations to be given to a diverse range of audiences. The approach provided both a Marine Park perspective as well as being tailored to a specific areas and themes of interest. These presentations led to a high degree of acceptance of the planning process, and confidence that the process had been rigorous, had objectively followed the published principles, and had taken stakeholder interests into consideration. While in the past the GBRMPA has been criticised for a lack of maps and materials (Brisbane Courier Mail, Jan 27 2000), the

RAP process is setting new standards for transparency and communication in marine planning.

Discussion

The RAP program is at a larger scale than any previous zoning exercise on the Great Barrier Reef, covering the entire 345,400 km^2 of the Marine Park. It is inherently complex, being guided by biophysical principles and social/economic/cultural principles (Day et al. 2002), which implicitly require consideration of scores of datasets and hundreds of pieces of information. RAP is more ambitious than previous zoning exercises, including a minimum 20% of every bioregion in the Marine Park in a marine sanctuary. The level of public engagement and the number of submissions received in the first community participation stage alone dwarfed all previous planning exercises in the Marine Park.

The importance of the spatial analysis infrastructure can be considered in terms of quality, quantity and time. There is little doubt that the quality of information analysis leading to the DZP was massively increased through GIS (however it should also be noted that the interpretation and synthesis of the 10,190 written submissions was not, and could not, be achieved with GIS). Equally important, spatial analysis and GIS allowed us to rapidly and reliably manipulate multiple themes of information as inputs to and results from the ‘reserve selection’ process. This ensured that the reserve selection tool produced the best possible results, to provide a reliable starting point for the human, committee-based, revisions that led to the DZP. The process has been rigorous, objective, and transparent to a degree that communicates well to stakeholders.

The GIS/spatial analysis infrastructure has been vital to mesh analytical reserve design methods such as MarXan with the human expertise needed to reach a final draft plan. Although analytical methods have been essential in developing the DZP, they will not provide the final, pragmatic solution (Day et al. in press). ‘Fine-tuning’, using human expertise, knowledge and judgement plays a major role. Analytical reserve design methods allow many layers of data to be assessed against ecological criteria to generate hundreds of options (networks of ‘candidate’ areas). These provide an informed, impartial starting point for human decision making. A generic GIS and spatial analysis framework can cater for both analytical reserve design and human decision-making, allowing a smooth transition between these two important phases of the planning process.

Post-hoc accounting against defined biophysical objectives has been an invaluable part of the GIS approach, providing a clear and rapid assessment of proposals, whether computer or human generated.

For some tasks GIS and spatial analysis cut time-frames by an order of magnitude compared to previous methods. In the past, maps of zoning have been produced by manual methods using CAD software, with lead times of months and poor consistency between GIS datasets and published maps. In this process we cut the map production time to weeks with the map boundaries drawn directly form the GIS dataset of the Draft Zoning. We also produced the legal boundary descriptions directly from GIS datasets, completing an inherently slow and error-prone task in only days, with little opportunity for error.

Conclusion

GIS has so far been a vital component of the Great Barrier Reef Marine Park Authority's most recent and perhaps most important zoning exercise – the Representative Areas Program (RAP). Although the final plan remains to be developed following community consultation on the draft zoning plan (DZP), there is little doubt that the major role played by GIS has led to a higher quality draft, with more community support and less conflict with existing users, than would otherwise have been possible.

In this paper we have tried to give some coverage of the ubiquitous nature of the GIS contribution to the RAP DZP. We have found that while reserve selection tools such as MarXan can be invaluable, their effective use relies on a comprehensive system of spatial analysis to maintain, pre-process, and post-process spatial information. Furthermore, the role of GIS and spatial analysis extends to publication of maps and the production of legal boundary descriptions, and can reduce the time frames for these tasks from months to days.

While the final outcome of the RAP will not be dictated by the technical/analytical processes, these processes have underpinned the decision process, and have made the DZP more explicit and acceptable to all stakeholders. The detailed technical basis for the RAP has been a prudent investment in ensuring the technical acceptability of the overall RAP outcomes.

Acknowledgements

Many people have made vital contributions to the Representative Areas Program over several years. We would especially like to acknowledge the contributions of Glenn De'ath, Trevor Ward, Hugh Possingham, Ian Ball and Bruce Mapstone whose suggestions and input from time to time have helped to shape the analytical side of the project, and Lindsey Jones, Megan Liddlelow, Doug Morrison, Kerrie Sutton and Jeff Shearin who have contributed to the hands-on GIS work.

References

Ball, I. and Possingham H. P. (2000) MarXan (V1.2) Marine Reserve Design using Spatially Explicit Annealing, A manual prepared for the Great Barrier Reef Marine Park Authority. March, 2000. 63pp. Also available at www.uq.edu.au.

Day, J, Fernandes , L, Lewis, A, De'ath, G, Slegers, S, Barnett, B, Kerrigan, B, Breen, D, Innes, J, Oliver, J, Ward, T, Lowe, D. 2002. The Representative Areas Program for Protecting Biodiversity in the Great Barrier Reef World Heritage Area. *Proceedings of the Ninth International Coral Reef Symposium*, Bali, Indonesia, 2000

Day, J, Fernandes, L, Lewis, A, and Innes, J. In press. RAP – an ecosystem level approacy to biodiversity protection planning. *International Tropical Marine Ecosystems Management Symposium (ITMEMS)* Manila, Philipines, March 2003.

GBRMPA (2002). *Great Barrier Reef Marine Park Authority (Australia) Far northern section zoning plan*. Townsville.

ICSM: Intergovernmental Committee on Surveying and Mapping (1999). *Geocentric Datum of Australia Technical Manual* Version 2.0. Geosciences Australia, Canberra.

Lewis, A, Stein, J L, Stein, J A, Nix, H A, Mackey, B G, Bowyer, J K. (1991) *An assessment of regional conservation adequacy: Tasmania.* Report to the Resource Assessment Commission (Forests and Timber Inquiry).

Lewis, A, Stein, J L, Stein J A, Nix, H A, Mackey, B G. (1993) Environmental conservation: Developing and applying measures of spatial relationships in reserve network design procedures. *International Congress on Modelling and Simulation,* December 6-10 1993, University of Western Australia.

Pressey, R L, Possingham, H P, Margules CR. (1996) Optimality in reserve selection algorithms: when does it matter and how much? *Biological Conservation* **76** (1996) 259-267.

Underhill, L G 9 (1994) optimal and suboptimal reserve selection algorithms. *Biological Conservation* **70** 85-87

Walmsley A J, Walker D H, Mallawaarachchi T, Lewis, A. (1999) Integration of Spatial Land Use Allocation and Economic Optimisation Models for Decision Support. Pp 1075 – 1080 in Oxley, L and Scrimgeour, F (Eds), *Proceedings of the International Congress on Modelling and Simulation*, 6-9 December 1999, University of Waikato New Zealand. The Modelling and Simulation Society of Australia and New Zealand Inc. ISBN: 0-86422-948-8