Identifying high conservation value aquatic ecosystems in northern Australia

Edited by Mark J Kennard
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TRaCK
Tropical Rivers and Coastal Knowledge

Australian Government
Department of the Environment, Water, Heritage and the Arts
National Water Commission

TRaCK brings together leading tropical river researchers and managers from Charles Darwin University, Griffith University, the University of Western Australia, CSIRO, James Cook University, the Australian National University, Geoscience Australia, the Environmental Research Institute of the Supervising Scientist, the Australian Institute of Marine Science, the North Australia Indigenous Land and Sea Management Alliance, and the Governments of Queensland, the Northern Territory and Western Australia. TRaCK receives major funding for its research through the Australian Government's Commonwealth Environment Research Facilities initiative; the Australian Government's Raising National Water Standards Program; Land and Water Australia; the Fisheries Research and Development Corporation and the Queensland Government's Smart State Innovation Fund.

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Front cover – *Pseudomugil tenellus* (delicate blue-eye), an inhabitant of the well-vegetated margins of lowland floodplain lacustrine and palustrine waterbodies in northern Australia. Photo by Neil Armstrong.

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NSW Department of Natural Resources, NSW Department of Environment and Conservation, NSW Royal Botanic Gardens
NT Department of Natural Resources, Environment and The Arts
QLD Herbarium, Environmental Protection Agency.
SA Department for Environment and Heritage.
TAS Department of Primary Industries, Water and Environment
VIC Department of Sustainability and Environment
WA Department of Agriculture
Geoscience Australia, National Mapping Division
Bureau of Rural Sciences
National Land and Water Resources Audit

Glossary

Aquatic ecosystem	are those that depend on flows, or periodic or sustained inundation/waterlogging for their ecological integrity (e.g. wetlands, rivers, karst and other groundwater dependent ecosystems, saltmarshes and estuaries) but do not generally include marine waters (Aurichts, 2010). For the purposes of this project, the definition excludes artificial waterbodies such as sewage treatment ponds, canals and impoundments.
Aquatic ecosystem dependent species	are those that depend on aquatic ecosystems for a significant portion or critical stage of their lives or are are dependent on inundation for maintenance or regeneration
Attribute	mathematical or statistical indicator or characteristic calculated from the raw biodiversity surrogate data and used to 'score' or characterise the Framework Criteria (often referred to elsewhere as 'index' or 'metric')
Biodiversity	variation of life at all levels of biological organisation (molecular, genetic, species, and ecosystems) within a given area
Biodiversity surrogate	commonly used in conservation assessment and prioritisation to optimally represent multiple components of unmeasured biodiversity. Biodiversity surrogates include taxa (e.g. species), the characters they represent (e.g. phylogenetic relationships) assemblages or environmental classes. Environmental classes (ecotopes) are often used as biodiversity surrogates as different types of environments are assumed to support different combinations of species.
Complementarity	the gain in representation of biodiversity when an area is added to an existing set of areas
Ecotope	the smallest ecologically-distinct features in a landscape classification scheme (e.g. a 'type' of lacustrine hydrosystem). The draft Australian National Aquatic Ecosystem (ANAE) classification scheme (Auricht, 2010) now refers to ecotopes as 'habitats'.
Framework Criteria	narrative expressions that describe six core biophysical characteristics that have been agreed by the Aquatic Ecosystems Task Group as appropriate for the identification of HCVAEs (these include Diversity, Distinctiveness, Vital habitat, Evolutionary history, Naturalness and Representativeness). In this project each criterion was quantified ('scored') mathematically or statistically using attributes calculated from the raw biodiversity surrogate data.
HCVAE	High Conservtaion Value Aquatic Ecosystem
Hydrosystem	large 'organising entities' designed to represent the variety of aquatic ecosystem types (e.g. estuaries, rivers, lakes, palustrine wetlands). The draft Australian National Aquatic Ecosystem (ANAE) classification scheme (Auricht, 2010) now refers to hydrosystems as 'aquatic systems'.
Planning unit	the spatial unit (in this project a hydrologically defined subcatchment) at which the attributes and criteria for identifying HCVAE were applied.
Systematic conservation planning	a structured, step-wise and iterative approach to identifying priority areas for conservation management actions to best represent and sustain the biodiversity of regions in the most cost-effective way (often used synonymously with spatial conservation prioritization, etc). Most modern systematic planning approaches are based on the *CARE* principles: comprehensiveness, adequacy, representativeness and efficiency. Efficiency is usually provided by a complementarity-based strategy.

Executive summary

Aquatic ecosystems of tropical northern Australian host a unique and diverse range of water-dependent plants and animals occurring across a range of hydrologic, geomorphic and topographic settings. Many aquatic ecosystems in northern Australia can therefore be considered to be of high conservation value. The challenge for managers is to objectively identify those that should be the focus of strategic investments and actions to protect and enhance these values in an efficient manner. To meet these needs a systematic approach to the identification and management of High Conservation Value Aquatic Ecosystems or HCVAE is required. This approach should clearly appreciate the inherent differences between terrestrial and aquatic ecosystems and the respective methods available for defining and measuring conservation value. To this end, the Aquatic Ecosystem Task Group was formed to develop a framework to identify and classify HCVAEs.

This report describes the outcomes of a trial of the draft HCVAE Framework in aquatic ecosystems in northern Australia. The project is led by a team of researchers through the Tropical Rivers and Coastal Knowledge (TRaCK) Commonwealth Environmental Research Facility in collaboration with the Department of the Environment, Water, Heritage and the Arts (DEWHA). The specific aims of the project are to identify key aquatic ecological assets in northern Australia and trial the draft HCVAE Framework to identify high conservation value aquatic ecosystems. This involves:

1. Identifying, mapping and evaluating aquatic ecosystem characteristics in northern Australia based on the draft Australian National Aquatic Ecosystem (ANAE) classification scheme (Auricht, 2010)
2. developing a method to apply and assess the draft HCVAE criteria that is based on the best available science and knowledge
3. defining key knowledge gaps and making recommendations for further work to refine the draft HCVAE Framework

The project is being undertaken as part of the Northern Australia Water Futures Assessment (NAWFA). The NAWFA is an Australian Government initiative to provide the science needed for sustainable development and protection of northern Australia's water resources. The current project provides a broad-scale assessment of key aquatic ecological assets and identification of high conservation value aquatic ecosystems in tropical rivers of the northern Australia. This report focuses on aquatic ecosystems within Timor Sea and Gulf of Carpentaria drainage divisions (Chapter 2), though additional work is currently being conducted in the northern part of the North-East Coast drainage division. Further fine-scale assessments are currently being conducted in selected high priority focal areas of northern Australia to understand ecological thresholds in relation to flow regimes and maintenance of particular aquatic ecosystem assets in terms of key ecological values, connectivity and ecosystem services.

The current project involved a number of key steps we viewed as being essential to applying the ANAE scheme and comprehensively assessing the draft HCVAE Framework. These steps are briefly summarized below and presented in more detail in Chapter 3.

We first developed and validated a spatially consistent and comparable hydrosystem delineation and ecotope classification of aquatic assets for the northern Australia HCVAE trial area based on the draft Australian National Aquatic Ecosystem (ANAE) Classification Scheme. The mapped riverine, lacustrine and palustrine hydrosystems and associated ecotopes provided a rich source of ecohydrological and biodiversity surrogate information for northern Australia and the necessary context for the delineation of HCVAEs of the region (detailed in Chapter 4).

We also assembled a comprehensive database with spatially explicit information on species occurrences across northern Australia for a range of freshwater-dependent taxonomic groups (macroinvertebrates, freshwater fish, turtles and waterbirds). These species records were used as biodiversity surrogates for the conservation assessments (Chapter 5).

This project was tasked with assessing and reporting HCVAEs at regional scales defined *a-priori* by the reporting regions used in the Northern Australia Sustainable Yield (NASY) project and was conducted for two AWRC (1976) drainage divisions (Gulf of Carpentaria and Timor Sea). We viewed it as critical to test whether this spatial partitioning of the study area was at all concordant with the distribution of different aquatic faunal groups based on individual taxon (species or family) and phylogentically distinctive evolutionary units and so would provide the appropriate regional context for assessment of HCVAEs. The outcomes of these analyses are presented in Chapter 6.

Substantial spatial biases were found to exist in the availability of species distribution records (Chapter 5). The use of such patchy data to derive biodiversity attributes can have potentially major implications for accurate and objective identification and prioritization of high conservation value areas. To address this problem, in Chapter 7 we describe the development of predictive models of the distributions of macroinvertebrates, freshwater fish, turtles and waterbirds. These predictive models were successfully calibrated and considered appropriate for making predictions of species distributions in unsurveyed areas. Using predictive modelling and hydrosystem classifications, we were able to generated spatially explicit biodiversity surrgogate datasets for the entire study region. This information was attributed to 5,803 planning units (mean area 204 km^2) and used to assess their relative conservation values.

Implementing the draft HCVAE Framework involved an exhaustive process (described in Chapter 8) of selecting appropriate attributes to characterise the six Framework criteria (which are: Diversity, Distinctiveness, Vital habitat, Evolutionary history, Naturalness and Representativeness) and applying them to the seven sets of biodiversity surrogate data (three hydrosystems and four species groups). A total of 65 raw attributes were calculated from these data, itegrated into 22 attribute types that shared similar properties and these were integrated to characterise the six Framework criteria for each of the 5,803 planning units. In Chapter 8 we evaluated the extent of redundancy between attributes and performed sensitivity analyses (using seven different methods) to establish a robust method of scoring and integration of individual attributes to generate scores for each criterion.

Based on this method, we implemented the draft Framework to identify high conservation value aquatic ecosystems of northern Australia (Chapter 9). We trialled a variety of scoring thresholds to identify which subsets of planning units may qualify as being of high conservation value based on the criteria. Using the strictest threshold, we identified the set of planning units potentially containing HCVAEs for each of three reporting scales: (1) the entire study region (total of 275 planning units representing 6.9% of the total area), (2) each drainage division (total of 282 planning units representing 6.9% of the total area), and (3) each NASY region (total of 308 planning units representing 7.7% of the total area). These planning units are listed in Appendix 9.1, together with the individual criteria met, the total number of criteria met as well as the major named hydrosystems (riverine, lacustrine, palustrine and springs) occurring within each of these planning units.

To further evaluate the draft HCVAE Framework, we tested the efficiency of the criteria in representing the full complement of biodiversity surrogates (i.e. species or environmental types - the fundamental currency of conservation assessments). This is a key conservation goal that is not explicity addressed by the Framework criteria. We therefore also implemented a systematic conservation planning assessment (Chapter 10) where our goal was to efficiently select a minimum set of areas to represent the full range of biodiversity surrogates. In these analyses we evaluated the influence of various target levels of occurrence of species or environmental types, and explored different longitudinal and lateral connectivity rules that we hypothesed would be important considerations in the selection and spatial configuration of high conservation value areas. The conservation priority areas were then compared with those obtained using the Framework criteria to evaluate the relative efficiency of each approach. The adequacy of the current reserve system in representing freshwater biodiversity was also evaluated.

The outcomes of these alternative approaches to conservation assessments enabled us to objectively assess the merits and limitations of the draft Framework in objectively and efficiently identifying high conservation value aquatic ecosystems in northern Australia (Chapter 11).

It should be recognized that this project has been undertaken within a limited time frame and we have tested the Framework with readily available resources. Recommendations about northern Australian HCVAEs are therefore provisional but, none-the-less, form a significant starting point for identifying and characterising the HCVAEs of northern Australia and the ecologically sustainable management of the region.

RECOMMENDATIONS

This project had the opportunity to evaluate the draft ANAE scheme and trial the draft national HCVAE Framework in northern Australia. Based on the outcomes and lessons learned from each of the major steps undertaken in the project, we make 19 recommendations in five key themes that we think will help to refine the ANAE scheme and the HCVAE Framework and improve their future implementation in northern Australia and elsewhere. We also hope that the outcomes of our project contribute a significant step towards the goals of identifying and characterising the HCVAEs of northern Australia and the ecologically sustainable management of the region.

1. APPLYING THE DRAFT AUSTRALIAN NATIONAL AQUATIC ECOSYSTEM CLASSIFICATION SCHEME

1. The draft ANAE Classification Scheme (Auricht, 2010) describes different aquatic ecosystems and the attributes which could be used to define "habitat" types across Australia within an integrated regional and landscape setting. While the current version of the ANAE scheme provides some implementation guidelines further development is recommended. Ideally, the ANAE scheme should offer further guidance on choice of appropriate attributes, methods of measurement or derivation, applicable spatial and temporal scales and so on to ensure consistent application across jurisdictions.
2. We employed bottom-up (i.e. data-driven) ecotope classifications to generate environmental surrogates for biodiversity for the HCVAE assessment. We recommend this approach when consistent high quality datasets are available (rather than top-down classifications as described in the ANAE scheme.
3. Further development of the ANAE scheme will be required to ensure that all integral components of aquatic ecosystems are effectively recognized across spatial scales, perhaps as emergent properties (i.e. bottom-up classifications as employed in the preset study) of the currently separate classifications of hydrosystems.

2. IMPROVEMENTS TO AQUATIC ECOSYSTEM MAPPING

4. The draft ANAE scheme to delineate hydrosystems was successfully implemented for the northern Australia HCVAE trial area. However, time constraints of the project meant that further development of the Geodata Estuarine, Lacustrine and Palustrine hydrosystem delineation is required. Further delineation of the estuarine ecosystems could be undertaken by using existing mangrove mapping, and the location of barrages to delineate the transition zones between Estuarine and Riverine hydrosystems. Further validation of the Geodata derived hydrosystems (e.g. the Lacustrine hydrosystem) could be undertaken using existing hydrosystem delineation such as the Queensland Wetland Mapping and Classification data set.
5. Remotely sensed information on flood frequency, extent and duration, available for a number of catchments in northern Australia could be generalised and used to update the existing attribution of hydrosystem inundation frequency. With suitable resourcing, the remote sensing archive could be used to evaluate and update the hydrosystem perenniality attribute.

3. Improvements to Aquatic Biodiversity data

6. Fundamental knowledge of the distribution of many freshwater dependent flora and fauna is lacking for much of northern Australia. We considered but did not assemble datasets other water-dependent fauna (i.e. frogs, crocodiles, lizards, snakes, riparian birds) or aquatic, semi-aquatic and riparian flora due to resource and/or data constraints. Whilst this project assessed molecular-level, phylogeographic data for a selected number of taxa, there remain substantial sampling gaps (particularly in the Kimberley region) for these species and many other species. More extensive phylogeographic data sets (in terms of both completeness of spatial coverage and greater number of taxa) would be very useful in future efforts to delineate freshwater bioregions and would enable more rigorous assessments of molecular-level patterns of biodiversity at a range of spatial scales.
7. Improved knowledge of the macroinvertebrate biodiversity of subterranean systems, springs and off-channel floodplain habitats is required. Limited data meant that the conservation values of these hydrosystems were not assessed with respect to macroinvertebrate biodiversity, despite the high likelihood that such habitats are of conservation significance.
8. Future research efforts that apply molecular data to freshwater biodiversity assessments in northern Australia should consider within- and between- river basin scale patterns of genetic-level biodiversity. Landscape genetic approaches could be coupled with phylogeographic analyses to identify the key landscape features (e.g. flow regime, river structure, landscape topography) that subdivide populations of freshwater species, thereby providing key information about genetic connectivity (or isolation) among populations. This would enable molecular-level patterns of biodiversity to be considered at the planning unit scale and allow measures of population connectivity to be applied in conservation planning assessments.
9. We used predictive models of species distributions to mitigate the problem of incomplete sample coverages. Greater confidence in the outputs from the predictive models could be obtained by improving the model validation process using true presence/absence data for all faunal groups. A research priority should be to collect these data in the future. The use of multiple predictive modelling methods and generation of consensus predictions would allow better quantification of uncertainty in the extrapolation of species distributions for use as biodiversity surrogates in conservation assessments.

4. Identifying high conservation value areas using the draft HCVAE Framework

10. We feel that implementing the draft HCVAE Framework criteria goes some way to identifying areas that are of potentially high conservation value. However, greater clarity as to the purpose of the HCVAE identification may further increase the efficient investment of resources to manage these areas effectively. The Framework criteria are not specifically designed to identify which management options are most appropriate for a particular area and require further development in this regard.
11. The lack of clear objectives as to the purpose of the HCVAE identification meant that it was difficult to select a subset of the most import attributes to characterise the criteria. Instead there was the strong temptation to characterise each criterion in as many ways as possible. We recommend that this temptation be resisted. Our overall philosophy was to only apply attributes that could be calculated from the biodiversity surrogates datasets, rather than applying attributes based on other data which was of variable quality and spatial extent and that would therefore potentially yield large gaps and uncertainties in the outcomes of an HCVAE assessment.
12. The nature of the Framework (i.e. a multi-criteria scoring approach) means that the method combines potentially numerous individual attributes that by themselves can be (and often are) used to assess conservation value. However, the integration process ultimately means a potential loss of transparency, in that it is unclear how many attributes (and which ones) contribute greatly to the integrated score for each criterion. It is important however that this integrative approach remains fully transparent; that is, it must be clear how many and which attributes contribute most to the integrated score for each criterion.

13. It is unclear which components of biodiversity (the fundamental currency of conservation assessments). contribute most to the final rankings based on criterion scores. Although it is certainly possible to interrogate the underlying data and maps to understand why a particular area scored highly for a particular criterion or set of criteria, this is not a simple process. One solution to this issue is to greatly reduce the number of attributes used to characterise the Framework criteria to only a few key ones that are deemed by experts to be most important indicators of conservation value (though this is obviously not a simple task). We suggest that the use of more attributes does not necessarily provide a better or more interpretable conservation assessment. In fact, the converse appears to be true.
14. The draft HCVAE Framework states that an ecosystem meeting any one of the criteria could be considered an HCVAE, but that appropriate thresholds for nationally significant HCVAE are yet to be determined. It is unclear what threshold should be used to discriminate those planning units that "meet" each criterion (i.e. that their criterion score exceeds the threshold and therefore could be considered to be of high conservation value based on that criterion). The choice of threshold is a somewhat arbitrary decision, but can have potentially important consequences for identifying which and how many planning units are considered of high conservation value.
15. It is unclear whether some criteria should be considered more important than others for identifying HCVAEs and whether particular planning units that meet a greater number of criteria are concordantly of higher conservation value. We agree with the approach taken in the Lake Eyre Basin trial that the lack of a specified purpose, for the identification of HCVAE, means that the criteria be considered to be equally important. We assumed that conservation value increased with increasing number of criteria met (i.e. a planning unit that met all six criteria had a greater potential for containing an HCVAE than a planning unit that met only one criterion).

5. PROMOTING EFFICIENCY IN THE IDENTIFICATION AND MANAGEMENT OF HIGH CONSERVATION VALUE AREAS

16. A fundamental goal of conservation assessments should be to efficiently identify sets of areas that need to be managed to conserve species and the processes that sustain them. The draft HCVAE Framework may be limited in the extent to which it can efficiently contribute to this conservation goal and ideally will require complementary approaches such as systematic planning that specifically address biodiversity representation in a more efficient way.
17. There are some key challenges that, if addressed, would lead to greater objectivity in systematic conservation planning. The incorporation of uncertainties in the distribution of conservation features or the vulnerability to future change of candidate high conservation value areas (e.g. due to land use or climate change) would increase the ability to assess the resilience of these areas and the likelihood of long-term persistence of the conservation values that they contain. Setting scientifically defensible conservation targets (e.g. the number of populations or areas required to maintain species) would help improve the efficiency of the resilience of high conservation value areas to future changes.
18. Estimates of the socioeconomic costs of different conservation management actions (e.g. threat mitigation, restoration, stewardship, acquisition) should ideally be incorporated into the conservation assessment process. Here, the aim is to optimize the set of management actions and the places where they should be implemented, required to achieve biodiversity conservation goals with the minimum cost (or impact in local economies). This would provide the first step in developing a strategic, efficient and effective approach to identify high conservation value areas and guide on-the-ground management actions to conserve freshwater biodiversity.
19. Finally, we view the application of systematic planning as a tool to help in the decision making process in identifying high conservation value areas. The incorporation of expert and stakeholders' knowledge, needs and interests is a fundamental next step at achieving the implementation of an efficient and realistic conservation plan. This information should be seen as an additional tool to guide future decisions on conservation management rather than a rigid and strict conservation plan itself.

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IDENTIFYING HIGH CONSERVATION VALUE AQUATIC ECOSYSTEMS IN NORTHERN AUSTRALIA

TABLE OF CONTENTS

(Wayne Robinson & Mark Kennard)

1. INTRODUCTION

MARK KENNARD

1.1 BACKGROUND TO HCVAE FRAMEWORK

The National Water Initiative (NWI), an agreement between the Australian Government and all the States and Territories, is a comprehensive strategy to improve water management across the country. The NWI (clause 25x) states that there is a '*national imperative to ensure the health of river and groundwater systems*'. All States and Territories need to 'identify and acknowledge surface and groundwater systems of high conservation value, and manage these systems to protect and enhance those values'. To meet these needs a systematic approach to the identification and management of High Conservation Value Aquatic Ecosystems or HCVAE is required (e.g. Georges & Cottingham, 2002; Saunders et al., 2002; Kingsford et al., 2005; Fitzsimons & Robertson, 2005). This approach should clearly appreciate the inherent differences between terrestrial and aquatic ecosystems and the respective methods available for defining and measuring conservation value (Dunn, 2003, 2004). To this end, the Aquatic Ecosystem Task Group was formed to develop a framework (Appendix 1.1) to identify and classify High Conservation Value Aquatic Ecosystems (HCVAEs).

The draft HCVAE Framework is designed to have multiple uses. The Framework will be used to:

1. establish a core set of criteria for identifying aquatic ecosystems of high conservation value
2. improve knowledge of the extent, distribution and characteristics of HCVAE
3. differentiate between HCVAEs of national and regional importance;
4. improve information sharing between NRM bodies, governments and other stakeholders
5. improve cross-jurisdictional coordination and cooperation
6. assist meeting national and international obligations for protection of aquatic ecosystems
7. guide Australian Government investment decisions

Several trials have been undertaken to test the applicability of the criteria to different ecosystem types. The full draft Framework is now undergoing evaluation in the Lake Eyre Basin and northern Australia (this study).

Six core biophysical criteria (Appendix 1.1) have been agreed as appropriate for the identification of nationally significant HCVAEs, and draft guidelines (Appendix 1.2) have been developed for their implementation.

As outlined in the draft Framework, the criteria for identifying High Conservtaion Value Aquatic Ecosystems are as follows:

1. Diversity – It exhibits exceptional diversity of species or habitats, and/or hydrological and/or geomorphological features/processes.
2. Distinctiveness – It is a rare/threatened or unusual aquatic ecosystem; and/or it supports rare/threatened species/communities; and/or it exhibits rare or unusual geomorphological features/ processes and/or environmental conditions.
3. Vital habitat – It provides habitat for unusually large numbers of a particular species of interest; and/or it supports species of interest in critical life cycle stages or at times of stress; and/or it supports specific communities and species assemblages.

4. Evolutionary history – It exhibits features or processes and/or supports species or communities which demonstrate the evolution of Australia's landscape or biota.
5. Naturalness – The aquatic ecosystem values are not adversely affected by modern human activity to a significant level.
6. Representativeness – It contains an outstanding example of an aquatic ecosystem class, within a Drainage Division.

1.2 Background to northern Australia HCVAE Trial

The project is being undertaken as part of the Northern Australia Water Futures Assessment (NAWFA). The NAWFA is an Australian Government initiative to provide the science needed for sustainable development and protection of northern Australia's water resources. The current project is focussed on testing the draft national HCVAE Framework to identify high conservation value aquatic ecosystems in tropical river basins of the Timor Sea and Gulf of Carpentaria Drainage Divisions (see chapter 2 for a background to the study area). Another test of the draft national HCVAE Framework is currently being undertaken in arid and semi-arid environments by applying it to the Lake Eyre Basin (LEB) (Hale, 2010).

The project is led by a team of researchers through the Tropical Rivers and Coastal Knowledge (TRaCK) Commonwealth Environmental Research Facility in collaboration with the Department of the Environment, Water, Heritage and the Arts (DEWHA). The specific aim is to test the draft national HCVAE Framework to identify high conservation value aquatic ecosystems. This involves:

1. identifying and evaluating aquatic ecosystem characteristics in northern Australia based on the draft Australian National Aquatic Ecosystem (ANAE) classification scheme (Auricht, 2010)
2. developing a method to apply and assess the draft HCVAE criteria that is based on the best available science and knowledge
3. defining key knowledge gaps and making recommendations for further work to refine the draft HCVAE Framework

To asses the utility of HCVAE Framework we apply and evaluate a variety of methods for scoring and combining the individual criteria and examine the effect of these decisions on the relatively prioritization of HCVAEs. We also evaluate the extent to which the set of HCVAEs identified contribute to the important goal of representing the full range of species or types of natural environments (so-called biodiversity surrogates) and whether more efficient ranking of HCVAEs based on this goal can be obtained. We view these steps (outlined in Chapter 3) as being critical to identifying the strengths and weaknesses of the HCVAE Framework and argue that the application of more than one complentary approach to defining high conservation value areas provides multiple lines and levels of evidence (and therefore greater confidence) in identification of HCVAEs.

This project is a trial of the draft national HCVAE Framework, and to this end we make recommendations for refining or improving the Framework. It should be recognized that this project has been undertaken within a limited time frame and we have tested the Framework with readily available resources. Recommendations about HCVAEs in northern Australia are therefore provisional but, none-the-less, form a significant starting point for identifying and characterising the HCVAEs of northern Australia and the ecologically sustainable management of the region.

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2. STUDY AREA

BRAD PUSEY

KEY POINTS

Northern Australia is a region distinguished by:

1. an ancient, highly weathered landscape of typically low relief and nutrient poor soils;
2. a climate influenced by the southern monsoon and proximity to the equator resulting in a well-defined summer wet season and high rainfall and high temperatures but also in an annual water deficit across the entire region;
3. pronounced common gradients in rainfall, temperatures, evapotranspiration and hence severity of the net water deficit with increasing distance from the coast, latitude and elevation;
4. rivers with large floodplains and flow regimes characterised by summer high flows and dry season winter intermittency with the extent of intermittency increasing with distance inland except where groundwater aquifers contribute to baseflows; and
5. aquatic habitats of good ecological condition supporting high levels of biodiversity

2.1 STUDY AREA

Northern Australia, here collectively defined as the Gulf of Carpentaria and Timor Sea AWRC drainage divisions, has a total land area of about 1.19 million km^2; encompassing about 15% of the Australian continental area. It spans Western Australia, the Northern Territory and Queensland. The overall proximity to the equator imparts a distinctively tropical character to the region, however substantial and frequently common gradients in landform and climate over this latitudinal range impart a great deal of physical diversity.

Little of the northern Australian landscape is more than 600m above sea level and in general, the inland southern and eastern boundaries of the region are the most elevated. The Kimberley Plateau (> 600 m.a.s.l.) and the Arnhem Land escarpment (> 400 m.a.sl.) are two isolated high elevation massifs within the Timor Sea drainage division, the former dividing the Kimberley region and the latter essentially demarking the Timor Sea and Gulf of Carpentaria drainage divisions. Both landforms are of great antiquity, containing deeply dissected and weathered rocks of Archaean and Proterozoic origin. Soils of the region are typically ancient, fragile, highly weathered and in decline (rates of loss exceed generation) (Wilson et al., 2009).

The climate of northern Australia is largely controlled by large scale atmospheric circulation associated with southern monsoon (McDonald & McAlpine 1991). However, four Köppen climate types (equatorial, tropical, subtropical and grassland) occur in northern Australia. Equatorial areas are limited to Bathurst/Melville Islands and the Coburg Peninsula in the Timor Sea drainage division and the northern tip of Cape York Peninsula (i.e. the most northern portions of each drainage division). The subtropical climate type is also limited in extent, occurring in the high elevation areas in the south-east of the Gulf of Carpentaria drainage division. The grassland zone is limited to the southern portion of the region and tropical zone is proximal to the coast. Although these zonal patterns imply crisply defined boundaries between climate types, in reality climatic variation is more clinal.

Rainfall over the region is immense (approximately one million gigalitres annually). Rainfall is highly seasonal with typically more than 90% of annual totals falling during the short and well-defined wet season from October to March. Dry season rainfall greater than 200 mm does not occur anywhere across northern Australia, although total dry season falls of 80 -110 mm occur in the coastal areas of the Darwin region, Cape Arnhem and the tip of Cape York Peninsula, and in the very upper headwaters of the Mitchell River (Cresswell et al., 2009). Rainfall declines very swiftly with increasing distance from the coast (often associated with increasing latitude and elevation as well).

Befitting its proximity to the equator, northern Australia is warmer than the remainder of Australia. Air temperatures vary seasonally and with distance from the coast, with the latter being largely a function of latitude and maritime proximity. During the wet season (October to March), mean maximum temperatures are between 30-33^{o} C for most of the region, exceeding 33^{o} C towards the inland fringe and not exceeding 30^{o} C in the most coastal of locations in Arnhem Land and Cape York Peninsula. During the dry season, mean maximum temperatures are consistently between 30-33^{o} C for the entire region with the exception of a small part of the Kimberley Plateau, the tip of Cape York Peninsula and the most inland western portion of the Gulf of Carpentaria drainage division where it is slightly cooler. Minimum air temperatures do not fall below 21-24^{o} C during the wet season for about 90% of the area and remain between 24-27^{o} C in coastal areas only. Minimum mean air temperatures during the dry season may fall as low as 12-15^{o} C in the most inland areas of the region and remain between 24-27^{o} in coastal regions. Average air temperature remains above 27^{o} C for most of the region (except for a very small part of the Kimberley region during the wet season) and, with the exception of the slightly warmer coastal areas, does not fall below 24-27^{o} C during the dry season.

High air temperatures ensure that evapotranspiration rates also remain high. Potential losses during the warm wet season are between 1100-1200 mm.yr^{-1} in the southern periphery of the region gradually decreasing to 900-1000 mm.yr^{-1} near the coast. Even during the cooler dry season, losses are between 700-900 mm over the entire region (Cresswell et al., 2009). Thus, annual deficits (rainfall minus evapotranspiration) approach -1400 to -1600 mm.yr^{-1} in the inland portion of the region and gradually decrease to -400 to -600 mm.yr^{-1} near the coast. An annual water deficit is experienced across the entire region except in the very wettest of years (Cresswell et al., 2009).

The large scale spatial and temporal patterns of rainfall, temperature and evapotranspiration are largely responsible for shaping the types and location of different flow regimes in the region. Kennard et al. (2010) identified six different flow regime types across northern Australia (from a total of 12 across the entire continent). Apart from a small spring fed creek (class 1) on Cape Arnhem and some unpredictable intermittent streams (class 7) in the subtropical south-eastern corner of the Gulf of Carpentaria region, the remaining flow regime classes are distinguished by a summer wet season flood period. Some basins (e.g. Daly, Roper and Gregory Rivers) receive substantial groundwater inputs or dry season rainfall (e.g. tip of Cape York Peninsula) that maintains their baseflows during this period and ensures their perenniality. The other flow classes cease to flow during the dry season, often for more than 270 days a year. Those distant from the coast and thus corresponding with reduced rainfall, high temperatures and high evaporation are the most intermittent. Moreover, flow becomes progressively less predictable with increasing distance inland. The proportion of rainfall converted to runoff across this gradient decreases from 60% to 3% (Cresswell et al., 2009).

Fifty-five major drainages are distributed across northern Australia and collectively they discharge about 1.8 x 105 Gl.yr^{-1}; 46% of the total Australian runoff. Few of the rivers of the north are impounded. A total of 24 storages greater than 1 GL (plus a further three > 0.2 GL) occur in the region, compared to a total of 467 elsewhere in Australia. The geomorphological nature of the region's rivers varies greatly across its breadth (see Chapter 4). Briefly, they are distinguished by the presence of large seasonally inundated floodplains, especially in the Gulf of Carpentaria region where floodplains may cover in excess of 20,000 km^2 and comprise more than 35% of total catchment area (Pusey & Kennard, 2009). Given that rainfall is greatest near the coast, a substantial proportion of the total runoff from many northern rivers may originate from lowland regions. As a consequence, floodplain wetland habitats of northern Australia are vast and comprise about 25% of the entire area (Pusey & Kennard, 2009) and represent the largest area of unmodified wetlands in all Australia (Woinarski et al., 2007). Most of the rivers, wetlands and estuaries of northern Australia are in good ecological condition (NLWRA 2002) but poorly protected and under-represented in the National Reserve System (Pusey & Kennard, 2009). The overall good condition is primarily because of the relatively good condition of the surrounding savanna ecosystem that represents about 90% of the total global savanna classified as in good ecological condition (Woinarski et al., 2007).

The diversity of aquatic habitats and their overall good ecological condition ensure that they are a "treasure trove of biodiversity" (Kutt et al., 2009). For example, approximately 75% of Australia's freshwater fish diversity is found in the region (Woinarski et al., 2007). Over 90 species of amphibian occur in the region; all of which are critically dependent on aquatic habitats for reproduction and survival (Kutt et al., 2009). Similarly, 12 of the 15 species of Australian freshwater turtle occur in northern Australia (Georges & Merrin, 2008; see this report also). Approximately one fifth of Australia's total bird diversity is comprised of waterbirds found in northern Australian wetlands. Moreover, these habitats form vital resting and feeding areas for many species of migratory birds. Add to this the vast diversity of aquatic invertebrates present and fauna indirectly supported by aquatic habitats (i.e. provision of adjacent moist habitats or provision of aquatically-derived food or water), and it is readily apparent that aquatic habitats are fundamentally important in the maintenance of regional and continental biodiversity.

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3. Overall approach

Mark Kennard

3.1 Introduction

The core objective of this project was to apply and assess the draft HCVAE Framework. This involved a number of interrelated steps (Fig. 3.1). These included defining appropriate scales for spatial units and reporting scales for attribution of biodiversity and environmental data and assessment of conservation values. Using predictive modelling and hydrosystem classifications, we generated spatially explicit biodiversity surrogate datasets for the entire study region. This information was attributed to planning units (hydrologically-defined sub-catchments) and used to assess their relative conservation values. We did this using two complentary approaches: the mutli-criteria draft HCVAE Framework and using a systematic conservation planning algorithm (see below).

Implementing the draft HCVAE Framework involved an exhaustive process of selecting appropriate attributes to characterise the Framework criteria and applying them to the biodiversity surrogate data. We next evaluated the extent of redundancy between attributes and performed sensitivity analyses to establish a robust method of scoring, and integrating individual attributes to generate scores for each criterion. We also trialled a variety of scoring thresholds to identify which subset of planning units may qualify as being of high conservation value based on the criteria. Finally we evaluated the efficiency of the criteria in representing the full complement of biodiversity surrogates (i.e. species or environmental types - the fundamental currency of conservation assessments), a key conservation goal not explicity addressed by the Framework criteria. We therefore also implemented a systematic conservation planning assessment where our goal was to efficiently select a minimum set of areas to represent the full range of biodiversity surrogates. In these analyses we used indices of river disturbance to penalise the spatial prioritization of high conservation value areas (i.e. avoiding highly disturbed areas where possible). We also evaluated the influence of various target levels of occurrence of species or environmental types, and explored different longitudinal and lateral connectivity rules that we hypothesed would be important considerations in the selection and spatial configuration of high conservation value areas.

The outcomes of these alternative approaches to conservation assessments enabled us to objectively asses the merits and limitations of the draft Framework in identifying high conservation value aquatic ecosystems in northern Australia. The key steps and their rationale are outlined in more detail below.

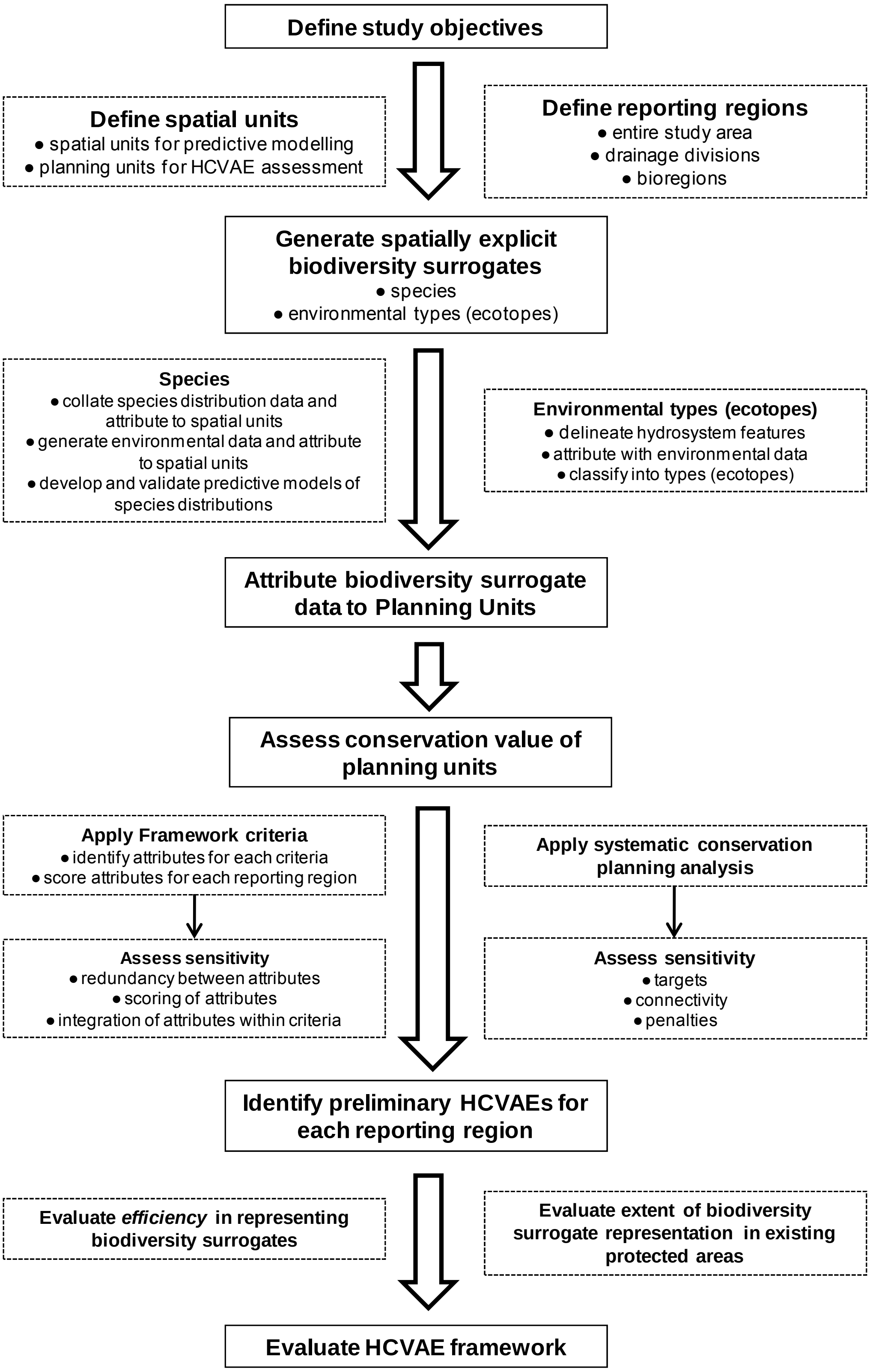

Figure 3.1. Key steps taken in this project to evaluate the draft HCVAE Framework

3.2 Spatial units and regionalisation

The assessment of HCVAEs depends critically upon the availability of a suitable spatial framework that underpins the comparative procedures in most conservation assessments. This framework supplies the spatial units and the definition of surface drainage pathways that enable regions, catchments and sub-catchments to be delineated and their environmental and biodiversity characteristics attributed (Table 3.1 and detailed below).

Table 3.1 Hierarchy of spatial units used in the assessment of HCVAEs.

Name	n	Spatial extent (km^2)	Data source/type	Purpose
Sampling unit	333,471 (birds: 16,597)	0.07 – 4953, mean = 3.58 (birds: 0.07 – 9650, mean = 72)	National Catchment Boundaries (NCB)	• Attribution of raw species records and environmental data • Basic unit for predictive modelling of species distributions
Planning unit	5,803	0.07 – 14,458, mean = 204	Aggregated spatial units	• Attribution of predicted species distribution data and environmental ecotopes • Calculation of biodiversity attributes • Assessment and prioritisation of HCVAEs according to the Framework criteria
River basin	24,820	0.07 – 230,618, mean = 49.4	National Catchment Boundaries (NCB)	• Attribution of species distribution data and environmental data for assessment of bioregions
Region	7	46,312 – 257,809, mean = 166,548	Aggregated River basins (approximating NASY reporting regions)	• Assessment and reporting of HCVAEs according to the Framework criteria
Drainage Division	2	547,664 and 621,855	National Catchment Boundaries (NCB)	• Assessment and reporting of HCVAEs according to the Framework criteria
Entire study region	1	1,169,519	National Catchment Boundaries (NCB)	• Assessment and reporting of HCVAEs according to the Framework criteria

3.2.1 Digital elevation model

Some existing spatial frameworks such as the Australian Water Resources Council (AWRC, 1976) drainage basins and divisions have significant shortcomings that are unlikely to make them unsuitable for this task. This includes their inconsistent adherence to topographically defined hydrological boundaries and coarse spatial scale (Stein et al., 2009). Accordingly, we used an interim version of a new spatial framework being developed by the Fenner School of Environment and Society ANU using novel methods of drainage analysis of a Digital Elevation Model (DEM) that are especially suited to regional to continental-scale application (Stein, 2007, Stein et al., in prep.). This new framework, incorporating a consistent, continent-wide stream network and accompanying nested catchment framework, to be known as the National Catchment Boundaries (NCB), will form an important component of the Bureau of Meteorology's Australian Hydrological Geospatial Fabric (AHGF) (http://www.bom.gov.au/water/about/publications/document/InfoSheet_5.pdf). It was derived from the national 9 second DEM version 3 (Fenner School of Environment and Society ANU and Geoscience Australia 2008; Fig. 3.2), a gridded elevation layer with a spacing of 9 seconds of latitude and longitude equating to a distance on the ground of between 194 m and 265 m in an east-west direction (depending on latitude) and about 270 m in a north-south direction. The scale of the 9 second DEM is approximately 1:250,000. The DEM has a standard error of 10 metres or less in the low relief areas that make up about half of the continental land area and up to about 60 metres in areas of steep and complex terrain. It is the highest resolution, drainage enforced DEM with consistent spatial coverage available for northern Australia and is considered suitable for applications at regional to continental scales (Fenner School of Environment and Society ANU and Geoscience Australia, 2008). The 9 second DEM thus provided an appropriate basis for delineating stream networks, and nested subcatchments for use in this project.

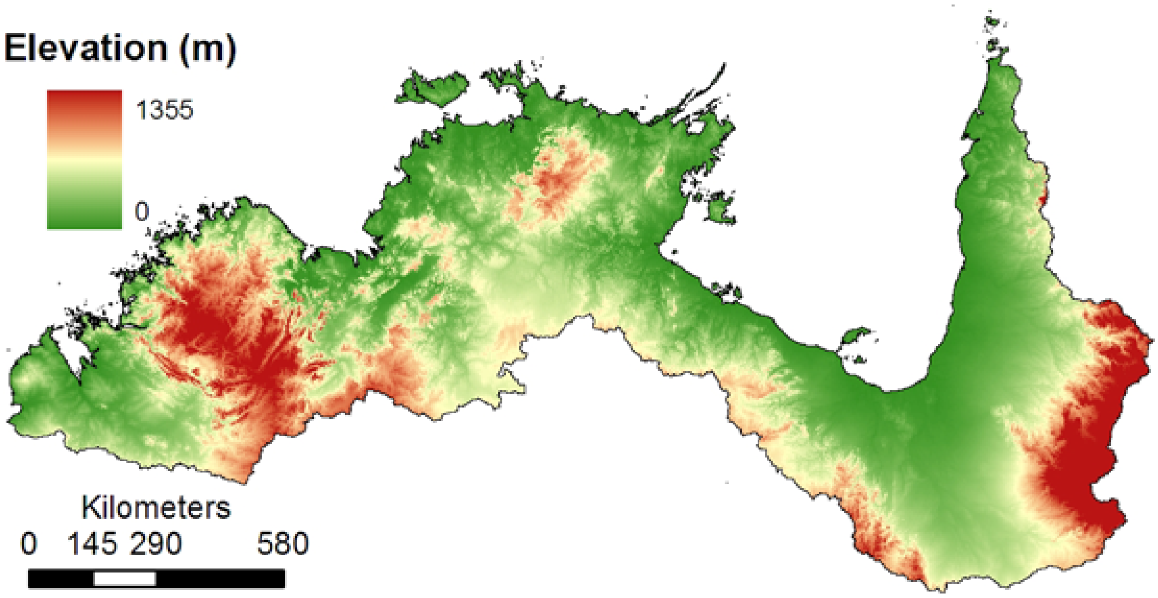

Figure 3.2. The 9 second Digital Elevation Model (Fenner School of Environment and Society, ANU and Geoscience Australia, 2008) for the study area

3.2.2 DELINEATING THE STREAM NETWORK

Streams were delineated by tracing the surface flow pathways coded by a multi-flow extension of the GEODATA 9 second Flow Direction Grid associated with the GEODATA 9 second Digital Elevation Model Version 3 2008 (Fenner School of Environment and Society ANU and Geoscience Australia, 2008). Source channels with a contributing area less than 1.25 km^2 were removed from the traced network because they could not be resolved from the 9-second DEM. However, main stem segments, defined as the segments draining the larger upstream contributing area, were retained to their source. Segment breaks were inserted at tributary confluences, distributary points, where a channel flows into or out of a lake or reservoir or over a cliff line and where the traced network connects gaps in the AusHydro watercourse lines. The stream network provides a fully connected network suitable for network tracing and other analytical uses. Further details on the methods for delineating the stream network are provided in Chapter 4.

3.2.3 SPATIAL UNITS FOR PREDICTIVE MODELLING OF SPECIES DISTRIBUTIONS

The stream network layer described above directly relates to the NCB using a shared segment identifier. The sub-catchment areas draining to each of the segments (links) in this layer form the lowest level sub-division of the NCB (Fig. 3.3, Fig 3.4a) and consisted of 333,471 individual sub-catchments within the study region, averged 3.58km^2 in area (Table 3.1). The stream segments and their sub-catchments supply the basic spatial units that were attributed with environmental data (Chapter 4) and species records (Chapter 5) for use in predictive modeling of species distributions (Chapter 7). Because waterbirds are potentially more mobile and range over larger spatial scales than other faunal groups, we used a coarser spatial grain for the analysis and prediction of waterbird distributions. Using the NCB Pfafstetter labeled sub-catchments, we aggregated up the finest scale spatial units to a mean spatial unit area of 100 km^2 (see Chapter 7). This resulted in 16,597 spatial units for waterbirds.

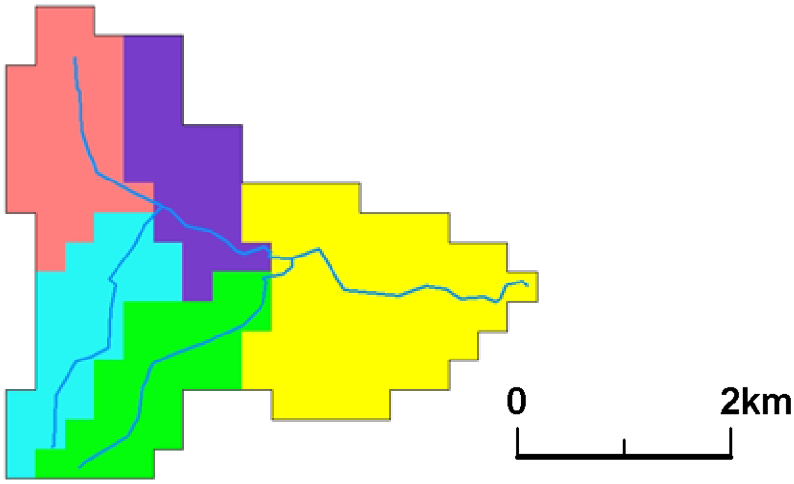

Figure 3.3. Catchments, sub-catchments and streams. Each of the coloured areas is a sub-catchment (i.e. the area contributing directly to a stream segment. The catchment is the entire area draining to a pour-point and thus also includes all of the sub-catchments upstream.

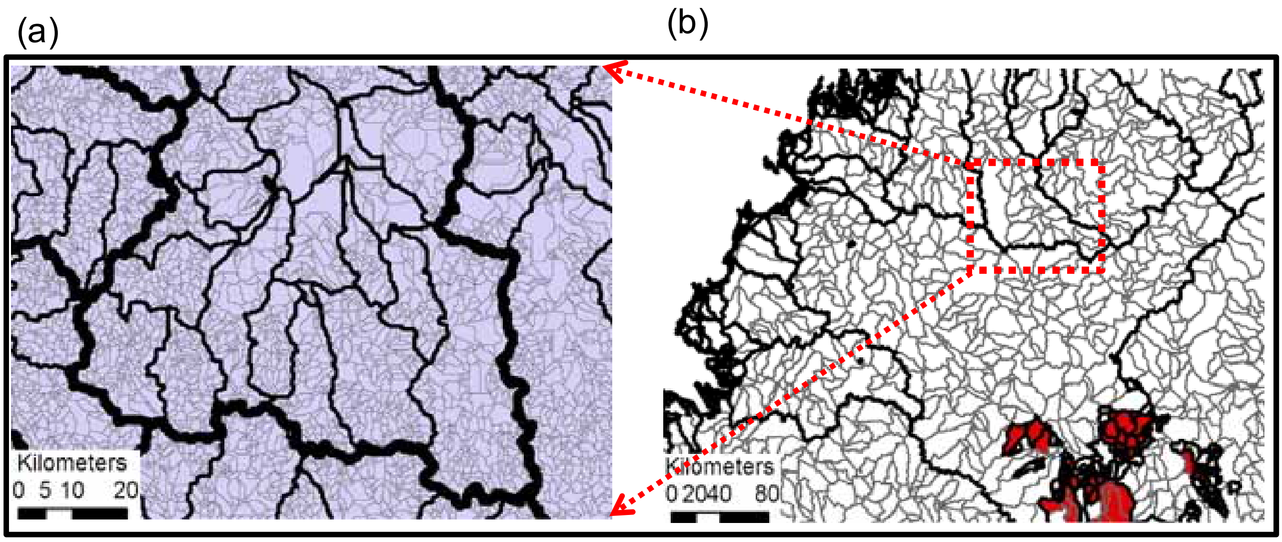

Figure 3.4. (a) Example of the finest scale spatial units (grey polygons), planning units (intermediate-sized dark polygons) and river basins (thick dark lines). (b) Example of planning units (grey polygons) within river basins (thick dark lines). Internally-draining basins and planning units are highlighted with red polygons, all others drain to the coast.

3.2.4 Planning units

Equal-sized grid cells are often used as planning units in terrestrial conservation assessments, but sub-catchments are more appropriate for freshwater ecosystems. This spatial approach accounts for the connected nature of rivers and natural boundaries of watersheds (Linke et al., 2007; Klein et al., 2010; Hermoso et al., 2010). We derived 5,803 planning units (Fig. 3.4a,b) from the 9 second digital elevation model using ARC Hydro (Maidment, 2002) within ArcGIS 9. These hydrologically-defined planning units represent aggregated spatial units (subcatchments) with a minimum target area threshold of 15 km^2, though this threshold was occasionally not met for certain segments in the river network where several subcatchments met one another. Planning units averged 204 km^2 (Table 3.1). Note that the study area contains numerous separate coastal basins with a total catchment area smaller than the 15 km^2 minimum target area and so were excluded from all HCVAE analyses (i.e. rather than being aggregated across river basins). The 5,803 planning units were attributed with environmental and biodiversity data (derived at the sampling unit scale) and formed the basic spatial unit for calculation and reporting of attributes for each HCVAE criterion and for the systematic conservation planning analyses.

3.2.5 Larger Regional Spatial Units (River Basins, Regions and Drainage Divisions)

Fine-scale spatial units and planning units were nested within larger spatial units defined by river basin boundaries, regions and drainage divisions. These larger regional units were used in the bioregionalisation (Chapter 6) and for reporting HCVAEs (Chapters 8, 9, 10). The topographically defined river basin boundaries group the nested sub-catchments that drain to either a common coastal outlet or inland sink (Fig. 3.4b). Unlike the AWRC (1976) River Basins, the catchments of rivers connected by distributaries (e.g. the Flinders, Norman and Gilbert Rivers in the Gulf of Carpentaria drainage division) are recognized as a single drainage basin.

In this project we were tasked with assessing and reporting HCVAEs at regional scales defined *a-priori* by the reporting regions used in the Northern Australia Sustainable Yield (NASY) project and the AWRC (1976) drainage divisions (Fig. 3.5a,b). Thirteen NASY regions were defined on the basis of landscape differences and jurisdictional imperatives (such as the Wild Rivers legislation of Queensland) (Fig. 3.5a) but their biological relevance is questionable (this is evaluated in chapter 6). We aggregated some of the original NASY regions on the basis of extant (e.g. present-day flooding patterns) or recent past (e.g. late Pleistocene lowered sea levels) hydrologic connectivity (see Chapter 6). Aggregated NASY regions and drainage divisions are shown in Figure 3.5b.

3.3 Hydrosystem delineation, environmental attribution and classification

Methodologies for identifying HCVAEs in northern Australia require the delineation of aquatic ecosystems at a spatially consistent and comparable scale across the study region. The Aquatic Ecosystem Task Group has produced a draft Australian National Aquatic Ecosystem (ANAE) Classification Scheme (Auricht, 2010). The ANAE classification scheme is a semi-hierarchical system that facilitates the classification of aquatic ecosystem at varying and multiple levels including hydrosystems and further refinement to ecotopes. For the Northern Australia HCVAE trial area, the ANAE classification scheme was applied to delineate four broad hydrosystems (Riverine, Lacustrine, Palustrine and Estuarine). Using the Geoscience Geodata 250k Hydrography theme feature classes, the ANAE Classification Scheme was applied to delineate Lacustrine, Palustrine and Estuarine hydrosystems in Northern Australia. Riverine hydrosystems were separately delineated based on the stream network derived from the national 9 second DEM for the Australian Hydrological Geospatial Fabric. Further application of the ANAE scheme involved the attribution of hydrosystems with ecologically relevant environmental data. Environmental characteristics included variables describing climate, terrain, substrate, vegetation, hydrology, stream network characteristics, terrestrial primary productivity, non-riverine hydrosystem area and shape characteristics and human disturbance (see Chapter 4). Due to the difficulty in adequately delineating the extent of the Estuarine hydrosystems and attributing them with ecologically relevent environmental data in the timeframe available for this project, they were omitted from the analysis.

The delineated hydrosystems and associated ecotopes provide base level mapped aquatic assets for the study area at a scale of 1:250,000. The environmental characteristics of riverine, lacustrine and palustrine hydrosystems were summarized at the river basin scale for assessment of bio-regional boundaries (Chapter 6). Environmental data was also summarized at the scale of individual (fine-scale) spatial units and used as predictors of species distributions (Chapter 7). Multiple statistical classifications of the riverine, lacustrine and palustrine hydrosystem objects were also performed to delineate hydrosystem ecotopes (Chapter 4). These were used as environmental surrogates for biodiversity assessment (Chapters 8, 9 and 10).

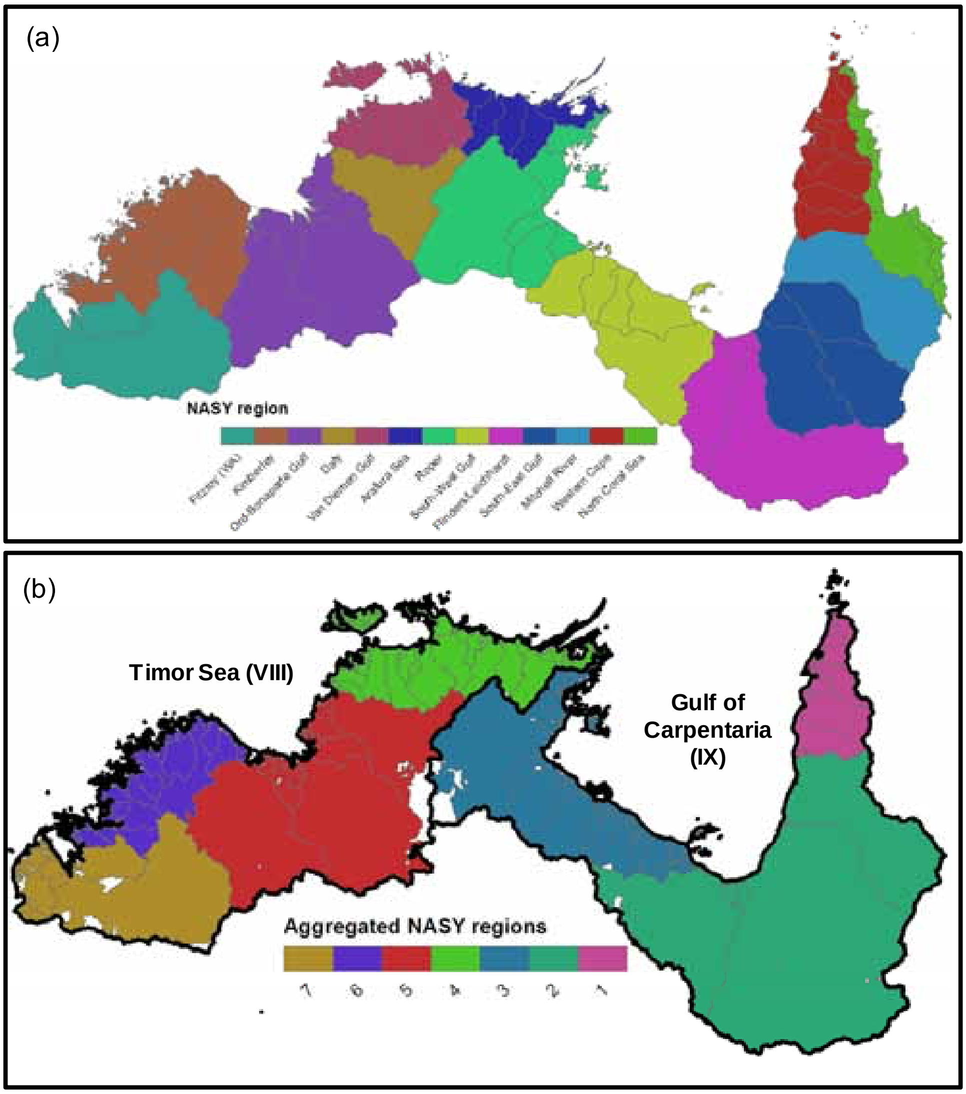

Figure 3.5. (a) Location of NASY regions using AWRC (1976) river basins as the basic sampling unit. (b) Location of the aggregated NASY regions defined using the new topographically-defined river basins as the basic sampling unit. Also shown are the boundaries of the drainage divisions VII and IX. Areas in white are seperate inland draining basins.

3.4 BIODIVERSITY SURROGATES

Surrogates are commonly used in conservation assessment and prioritisation to optimally represent multiple components of biodiversity. Biodiversity surrogates include taxa (e.g. species), the characters they represent (e.g. phylogenetic relationships) assemblages or environmental classes (Margules et al., 2002, Pressey 2004). Usually (and certainly in our study region) groups of taxa representing only a very small proportion of the total biodiversity are available or suitable for use in conservation assessment (Margules et al., 2002). This is often due to limited, unstandardised and spatially biased field survey effort, poor knowledge of true species' absences (i.e. most species records are presence-only), lack of easily available databases containing accurate locality data, or up to date taxonomy. Though not without potential problems, environmental gradients or environmental classes (ecotopes) are often used as biodiversity surrogates as different types of environments are assumed to support different combinations of species (Lombard et al., 2002, Margules et al., 2002, Pressey, 2004; Ausseil et al., 2010).

We considered a range of species groups and environmental information as potential candidates for further development and application as biodiversity surrogates. Our choice was guided by a desire to assemble accurate datasets with as broad spatial coverage as possible, within the time and budgetary constraints of our project. Water-dependent species groups for which we assembled data and used as biodiversity surrogates included aquatic macroinvertebrates, fish, turtles and waterbirds (see Chapter 5). We considered but did not assemble datasets for other water-dependent fauna (i.e. frogs, crocodiles, lizards, snakes, riparian birds) or aquatic, semi-aquatic and riparian flora due to time, budgetary and/or data constraints. Environmental surrogates for biodiversity included the riverine, lacustrine and palustrine ecotopes described above (and detailed in Chapter 4). We considered but rejected the idea of using an existing estuarine classification scheme (OzCoasts Geomorphic Habitat Mapping - http://www.ozcoasts.org.au/) to define estuarine ecotopes as we did not consider this classification scheme to be of sufficient spatial resolution, ecological relevance (particularly with respect to the catchment processes that influence estuarine structure and function) or be sufficiently validated with respect to the spatial accuracy of ecotope boundaries.

3.5 Predictive models of species distributions

Lack of complete survey coverage is a common problem in conservation assessment (Margules & Pressey, 2000; Van Teeffelen et al., 2006; Linke et al., 2007) and is a particularly germane issue for northern Australia where substantial spatial biases exist in the availability of species distribution records (Chapter 5). The use of such patchy data to derive biodiversity attributes can have potentially major implications for accurate and objective identification and prioritization of high conservation value areas (Underwood et al., 2009). For example, there is a substantial risk that maps of species richness or endemism generated using incomplete survey data will simply yield maps of relative sampling intensity and lead to little confidence if these maps were used to assess conservation values and prioritise areas for conservation management. One way to partially (though not entirely – see Underwood et al., 2009) overcome this issue is to develop predictive models of species distributions and use them to extrapolate distributions beyond the often sparse sampling network (Wilson et al., 2005, Hermoso et al., 2010). Species distribution predictive models rely on the association between a species' occurrence or abundance and environmental or geographical predictors (see reviews by Guisan & Zimmerman, 2000 and Araújo & Guisan, 2006). Species distribution models (also called 'ecological niche models' or 'habitat suitability models') now have an established place within conservation biology and biodiversity assessment (Elith & Leathwick, 2007, 2009). Chapter 7 describes the development, validation and application of predictive models of species distributions for aquatic macroinvertebrates, fish, turtles and waterbirds. The predictive models were used to generate nearly-complete species distributions coverage for the entire study region (predictions were not generated for the small number of internally draining basins and those planning units that did not contain a stream segment). These data were used as surrogates for biodiversity in the HCVAE assessment process (Chapters 8, 9 and 10).

3.6 HCVAE criteria and attributes

The attributes used to characterise each of the HCVAE criteria are listed in Table 3.2 together with a brief description of the method for calculation, rationale for their inclusion and key references for further information. Attributes for each criterion were calculated for each of the biodiversity surrogate sets, where appropriate and where suitable data was available (Table 3.2). Nearly complete coverages of biodiversity surrogate data meant that these attributes were calculated for almost all the 5,803 planning units. The exceptions to this were 191 planning units (for attributes based on species-based biodiversity surrogates) and 113 planning units (for the riverine connectivity attribute).

We also considered a number of other attributes to characterise the criteria but did not apply them due to time limitations or data constraints. Our overall philosophy was to only apply attributes that could be calculated from the biodiversity surrogates datasets with (nearly) complete coverages, rather than applying attributes based on other data which was of variable quality and spatial extent and that would therefore yield large gaps and uncertainties in the datasets used to assess HCVAEs (refer to Chapter 8 for more details on the rationale for our choice of attributes and those that we omitted).

Table 3.2 Attributes used to characterise each of the draft HCVAE Framework Criteria. Attributes for each criterion were calculated for each of the biodiversity surrogate sets where suitable data was available (depicted with dark shading). Abbreviations used for biodiversity surrogates are: macroinvertebrates (Bug), fish (Fish), turtles (Turt), waterbirds (Bird), riverine ecotopes (Riv), lacustrine ecotopes (Lac) and palustrine ecotopes (Pal). Attributes for Criterion 5 (Naturalness) were summarized for the planning unit (PU) (i.e. were not based on the biodiversity surrogate data). See Chapter 8 for rationale, methods of attribute calculation and key references.

Criterion, Attribute type and code	**Biodiversity surrogate set**							
	Bug	Fish	Turt	Bird	Riv	Lac	Pal	PU
1. Diversity								
Richness (S_i)	■	■	■	■	■	■	■	
Diversity (H')	■	■	■	■				
Richness Index (I_i)	■	■	■	■				
Phylogenetic Diversity (PD)	■	■	■	■				
2. Distinctiveness								
Rarity Index (Q_i)	■	■	■	■	■	■	■	
Rare & Threatened species score (R&T)		■	■	■				
3. Vital habitat								
Number/area permanent/perennial dry season refugia (P)					■	■	■	
Degree of natural longitudinal connectivity (con)								■
Number of migratory bird species (Mbird_S)				■				
4. Evolutionary history								
Number of monospecific Genera (monG)		■	■	■				
Number of species endemic to each NASYagg Region (SES)		■	■					
Taxonomic endemism index (TE)	■	■	■	■	■	■	■	
Phylogenetic Endemism index (PE)	■	■	■	■				
5. Naturalness								
Catchment Disturbance Index (CDI)								■
Flow Regime Disturbance Index (FRDI)								■
6. Representativeness								
Representativeness (R)	■	■	■	■	■	■	■	

3.7 Sensitivity analyses: Scoring, weighting and integration of attributes and redundancy

The methods used to score, weight and integrate attributes and criteria can lead to substantially different final scores and so have major implications for assigning conservation value to planning units and prioritizing areas for conservation management. We address these issues in Chapter 8 where we investigate a number of options for combining the attributes to give integrated (criteria) assessments for the planning units. We also investigate the degree of redundancy among attributes within each criterion and the influence that each of the attributes has on the overall conservation value assessment. These analyses allowed us to identify the most robust methods for scoring and integrating attributes within each criterion.

3.8 Assessment of HCVAEs identified using the Framework

The sensitivity analyses allowed us to identify the most robust approach to implementing the Framework. In Chapter 9 we present the outcomes of this implementation. We report HCVAEs identified at three separate spatial scales: referential to the entire study region, each Drainage Division, and each bioregion, respectively.

The multi-criteria HCVAE Framework represents a spatially explicit 'scoring' approach to prioritizing freshwater systems. Such approaches continue to be used in Australia and elsewhere, and are also used in broad-scale terrestrial assessments, e.g. global biodiversity hotspots based on species richness, rarity, endemism, etc. Importantly however, none of the Framework criteria are designed to identify a set of areas that represent the full range of species or types of natural environments (so-called biodiversity surrogates or conservation features). Scoring approaches assess each area individually. Highest ranking areas can contain the same conservation features which are duplicated, while other features remain completely unrepresented, especially if they occur only in low-ranking areas (Carwardine et al., 2007). We consider it important to evaluate the extent to which the set of areas identified using the Framework as being of high conservation value contribute to the goal of representing the full range of species or type of natural environments (so-called biodiversity surrogates).

The conservation of freshwater ecosystems and biodiversity is rarely the basis for declaration of reserves (e.g. National Parks, and other conservation areas) unless it is considered important for maintenance of terrestrial biodiversity patterns and processes (Saunders et al., 2002; Nel et al., 2007). We assume here that a reserve system designed primarily for maintenance of terrestrial biota may also have significant value for aquatic systems, although this has yet to be adequately demonstrated in Australia. We therefore also evaluate the extent to which the existing set of conservation reserves (based on the most recent available (2006) version of the Collaborative Australian Protected Area Database; CAPAD, 2009) encompasses the distribution of freshwater biodiversity surrogates.

3.9 Identification of HCVAEs using a complementary approach – systematic conservation planning

Based on the outcomes of the analyses described above, we also evaluate whether more efficient ranking of HCVAEs based on the goal of representing the full range of species or type of natural environments can be obtained (Chapter 10). To do this, we apply an alternative approach to identifying high conservation value aquatic ecosystems (namely systematic comnervation planning) using a complementarity-based algorithm (Marxan – Ball et al., 2009). Complementarity is defined as the gain in representativeness of biodiversity when a site is added to an existing set of areas (Possingham et al., 2000). Therefore a site or a subcatchment is evaluated in the light of what is already selected and in light of the uniqueness of its features. A large body of research indicates that conservation planning approaches that incorporate complementarity lead to a more efficient representation of biodiversity features and more cost-effective solutions than ad hoc, scoring or ranking strategies (Pressey & Nicholls, 1989; Pressey & Tully, 1994; Margules et al., 2002). Including cost or effort in an assessment and optimization framework guarantees minimum impact on stakeholders while maximizing outcomes. We here emphasise that systematic conservation planning is not (necessarily) about designing protected area networks (i.e. selecting and 'locking up' areas in National Parks). Rather, it is about efficiently and effictively identifying priority areas for conservation management actions (e.g. threat mitigation, restoration, stewardship, acquisition) to maintain conservation values. In essence, the objective is to select a minimum set of areas to represent pre-specified biodiversity targets (e.g. five populations of each species, 10 representatives of each environmental class) whilst minimising socioeconomic costs (e.g. costs of various management actions). Ultimately the approach aims to achieve comprehensiveness, adequacy, representativeness and efficiency in the identification of priority areas for conservation management (Linke et al., 2010; Chapter 10). We view the implementation of a systematic conservation planning analysis as being critical to identifying the strengths and weaknesses of the HCVAE Framework and argue that the use of more than one complementary approach to defining high conservation value areas provides multiple lines and levels of evidence (and therefore greater confidence) in identification of HCVAEs.

3.10 Knowledge gaps, next steps and recommendations

Based on the collective outcomes of the analyses described above, we conclude with an assessment of key limitations and knowledge gaps. We also make specific recommendations on the Australian National Aquatic ecosystem Classification Scheme and the HCVAE Framework. Finally we recommend next steps that we consider priorities for the identification and management of HCVAEs in northern Australia

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4. Hydrosystem delineation, environmental attribution and classification

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Key points

1. **Aim:** To develop a spatially consistent and comparable hydrosystem delineation and ecotope classification of aquatic assets for the Northern Australia HCVAE trial area based on the draft Australian National Aquatic Ecosystem (ANAE) Classification Scheme.
2. **Methods:** Using the Geoscience Australia Geodata 250k Hydrography theme feature classes, the ANAE Classification Scheme was applied to delineate Lacustrine and Palustrine hydrosystems in Northern Australia. Riverine hydrosystems were separately delineated based on the stream network derived from the national 9 second DEM for the Australian Hydrological Geospatial Fabric. Further application of the ANAE Classification Scheme involved the attribution of hydrosystems with ecologically relevant environmental data and statistical classifications to delineate hydrosystem ecotopes.
3. **Results:** Riverine, Lacustrine, and Palustrine hydrosystems and ecotopes were successfully delineated and classified for the Northern Australia HCVAE trial area, including the incorporation of perenniality and inundation frequency attributes. The results of the delineation and classification process provide base level mapped aquatic assets for the Northern Australia HCVAE trial area at a scale of 1:250,000.
4. **Implications:** The derived hydrosystems and associated ecotopes provide a rich source of ecohydrological information for Northern Australia and the necessary context for the delineation of HCVAEs of the region.
5. **Limitations / Knowledge gaps / next steps:** Main limitations of the use of the data are associated with local scale inconsistencies and mapping errors. Major knowledge gaps include knowledge of the transition zones between Estuarine and Riverine hydrosystems, flood residence times and associated inundation frequency, and perenniality, and methods to more effectively describe critical landscape processes that shape aquatic ecosystems. Further development of the ANAE Classification Scheme will involve expert workshops and the use of remote sensing to address knowledge gaps for hydrosystem delineation and effective classification of higher level aquatic ecosystems.

4.1 Introduction

Northern Australia hosts a range of aquatic ecosystem types (estuaries, rivers, lakes, wetlands) supporting high biodiversity and many endemic species of aquatic plants and animals. In order to implement a method for identifying HCVAEs, the collation and classification of aquatic ecosystems at a spatially consistent and comparable scale across the Northern Australia HCVAE trial area is required. The Aquatic Ecosystem Task Group (AETG) has produced a draft Australian National Aquatic Ecosystem (ANAE) Classification Scheme that facilitates the classification of aquatic ecosystems at varying and multiple levels including hydrosystems and further refinement to ecotopes (Auricht, 2010). This Classification Scheme emphasizes the connectivity between the different ecosystem types, a critical feature in aquatic ecology, and their dependence on the amount and temporal availability of the water that sustains them. Examples of the different types of hydrosystems are listed in Table 4.1 (note that marine and coastal foreshore hydrosystems are not considered in this Chapter).

Table 4.1. Northern Australian hydrosystems and their associated aquatic ecosystem types within the Australian National Aquatic Ecosystem (ANAE) Classification Scheme (Auricht, 2010).

Hydrosystem	Ecotope types present in northern Australia
Estuarine	Semi-enclosed embayments receiving sea water and fresh water inputs, mangrove forests, saltmarshes, saltflats, intertidal flats.
Riverine	Rivers, streams and waterbodies that may have fringing aquatic vegetation (but not including the hyporheic zone).
Lacustrine	Large waterbodies situated in a topographic depression or river channels that are largely open water features but may contain fringing aquatic and terrestrial vegetation.
Palustrine	Floodplains and vegetated wetlands such as marshes, bogs and swamps, and including small, shallow, permanent or intermittent water bodies.
Subterranean	Groundwater environments including the hyporheic zone and underground streams, lakes and water-filled voids
Artificial	Reservoirs, farm dams, mine tailings dams, flood irrigated field, canals and drainage channels

This chapter describes the application of the ANAE Classification Scheme to delineate four broad hydrosystems (Riverine, Lacustrine, Palustrine and Estuarine) for the Northern Australia HCVAE trial area (i.e. the study area). Further application of the ANAE Classification Scheme was implemented in the classification of ecotopes. Hydrosystem classes were attributed with ecologically relevant environmental data and statistical classifications applied to delineate ecotopes within each hydrosystem class. The delineated hydrosystems and associated ecotopes provide the base level mapped aquatic assets for the study area. The environmental data attributed to each hydrosystem class were used as predictor variables in the species distribution models (Chapter 7) and the delineated hydrosystems and associated ecotopes were used as environmental surrogates for biodiversity in the HCVAE assessment process (Chapters 8, 9 and 10).

4.2 Methods

4.2.1 Hydrosystem delineation

Riverine Delineation

The AusHydro National Surface Hydrology Dataset supplies the surface water hydrology features for the Australian Hydrological Geospatial Fabric (AHGF) that will underpin the Australian Water Resources Information System (AWRIS) (http://www.bom.gov.au/water/about/publications/document/InfoSheet_5.pdf). The AusHydro dataset is being developed jointly by Geoscience Australia and the Fenner School of Environment and Society at the Australian National University (ANU). A pre-publication version of the dataset was made available for this project. It includes two layers that support the baseline mapping for Riverine hydrosystems: i) watercourse lines based on the Geodata 1:250,000 scale hydrography theme series 1, supplemented by streamlines digitized by the ANU Fenner School of Environment and Society from 1:100,000 scale topographic mapping where necessary to assist drainage enforcement for the GEODATA national 9 second Digital Elevation Model (DEM) (Fenner School of Environment and Society ANU and Geoscience Australia, 2008) and ii) a stream network derived from the DEM. The watercourse lines, however, are a cartographic product and not readily amenable to spatial analysis tasks such as catchment delineation and network tracing. Accordingly, it is the AusHydro DEM derived streams that are used to delineate the Riverine hydrosystems for attribution with relevant environmental data and statistical classification.

The AusHydro DEM derived streams were delineated by tracing the surface flow pathways coded by a multi-flow extension of the GEODATA 9 second Flow Direction Grid associated with the GEODATA 9 second Digital Elevation Model Version 3 2008 (Fenner School of Environment and Society ANU and Geoscience Australia, 2008) from the channel heads of the AusHydro watercourse lines to either a coastal outlet or inland sink (Stein et al in prep.). Bifurcations in the AusHydro channel network were coded with multiple flow directions enabling the flow pathways to be traced downstream along both the river and its anabranch. Source channels with a contributing area less than 1.25 km^2 at their pour-point were removed from the traced network. These drain areas smaller than that which can be resolved from a DEM of 9 second resolution (about 270 m). However, main stem segments, defined as the segments draining the larger upstream contributing area, were retained to their source. Segment breaks were inserted at tributary confluences, distributary points, where a channel flows into or out of a lake or reservoir or over a cliff line and where the traced network connects gaps in the AusHydro watercourse lines.

The stream network represents the AusHydro watercourse line features, generalised to the 9 second grid resolution. It adds DEM connectors where there are breaks in the AusHydro watercourse lines to provide a fully connected network suitable for network tracing and other analytical uses. This layer also relates to the National Catchment Boundaries (NCB) that supply the conservation planning units (Chapter 3) through a shared segment identifier. The sub-catchment areas draining to each of the segments (links) in this layer form the lowest level sub-division of the NCB while the topological relationships among the streams provide the basis for assignment of the Pfafstetter (Verdin and Verdin, 1999) coding to each of the NCB units. While not available in time for this project, the Pfafstetter coding will facilitate easy aggregation of the catchment units and analysis of riverine connectivity for future HCVAE assessments.

Lacustrine, Palustrine and Estuarine Delineation

Two nationally available data sets were combined to provide the base level mapping of Estuarine, Lacustrine and Palustrine water features used in the application of the ANAE Classification Scheme: the Hydrography theme from Geoscience Australia's Geodata National Topographic Database (NTDB) (version 3), and the OzCoasts Geomorphic Habitat Mapping (Version 2). The Geodata Hydrography theme (Geoscience Australia, 2006) is a seamless coverage across Australia at a scale of 1:250,000, comprising 17 feature class representations of water features such as drainage, waterpoints, and waterbodies as lines, points and polygons, with some feature classes having attributes such as perenniality, and inundation frequency. Due to the complexity of estuarine processes, the Hydrography theme has relatively poor representation of estuarine and coastal features. To improve the estuarine and coastal mapping, the OzCoasts Geomorphic Habitat Mapping (http://www.ozcoasts.org.au/) was combined with the Hydrography theme.

The ANAE Classification Scheme is intended to build on the existing classifications currently applied in Australia by jurisdictions and consequently the scheme has no specific decision rules at any level in the classification hierarchy. The Queensland Department of Environment and Resource Management (DERM) have been the first Australian jurisdictions to implement the Classification Scheme under the Queensland Wetland Mapping and Classification program, and have implemented hydrosystem delineation at a scale of 1:100,000 across the entire state. As part of the Queensland mapping program, a set of specific decision rules for the delineation of hydrosystems was developed and published (EPA, 2005). For the purposes of the Northern Australia HCVAE trial, a modified version of the Queensland hydrosystem delineation decision rule set was implemented for the Geodata Hydrography theme and OzCoasts data over the study area.

The hydrosystem delineation rule set used for the Northern Australia HCVAE trial is summarised in Figure 4.1. An initial study was undertaken to provide interpretation of the Geodata Hydrography features in the context of hydrosystems delineation used in the Queensland methodology (Appendix 4.1). This study involved an assessment of the Geodata representation of water features in different catchment geomorphic environments and provided the basis for developing a modified version of the Queensland hydrosystem delineation rule set. Extensions of the Queensland methodology included specific feature interpretation of the Geodata feature classes, additional topological rules associated hydrosystem delineation, and variation in the interpretation and classification of inundation frequency and perenniality. Appendix 4.1 outlines in more detail the implementation of hydrosystem delineation within the ANAE Classification Scheme.

The Geodata cartographic representation of Riverine hydrosystems includes linear drainage networks, watercourse areas and waterbody features. To incorporate Riverine Hydrography features with the Riverine analysis being undertaken by ANU Fenner Scheool of Environment and Society, the Riverine hydrosystems were classed as either River Watercourse or Riverine Waterbody. The Riverine Watercourse areas were delineated based on Hydrography feature classes but were then combined with the classification associated with Riverine line features derived from the 9 sec DEM by the ANU. Riverine Waterbodies were delineated based on the Hydrography feature classes of Waterholes, Waterpoints and Lakes (Fig. 4.1). The ANAE Classification Scheme does not provide any specific decision rules for deciding if a large waterbody is Lacustrine. The QLD mapping program use the Cowardin et al. (1979) definition: “The Riverine System includes all wetlands and deepwater habitats contained within a channel”. A post delineation modification to the scheme outlined in Figure 4.1 was introduced such that river channel waterbodies (e.g. oxbow lakes) are classified as Lacustrine. Large artificial storages, such as Reservoirs, Town Storage and Rural Irrigation storages were also classified as Lacustrine but were not included in the analysis.

Perenniality

Perenniality is an important functional trait of all hydrosystems. The Geodata Hydrography theme contained a populated perenniality attribute (Perennial or Non-Perennial) for many, but not all water features. Geodata perenniality is defined as “Where an area normally contains water for the whole year, except during unusually dry periods, in at least nine years out of ten”. This definition implies a 1 in 10 year return interval for a drying event. Following the classification of the Hydrography feature classes to hydrosystems, an analysis of perenniality attribution revealed that, except for tidally influenced Estuarine hydrosystems a large proportion of the Palustrine hydrosystems lacked a perenniality attribute. Based on the assumption that most Palustrine waterbodies do not persist through the dry season and as such are non-perennial, all unattributed Palustrine hydrosystems were attributed with a ‘Non-Perennial’ attribute. However, it is known that not all unattributed Geodata derived Palustrine hydrosystems in Northern Australia are non-perennial and identification of these will need to be addressed in future updates of the ANAE Classification Scheme.

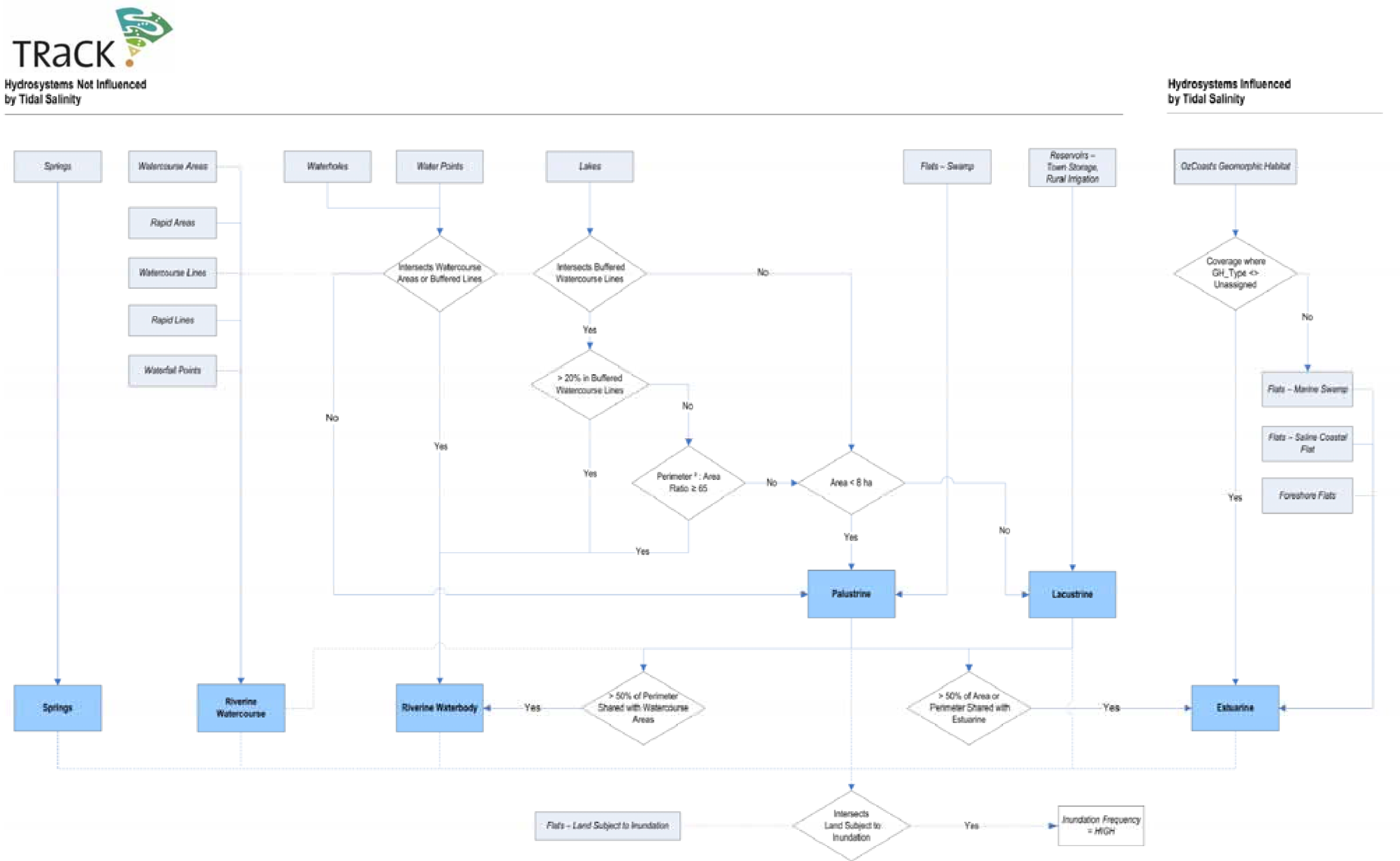

Figure 4.1. Decsision tree used to classify hydrosystems based on Geoscience Australia Geodata 250k Hydrography and OzCoasts Geomorphic Habitat mapping data. Classification model based on EPA (2005).

Inundation Frequency

The inundation frequency of aquatic ecosystems has a range of ecological implications, particularility those related to connectivity, influencing the movement of biota between waterbodies or onto the floodplain. The Geodata Hydrography feature classes have no specific attribute for inundation frequency. However, the Geodata Flats feature class has a "Land Subject to Inundation" attribute. Using remotely-sensed inundation frequency mapping for the Mitchell, Daly and Fitzroy catchments (Ward, D.P unpublished), the "Land Subject to Inundation" attribute was tested for its representation of inundation frequency. Based on remote sensing derived inundation frequency it was found that the "Land Subject to Inundation" attribute adequately represented inundation frequency for floodplains with long flood residence times (e.g Daly River floodplain), but did not capture the extent of more extreme events (> 1 in 10yr) for floodplains with more 'flashy' flood events (eg. Mitchell River floodplain). Despite not capturing the extent of extreme events , the "Land Subject to Inundation" attribute was considered an ecologically meaningful attribute and the following rules were developed to attribute hydrosystems with an inundation frequency value. If a water feature intersected an area designated as "Land Subject to Inundation" then the feature is classified as having a "High" inundation frequency. All non-intersecting features have a default value of "Low" inundation frequency.

Point Feature Represenation

A large proportion of the Geodata derived Palustrine hydrosystems were point features and lacked an estimate of area. Much of the summarization of hydrosystems by Planning Units utilizes water feature area. To accommodate the Planning Unit summarization process a nominal area based on a Palustrine feature radius of 25m was allocated to all Palustrine point features. This nominal area was spatially implemented by buffering all Palustrine features by 25m. This buffer distance is very conservative as Palustrine hydrosystem vary significantly in size and consequently area calculations using buffered Palustrine features will underestimate the area of these hydrosystems. Knowledge of the size distribution of point based water features is a fundamental limitation of the Geodata mapping of water features.

Estuarine Hydrosystems

We classified hydrosystem classes that intersected either the OzCoasts Geomorphic Habitat extent or Geodata Saline Coastal Flat, Saline Swamp, or Foreshore Flats classes as Estuarine. Large linear features such as Riverine Watercourse polygons that intersect Estuarine polygons may extend a significant distance inland away from the estuarine zone. As the proportion of the feature in the estuarine zone can vary dramatically depending on their length, it is innapropriate to reclassify the entire feature as Estuarine. A meaningful reclassification would involve identification of the transition zone from Estuarine to Riverine. Defining the extent of the Estuarine hydrosystems is beyond the capacity of this project and will be addressed in future updates of the ANAE Classification Scheme. Further to this, we found the Geodata and OzCoasts estuarine classes to be of inadequate spatial resolution and were not sufficiently validated with respect to the spatial accuracy of hydrosystem boundaries. Due to the difficulty in adequately delineating the extent of the Estuarine Hydrosystems in the timeframe available for this project, they were omitted from the analysis for the study area.

Hydrosystem Validation

To gain some insight into the validity of delineating hydrosystem based on the ANAE Classification Scheme using the 1:250,000 Geodata Hydrography features, a comparison was made between the Geodata derived hydrosystems and the hydrosystems delineated by the Queensland Wetland Mapping and Classification program. Water features mapped by the Queensland program comprise mainly two sources: 1:50,000 topographic mapping, and analysis of a 20 yr dry season Landsat TM time series. The Palustrine hydrosystems were chosen as the test hydrosystem because the same delineation rules were applied to both the Geodata and the Queensland program data. Since a large proportion of the Geodata derived Palustrine features are point features and do not have a spatially explicit area, hydrosystem counts within river basins were used for comparisons. The underlying premise for the comparison is that while different river basins will have different configurations of Palustrine systems, and mapping scale will significantly influence the number of mapped features, the resulting proportions between river basins should be similar.

4.2.2 Environmental attribution

The approach adopted in implementing the ANAE ecotope classification was to attribute hydrosystem-level water features with environmental data and apply statistical classification techniques to delineate ecotopes within each hydrosystem class. The environmental data used in attributing hydrosystems comprised the broad themes of Climate, Catchment Water Balance, Vegetation, Substrate and Topography. The data were compiled as a series of rasters of consistent spatial extent gridded at a resolution of 9 seconds of latitude and longitude or an integer multiplier consistent with the scale of the source data mapping.

Climate

Climate ultimately controls many of the processes that shape streams and their associated ecosystems (Knighton, 1998). Solar radiation, for example, is the major factor influencing stream temperature (Johnson, 2003) and through it the rate of in-stream chemical and biological processes. Rainfall and temperature affect rates of weathering of rock and hence their hydrogeological properties and the release and transport of solutes and bed and bank materials (Knighton, 1998). Climatic parameters supply surrogates for the critical environmental regimes (light, moisture, thermal) that control plant growth (Nix, 1981). In turn, plant productivity influences catchment erosion and runoff processes and organic matter inputs to streams.

Climate was characterise d by a set of bioclimatic parameters and plant growth indices (Table 4.2) computed with the BIOCLIM and GROCLIM programs from the ANUCLIM software package version 6 (Hutchinson et al., 2009). BIOCLIM produces ecologically relevant parameters from weekly mean values of maximum temperature, minimum temperature, rainfall, radiation and evaporation. These parameters summarize annual and seasonal mean conditions, extreme values and intra-year seasonality (Hutchinson et al., 2009). GROCLIM, a simple, generalised model of plant growth (Hutchinson et al., 2009), derives separate indices, each scaled between zero (completely limiting to growth) and one (not limiting), that describe the plant response to the light, thermal and moisture regimes. The Growth Index (GI) is the product of these three indices. Gridded estimates of GI were computed on a weekly time step for plants with different growth responses: i) mesotherm plants with an optimal temperature for growth of 19°C , range 3-36°C and ii) megatherm plants with an optimal temperature of 28°C, range 10-38°C. The moisture index calculations did not account for the spatial variability in soil properties as negligible changes in soil water storage could be assumed for the water balance calculations that were based on long term mean rainfall and evaporation values. A measure of average conditions and seasonality was derived for each grid cell by calculating, respectively, the annual mean and the coefficient of variation of the weekly GI values (Table 4.2). Gridded values of modelled monthly and mean annual baseline (pre-1788) Net Primary Productivity compiled for the National Land and Water Audit (NLWRA) (Raupach *et al.*, 2001) supplied a more direct indicator of productivity though at the coarser resolution of 0.05 degrees of latitude and longitude (about 5 km).

The rainfall erosivity R factor was included as an indicator of rainfall intensity, an important influence on processes of infiltration and runoff generation. It describes the potential for rainfall induced soil loss based on storm kinetic energy and the maximum, 30-minute rainfall intensity (Lu & Yu, 2002). A grid of the rainfall erosivity R factor was obtained from the NLWRA, Australian Natural Resources Data Library (ANRDL) (National Land and Water Resources Audit, 2000).

Table 4.2. Climatic parameters showing spatial scale at which the mean value was calculated for attribution to Riverine hydrosystems.

Climate variable	Units	Stream and valley bottom	Sub-catchment	Catchment
Annual Mean Solar Radiation	$MJ/m^2/day$	X		X
Annual Mean Temperature	°C	X		X
Coldest Month Mean Temperature	°C	X		X
Hottest Month Mean Temperature	°C	X		X
Average Coldest Quarter Mean Temperature	°C	X		
Average Driest Quarter Mean Temperature	°C	X		
Average Wettest Quarter Mean Temperature	°C	X		
Average Annual Mean Rainfall	mm	X		X
Average Driest Quarter Mean Rainfall	mm	X		X
Average Wettest Quarter Mean Rainfall	mm	X		X
Average Warmest Quarter Mean Rainfall	mm	X		X
Average Coldest Quarter Mean Rainfall	mm	X		X
Rainfall Erosivity R Factor	(MJ mm)/(ha hr yr)		X	X
Annual Growth Index (Megatherm Plants)	dimensionless	X		X
Annual Growth Index (Mesotherm Plants)	dimensionless	X		X
Growth Index Seasonality (Megatherm Plants)	dimensionless	X		X
Growth Index Seasonality (Mesotherm Plants)	dimensionless	X		X

Catchment Water Balance

The catchment water balance attributes describe more directly key aspects of the climatic influence on stream hydrology. They were derived from real time estimates of monthly runoff computed with the water balance module of the GROWEST program (Nix, 1981; Hutchinson et al., 2004). This or similar models have been found to reasonably reproduce annual (Atkinson et al., 2002; Stein et al., 2002) or monthly flows (Jellett, 2005). Unlike more complex rainfall-runoff models, catchment specific calibration of model parameters could be avoided by setting the two required parameters, a soil texture category and the maximum available soil water, based on broadly known soil attributes. It was thus suitable for continent-wide application.

The water balance module is conceptualised as a single “bucket” model. It adds rainfall to the previous soil storage and removes it by means of evapotranspiration. The soil water surplus or “runoff” is the rainfall exceeding “bucket full” after allowing for evapotranspiration. Monthly rainfall and pan evaporation estimates were generated at a grid spacing of 0.01 degrees (approximately 1km) using elevation values derived by resampling the 9 second DEM version 3 with bilinear interpolation, and monthly climate surface coefficients (Kesteven et al., 2004) for a 30 year period from 1971 to 2000. GROWEST operates on a weekly time step, converting the monthly input rainfall and evaporation data to weekly values via cubic Bessel interpolation. The model requires data for soil texture and the maximum available soil water to infer the relative water retention capabilities of the soil. Soil texture was defined by classifying the values in the Australian Soil Resource Information System (ASRIS) grid of percent of clay in the A horizon (National Land and Water Resources Audit, 2001c). Maximum available soil water parameters were derived by summing the ASRIS gridded values for the soil A and B horizons (National Land and Water Resources Audit, 2001a, 2001b).

The catchment water balance of a segment is the sum of the runoff contributions of all grid cells upstream of the segment pour-point, expressed as a flow volume by multiplying by the grid cell area. Upstream grid cell contributions were accumulated downstream along the DEM-defined flow pathways and distributed to major anabranches in accordance with stream name (in the ratio of 8 rivers: 4 creeks: 1 unnamed: 0.1 floodplain wetlands) following the method of Stein (2007). Summary statistics were derived from the time series of monthly catchment water balance values as indicated in Table 4.3.

Table 4.3. Catchment water balance attributes derived from the monthly accumulated soil water surplus values (1971 to 2000) calculated in units of ML/month. The attributes shown in the left column in bold were selected to classify Riverine ecotopes.

Mean of the annual and maximum monthly totals	Coefficient of variation of the annual maximum monthly
Coefficient of variation of the annual and monthly totals	Coefficient of variation of the annual minimum monthly
Minimum and maximum of the annual totals	Mean of the monthly totals (January to December)
Seasonal mean (summer, winter, autumn and spring)	Percentiles of the annual totals (5,10,20,30,40,50,60,70,80,90,95%),
Skewness (Median annual accumulated soil water surplus / mean annual accumulated soil water surplus)	Mean of the annual minimum monthly
Perenniality (proportional contribution to mean annual discharge by the six driest months of the year) (%)	

Substrate

Substrate properties play a major role in shaping aquatic systems, influencing the type of material available for erosion, its weathering and transport (Montgomery, 1999). Runoff carries the geochemical signature of the underlying geology (Smith, 1998) while ecologically important properties of a stream's hydrograph, such as the contribution from groundwater or the size of the peak flows, are related to the hydrogeological properties of the geological substrate underlying the catchment (McMahon, 1977).

The state coverages that together comprise the digital 1:1 million scale Surface Geology of Australia (Liu *et al.*, 2006; Raymond, Liu & Kilgour, 2007; Raymond, et al., 2007; Whitaker et al., 2007; Stewart et al., 2008; Whitaker et al., 2008) provide seamless national mapping of geology. The many thousands of lithological units mapped by this data were classified according to their broad lithological composition as coded in the gross rock descriptor field that is attributed to each mapping unit (Table 4.4.). A raster coding the occurrence of each lithological class was derived at 9 second resolution. These classes were expected to reflect variation in rock hydrogeological, geophysical and geochemical properties and hence their influence on aquatic ecosystems. An additional class, based on the age of the rocks, was derived to reflect the increased porosity and permeability that accompanies weathering and fracturing of rocks over time (Le Moine et al., 2007). The hydraulic conductivity of the materials in the immediate environs of the stream is also an important influence on stream and aquifer connectivity (Ransley et al., 2007). Accordingly, the proportion of coarse grained unconsolidated materials in the immediate vicinity of the stream and its associated environs was taken to be an indicator of the potential for groundwater recharge. These materials generally have high conductivities (Cook, 2003).

Table 4.4. Lithology classes used to group mapping units from the digital 1:1 million scale Surface Geology of Australia

Attribute
Old bedrock (rocks >570My)
Siliciclastic/undifferentiated sedimentary rocks (e.g. sandstones, conglomerate, mudstone, siltstone)
Carbonate sedimentary rocks (e.g. limestone, marl, dolomite)
Other sedimentary rocks (includes volcanogenic sediments, non-carbonate chemical sediment, organic-rich rocks)
Igneous rocks (includes felsic, mafic, ultramafic intrusives and extrusives)
Mixed sedimentary and igneous rocks
Metamorphic rocks (e.g. slate, schist, gneiss, serpentinite, hornfels)
Unconsolidated rocks (regolith)

Gridded layers of soil hydraulic properties with a grid resolution of 0.01 degrees were derived from the Soil Hydraulic Properties of Australia dataset (Western & McKenzie, 2004) while soil texture data similarly gridded at 0.01 degree resolution was obtained from the Australian Soil Resource Information System (ASRIS) through the Australian Natural Resources Data Library (ANRDL) (Table 4.5.).

Table 4.5. Soil attributes compiled from the Australian Soil Resource Information System and the Soil Hydraulic Properties of Australia dataset

Attribute
Percent clay in the A horizon
Percent clay in the B horizon
Percent sand in the A horizon
Saturated hydraulic conductivity
Solum plant available water holding capacity

Terrain

The elevation of the land surface plays a critical role in modulating the Earth surface processes that shape aquatic ecosystems (Hutchinson, 2008). Elevation across the NAWFA project area is described by the national 9 second DEM (Fenner School of Environment and Society ANU and Geoscience Australia, 2008), a drainage enforced DEM with national coverage. In addition to elevation *per se* the 9 second DEM accurately represents the shape of the land surface enabling secondary terrain attributes to be derived to describe the significant influence of topography on aquatic ecosystem character and behavior.

The intensity of erosion processes on hillslopes is associated with their slope. Slope also exerts a significant control on hillslope-stream coupling and thus the transfer of material from hillslopes into the channel (Brierley *et al.*, 1996). A grid of slope was calculated from the 9 second DEM using biquadratic spline interpolation with the SLPGRD program (Michael Hutchinson, ANU, unpublished). While slopes computed from the 9 second DEM seriously underestimate local slopes, they are nonetheless an important predictor of slope (Gallant, 2001) and can therefore be expected to differentiate the relative strength of erosion processes. Values of the multi-resolution Valley Bottom Flatness (mrVBF) and multi-resolution Ridge Top Flatness (mrRTF) indices (Gallant & Dowling, 2003) were also computed from the DEM. These indices separate erosional and depositional areas in the landscape dependent upon their areal extent, relative position and slope. A Flatness Class (John Gallant, CSIRO Land and Water pers. comm. 16/4/2004), one of valley bottom, ridge top flat, hillslope or indeterminate, was assigned based on the relative grid cell values of mrVBF and mrRTF.

Additional terrain parameters (Table 4.6.) were computed from the national 9 second DEM to account more specifically for the influence of catchment and valley morphology on stream hydrological, geomorphological and ecological properties.

Vegetation

The type and cover of vegetation has wide ranging influence on freshwater systems exerting control on the hydrologic and sediment supply regimes (Brooks, 1994) and the supply of organic material and woody debris (Boulton and Brock, 1999). Vegetation cover and type was described by the “Estimated pre-1750 Major Vegetation Subgroups” raster dataset from the National Vegetation Information System (NVIS) Version 3.1 (Australian Government Department of the Environment and Water Resources, 2006). Pre-1750 vegetation, rather than present day vegetation, was used to avoid confounding the classification with the effects of recent (post European) industrial society. The 67 major vegetation subgroups were grouped to form 5 broad classes (Table 4.7., Appendix 4.3).

Table 4.6. Terrain attributes describing the catchment and valley morphology calculated for each stream segment. Attributes indicated in bold italics were selected for the Riverine ecotope classification.

Attribute	Units	Definition
Valley confinement	%	Percentage of stream segment grid cells and their immediate neighbours that are not Flatness Class valley bottoms
Aspect	°	Mean aspect of the stream segment grid cells (computed by taking the mean of the northerly and easterly components of the direction of flow separately)
Valley Slope	%	Stream segment slope: computed as the difference in elevation between the highest and lowest cells of the stream segment divided by its length
Maximum downstream slope	%	Maximum slope from one grid cell to the next in the direction of flow downstream to the stream outlet. At stream bifurcations direction is always that to the main channel
Average downstream slope	%	Average slope from one grid cell to the next in the direction of flow downstream to the stream outlet (either the sea or an internal sink). At stream bifurcations direction is always that to the main channel
Catchment slope	°	Mean slope of all grid cells upstream of the segment pour-point (including both valley and hillslope cells)
Sub-catchment slope	°	Mean slope of all grid cells in the segment sub-catchment
Slopes > 10%	%	% grid cells in segment sub-catchment with slope > 10%
Slopes > 30%	%	% grid cells in segment sub-catchment with slope > 30%
Catchment area	km^2	The contributing area upstream of the segment pour-point
Catchment length (Distance to source)	km	Maximum flow path length upstream from the segment pour-point cell, calculated by incrementing the maximum upstream length of neighbouring contributing cells. Flow path distance is the distance to move across the surface, allowing for the change in elevation, from the centre of the grid cell to the centre of the next grid cell downstream in the direction of flow.
Distance to outlet	km	Distance to outlet
Maximum upstream elevation	m	Maximum elevation value of all upstream grid cells
Mean upstream elevation	m	Mean elevation value of all upstream grid cells
Mean segment elevation	m	Mean elevation value of all cells in segment
Catchment relief		(mean upstream elevation-pour point elevation)/(max upstream elevation-pour point elevation).
Catchment relief ratio		(maximum upstream elevation-pour point elevation)/(flow path distance from source)
Catchment storage	%	Proportion of upstream grid cells that are classed as valley bottoms
Catchment shape (Elongation ratio)		$R_e = D_c / L$, where: D_c = the diameter of a circle with the same area as the catchment area upstream of the segment, L = the maximum length of the catchment along a line basically parallel to the main stem (Gordon et al., 2004)
Stream density	km/km^2	Accumulated length of DEM derived stream upstream of the segment pour-point cell / upstream area

Table 4.7. Vegetation classes defined by grouping the NVIS Major vegetation subgroups. See Appendix 4.3 for details.

Attribute
Melaleuca dominated forests, woodlands and shrubs
All other forests, woodlands and shrublands
Naturally bare areas
Coastal vegetation communities
Sedgelands and grasslands

Riverine Environmental Attribution

Environmental attributes were summarized at multiple scales to account for the different spatial scales at which environmental controls operate on Riverine ecosystems. Summary statistics compiled for the climatic attributes are indicated in Table 4.2. Table 4.6. describes the scale at which each of the terrain attributes is computed. The catchment water balance summary statistics attributed to the stream segment (Table 4.3) were based on the totals of the accumulated soil water surplus values at the pour-point of the stream segment. Lithological attributes were derived at two spatial scales, the valley and the catchment by calculating the areal proportion of firstly, the stream segment and associated valley bottom and secondly, the upstream catchment, that was underlain by rocks of the respective lithology class. For this purpose, the 1:1M digital Geology was gridded at a resolution 4 times finer then aggregated to 9 second resolution by calculating the area of the larger cell occupied by the lithological class so increasing the likelihood that smaller mapping units were represented. The classes derived from the NVIS pre-European major vegetation sub-groups raster were similarly aggregated to 9 second resolution from the finer scale NVIS raster and areal proportions calculated for, respectively, the stream and its valley and the upstream catchment. Soil hydraulic properties were attributed as catchment mean values while those describing the soil texture were summarized as the mean of the grid cell values within the segment and its associated valley bottom. In all cases, catchment average values were calculated by accumulating the values of all upstream grid cells and dividing by the count. At bifurcations in the stream network accumulated totals and cell counts were divided in the ratio of 8 rivers: 4 creeks: 1 unnamed streams: 0.1 floodplain wetlands as described above for the catchment water balance.

Lacustrine, Palustrine and Estuarine Environmental Attribution

Lacustrine, Palustrine and Estuarine hydrosystems were attributed with environmental data under the themes of Geology (Table 4.4), Soils (Table 4.5), Terrain (Table 4.6), and Vegetation (Table 4.7). Vector intersects, raster zonal statistics and vector area proportioning was used to attribute hydrosystem points and polygons with environmental data. A unique ID was developed for each individual aquatic feature (point and polygon). The process of attributing Lacustrine, Palustrine and Estuarine hydrosystems with environmental data resulted in a data table comprising a unique ID, hydrosystem class and list of environmental variable statistics for each individual aquatic feature (point and polygon). The unique ID formed the basis for linking the results of the statistical classification back to the individual hydrosystem features.

4.2.3 Statistical Classification of ecotopes

Ecotopes for Riverine, Lacustrine and Palustrine hydrosystems were derived by classifying individual features (lakes, wetlands and river segments) using the numerical clustering procedure ALOB from the PATN software package (Belbin, 1993). ALOB employs a non-hierarchical allocation method that is well suited to classifying very large numbers of objects and produces results that are at least comparable with traditional agglomerative hierarchical methods (Belbin, 1987). It employs a simple iterative procedure to allocate objects into groups reflecting the shared similarities of the attributes that describe them. Classes are thus an emergent property of the data rather than defined *a priori* as for example is the case for New Zealand's River Environment Classification (Snelder & Biggs, 2002).

Hydrosystem features were classified using a selected set of the environmental attributes, grouped so that each set of attributes contributed equally to the calculation of the distance measure regardless of the number of attributes within the set.

The distance of a feature from the group centroid was measured by the Gower metric (Gower, 1971). An initial set of classifications was generated with varying numbers of groups (between 10 and 41 for the riverine segments and between 10 and 20 for the Lacustrine and Palustrine features). The final number of groups was chosen to balance the trade off between increasingly homogeneous groups with greater numbers of groups and the maintenance of recognisable differences in environmental characteristics between the groups and ease of communication and interpretation. The set of environmental attributes used to classify riverine ecotopes was reduced for the final classification by omitting those attributes that contributed little to the discrimination of groups as judged by the value of the Kruskal Wallis test statistic (Belbin, 1993) .

To assist understanding of the relationships between the groups, the centroids of the groups generated with the ALOB non-hierarchical algorithm were themselves classified using the hierarchical agglomerative clustering routine, flexible UPGMA (Un-weighted Pair Group Mean Averaging), implemented in the FUSE module of PATN, using the recommended value of –0.1 for the β parameter that controls the degree of dilation or contraction (Belbin *et al.*, 1992). A 3-dimensional ordination of the group centroids was constructed with the semi-strong hybrid multi-dimensional ordination method available in PATN using the Gower metric.

4.3 RESULTS

4.3.1 RIVERINE

The AusHydro DEM derived streams map nearly 1.4M stream segments across the country of which 334,468 occur within the Northern Australia HCVAE trial project area. Segments vary in length from a single grid cell (about 270m) up to 61km (mean 2.3km) reflecting the natural variation in drainage density across the region. Assessment of the accuracy of the AusHydro DEM derived streams is yet to be completed, however, it can be expected that it will equal or exceed that of the streams derived from an interim version of the DEM (Stein et al., 2008) that were found to be on average just 61.6m from the mapped streams. This is the expected difference due to gridding and generalization of the vector stream lines to the grid cell resolution of 9 seconds of latitude and longitude.

Riverine ecotopes were delineated by the 20 group classification. Stream segments are distributed among the ecotopes somewhat unevenly. The most commonly occurring of the ecotopes (18) includes almost 14% of the total stream length within the project area while the rarest (19) less than 1%. Ecotopes need not be spatially cohesive and a single river may traverse many ecotopes. The main stem of the South Alligator River, for instance, flows through six of the ecotopes (4, 6, 7, 10, 11 and 18) and even more if its tributaries are also considered (Table 4.8 and Table 4.9).

Table 4.8. Attributes selected for classification of Lacustrine and Palustrine features showing attribute groupings used for the calculation of the Gower dissimilarity measure. Each attribute group contributes equally to the value of the Gower metric regardless of the number of attributes within the group.

Attribute group	No. attributes in group	Attribute
1	2	Perenniality of water feature from Geodata TOPO 250K. "Non-perennial" if unknown. Inundation frequency attribute derived from Geodata Topo 250K Land Subject to Inundation theme
2	2	Feature area in square metres. (fixed at 1737m^2 for Palustrine points) Shape statistic - perimeter squared : area ratio (fixed at 12 for Palustrine points)
3	4	Saturated hydraulic conductivity (mm/h) Solum plant available water holding capacity (mm) Soil clay content in the A horizon (%) Soil clay content in the B horizon (%)
4	8	Carbonate sedimentary lithology over feature Igneous lithology over feature Metamorphic lithology over feature Other sedimentary lithology over feature Mixed sedimentary / igneous lithology over feature Siliciclastic/undifferentiated sediment lithology over feature Unconsolidated rocks (regolith) over feature Old rocks (> 570my) over feature
5	4	% of feature intersected with Flatness class: Erosional % of feature intersected with Flatness class: Indeterminate % of feature intersected with Flatness class Valley Bottom Flat % of feature intersected with Flatness class: Ridge Top Flat
6	1	Elevation (m) from Digital Elevation Model (version 3)
7	5	% of feature intersected with Vegetation class: Grasslands/ Sedgelands % of feature intersected with Vegetation class: Melaleuca % of feature intersected with Vegetation class: Coastal communities % of feature intersected with Vegetation class: Naturally bare % of feature intersected with Vegetation class: Trees and Shrubs

Table 4.9. Attributes used to classify riverine ecotopes showing attribute groupings used for the calculation of the Gower dissimilarity measure. Each attribute group contributes equally to the value of the Gower metric regardless of the number of attributes within the group. To reduce data skew selected attributes were transformed as indicated.

Attribute group	No. attributes in group	Attributes	Transformation
1	31	Climatic attributes as indicated in Table 4.2	square root all rainfall attributes, log(x+1) rainfall erosivity
2	14	Terrain attributes as indicated in Table 4.6.	
3	15	Stream and valley and catchment areal proportions of each of the lithology classes indicated in Table 4.4. excluding the mixed sedimentary and igneous rocks and other sedimentary classes Stream and valley average % clay in the A horizon Stream and valley average soil hydraulic conductivity	
4	12	Catchment water balance attributes as indicated in Table 4.3	log(x+1) all runoff volume attributes
5	8	Stream and valley proportions of each of the 5 vegetation classes indicated in Table 4.7. Catchment proportion of each of vegetation class: trees and shrubs, grasses and sedges and naturally bare	

The ecotopes form three broad meta-groups (Figure 4.2), each widely distributed across the project area (

Figure 4.3.). The streams in Meta-group 1 are typically small, often occupying upper catchment positions and flowing in lower rainfall parts of the region. The vegetation cover of catchments in this meta-group is naturally dominated by grasses. In contrast, the dominant vegetation cover in the catchments of meta-group 2 streams is trees and shrubs. The streams included in this meta-group have higher runoff volumes than those in meta-group 1 though typically less than those in meta-group 3. Meta-group 3 includes the largest rivers with high runoff volumes and lower inter-annual runoff variability that occur in largely unconfined settings at lower elevations. The environmental characteristics that distinguish the riverine ecotopes within each meta-group are shown graphically in the box plots presented in Appendix 4.4 and summarised in Table 4.10.

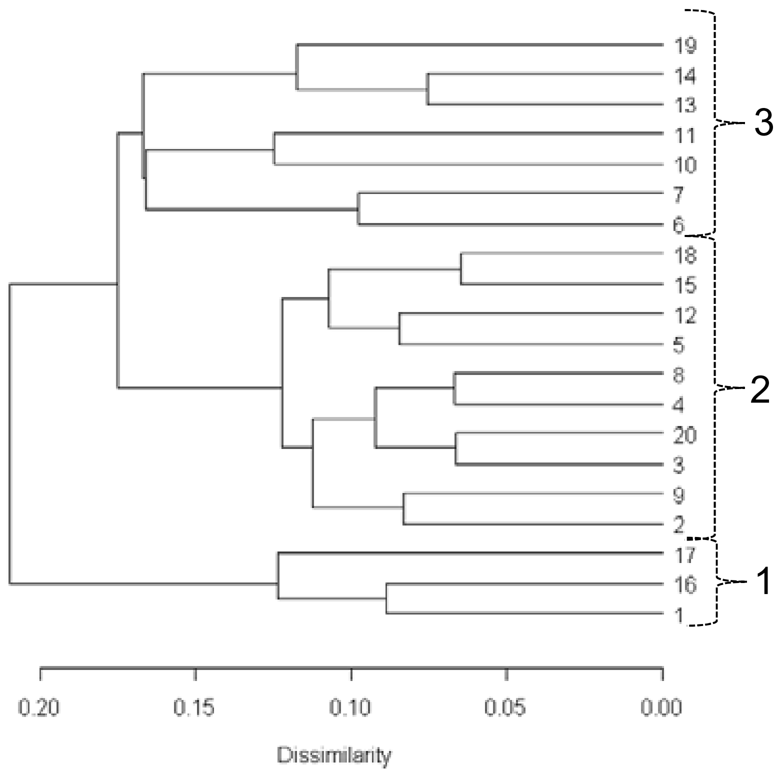

Figure 4.2. Dendrogram showing the relationship among the riverine ecotopes derived by hierarchical clustering of group centroids. Numbered meta-groups are indicated with vertical dashed lines (see also Fig. 4.3 and Table 4.10).

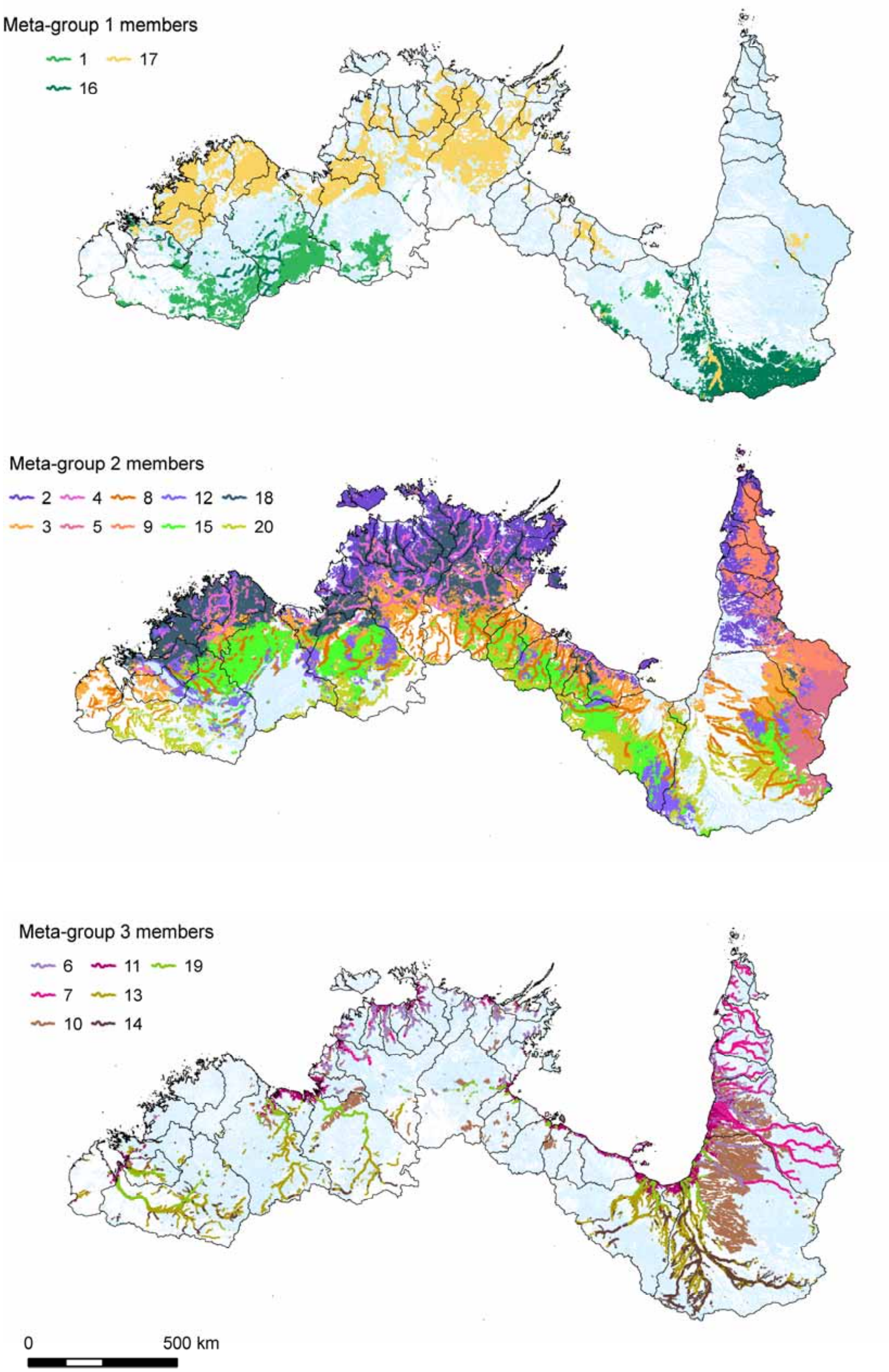

Figure 4.3. Riverine ecotopes by meta-group. Colours used to map the groups were derived by aligning the ordination axes of a 3-dimensional ordination of the ecotope centroids (not shown) with the three primary colours and assigning a colour to each ecotope based on its position in the configuration. Ecotopes that are closer in environmental space are mapped in similar colours.

Table 4.10. Riverine ecotopes indicating the environmental characteristics that distinguish ecotopes from others in the meta-group.

Meta-group	Ecotope	Total stream length (km)	Characteristics
	1	41,404	high radiation, moderate growth potential between ecotopes 16 and 17, catchments underlain by younger rocks often igneous rarely siliclastic sediments and soils with lower hydraulic conductivity
	16	40,797	higher plant growth potential, high radiation, less seasonal variability, confined valley setting with steeper hillslopes at higher elevations draining steeper catchments of moderate to high relief underlain by sedimentary or igneous parent materials (> 570My) with, little unconsolidated material
1	17	30,283	lower rainfall, cooler temperatures, draining gently sloping and more elongated catchments that receive higher rainfall intensities
	2	61,743	lower elevations, cooler temperatures in the wet season, higher potential and less seasonal megatherm plant growth, higher rainfall intensities
	3	73,830	hotter temperatures, high radiation and higher rainfall than most similar ecotope (20), unconsolidated materials reasonably common in the catchment, but igneous rocks very rare
	4	20,745	higher rainfall intensities, mostly falling in warmer months, more elongated catchment producing highly skewed runoff, less variable monthly and annual runoff, higher mean and maximum annual runoff volumes
	5	32,979	lower temperatures, confined valley setting with steeper hillslopes at higher elevations
	8	21,460	draining more elongated catchments with higher relief, runoff less skewed, higher mean and maximum annual runoff volumes
	9	42,636	higher potential and less seasonal megatherm plant growth, steeper valleys, cooler temperatures in the wet season, pockets of steeper slopes on hillslopes, draining catchments with higher relief that receive higher rainfall intensities
	12	52,507	confined valley setting draining catchments with higher relief underlain by old rocks often igneous rarely siliclastic sediments
	15	87,962	confined valley setting with steeper hillslopes at higher elevations draining catchments with higher relief underlain by old rocks often siliclastic sediments
	18	104,930	confined valley setting draining catchments with higher relief underlain by old rocks often siliclastic sediments
2	20	51,227	less erosive rainfall, lower growth potential for both mesotherm and megatherm plants, unconsolidated materials reasonably common in the catchment, but igneous rocks very rare
	6	9,668	high annual mean and maximum runoff totals ,with gently sloping hillsides draining low relief catchments, higher rainfall intensities
	7	6,919	high annual mean and maximum runoff totals, relatively more runoff in winter months, draining low relief catchments, higher rainfall intensities
	10	31,470	lower and less variable runoff, draining catchments with higher relief, valley vegetation cover typically dominated by Melaleuca communities
	11	16,251	moderately skewed runoff, lower and less variable runoff volumes, unconfined valley setting with gently sloping hillsides at lower elevations
	13	15,607	more variable runoff, valley vegetation cover naturally dominated by grasses and sedges, less favourable conditions for plant growth across the catchment, cooler temperatures at times though warmer in wetter periods, less erosive rainfall
	14	14,035	more variable runoff, gently sloping hillsides draining low relief catchments, valley vegetation cover naturally dominated by trees and shrubs, less favourable conditions for plant growth across the catchment, cooler temperatures at times though warmer in wetter periods, less erosive rainfall
3	19	4,619	higher annual mean and maximum runoff totals, lower elevations, draining low relief catchments, higher temperatures

4.3.2 Lacustrine and Palustrine

Application of the Hydrosystem delineation (Fig. 4.1) to the Geodata Hydrography feature classes resulted in the delineation of 26,075 Riverine Waterbodies and Lacustrine and Palustrine individual hydrosystem features across the study area. Additional development of the Geodata 'Perennial ' and 'Land subject to inundation' attributes resulted in binary attribution of Perenniality and Inundation Frequency for all hydrosystem features.

Lacustrine Hydrosystems

Lacustrine Hydrosystem classification resulted in a total 7,740 individual features comprising an area of 104,210 ha within the Northern Australia HCVAE trial area. Lacustrine hydrosystems are widespread across the study area with the largest areas of Lacustrine systems occurring in the Alligator, Mary, Adelade and Finnis River systems in the Northern Territory and the Fitzroy River system in Western Australia (Fig. 4.4). Significant areas of smaller Lacustrine features (predominately Riverine waterbodies) also occur in the Fitzroy, Ord-Pentecost, and Victoria River systems in Western Australia, and the Flinders, Norman and Nicholson-Leichhardt River systems in the Southern Gulf in Queensland (Fig. 4.4).

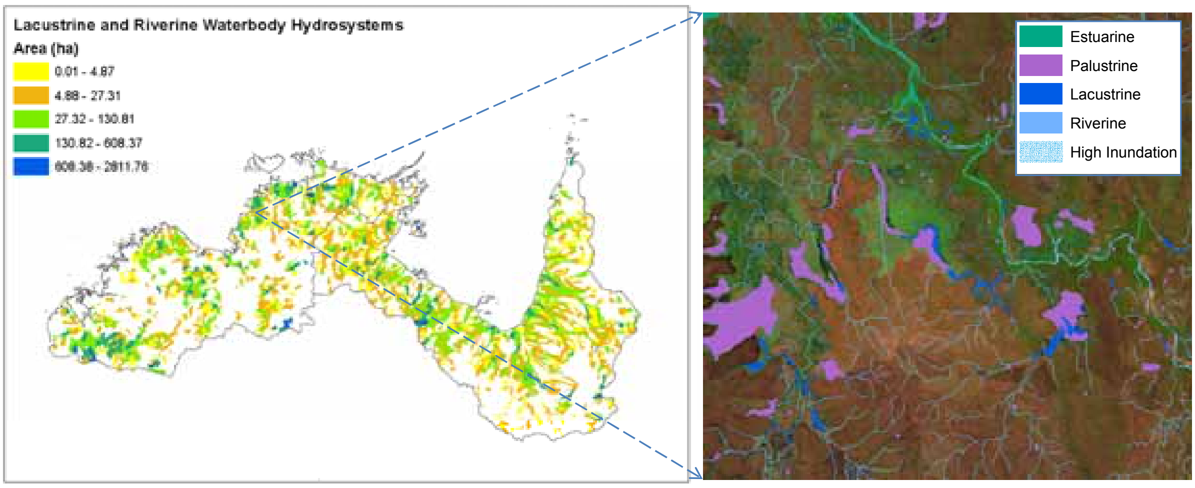

Figure 4.4. Lacustrine and Riverine Waterbody Hydrosystems: a) summarized by area within planning units, and b) showing Lacustrine hydrosystems typical of the Daly River floodplain in the Northern Territory.

Palustrine Hydrosystems

Palustrine Hydrosystem delineation resulted in a total 18,335 individual features comprising and area of 366,070 ha within the Northern Australia HCVAE trial area. The largest areas of Palustrine features occur in the Alligator and Goyder River systems and are associated with the extensive wetland areas of Kakadu National Park and the Arafura Swamp in Arnhem Land. Significant areas of smaller Palustrine features occur in the Embley and Wenlock River systems on Cape York. In contrast to the locations of the largest areas of Palustrine features, the largest numbers of Palustrine features are found on the extensive floodplains of the Flinders, Norman, Mitchell and Coleman River systems of the Southern Gulf and western Cape York (Fig. 4.5)

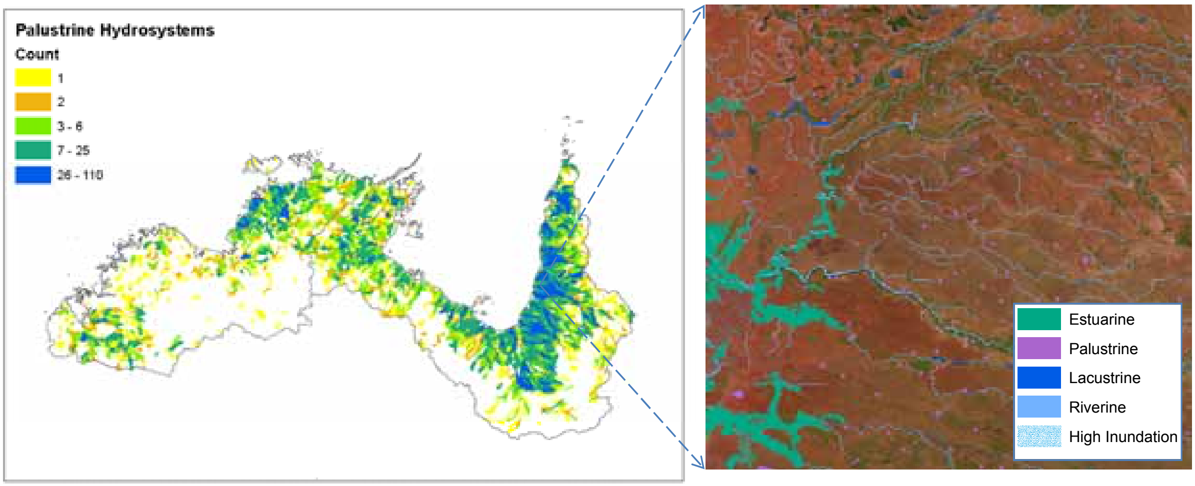

Figure 4.5. Palustrine Hydrosystems: a) summarized by count within planning units, and b) showing the large numbers of Palustrine hydrosystems typical of the Mitchell River floodplain in the Queensland.

Perennaility

Lacustrine perenniality reflects the area distribution of Lacustrine hydrosystems with 83% of all Lacustrine hydrosystems being perennial, and covering 58% of the area of Lacustrine features (Fig. 4.6). In contrast, perennial Palustrine hydrosystems occur in 16% of all Palustrine hydrosystems, and cover only 2.5% of the area of Palustrine hydrosystems .

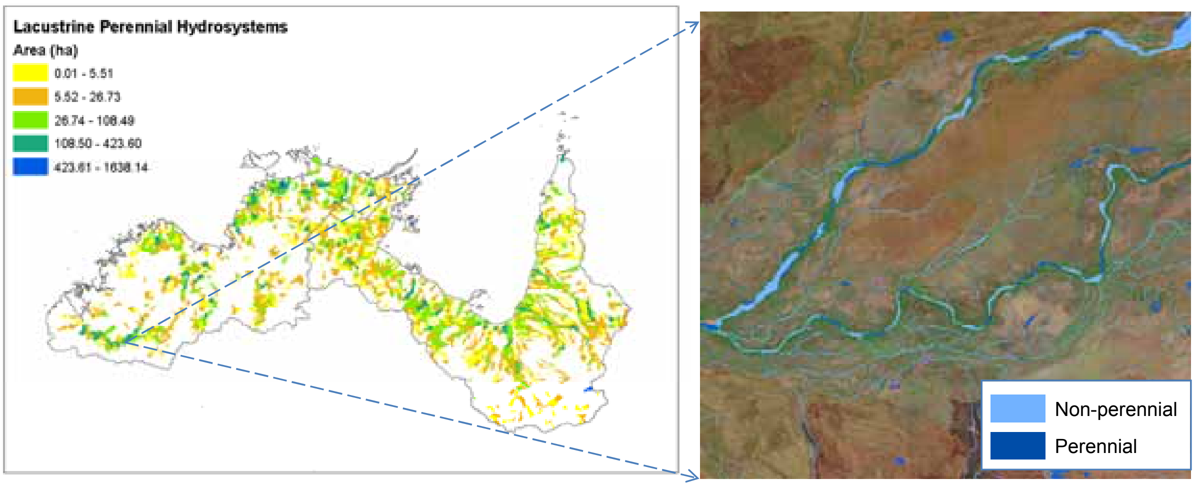

Figure 4.6. Hydrosystem perenniality: a) summarized by Lacustrine perennial area (ha) within planning units, and b) showing mixed perennial and non-perennial hydrosystems typical of the main channel of the Fitzroy River system in Western Australia.

Inundation Frequency

The majority of Palustrine hydrosystems occur on floodplains, and consequently the largest areas of Palustrine hydrosystems with high inundation frequency occur on the regularly flooded floodplains of the Alligator, Goyder, and Daly-Douglas River systems (Fig. 4.7). Palustrine hydrosystems with high inundation frequency cover 68% of the total area of all Palustrine hydrosystems. This contrasts with Lacustrine hydrosystems with high inundation frequency which cover 37% of the total area of Lacustrine hydrosystems.

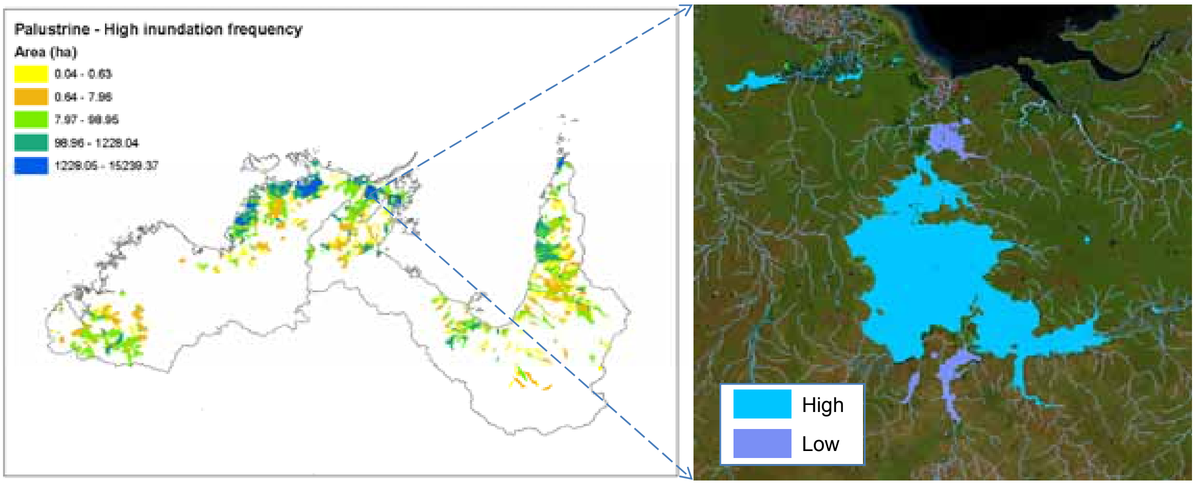

Figure 4.7. Hydrosystem inundation frequency: a) summarized by Palustrine high inundation frequency area (ha) within planning units, and b) showing the Arafura Swamp in Arnhem Land in the Northern Territory.

Hydrosystem Validation

The result of comparing 1:250,000 Geodata Palustrine hydrosystem with the Queensland DERM 1:100,000 and 1:50k Palustrine hydrosystems generally supports the premise that while mapping scale will significantly influence the number of mapped features, the resulting proportions between river basins are similar (Fig. 4.8). The Pearson correlation coefficient for the relationship between the raw counts of the 1:250,000 Geodata and the raw counts of the DERM 1:50,000 data is 0.97. The DERM 1:50,000 Topographic mapping derived Palustrines were the most numerous, and analysis of the count proportions revealed that the 1:250,000 Geodata derived Palustrine hydrosystems had basin counts that were consistently 25% of the number of features delineated from the 1:50,000 Topographic mapping data. This result indicates that Palustrine water features mapped at 1:250,000 capture 25% of the features mapped at a scale of 1:50,000. The results of the comparison with the DERM 1:100,000 Landsat derived data were less consistent with some basins having greater numbers of Palustrine hydrosystems derived from the 1:250,000 Geodata than the 1:100,000 Landsat derived hydrosystems. This may reflect the Landsat image capture dates which are generally towards the end of the dry season when many Palustrine hydrosystems have dried up.

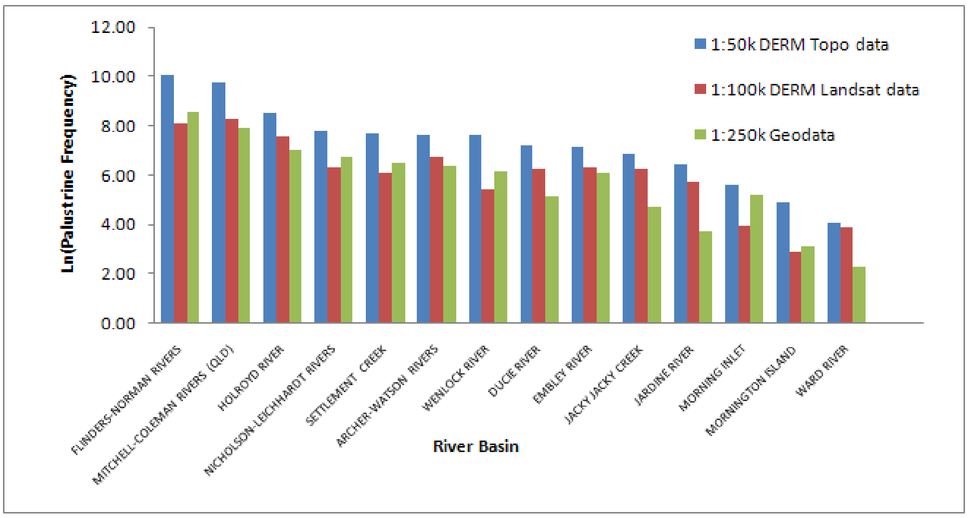

Figure 4.8. Results of a comparison between the natural log of the number of 1:250k Geodata derived Palustrine hydrosystems and the Queensland DERM 1:100k and 1:50k derived Palustrine hydrosystems. Natural Log of the Palustrine frequency is used because of the large difference in the number of Palustrine features between river basins.

Lacustrine and Palustrine Ecotopes

A 14 group classification was chosen to delineate Lacustrine ecotopes (Fig. 4.9), and a 16 group classification was chosen to delineate Palustrine ecotopes (Fig. 4.11). The classification for both Lacustrine and Palustrine ecotopes identifies groups that tend to be mostly one or other of the perenniality (Perennial or Non-perennial) or inundation frequency (High or Low) classes (Table 4.11 and 4.12, Appendix 4.5 and 4.6). Geology and terrain were the next most significant distinguishing characteristics of the ecotope groupings, followed by vegetation and soils. Elevation produced unique groupings, identifying a small number of unique high elevation groups. Lacustrine ecotopes tended to be very spatially mixed with local clustering (Fig. 4.10). The Lacustrine groups have a fairly uniform size distribution with most groups covering between 5% and 10% of the total area of the Lacustrine features (Table 4.11). In contrast, the Palustrine groupings had an uneven size distribution, with group 13 covering 50% of the palustrine area and group 5 cover 15% of the Palustrine area (Table 4.12). The remaining palustrine groups ranged from 1% to 10% of the area. Palustrine ecotopes tended to be more spatially uniform reflecting the area dominance of ecotope 13 and 5 (Fig. 4.12).

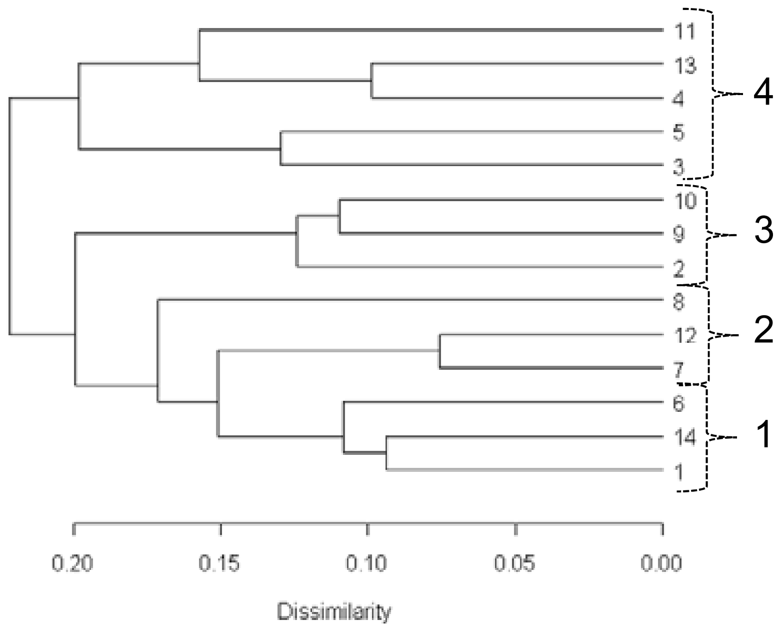

Figure 4.9. Dendrogram showing the relationship among the lacustrine ecotopes derived by hierarchical clustering of group centroids. Numbered meta-groups are indicated with vertical dashed lines (see also Table 4.11).

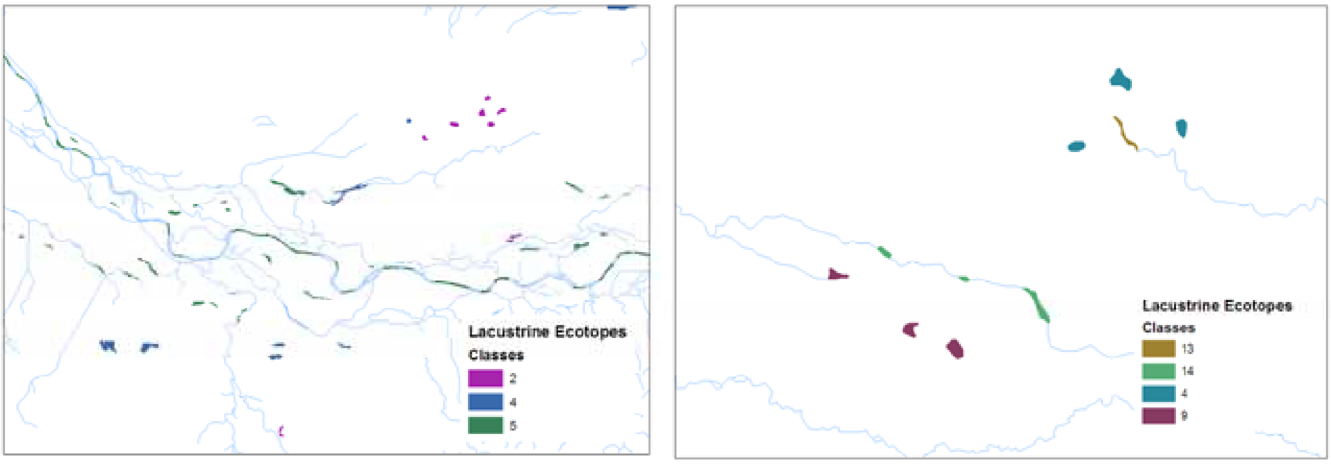

Figure 4.10 Lacustrine Ecotopes (a) main channel of the Fitzroy River showing ecotope classes 2, 4 and 5, and (b) Mitchell River floodplain showing ecotope classes 4, 9, 13 and 14.

Table 4.11. Lacustrine ecotopes indicating the environmental characteristics that distinguish ecotopes from others in the meta-group.

Meta-group	Ecotope	Area	Characteristics
1	1	12349.3	Low inundation frequency, perennial, low elevation, young rocks overlain by unconsolidated sediments, valley bottom terrain, largely trees and shrubs with some melaleuca, mixed soil properties
	14	3762.7	Low inundation frequency, perennial, low elevation, young rocks overlain by unconsolidated sediments, indeterminate terrain, mixed melaleuca and trees and shrubs, mixed soil properties
	6	3296.9	Low inundation frequency, perennial, low elevation, young rocks overlain by unconsolidated sediments, highly erosional terrain, largely trees and shrubs, mixed soil properties
2	7	7706.4	Low inundation frequency, perennial, low elevation, old rocks overlain by siliclastic sediments, highly erosional terrain, largely trees and shrubs with some melaleuca, low A and B horizon clay content
	12	4846.0	Low inundation frequency, perennial, low elevation, old rocks overlain by siliclastic sediments, largely valley bottom terrain, largely trees and shrubs with some melaleuca, low A and B horizon clay content
	8	1504.4	Low inundation frequency, perennial, high elevation, largely by igneous rocks, highly erosional terrain, largely trees and shrubs with some grassland/sedgeland, low B horizon clay content
3	2	11205.7	Low inundation frequency, non-perennial, low elevation, young rocks overlain by unconsolidated sediments, valley bottom flat, mixed vegetation, high water holding capacity and high B horizon clay content
	9	10522.8	Low inundation frequency, non-perennial, low elevation, young rocks overlain by unconsolidated sediments, mixed trees and shrubs and melaleuca, mixed intermediate flatness class, high low A horizon clay content
	10	10577.6	Low inundation frequency, non-perennial, low elevation, young rocks overlain by unconsolidated sediments, mixed valley bottom flat and erosional, trees and shrubs, low A and B horizon clay content
4	3	4396.8	High inundation frequency, perennial, low elevation, young rocks overlain by unconsolidated sediments, valley bottom terrain, mixed proportions grassland/sedgeland, high A and B horizon clay content
	5	13444.4	High inundation frequency, perennial, low elevation, young rocks overlain by unconsolidated sediments, valley bottom terrain, high proportion of grassland/sedgeland vegetation, high A and B horizon clay content
	4	9370.3	High inundation frequency, non-perennial, low elevation, young rocks overlain by unconsolidated sediments, valley bottom terrain, high proportion trees and shrubs, mixed soil properties
	13	10254.0	High inundation frequency, perennial, low elevation, young rocks overlain by unconsolidated sediments, valley bottom terrain, high proportion of trees and shrubs, relatively high B horizon clay content and water holding capacity
	11	972.9	High inundation frequency, perennial, range of elevations, mixed geology overlain by unconsolidated sediments, terrain highly erosional, mixed trees and shrubs with some Melaleuca, mixed soil properties

The 14 Lacustrine ecotopes form 4 broad meta-groups (Table 4.11). Lacustrine meta-groups 1 and 2 are low inundation frequency, perennial with distinguishing characteristics between groups being the rock age and the types of overlying sediments. Lacustrine meta-group 3 is low inundation frequency but non-perennial with distinguishing characteristics between ecotopes being largely associated with terrain and vegetation. Lacustrine meta-group 4 is a high inundation frequency group with mixed perenniality. For the 3 broad Palustrine meta-groups, perenniality was less of a distinguishing characteristic between meta-groups (Table 4.12). Palustrine meta-groups 1 and 2 are low inundation frequency, mixed perenniality groups with distinguishing characteristics being the rock age and the types of overlying sediments. Palustrine meta-groups 3 is a high inundation frequency group with mixed perennaility, with distinguishing characteristics between ecotopes being largely terrain and vegetation. Palustrine meta-group 3 contains a high elevation ecotope on igneous rocks. This ecotope is unique but was combined with Palustrine meta-group 3 because of its very small area. The environmental characteristics that distinguish Lacustrine and Palustrine ecotopes within each meta-group are shown graphically in the box plots presented in Appendix 4.5 and Appendix 4.6.

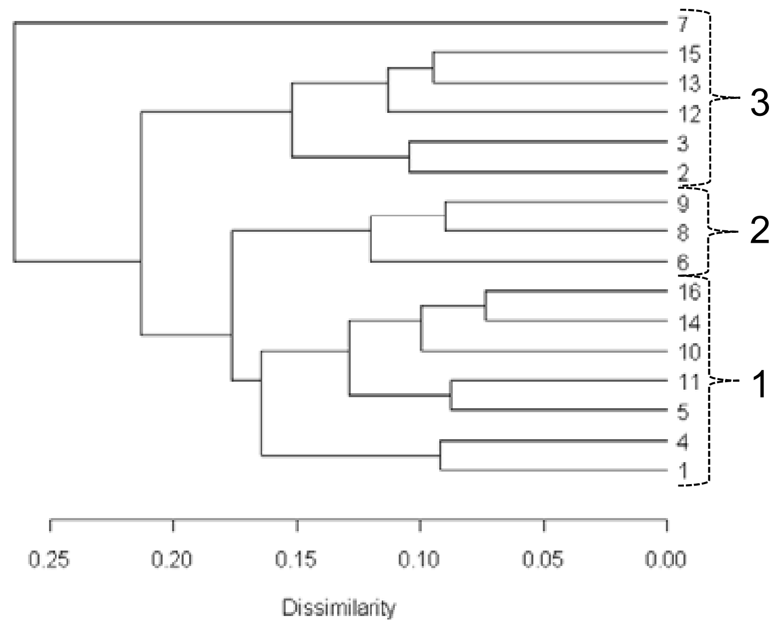

Figure 4.11. Dendrogram showing the relationship among the palustrine ecotopes derived by hierarchical clustering of group centroids. Numbered meta-groups are indicated with vertical dashed lines (see also Table 4.12).

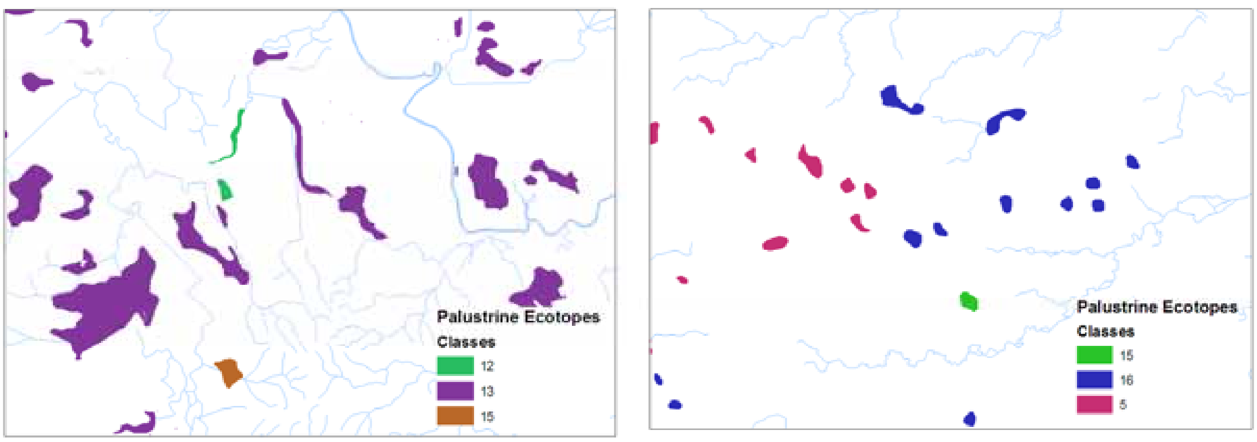

Figure 4.12. Palustrine Ecotopes a) Daly river floodplain showing ecotope classes 12, 13 and 15, and b) the Nicholson river showing ecotope classes 5, 15 and 16.

Table 4.12. Palustrine ecotopes indicating the environmental characteristics that distinguish ecotopes from others in the meta-group.

Meta-group	Ecotope	Area (ha)	Characteristics
1	1	3765.4	Low inundation frequency, young rocks overlain with unconsolidated sediments, low elevation, perennial, valley bottom flat, mixed trees and shrubs, high B horizon clay content – low saturated hydraulic conductivity
	4	1671.2	Low inundation frequency, young rocks overlain with unconsolidated sediments, low elevation, perennial, indeterminate, mixed melaleuca and trees and shrubs, high B horizon clay content
	5	53228.0	Low inundation frequency, young rocks overlain with unconsolidated sediments with some siliclastic sediments, low elevation, non-perennial, valley bottom flat, mixed melaleuca, trees and shrubs
	11	11171.5	Low inundation frequency, young rocks overlain with unconsolidated sediments with some siliclastic sediments, low elevation, non-perennial, ridge top, mixed melaleuca, trees and shrubs, mixed soil
	10	15574.2	Low inundation frequency, young rocks overlain with unconsolidated sediments, low elevation, non-perennial, valley bottom, mixed grassland/sedgeland and trees and shrubs, high A and B horizon clay content
	14	14838.4	Low inundation frequency, young rocks overlain with unconsolidated sediments and other sediments, low elevation, non-perennial, valley bottom, largely melaleuca, mixed soil properties
	16	23568.4	Low inundation frequency, young rocks overlain with unconsolidated sediments with some siliclastic sediments, low elevation, non-perennial, valley bottom flat, trees and shrubs, mixed soil propertiues
2	6	483.0	Low inundation frequency, mixed young and old rocks overlain with unconsolidated sediments with some siliclastic sediments, low elevation, perennial, high erosional, largely trees and shrubs, mixed soil properties
	8	6988.9	Low inundation frequency, mixed young and old rocks overlain with unconsolidated sediments with some siliclastic sediments, low elevation, non-perennial, high erosional, trees and shrubs, mixed soil properties
	9	4026.3	Low inundation frequency, mixed young and old rocks overlain with unconsolidated sediments with some siliclastic sediments, low elevation, non-perennial, high erosional, largely melaleuca, mixed soil properties
3	2	1463.1	High inundation frequency, young rocks overlain with unconsolidated sediments, low elevation, perennial, valley bottom, mixed grassland/sedgeland and trees and shrubs, high A and B horizon clay content – low hydraulic conductivity
	3	1075.5	High inundation frequency, young rocks overlain with unconsolidated sediments, low elevation, perennial, mixed valley bottom and indeterminate, largely trees and shrubs, mixed soil properties
	12	33667.3	High inundation frequency, young rocks overlain with unconsolidated sediments, low elevation, non-perennial, indeterminate, mixed melaleuca, trees and shrubs, low hydraulic conductivity
	13	171920.5	High inundation frequency, young rocks overlain with unconsolidated sediments, low elevation, non-perennial, valley bottom, mixed melaleuca and grassland/sedgeland, high B horizon clay content and low hydraulic conductivity
	15	21700.4	High inundation frequency, young rocks overlain with unconsolidated sediments, low elevation, non-perennial, valley bottom, largely trees and shrubs, mixed soil properties
	7	926.6	Low inundation frequency, young igneous rocks, overlain with some unconsolidated and siliclastic sediments, high elevation, largely non-perennial, high erosional, all trees and shrubs, high B horizon clay content

4.4 Discussion and knowledge gaps/next steps

Riverine Hydrosystem and Ecotope Classification

The AusHydro DEM derived streams delineate riverine hydrosystems at a consistent map scale of about 1:250,000, comparable with the Geodata representation of Lacustrine and Palustrine hydrosystems. While this scale is appropriate for regional studies such as the Northern Australia HCVAE trial it is likely to greatly underestimate the true extent of the stream network, especially in higher relief areas. A similarly derived stream network for the Cotter Catchment in the ACT, for example, was found to capture just 26% of the stream length mapped at the finer scale of 1:25,000 (Stein, 2007). The expected completion of a drainage enforced 1 second DEM based on the Shuttle Radar Technology Mission (SRTM) data later this year, a component of the ongoing development of the AHGF (http://www.bom.gov.au/water/about/publications/document/InfoSheet_5.pdf), may offer the opportunity to include these smaller, but nevertheless important, streams into future HCVAE assessments.

Our analysis delineated 760,000 km of streams within the Northern Australia HCVAE trial study area, sub-divided into some 334,000 stream segments. Each stream segment was individually attributed with a large set of variables describing characteristics of the local and catchment environment that are indicative of the landscape processes that shape riverine ecosystems function and character. Riverine ecotopes were then derived by clustering stream segments based on the similarity of their environmental attributes. Ecotopes are thus defined in environmental rather than geographic space and are not necessarily spatially cohesive. They describe relatively consistent associations of environmental factors that drive the pattern of flow, channel morphology, substratum, temperature and mineral nutrients that collectively define the physical habitat of riverine systems.

The riverine ecotopes depict reasonably broad scale patterns of variation in riverine habitat. Improvements in the quality and resolution of environmental data and the methods used to describe critical landscape processes will be required if finer scale patterns are to be portrayed. For instance, the proportion of the valley and the catchment underlain by broad groupings of the mapping units on a 1:1M scale geology map provided a crude indicator of the influence of lithology on riverine ecosystems. Data on the hydrogeological, geophysical and geochemical properties of the individual lithologies within a mapping unit would have been far more informative but were not available. Even if such data becomes available in the future there remains the problem of integrating these values across the catchment. Catchment averages may be uninformative and even misleading, especially in large catchments.

Lacustrine, Palustrine Hydrosystem and Ecotope Classification

Water features represented in the Geodata Hydrography theme and the OzCoasts Geomorphic Habitat Mapping were successfully delineated to hydrosystems based on modified version of Queensland decision rules (EPA ,2005), resulting in delineation of 26,075 Lacustrine and Palustrine individual hydrosystems features. Modifications to the Queensland decision rules included specific feature interpretation of the Geoata feature classes, additional topological rules for hydrosystem delineation, and variation in the interpretation and classification of inundation frequency and perenniality. Due to issues of data scale, and representation of structure and function, the hydrosystem classification proved inadequate in delineating estuarine hydrosystems. Consequently, estuarine hydrosystems were omitted from the analysis for the Northern Australia HCVAE trial area.

As with riverine hydrosystems, Lacustrine and Palustrine ecotopes were derived by clustering hydrosystem water features based on the similarity of their environmental attributes. To some degree the resulting Lacustrine and Palustrine ecotopes reflect their relationship with the riverine hydrosystems, highlighting the connectivity and the continuous nature of these systems. Lacustrine ecotopes occur on, or near the riverine hydrosystems across most catchments, and consequently are distributed across a range of hydrologic, topographic, and substratum domains similar to the riverine ecotopes. This is evidenced in the relatively uniform size distribution of the Lacustrine ecotopes. In contrast, Palustrine ecotopes are more influenced by the flood patterns of the riverine hydrosystems and consequently are more associated with the hydrologic, topographic, and substratum domains of floodplain environments. This association is evidenced in the non-uniform size distribution of the Palustrine ecotopes, with the ecotopes with the largest areas being associated with floodplain environments.

Perenniality is a difficult water feature to attribute based on field observations and may change over time due, for example to the sediment deposition and other processes. Geodata perennaility definition implies a 1 in 10 year return interval. Limited field observations indicated that this definition appeared adequately applied in the Geodata mapping. However, in the absence of long term water depth or inundation monitoring, there will always be some degree of mapping interpretation associated with the attribution of perenniality. Consequently, the perenniality attribute is likely to have the largest uncertainty of all hydrosystem attributes. However, it is likely that the broader patterns of Geodata derived Lacustrine perenniality remain reasonably representative. This is particularly the case for the HCAVE trial work where all data is summarized to planning units and no individual water features are used.

Inundation frequency is an important aquatic ecological attribute due to its relationship with aquatic connectivity. Comparisons of inundation frequency derived from satellite mapping showed that the Geodata derived inundation frequency was geographically variable in the level of accuracy of its representation. The general pattern that emerged was that those Geodata mapped areas of high inundation tended to be more accurate the longer the floodplain residence time. For example, the Daly River high inundation areas were mapped very accurately when compared to time series of satellite imagery. However, the Geodata mapped high inundations areas in the Mitchell catchment showed only inundations areas with less than a 1 in 10yr return interval. Inundation frequency in the Southern Gulf was significantly underestimated.

Northern Australian fluvial landscapes are highly dynamic, and many water features will have changed in spatial location, extent, and perenniality since the initial Geodata mapping was undertaken. However, the landscape characteristics and fluvial process that shape these landscapes remain relatively unchanged in the timeframes of this project. Consequently, the Geodata derived hydrosystems, while having local spatial inaccuracies, remain representative of the broader scale patterns of these fluvial landscapes (eg. water feature density, depth, perenniality etc). An important implication of this interpretation of the Geodata water feature mapping is that a suitable sampling scale must be used such that local scale issues such as landscape changes since the time of mapping and inconsistencies in interpretation are taken into account.

Preliminary validation indicate that Palustrine water features mapped at 1:250,000 capture 25% of the features mapped at a scale of 1:50,000. This finding parallels the finding for a similar comparison for riverine hydrosystems (Stein, 2007). The important finding from this comparison was that the scaling of the representation of Palustine features remained consistent across the 14 Queensland river basins that were tested. Even though many of the 14 river basin used in the analysis will have widely varying topography, substrate, and fluvial processes, the representation of Palustrine features remained consistent.

Applying the Australian National Aquatic Ecosystem Classification Scheme

The ANAE Classification Scheme was successfully implemented to delineate hydrosystems for the Northern Australia HCVAE trial area. However, time constraints of the project meant that further development of the Geodata estuarine, Lacustrine and Palustrine hydrosystem delineation is required. Further refinement of the ANAE Classification Scheme will involve addressing issues of Geodata scale, estuarine delineation (e.g. using existing Mangrove mapping), updating of the interpretation of the Geodata inundation frequency and perenniality, and improved utilization of the Palustrine point data.

While hydrosystems were successfully delineated, the broader goal of classifying aquatic ecosystems was not readily facilitated by the ANAE Classification Scheme. The Riverine, Lacustrine and Palustrine ecotopes were classified independently based on attributes variously describing the local and catchment scale environment. In reality, however, they are all components of an aquatic ecosystem comprising a naturally nested hierarchy of smaller scale ecosystems controlled by processes operating at different spatial and temporal scales (Frissell *et al.*, 1986) each functionally constrained by higher levels of the system (O'Neill et al., 1989). They are much more than water features represented by the blue lines on a map. Surface waters, sub-surface waters, riparian / floodplain systems and associated processes are all integral components of aquatic ecosystems or “riverscapes” (Ward, 1998).

The draft ANAE Classification Scheme (Auricht, 2010) describes different aquatic ecosystems and habitats across Australia within an integrated regional and landscape setting. However, as pointed out in Auricht (2010) “*considerable work is required to refine the attributes within the scheme and testing them in a practical manner*”. While the current version of the ANAE Classification Scheme provides some implementation guidelines further development is recommended. It is not recommended however, that the ANAE Classification Scheme adopt hard, prescriptive categories as used in the Cowardin classification of U.S. wetlands on which the ANAE Classification Scheme is based.

Ideally, the ANAE Classification Scheme should offer guidance on choice of appropriate attributes, methods of measurement or derivation, applicable spatial and temporal scales and so on to ensure consistent application across jurisdictions. Further development of the ANAE Classification Scheme will be required to ensure that all integral components of aquatic ecosystems are effectively recognized, perhaps as emergent properties of the currently separate classifications of hydrosystems.

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5. Compilation of species distribution datasets for use as biodiversity surrogates

Mark Kennard, Brad Pusey, James Boyden, Damien Burrows, Catherine Leigh, Colton Perna, Peter Bayliss & Arthur Georges

Key points

1. **Aim:** To assemble a comprehensive database with spatially explicit information on species occurrence across northern Australia for a range of freshwater-dependent taxonomic groups to support the development of predictive models relating species occurrence to environmental attributes.
2. **Methods:** Individual data sets for macroinvertebrates, freshwater fish, turtles and waterbirds were sourced from government agencies, the scientific literature, research scientists and on-line databases and substantial time and effort was expended checking the accuracy of the locality records and taxonomic idenitifcations.
3. **Results:** The data set for macroinvertebrates consisted of 11,598 records for 123 taxa from 343 unique locations. The turtle data set consisted of 445 records for 13 taxa from 374 unique locations. The data set for waterbirds consisted of 54,518 records for 163 taxa from 7,922 unique locations. The fish data set consisted of 21,357 records for 104 species from 3,866 unique locations. Of these 3,866 locations, 838 were considered true presence/absence data. All other data sets were presence only.
4. **Implications:** The assembled data sets, when combined with environmental data described in Chapter 4, provide a rigorous basis for the development of predictive models of taxon distribution across the aquatic landscape of northern Australia required to define conservation value at different spatial scales.
5. **Limitations/knowledge gaps/next steps:** The data sets assembled for macroinvertebrates, turtles and waterbirds provide presence data only, in contrast to that assembled for fish that represent the necessary data for predictive models based on both presence and presence/absence data. However, the large sample sizes involved and their spatially comprehensive nature minimise against possible deficiencies due to the lack of true presence/absence data. Despite this some areas of northern Australia could benefit from further survey work. Similarly, additional information about the distributional limits of genetically distinctive taxa would allow genetic distinctiveness to be incorporated in a more rigorous manner. We considered but did not assemble datasets for other water-dependent fauna (i.e. frogs, crocodiles, lizards, snakes, riparian birds) or aquatic, semi-aquatic and riparian flora due to resource and/or data constraints. Their use in any future assessments of conservation value of the region would be of benefit. Some aquatic habitat types present in northern Australia such as subterranean systems or springs, or off-channel floodplain habitats in the case of macroinvertebrates, were not covered in the existing data sets despite the high likelihood that such habitats are of conservation significance.

5.1 INTRODUCTION

Aquatic biodiversity can be defined in many ways using many different groups of organisms such as aquatic plants and algae, macroinvertbrates, fish, turtles, amphibians and waterbirds. Each taxonomic group can be used to describe specific aspects of biodiversity or may be grouped to define a collective aspect of biodiversity. Often, however, information is more comprehensive for some groups than others and pragmatic decisions about how to define biodiversity need to be made. Some groups, especially those for which comprehensive data is available, may be used as surrogates for other less well-known groups.

Biodiversity can also be defined at a hierarchy of spatial scales (e.g. bioregion » river basin » river reach » mesohabitat » microhabitat). Importantly, whilst information on biodiversity at subsidiary levels of the spatial hierarchy can be used to determine biodiversity at higher levels of the hierarchy, such capacity is not symmetric. Knowing what species occur at broad spatial scales (i.e. a catchment) is useful for determining whether a species is *potentially* present at smaller scales within the spatial hierarchy, however, it does little to inform about the distribution at that smaller scale. Consequently, investigations at smaller subsidiary spatial scales are needed, although this may require a great deal of effort to achieve with any degree of rigour (i.e. many sampling locations across all hierarchical scales). An alternative means to achieve this is the development of models based on field data that allow the distribution of individual taxa to be predicted with certainty.

Biological organisms, especially those restricted to aquatic habitats, are not distributed uniformly across the landscape (Olden et al., 2010). Species vary in incidence according to physical or biological gradients in the environment and according to the scale at which those gradients occur. If the nature and strength of those gradients is known then they may be used to predict the distribution of species across space. Predictive models may be based on field data that informs about the presence of a species and the nature of the environment at that location. Whilst the presence of a species at a location may be determined with certainty, determining whether it is absent is often challenging. Ideally from a modelling perspective, a species is absent because the physical nature of the habitat is not suitable (i.e., requirements of the species ecological niche are not met). However, a species may be absent from a location at the time of sampling because its incidence varies with time (i.e. as in migratory species) or because it has formerly been extirpated and insufficient time has elapsed for it to recolonise despite physical conditions being appropriate. As importantly, a species may appear to be absent from a habitat simply because the sampling procedure failed to detect it there (i.e. a false negative). Surveys employing protocols aimed at defining biodiversity with high levels of precision and accuracy are considered to have a low likelihood of false negative. Predictive models based on both presence and absence data are more powerful than those based on presence only.

This chapter describes the species distribution datasets collated for use as biodiversity surrogates. We considered a range of species groups as potential candidates for further development and application as biodiversity surrogates. Given that collating such datasets is an extremely time-consuming task, our choice was guided by a desire to assemble accurate datasets with as broad spatial coverage as possible, within the time and budgetary constraints of our project. Water-dependent species groups for which we assembled data and used as biodiversity surrogates included aquatic macroinvertebrates, fish, turtles and waterbirds. We considered but did not assemble datasets for other water-dependent fauna (i.e. frogs, crocodiles, lizards, snakes, riparian birds) or aquatic, semi-aquatic and riparian flora due to time, budgetary and/or data constraints.

5.2 METHODS AND RESULTS

5.2.1 AQUATIC MACROINVERTEBRATES

Data sources

Data on aquatic macroinvertebrate and environmental attributes was obtained from the Queensland, Northern Territory and Western Australia agencies under the Australian Government Department of the Environment and Water Resources AusRivAS (Australian River Assessment Scheme) model protocol and river bioassessment program (Coysh et al., 2000; Gray & Hosking, 2003).

The AusRivAs protocol uses rapid sampling methods to develop predictive models for macroinvertebrate communities within each Australian state and territory, using a 'reference' site approach to assess biological responses to changes in water quality and/or habitat condition in rivers and streams.

Queensland databases were provided by the Department of Environment and Resource Management; Northern Territory databases by the Department of Natural Resources, Environment, The Arts and Sport; and Western Australian databases by the Department of Water.

Databases were assessed in terms of habitats sampled, sampling methods, pick methods (i.e. method used to extract organisms from sample), macroinvertebrate identifications and taxonomic resolution (Table 1). The protocol used to ensure consistency among data across the three jurisdictions is outlined below.

Table 5.1. Database requirements and compliance with these requirements across jurisdictions.

	QLD	NT	WA
Catchment name	yes	yes	yes
Stream/river name	yes	no	yes
Site name	yes	no	yes
Site number	yes	yes	yes
Latitude and longitude	yes	yes	yes
Number of unique sampling locations	77	119	147
Years (of sampling)	1994-1995	1995-1996	1994-1998
Season (or month/date) of sampling	date provided	Early or late dry	Dry or wet
Site type (reference, test or other)	Reference, test, long-term monitoring site or unknown	Reference or test	Reference or test
Habitat sampled (e.g. edge, riffle, pool, macrophytes, etc)	Edge, sandy bed (pool), sandy bed with *Nitella*, macrophyte, Nymphoides, rocky bed (pool), rocky pool with *Ceratophyllum*, riffle and run	Edge or sandy bed	Channel, macrophyte, pool rocks, riffle, and organics
Sampling method (e.g. sweep, kick, etc)	Sweep and /or kick depending on habitat	Rake and sweep	Sweep and /or kick depending on habitat
Sampling distance	10 meters	10 meters	10 meters
Pick method (e.g. 30 min live pick)	30-60 minute live pick or until 200 animals collected (max 10 of each type)	Preserved sample identified until 200 animals collected from subsamples	60 minute live pick or until 200 animals collected (max 10 of each type, except for chironomids with a max of 30)

Sampling and pick methods

Differences among the sampling and pick methods among jurisdictions was evident and was considered to have potential implications for data consistency and comparability across the three jurisdictions.

Habitats sampled

Greater consistency among habitat types sampled across the jurisdictions was achieved by combining count data from the two sand habitats sampled in Queensland, which was considered analogous with the sandy bed habitat sampled in the Northern Territory. Pool rocks habitat (WA) was considered analogous with rocky bed (pool) and rocky pool with *Ceratophyllum* habitat (QLD). Macrophyte and *Nymphoides* (QLD) habitats were considered analogous, and analogous to macrophyte habitat sampled in Western Australia. Riffles were sampled in both Queensland and Western Australia; runs only in Queensland; and 'organics' only in Western Australia. The two data points corresponding to the latter two habitat types were discarded from the datasets. Channel habitat in Western Australia is defined as the central part and edges of the main channel and excludes riffles, submerged macrophytes and pool rocks. This constituted a separate habitat that did not match with any one habitat sampled in Queensland or the Northern Territory. In total, channel, edge, macrophyte, riffle, rocky bed (pool) and sandy bed (pool) made up the final suite of habitat types included in the macroinvertebrate dataset used in subsequent chapters.

Although the final suite of habitat types were not sampled consistently across (or within) the jurisdictions, the above steps improved the consistency as much as was possible. Further removal of habitat types (e.g. retaining only channel, edge and sandy bed habitats) would have resulted in a substantial reduction in the number of macroinvertebrate sampling locations available for modelling.

Macroinvertebrate data

Taxa that were not included under the AusRivAs sampling protocol but that had occasionally been collected and identified were excluded (i.e. all microcrustaceans except for conchostracans and oniscid isopods). When taxa were included by one jurisdiction only and less than 10 individuals had been counted, these taxa were discarded (e.g. tenebrionid coleopterans, thaumaleid dipterans, oniscigastrid ephemeropterans, synthemistid and telephlebiid epiproctophorans, neurorthid neuropterans, megapodagrionid zygopterans, philorheithrid trichopterans, nematophorans, nemerteans and rotifers). The sampling method used in the AUSRIVAS protocol does not allow an objective assessment of the true presence or absence of a taxon as it is unclear whether a particular taxon was present in a sample but not picked and identified or if it was simply not present. We attempted to minimise the mismatch among jurisdictions in taxonomic resolution (when one or more jurisdictions included the coarsest level only) by summing count data across finer levels of taxonomic resolution (i.e. family levels within Oligochaeta were summed). Conversely, count data for unclassified invertebrates within taxonomic Classes, Orders or Suborders that were otherwise identified to lower levels of resolution consistently across the jurisdictions were discarded. This included counts for Crustacea, Diptera, Chironomidae, Ephemeroptera, Epiproctophora, Zygoptera, and Trichoptera for which family or subfamily (for Chironomidae only) level count data were otherwise provided. In total, 44 taxa were discarded from the original databases.

The final macroinvertbrate dataset contained 11,598 distribution records for 123 taxa (Appendix 5.1). These were available for a total of 343 unique sampling locations (Fig. 5.1). Given the sampling and taxonomic identification inconsistencies detailed above, we treated these data as presence-only records for use in the development of predictive models of species distributions (Chapter 7).

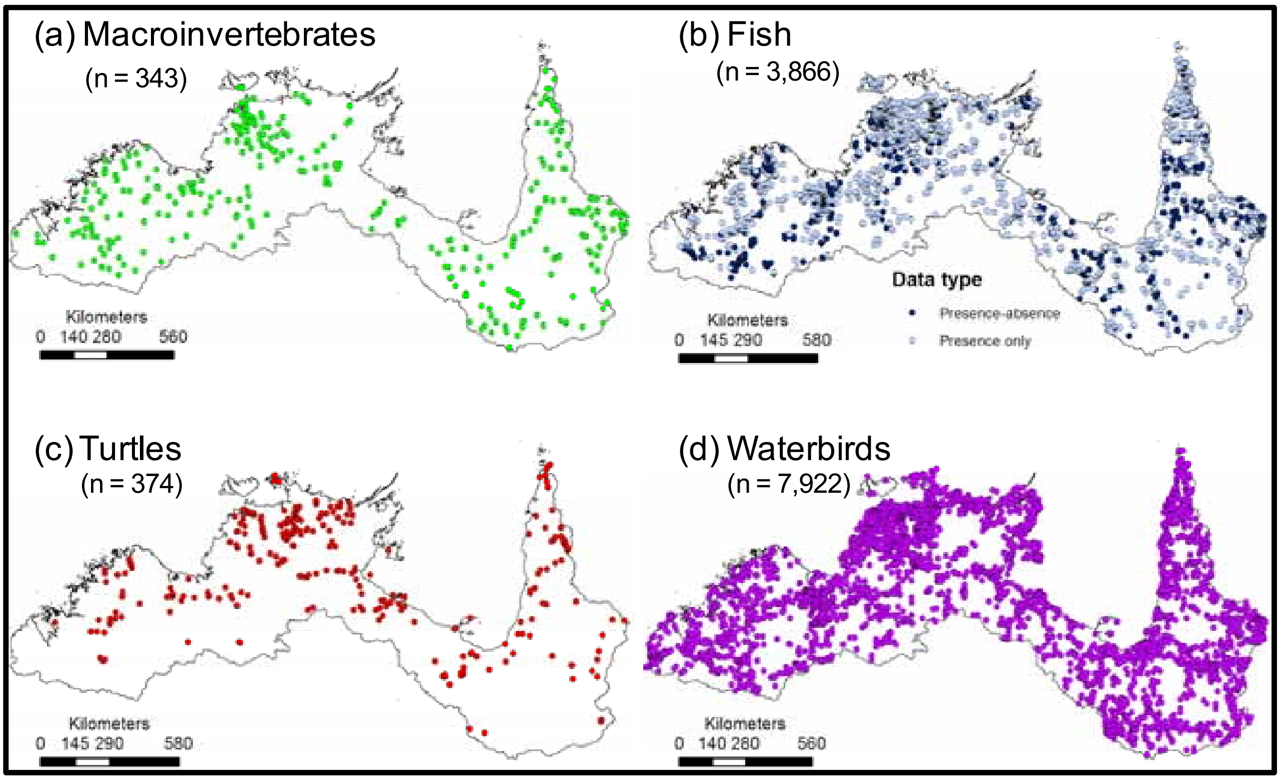

Figure 5.1. Sampling locations for (a) macroinvertebrates, (b) fish, (c) turtles and (d) waterbirds. The total number of unique sampling locations are given in parentheses. All points represent presence-only data, with the exception of fish where both presence-only and presence-absence data are shown.

5.2.2 Fish

Data sources

Information concerning the distribution of freshwater fish species was gained from an updated version of the Northern Australian Freshwater Fish Atlas (www.jcu.edu.au/actfr). The updated version (March 2010) differs from the online version in that it contains museum records derived from the Australian Museum, Queensland Museum, Museum of Western Australia and the Museum and Art Gallery of the Northern Territory, in addition to pre-existing records derived from published (peer-reviewed and consultancy reports) and unpublished surveys. The latter consists of electrofishing survey work targeted at poorly surveyed regions undertaken as part of the NHT funded Northern Australian Freshwater Fish Project (a joint project between James Cook University and Griffith University led by Damien Burrows, Brad Pusey and Mark Kennard) and as part of the Tropical Rivers and Coastal Knowledge research program. In total, the database contains 2,852 survey locations with multiple species information and a further 3,846 museum locations containing both single species or multispecies information. The geographic extent of data ranges from the Kimberley region eastward to and including the Burdekin River, however only that data pertinent to northern Australia (i.e. divisions 8 and 9) were included in analyses presented here. A total of 263 species are present within the database; some of which (59) are more frequently found in estuarine environments and many more of which require access to estuaries to breed. We included in our analyses those fish species that can reproduce in freshwater and diadromous (migratory) species that spend the majority of their lives in freshwater. We excluded numerous species with strong marine or estuarine affinities (including all sharks and rays) that may enter freshwater for only short periods of time.

We spent a considerable amount of time exhaustively checking the spatial accuracy and taxonomic validity of all records. Unfortunately, numerous errors were found and were corrected where possible. After deleting all unreliable sampling records and those collected prior to 1970, as well as excluding all records located outside the study area, the final fish dataset contained 21,357 distribution records for 104 taxa (Appendix 5.2). These were available for a total of 3,866 unique sampling locations (Fig. 5.1b). We considered 838 of these sampling locations to contain reasonably reliable estimates of true species presence or absence because the fish were collected using multiple sampling methods at what we considered to be a sufficient spatial scale and sampling intensity. The remaining sampling locations were treated as presence-only records. These datasets were used in the development and external validation of predictive models of fish species distributions (Chapter 7).

5.2.3 Turtles

Full details on the turtle dataset used in this project are available in Georges & Merrin (2008). The raw distribution records were sourced from the tissue database held at the University of Canberra, verified records from museum collections, data from published accounts and records supplied by registered herpetologists. The location of all records has been verified to the extent possible using Google Earth, and species designations are considered accurate. Data where the species identity or the locality data are uncertain have been omitted. Species generally follow those listed by Georges & Thomson (2010). Up-to-date information on the distribution of Australasian freshwater turtles is now available via an online database named *Turtlebase* (developed by Arthur Georges, University of Canberra, and available at (http://piku.org.au/cgi-bin/locations.cgi). After deleting all sampling records collected prior to 1970 and excluding all records located outside the study area, the final turtle dataset contained 445 distribution records for 13 taxa (Appendix 5.3). These were available for a total of 374 unique sampling locations (Fig. 5.1c). Given the lack of quantitative presence-absence sampling data for northern Australia, we treated these data as presence-only records for use in the development of predictive models of species distributions (Chapter 7).

5.2.4 Waterbirds

Full details on the waterbird datasets compiled for this project are listed in Appendix 5.5. Waterbird survey data covering either part or the entire NAWFA study area were sourced from relevant State, Territory, and Commonwealth Agencies, and the University of New South Wales. While every effort was made to consolidate datasets over the project time-line, some of the datasets (e.g. those acquired from the Parks & Wildlife Service of the NT) were incomplete at the time of compiling this report.

Specific datasets included:

1. The National Water Birds Survey (NWBS, 2008), sourced through John Porter of the University of New South Wales. Ancillary environmental data include information on associated wetland names and area. The dataset is complete for the NAWFA coverage area.
2. Presence-only distribution records collated for the Tropical Rivers Inventory and Assessment Project (TRIAP) from Australian Bird Atlas records- see (Franklin, 2008). Data cover the entire NAWFA area.
3. Quantitative aerial surveys (1984-2000) of waterfowl (Magpie Geese) for the Top End of the Northern Territory (NT), sourced from the Parks and Wildlife Service of the Northern Territory (PWSNT). At the time of collating this report, some gaps were apparent in the data provided.
4. Quantitative ground and aerial surveys of shorebirds, and significant breeding colonies for the northern regions of the Northern Territory (NT), sourced from the Parks and Wildlife Service of the Northern Territory (PWSNT). At the time of collating this report, some gaps were apparent in the data provided. Data exist from 1990-1999, but records from 2000-2003 are missing.

5. Quantitative waterbird surveys over seasonal wetlands of the Alligator Rivers Region (ARR) of the NT, provided by the Supervising Scientist Division (SSD) of the Commonwealth Department of the Environment, Water, Heritage and the Arts (DEWHA). These data include:
    a. Systematic aerial survey, conducted monthly from June 1981 to August 1984. Environmental information on dominant cover types is also included (Wet Plain, Dry Plain, Wet Melaleuca, Dry Melaleuca, Open Water, Dry Woodland, Mud);
    b. For the same period and sampling frequency above, systematic ground surveys from 30 sites on the Magela Floodplain, Kakadu National Park;
    c. For the same period and sampling frequency above, ground and aerial surveys at 17 billabongs within the Magela Creek catchment. Environmental information includes structural classification of each billabong surveyed.
6. Presence-only distribution records sourced from the WildNet database through the Queensland Department of Environment and Resource Management (DERM).
7. Miscellaneous waterbird records for WA provided from various sources through Peter Bayliss.

After deleting all sampling records collected prior to 1970 and excluding all records located outside the study area, the waterbird dataset contained 54,518 distribution records for 163 taxa (Appendix 5.4). These were available for a total of 7,922 unique sampling locations (Fig. 5.1d). Given the lack of quantitative presence-absence sampling data for northern Australia, we treated these data as presence-only records for use in the development of predictive models of species distributions (Chapter 7).

5.3 Discussion and knowledge gaps/next steps

The data sets required to model the distribution of aquatic taxa across northern Australia, and described here, are both spatially and taxonomically extensive and comprehensive. Moreover, they collectively account for most of the aquatic dependent taxonomic groups. They are thus likely to provide the basis for comprehensive and realistic models of species' distribution, and hence biodiversity, across the study area. However, only the data set available for freshwater fishes was able to provide a subset of samples enabling species' distributions to be based on presence *and* absence data; all other models are based on presence data only. Whilst it is preferable to base models of species distribution on data summarising where species may be found as well as where they are truly absent (as the latter may reflect or indentify factors that limit a species distribution), the spatial extent of sampling locations described here goes a long way to mitigate against the absence of true absence data.

Each dataset provides an important basis for defining conservation value across northern Australia. However, further development of these datasets, and of others, would provide an improved basis for defining conservation value of aquatic habitats in the future. These improvements are detailed below for each data set.

5.3.1 MACROINVERTEBRATES

- Greater consistency among sampling habitats across the jurisdictions may improve the quality and interpretative capacity of predictive models of biodiversity. Although habitat types are unlikely to occur consistently across all sites, regions and jurisdictions, there may be benefit in selecting at least one habitat type that is found most frequently to include in the sampling protocol of all jurisdictions.
- Data was only available for stream and riverine habitats. The AusRivAs sampling protocol does not appear to include refugial habitats or wetlands located away from the main channel, whether on floodplains, anabranches or multiple channel networks. As such, predictions based on the present regional databases may underestimate the true biodiversity. Inclusion and sampling of off-channel sites is recommended.

- Increased taxonomic resolution beyond family level identification is also recommended. This may reveal greater distinction among sites in terms of the ability to predict biodiversity hotspots (cf. Hewlett 2000). This is important for Australian macroinvertebrate taxa, which are typically adapted to high levels of environmental variation. Family-level resolution may mask any differentiation in ecological responses to environmental variation that could exist among taxa within families.

5.3.2 FISH

- Ongoing research aimed at defining genetic variation in freshwater fish species has (and is expected to continue to do so) demonstrated substantial genetic variation and phylogeographic partitioning in many species of freshwater fish. Indeed, the extent of this variation is sufficient to warrant a reexamination of the species level taxonomy of some taxa (see Chapter 6). At present, this variation is not accommodated within the Northern Australian Freshwater Fish Atlas. There is thus a potential for the true biodiversity of this group to be underestimated. Similarly, the distributional boundaries of many genetically distinct taxa are imprecisely known.
- Some areas of northern Australia remain undersampled despite the otherwise comprehensive coverage. For example, parts of the Kimberley region, Arnhem Land (e.g. Roper River *inter alia*), the southern Gulf region and Cape York Peninsula (e.g. Staaten River) are sparsely sampled. Addressing these gaps would greatly assist in providing the material required to address the issue of genetic distinctiveness outlined above.
- Although it is not apparent in Figure 5.1 due to the map scale used, many, if not most, rivers of northern Australia are inadequately sampled in their lowermost freshwater reaches (i.e. immediately above the interface between freshwater and estuarine habitats). Riverine fish diversity tends to strongly increase downstream and there is the potential for river basin-scale diversity to be underestimated as a consequence. Estuarine fish biodiversity is very poorly documented for northern Australia.

5.3.3 TURTLES

- In comparison to the data sets available for macroinvertebrates, fish and waterbirds, the freshwater turtle data set contains fewer records. Greater survey effort would result in an increased capacity to model the distribution of turtle species.

5.3.4 OTHER TAXA

- Data sets concerning the distribution of other water-dependent fauna (i.e. frogs, crocodiles, lizards, snakes, riparian birds) or aquatic, semi-aquatic and riparian flora could not be assembled in the time frame of the current project, yet no doubt these taxa substantially contribute to determining the conservation significance of particular areas.

5.3.5 OTHER HABITAT TYPES

- Subterranean and spring habitats have generally not been included in surveys of macroinvertebrates nor fish. Elsewhere such habitat-speciifc taxa are very important in the definition of conservation value. Spring-associated and subterranean fish diversity remains very poorly documented for northern Australia and yet such habitats are likely to contain species of high conservation value due to the extremely restricted and disjunct nature of these habitats.

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6.0 Delineation of freshwater bioregions in northern Australia

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Key Points

1. **Aim**: To test whether existing spatial partitioning of the study area (e.g. drainage divisions and aggregated NASY regions) was concordant with the distribution of different aquatic faunal groups based on individual taxon (species or family) and phylogentically distinctive evolutionary units.

2. **Methods**: Statistical analyses of available data and expert judgment were used to consider the applicability of *a priori* surrogate regionalisations [i.e. the AWRC Drainage Divisions and the North Australia Sustainable Yields (NASY) reporting regions] in demarcating evolutionary cohesive units of freshwater biodiversity. The data we assessed included numerous environmental attributes, species occurrences for freshwater fish (species level), turtle (species level), waterbird (species level) and macroinvertebrate (family level), and phylogeographic (i.e. molecular level) data for selected species of freshwater fish and macroinvertebrate.

3. **Results**: We tested the applicability of the seven aggregated NASY regions, with our analyses indicating all but one of these regional boundaries reflected substantial partitioning of freshwater biodiversity, i.e. we lumped the two of the aggregated NASY regions. Thus, we identified a total of six freshwater bioregions in northern Australia, although the degree of biogeographic concordance among faunal groups varied considerably. For some faunal groups, biogeographic organisation transcended some of the boundaries of the NASY regions, thus the bioregion boundaries we identify should be regarded as 'fuzzy', and the bioregional subdivision in some areas should be regarded as a zootones, because strong biodiversity changes did not occur abruptly at a single location

4. **Implications**: We have built upon earlier freshwater bioregionalisations in northern Australia based on only freshwater fish, and have identified smaller units more relevant for the management of total freshwater biodiversity in northern Australia. However, substantial sub-regional variation in biodiversity is evident within all of the identified bioregions which should also be accommodated in relevant conservation and environmental management initiatives.

5. **Limitations / knowledge gaps / next steps**: A limitation of integrative bioregionalisations, such as the one we present, is that they are only summaries of the major partitions of biodiversity as identified for multiple taxonomic groups; thus, all bioregional boundaries will not be applicable for all species, and there will always be substantial sub-regional patterns of biodiversity. Knowledge gaps relate to both data issues (spatial sampling gaps, key fauna groups, taxonomic resolution for macroinvertebrates) and conceptual issues (identification of landscape metrics relating to evolutionary history, accounting for cryptic species). Next steps would therefore involve formulation of taxon-specific bioregionalisations, filling the data gaps and exploring the conceptual issues identified by this study.

6.1 INTRODUCTION

Bioregionalisations systematically identify spatially nested geographic units of biodiversity that reflect hierarchical patterns of biotic distinctiveness, and therefore the degree of shared evolutionary history, of biota across landscapes (e.g. Brown & Lomolino, 1998; Spalding et al., 2007; Last et al., 2010). Geospatial units within a bioregionalisation hierarchy may follow: realm > biome > bioregion > subregion. For example, within Australia's terrestrial realm, the arid zone biome (*sensu* Byrne et al., 2008) contains 23 bioregions and more than 100 subregions (Interim Bioregionalisation of Australia, IBRA; Thackway & Creswell 1995); although see Last et al. (2010) and Butler et al. (2001) for examples of alternative bioregional hierarchies applied to Australia's marine biodiversity. The intent of undertaking a bioregionalisation is to identify units of biodiversity for large scale conservation planning, reserve system development and natural resource management, including continent-wide assessment and reporting on the status of ecological systems (Olson et al., 2001; Spalding et al., 2007; Abell et al., 2008), with the 'bioregion' being the appropriate geospatial unit for these purposes. Various definitions of 'bioregion' have been used in the literature, many on the basis of ecological criteria (see Hale & Butcher, 2008). However, we suggest that an evolutionary definition is most appropriate for the resolution of cohesive units of biodiversity for conservation management, with bioregions being 'geospatial units that bound biodiversity with recent shared evolutionary history relative to biodiversity elsewhere in the landscape'. The 'bioregion' term we use is analogous to the 'ecoregion' (see Olson et al., 2001; Spalding et al., 2007; Abell et al., 2008) and freshwater 'province' used by Unmack (2001). We note that bioregionalisations are distinct from 'classification' schemes, which categorise ecosystem types at individual habitat scales, rather than categorising broader areas across landscapes on the basis of shared evolutionary history (see Hale & Butcher, 2008). Whilst national-scale bioregionalisations exist for terrestrial (e.g. Thackway & Cresswell, 1995) and marine (e.g. Butler et al., 2001; Lyne & Hayes, 2005) realms, no equivalent bioregionalisation has been implemented for Australian freshwaters (Kingsford & Nevill, 2005).

Approaches towards bioregion boundary delineation may follow strictly bottom-up, data-driven, statistical methods, such as Parsimony Analysis of Endemicity (PAE; Rosen, 1988; Morrone, 1994) or statistical classifications of biotic similarity (see Snelder et al., 2010). Whilst these bottom-up approaches may be preferred by biogeographers, there is debate surrounding the application of alpha (i.e. within site) versus beta (i.e. among-site) components of biodiversity in such analyses, and thresholds for spatial changes in biodiversity that reflect places with unique evolutionary history are not established in biogeographic theory (Whittaker et al., 2005). Furthermore, the Wallacean shortfall (sensu Lomolino 2004; i.e. inadequate knowledge of species distributions at continental, regional and even local scales) characteristic of much of the world's freshwater fauna, coupled with poor taxonomic knowledge (i.e. the Linnean shortfall, Brown & Lomolino, 1998) of freshwater species diversity globally (Allan & Flecker, 1993; Dudgeon et al., 2006) and in Australia (e.g. see Cook et al., 2008 and references therein), however, can make such bottom up approaches towards bioregionalisation unrealistic or biased. Consequently, strictly top-down, expert opinion (Delphic) approaches have been used for some regional faunal groups that are especially understudied, such as freshwater fishes for several regions of Africa (Abell et al., 2008). However, such Delphic approaches are highly dependent on the knowledge of the experts involved and may not yield repeatable results (Lyne & Hayes, 2005). An alternative approach, that integrates elements of both top-down and bottom-up approaches towards bioregionalisation, is to assess the validity of a priori 'surrogate bioregionalisations' (i.e. geospatial units based on geophysical or climatic boundaries) in reflecting meaningful units of evolutionarily cohesive biodiversity, such as performed for Australian freshwater crayfish using the terrestrial IBRA bioregions (Whiting et al., 2000). This approach was heavily used in the development of terrestrial, marine and freshwater ecoregions of the world (Olson et al., 2001; Spalding et al., 2007; Abell et al., 2008) and uses statistical analyses of the available data to confirm or deny the validity of hypothesized bioregional boundaries, but allows also for expert judgment to qualitatively consider the validity of 'surrogate' bioregion boundaries for cases in which data may be limited. The expert judgment facets of this approach also allow multiple types of data to be considered for a hypothesized bioregional boundary which would otherwise not be easily accommodated by strictly bottom-up approaches.

Other central issues in freshwater bioregionalisation relate to the need for bioregions to be contiguous geospatial units, as geographically separated places are unlikely to have common evolutionary histories. However, some presently non-contiguous catchments may have had hydrological and biotic connections in the recent past (e.g. during Pleistocene glacial phases), meaning that occasionally a non-contiguous bioregion may be identified (see Filipe et al., 2009). Furthermore, it is generally accepted that the boundaries of freshwater bioregions should follow catchment boundaries, as it is unlikely for biota within a catchment to be significantly isolated over long periods, perhaps with the exception of very large catchments (e.g. the Amazon Basin) or catchments within which large waterfalls occur (e.g. McGlashan & Hughes, 2000; Abell et al., 2008). In such cases, sub-catchment boundaries would be best suited to the demarcation of freshwater bioregional boundaries. In contrast, classifications may identify multiple discrete habitat units with similar ecological characteristics scattered across landscapes (see Hale & Butcher, 2008). Thus, there may be multiple classification groups within a bioregion based on numerous distinct habitat features (e.g. floodplain wetlands, high-gradient stream segments, meandering or anabranching river segments). This is not to say that bioregions need to be homogeneous units of biodiversity, as the biodiversity attributes of one catchment or even subcatchment are unlikely to be strictly representative of the biodiversity of other rivers or subcatchments within the same bioregion (Dudgeon et al., 2006; Cook et al., 2008), but bioregions must reflect some logical grouping of biodiversity with a cohesive evolutionary past. Sub-bioregional structuring in biodiversity, however, is also an important facet of freshwater biodiversity, which would be well suited to locally-focused river conservation and management systems (e.g. Abell et al., 2007).

Finally, no single bioregionalisation will be optimal for all species (Olson et al., 2001; Abell et al., 2008). Thus, there is debate as to the usefulness of a single, integrated bioregionalisation across diverse taxa which are unlikely to have shared evolutionary histories or have patterns of species turnover that are determined by different environmental and evolutionary drivers, as opposed to bioregions defined for specific groups for which geographical places of shared history may be more clearly identified. Even closely related sister species within a genus may have markedly contrasting biogeographic histories in the same landscape (e.g. Cook et al., 2007; Page & Hughes, 2007), indicating that phylogenetic proximity may not be a reliable predictor of a common, among-species biogeographic history. However, if the aim was to arrive at a single bioregionalistion across diverse taxonomic groups for biodiversity conservation and management purposes, it would be necessary to assess the degree of concordance of bioregional boundaries among the taxon-specific bioregionalisations. Considering that it is extremely unlikely for multiple species to have exactly the same biogeographic patterns, multi-species bioregional boundaries may be 'fuzzy' boundaries or 'zootones' , which are geographic zones containing varying mixtures of species or divergent genetic lineages within species from otherwise disparate bioregions (Lyne & Hayes, 2005).

Here, we use an approach towards freshwater bioregionalisation in northern Australia that uses statistical analyses of available data and expert judgment to consider the applicability of *a priori* surrogate regionalisations [i.e. the AWRC Drainage Divisions and the North Australia Sustainable Yields (NASY) reporting regions] in demarcating units of freshwater biodiversity with shared recent evolutionary history. The data we assess include numerous environmental attributes, species occurrences for freshwater fish (species level), turtle (species level), wetland bird (species level) and macroinvertebrate (family level), and phylogeographic (i.e. molecular level) data for selected species of freshwater fish and macroinvertebrate. The objectives of the bioregional analyses are to:

1. identify the applicability of the *a priori*, 'surrogate' bioregional units for various biophysical data sets;
2. identify the degree to which analyses of the various data sets are concordant in validating hypothesized bioregional boundaries;

3. provide recommendations regarding the application of freshwater bioregional units for broad scale assessment of freshwater conservation values

6.2 METHODS

6.2.1 SPATIAL SCALE OF UNITS OF ANALYSIS

The grain size used for all analyses was 'catchment' as defined in Chapter 3. All data for bioregional analyses were summarised at the catchment scale for AWRC (1976) Drainage Divisions 8 and 9 (Timor Sea and Gulf of Carpentaria; Fig. 6.1) and aggregated North Australian Sustainable Yields (NASY) reporting regions (Fig. 6.2). We aggregated some of the original NASY regions on the basis of extant (e.g. present-day flooding patterns) or recent past (e.g. late Pleistocene lowered sea levels) hydrological connectivity. The catchment unit we base our analyses on is a much finer grain size than used in previous freshwater bioregionalisation that have been undertaken in northern Australia, which used grouping of catchments as units of analysis (e.g. Unmack, 2001; Abell et al., 2008).

Figure 6.1. AWRC (1976) Drainage Divisions 8 and 9.

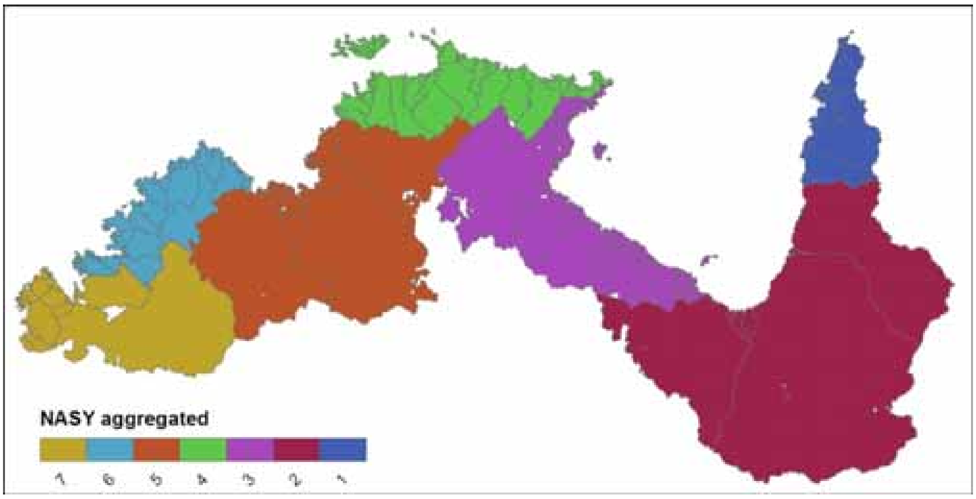

Figure 6.2. Aggregated North Australian Sustainable Yields (NASY) reporting regions based on catchment boundaries as defined in Chapter 3.

6.2.2 Data sources

Environmental and species-level biological data

The source of environmental attribute and species-level biological data is described in Chapters 4 and 5, respectively.

Molecular data

Phylogeographic data consisted of mitochondrial DNA sequences for 13 species of freshwater fish (i.e. *Glossamia aprion, Neosilurus hyrtlii, Neosilurus ater, Neosilurus pseudospinosus, Oxyeleotris selheimi, Oxyeleotris lineolatus, Denariusa bandata, Pseudomugil gertrudae, Melanotaenia maccullochi, Craterocephalus stercusmuscarum, Craterocephalus stramineus, Ambassis macleayi, Ambassis* sp. NW) and several species of freshwater macroinvertebrate (i.e. *Caridina* spp., *Velesunio* spp., *Macrobrachium Rosenbergi*, *Macrobrachium bullatum*, and *Cherax quadricarinatus*). Most data was generated as part of the Tropical Rivers and Coastal Knowledge Commonwealth Environmental Research Facility's Biodiversity Project (Cook, Hughes et al., unpublished), although data was also sourced from published studies for some of the taxa (i.e. Cook & Hughes, 2010; de Bruyn et al., 2004; Baker et al., 2008; Fawcett, 2008; Unmack & Dowling, 2010).

6.2.3 Data analyses

Statistical classification of environmental attributes and species composition data

Data relating to the spatial arrangement of catchments based on environmental or faunal attributes was treated in the same manner. The intent was to determine whether natural groupings as recognised by multivariate similarity analysis (ordination and classification) were concordant with 'surrogate' regionalisations; in this case AWRC drainage divisions and the aggregated NASY regions. A Bray-Curtis dissimilarity matrix was first generated for each data set (environment and faunal groups) in the PRIMER V5 statistical package (Clarke & Gorely, 2001). ANOSIM (analysis of similarity) tests were used to test whether catchments grouped according to either drainage division or aggregated NASY region. This procedure is analogous to an analysis of variance testing for within-group differences in distribution in multivariate space. As part of this process, between-group dissimilarities were generated based on all catchments within each group. These data were then used to construct a between-group (rather than between-catchment) dissimilarity matrix that informed the construction of a hierarchical dendrogram using the unpaired group mean averaging technique (UPGMA). The average similarity of all catchments within a group was estimated and used as an indicator of the variability present within that group. The contribution of individual taxa or attributes to the distinction between groups was determined using the SIMPER (similarity percentage) routine in PRIMER. Two sets of analyses were conducted for the freshwater fish fauna; all species and strictly freshwater species excluding species that also occur in estuaries or the marine environment at some point during their life history.

Molecular analyses

The genetic data (i.e. sequences of mitochondrial DNA genes) were first analysed using Analysis of Molecular Variance (AMOVA, Excoffier et al., 1992), using 10,000 bootstrap replicates of the observed genotypes in ARLEQUIN (Schneider et al., 2000) and *a priori* freshwater geospatial units [i.e. AWRC (1976) Drainage Divisions and aggregated NASY regions, respectively] as groups. Secondly, phylogenetic analysis of the DNA sequence data was performed for each species using 1000 bootstrap replicates of the Maximum Likelihood (ML) method as implemented in PHYML (Guindon & Gascuel, 2003). The geographical places across which phylogenetic breaks occurred were identified for well-supported (i.e. >70 % bootstrap support) genetic lineages. Phylogeographic breaks greater than two percent were designated 'major' breaks, whereas 'minor' breaks were less than two percent but greater than one percent divergence. The locations of these breaks were considered for each species with respect to the aggregated NASY boundaries, and we used three categories to define the correctness of the boundary: '*best-fit boundary*', where the aggregated NASY boundary likely reflect the true phylogeographic split, '*approximate boundary*', where the aggregated NASY boundary is spatially proximate to the true phylogeographic break, and '*tentative boundary'*, where the aggregated NASY boundary is in a general area where a phylogeographic split occurs but sampling gaps prohibit determination of how closely the boundary fits the phylogeographic break. *'No fit'* boundaries were where a species did not have a phylogeographic break at, near or in the general area of an aggregated NASY regional boundary.

BIOREGION DELINEATION

Using results of all data analyses, we used 'top-down' expert opinion to decide the validity and nature of the *a priori*, hypothesized bioregional boundaries we tested. We considered firstly if the boundary reflected a partition between significantly different fauna groups (at species and/or molecular levels of biological organisation) that would indicate evolutionary distinctiveness. Secondly, we considered how geographically accurate the boundary was, using the terminology outlined above, i.e. 'best-fit', 'approximate' or 'tentative'. Finally, we considered whether the boundary represented either a relatively abrupt change in landscape-scale biodiversity patterns or a more gradual change in biodiversity structuring, similar to the concept of 'zootones' used in some bioregionalisation studies (e.g. Lyne & Hayes, 2005).

6.3 RESULTS

The results of analyses of the match between the *a priori*, hypothesised regions (i.e. AWRC Drainage Divisions and aggregated NASY reporting regions) and spatial patterns of freshwater biodiversity in northern Australia is reported separately for environmental attributes, each faunal group, and the molecular analyses.

6.3.1 ENVIRONMENTAL ATTRIBUTES

ANOSIM revealed significant spatial structuring in environmental attributes between the AWRC Drainage Divisions (Global R = 0.185, $p< 0.001$) and among the aggregated NASY regions (Global R = 0.153, $p<0.001$). However, the disimilarity scores revealed that catchments were partitioned into two principle groups that do not relate to region. These groups are significantly distinct from one another in many respects, including catchment size, slope, vegetative cover, and the nature, size and inundation frequency of floodplain habitats (Appendix 6.1). Thus, one group of basins were all large basins, with long rivers of low stream density and extensive palustrine and lacustrine habitats of differing inundation frequency. In contrast, basins within the other group were all small basins with almost no floodplain habitats. Low within-region mean similarity among catchments for these environmental attributes indicates that each aggregated NASY region contains environmentally dissimilar catchments; thus explaining the relatively low R values for the ANOSIM analyses.

6.3.2 MACROINVERTEBRATES

There was no significant structuring of macroinvertebrate fauna across northern Australian when examined for the AWRC Drainage Divisions (R = 0.03, $p>0.05$) or the aggregated NASY regions (R = -0.001, $p>0.05$) indicating that the family level macroinvertebrate data does not have a biogeographic signal.

6.3.3 WATERBIRDS

The distribution of waterbird species across northern Australia was significantly but weakly structured according to Drainage Division (Global R = 0.051, $p < 0.001$), suggesting substantial overlap in the water bird fauna of each division. A stronger differentiation between regional waterbird faunas was detected by ANOSIM when analyses were undertaken using the aggregated NASY regions (R = 0.216, $p<0.001$). Despite this significant ANOSIM result, little clear distinction between the aggregated NASY regions is evidenced by the low mean dissimilarity between regions - only 38.4% ± 1.1% (SE). The UPGMA dendrogram (Fig. 6.3) indicated little significant differentiation between regions, but instead showed the sequential splitting off of a single region at each division (termed 'chaining'), suggesting little evidence for a consistent regionalisation based on this taxon group.

In addition to the widespread distribution of many waterbird species among regions, their occurrence within regions was high (77.2 % - 96.5% frequency of occurrence within regions), giving moderately high within-region similarity among catchments (71.0 ± 3.8 %). Almost a quarter (i.e. 23%) of waterbird species that were common (i.e. occurred in 90 % or more of catchments) within one region were widely distributed throughout at least four or more regions at the same level of occurrence (Appendix 6.2). Indeed, almost as great a proportion of the total number of waterbirds present in northern Australia was in all regions as was in only one region (Appendix 6.3). However, SIMPER analysis indicated 42 species common (i.e. occurred in 90 % of catchments) in aggregated NASY region 2 that did not attain the same level of occurrence in any other region, despite their common widespread distributions. The varied patterns of abundance in this group of species, rather than any bioregional pattern, likely explain the significant ANOSIM results. Finally, we note that more than one-third (i.e. 34.57 %) of the common, widely distributed waterbird species in northern Australia were international migrants (Appendix 6.2).

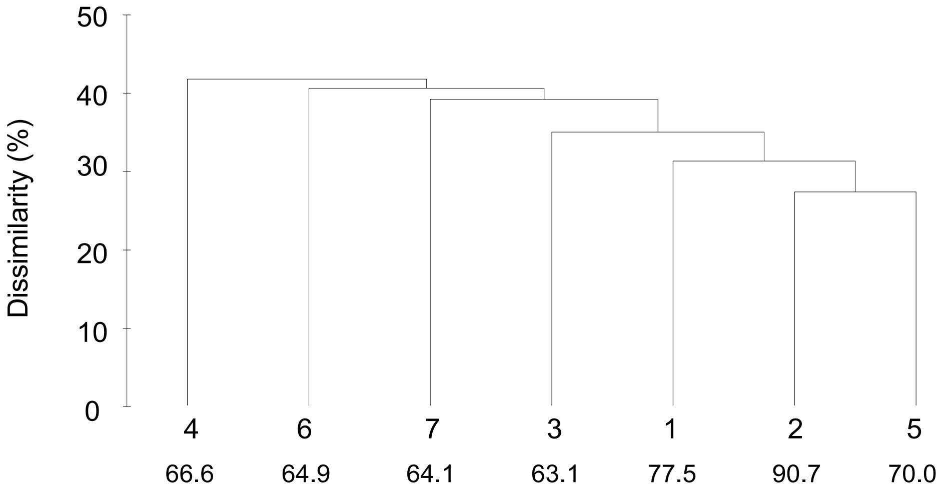

Figure 6.3 UPGMA dendrogram of northern Australian aggregated NASY regions based on waterbird fauna showing mean percentage dissimilarity between regions, and mean within-region percent similarity (along *x*-axis).

6.3.4 Turtles

Significant spatial structuring of the turtle fauna of northern Australia was evident at both Drainage Division ($R = 0.45$, $p<0.001$) and aggregated NASY region ($R = 0.66$, $p<0.001$) scales. The UPGMA dendrogram indicates that the Kimberley region (i.e. aggregated NASY regions 6 and 7) was the most distinctive (i.e. ~ 80% dissimilarity), although regions 4 and 5 also had a reasonable degree of dissimilarity (~ 55% dissimilarity) in their turtle fauna (Fig. 6.4). The relatively high within-aggregated NASY region similarity (i.e. all > 60 % similarity) suggests that turtle species were widely distributed within regions (i.e. occurred in many of the catchments within each region). Moreover, these data suggested that species within regions 4 and 5 were relatively widespread throughout these two regions, as were species within aggregated NASY regions 1, 2 and 3. The two Kimberley regions were the most distinctive. However, apparently crisp boundaries between regions were in fact rather indistinct because turtle species such as *Chelodina rugosa* were widely distributed at high occurrence across regions (i.e. 100% occurrence in regions 1, 2, 3, 4 and 5). Similarly, both *C. burrungandjii* and *Elseya dentata* were relatively commonly distributed across all catchments (60 – 100% occurrence within regions) within regions 5, 6 and 7 (Appendix 6.4).

Chelodina regusa was frequently important in defining differences between the two Kimberley drainages and the remaining drainages, in which it was ubiquitous (Appendix 6.5). The two Kimberley regions differed from one another due to the consistent presence of *E. victoriae* in region 7. *Chelodina burrungandjii* and *Emydura dentata* were both distinctive and widespread members of the turtle fauna of region 5, 6 and 7. Comparisons between regions 1 and 3 uniquely required only two species, *Myuchelys latisternum* and *E. worreli*, to separate them from each other; all other comparisons required three or four species.

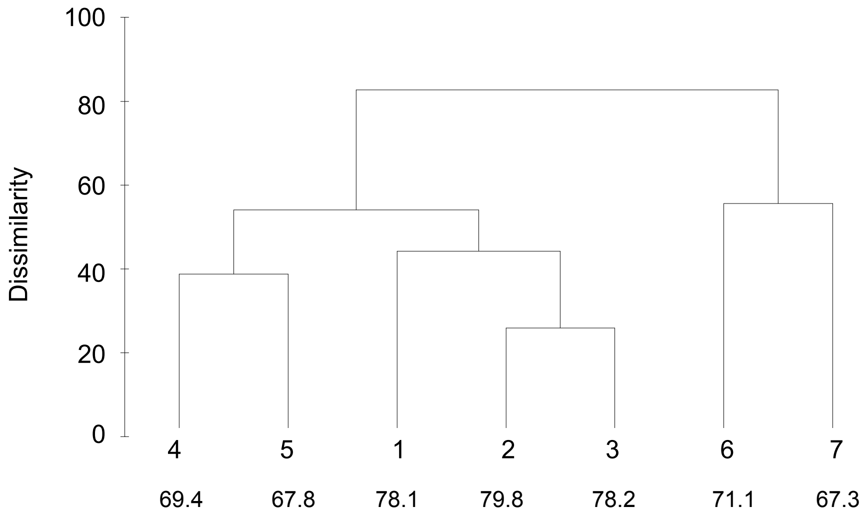

Figure 6.4 UPGMA dendrogram of northern Australian aggregated NASY regions based on freshwater turtle fauna showing mean percentage dissimilarity between regions, and mean within-region percent similarity (along *x*-axis).

6.3.5 FISH

Significant spatial structuring in freshwater fish communities was detected by ANOSIM for regions defined by Drainage Division (R = 0.322, p<0.001 and R = 0.376, p<0.001 for entire fish fauna and strictly freshwater species, respectively) and by aggregated NASY regions (R = 0.516, p<0.001 and R = 0.550, p<0.001). Very similar patterns were obtained when the assessed fauna contained all fish species or only those that were strictly freshwater. The inclusion of species requiring access to estuarine or marine areas to breed and hence tolerant of elevated salinities did not greatly decrease the average between-region dissimilarity (58.1 ± 2.3 % dissimilarity for entire fish fauna *vs* 62.7 ± 2.7 % dissimilarity for freshwater only fish fauna). The following discussion is based on freshwater species only given the greater distinction between the aggregated NASY regions detected by ANOSIM for this group and, moreover, the existence of the same pattern irrespective of which group was used.

The aggregated NASY regions could be divided into three main groups (Fig. 6.5). The first consisted of the western regions 5, 6 and 7, all of which were most dissimilar to the remaining groups. Rivers within this group were relatively similar to one another. Region 1 (Cape York Peninsula) did not group with other regions in the Gulf of Carpentartia, but rather grouped with region 4 (Top End of the NT), which was roughly equivalent in size and latitude. These regions tended to have relatively high similarity (i.e. > 60 % similarity) in their within-region fish fauna. In contrast, the fish fauna of the Gulf of Carpentaria (i.e. regions 2 and 3) differed substantially among catchments, especially within region 2 with only 38.3 % similarity. Indeed, this especially high among-catchment beta diversity within region 2, coupled with slight differences in the frequency of occurrence of multiple fish species, explains the high dissimilarity between regions 2 and 3, rather than differences in their fish fauna. Other regions, excluding regions 6 and 7, also had relatively high among-catchment beta diversity which related mainly to catchment size, as small catchments tended to have a reduced species complement comprised of widespread species. However, widespread species exclusively were identified as the important taxa contributing to within-region similarity, often with the same species driving within-region similarity for multiple regions (Appendix 6.6). For example, *H. compressa* and *G. aprion*, both lowland species, were present in seven and five regions, respectively. The exceptions were *O. nullipora*, *D. bandata*, *P. gertrudae* and *I. werneri* which were widespread within, but limited to, regions 1 and 4.

SIMPER revealed that, with the exception of *Ambassis* sp.NW, which was more than three times more common in aggregated NASY region 6 than region 7, and hence contributed 13.5% of the overall difference between these regions, no other single species attained an importance greater than 10% in any two region comparison. In fact, a mean of 28.9 ± 1.0 species was required to explain more than 90% of the difference between any two region comparison. Thus, although the aggregated NASY regions were significant in defining bioregions, the distribution of a great majority of the species considered transcended these regional boundaries.

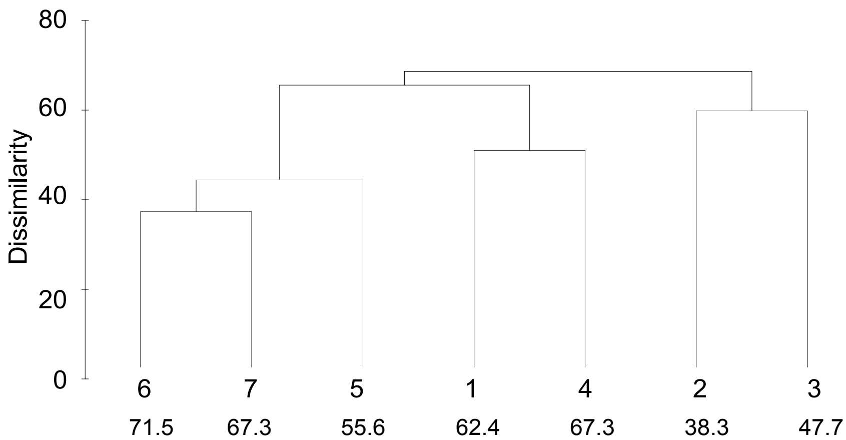

Figure 6.5. UPGMA dendrogram of northern Australian aggregated NASY regions based on freshwater fish fauna showing mean percentage dissimilarity between regions, and mean within-region percent similarity (along *x*-axis).

6.3.6 Molecular analyses

Analysis of Molecular Variance (AMOVA) indicated that greater genetic variation was partitioned among the AWRC Drainage Divisions than within the divisions for only one species, *M. maccullochi*, and greater partitioning of genetic variation among the aggregated NASY regions than within the regions for two species, *M. maccullochi* and *N. ater* (Table 1). However, the analysis for *M. maccullochi* demonstrated only that there is significant genetic structuring between regions 1 and 4, as this species is absent from regions 2, 3, 5, 6, and 7. Thus, this result should not be interpreted as support for the *a priori* regions we considered. Interestingly, a similar result would have been obtained for *P. gertrudae*, which has a similar disjunct distribution between regions 1 and 4, except that a highly divergent population of the species was revealed from Leichardt Springs (escarpment in upper South Alligator River), giving region 4 higher within-region genetic variation than was apparent between regions 1 and 4). Similarly, the significant result for *N. ater* should not be taken as support for major genetic subdivisions among the *a priori* aggregated NASY regions, as this species has amongst the lowest degree of genetic subdivision of all assessed freshwater species in northern Australia (Cook, Hughes, et al., unpublished data). The AMOVA result for this species therefore only indicated differences in the distribution of very closely related genotypes within this species. For all other species, greater genetic variation was evident among catchments within the AWRC Drainage Divisions than was between the divisions. The partitioning of genetic variation among the aggregated NASY regions was similar to the within region genetic variation for four species (i.e. *M. rosenbergi*, *O. selheimi*, *O. lineolatus*, and *N. hyrtlii*; Table 6.1), although for all other species the within-region genetic variation was greater than among the regions. These results suggest that overall the AWRC Drainage Divisions and the aggregated NASY regions do not reflect patterns of genetic biodiversity in freshwater species in northern Australia and are inadequate representations of freshwater bioregional patterns.

Table 1. Results of Analysis of Molecular Variance (AMOVA), showing the relative partitioning of genetic variation among and within the AWRC Drainage Divisions and NASY regions, respectively, for 13 freshwater species.

Species	***AWRC Drainage Divisions***		***Aggregated NASY regions***	
	Among Region	Within Region	Among Region	Within Region
D. bandata	0.012 (P=0.182)	0.717 (P<0.001)	-0.230 (P=0.755)	0.765 (P<0.001)
P. gertrudae	0.331 (P=0.016)	0.672 (P<0.001)	0.188 (P=0.075)	0.684 (P<0.001)
C. stramineus	0.385 (P=0.252)	0.996 (P<0.001)	0.067 (P=0.335)	0.997 (P<0.001)
O. selheimi	0.227 (P=0.029)	0.844 (P<0.001)	*0.730 (P<0.001)*	*0.542 (P<0.001)*
O. lineolatus	0.682 (P=0.002)	0.696 (P<0.001)	*0.666 (P=0.014)*	*0.600 (P<0.001)*
M. maccullochi	**0.880 (P=0.333)**	**-0.061 (P=0.251)**	**0.880 (P=0.333)**	**-0.061 (P=0.251)**
N. hyrtlii	0.489 (P<0.001)	0.561 (P<0.001)	*0.612 (P<0.001)*	*0.246 (P<0.001)*
N. ater	0.460 (P=0.052)	0.884 (P<0.001)	**0.926 (P=0.119)**	**-0.040 (P<0.001)**
N. pseudospinosus	-	-	0.626 (P=0.251)	0.899 (P<0.001)
C. stercusmuscarum	0.623 (<0.001)	0.949 (P<0.001)	0.491 (P=0.002)	0.951 (P<0.001)
G. aprion	0.070 (P=0.003)	0.799 (P<0.001)	0.310 (P<0.001)	0.731 (P<0.001)
M. rosenbergi	0.101 (P=0.063)	0.606 (P<0.001)	*0.426 (P=0.004)*	*0.386 (P<0.001)*

To explore further phylogeographic patterns of freshwater species in northern Australia, we built Maximum Likelihood (ML) gene trees using mitochondrial DNA (mtDNA) sequence data for various species of fish and crustacean, or considered previous phylogeographic studies of freshwater species in northern Australia. These ML gene trees are not presented, although an example ML gene tree for hyrtl's catfish, *Neosilurus hyrtlii*, is presented in Figure 6.6, showing four divergent genetic lineages, corresponding to three major phylogeographic breaks (i.e. greater than two percent genetic divergence) and one minor phylogeographic break (i.e. less than two percent but greater than one percent genetic divergence). For each species, major and minor phylogeographic breaks were identified from their respective ML gene trees and overlain with the aggregated NASY regions (Fig 6.7). The degree to which the aggregated NASY regions corresponded to phylogeographic subdivisions for each taxon was considered in terms of 'no fit', 'best-fit', 'approximate' or 'tentative' boundaries, as described in the methods. Note that 'no fit' partitions are not shown.

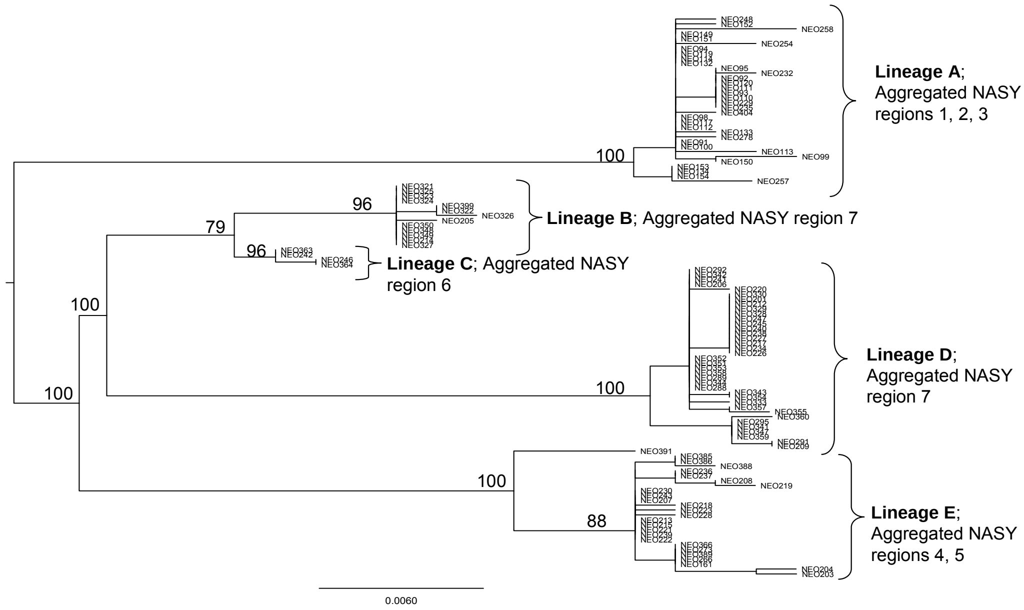

Figure 6.6. Maximum Likelihood (-ln = -1587.386) mtDNA gene tree for *Neosilurus hyrtlii* sampled from throughout northern Australia. Numbers along branches are bootstrap values. Lineage names (i.e. Lineages A-E) and their distributions with respect to the aggregated NASY regions are indicated to the right. Major phylogeographic breaks (i.e. > 2 % genetic divergence) occur between aggregated NASY regions 3 and 4 (Lineages A and E), regions 5 and 6 (Lineage E and C) and regions 6 and 7 (Lineages C and D). A minor phylogeographic break (i.e. < 2 >1 % genetic divergence) also occurs between regions 6 and 7 (Lineages B and C). The precise location of the phylogeographic break between regions 5 and 6 can reasonably be said to be between the Durack and Drysdale Rivers; thus, this is a 'best-fit' boundary. In contrast, the location of the phylogeographic break between regions 3 and 4 probably roughly coincides with the location of the aggregated NASY boundary; thus, this is defined as an 'approximate' boundary. Finally, both the major and minor phylogeographic breaks between regions 6 and 7 may be near the aggregated NASY boundary (certainly they should be on the northern catchment boundary of the Isdell River, rather than the southern catchment boundary of the Isdell River, as the aggregated NASY boundary currently is) or may be even further to the north. Thus, this boundary is defined as a 'tentative' boundary.

When the molecular data were considered for all species (Fig 6.7), some key patterns emerge. First, major phylogeographic breaks between aggregated NASY regions 1 and 2, and 2 and 3 were absent, except for *C. quadricarinatus*, which has a major break coinciding with the eastern catchment boundary of the Roper River (within region 3, close to the boundary between regions 3 and 4). The two species of *Ambassis* assessed in the study each had a minor phylogeographic break on the eastern side of the Gregory River (not the east of the catchment, which is where the aggregated NASY regional split occurs), although this level of phylogeographic subdivision does not offer compelling evidence for a bioregional boundary. Thus, overall the assessed freshwater biota within the Gulf of Carpentaria catchments had a fairly cohesive recent evolutionary past, as it is likely that the divergent lineage of *C. quadricarinatus* in the Roper River reflects a relatively recent range expansion from aggregated NASY region 4 rather than a long-standing biogeographic partition (Baker et al., 2008). Second, for every phylogeographic break identified for a given taxon or suite of taxa, there are other taxa that do not share a phylogeographic subdivision at that location (i.e. had 'not fit' biogeographic relationships with the aggregated NASY boundary). For example, four species (*G. aprion*, *N. hyrtlii*, *N. pseudospinosus* and *M. bullatum*) each had a major, 'best-fit' phylogeographic break between aggregated NASY regions 5 and 6, and multiple cryptic species within the freshwater shrimp genus *Caridina* had a strong pattern of species turnover, whereas *C. stercusmuscarum*, *Ambassis* sp. NW, and *O. selheimi* had 'no fit' phylogeographic substructure between these regions (other species were unable to be assessed for this boundary due to either sampling gaps or because this area is outside their distributions). This suggested that despite the presence of a relatively strong biogeographic boundary in the landscape, not all species perceive the boundary in the same way (i.e. some species terminate their range, some species have major phylogeographic breaks, and other species have continuous distributions); thus, varied biogeographic patterns are evident among species even for relatively strong biogeographic boundaries. Third, only one bioregional boundary was identified as a 'best-fit' boundary (i.e. the boundary between aggregated NASY regions 5 and 6), we suggest that a 'best-fit' boundary would have become evident between regions 3 and 4 if we had better spatial coverage of samples from the area. The boundary between regions 4 and 5 was identified as 'approximate', as numerous taxa had substantial phylogeographic subdivisions either at the aggregated NASY boundary, near the boundary slightly to the north in the Darwin area or slightly to the south at the southern catchment divide of the Daly River. This suggests quite strongly that this bioregional boundary should be regarded as a 'zootone', whereby strong biodiversity changes accumulate over a geographic zone of mixing of divergent genetic lineages within various taxa that were otherwise characteristic of regions 4 and 5, respectively. This zone of multiple species-specific phylogeographic subdivisions occurred approximately between the Adelaide and Daly Rivers (inclusive). The boundary between regions 6 and 7 was identified as a 'tentative' boundary, as the location of the substantial phylogeographic breaks for various species in the general area cannot be reasonably determined as the Kimberley is an area that is very poorly sampled with respect to other regions in northern Australia. Finally, the available genetic data also indicated various patterns of localized, cryptic endemism at sub-regional scales, including within the Gregory-Nicholson Catchment (aggregated NASY region 2, Fawcett 2008; Unmack and Dowling 2010), at Leichardt Springs (upper South Alligator River, region 4), within the Daly River (region 5), and within several catchments of the central-north Kimberley region (Cook et al., in review), amongst other examples.

6.4 Discussion

6.4.1 Freshwater bioregions in northern Australia

Overall, analyses indicate that the AWRC Drainage Divisions and the aggregated NASY regions inadequately reflect cohesive units of freshwater biodiversity in northern Australia, although for many of the analyses the aggregated NASY regions performed better than the Drainage Divisions, and some (but not all) of the aggregated NASY regional boundaries appeared to coincide reasonably well with some of the major biodiversity partitions we identified. Thus, the results of analyses of environmental and biological data were considered for the aggregated NASY regions further in developing a freshwater bioregionalisation for northern Australia.

The environmental attribute data split catchments into groups based principally on their size and inundation frequency of their floodplains, rather than on the basis of regional affinity. This indicates that such applications of environmental data are best suited to the determination of habitat 'classification' systems, rather than bioregionalisations. Perhaps environmental metrics relating to landscape evolution (e.g. continental shelf width, historical river connectivity, bathymetry, palaeoclimatc data) may identify regional groups of catchments that reflect evolutionary cohesive units of biodiversity, although this would need further exploration. Similarly, the family-level macroinvertebrate data and the species-level waterbird data both found no regional groupings of catchments. With respect to the macroinvertebrates, this is very likely due to the course taxonomic resolution of the data (i.e. family level), as finer-scale taxonomic analyses of some macroinvertebrate groups (i.e. cryptic species within freshwater shrimps, genus *Caridina*) indicated multiple and very strong bioregional patterns in northern Australia (Cook et al., in review). Whilst family-level macroinvertebrate data can often discriminate between freshwater habitats with different disturbance regimes at within-catchment spatial scales (e.g. Bailey et al., 2004), all macroinvertebrate families tend to be represented in the majority of catchments across landscapes, meaning that catchments do not differ in their family-level macroinvertebrate fauna. Many species of water bird are international migrants; thus, these species represent a highly vagile group. It is therefore not surprising that this group did not indicate any bioregional patterns. We therefore excluded the environmental, macroinvertebrate and waterbird data from the remainder of the discussion, and considered only the fish and turtle species data and the phylogeographic data. The salient results for these data are summarised in Table 6.2.

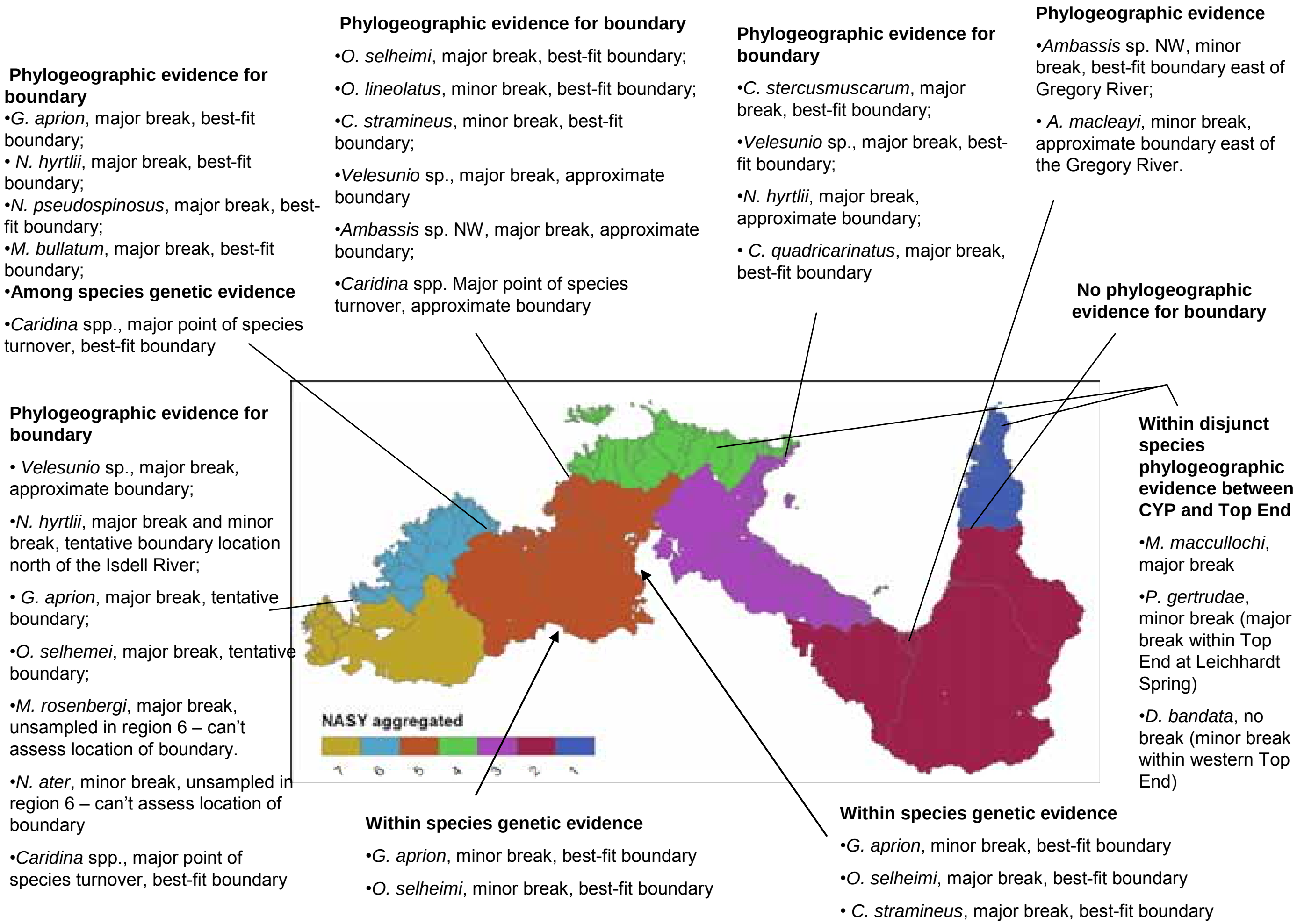

Figure 6.7. Summary of both major and minor phylogeographic subdivisions identified for numerous freshwater species in northern Australia. Text indicates the species, the strength of the break (i.e. major or minor), and the geographical accuracy of the hypothesized regional boundaries as either 'best-fit', 'approximate' or 'tentative'.

The Gulf of Carpentaria is a known biogeographic partition for many terrestrial species (e.g. Bowman et al., 2010), however, various freshwater biogeographic theories (e.g. Allen and Hoese 1980; Unmack 2001) and empirical studies (e.g. de Bruyn et al., 2004; Cook & Hughes, 2010) suggest that the region is evolutionarily cohesive for freshwater species. In support of this assertion, the boundaries between aggregated NASY regions 1 and 2, and 2 and 3, were not supported by the phylogeographic data (i.e. no species had strong phylogeographic breaks among the Gulf of Carpentaria regions). Analyses of the turtle species data also suggests that the boundary between regions 2 and 3 does not reflect a partition between different faunas, although some change in species composition occurred between regions 1 and 2. In striking contrast, the freshwater fish species data indicated a strong biotic subdivision between regions 1 and 2, as these regions have significantly different freshwater fish faunas. The freshwater fish data also indicated substantial dissimilarity between regions 2 and 3. However, this result is driven by slight differences in the frequency of occurrence of multiple, shared species rather than the regions having different fish faunas (see Results section and discussion on beta-diversity for region 2 driven by environmental variables). Interestingly, the fish species data indicated greater similarity in species composition between regions 1 and 4 than between 1 and 2, a pattern largely driven by numerous species with disjunct distributions shared between Cape York Peninsula and the Top End, including *P. gertrudae*, *P. tenellus*, *M. maccullochi, M. nigrans, I. werneri, O. nullipora, D. bandata* and others. Whilst Unmack (2001) grouped these two areas into a single disjunct sub-province on the basis of these shared species, two of them (*M. maccullochi* and *P. gertrudae*) have major and minor phylogeographic breaks between regions 1 and 4, respectively, and the population divergence estimate between these regions for *D. bandata* (which does not have a phylogeographic break) is about 400,000 years (Cook & Hughes, 2010), suggesting that despite repeated Pleistocene land-bridges and associated freshwater habitats connecting these regions across the Gulf of Carpentaria, their freshwater biota have remained independent evolutionary units. Overall, analyses uphold the aggregated NASY boundary between regions 1 and 2, but do not validate the boundary between regions 2 and 3 as a partition between distinct freshwater faunas.

Table 6.2. Percentage dissimilarity in species composition for turtle and freshwater fish species data, and percentage of assessed species with major phylogeographic breaks, for each regional boundary. The ranked order of biotic dissimilarity between the regions is indicated in parenthesis.

Pairwise region comparison	Turtle dissimilarity	Fish dissimilarity	Percentage of assessed species with major phylogeographic breaks*
Region 1 vs Region 2	46.96 (4)	70.16 (1)	0.00 (5)
Region 2 vs Region 3	25.89 (6)	59.76 (2)	0.00 (5)
Region 3 vs Region 4	48.09 (3)	55.60 (3)	44.44 (3)
Region 4 vs Region 5	38.79 (5)	51.83 (4)	36.36 (4)
Region 5 vs Region 6	48.36 (2)	41.69 (5)	71.43 (2)
Region 6 vs Region 7	55.56 (1)	37.33 (6)	85.71 (1)

* all major breaks were considered in the summary, including 'best-fit', 'approximate' and 'tentative'. Minor breaks were not considered.

The boundary between aggregated NASY regions 3 and 4 was ranked third highest for each of the three data sets (Table 6.2) and reflects the strongest degree of biogeographic concordance between these data. This boundary is therefore supported as a valid partition of unique units of freshwater biodiversity. Whilst the phylogeographic break for *C. quadricarinatus* was further south than the aggregated NASY region boundary (i.e. the eastern catchment divide of the Roper River), it was suggested that this biogeographic pattern is likely due to recent easterly range expansion by this species from region 4, possibly due to anthropogenic translocation (Baker et al., 2008); thus, we regarded the aggregated NASY boundary between regions 3 and 4 as the 'best-fit' for this species. The break between regions 4 and 5, however, was not as strong for any of the data sets, and the molecular data indicated that numerous taxa had substantial phylogeographic subdivisions either at the aggregated NASY boundary, slightly to the north in the Darwin area, or slightly to the south between the Daly and Victoria Rivers. This suggests quite strongly that this bioregional boundary should be regarded as a 'zootone' (*sensu* Lyne & Hayes, 2005), whereby strong biodiversity changes do not occur abruptly at a single location, but rather strong biodiversity changes accumulate over slightly larger geographic distances (i.e. between about the Adelaide and Daly Rivers). Thus, the aggregated NASY boundary between regions 4 and 5 must be regarded as an 'approximate' boundary reflecting a freshwater zootone in the northwestern portion of the Top End.

Previous freshwater bioregionalisations in northern Australia based on freshwater fish species data found the strongest biogeographic partition at the boundary between regions 5 and 6 (Unmack, 2001; Abell et al., 2008). In striking contrast, our analyses of freshwater fishes indicated reasonably weak dissimilarity freshwater fish species at this location. This discrepancy is a consequence of different analytical methods and the different grain size of units of analysis between the studies. However, the species composition of turtles changed substantially across this regional boundary and a very high proportion of freshwater species had major phylogeographic subdivisions across the regional divide. Indeed, some freshwater fish species distributed within region 6 were likely to be endemic cryptic species, such as *G. aprion* and *N. hyrtlii* (Cook, Hughes et al., unpublished data); thus suggesting that if our ANOSIM analyses of species level data incorporated these cryptic elements of species diversity we may have found stronger biotic segregation in freshwater fish species between these regions. Furthermore, many freshwater fishes are endemic to aggregated NASY region 6 (Allen et al., 2002; Unmack, 2001), and the King Edward-Carson River (centrally located in region 6) is the most species-rich for freshwater fish in Western Australia (Morgan et al., 2009). These strong patterns of endemism, species richness and phylogenetic diversity were also reflected in cryptic species of freshwater shrimp, genus *Caridina* (Cook et al. in review). Whilst our analyses of similarity focused on beta components of biodiversity (i.e. among-region partitions in biodiversity), perhaps analyses of alpha components of biodiversity, especially endemism, would indicate stronger bioregional changes in fish biodiversity at this aggregated NASY boundary (see Whittaker et al., 2005). We support earlier freshwater bioregionalisations that indicate the boundary between aggregated NASY regions 5 and 6 is a bioregional divide.

The last boundary to consider is between aggregated NASY regions 6 and 7. This was ranked the strongest bioregional boundary for both turtles and the genetic data, although for the genetic data this boundary was almost always identified as a 'tentative' boundary on account of substantial sampling gaps in the Kimberley region. At very least, some of the genetic data indicate that the boundary should be at least as far north as the northern catchment divide of the Isdell River. Again the freshwater fish showed reasonably weak change in biotic structuring between aggregated NASY regions 6 and 7, although consideration of cryptic biodiversity and alpha components of biodiversity (e.g. endemism) may indicate stronger subdivision between these regions. Interestingly, several species of freshwater fish are shared between aggregated NASY regions 5 and 7, to the exclusion of region 6 (Unmack, 2001), which is a biogeographic pattern mirrored by cryptic species of freshwater shrimp, genus *Caridina* (Cook et al., in review). Thus, we suggest that the bioregional boundary between region 6 and 7 be regarded as a 'tentative' boundary until further research can identify with greater certainty the true location of the boundary, although for interim continent-wide freshwater conservation purposes, we suggest that the interim boundary be moved to the northern catchment divide of the Isdell River.

Overall, there was mixed support from the turtle, fish and phylogeographic data for all but one (i.e. between regions 2 and 3) of the aggregated NASY regions, with no single boundary performing best for all data sets (Table 6.3). The strongest concordance for all three data sets was for the boundary between regions 3 and 4 (ranked third for each data set), although the splits between regional boundaries 6 and 7, and 5 and 6, were ranked first and second, respectively, for both the turtle and genetic data, although the position of the boundary between regions 6 and 7 should be moved north to include the Isdell River within region 7. The ordination plots for the fish and turtle species analyses showed that regions did not form well separated clusters of catchments, but instead showed varying degrees of overlap in regional faunas. However, when identifying bioregions for broad-scale conservation and environmental management, bioregional boundaries do not need to be determined strictly by the turnover in distribution of many species (McDonald et al., 2005), but must reflect some logical grouping of biodiversity with a cohesive evolutionary past. This may be indicated by turnover in range for select subsets of the relevant faunal groups and major phylogeographic breaks in at least some of the species considered, although other criteria may relate to changes in alpha components of biodiversity (e.g. delta endemism).

Whilst the generation of a single, integrative multi-species map is a key goal in conservation biogeography, it would also be prudent to identify suites maps based on specific sub-sets of taxa or alternative parameters (Whittaker et al., 2005). The boundaries of multi-species, integrative bioregions, such as we have identified, must therefore be acknowledged as 'fuzzy boundaries' at which different species have different biogeographic responses. Importantly, some regional divides, such as the boundary between regions 4 and 5 we identified, must be considered and managed as 'zootones'.

Finally, we identified six bioregions throughout northern Australia, encompassing some 1,190,000 km^2 (mean of 198,333 km^2 per bioregion). Previous freshwater bioregionalisations in northern Australia based on freshwater fish identified only two bioregions (i.e. Kimberley and non-Kimberley regions, Unmack, 2001; Abell et al., 2008), although the former study (Unmack 2001) identified several sub-regions, yielding a total of four units (although one of these was comprised of two disjunct areas). Most boundaries of these sub-regions are roughly similar to the bioregional boundaries we have identified, with the exception that the Kimberley was identified as a single unit in Unmack's (2001) study and we recognize the identified units as bioregions rather than as sub-regional units. Although our study has thus identified smaller and a greater number of bioregions than these earlier studies, some other freshwater bioregionalsiations have considered smaller geographic areas and identified an even greater number of bioregional units. For example, a recent freshwater fish bioregionalisation of the Iberian Peninsula (i.e. Spain, Portugal and southern France), covering a total of 581,000 km2, identified 11 bioregions (Filipe et al., 2009; mean of 52,818 km^2 per bioregion, which is almost one quarter the size of the bioregions we identified in northern Australia). Thus, there will be substantial heterogeneity of freshwater biodiversity within each of our bioregions, and this biodiversity must also be accommodated in relevant freshwater conservation and environmental management initiatives.

6.4.2 Knowledge gaps, next steps and recommendations

There are a number of issues associated with assessing the concordance between existing regionalisations and those based on a suite of different species or taxonomic units. Foremost among these are issue associated with the comprehensiveness and quality of the data used. For example, significant sampling gaps still exist, notably with current phylogeographic data being restricted to only a few catchments in regions 6 and 7, and some apparent gaps in distribution for freshwater fishes. Similarly, the taxonomic resolution of freshwater macro-invertebrates was low (i.e. family level only), thus limiting the ability to distinguish between regions given the widespread nature of many aquatic invertebrate families. Finally, we considered a limited suite of taxa, albeit a comprehensive suite in light of the time frame of the project. Inclusion of other key freshwater fauna, especially species occurrence and phylogeographic data for frogs and phylogeographic data for turtles, would be beneficial.

Conceptual issues are also of relevance. First, it may not be possible to construct freshwater bioregions when different taxa are considered. Some taxon groups may be far more vagile than others and accordingly, unresponsive to catchment boundaries. Waterbirds, many of which are migratory, are a good example. Moreover, biogeographic patterns may not be common to all groups as individual groups may respond to a unique set of environmental and evolutionary [e.g. continental shelf width, historical river connectivity, bathymetry, palaeoclimatc data] drivers of little relevance to other groups. Similarly, some taxa within faunal groups may be responsive to particular suites of environmental and evolutionary drivers, depending on their population history, habitat requirements and vagility. It would therefore be prudent to construct taxon-specific bioregionilisations for key taxa from each of the broader faunal groups we considered.

Finally, alternative means of characterising the biotic nature of catchments or regions may be useful. For example, incorporation of genetically identified lineages in traditional 'species' based analyses (e.g. ANOSIM, SIMPER) may improve the ability to objectively define bioregions. Analyses focused on alpha-components of biodiversity, particularly endemism but also species richness and phylogenetic diversity may also aid in this process.

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7. Development of predictive models of species distributions

Mark Kennard, Virgilio hermoso & Brad Pusey

Key points

1. **Aim:** To develop predictive models of the distributions of aquatic macroinvertebrates, fish, turtles and waterbirds so that complete coverages of biodiversity data could be used to assess and identify high conservation value aquatic ecosystems.
2. **Methods:** Species occurrence data described in Chapter 5 and environmental data described in Chapter 4 were used to develop the models. The nested subcatchment layer was used as the basic spatial unit. Models were developed using Multivariate Adaptive Regression Splines (MARS) and validated using measures of deviance and the area under the receiver operating characteristic curve (AUC).
3. **Results:** The predictive models developed performed with moderate to high predicitve success. AUC values were 0.87, 0.82, 0.78 and 0.75 for turtles, fish, waterbirds and macroinvertebrates, respectively.
4. **Implications:** The models provide an accurate and objective means of predicting the distribution of aquatic biota across northern Australia, thus enabling conservation value to be estimated for planning units for which little or no data previously existed.
5. **Limitations / Knowledge gaps / next steps:** The presence-only models developed for macroinvertebrates, turtles and waterbirds risk over-predicting presences and under-predicting absences because we did not have true absence data to validate the models for these faunal groups. Model validation would be improved by using true presence/absence data – there is therefore a need to collect these data. The use of multiple statistical modeling methods and generation of consensus predictions would allow better quantification of uncertainty in predictive modelling of species distributions. Macroinvertebrate family-level data may be too coarse for conservation assessment because the majority of taxa were predicted to be so widespread when predictions were aggregated to planning units. This is likely to yield a loss of sensitivity in distinguishing the conservation value of different planning units when based on attributes such as taxonomic richness, and thus minimise the contribution of macroinvertebrate diversity in the identification of important planning units.

7.1 Introduction

Substantial spatial biases exist in the availability of species distribution data across northern Australia (Chapter 5); a problem that is common to most conservation planning exercises (Margules & Pressey, 2000; Van Teeffelen et al., 2006; Linke et al., 2007). Incomplete distribution data has major implications for calculating attributes and objectively identifying HCVAEs. Here, we circumvent this problem by building predictive models for the distribution of conservation features throughout the landscape (Wilson et al., 2005). This chapter describes the development, validation and application of predictive models of species distributions for aquatic macroinvertebrates, fish, turtles and waterbirds. These models are based on statistical associations between species occurrence and habitat attributes at the sites sampled and are used to infer the composition of biotic communities from habitat data in unsampled planning units. The predictive models were used to generate complete species distributions coverages for the entire study region, which were subsequently used as surrogates for biodiversity in the HCVAE assessment process (Chapters 8, 9 and 10).

Species distribution models (also called 'ecological niche models', 'habitat suitability models' or 'bioclimatic envelope models') are now firmly established in conservation biology, where they inform survey design, strategic reserve placement, biosecurity risk assessment, and identification of suitable restoration sites (Elith & Leathwick 2007). Distribution models may be of different forms (i.e. their statistical basis differs) and may be based on presence-only data or presence/absence data. Although species data from planned surveys that describe presence–absence or abundance are ideal for modelling distributions (Cawsey et al., 2002), most records are derived from ad-hoc compilations of observations (e.g. from museums and herbaria) and are in a 'presence-only' form. There are many issues associated with the use of such data, many of which are also common to presence/absence data. These include bias, errors in identification of taxa and of locations, choice of appropriate grain size (spatial resolution), sparseness of records and the choice of appropriate modelling methods (Freitag et al., 1998; Guisan et al., 2007; Ferrier, 2002; Engler et al., 2004).

The dominance of presence-only data and the urgent need to manage and conserve biodiversity collectively require that such data, whilst not optimal, be incorporated into biodiversity assessment and conservation planning (e.g. estimating species' ranges, patterns in richness and turnover, biodiversity hotspots, development of predictive maps of species' occurrence) and that statistical methods are developed that minimise the disadvantage of using presence only data (e.g. Robertson et al., 2001). Ideally, models should be validated with reliable estimates of species' presence and absence, though this is not always available.

Recent investigations have revealed that the data from multiple species can be used to inform model development for a target species, a feature achieved with a 'multiresponse' model (Hastie et al., 1994) that is potentially useful for species with few records. In a recent comparative assessment, models based on Multivariate Adaptive Regression Splines (MARS) performed particularly well for predicting occurrence patterns in independent data sets and performed better than models in which species were analysed singly (Elith et al., 2006; Elith & Leathwick, 2007). Simultaneous consideration of the signal from many species may identify relevant predictors because of their strong signal across all species, whereas that signal might be inadequate or too small to result in inclusion in single-species models (Leathwick et al., 2005; Ferrier & Guisan, 2006). Multiresponse models are effective for presence–absence data (Olden, 2003; Leathwick et al., 2006) and conceptually are likely to be useful for presence-only data, in which some species may be poorly represented (Elith & Leathwick, 2007).

In this chapter we develop multi-response predictive models of species distributions and evaluate whether they are sufficiently accurate to be useful in conservation assessment at regional scales for the purposes of the HCVAE assessment.

7.2 Methods

7.2.1 Spatial units for predictive modelling

We used the nested sub-catchments layer (Chapter 4) as the basic spatial unit for attributing species records and environmental data and developing the predictive models of species distributions (Fig 7.1). This included a total of 333,430 individual polygons (mean area = 3.58 km^2). Because waterbirds are potentially more mobile and range over larger spatial scales than other faunal groups, we used a coarser spatial grain for the analysis and prediction of waterbird distributions. Using the NCB Pfafstetter labled sub-catchments, a Pfafstetter level was determined such that the mean area of sub-catchments within a Basin had an approximate mean spatial unit area of 72km^2. The spatial layer used in the prediction of waterbird distributions was then created by collating the Basins at the determined Pfafstetter level into a single spatial unit layer (Fig 7.1).

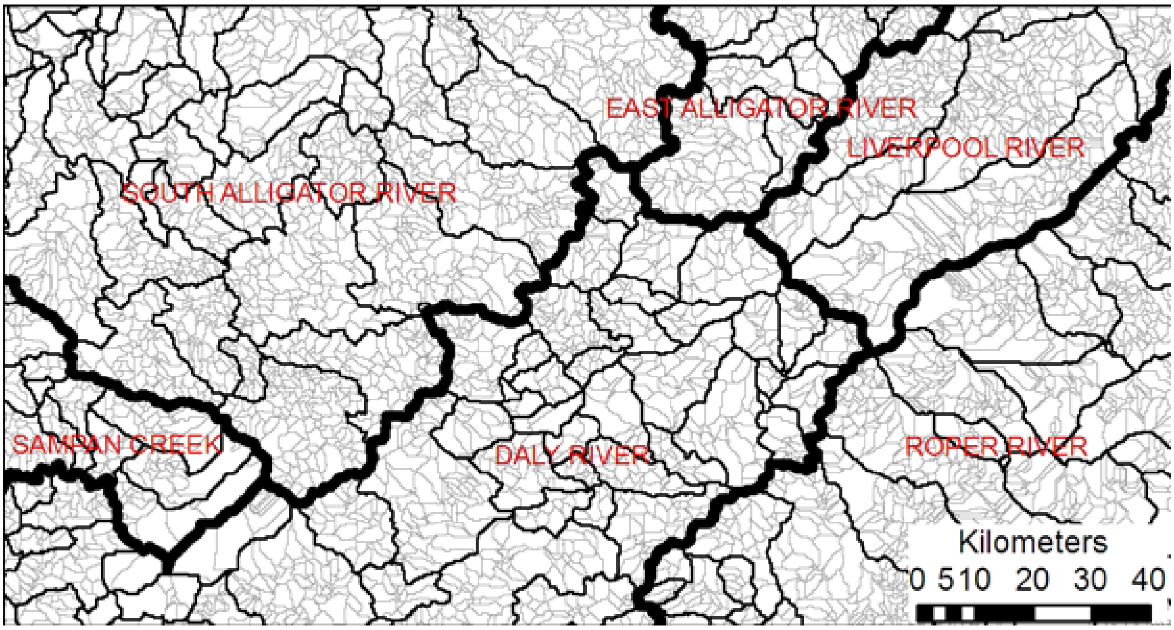

Figure 7.1. Spatial units used for predictive modeling of species distributions for macroinvertebrates, fish and turtles (grey polygons) and waterbirds (black polygons). River basin boundaries are depicted by thick black lines.

7.2.2 Species distribution data

Details on sampling records available for modeling the distributions of aquatic macroinvertebrates, fish, turtles and waterbirds are described in Chapter 5. The total number of spatial units containing records for macroinvertebrates, fish, turtles or waterbirds, respectively and used to calibrate the predictive models is shown in Table 7.1. Of the 2328 fine-scale spatial units containing fish records, 719 units contained true presence-absence data and 604 of these were randomly selected and removed from the model calibration data to be used as an independent model validation dataset (see below).

Preliminary modelling revealed difficulties in predicting the occurrence of extremely rare species so we removed taxa occurring in less than 10 spatial units for macroinvertebrates and waterbirds, respectively, or 5 spatial units for fish and turtles, respectively. The total number of taxa remaining and used to develop the final predictive models is shown in Table 7.1 and taxon rank-dominance curves for each faunal group are shown in Figure 7.2.

Table 7.1. Number of spatial units and number of taxa used to develop the species distribution predictive models. The number of planning units used for validation of the fish predictive model is shown in parentheses.

Faunal group	Macroinvertebrates	Fish	Turtles	Waterbirds
Number of spatial units	333	2328 (604)	350	2109
Number of taxa	89	89	13	106

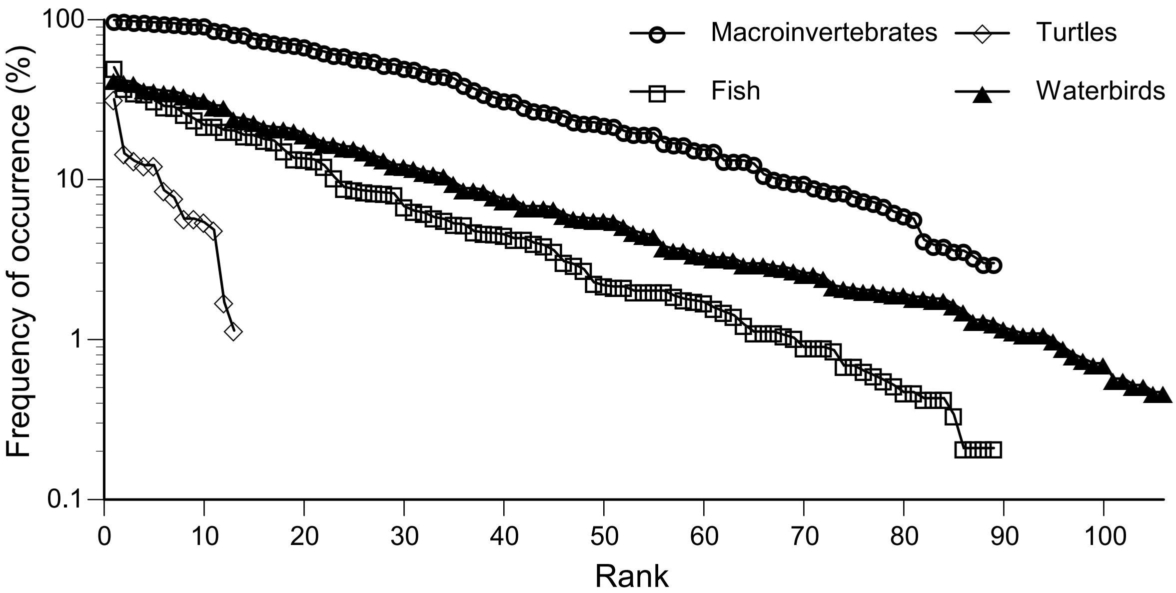

Figure 7.2. Rank-dominance curves for taxa within each faunal group.

7.2.3 Environmental predictor variables

A range of ecologically-relevant local and catchment scale environmental variables were selected from a larger number of candidate variables (listed in Chapter 4) for use in the predictive models of species distributions. The candidate variables described climate, terrain, substrate, vegetation (present day), hydrology, stream network characteristics, terrestrial primary productivity, non-riverine hydrosystem area and shape characteristics and human disturbance. As we aimed to predict present-day distributions, not re-construct historical distributions prior to human activities, we also included an indicator of human disturbance (River Disturbance Index; Stein et al., 2002; Chapter 4) as a predictor variable. Principal Components Analysis and Spearman's correlations among candidate variables were used to identify and remove those that were highly correlated. From this subset, expert knowledge was used to inform the choice of initial predictor variables for each faunal group and the subset of environmental predictor variables that were actually selected in one or more of the final predictive models are listed in Table 7.2. Spearman's correlation coefficients among the final sets of predictor variables usually ranged between –0.5 and +0.5.

Table 7.2. Environmental predictor variables that were selected in one or more of the final predictive models of species distributions.

Code	Attribute
	Climate
STRANNRAD	Stream and environs annual mean solar radiation
STRANNTEMP	Stream and environs annual mean temperature
	Terrain
STRELEMEAN	Mean segment elevation
CATAREA	Catchment Area
CATELEMAX	Maximum upstream elevation
CATRELIEF	Catchment relief ((mean upstream elevation-pour point elevation)/(max upstream elevation-pour point elevation))
D2OUTLET	Distance to outlet
CATSLOPE	Catchment average slope
CATSTORAGE	Catchment storage (Proportion of upstream grid cells that are valley bottoms)
	Vegetation
STRBARE-EXT	Stream and valley extant percentage naturally bare
STRGRASSES-EXT	Stream and valley percentage extant grasses cover
STRFORESTS-EXT	Stream and valley percentage extant forests cover
	Hydrology
RUNANNMEAN	Annual mean accumulated soil water surplus
RUNANNCOFV	Coefficient of variation of annual totals of accumulated soil water surplus
	Stream network
STRDENSITY	Stream density
WATERYNESS	Proportion of stream segment and associated valley bottom grid cells that contains one or more of a waterhole or spring or the majority of the grid cell is occupied by a lake or watercoursearea.
	Primary Productivity
NPPBASEANN	Annual mean Net Primary Productivity (terrestrial)
	Lacustrine, palustrine, estuarine characteristics
SUM_PL_A_P	sum lacustrine & palustrine area proportion
MEAN_L_A2P	mean lacustrine area to perimeter ratio
STD_L_A2P	Standard deviation of lacustrine area to perimeter ratio
SUM_E_A_P	sum estuarine area proportion
	River Disturbance
RDI	River Disturbance Index

7.2.4 Predictive model calibration

Modelling method

Multivariate Adaptive Regression Splines (MARS) is a method of flexible non-parametric regression modelling (Elith & Leathwick, 2007). It is useful for modelling complex non-linear relationships between response and explanatory variables with similar levels of complexity to that of a Generalized Additive Model (GAM) (Hastie, 1991). MARS models have been used to predict the probability of occurrence of different terrestrial taxa, such as plants, from museum records using presence only data (Elith & Leathwick, 2007), and of trees, birds, mammals and reptiles using both presence-absence data and presence only data (Elith et al., 2006). It has also been successfully applied to aquatic biota, such as modelling fish species occurrences (Leathwick et al., 2005, Hermoso et al., 2010) or vegetation condition in riparian areas (Cunningham et al., 2009).

MARS fits a nonlinear function to the relationships between dependent and predictor variables by breaking the range of each predictor into a subset of portions or “knots”, and fitting linear relationships for each of them (basis functions). Knots are chosen automatically in a forward stepwise manner and can be allocated at any position within the range of each predictor variable. Once the knot has been placed it defines a pair of basis functions, where a linear relationship between the dependent and the predictor variables is fitted. Knot selection continues until some maximum model size is reached, after which a backwards-pruning procedure is applied in which those basis functions that contribute least to model fit are progressively removed. Some predictors can be dropped from the model completely if none of its basis functions contribute meaningfully to predictive performance. MARS allows the slope of the fitted linear segments between pairs of segments to vary while ensuring that the full fitted function is without breaks or sudden steps (Elith & Leathwick, 2007). The predictive function is finally composed of a series of connected straight line segments, rather than the smooth curve of a GAM. MARS also allows exploring interactions between predictors (Leathwick et al., 2006), and is able to fit a multi-response model which can simultaneously relate variation in the occurrence of all species to the environmental predictors in one analysis.

In an extensive review of different predictive methodologies such as GLM, GAM, BRUTO, GARP or MAXENT, MARS was highlighted as one of the most accurate approaches across the different taxonomic groups and regions for which the models where tested (Elith et al., 2006). In terms of predictive ability, MARS and other non-linear methods (GAM or ANN) are often superior to methods such as traditional single decision trees (Olden, 2003, Elith et al., 2006). Moreover, in a comparative study of MARS vs GAM, Leathwick et al. (2006) also highlighted that results from MARS models are much more easily incorporated into other analyses than those from GAM models. The strong performance of a MARS multiresponse model, particularly for species of low prevalence, has important advantages for the analysis of large datasets. These kinds of multiresponse models are useful to model species with few records (Elith & Leathwick, 2007), since the data from multiple species can be used to inform model development for those target species with low prevalence values (Ferrier & Guisan, 2006). MARS can be used to model abundance, presence-absence, and presence-only data (Elith et al., 2006).

Predictive model development

MARS models were fitted using the mda (Mixture and Flexible Discriminant Analysis) package within the free statistical software R (R Development Core TEAM, 2004). Given that this procedure was originally designed to model continuous data the common function provided in R for MARS uses least squares to fit the model, which works appropriately for data with normally distributed errors. With binomial (presence-absence or presence only) data this results in the range of predicted values being expanded beyond the acceptable range [0-1] (Leathwick et al., 2006). To solve this problem Leathwick et al. (2006) provided new code that fits a MARS model using the standard R code, extracts the basis functions, and computes a Generalized Linear Model (GLM) which uses the basis functions as predictors of each species´ presence-absence (or pseudo-absence for presence only data). This procedure constrained the predicted probabilities of occurrence between zero and one.

Models were fitted using presence only data for all the faunal groups. When modeling probabilities of occurrence using presence-only data, information on potential absences is also required. A common practice to deal with the lack of absence data is to create a set of pseudoabsences, or background points where the taxa being modelled are assumed to be absent. In multiresponse models these pseudoabsences are taken from the presence only data set (so-called "inventory absence", so new pseudoabsences are not necessary (Elith et al., 2007). Because the aquatic macroinvertebrate data exhibited few absences and low beta diversity (i.e. many species occurred at most sites; Fig. 7.2), it was difficult to find pseudoabsences in the presence only data set. So, the MARS model developed for aquatic macroinvertebrates was fitted using 300 random pseudoabsences weighted so that the total weight for presences equalled the total weight for absences. The weighting allowed the use of many pseudo-absences that sample the environmental space of the region thoroughly, while avoiding 'swamping' the model with so much absence data that trends in presence were hard to detect. The MARS models developed for fish, turtles and waterbirds were fitted using the inventory absences because there were sufficient data points containing zeroes.

7.2.5 Predictive model validation and performance

Model performance was assessed using measures of deviance and the area under the receiver operating characteristic (ROC) curve (AUC) (Fielding & Bell, 1997) using the code provided by Leathwick et al. (2006). The code provided by Leathwick et al. (2006) uses a k-fold cross validation procedure to assess the AUC (Hastie et al., 2001). In this procedure the data are randomly divided into exclusive sub-sets (10 in our case) and model performance is calculated by successively removing each sub-set, re-fitting the model with the remaining data, and predicting the omitted data. The average error when predicting occurrence in new sites can then be calculated by averaging the AUC across each of the subsets (Leathwick et al., 2005). An AUC>0.6 is usually defined as acceptable model performance (Fielding & Bell, 1997). Deviance complements AUC because it expresses the magnitude of the deviations of the fitted values from the observations. Explained deviance in previous studies typically ranges between 20% and 40% (Leathwick et al., 2006; Hermoso et al., 2010). Both statistics (AUC and deviance) were calculated using presence only data for all the taxa except for fish (the only taxa for which an independent presence-absence data set was available).

Deviance has only a limited applicability for presence-only evaluation (i.e. all datasets except fish, where we had true presence-absence data), because it is affected by the calibration of the models (i.e. how accurately predictions match the response, Pearce & Ferrier, 2000) and we do not expect presence-only models to be properly calibrated due to the lack of true absence data. It should therefore not be used independently of other measures for presence-only models because results could be misleading. In addition, AUC values calculated on presence only data must be interpreted in a different way to presence-absence data. In the former case the AUC provides information on the probability that a randomly chosen presence site is ranked above a random background site (Phillips et al., 2006). In this way predictive models validated on presence only data are tested for their ability to correctly predict presences. Given that the main aim of this study is the identification of high conservation value areas, this method seems appropriate to reduce commission errors (selecting an area where the species is erroneously expected to be present).

The predictive probabilities of occurrence (ranging from 0 to 1) were converted to a presence/absence estimate with a threshold (Liu et al., 2005). The choice of probability threshold above which each species is predicted to occur is often arbitrarily set to 0.5, but this does not necessarily preserve the observed prevalence or result in the highest prediction accuracy, especially for data sets with very high or very low observed prevalence (Freeman & Moisen, 2008). There are many criteria that can be used to determine the optimum threshold but the choice ultimately depends on the intended use of the predictive model. Nevertheless, comparative studies (see Freeman & Moisen, 2008 for review) have shown that the choice of criteria can substantially affect model prediction error. Our objective was to derive unbiased estimates of species' prevalence (i.e. minimise false presences and absences). For fish, where we had true presence-absence data we used a threshold in which the predicted prevalence equalled the observed prevalence (as recommended by Freeman & Moisan, 2008). For all other response datasets we used the threshold where the ROC curve makes closest approach to 0 or 1 (Freeman & Moisan, 2008).

7.2.6 Predictive model extrapolation

The predictive models were used to generate nearly-complete species distributions coverages for the entire study region. Predictions were not generated for 191 planning units located in internally draining basins and those planning units that did not contain a stream segment, due to a lack of environmental data used to make predictions. We removed predictions for all spatial units beyond the range of environmental variation of the calibration sites.

7.3 Results

7.3.1 Predictive performance

The multi-response predictive models exhibited moderate to high success in predicting individual taxon occurrences across all faunal groups with AUC values for individual taxa almost always greater than 0.6 (Fig. 7.3). Predictive success was generally highest for turtles, followed by fish, waterbirds and macroinvertebrates (mean AUC = 0.87, 0.82, 0.75 0.72, for each faunal group, respectively). The deviance explained by the models was almost always greater than 10% for individual taxa and the average deviance explained for each faunal group ranged between 0.17 (macroinvertebrates) to 0.59 (turtles).

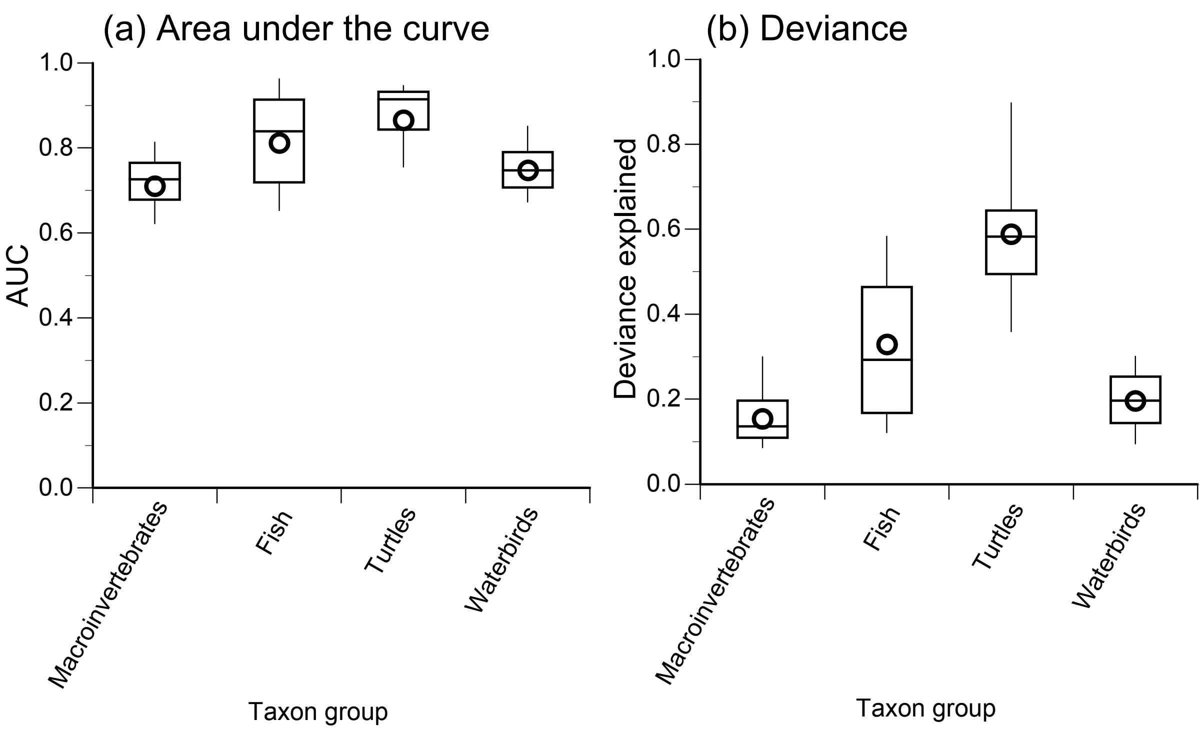

Figure 7.3. Box plots showing variation across taxa within each faunal group for (a) AUC values and (b) deviance explained by the predictive models of species distributions. The lines at the top, middle and bottom of each box represent the 75th percentile, median and 25th percentile of metric values, respectively. Vertical bars (whiskers) represent 90th and 10th percentiles and mean values are represented by symbols.

7.3.2 Relative importance of environmental predictor variables

A relatively small number of environmental variables were selected as predictors of species distributions, ranging from 6 variables for turtles to 12 variables for waterbirds (Fig 7.4). Macroinvertebrate distributions were best predicted by a combination of terrain variables (CATSLOPE and STRDENSITY), hydrological variables (RUNANNMEAN and WATERYNESS) and variables describing catchment condition (STRFORESTS-EXT and RDI) (Fig. 7.4a). Selection of these variables suggests that macroinvertebrate distributions are influenced by the nature and size of aquatic habitat available (i.e. CATSLOPE and STRDENSITY determine habitat structure and RUNANNMEAN determines the amount of habitat structure), the nature of disturbance (RUNNANNMEAN when high suggests that stream unlikely to be ephemeral but when CATSLOPE also high suggests that flood-associated disturbance may be important), the nature of refugial habitats (WATERYNESS is a measure of the availability of permanent water and STRDENSITY a measure of the density and proximity of stream to one another) and the general characteristics and condition of the surrounding landscape (STRFORESTS-EXT and RDI).

Fish in contrast to many aquatic insects are longer lived and less able to disperse between non-contiguous aquatic habitats. Consequently, individual taxa are less widespread than macroinvertbrate taxa and the variables selected reflect the greater spatial organisation of fish assemblages, both within and between catchments (Fig. 7.4b). For example, the terrain variables CATAREA, D2OUTLET, CATRELIEF, CATSLOPE, CATELEMAX and STRELEMEAN all refer to position in the riverine landscape and the importance of slope and relief in determining the types of habitat present. Climate (STRANNRAD and STRANNTEMP) was also important, probably due to its role in determining upper temperature lethal limits and in influencing the permanence of refugial habitats. Turtles were predicted using a combination of variables not dissimilar to that used for fish (Fig. 7.4c)

Waterbirds, the most vagile of the faunal groups examined, were predicted by a combination of terrain, climate and habitat variables related to the distribution, size, productivity and characteristics of lacustrine and palustrine waterbodies (Fig. 7.4d)

7.3.3 Predictions for unsampled units

The moderate to high predictive performance of the species distributions models supported the application of the models to derive predictions of species occurrences at the remaining unsampled units based on their environmental characteristics. Examples of these predictions are shown in Figure 7.5. Changes in the predicted frequency of occurrences of taxa occurred when the predictions were aggregated to the planning units (Fig. 7.6a,b), particularly for macroinvertebrates, where the majority of taxa (65 of 89) were predicted to occur in more than 70% of all planning units (Fig. 7.5b). This effect was less evident when the predicted area of occurrence was summed in each planning unit (i.e. a steeper macroinvertebrate rank-dominance curve in Figure 7.6c).

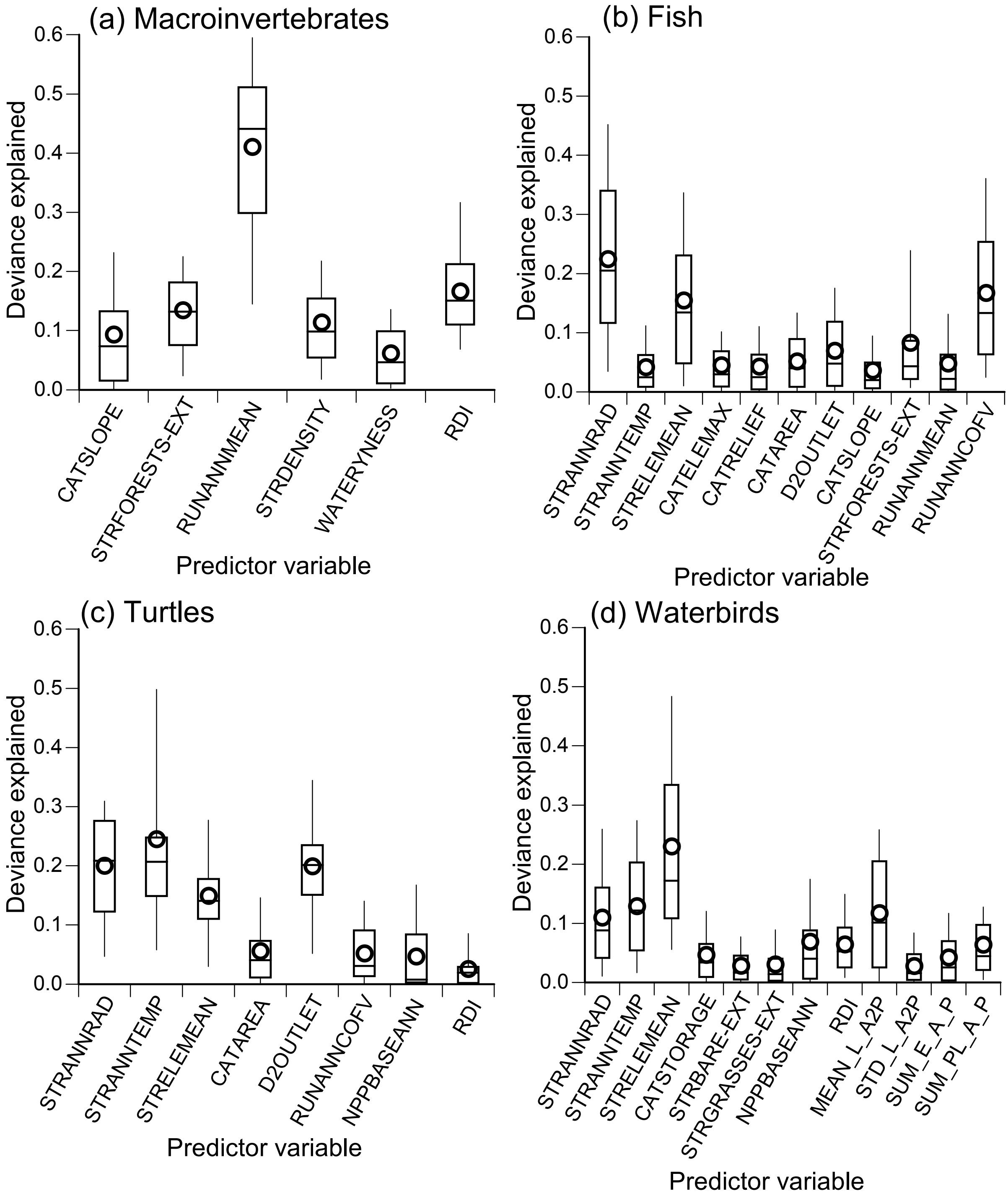

Figure 7.4. Box plots showing variation across taxa in the deviance explained by each environmental variable for predicting (a) macroinvertebrates, (b) fish, (c) turtles, and (d) waterbirds.

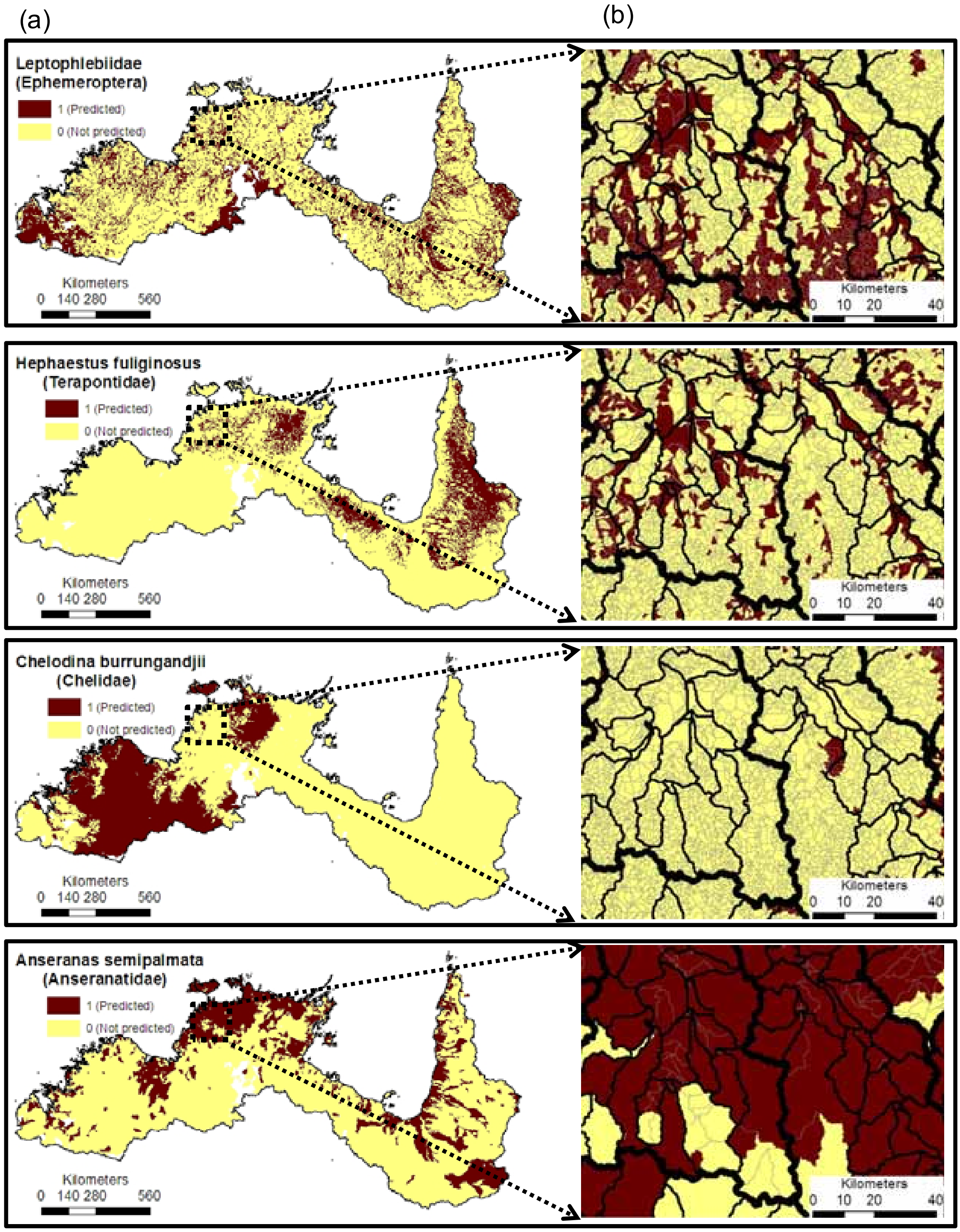

Figure 7.5. Examples of predicted distributions of selected taxa for each faunal group. Predictions are shown for (a) the entire study region and (b) the upper Mary River and South Alligator River, Northern Territory. Also shown in (b) are the spatial units used for predictive modelling of species distributions (grey polygons), the planning units used for conservation assessment (black polygons) and river basins boundaries (thick black lines).

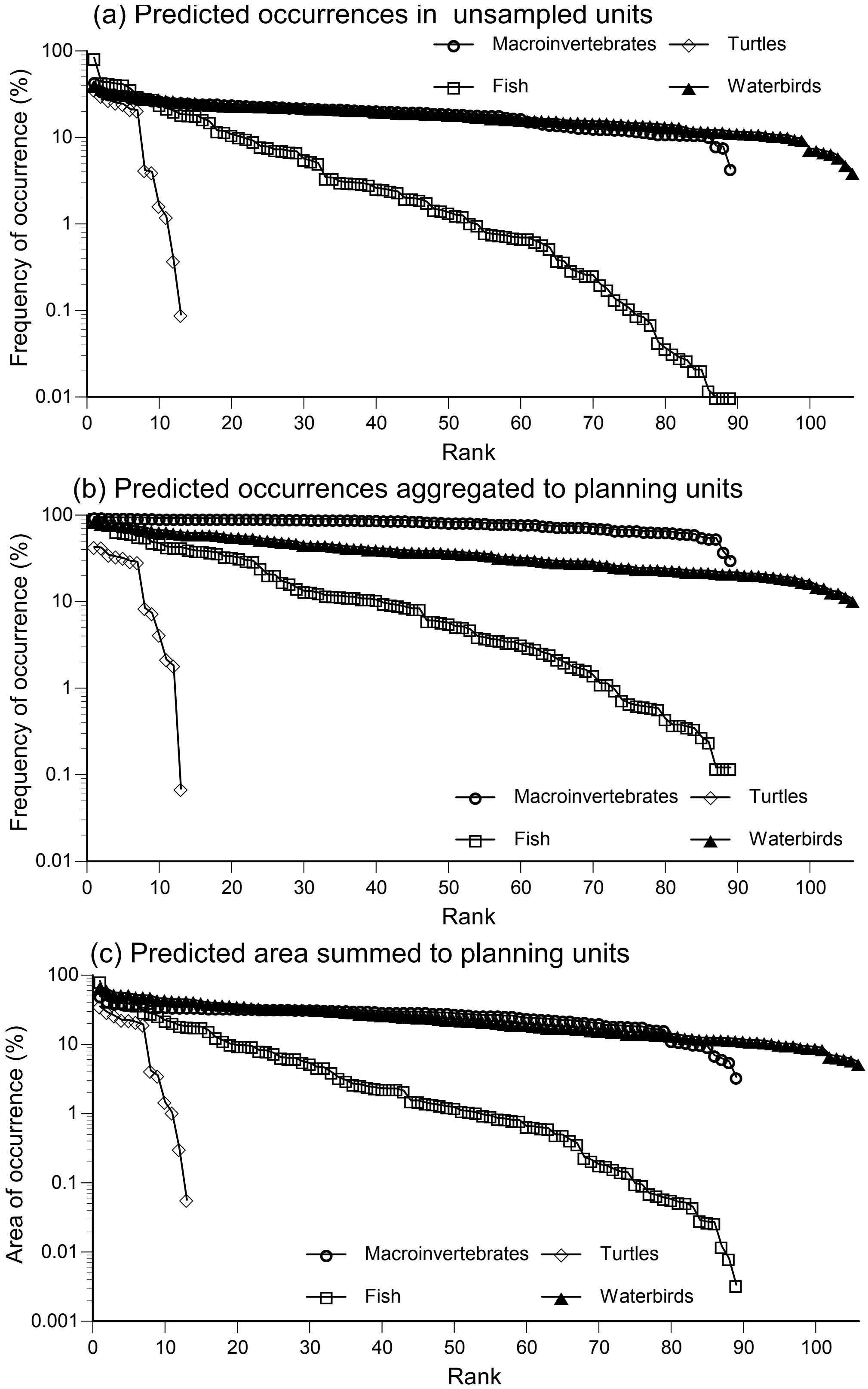

Figure 7.6. Rank-dominance curves for taxa within each faunal group calculated using (a) predicted occurrences across the entire study region (n = 16,597 for waterbirds and n = 333,430 for all other faunal groups), (b) predicted occurrences aggregated to planning units (n = 5,803) and (c), predicted area summed to planning units (n = 5,803).

7.4 Discussion and knowledge gaps/next steps

A common problem in biodiversity assessment and conservation planning is that species distribution data are often incomplete; a proposed solution is to fill distributional gaps using predicted species distributions (Cabeza, 2003; Cabeza et al., 2004; Linke et al., 2007). Two different approaches have been previously followed: using direct probability of occurrence or transforming them into presence–absence data using thresholds. The latter approach has been tested and used in previous studies (see Polasky et al., 2000; Wilson et al., 2005) and we used this approach for two reasons. First, the selection of places where conservation features have a high probability of occurrence might be a more risk-averse approach to conservation planning, since the risk of selecting a place based on a false positive, or on omission errors, is reduced (Wilson et al., 2005). Second, the calculation of many of the biodiversity attributes used to address the Framework criteria (Chapters 3 and 8) required presence-absence data, rather than continuous probabilities of occurrence, and knowledge of the area of each planning unit in which each species was predicted to occur. We do however recognize two primary limitations of converting continuous species predictions to presence-absence. First, it results in a net loss of information on species distribution data. Probability of occurrence indicates only the likelihood with which a species is present in a planning unit considering different species-dependent factors such as habitat quality requirements or vulnerability to threats (Araujo & Williams, 2000). Second, the choice of decision threshold to which species are either predicted present or absent can influence the predicted distribution area for the biodiversity targets (species), and it can strongly affect the outputs of conservation planning process. These potential problems can be minimised by careful selection of appropriate and objective threshold criteria (Wilson et al., 2005), as we did.

Our species distribution models were built using data sampled across a gradient of human disturbance (rather than restricting our data to 'reference' or 'least disturbed' sites) as we aimed to predict present-day distributions, not re-construct historical distributions prior to human activities. To this end, we included an indicator of human disturbance (River Disturbance Index; Stein et al., 2002; Chapter 4) as a predictor variable, although it did not contribute greatly to species predictions (Fig. 7.4). Given that some species may have been pushed out to marginal areas within their original distribution or displaced to new areas because of human-induced impairment (Kouamelan et al., 2003; Light & Marchetti, 2007), we felt that this approach is appropriate for identification of high conservation value areas in which the objective is to optimise the use of the scarce resources for managing species where they now occur, rather than where they have become locally extinct (e.g. Knight et al., 2007).

In summary, the predictive models developed here performed adequately with respect to classification accuracy. However, the nature of the data upon which they were based requires us to express some caveats.

- The presence-only models developed for macroinvertebrates, turtles and waterbirds risk over-predicting presences and under-predicting absences because we did not have true absence data to validate the models for these faunal groups.
- Model validation would be improved by using true presence/absence data – therefore a research priority should be to collect these data in the future
- The use of multiple statistical modeling methods and generation of consensus predictions would allow better quantification of uncertainty in predictive modelling of species distributions.
- Macroinvertebrate family-level data may be too coarse for conservation assessment because the majority of taxa were predicted to be so widespread when predictions were aggregated to planning units (Fig. 7.6b). This is likely to yield a loss of sensitivity in distinguishing the conservation value of different planning units when based on attributes such as taxonomic richness, and thus minimise the contribution of macroinvertebrate diversity in the identification of important planning units.

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8. ASSIGNING CONSERVATION VALUE USING THE FRAMEWORK CRITERIA: ATTRIBUTE REDUNDANCY AND SENSITIVITY TO METHODS OF SCORING, WEIGHTING AND INTEGRATION

WAYNE ROBINSON & MARK KENNARD

KEY POINTS

1. **Aim:** To detail the methods used to characterise the HCVAE Framework criteria and investigate their statistical properties in terms of redundancy and sensitivity to methods of scoring, weighting and integration.
2. **Methods:** The raw data were converted to Indices that ranged between 0 and 1. Seven potential methods of integrating the Indices to Attribute types and then from Attribute types to the draft HCVAE Framework criteria were applied. The relationships of each the indices to each other, to their attribute types and their criteria was investigated.
3. **Results:** Using the seven different methods of integration, the data were successfully combined into 49 potential HCVAE criteria scores for each of the six criteria for a) the entire study region, b) the two Drainage Divisions, and 3) the 7 Northern Australia Sustainable Yields regions. We present some preliminary results for comparisons and select one method as being conceptually sound for application in this Framework. We identify several areas of redundancy in the data and note that many of the raw data that are combined into Attribute types are not measuring in the same domain. This results in the intergrated scores having a narrow distribution of values but their relative values maintain integrity. We recommend integration from raw attributes to the 22 attribute types using simple averaging and integration to HCVAE criteria using Euclidean distance.
4. **Implications:** The HCVAE Framework should be applied with caution and further investigations of redundancy and integration methods should be undertaken prior to full implementation and public release of the results. The consequences of combining so many unrelated data are potentially important but are not addressed in detail here.
5. **Limitations / Knowledge gaps / next steps:** This chapter has highlighted several key issues. There are large knowledge gaps in the consequences resulting from using many of the different integration methods available and in particular from combining so many unrelated data. Given that that the attributes and biodiversity surrogate sets they were derived from represent many uncorrelated domains, the most transparent approach to conservation assessment using this type of information would to present and assess them individually, without any integration. This obviously becomes unwieldy with large numbers of attributes. There is no way of statistically assessing which is the best integration option without knowing the true Conservation Values for the spatial units or having a measure of the error associated with each raw attribute. We explored numerous integration options and opted for simple averaging to attribute type and standardised Euclidean distance to HCVAE criteria. There are many redundant or ineffective raw attributes in the data set. These may be different at different spatial scales or according to integration methods used

8.1 Introduction

8.1.1 Methods used to characterise the Framework Criteria

Six core biophysical criteria (Appendix 1.1) have been agreed as appropriate for the identification of nationally significant HCVAEs, and draft guidelines (Appendix 1.2) have been developed for their implementation.

The criteria are as follows:

1. Diversity - It exhibits exceptional diversity of species or habitats, and/or hydrological and/or geomorphological features/processes.
2. Distinctiveness - It is a rare/threatened or unusual aquatic ecosystem; and/or it supports rare/threatened species/communities; and/or it exhibits rare or unusual geomorphological features/ processes and/or environmental conditions.
3. Vital habitat - It provides habitat for unusually large numbers of a particular species of interest; and/or it supports species of interest in critical life cycle stages or at times of stress; and/or it supports specific communities and species assemblages.
4. Evolutionary history - It exhibits features or processes and/or supports species or communities which demonstrate the evolution of Australia's landscape or biota.
5. Naturalness - The aquatic ecosystem values are not adversely affected by modern human activity to a significant level.
6. Representativeness – It contains an outstanding example of an aquatic ecosystem class, within a Drainage Division.

The attributes we used to characterise each criterion are listed in Table 8.1 together with a brief description of the method for calculation, rationale for their inclusion and key references for further information. Attributes for each criterion were calculated for each of the biodiversity surrogate sets (macroinvertebrates, fish, turtles, waterbirds, and riverine, lacustrine and palustrine ecotopes), where appropriate and where suitable data was available (Table 8.1). Nearly complete coverages of biodiversity surrogate data meant that these attributes were calculated for almost all the 5803 planning units. The exceptions to this were 191 planning units (for attributes based on species-based biodiversity surrogates) and 113 planning units (for the riverine connectivity attribute).

Our choice of attributes was guided by our interpretation of the HCVAE Framework criteria (Appendix 1.1) and draft guidelines (Appendix 1.2). We considered all the attributes used in the regional criteria trials (i.e. NSW estuaries, VIC rivers, WA Mound springs, MDB) and the LEB framework trial. We also considered a number of other attributes to characterise the criteria but did not apply them due time limitations or data constraints. Our overall philosophy was to only apply attributes that could be calculated from the biodiversity surrogates datasets with (nearly) complete coverages, rather than applying attributes based on other data which was of variable quality and spatial extent and that would therefore yield large gaps and uncertainties in the datasets used to assess HCVAEs. For example, a measure of waterbird abundance could have been used to characterise Criterion 3 – Vital Habitat using the raw data we have collated (See Chapter 5). Unfortunately, time constraints precluded the necessary data-screening and assessment required to minimise error and uncertainty and derive a meaningful attribute based on this information. In addition, the attributes we used to characterise Criterion 5 – Naturalness summarised human impacts on aquatic ecosystems. Importantly however, we could not characterise the extent of feral plant (e.g. mimosa) and animal (e.g. pigs, buffalo, cane toads) impacts on aquatic ecosystems in northern Australia but these are a major source of disturbance to aquatic biodiversity in the region (Pusey & Kennard, 2009). The dynamic nature of alien species distributions and abundance meant that we could not readily access up-to-date data and use this to derive a meaningful index of alien disturbance.

Table 8.1 Attributes used to characterise each of the draft HCVAE Framework Criteria. Attributes for each criterion were calculated for each of the biodiversity surrogate sets where suitable data was available (depicted with dark shading). Abbreviations used for biodiversity surrogates are: macroinvertebrates (Bug), fish (Fish), turtles (Turt), waterbirds (Bird), riverine ecotopes (Riv), lacustrine ecotopes (Lac) and palustrine ecotopes (Pal). Attributes for Criterion 5 (Naturalness) were summarized for the planning unit (PU) (i.e. were not based on the biodiversity surrogate data).

Criterion, Attribute type and code	**Biodiversity surrogate set**								**Method, rationale and key reference**
	Bug	Fish	Turt	Bird	Riv	Lac	Pal	PU	
1. Diversity									
Richness (S,)									Number of taxa in a planning unit (also referred to as alpha diversity)
Diversity (H')									Shannon Diversity. An index that incorporates the number of species and the evenness of the distribution of individuals across species (we used area of occurrences in a planning unit as our measure of abundance). The index can increase either by having additional unique species, or by having greater species evenness (Shannon, 1948)
Richness Index (I_i)									An index of species richness which is weighted by individual species' frequencies of occurrence. Planning units with high *Ii* values contain many widespread species (Minns, 1987, Chu et al., 2003)
Phylogenetic Diversity (PD)									A measure of diversity based on units of phylogenetic variation (instead of species) (Faith 1992, Faith et al., 2004). For a given faunal group, PD is calculated as the sum of those branch lengths of the phylogenetic tree representing the species occurring in a planning unit. Areas with high PD may represent centres of current speciation and may be important areas to protect for maintenance of evolutionary processes. High PD could arise by having a high number of closely related species or by having few species that are phylogenetically divergent from one another. PD incorporates complementarity in that the score contributed by a given taxon in a planning unit depends on how closely it is related to other species present. Moleclular phylogenies are not available for most faunal groups and taxa considered in this report, so we used published phylogenies and assumed equal branch lengths. The level of taxonomic resolution used to calculate PD varied among faunal groups (order for macroinvertebrates, family-level for fish and waterbirds, and species-level for turtles).
2. Distinctiveness									
Rarity Index (Q_i)									An index of species rarity based on the mean frequency of occurrences of individual species/ ecotopes. Planning units with high *Qi* values are dominated by rare species with narrow distributions (Minns, 1987, Chu et al., 2003).
Rare & Threatened species score (R&T)									The number of species listed on the IUCN Red List and/or the EPBC Act as Endangered, Vulnerable or Conservation dependent multiplied by an arbitrary ranking of 3, 2 or 1, respectively. Note that this attribute was not calculated for macroinvertebrates as available data contained taxa identified to family level only (not species).
3. Vital habitat									
Number/area permanent/perennial dry season refugia (P)									Hydrosystem areas that are permanent/perennial provide important dry season refugia for many species of flora and fauna in northern Australia (Pusey & Kennard, 2009). This attribute was calculated as the length of perennial streams/rivers (riverine) or area of permanent lacustrine or palustrine areas in each planning unit. See Chapter 4 for more details.
Degree of natural longitudinal connectivity (con)									Natural longitudinal connectivity facilitates movement of biota and materials along river networks and is critical to long-term persistence of biodiversity and ecosystem processes. This attribute was calculated as the proportional stream length within each planning unit that was unaffected by artificial barriers (dams, reservoirs and large weirs) downstream, within or upstream of each planning unit. Artificial barriers data was sourced from AusHydro version 1.1.6, (Geoscience Australia and the Fenner School of Environment and Society, ANU. unpublished) and Dams and Water Storages 1990 data (Geoscience Australia, 2004).
Number of migratory bird species (Mbird_S)									Planning units containing vital habit for international migratory waterbirds may be considered to be of high conservation value. This attribute was calculated simply as the number of migratory waterbird species recorded from a planning unit. Migratory waterbirds species were sourced from the national list of migratory species. (http://www.environment.gov.au/biodiversity/migratory/list.html)

Criterion, Attribute type and code	Biodiversity surrogate set								Method, rationale and key reference
	Bug	Fish	Turt	Bird	Riv	Lac	Pal	PU	
4. Evolutionary history									
Number of monospecific Genera (monG)									Genera (or families) of taxa that contain only a single species may be considered to be of high conservation significance as they often represent faunal groups with ancient evolutionary origins. Planning units containing one or more such species may therefore also be of high conservation value. This attribute was calculated simply as the number of monospecific genera recorded from a planning unit. Note that this attribute could not be calculated for macroinvertebrates as taxa within this faunal group were identified to family level only.
Number of species endemic to each NASYagg Region (SES)									A simple index of endemism calculated as the number of species present in a single region (NASYagg). A limitation of this attribute is that it requires an a priori definition of the area of endemism, rather than letting the data define the areas of interest. Note that no macroinvertebrate familes or waterbird species were endemic to a seingle region.
Taxonomic endemism index (TE)									An index of endemism identifying areas where species with restricted ranges are concentrated. Based on the number of species within a planning unit weighted by the inverse of each species' distribution range (also known as weighted endemism). This index ranges from one, where all species in a planning unit have broad geographical ranges, to infinity, with large values indicating the presence of species with range-size rarity (i.e. areas with high endemism) (Rebelo & Siegfried, 1992).
Phylogenetic Endemism index (PE)									Phylogenetic endemism (PE) is a measure of the degree to which elements of evolutionary history are spatially restricted in space. PE combines the phylogenetic diversity (PD) and taxonomic endemism (TE) measures to identify areas where substantial components of phylogenetic diversity are restricted (Rouser et al., 2009). To estimate the degree of PE represented by the taxa in a given area, the range size of each branch of the phylogenetic tree (rather than the range of each taxon) is quantified. PE is therefore the sum of branch length ⁄ clade range for each branch on the tree (where a clade is a single branch on the tree consisting of an organism and all its descendants).
5. Naturalness									
Catchment Disturbance Index (CDI)									The Catchment Disturbance Index (CDI) is a catchment summary of human settlements, infrastructure, landuse and point sources of pollution that are expected to impact on aquatic ecosystem health (Stein et al., 2002). The method uses geographical data recording the extent and intensity of human activities known to impact upon river condition to quantify disturbance along a continuum from near-pristine to severely disturbed. The index is calculated as a runoff contribution-weighted summary of these impacts in the catchment upstream and within each planning unit. This index was calculated using the data on human activities detailed in Stein et al. (1998, 2002) with recent (2009) Land Use Mapping data for Australia (BRS 2009a), clearing information (BRS Integrated Vegetation dataset, 2009) and infrastructure data from the Geodata TOPO 250K series 2 database (Geoscience Australia, 2003)
Flow Regime Disturbance Index (FRDI)									The Flow Regime Disturbance Index (Stein et al., 2002) is a catchment summary of impoundments, flow diversions and levee banks within and upstream of each planning unit (calculated using data sources as per CDI).
6. Representativeness									
Representativeness (R)									Bray-Curtis similarity of each planning unit to the group centroid, where group is defined for the entire study region, each drainage division, and each NASY aggregated region. Those planning units with higher Bray-Curtis similarity to group centroid are more representative of the group (Belbin, 1993). This attribute was calculated separately for each set of biodiversity surrogates.

8.1.2 Available methods of scoring, weighting & integration of Attributes & Criteria

The final conservation value that is given to the spatial unit is in effect a summary of all of the data that has been collated as described in the previous sections. There are many different ways in which the data could be summarized for the chosen spatial units and these are referred to as integration methods. In this section we look at options for how the raw data are scored, then converted to attributes and combined to give integrated (criteria) assessments for the spatial units. We also investigate the influence that each of the attributes has on the overall criteria score and subsequently whether some attributes may be omitted from future data collection and modelling. We do not attempt to integrate the six criteria to one overall HCVAE score in this chapter, but this is addressed in chapter 9.

There are two vital stages of integration for this project and they are highlighted using Criteria 1 and its attribute types and indices in Figure 8.1. The two integration stages require consideration of which method of integration to use (for example, just averages or perhaps a precautionary principle?). Regardless of the method used there are several mathematical principles that apply. Integration should involve sub-indices that measure similar attributes, or in a statistical sense, attributes that are correlated. For example, height and weight of humans are correlated attributes that measure size. Integration of these attributes is fairly simple because they act in the same mathematical sphere. That is tall people tend to weigh more and a simple combined index of size may be to classify people as being small medium large or extra large. Of course the combined index of size is not perfect because the two sub-indices are not perfectly correlated and the size measure sometimes accounts for this by using a second descriptor of size. For example, men's pants may indicate waist size and leg style, 32R or 32S for regular or stout respectively. In other words, when the sub-indices are not perfectly correlated with each other, it is not simple to generate a single score to summarize or assess both attributes. In these cases it is always statistically more valid and more sensible to report and act on the sub-indices independently. Recent developments in artificial intelligence and related fields have resulted in some agencies (E.g. MDBA, DPIPWE) applying expert rule sets for integrating indices that may not necessarily be correlated. However, the expert rules approach requires considerable lead time and logistics before implementation and is not been sufficiently evaluated statistically so is not available for this report.

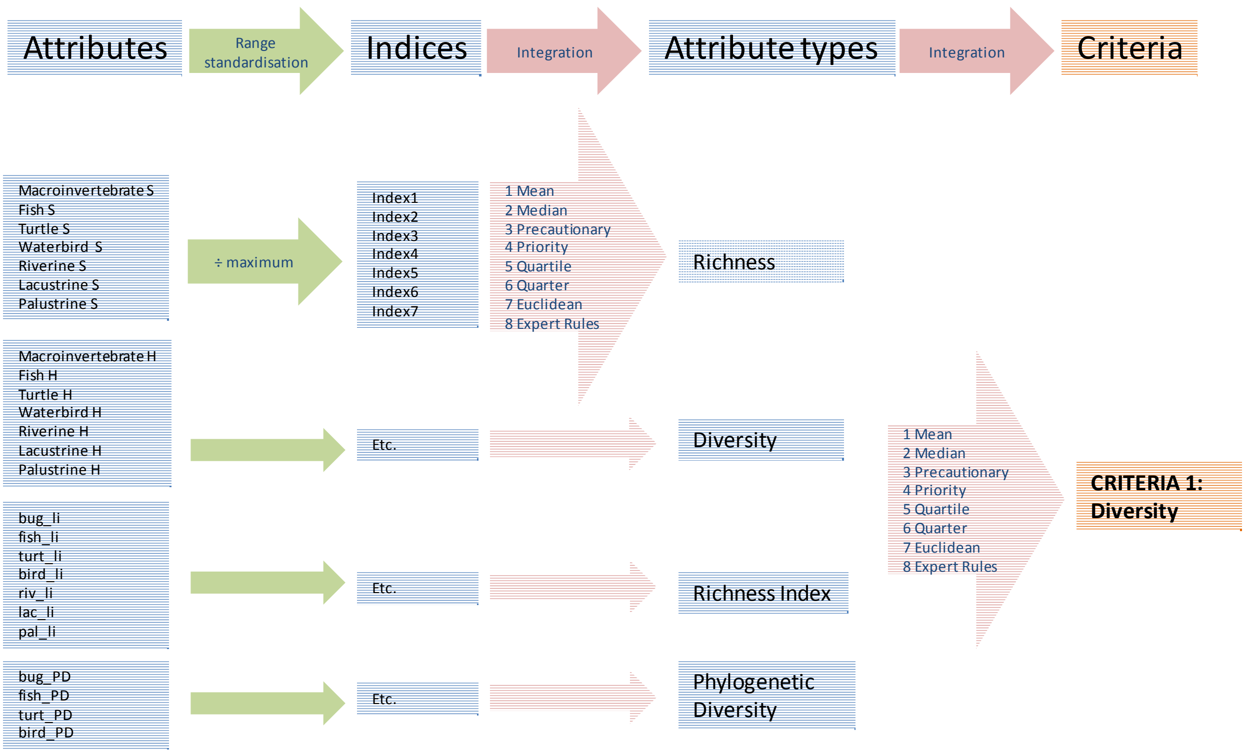

Figure 8.1. Standardising and integrating attributes to criteria using Criteria 1 as an example. The pink arrows list some of the potential integration methods available.

Scoring is the application of a score for each raw attribute measured. There needs to be some consistency because the raw attribute data come in many different scales and types. The raw attribute data firstly should be standardised, that is, converted to a score between 0 and 1. This is necessary to allow equal influence in the analyses if desired. For example, a spatial unit may have 75 macroinvertebrate taxa and 6 turtle taxa recorded. If taxa richness was not standardised then a loss of one turtle species (1/6) would have the same influence as a loss of one macroinvertebrate species (1/75). Standardisation allows a macroinvertebrate index and a turtle index to have equal or differential weight as desired. Weighting is the amount of influence a change in the score has in the next part of the process. Some programs (e.g. SRA) also perform a transformation to linearise the response at this stage, however this is not an option for the current data without performing a thorough analysis of individual attribute distribution properties. The consequences are minimal because the integration method used can account for any shape anyway.

The integration method chosen influences the scoring and weighting of the attributes. For example, if the integration of four indices into one attribute type is by simply taking the average, then the four indices are weighted equally. However if there are four indices in one attribute and two indices in another and the two attributes are then integrated into a criterion, the indices in the first attribute have only a half of the implied or effective weight of the two in the second attribute. For example, the Vital Habitat criterion is made up of 5 indices, but three are combined into a 'dry refugia' attribute type first (Table 8.2).

Table 8.2. Five scores/indices that are combined into three attribute types and then into the Vital Habitat criterion. Effective weights of each index/attribute type in the final criterion are shown in brackets.

Index	Attribute Type	Criterion
riv_P (0.11)	dryrefugia (0.33)	Vital Habitat
lac_P (0.11)		
pal_P (0.11)		
riv_con (0.33)	riv_con (0.33)	
Mbird_S (0.33)	Mbird_S (0.33)	

It is extremely unlikely that all of the indices or attributes used would be desired to have the same weight (i.e. equal contribution) in the final criterion score for each spatial unit. One option is to manually infer *effective* weights by joining some indices into attributes first and then joining attributes later, as demonstrated in Table 8.2. Alternatively, contributions made by the index or attribute types can be manipulated by using mathematical weighting as part of the integration process. Weightings can be applied manually or automatically to indices or attribute types if there is a sound reason for doing so. For example, it may be obvious that total annual flow of water is considerably more important than the number of days with above average flow and so a weighting factor can be manually applied to increase the contribution of the total flow index. Alternatively, a precautionary principle is sometimes used where a weight is applied to the index that has the highest (or lowest) score. For example, in the Vital Habitat criterion (Table 8.2) it may be in one spatial unit that the dry refugia attribute type scores 0.9 (very high) but at the same time very low on river connectivity (riv_con) and migratory birds (mig_bird). If averages were taken then the spatial unit will get a fairly low score for Vital Habitat values[1]. However if the precautionary principle was applied then a weighting could be used to ensure the 0.9 had a higher influence on the Vital Habitat score for the spatial unit. The next spatial unit may score higher on the migratory bird attribute type and then the weighting is applied to migratory birds, and so on.

[1] The only possible outcome from taking the average of two non-correlated variables is to obtain a number somewhere in between. Subsequently, the more variables that are used the more likely they will not be correlated with each other and the more likely the final score will be somewhere near the middle of the range of possible outcomes. This is akin to the Central Limit Theorem.

The use of any weighting method requires considerably more time than available here as it demands sound expert opinion and statistical reasoning and thus neither manual or automatic weightings are attempted in this project. Some commonly used integration methods, where they have been used and their characteristics are described in Table 8.3. All of those listed except Expert Rules were trialled in this project.

An example of how integration could be applied to a single planning unit for this project is demonstrated in Figure 8.2 and the generation of the complete set of criterion 1 scores for all planning units is shown in Figure 8.3. The muddying effect or central tendency that results from taking lots of averages of lots of uncorrelated indices is obvious in Figure 8.3. However, even though simple averaging of uncorrelated scores returns a narrower distribution than the raw attributes, the *relative* position of scores in the distribution are still important and interpretable. For example, if averaging 10 scores with ranges of 0 to 1 results in an integrated score with a range of 0.35 to 0.65 then those with scores near 0.65 are of higher value on average than those on say 0.35. An expert rules set or weighted averaging on the same data may have returned integrated scores with a range of 0 to 1, but the interpretation is the same. Those with higher scores have higher value than those with lower scores.

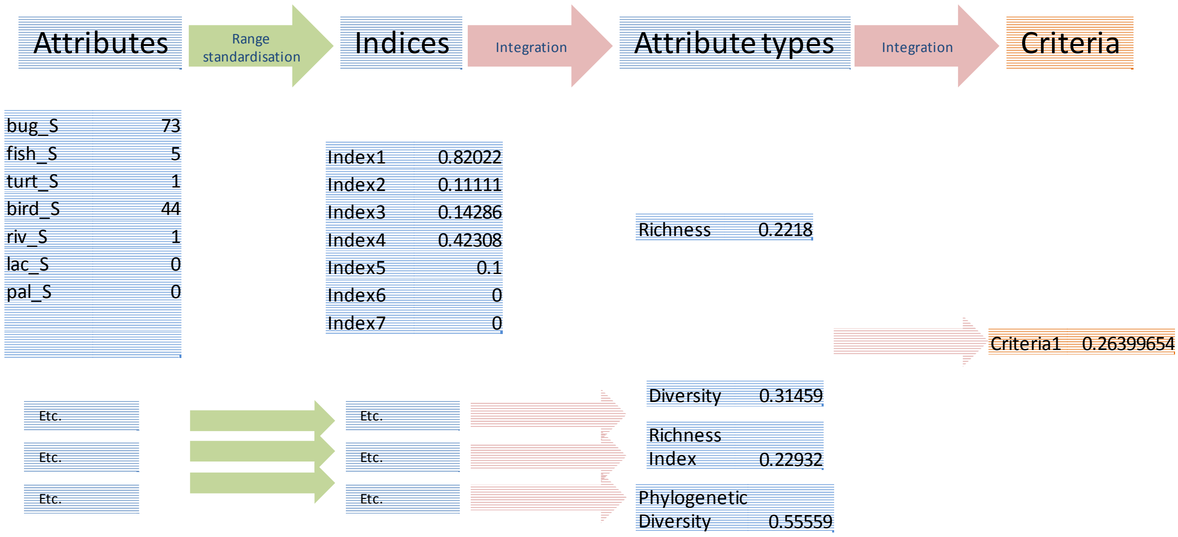

Figure 8.2. An example of scoring and data integration (for planning unit 74) using simple averages (Method 1).

8.2 Methods

8.2.1 Methods of scoring, weighting & integration of Attributes & Criteria

The analyses included 49 combinations of integration (seven methods to attribute type scores × seven methods to criterion scores) and 3 spatial scales of reporting. As a preliminary investigation of concordance among integration methods we performed a rank correlation analysis to determine whether the relative criterion scores given to each spatial unit was consistent between integration methods. Further investigations may reveal that the integrations are best performed using different methods for each criterion. To keep it manageable however, we use an example of how variable the results can be depending on the integration method used and only present in detail those data that have been integrated using simple averaging to generate the attribute type scores and standardised Euclidean distance when integrating to criterion scores. We have chosen simple averaging to get to the Attribute type level because this method is intuitive when the indices within each attribute type are selected to return similar assessments. For example, all of the indices within the Richness Attribute type are measures of Species Richness, therefore they are expected to return scores that are relevant within the same 'domain'. Whether or not they are measuring in the same domain is addressed in the redundancy section below.

Table 8.3: Some of the common methods that can be used to integrate information from several sub-indices into an index that reflects the assessment score for a planning unit. Methods 1, 2, 3 and 7 use *a-priori* based rules and Methods 4, 5 and 6 interrogate the distribution of the indices across the reporting region before integrating.

Method	Description	Example of where it is used	Advantages	Disadvantages
1. Simple averaging (mean)	Take the mean of the sub-indices (these may be weighted)	• Victorian index of stream condition (ISC) (e.g. hydrology theme) • South-east Queensland Ecosystem Health Monitoring program (EHMP)	• Simple and Intuitive	• Assumes sub-indices are correlated • Will return muddy results (values tend to the middle of the distribution) especially with more sub-indices. • Requires sound conceptual framework to establish appropriate weightings. • Weightings subject to expert opinion • Which experts? • Cost of meetings, etc, • Weightings are susceptible to missing data
2. Simple averaging (median)	Take the median of the sub-indices (these may be weighted)	• Sustainable Rivers Audit	• Simple and Intuitive • Less constrained by statistical assumptions of shape of distributions	• As per method 1.
3. Precautionary principle	Applying a weight to the most conservative sub-indices	• Across the themes of the Victorian index of stream condition (ISC)	• Simple and intuitive • Systematically returns more conservative scores than any other method	• Susceptible to missing data
4. Priority principle	Only considering the indicators that are above average (say in the top 10% of values for that indicator across all spatial units). All non-significant values are removed from the analysis	• Not currently used	• Generally removes the greater majority of sub-indices which then reduces the amount of muddying going on • Handles missing data	• Needs development
5. Quartile / threshold	The quartiles of the data are used to set thresholds and each unit receives an ordinal score for each index. E.g. 1= poor, 2= acceptable, 3 = good, 4 = very good.	• More commonly used in social type research	• 25% of the spatial units are in every category • Outputs are simple categories that are easily interpreted	• More muddier results than simple averaging as it adds further error by converting ratio to ordinal scale data • Some sub-indices can't be quartered
6. Quartered / threshold	The range of the data are used to set thresholds and each unit receives an ordinal score for each index. E.g. 1= poor, 2= acceptable, 3 = good, 4 = very good.	• AquaBAMM • Some HCVAE Framework regional trials	• Outputs are simple categories that are easily interpreted	• More muddier results than simple averaging as it adds further error by converting ratio to ordinal scale data • Some sub-indices can't deliver four categories
7. Standardised Euclidean distance	Pythagoras's theorem extended across multiple dimensions. The standardised Euclidean distance tends to return values lower than the mean of the two scores and higher than the precautionary principle method.	• The Framework for the Assessment of River and Wetland health (FARWH)	• Returns the Euclidean distance from a reference (e.g. a perfect or a desirable) condition	• Susceptible to missing data
8. Expert Rules/ Fuzzy Logic (not trialled in this report)	Intelligent decision making involved before including all sub-indices	• Sustainable Rivers Audit (SRA) • CFEV	• Intuitive • Can make very complex integrations simple	• Results can be considerably more variable than other methods • Requires sound conceptual framework to establish weightings. • Weightings subject to expert opinion • Which experts?, Cost of meetings, etc, • Weightings are susceptible to missing data

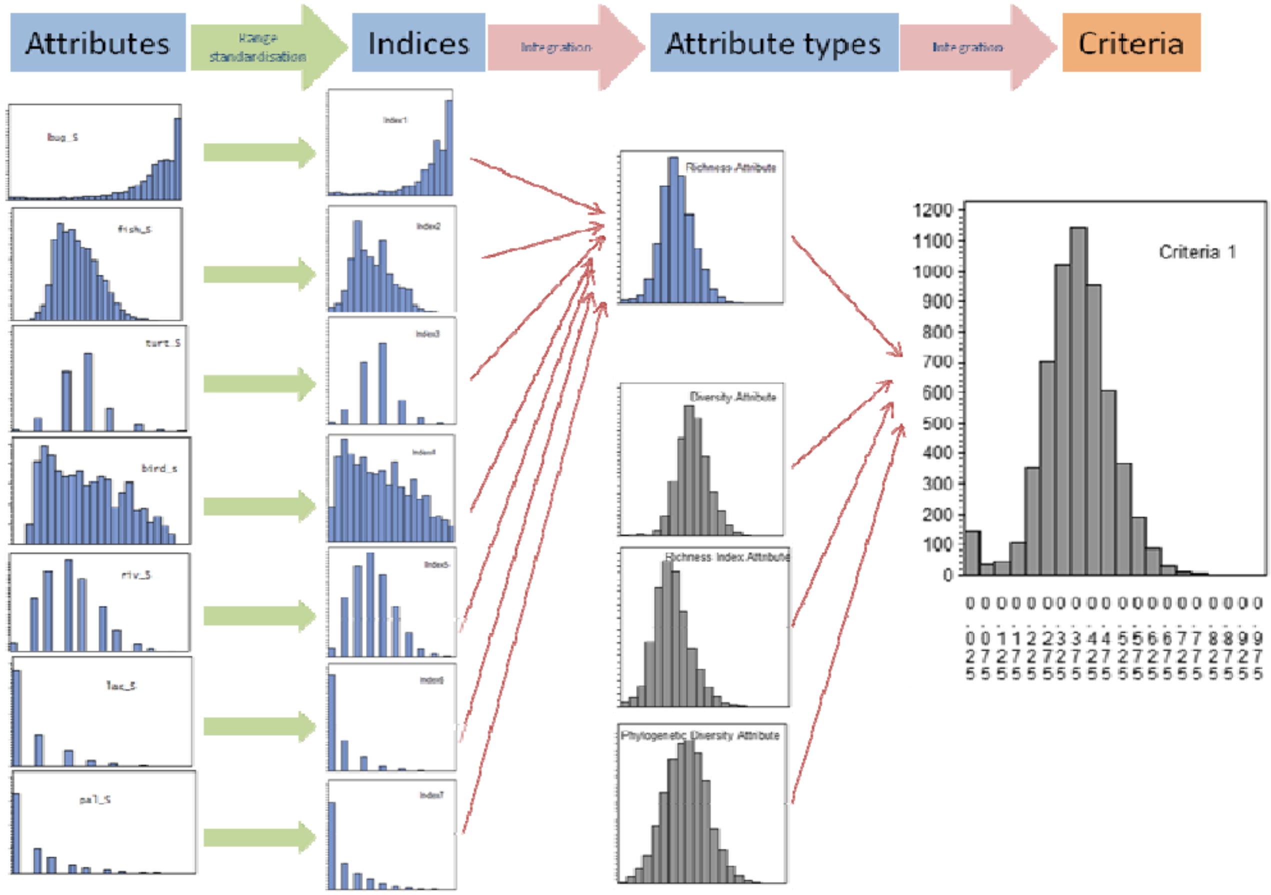

Figure 8.3: The complete data set showing the distributions of the raw data, the standardised indices, an integrated attribute, and Criteria 1 for all planning units using simple averaging (Method 1).

An interesting dilemma can occur in this type of analysis because the integration of indices using any type of mathematical averaging (such as simple or weighted means) infers that the indices are related to each other. On the other hand, if they are strongly related to each other then why measure them all? There are two separate but related issues that we address here, redundancy and sensitivity. Redundancy is the usefulness of an index or attribute considering what other indices or attributes are also included. Sensitivity is the overall contribution, or affect the index has on the attribute or criteria. In this report we look at redundancy and sensitivity for all the indices and attributes chosen and make suggestions but keep all values in for the reporting phase (Chapter 9).

8.2.2 Sensitivity (of Attributes & Criteria to each index)

For the sensitivity analysis the correlation between every index and its attribute type and/or criteria are reported. Furthermore, we re-ran the complete analysis with every index omitted and the average percent change in its associated attribute type and/or criteria is reported.

8.2.3 Redundancy (among Attributes & Criteria)

The extent of redundancy among Indices within attributes and attributes within each criterion was evaluated by examining cross-correlation matrices (using Spearman's rank correlations). Very similar results were found when we conducted the above analyses using Pearson's and Spearman's rank correlations, so we report only the results of the latter. We also used correlations to look at how the six criteria were related.

To keep the results section manageable, sensitivity and redundancy analyses are only reported for the integration to attribute types by simple averaging and integration to criteria by standardised Euclidean distance and only on the largest spatial scale, incorporating all drainage divisions and NASY divisions.

8.3 Results

8.3.1 Scoring, weighting & integration of Indices, Attributes & Criteria

The statistical distributions of the standardised indices for the first seven variables (all richness related measures) were shown in Figure 8.3 and are now represented spatially in Figure 8.4. It is obvious whether looking at the histograms of Figure 8.3 or the spatial distribution of Figure 8.4 that the spatial units score relatively high on the Macroinvertebrate richness index and low on the Paulstrine and Lacustrine richness indices. When the seven scores are integrated into the Richness Attribute type (Fig. 8.5a) one can see the increased differentiation between the spatial units. It is also noted that the integrated Richness Attribute scores (Fig. 8.5a) is an example of averaging leading to more centralized scores, as there are considerably fewer very rich or not very rich spatial units identified.

When the four diversity attribute types (Fig. 8.5a-d) are integrated to the Criterion 1 scores using the seven different integration methods the variability in the assessments that can be obtained are obvious (Fig. 8.6). Notably, the precautionary principle locates many spatial units as having high value whilst the priority method gives quite a few units no score at all (Figure 8.6.3 and 8.6.4). The two threshold methods (Figures 8.6.5 and 8.6.6) tend to give more spatial units higher values than either of the averaging type approaches (Figure 8.6.1, 8.6.2 and 8.6.7). In the absence of the truth, which of the methods are the best is largely unknown. However there is very strong concordance in the relative assessments given by most of the integration methods. Using any combination of the five averaging methods - simple averaging by means, medians, quartiles, quartered or standardised Euclidean distance - gave average correlation coefficients of 0.93 and never below 0.80 for Criterion 1. In other words the order of conservation value of the spatial units according to Criterion 1 is extremely similar regardless of which of these methods is used in integration steps 1 or 2. Methods 3 and 4, the precautionary or priority approaches give very different orders of conservation values for Criterion 1 and the correlation coefficients with the other combinations were generally < 0.6 and as low as 0.11. For Criterion 2 the average concordance was about 0.83 but as low as 0.4 for the five averaging coefficients. For Criterion 3 the concordance averaged 0.93 with a minimum of 0.8 for all combinations of the five averaging type methods. For Criterion 4 the average was 0.82 with a minimum of 0.36. For Criterion 5 the average was 0.92 and the minimum 0.58. Therefore it appears that there is a lot of agreement as to which spatial units are awarded the highest criterion scores using most combinations of the five averaging type integration methods. Using either the Priority principle or precautionary principle methods at this point of the integration process could give quite different results.

Although the methods that rely on some form of averaging (by means, medians, quartiles, quartered or standardised Euclidean distance) have strong concordance we must choose only one to progress this framework and have chosen to use the simple means in the first integration step and standardised Euclidean distance for further reporting in this project for reasons described in the discussion section below. We discuss the merits of the methods for the final stage of integration, reporting across all six criteria in the next chapter.

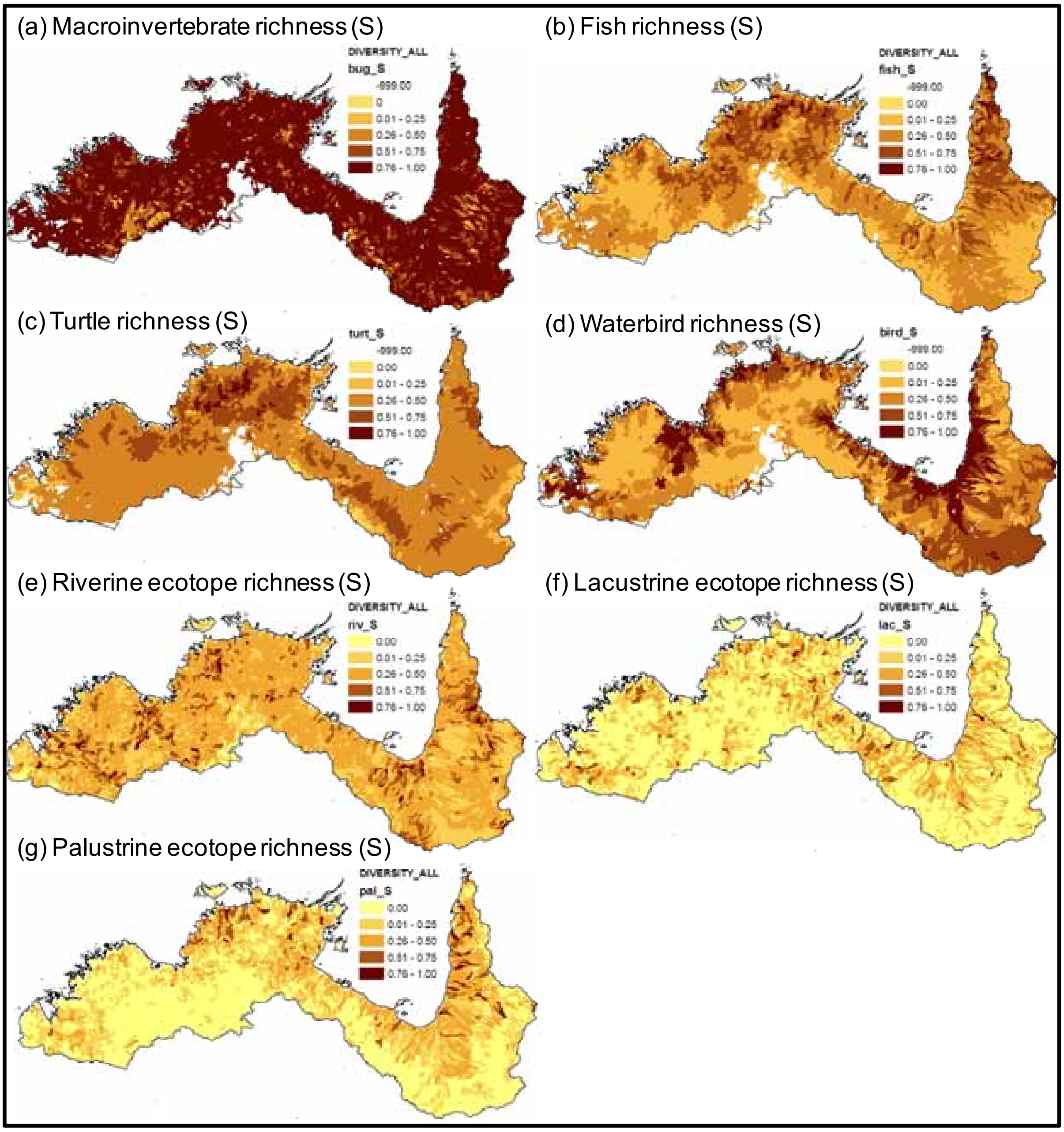

Figure 8.4. Spatial variation in the seven range-standardised indices of richness (S) (a – g) that were used to calculate the integrated Richness attribute (individual indices were integrated using Method 1 - Averaging).

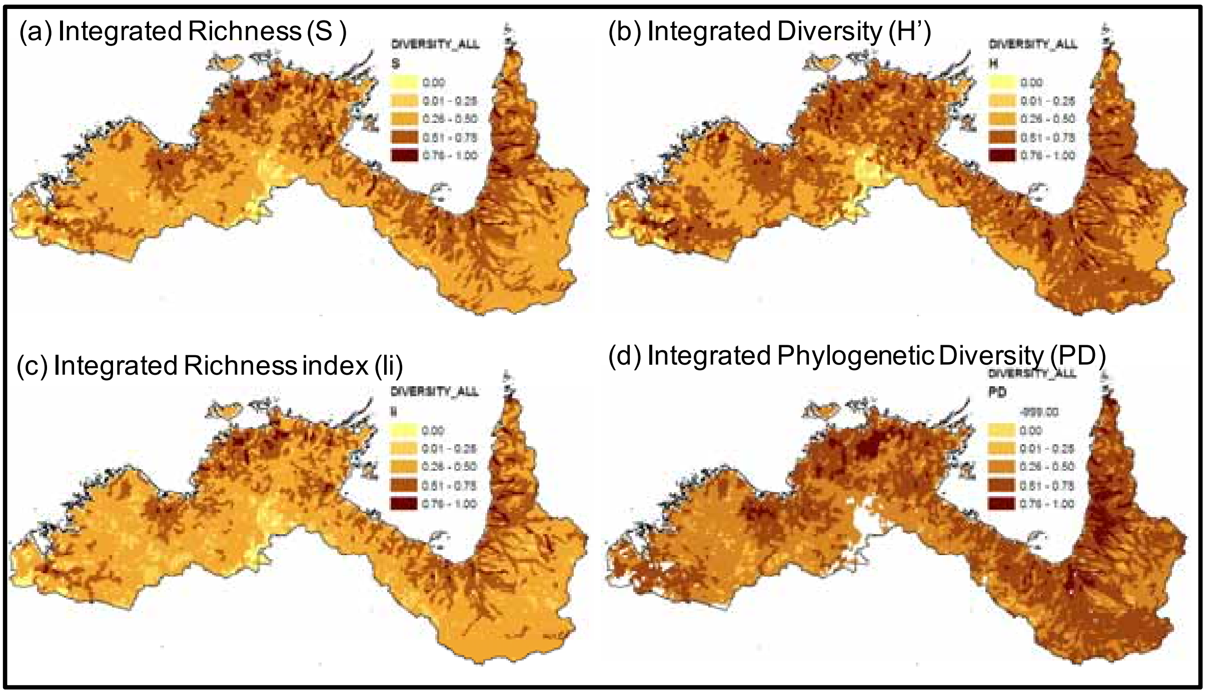

Figure 8.5. Spatial variation in the four integrated attribute types (a – d) used to calculate Criterion 1 (Diversity) scores (individual indices were integrated within attribute types using Method 1 - Averaging).

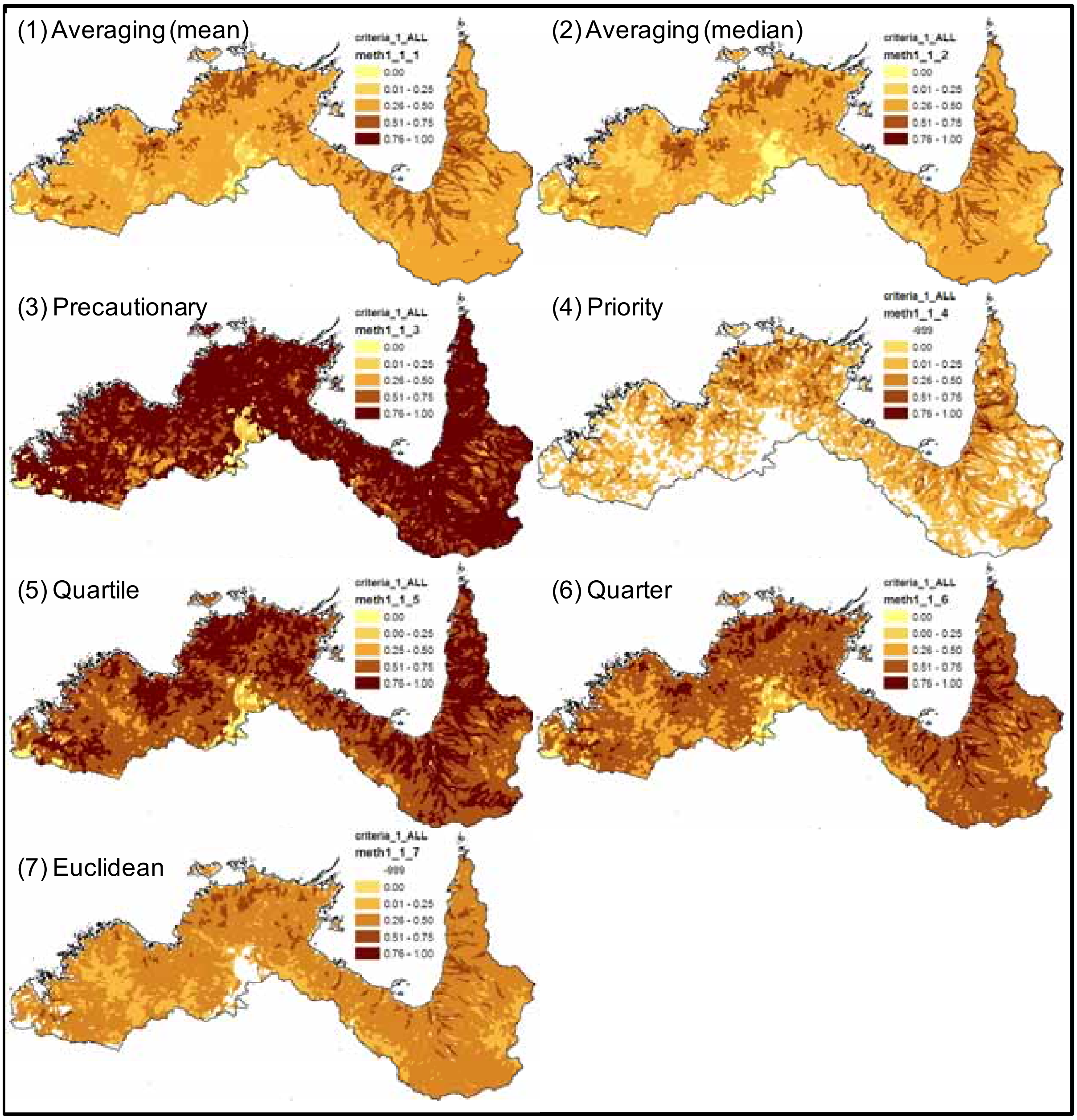

Figure 8.6. Spatial variation in Criterion 1 (Diversity) scores according to the 7 different methods of integration of attribute types as shown in Figure 8.5 (individual indices were first integrated within attribute types using Method 1 - Averaging).

8.3.2 Sensitivity (of Attributes & Criteria to each index)

Many of the indices have very little effect on their criteria if removed from the analyses (Table 8.4). This is particularly obvious for Criterion 1 (Diversity), which has 25 individual indices contributing to it. However there are some trends for Criterion 1, in particular, the macroinvertebrate indices (Bug_S, Bug_H, Bug_Li and Bug_PD) all change the average spatial unit criterion scores by more than 4% and attribute type scores by more than 15% when omitted. On the other hand, Turtle and Bird Richness (Turt_S and Bird_S), Diversity (Turt_H and Bird_H) and Richness Indices (Turt_Li and Bird_Li) have negligible influence or relationships with their attribute types or Criterion 1. Similar examples can be found within each criterion and two points appear consistent, 1) Indices that have very high coefficients of variation (CV) are more likely to have a strong effect on their attribute type when omitted, and 2) these high CV indices tend to have very low average values, suggesting strongly skewed distributions (as demonstrated by Lac_S and Pal_S easily observed in Figure 8.3). Also noteworthy is the relatively high overall correlations of the indices with their attribute types. Even those indices that seem to have no influence on their respective criterion scores are still reasonably well correlated with their attribute type, with 95% of indices having a correlation coefficient of 0.24 or higher. The only really non-relationship was the Turtle Rarity Index (Turt_Ri) which had a correlation coefficient of only 0.04. Other mediocre correlations were the Turtle and Fish Taxonomic endemism (r=0.24 and -0.15 respectively) and Turtle and Fish Phylogenetic endemism (r=0.25 and 0.15 respectively). The general suggestion from these preliminary analyses is that Turtle and Bird indices appear to have lesser effect in the assessments than the other indices.

8.3.3 Redundancy (among attribute types & Criteria)

For all criteria, the majority (i.e. > 85%) of between-attribute comparisons had absolute correlation coefficients < 0.5. The greatest extent of attribute redundancy was for Criterion 1 (Diversity), where about 10% of between-attribute correlations were > 0.8. These observations were consistent when examining for linear (Pearson's correlation; data not shown) and rank-order (Spearman's correlation; Fig. 8.7a) relationships among variables.

There was a relatively high degree of redundancy between attributes used to characterise macroinvertebrates, birds, palustrine and lacustrine biodiversity surrogate sets (Fig. 8.7b). For example, 70% of pairwise comparisons between attributes had absolute correlation coefficients > 0.6 for these biodiversity surrogates. The extent of redundancy was lower for fish, turtles and river biodiversity surrogate sets (Fig. 8.7b).

The extent of redundancy between integrated attribute types was also low, except for Criterion 1 (Diversity) (Table 8.5). The four attribute types of Criterion 1 had correlation coefficients with each other > 0.7 with the highest correlation being between Richness (S) and Richness Index (li) (correlation coefficient = 0.988).

There was substantial redundancy between criteria with only the naturalness criterion showing little relationship with the others. Of particular note, Criterion 1 (Diversity), Criterion2 (Distinctiveness), Criterion 3 (Vital habitat) and Criterion 4 (Evolutionary history) all had correlation coefficients with each other > 0.50 (Table 8.5). Criterion 6 (Representativeness) was also strongly correlated with Criterion 1 (Diversity) and Criterion2 (Distinctiveness).

Table 8.4 Summary statistics and relationships of each index to its Attribute Type and/or Criteria. CV is the coefficient of variation, % Effect is the change observed in the Attribute Type or Criteria when the index is omitted. Purple shaded cells are notably high; CV > 100%, correlations higher than 0.7, contribution effect > 10%. Orange shaded cells are notably low values; CV < 30%, correlations less than 0.5, contribution effect < 1%.

Index	MEAN	CV	CORRELATION WITH ATTRIBUTE TYPE	% EFFECT ON ATTRIBUTE	ATTRIBUTE TYPE	CORRELATION WITH CRITERIA	% EFFECT ON CRITERIA	CRITERIA
bug_S	0.83	24.46	0.64	21.86	Richness (S)	0.65	-5.61	Diversity
fish_S	0.35	46.28	0.65	2.42		0.67	-0.61	
turt_S	0.39	36.89	0.45	2.43		0.45	-0.63	
bird_S	0.41	61.75	0.53	-1.26		0.55	0.27	
riv_S	0.32	51.69	0.61	-2.42		0.58	0.57	
lac_S	0.09	161.89	0.53	-12.79		0.49	3.02	
pal_S	0.1	155.33	0.62	-10.23		0.58	2.42	
bug_H	0.88	16.8	0.46	15.93	Diversity (H')	0.52	-4.37	
fish_H	0.65	23.08	0.56	9.05		0.51	-2.45	
turt_H	0.45	46.83	0.48	-0.70		0.34	0.12	
bird_H	0.67	31.34	0.42	6.00		0.45	-1.64	
riv_H	0.35	68.41	0.61	-3.84		0.53	0.96	
lac_H	0.06	261.19	0.43	-14.49		0.40	3.55	
pal_H	0.09	206.72	0.49	-11.96		0.49	2.97	
bug_li	0.73	31.18	0.72	23.65	Richness Index (Li)	0.71	-5.76	
fish_li	0.26	56.93	0.68	0.16		0.68	-0.05	
turt_li	0.33	40.5	0.39	1.75		0.42	-0.42	
bird_li	0.35	72.61	0.54	-1.91		0.54	0.38	
riv_li	0.31	52.68	0.63	-1.40		0.59	0.32	
lac_li	0.08	162.14	0.53	-12.47		0.48	2.82	
pal_li	0.1	156.07	0.64	-9.77		0.58	2.20	
bug_PD	0.81	29.61	0.67	35.48	Phylogenetic Diversity (PD)	0.63	-9.85	
fish_PD	0.27	69.95	0.64	-6.40		0.64	1.51	
turt_PD	0.12	88.63	0.41	-21.18		0.44	4.84	
bird_PD	0.42	69.35	0.63	-7.90		0.53	1.74	
bug_Qi	0.41	15.13	0.33	-4.13	Rarity Index (Qi)	0.28	1.81	Distinctiveness
fish_Qi	0.56	19.57	0.46	0.87		0.43	-0.66	
turt_Qi	0.71	12.7	0.04	3.46		0.04	-2.15	
bird_Qi	0.63	21.64	0.33	1.00		0.48	-0.69	
riv_Qi	0.83	16.39	0.53	7.23		0.44	-4.22	
lac_Qi	0.34	132.67	0.68	-6.95		0.47	3.70	
pal_Qi	0.39	115.85	0.71	-1.48		0.53	0.95	
fish_SRT	0.18	115.25	0.62	1.26	Rare and Threatened (R&T)	0.62	-0.45	
turt_SRT	0.04	489.46	0.47	-44.23		0.34	12.79	
bird_SRT	0.39	64.69	0.70	42.98		0.68	-12.92	
riv_P	0.01	359.94	0.79	4.16	Dry Refugia	0.21	-0.75	Vital Habitat
lac_P	0.01	403.42	0.58	14.60		0.12	0.26	
pal_P	0.01	403.92	0.61	-18.76		0.11	0.48	
riv_con	0.95	14.84	1.00		Connectivity	0.20	-57.46	
Mbird_S	0.37	72.07	1.00		Migratory birds	0.93	7.15	
fish_monG	0.08	191.67	0.46	-33.51	Monospecific Genera (Mon_G)	0.42	6.36	Evolutionary
turt_monG	0.02	720.78	0.40	-41.65		0.23	7.74	
bird_monG	0.43	61.33	0.79	75.16		0.42	-16.90	
fish_SES	0.02	388.51	0.94	94.19	Endemic Species (SES)	0.33	-0.87	
turt_SES	0	3744.66	0.60	-94.19		0.24	0.76	
bug_TE	0.8	25.85	0.66	48.73	Taxonomic Endemsism (TE)	0.51	-15.08	
fish_TE	0.01	278.15	0.24	-15.38		0.34	4.51	
turt_TE	0.01	303.54	0.15	-15.64		0.30	4.59	
bird_TE	0.33	75.34	0.69	4.22		0.49	-1.48	
riv_TE	0.24	64.16	0.68	1.35		0.51	-0.42	
lac_TE	0.06	187.6	0.49	-12.62		0.30	3.63	
pal_TE	0.06	186.19	0.56	-10.66		0.33	3.04	
bug_PE	0.89	18.75	0.46	59.01	Phylogenetic Endemism (PE)	0.47	-25.85	
fish_PE	0.01	244.35	0.15	-33.12		0.23	11.76	
turt_PE	0.03	176.31	0.25	-29.94		0.22	10.64	
bird_PE	0.53	56.68	0.84	4.05		0.47	-1.63	
CDI	0.86	8.67	1.00		Catchment Disturbance (CDI)	0.60	4.10	Naturalness
FRDI	0.94	21.03	1.00		Flow Disturbance (FRDI)	0.93	-0.82	
bug_R	0.74	30.84	0.53	8.24	Representativeness			Representativeness
fish_R	0.58	33.43	0.54	4.30				
turt_R	0.56	28.63	0.43	2.23				
bird_R	0.46	55.37	0.45	-3.71				
riv_R	0.45	40.53	0.42	-1.10				
lac_R	0.31	134.92	0.69	-6.68				
pal_R	0.32	118.41	0.69	-3.28				

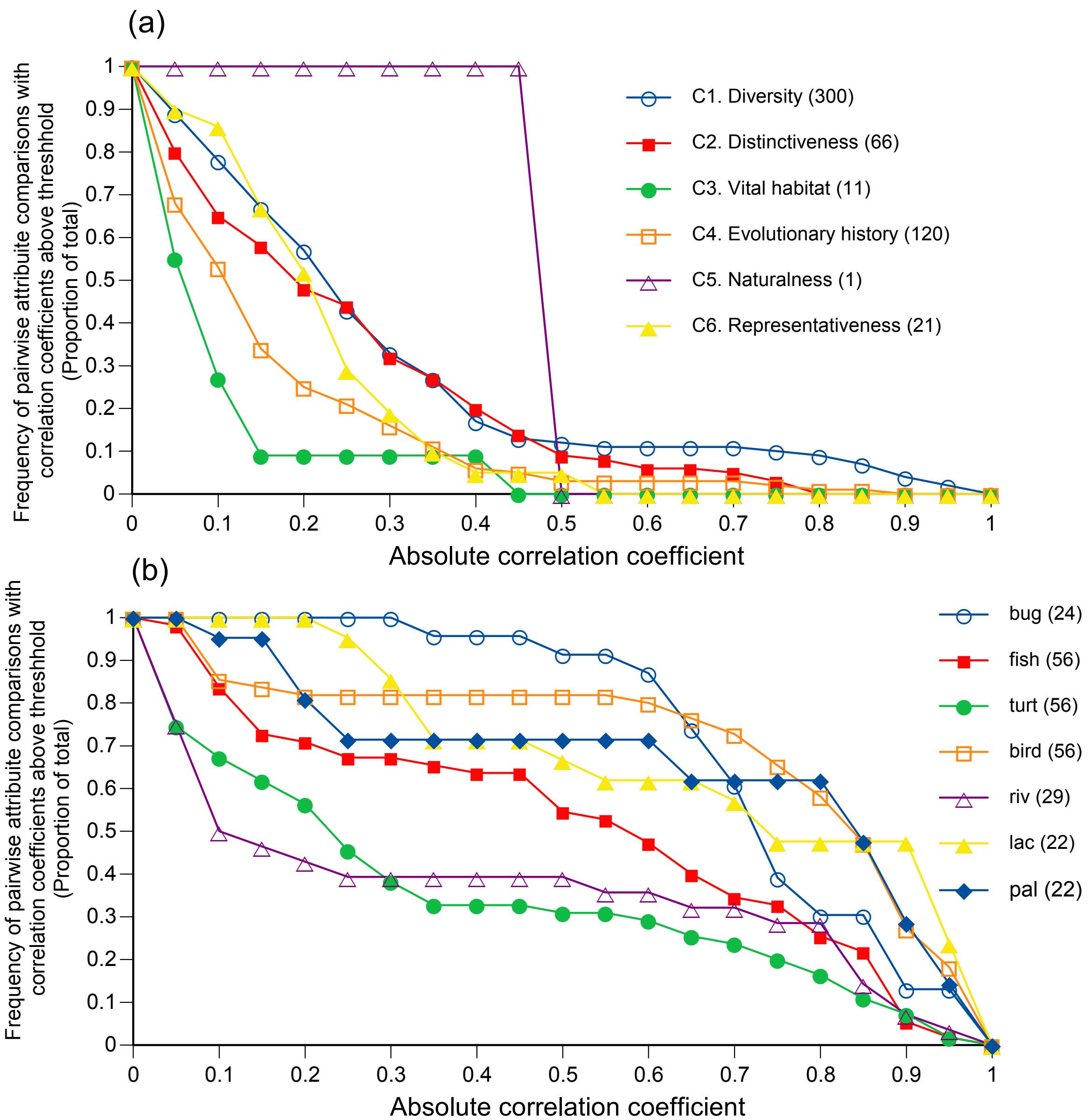

Figure 8.7. (a) Frequency of cross-correlations between attributes within each criterion for varying threshold values of the absolute correlation coefficient (Spearman's rank). For each criterion, the number of pairwise comparisons between attributes is given in parentheses. (b) Frequency of cross-correlations between attributes within each set of biodiversity surrogates for varying threshold values of the absolute correlation coefficient (Spearman's rank). For each set of biodiversity surrogates, the number of pairwise comparisons between attributes is given in parentheses.

Table 8.5 Spearman's rank correlation coefficients for relationships between integrated attribute types (or raw attributes) within each criterion and relationships between these and overall criterion scores.

	Attribute type						**Criteria**
C1. Diversity	S	H'	Ii				**C1**
Richness (S)							0.987
Diversity (H')	0.873						0.898
Richness Index (Ii)	0.988	0.851					0.980
Phylogenetic Diversity (PD)	0.883	0.728	0.875				0.930
C2. Distinctiveness	Qi			.			**C2**
Rarity (Qi)							0.711
Rare & Threatened (R&T)	0.464						0.666
C3. Vital habitat	P	Rcon					**C3**
Refugia (P)							0.176
River connectivity (Rcon)	0.041						0.122
Migratory Birds (Mbird)	0.084	0.059					0.952
C4. Evolutionary history	Mon_G	SES	TE				**C4**
Monospecific Genera (Mon_G)							0.598
Endemic species (SES)	0.081						0.283
Taxonomic endemism (TE)	0.020	0.124					0.769
Phylogenetic endemism (PE)	0.020	0.057	0.859				0.731
C5. Naturalness	CDI						**C5**
Catchment Disturbance (CDI)							0.946
Flow disturbance (FRDI)	0.475						0.627
C6. Representativeness	bug_R	fish_R	turt_R	bird_R	riv_R	lac_R	**C6**
bug_R							0.524
fish_R	0.323						0.528
turt_R	0.195	0.507					0.393
bird_R	0.229	0.007	0.106				0.443
riv_R	0.328	0.366	0.288	-0.028			0.409
lac_R	0.212	0.201	0.099	0.181	0.134		0.665
pal_R	0.250	0.297	0.147	0.145	0.165	0.239	0.672
Criteria	**C1**	**C2**	**C3**	**C4**	**C5**		
C1. Diversity							
C2. Distinctiveness	0.776						
C3. Vital habitat	0.549	0.698					
C4. Evolutionary history	0.710	0.630	0.545				
C5. Naturalness	0.096	0.213	0.262	0.193			
C6. Representativeness	0.781	0.695	0.359	0.490	0.018		

8.4 Discussion and knowledge gaps/next steps

The choice of integration method can have a huge effect on the eventual criterion score as demonstrated in Figure 8.6). The consequences of using the various approaches have received very little attention, probably because it would require a rather intensive research effort for a perceived small benefit. In the meantime a sound conceptual basis is required for applying the draft HCVAE Framework for the purposes of this project. We provided that in this Chapter.

Whilst considerable expert opinion is required for some of the more recent in vogue methods of integration there are two reasons why expert rules or subjective weightings are not recommended by us for this project. First, it is logistically challenging to get the expertise together and technology applied within a short time frames and small budget. Second, none of the expert rules or weighted averaging methods in use (e.g. CFEV, SRA, EHMP, TRCI, ISC, AquaBAMM) have been subjected to rigorous statistical interrogation. So we have no evidence that they are in any way better than averaging or Euclidean distance. A preliminary investigation has found these basic points apply when integrating; 1) expert rules returns more variable results, 2) precautionary principles return lower (or higher depending on direction of caution) average scores and reduce variability, and 3) averaging returns results towards the centre of the distributions, hence less variability in the results and potentially more difficulty in identifying extreme cases (Robinson, 2007). In other words, averaging large numbers of scores results in a narrow distribution of integrated scores as described in Section 8.1.2. However the *relative* scores maintain integrity and in lieu of further research we see little problem with using simple averaging in the first integration phase.

In this report we recommend using simple averaging in the first phase. That is, no expert opinion or precautionary principle weightings are applied to the data. This also has the benefit of reducing added variability in the Attribute types that can be created from differential weights resulting from missing values in the data set. Specifically, when weights are used, the effective weights change for every spatial unit that has a different raw attribute missing. When weights are not used, all attributes are weighted equally regardless of which attributes are missing. In the absence of an expert rules system, un-weighted averaging is the soundest approach that can be taken. However there is a caveat, we found that the variables within each of the attribute types showed little correlation with each other. That is, the seven indices in say the Diversity attribute type have 21 cross tabulated correlations but the maximum correlation was only 0.48 and the average correlation was only 0.23. As mentioned in Section 8.1.2, when two variables are related to each other it is simple to combine them, when they are not related combining them can only give a result in between. We justified our approach stating that indices developed to be conceptually related can be combined. But because in reality, the indices have little actual relationship with each other the results for the Attribute types will tend to the centre of the distribution. The best possible way to report these data is to report them independently, without any integration at all. This is not a feasible outcome for this project, so an integration method must be used. We opted to apply simple averaging for two main reasons; 1) Spatial units that score higher on more Indices will have a higher average, so will still be identified although the range of attribute scores will be narrower, and 2) without the sound reasoning of expert opinion and complexity of expert rules, we have no reason to differentiate between an average of say 0.4 generated from Index values of say 0.1, 0.1, and 1.0 and the same average generated from Index values of say 0.4, 0.4 and 0.4.

The attribute types within each criterion should be less correlated with each other because they were selected to represent different domains. This proved to be the case for all except the Diversity criterion. Euclidean distance was therefore chosen as the preferred integration method for the second step to get from attribute type to criteria because it is very robust when there are very few missing values in the data set (there are no attribute types without scores because we used simple averaging in the first step which returned scores for all attribute types), it is simple and intuitive to interpret (Norris et al., 2006), and offers flexibility later when determining which spatial units have the highest possible values.

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9. Identifying high conservation value aquatic ecosystems using the draft HCVAE framework

Mark Kennard, Brad Pusey, Wayne Robinson & Virgilio Hermoso

Key points

1. **Aim:** To identify high conservation value areas in northern Australia by implementing the HCVAE framework at three different spatial scales.
2. **Methods:** Based on the recommendations presented in Chapter 8, we used a robust approach to characterising the framework criteria that involved averaging to integrate scores for each attribute into attribute types. The scores for each attribute types within each criterion were then integrated using Euclidean distance. This gave us final criterion scores for each planning unit. We used maps to show spatial variation in each of the attribute types and criteria. We evaluate several options for identifying which subset of planning units might be considered to qualify as being of high conservation value based on their respective criterion scores. We identify HCVAEs at three separate spatial scales: referential to the entire study region, each Drainage Division, and each bioregion, respectively. We evaluated the extent to which the set of areas identified as being of high conservation value using the framework efficiently contribute to the important goal of representing the full range of species or type of natural environments (so-called biodiversity surrogates). We also evaluate how well the current reserve system encompasses the distribution of freshwater biodiversity surrogates.
3. **Results:** Twenty-two attribute types were calculated from the 65 raw attributes and used to characterise the six criteria for each of the 5,803 planning units. Several criteria (e.g. Diversity, Distinctiveness, Vital Habitat) consistently identified certain areas of northern Australia as being of high conservation value. In contrast, the criteria describing Evolutionary History and Representativeness tended to identify different areas that were patchily distributed within and between individual river basins. Planning units having met at least one criterion for a given threshold level were distributed widely across the entire study region and planning units having met four or more criteria were concentrated in the northern top end of the Northern Territory and the tip of Cape York Peninsula. As the threshold for having met the criteria was relaxed, increasing numbers of planning units qualified as HCVAEs and these surrounded the core areas identified using the strictest threshold. Based on a strict 99th percentile threshold we identified subsets of planning units potentially containing HCVAEs for each of three reporting scales: (1) the entire study region (total of 275 planning units representing 6.9% of the total area), (2) each drainage division (total of 282 planning units representing 6.9% of the total area), and (3) each NASY region (total of 308 planning units representing 7.7% of the total area). These planning units are listed in Appendix 9.1, together with the individual criteria met, the total number of criteria met as well as the major named hydrosystems (riverine, lacustrine, palustrine and springs) occurring within each of these planning units. The existing protected area network and the set of planning units identified as containing HCVAEs, were ineffective or inefficient at representing the distribution of some biodiversity surrogates (in particular certain rare fish and turtle species).
4. **Implications:** Implementing the Framework criteria as they currently stand goes some way to identifying areas that are of high conservation value. Greater clarity as to the purpose of the HCVAE identification may further increase the efficient investment of resources to manage these areas effectively. The Framework criteria are not specifically designed to identify which management options are most appropriate for a particular area and will require further investigation.
5. **Limitations / Knowledge gaps / next steps:** A fundamental goal of conservation assessments should be to efficiently identify sets of areas that should be managed to conserve species and the processes that sustain them. The draft HCVAE Framework is limited in the extent to which it can efficiently contribute to this conservation goal and will require complementary approaches that specifically address this.

9.1 Introduction

The sensitivity analyses presented in Chapter 8 allowed us to objectively identify a robust approach to implementing the HCVAE Framework. In this chapter we present the outcomes of this implementation. We provide a summary of the outcomes of the application of scoring planning units for each attribute type and criterion. We evaluate several options for identifying which subset of planning units might be considered to qualify as being of high conservation value based on their respective criterion scores. We identify HCVAEs at three separate spatial scales: referential to the entire study region, each Drainage Division, and each bioregion, respectively. Due to the very large number of resulting maps and tables, in this chapter we focus on HCVAEs identified across the entire region. We tabulate the subsets of planning units and the named hydrosystems within them that were identified as being of potentially high conservation value (using a strict threshold – see below) at each spatial scale. A geo-database held by the Australian Government (DEWHA) contains the raw scores for all attributes, attribute types and criteria calculated for all planning units and referential to all three spatial scales.

The multi-criteria HCVAE Framework represents a spatially explicit 'scoring' approach to prioritizing freshwater systems. Importantly however, none of the Framework criteria are designed to identify a set of areas that represent the full range of species or types of natural environments (so-called biodiversity surrogates or conservation features). Scoring approaches assess each area individually. Highest ranking areas can contain the same conservation features which are duplicated, while other features remain completely unrepresented, especially if they occur only in low-ranking areas (Carwardine et al., 2007). This can lead to inefficiencies in identifying high conservation areas that should be prioritised for ongoing management actions. This is a potential weakness of the Framework as it currently stands. We therefore consider it important to evaluate the extent to which the set of areas identified using the Framework as being of high conservation value contribute to the goal of representing the full range of species or type of natural environments (so-called biodiversity surrogates).

The conservation of freshwater ecosystems and biodiversity is rarely the basis for declaration of reserves (e.g. National Parks, and other conservation areas) unless it is considered important for maintenance of terrestrial biodiversity patterns and processes (Saunders et al., 2002; Nel et al., 2007). We assume here that a reserve system designed primarily for maintenance of terrestrial biota may also have significant value for aquatic systems, although this has yet to be adequately demonstrated in Australia. We therefore also evaluate the extent to which the existing set of conservation reserves (based on the most recent available (2006) version of the Collaborative Australian Protected Area Database; CAPAD, 2009) encompasses the distribution of freshwater biodiversity surrogates.

9.2 Methods

9.2.1 Framework criteria

For each of the 5,803 planning units, attributes for each criterion were calculated for each of the biodiversity surrogate sets (macroinvertebrates, fish, turtles, waterbirds, and riverine, lacustrine and palustrine ecotopes), where appropriate and where suitable data was available (Chapter 8). Attributes for each planning unit were scored at three separate spatial scales: referential to the entire study region, each Drainage Division, and each bioregion, respectively. Based on the recommendations presented in Chapter 8, we used simple averaging to integrate scores for each attribute into attribute types. The scores for each attribute types within each criterion were then integrated using Euclidean distance. This gave us final criterion scores for each planning unit. We use maps to show spatial variation in each of the attribute types and criteria.

9.2.2 IDENTIFYING HCVAEs

The draft HCVAE Framework (Appendix 1.1) states that an ecosystem meeting any one of the criteria could be considered an HCVAE, but that appropriate thresholds for nationally significant HCVAE are yet to be determined. It is unclear what threshold should be used to discriminate those planning units that "meet" each criterion (i.e. that their criterion score exceeds the threshold and therefore could be considered to be of high conservation value based on that criterion). The choice of threshold is a somewhat arbitrary decision, but can have potentially important consequences for identifying which and how many planning units are considered of high conservation value. We evaluated a range of thresholds based on percentiles of the distributions of criterion scores for all planning units. For each criterion, we identified those planning units that exceeded the upper 99th, 95th and 90th percentiles, respectively, of the distribution of criterion scores for all planning units, and considered these planning units to have "met" each criterion. The percentile method complements the integration methods used in Chapter 8 because the highest value sites are identified according to position in the distribution relative to other spatial units, not the distribution itself. In other words, because we used simple averaging and standardised Euclidean distance, the range of criterion scores calculated is narrower than the 0-1 range of the raw indices, however the best spatial units still get higher scores than the other units.

It is unclear whether some criteria should be considered more important than others for identifying HCVAEs and whether particular planning units that meet a greater number of criteria are concordantly of higher conservation value. We considered various options for how HCVAEs might be identified based on their combined criterion scores and whether some criteria should be treated as more important than others for assigning conservation value and identifying HCVAEs. However, we agree with the approach taken in the Lake Eyre Basin trial (Hale, 2010) that the lack of a specified purpose, for the identification of HCVAE, means that the criteria be considered to be equally important. We assumed that conservation value increased with increasing number of criteria met (i.e. a planning unit that met all six criteria had a greater potential for containing an HCVAE than a planning unit that met only one criterion). In addition to simply counting the number of criteria met (based on the three thresholds), we also integrated the six criteria using standardised Euclidean distance – this produced a threshold-independent measure of relative conservation value for each planning unit based on all criteria.

9.2.3 HOW WELL DO HCVAEs IDENTIFIED USING THE FRAMEWORK CRITERIA *REPRESENT* THE DISTRIBUTION OF BIODIVERSITY SURROGATES?

As none of the Framework criteria are designed to identify a set of areas that represent the full range of species or types of natural environments (so-called biodiversity surrogates or conservation features), we evaluated the extent to which the set of areas identified as being of high conservation value using the Framework contribute to the goal of representing the full range of species or type of natural environments (so-called biodiversity surrogates). These analyses were conducted using each of the thresholds.

To evaluate how well the current reserve system encompasses the distribution of freshwater biodiversity surrogates, we measured the total amount of each taxa included in the planning units currently reserved. To identify the planning units that are reserved, we intersected them with the layer of IUCN protected areas (CAPAD, 2006) (Fig. 9.1a). Whenever more than 75% of the area of a planning unit fell within a reserve we considered it as reserved in the analysis (Fig. 9.1b).

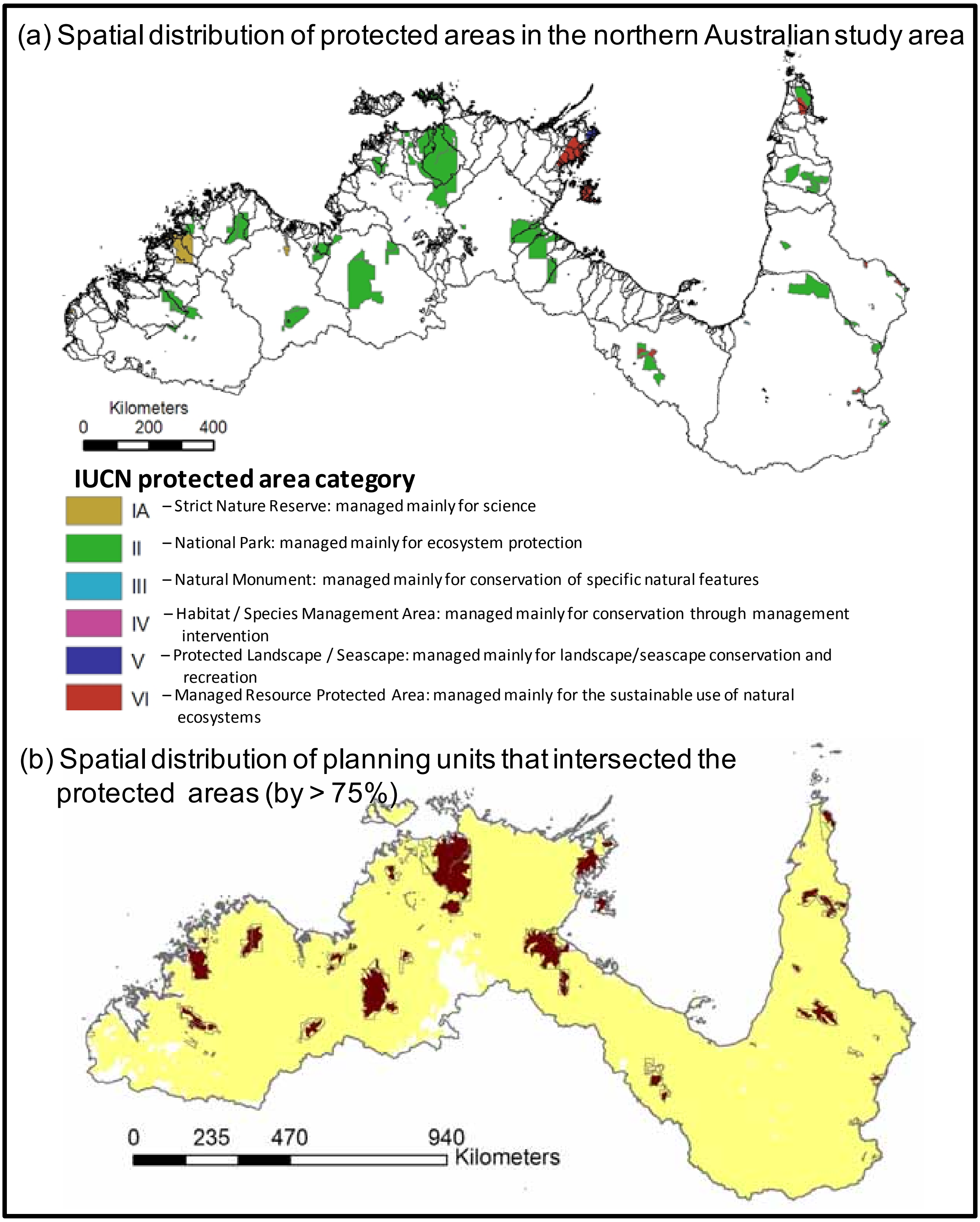

Figure 9.1. (a) Location of protected areas (CAPD 2006) in northern Australia according to the IUCN (1994) protected area definition: "A protected area is an area of land and/or sea especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means". (b) Spatial distribution of planning units (highlighted in red) that intersected the protected areas by more than 75%.

9.3 Results

9.3.1 Spatial distribution of planning unit scores for attribute types and criteria

Twenty-two attribute types were calculated from the 65 raw attributes and used to characterise the six criteria for each of the 5,803 planning units. These calculations were repeated for each of the three reporting scales. A geo-database held by the Australian Government (DEWHA) contains these raw data. Results of scoring and integration to attribute types and final criterion scores for each planning unit and calculated over the entire study region are presented in Figures 9.2 – 9.7 and summarized briefly below.

Diversity (Criterion 1) varied extensively within the study region (Fig. 9.2). Highest levels of diversity (>95th percentile) occurred in a band located near the coast and decreased further inland. This pattern corresponded to a change from large lowland rivers with extensive floodplains to smaller headwater streams. The Kimberly region, with the exception of the Fitzroy and Ord River basins, was comparatively less diverse than elsewhere, especially in the vicinity of the Kimberley Plateau. In contrast, rivers draining the Arnhem Land Escarpment were very diverse. High levels of diversity (>95th percentile) occur in a contiguous band across the region except for the central part of the Kimberley region and perhaps in the very eastern part of Arnhem Land where the basins are numerous but small. Even this latter area is still comparatively diverse at the 90th percentile level.

As with Diversity, Distinctiveness (Criterion 2) attained highest levels close to the coastal boundary of the region (Fig. 9.3). In contrast however, high levels of distinctiveness were not contiguous across the region. Three separate domains of high distinctiveness were present: the southern Gulf region (only partly extending up into western Cape York Peninsula); the western half of the Top End of the Northern Territory (from the East alligator River westward to the Daly River); and the Fitzroy River of the Kimberley region. The western Top End of the Northern Territory can be divided into two regions defined by the Daly River in the west and the East and South Alligator Rivers in the east. The latter two rivers are the principal rivers of the Kakadu region. Whilst still highly distinctive, the river basins between these two areas (i.e. the Mary River, Adelaide River, Finniss River) do not contain planning units of the highest levels of distinctiveness (i.e. >95th percentiles). Isolated patches of planning units of high distinctiveness also occur outside of these three regions but are very limited in extent.

The distribution of planning units scoring high for Vital Habitat (Criterion 3) approximated that for Distinctiveness except that the inland reduction in scores was greater, resulting in an even more coastal pattern of distribution of high scoring areas for this criterion (Fig. 9.4). This is especially so for the Kimberley region and the Northern Territory. Areas with high values for this criterion were not contiguous. The southern Gulf region and western Cape York Peninsula formed one contiguous coastal band, Coburg Peninsular to the Finniss River formed another, the Molyle to the Ord River formed another, but more diffuse band, and the lower reaches of the Fitzroy River formed the final aggregation of planning units characterised as vital habitat. There were also isolated aggregations of planning units of high value not associated with these larger groups. The presence of refugial habitat appears most important in defining the distribution of vital habitat in the Northern Territory whereas the number of migratory birds appears more important elsewhere where this criterion was high.

Areas of high conservation value with respect to Evolutionary History (Criterion 4) were not contiguously aggregated across the study region and were patchily distributed within and between individual river basins (Fig. 9.5). Notably high areas occurred in the Alligator Rivers region and the Daly River in the Northern Territory; the Drysdale, Edward and Fitzroy Rivers of the Kimberley region; and throughout the southern Gulf region and western Cape York Peninsula, including the Jardine River. Unlike Criteria 1 – 3, areas rated highly for Evolutionary History were not limited to areas close to the coast and were distributed much more widely throughout the landscape.

Vast areas of northern Australia were rated highly (> 99th percentile) with respect to Criterion 5 – Naturalness (Fig. 9.6). Areas scoring highly for Naturalness included all of Arnhem Land and including the upper reaches of the Daly River and most of the Roper River basin; the Fitzmaurice, Moyle and Victoria rivers, especially the headwaters of the latter; small northern basins of the Kimberley regions in the vicinity of the Berkely and Prince Regent Rivers; and the upper portion of western Cape York Peninsula. Southern Gulf of Carpentaria rivers such as the Flinders, Norman and Mitchell rivers are notable for the paucity of planning units designated as having high levels of naturalness, although they do occur in these basins.

Areas scoring highly on Citerion 6 (Representativeness) were distributed patchily across northern Australia (Fig. 9.7). No one region or river basin was particularly notable for the number of planning units rated highly on this criterion although basins within the Kimberley, with the exception of the Fitzroy and Ord rivers, and the very tip of Cape York Peninsula were distinguished by their low scores. The most inland areas of the region were consistently ranked low according to this criterion, most likely due to their low diversity.

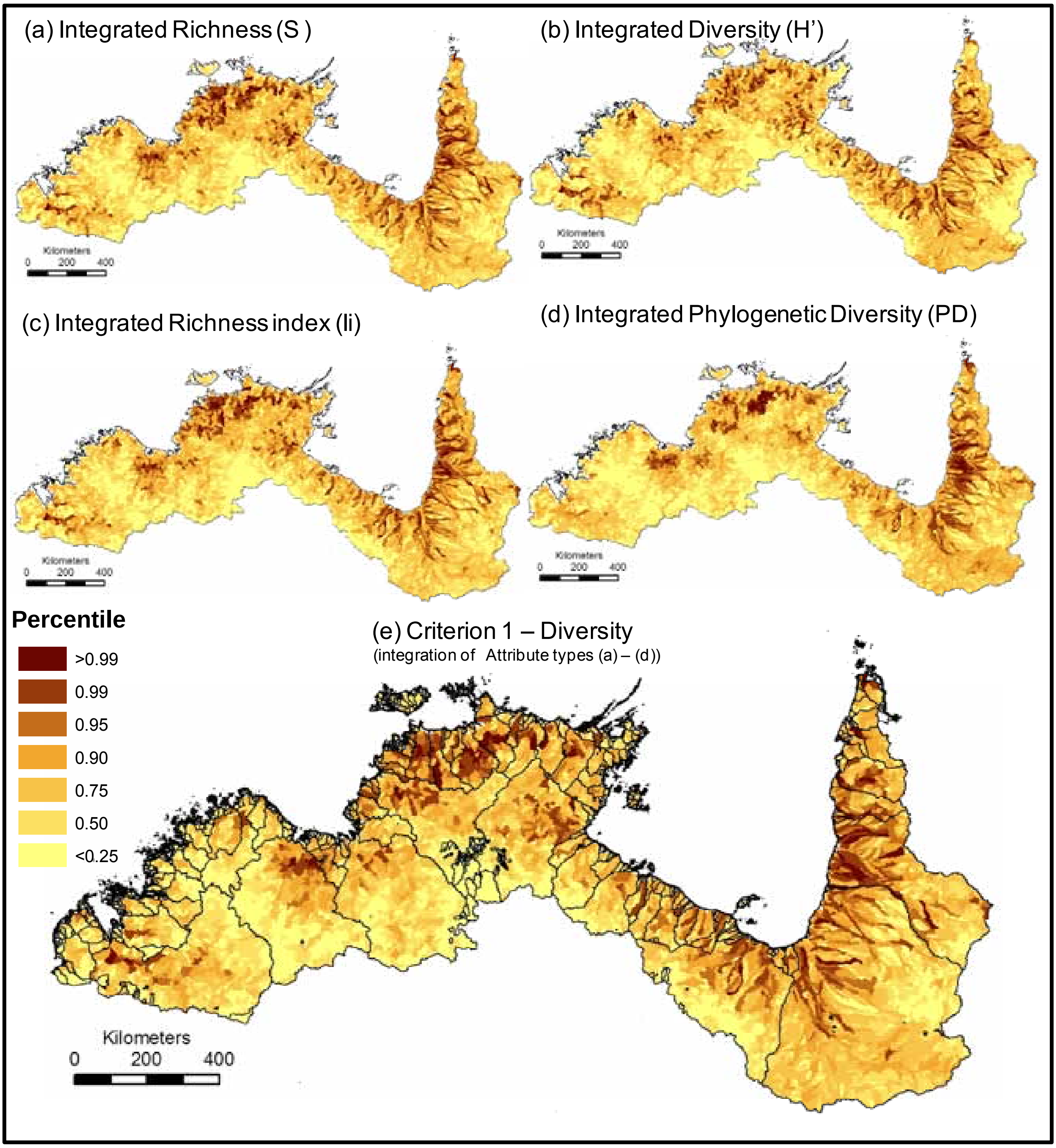

Figure 9.2. Spatial distribution of planning unit scores for the four integrated attribute types (a – d) used to calculate (e) Criterion 1 (Diversity). Scores are calculated referential to the entire study region and range-standardised. Planning units are coloured according to their respective percentile score for each attribute type and criterion. Dark coloured planning units have higher percentile scores and hence higher conservation value.

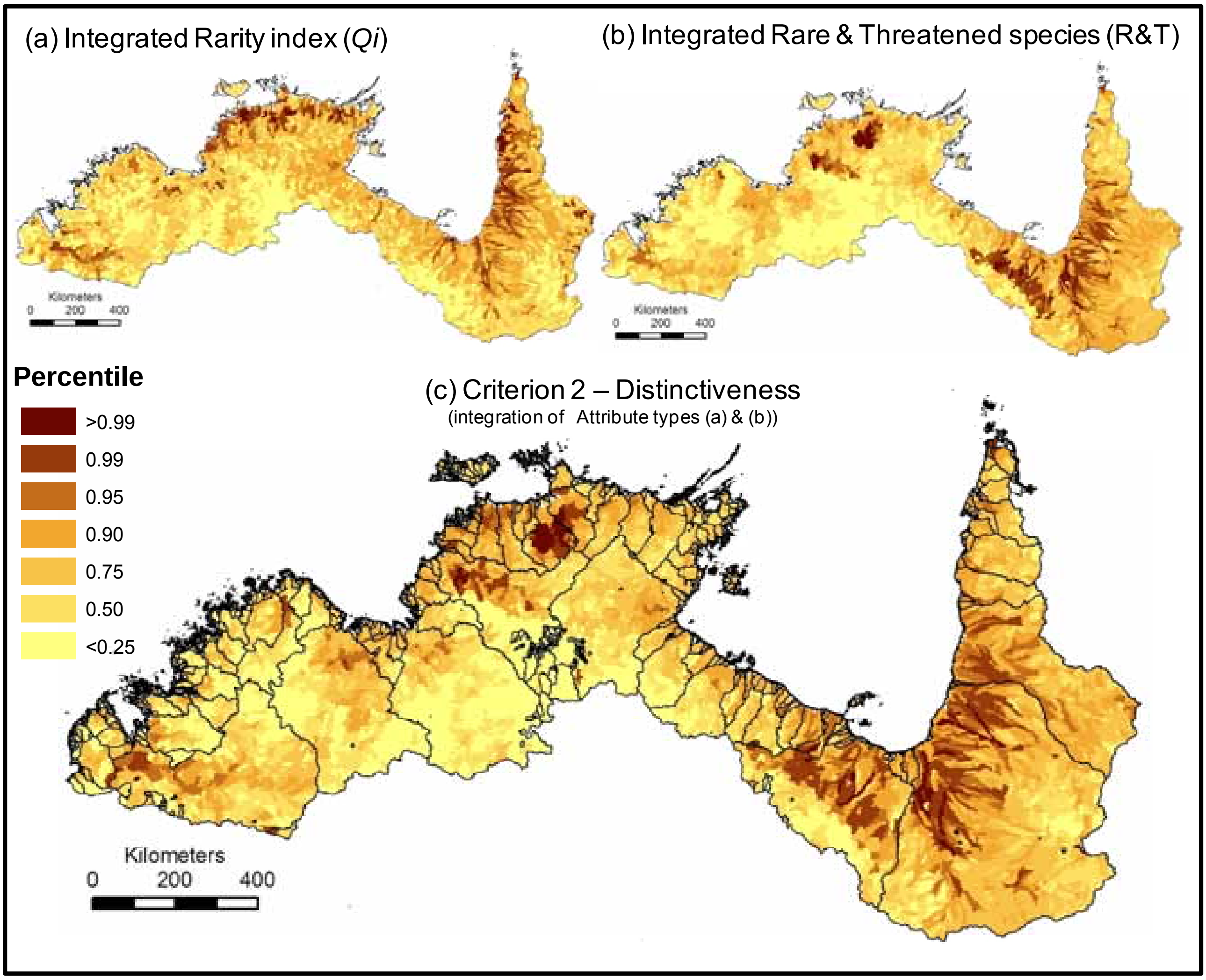

Figure 9.3. Spatial distribution of planning unit scores for the two integrated attribute types (a and b) used to calculate (c) Criterion 2 (Distinctiveness). Scores are calculated referential to the entire study region. Scores are calculated referential to the entire study region and range-standardised. Planning units are colored according to their respective percentile score for each attribute type and criterion. Dark coloured planning units have higher percentile scores and hence higher conservation value.

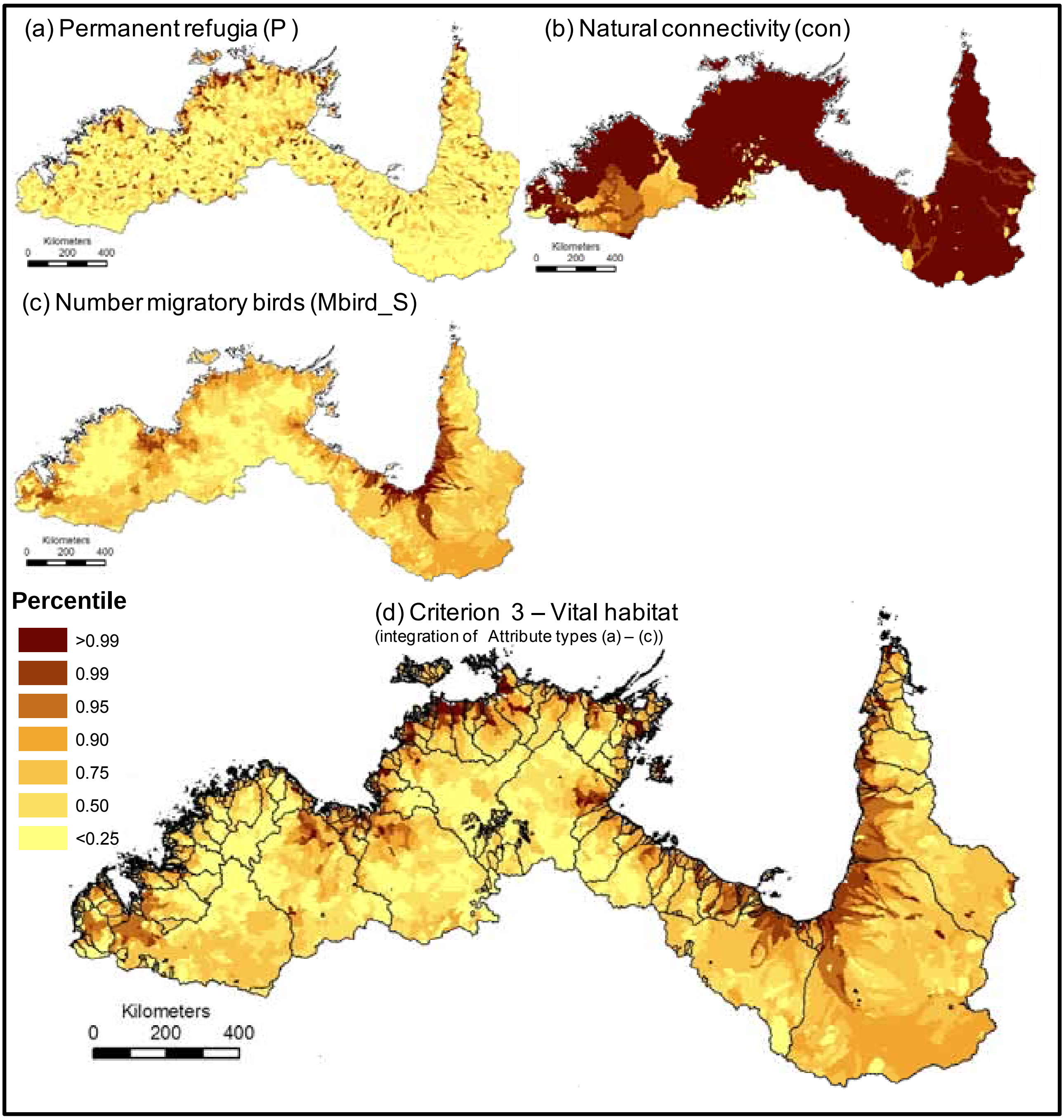

Figure 9.4. Spatial distribution of planning unit scores for the three integrated attribute types (a – c) used to calculate (d) Criterion 3 (Vital habitat). Scores are calculated referential to the entire study region. Scores are calculated referential to the entire study region and range-standardised. Planning units are colored according to their respective percentile score for each attribute type and criterion. Dark coloured planning units have higher percentile scores and hence higher conservation value.

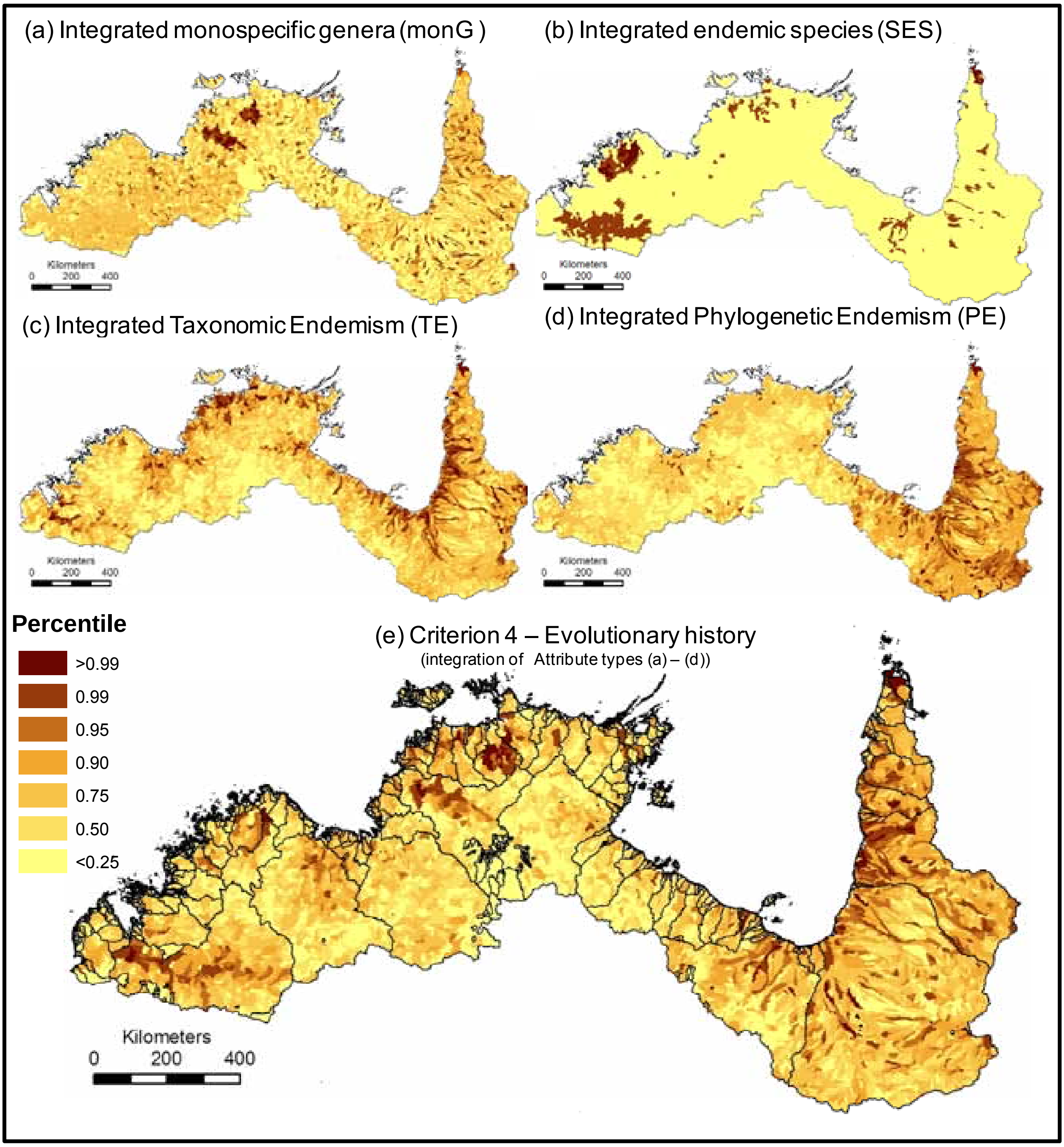

Figure 9.5. Spatial distribution of planning unit scores for the three integrated attribute types (a – d) used to calculate (e) Criterion 4 (Evolutionary history). Scores are calculated referential to the entire study region. Scores are calculated referential to the entire study region and range-standardised. Planning units are colored according to their respective percentile score for each attribute type and criterion. Dark coloured planning units have higher percentile scores and hence higher conservation value.

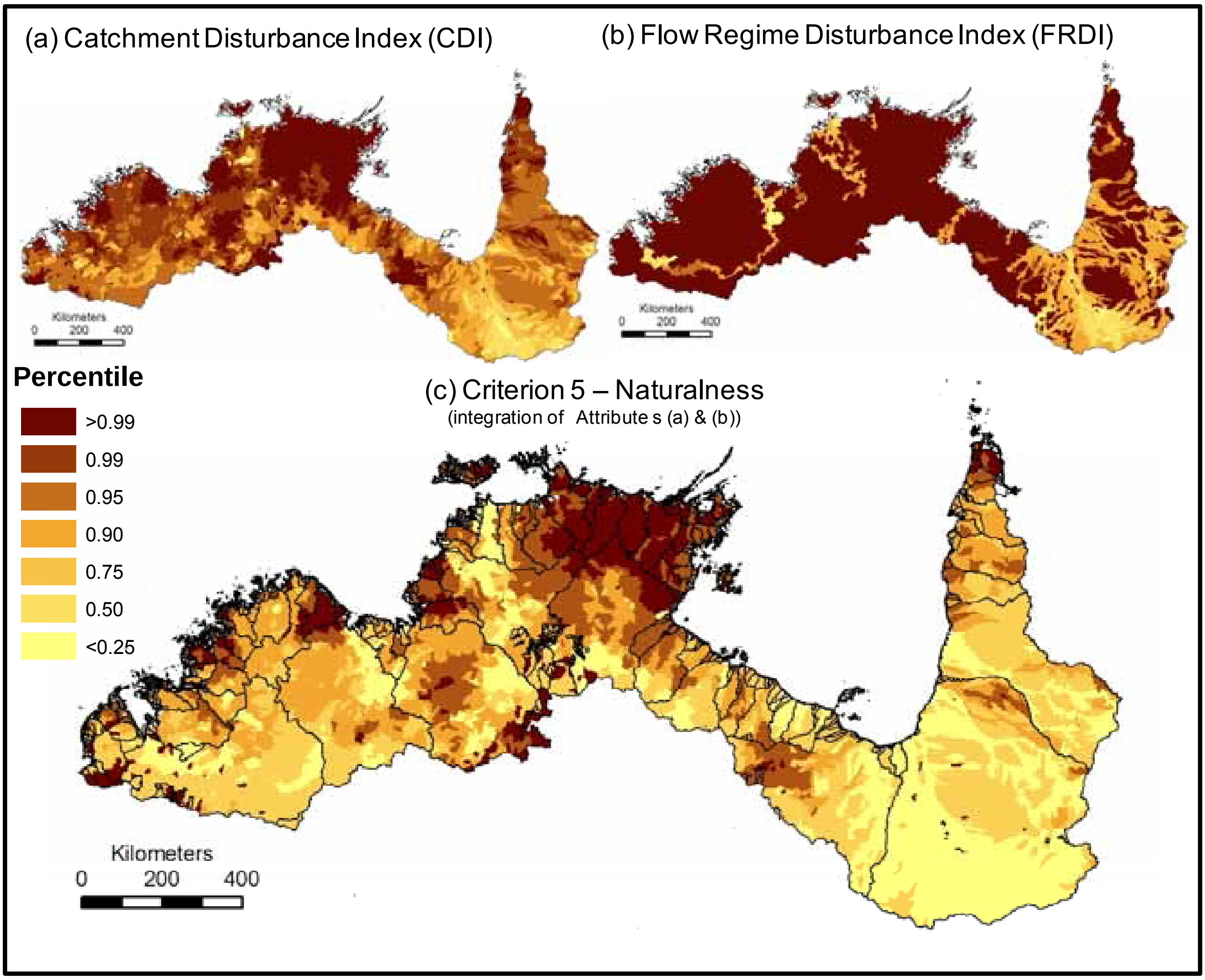

Figure 9.6. Spatial distribution of planning unit scores for the two integrated attribute types (a and b) used to calculate (c) Criterion 5 (Naturalness). Scores are calculated referential to the entire study region. Scores are calculated referential to the entire study region and range-standardised. Planning units are colored according to their respective percentile score for each attribute type and criterion. Dark coloured planning units have higher percentile scores and hence higher conservation value.

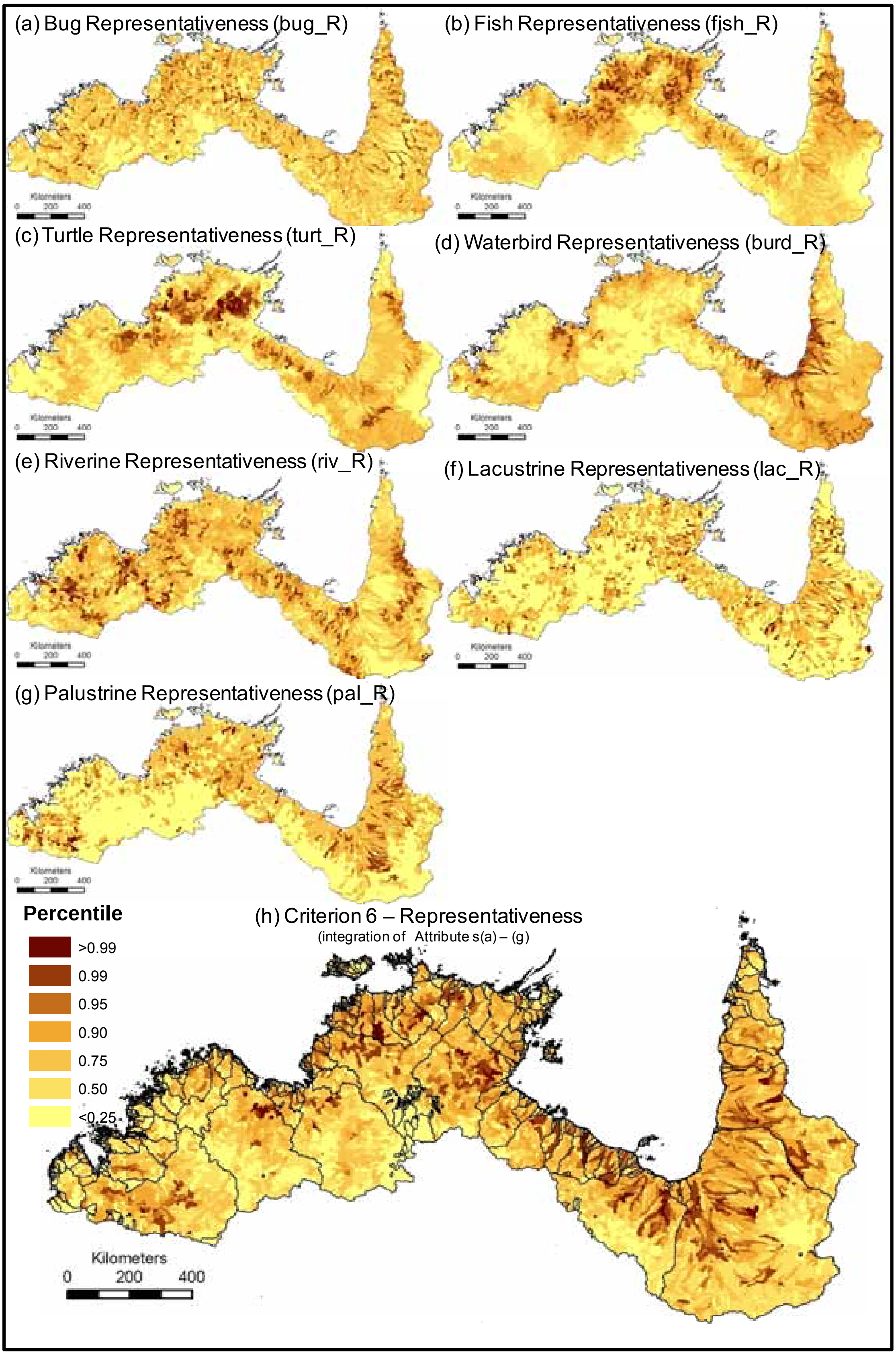

Figure 9.7. Spatial distribution of planning unit scores for the seven biodiversity surrogate sets (a – g) used to calculate (h) Criterion 6 (Representativeness). Scores are calculated referential to the entire study region**.** Scores are calculated referential to the entire study region and range-standardised. Planning units are coloured according to their respective percentile score for each attribute and criterion. Dark coloured planning units have higher percentile scores and hence higher conservation value.

9.3.2 Identifying HCVAEs and their distribution across northern Australia

A total of 275 planning units met one or more criteria at the strictest threshold (99th percentile), but few of these met more than one criteria (maximum of four) and no planning units met all six criteria (Fig. 9.8). As the threshold was relaxed, the number of planning units meeting one or more criteria increased rapidly (Fig. 9.8). For example 275, 1,146 and 1,924 planning units met one or more criteria at the 99th, 95th and 90th percentile thresholds, respectively. This represented 6.9%, 24.5% and 38.9% of the total study region, respectively (Fig. 9.8). When conservation value was assigned to planning units by integrating scores across all six criteria (using Euclidean distance) and applying the 99th, 95th and 90th percentile thresholds, a total of 58, 290 and 580 planning units met these thresholds respectively (Fig. 9.9). This represented 1.6%, 7.8% and 9.4% of the total study region, respectively. This method of HCVAE identification therefore appears to give a stricter qualification for HCVAE status (fewer planning units and overall smaller proportion of the total area at each threshold), however, the method is less transparent in that it is unclear how many criteria (and which ones) contribute greatly to the integrated score (note that this issue also applies to integrating raw attributes to attribute types).

Planning units having met at least one criterion at the 99th percentile threshold level were distributed widely across the entire study region and planning units having met four or more criteria were concentrated in the northern top end of the Northern Territory and the tip of Cape York Peninsula (Fig. 9.10a). As the threshold for having met the criteria was relaxed, increasing numbers of planning units qualified as HCVAEs and these surrounded the core areas identified using the strictest threshold (compare Figures 9.10a, b and c). A similar spatial pattern of notionally high conservation value areas was observed when all six criteria were integrated into a single score (using Euclidean distance). This can be seen by visually comparing the spatial distribution of planning units greater than the upper 90th percentile of integrated criterion scores (Fig. 9.10d) with those identified as having met each threshold (Fig. 9.10a, b, c).

Based on these results, we suggest that the most robust and transparent approach to identifying the subset of planning units that are likely to contain aquatic ecosystems of the highest conservation value is simply to identify those that meet the threshold for one or more criteria (akin to the precautionary principle described in Chapter 8) and that the total number of candidate planning units can be restricted by simply using a strict threshold (e.g. 99th percentile). Following this approach, we have identified the set of planning units potentially containing HCVAEs for each of three reporting scales: (1) the entire study region (total of 275 planning units representing 6.9% of the total area), (2) each drainage division (total of 282 planning units representing 6.9% of the total area), and (3) each NASY region (total of 308 planning units representing 7.7% of the total area) (Fig. 9.11a, b, c). These planning units are listed in Appendix 9.1, together with the individual criteria met, the total number of criteria met as well as the major named hydrosystems (riverine, lacustrine, palustrine and springs) occurring within each of these planning units.

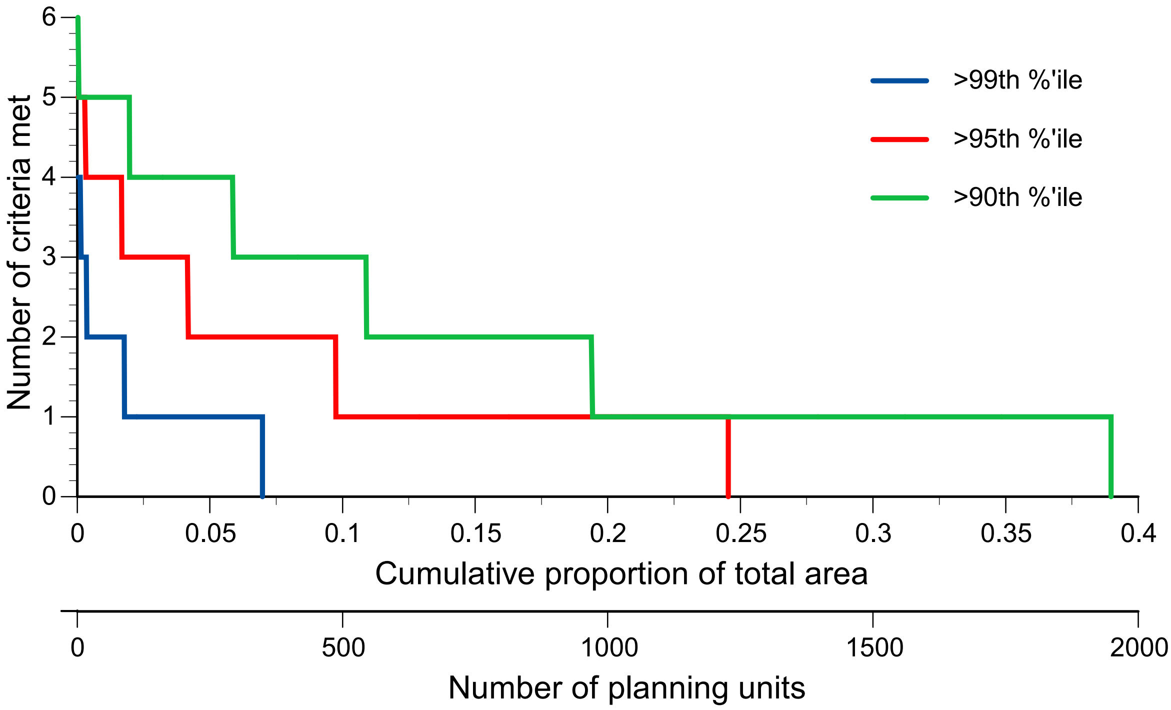

Figure 9.8. The number of planning units that met one, two, three, four, five and six criteria at each percentile threshold. Also shown is the cumulative proportion of the total study area (1.169 million Km^2).

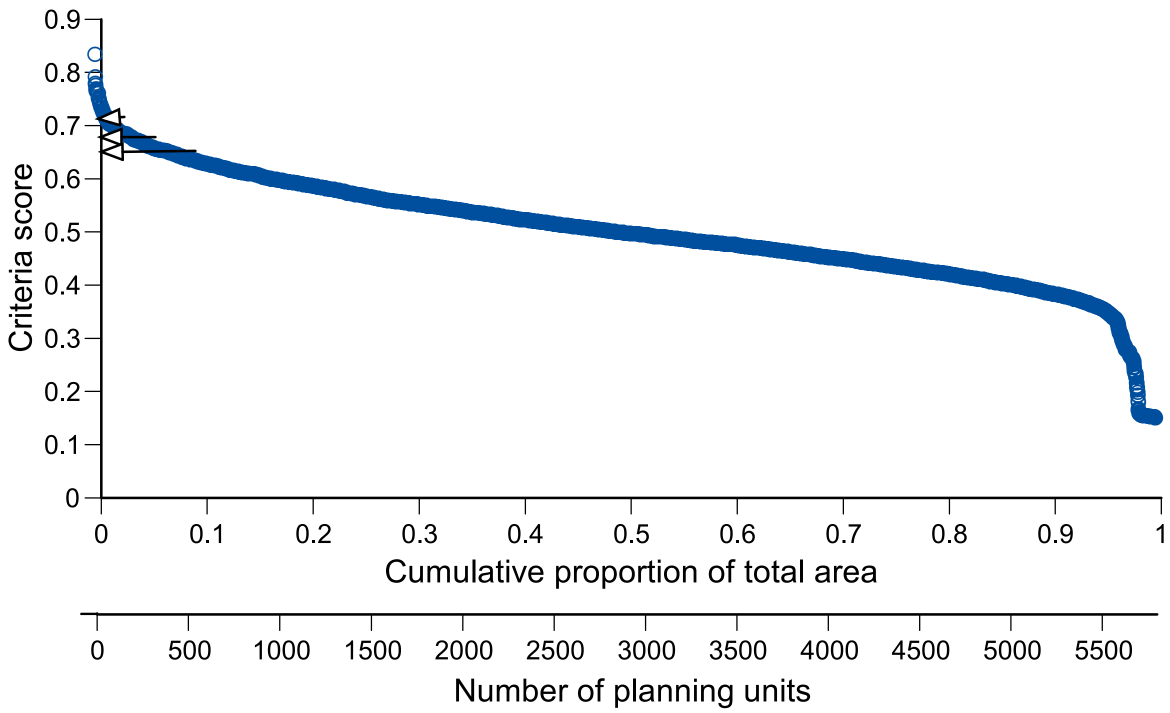

Figure 9.9. Cumulative frequency distribution of planning units ranked by their criterion score integrated across all six criteria (using Euclidean distance). Arrows indicate the criterion scores for each of the 99^{th}, 95^{th} and 90^{th} percentile thresholds. Also shown is the cumulative proportion of the total study area (1.169 million Km^2).

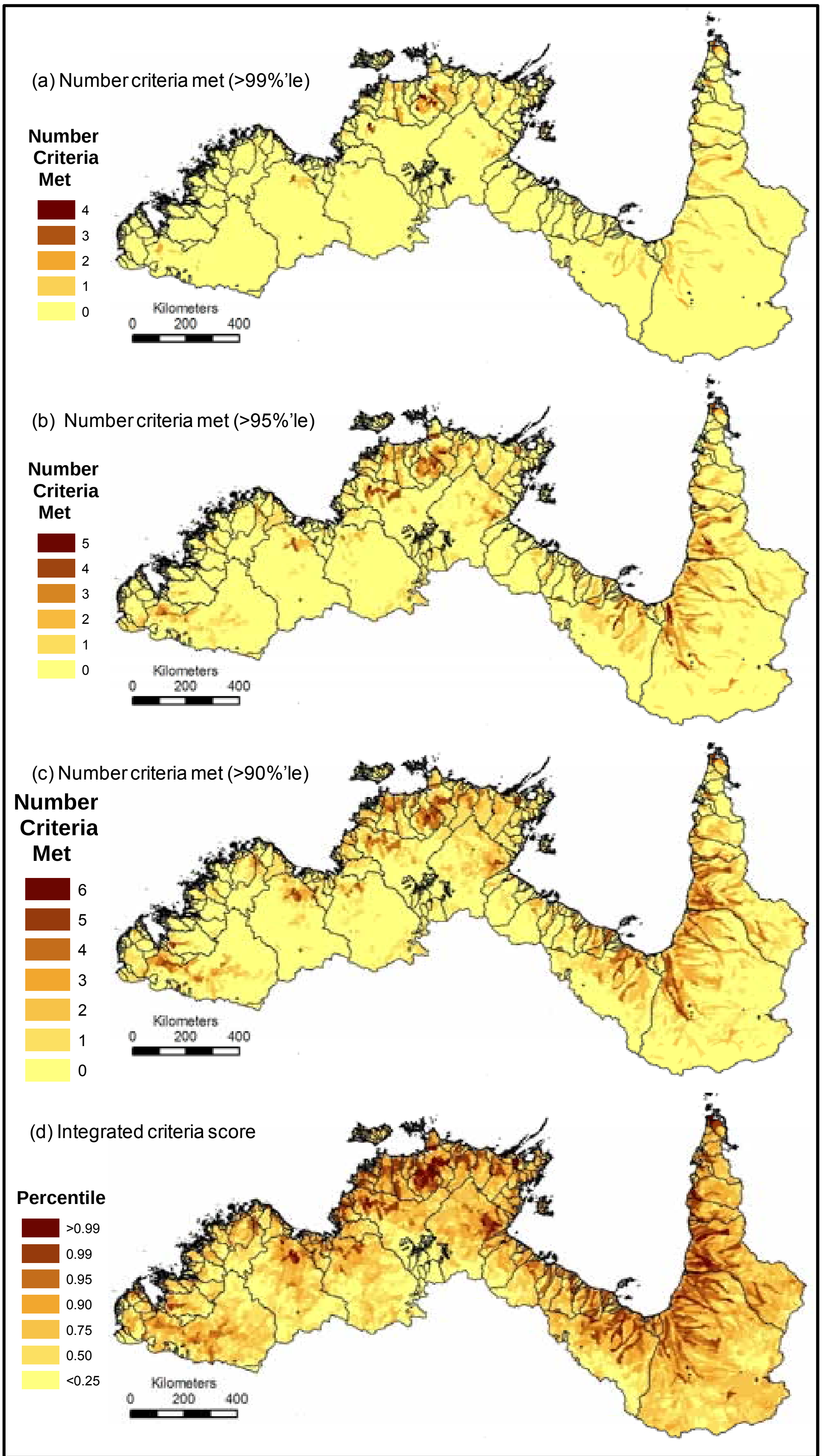

Figure 9.10. The number of criteria met for each planning unit defined using 99th, 95th and 90th percentile thresholds (a, b and c, respectively). Also shown is the integrated HCVAE score for each planning unit (integrated across all six criteria using Euclidean distance).

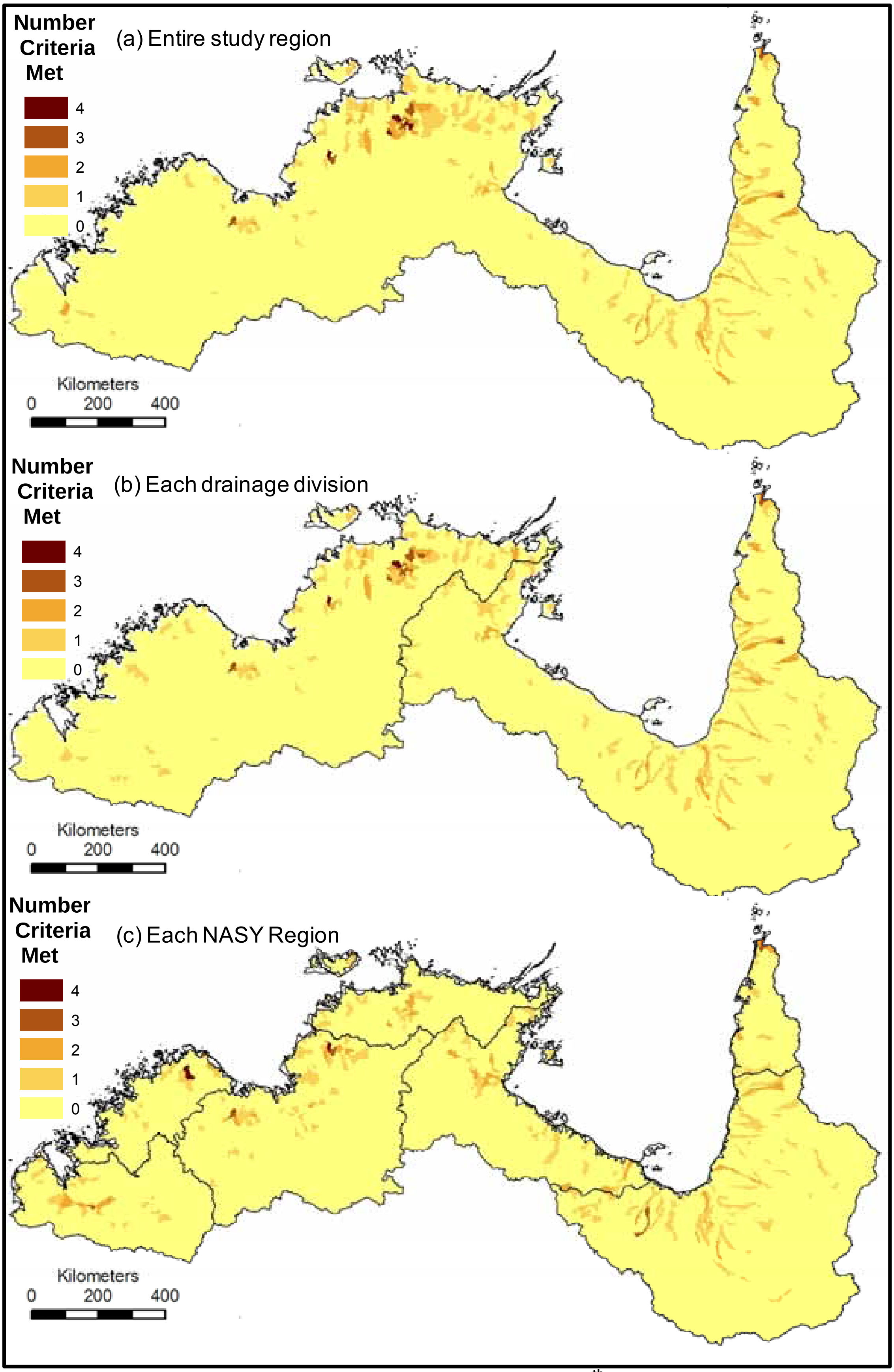

Figure 9.11. The number of criteria met for each planning unit defined using the 99th percentile threshold and referential to (a) the entire study region, (b) each drainage division, and (c) each NASY region.

9.3.3 How well do HCVAEs identified using the framework criteria *represent* the distribution of biodiversity surrogates?

The existing network of protected areas in northern Australia do not encompass the distribution of one species of turtle, 12 species of fish, one riverine type and one lacustrine type (Table 9.1). The set of planning units identified as containing HCVAEs by meeting at least one criterion using the strictest threshold (99th percentile) did not appear to perform much better in representing the full range of biodiversity surrogates in that 11 species of fish and one palustrine ecotope were not represented within these planning units. Even if the criterion thresholds were relaxed to the 90th percentile, two fish species were still not represented. These results indicate that the criteria are potentially inefficient at identifying a subset of areas to represent all taxa. This is especially evident when the planning units are ranked by their integrated (Euclidean distance) criteria score and the total number of taxa represented at least once is counted as individual planning units are sequentially added (Fig. 9.12). Turtles required about 30% of the entire study region to be selected before all 13 taxa are represented. Fish required more than 85% of the study region to be selected before all 103 taxa are represented. This no doubt is due to the extreme rarity of some turtle and fish taxa (see Chapters 5 and 7), and that the criteria did a poor job of prioritizing planning units containing these species.

Table 9.1. The total number of taxa or hydrosystem type in each biodiversity surrogate set that are *not* currently represented within existing protected areas and also *not* represented in the set of planning units identified as being HCVAEs based on each percentile threshold.

Biodiversity surrogate set	**Existing protected areas (IUCN)**	**Potential HCVAE planning units**		
		99th percentile threshold	95th percentile threshold	90th percentile threshold
Macroinvertebrates	0	0	0	0
Fish	12	11	2	2
Turtles	1	0	0	0
Waterbirds	0	0	0	0
Riverine	1	0	0	0
Lacustrine	1	0	0	0
Palustrine	0	1	0	0

9.4 Discussion and knowledge gaps/next steps

In this chapter we have successfully implemented the HCVAE Framework criteria using a robust approach to scoring and integration of attributes, attribute types and criteria (as outlined in Chapter 8). We used as simple and as transparent an approach as possible to identify the subset of planning units that may contain aquatic ecosystems of the highest conservation value (i.e. those that meet a strict (99th percentile) threshold for one or more criteria). We conducted these assessments at three separate reporting scales: across the entire study region, each drainage division and each NASY reporting region.

Based on our approach to implementing the Framework and the outcomes of our analyses, we offer the following conclusions as to its utility for accurately and efficiently identifying areas of high conservation value.

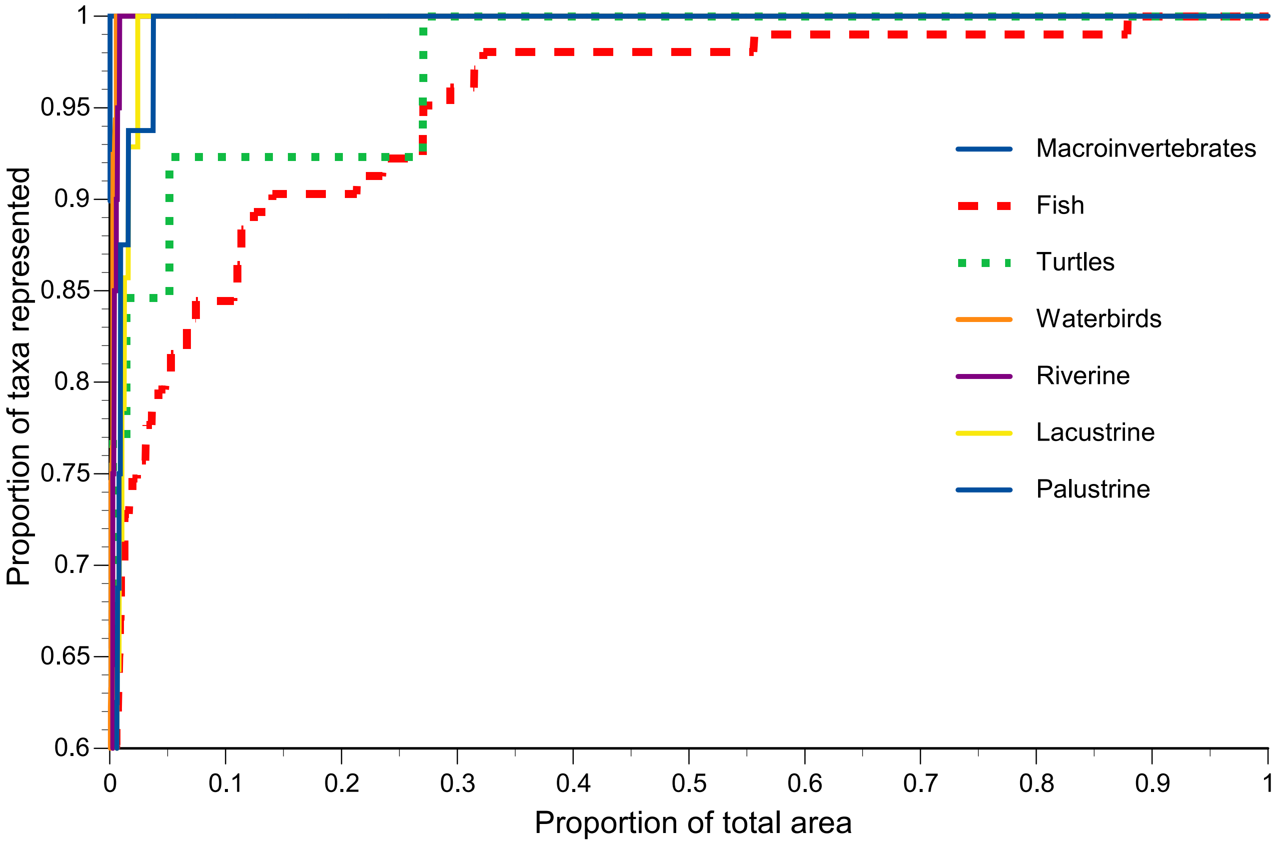

Figure 9.12. The proportion of the total study region (by area) required to represent at least one occurrence of each taxa within each planning unit when the planning units were ranked by their integrated criteria score.

The very nature of the Framework (i.e. a multi-criteria scoring approach) means that the method combines potentially numerous individual attributes that by themselves can be (and often are) used to assess conservation value. The integration process ultimately means a potentially major loss of transparency, in that it is unclear how many attributes (and which ones) contribute greatly to the integrated score for each criterion. It is also unclear which components of biodiversity (the fundamental currency of conservation assessments) contribute most to the final rankings based on criterion scores. Although it is certainly possible to interrogate the underlying data and maps to understand why a particular area scored highly for a particular criterion or set of criteria, this is not a simple process. One solution to this issue is to greatly reduce the number of attributes used to characterise the Framework criteria to only a few key ones that are deemed by experts to be most important indicators of conservation value (though this is obviously not a simple task). We conclude that the use of more attributes does not necessarily provide a better or more interpretable conservation assessment. In fact, the converse appears to be true.

As an example of the potential consequences of the integration process to generate criterion scores, our analyses showed that the final sets of highest conservation value planning units identified using the Framework did not actually represent up to 11 of the 103 fish species and one of 16 palustrine ecotopes (using the strictest threshold). These "taxa" were comparatively rare throughout the study region, but one might have expected certain Framework criteria such as (2) Distinctiveness or (3) Evolutionary history (which quantify aspects of rarity and endemism, respectively) to have identified appropriate areas as being of high conservation value. However, because the individual attributes describing rarity or endemism are integrated across multiple sets of biodiversity surrogates, and then further integrated with other attribute types to arrive at final criterion scores, individual rare species potentially indicative of indicate high conservation value can become swamped and fail to contribute meaningfully to the conservation assessment. A potential outcome of this is that species of high conservation value may be placed at risk because they are not represented in high value areas identified using other criteria.

The Framework, as it stands, considers all criteria as having equal value for identifying HCVAEs and does not consider planning units that meet a greater number of criteria as necessarily having an elevated conservation value. As highlighted in the HCVAE Framework trial for the Lake Eyre Basin (Hale, 2010), this raises the issue of the purpose of the HCVAE identification. The draft HCVAE Framework (Appendix 1.1) indicates that the Framework will be used for a "number of purposes including to assist the Australian Government to focus and prioritise its natural resource management investments". It is possible that these management actions could include restoration, rehabilitation, environmental water allocation, protection, etc but the criteria as they currently stand are not specifically designed to identify which management options are most appropriate for a particular area. To do this would require additional criteria/attributes based on the rehabilitation need and potential (Hale, 2010). We agree with Hale (2010) that the criteria serve to identify assessment units that have the potential to contain HCVAE based on ecological value alone.

We considered various options for how HCVAEs might be identified based on their combined criterion scores and whether some criteria should be treated as more important than others for assigning conservation value and identifying HCVAEs. However, we agree with the approach taken in the Lake Eyre Basin trial (Hale, 2010) that the lack of clearly defined objectives for the identification of HCVAE, means that the criteria should be considered to be equally important.

A fundamental goal of conservation assessments should be to efficiently identify sets of areas that should be managed to conserve the species and processes that sustain them. The HCVAE Framework goes some way towards achieving this conservation goal, but as it currently stands may be limited in the extent to which it can achieve it efficiently. Chapter 10 presents an alternative approach to identifying high conservation value aquatic ecosystems using a complementarity-based algorithm (Marxan, Ball et al., 2009). By doing this we evaluate whether more efficient ranking of HCVAEs based on the goal of representing the full range of species or type of natural environments can be obtained in comparison to the outcomes of the conservation assessment generated using the Framework criteria.

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10. A COMPLEMENTARY APPROACH TO IDENTIFYING HCVAEs – SYSTEMATIC CONSERVATION PLANNING

VIRGILIO HERMOSO, MARK KENNARD & SIMON LINKE

KEY POINTS

1. **Aim:** To identify high conservation value areas using a systematic approach addressing complementarity in the context of different kinds of spatial connectivity and to compare it with the Framework approach.
2. **Methods:** High conservation value areas were identified for each conservation feature (water birds, fish, turtles, macroinvertebrates, river types, lacustrine types and palustrine types) using the complementarity based optimization algorithm in the software Marxan. Three different connectivity rules were applied to ensure the selection of priority areas that encompass basin processes (longitudinal connectivity) and lateral movements within and between priority areas (lateral connectivity). The general disturbance status was also included as a penalty to the selection, so high conservation values were mainly assigned to areas in good condition whenever possible. The conservation values were then compared with the ones obtained using the Framework criteria to evaluate the spatial allocation of the highly priority areas and the relative efficiency of each approach. Moreover, the adequacy of the current reserve system in representing freshwater conservation features was also estimated by comparing the spatial distribution of high conservation values when the inclusion of reserved planning units was obligatorily included in the solutions.
3. **Results:** Three main focal areas of high conservation value were identified using the systematic approach: the East Arnhem area and lower Daly River basin in the Northern Territory, the Kimberley region in Western Australia, and northern Cape York Peninsula in Queensland. High conservation values were consistent across conservation features but differed from the ones assigned through the Framework approach, illustrating that different priority areas would be identified using different methods. The systematic approach proved to be more efficient at representing all the conservation features than the Framework approach (e.g., 12% vs 87% or 5% vs 24% of the total area was needed to represent at least once each fish and turtle species for the systematic and scoring approach respectively). The set of currently reserved planning units (5% of total area) failed to satisfy the criterion of representativeness (i.e. did not represent all the conservation features) and did not include most of the high conservation value areas identified using the systematic approach.
4. **Implications:** The systematic approach performed differently to the Framework approach and appeared to be more effective at identifying a minimal area (i.e. number of planning units) required to conserve a maximum amount of identified HCVAEs. The systematic approach provides an efficient method for identifying high conservation value areas within the constraints of limited conservation budgets and can incoporate spatial connectivity requirements to promote long-term persistence of biodiversity (these issues are usually ignored in scoring methods for spatial conservation prioritisation).
5. **Limitations / Knowledge gaps / next steps:** The incorporation of uncertainties in the distribution of conservation features or the vulnerability to future change of candidate areas (e.g., land uses or climate change) in the selection process would increase the resilience of protected areas and the probability of long-term persistence of the conservation values that they contain. Better informed selection of conservation targets and the use of better surrogates for the economic cost of conservation are some of the key points that would help improve the resilience of high conservation value areas to future changes and make better informed decisions.

10.1 INTRODUCTION

Conservation of biodiversity values usually competes with other human interests and activities (Margules et al., 2002), hence protection of all the areas that contribute to the persistence of those values is unfeasible from a socio-economic perspective. Given these constraints, the prioritization of areas in terms of their importance or contribution to the conservation of biodiversity is a reasonable solution to find where to expend the limited resources intended for conservation purposes (Knight et al., 2007). Conservation planning aims to find the areas that best represent the biodiversity under consideration and the processes that will allow its long term persistence (Margules & Pressey, 2000). The inclusion of socio-economic costs helps to achieve the conservation goals more efficiently (Ando et al., 1998; Carwardine et al., 2008) while minimising impacts on stakeholders.

Different methods have been used to identify key conservation areas, such as scenic value, remoteness, low agricultural production potential or simply availability (Margules, et al., 1988; Pressey, et al., 1996; Sarkar, 1999). These methods are based either on subjective judgments of biodiversity value, or on other criteria extraneous to biodiversity conservation. These ad hoc conservation strategies tend to focus conservation efforts on areas that are easy to protect, sometimes with least need for urgent or immediate protection (Pressey, 1994; Knight, 1999; Pressey et al., 2000). Other methods identify high conservation value areas by ranking them according to the biodiversity features that they contain using different criteria such as richness or rarity (Williams et al., 1996; Myers et al., 2000). This is an advance with respect to the former methods, since they use the conservation features intended to be protected in the identification of high conservation value areas. However, they do not ensure the fulfillment of the principle of *representativeness*. The selection of priority areas using scoring criteria such as richness does not guarantee the adequate representation of all the conservation features (Williams et al., 1996). For example, some biodiversity might not occur in richness hotspots and would not be adequately covered. Moreover, these former methods also lack a consistent way of incorporating management costs in the selection process.

To address the lack of representativeness and the management costs associated to the implementation of conservation practices, an alternative methodology has been used in the last two decades. Systematic conservation planning (Margules & Pressey, 2000) aims to identify an optimum set of areas that cost-efficiently represent the desired conservation features, using complementarity-based approaches and incorporating cost in the selection process. Complementarity is defined as the gain in representativeness of biodiversity when a site is added to an existing set of areas (Possingham et al., 2000). Methods that incorporate complementarity have been shown to lead to more effective representations of biodiversity features and more cost-efficient solutions than ad-hoc (Pressey & Tully, 1994), scoring or ranking strategies (Margules et al., 2002; Pressey & Nicholls, 1989). Systematic conservation planning methods have been extensively applied to conservation problems in marine and terrestrial environments (e.g. Carwardine et al., 2008; Klein et al., 2008). However, most conservation planning approaches have so far overlooked freshwater biodiversity, because incorporating freshwater species and habitats adds several layers of complexity to an already complicated task (Abell, 2002). Nevertheless, systematic conservation planning studies specifically targeting freshwater ecosystems have started to emerge (Nel et al., 2007; Linke et al., 2007, 2010; Moilanen et al., 2008; Hermoso et al., 2010).

Suggested advantages of systematic planning approach over scoring systems such as the HCVAE Framework are:

1. *Explicit and quantitative targets or objectives.* These can be set and achieved in line with quantitative policy guidelines (e.g. Australia is committed to the protection of representative ecosystems and to the protection of rare and endangered species). For example, a set of targets might be to conserve 15% of each ecosystem type, or 50% of the range of all rare species. The equivalent index-based approaches can only set targets such as: to conserve the largest, most biodiverse, and/or rarest areas, which informs little about the overall amounts of each asset that will end up in our final set of conservation priority areas. Other objectives in systematic methods can be framed to

promote the persistence of biodiversity processes (Pressey et al., 2007) or to represent ecosystems with stewardship covenants whilst minimizing the opportunity costs of reduced grazing to the landholder. Without explicit objectives and targets, index-based approaches struggle to deal with these kinds of trade-offs.

2. *Complementarity and efficiency.* Because the whole of a conservation area system is worth more than the sum of the parts, the systematic approach aims to select areas that complement each other and the existing network in terms of the conservation assets. Scoring approaches, in contrast, assess each area individually. Highest ranking areas can contain the same conservation features which are duplicated, while other features may remain completely unrepresented, especially if they occur only in low-ranking areas. This was the single most important motivation for developing systematic methods (Margules & Pressey, 2000) that identify sets of complementary areas. Complementarity promotes efficiency. Accounting for spatially variable information on the cost of specific actions has been shown to substantially improve efficiency, compared with the approach of designating 'priority areas' and considering actions and their costs *post hoc* (Carwardine et al., 2007). Scoring approaches (and some systematic assessments), tend to ignore cost *a priori*. Systematic conservation planning approaches have the advantage of being able to synthesize multiple alternative costs and actions, without using scoring techniques.

3. *Irreplaceability and flexibility.* Systematic conservation planning tools generate multiple alternative sets of areas that meet conservation objectives, providing flexible options and measures of irreplaceability (selection frequency, or a modelled approximation of the likelihood that an area is needed to meet the conservation objectives). Irreplaceability can be used as a quantitative measure of priority: areas with higher irreplaceability are likely to require more urgent action because, if they are lost, targets for one or more biological assets are unable to be met. Higher scores in index-based systems do not necessarily equate to a required urgency of action to protect assets.

4. *Adequacy and persistence.* Adequacy refers broadly to the persistence of biodiversity processes, including population dynamics, movement and migration, patch dynamics, catchment processes and river flows, and many others. Adequacy is difficult to quantify and implement, but systematic methods are being developed that achieve explicit objectives related to adequacy (Pressey et al., 2007). Some of these are being adapted specifically for freshwater systems to consider longitudinal and lateral connectivity (below).

10.2 Methods

10.2.1 Identification of priority areas using a systematic conservation planning approach

Setting conservation targets

The spatial allocation and extent of priority areas depends on the total amount of each conservation feature that should be represented in the solution. For example, a higher number of planning units would be needed to represent a species in 100 ha than in just 1 ha. This will be referred hereafter as the target level. The decision on establishing target levels should be ideally led by ecological information, such as the minimum area or river length that each species need to complete their life cycle, or essential ecological processes that need to be maintained (e.g. migrations or connectivity between populations). However, this information is often lacking in conservation planning and target levels are set subjectively in a way that they are thought to ensure the long term persistence of conservation features.

To overcome this problem we used five different target levels for each conservation feature ($10km^2$, $100km^2$, $1000km^2$, $10,000km^2$ and $100,000km^2$) and then averaged the solutions across all. We avoided using a single percentage targets for all the conservation features as commonly used (e.g. 10 or 30% of current distribution as used in other studies) since this approach is prone to under-representing rare features while over-representing common ones.

Identification of priority areas

We used the simulated annealing selection algorithm provided in Marxan (Ball et al., 2009) to identify priority areas for each conservation feature. Marxan aims to find an optimal subset of planning units by minimizing an objective function where feature penalties for not representing adequately all the conservation features, spatial design (concerning clustering of areas through connectivity or boundary length penalties) and cost tradeoffs are considered (Equation 1). Therefore, the mathematical objective in Marxan is to minimise the cost of all the sites included in the set or priority areas while placing penalties on each solution that does not reach the conservation target for all the conservation features and that lack connections weighted by CP, the “connectivity parameter” (see below). The feature penalty (SPF) is a penalty for not fully representing all the features in the final solution at the targeted level. Marxan considers features as objectives rather than constraints so the final solution might fail to achieve the target level for a feature if it was “too expensive”. However, since correct representation was a priority in our study, we set the weight of the feature penalties for unmet targets high (SPF=100), to ensure that the targets for all the conservation features were met.

$$Objective\ function = \sum_{planning\ units} Cost + SPF \sum_{features} Feature\ Penalty + CP \sum ConnectivityCost$$

Equation 1

After an initial random allocation of planning units in the solution, Marxan iteratively adds or drops planning units from the solution in an attempt to minimise the objective function. The simulated annealing algorithm used in the optimization process works until the specified number of iterations has been reached. The combination of planning units that produce the lowest value for the objective function will be referred hereafter as the best solution. This solution represents the cheapest combination of planning units that minimises the connectivity and conservation features penalties applied (e.g. the solution with the highest connectivity and closer to fulfil the target level).

Single best solutions are very rigid; they do not show the conservation practitioner the potential benefit that different areas can bring to the achievement of the conservation goals. A common practice to allow more flexible solutions and foster easier decision making is to show the frequency of selection or irreplaceability of each planning unit. The frequency of selection measures the likelihood that a planning unit will be required to meet a given set of targets (Pressey, 1994; Ferrier et al., 2000). It is estimated as the frequency of occurrence of each planning unit in the best solution after *n* number of independent runs. In this way, high frequency of selection highlights those planning units that have been included in all, or most of the *n* best solutions, and indicates that they are highly necessary to fulfil the conservation targets. Low frequency of selection shows planning units that contain conservation features that can be represented more efficiently using other combinations of planning units in the study area.

Dealing with spatial connectivity

Why is connectivity important in conservation planning?

Although dealing with connectivity issues when planning for conservation affects the spatial configuration and extent of priority areas (see Carwardine et al., 2007; Klein et al., 2008), there is a general agreement about the benefits of this approach (Cabeza et al., 2004). Basically, clustered priority areas are less prone to the effects of "outside" perturbations and favour the persistence of the conservation features that they contain. Moreover, a few aggregated priority areas are easier to manage than when many are widespread across the landscape.

As stated above, spatial connectivity is considered in the optimization algorithm by the inclusion of a connectivity penalty in the objective function. We wanted to consider the particular spatial connectedness of freshwater ecosystems, which has been highlighted as a significant component in structuring healthy systems (Abell 2002). Here we have addressed two different kinds of connectivity: i) longitudinal connectivity along river systems within each hydrologic catchment and ii) lateral connectivity within wetlands and between contiguous catchments.

i) Longitudinal connectivity

In terrestrial applications with Marxan, spatial connectivity is addressed by a boundary length penalty that forces priority areas to be compact. This basically works by applying penalties to the objective function when the planning units included in the solution are not in contact. Hermoso et al. (2010) recently modified the boundary length function in Marxan to account for the special longitudinal connectivity in rivers in order to make it more appropriate for freshwater conservation planning issues. They introduced 'virtual boundaries' between non-headwater planning units by adding penalties to the overall connectivity cost when planning units upstream of the selected ones are not included in the solution. The penalty for each upstream planning unit not included decreases by a factor proportional to the reciprocal of the distance to the selected ones. For instance, a planning unit that is 1 km away from the selected one incurs a penalty of 1 if not included, while a planning unit 2 km away incurs a penalty of 0.5 (= 1/2). Hence, the penalty decays over the distance to the planning unit containing the targets. The emphasis placed on upstream connectivity can be adjusted using the connectivity penalty (CP). A CP of 0 means that a planning unit can be selected without incurring any penalties for not including upstream ones (Fig. 10.1). Using this approach Hermoso et al. (2010) softened the strict rules that were being applied in previous freshwater conservation planning exercises (e.g. Linke et al 2007) that requires all the upstream river stretches to be protected. This rule led to unrealistic solutions where whole catchments needed to be protected to ensure that no upstream perturbation would affect the biodiversity within the priority area. Through this new rule Hermoso et al. (2010) did not force the selection of whole upstream areas, but an optimum number of connected upstream planning units away from potential perturbations. The exponential decrease with distance simulates the natural decay in the influence of river segments with distance (Wiens, 2002). This penalty was only applied within hydrologic catchments and was used for all the independent conservation features' plans in the current study.

ii) Lateral connectivity

An additional important part of connectivity in freshwater systems is the lateral component that allows movements between hydrologic catchments or within wetlands (Fig. 10.1). This component of connectivity is essential for some of the conservation features included in this study, such as birds that can move between feeding and nesting areas.

We addressed lateral connectivity issues at two different spatial scales. The first component for lateral connectivity was focused at the within palustrine and lacustrine features. Lakes and wetlands should be managed as single units, given the high connectivity that characterise s them, even though they might be split into different planning units (especially large ones). At this scale we included spatial penalties for solutions that did not include whole palustrine or lacustrine features. In this way we forced the selection of whole lakes or wetlands whenever they were necessary for achieving the conservation targets. Whenever a palustrine or lacustrine feature fell in more than one planning unit, a high penalty was applied to all those planning units that contain the feature (Fig. 10.1).

At a different scale, we also addressed connectivity between neighboring lakes and wetlands, to facilitate lateral movements between different water bodies. These might be located within the same hydrologic catchment or not (Fig. 10.1). In this case we applied a penalty weighted by the distance between them, similar to that we used for the longitudinal connectivity (the closer the neighbor lake or wetland is the higher the penalty applied when not selected together in the solution).

When applied together, these three connectivity penalties allow the selection of whole lakes or wetlands, their neighbors and the immediate upstream/downstream tributaries. However, not all of the considered conservation features require this strict connectivity rule (e.g. fish movements are limited to hydrological basins). So the connectivity penalty was specifically designed for each conservation feature (Table 1).

Table 10.1 Type of connectivity considered for each conservation feature.

Conservation feature	Type connectivity
Birds	• Lateral • Longitudinal
Fish	• Longitudinal
Turtles	• Lateral • Longitudinal
Macroinvertebrates	• Longitudinal
Lacustrine	• Lateral • Longitudinal
Palustrine	• Lateral • Longitudinal
Riverine	• Longitudinal

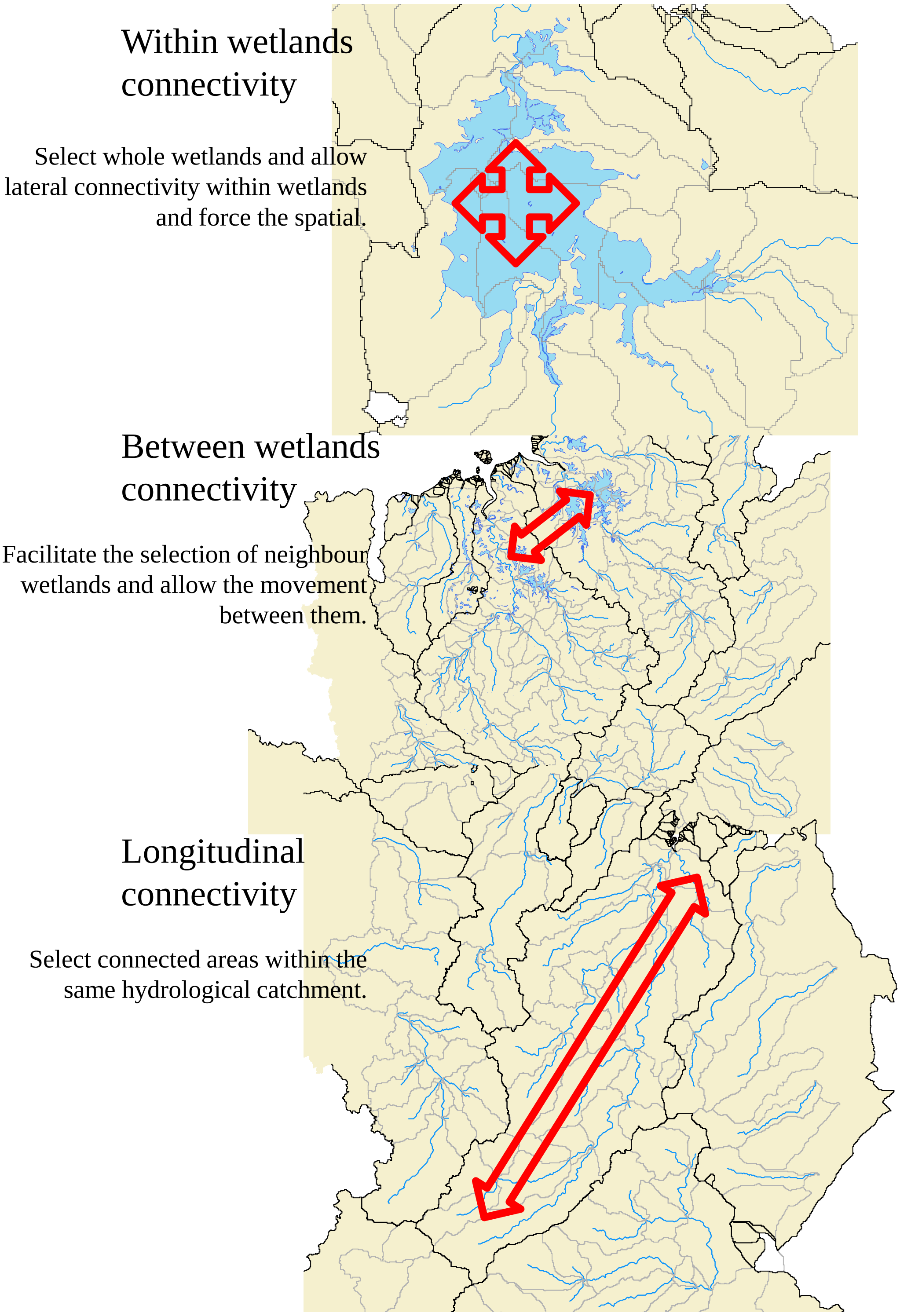

Figure 10.1. Components of connectivity addressed in this study. Boundaries between different hydrological catchments and planning units are shown in black and grey respectively.

Surrogates of conservation cost

In this study we penalized the selection of planning units based on the average value of the Catchment Disturbance Index and the Flow Regime Disturbance Index (Stein et al., 2002) described in table 3.2. Using the disturbance status of each planning unit to guide the identification of priority areas in conservation planning has to main advantages. Firstly, the avoidance of highly perturbed planning units will help to identify areas where the conservation features have a higher likelihood of persistence if current condition remain or do not strikingly change. Secondly, less disturbed planning units entail lower management costs (protecting a perturbed area needs expensive rehabilitation and control management programs if the persistence of current conservation features wants to be ensured), so we also favoured the selection of the 'cheapest' planning units. Similar approaches have already been used in systematic conservation planning to penalize the selection of perturbed areas [e.g. distance to roads in Williams et al. (2003) or population density in Rouget et al. (2006)].

10.2.2 Are current reserves the most efficient way of representing freshwater biodiversity and do they represent all the freshwater biodiversity?

To evaluate the efficiency of the current reserve system representing freshwater biodiversity, under the same target levels and connectivity constraints, we evaluated the effect of including current reserves in the identification of priority areas process. In this case we used Marxan on a new scenario where we blocked all the currently reserved planning units. To identify the planning units that are reserved, we intersected them with the layer of IUCN protected areas (CAPAD, 2006) (see Fig. 9.1a). Reserved planning units are those planning units with more than 75% of its area included in some of the current reserved areas (Fig. 10.2). Protected areas were dominated by National Parks, Natural Reserves and Managed Resource Protected Areas. In this scenario, all the reserved planning units were forced to be selected independently of the conservation features that they might contain, the benefits in term of complementarity that they could offer, or the cost that their inclusion could entail. Marxan was forced to find the best way to incorporate them in the selection process, trying to find the most complementary areas to these reserves to achieve the conservation targets. We ran five different scenarios for the same target levels used in the analyses before and then averaged across them. Then we assessed the difference in the conservation value of each planning unit under the two alternative scenarios (with and without current reserves) by comparing the average selection frequency across the five target levels. We expected to find no differences in the selection frequency of currently reserved planning units between both scenarios if currently reserved planning units were the most efficient way of achieving the conservation goals (i.e. represent all the conservation features at the minimum cost and connectivity penalty).

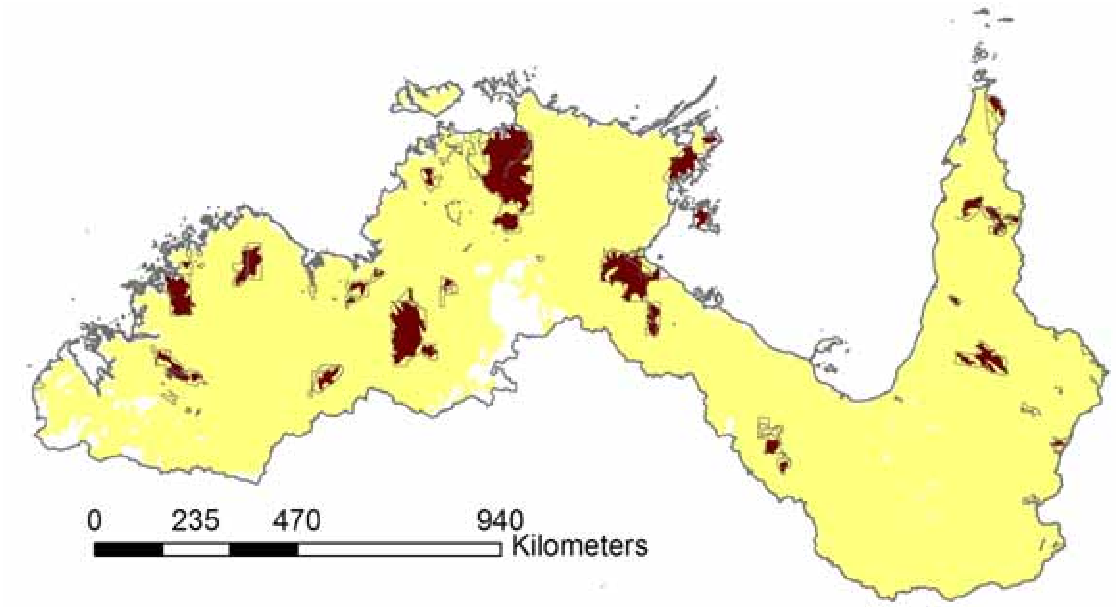

Figure 10.2. Spatial distribution of the reserved planning units as considered in this study (>75% within a current reserve, highlighted in red). A total of 312 planning units were considered reserved.

10.2.3 Comparison of the HCVAE Framework scoring criteria and systematic planning.

An efficient approach to identifying high conservation value areas should be able to represent all the conservation features at the target level required in the minimum set of planning units. In other words, an efficient method would need a reduced number on planning units to achieve the conservation targets. To evaluate the ability of the scoring and the systematic approaches to adequately represent freshwater conservation features we calculated the accumulation curve of conservation features' occurrences across the planning units ranked according to their conservation value (either scoring value or frequency of selection). This curve represents the proportion of each conservation feature that is represented for a given area (Pressey & Nicholls, 1989). The higher the proportion of the area needed to represent each conservation feature (taxa or ecotope) at least once, the lower the efficiency.

In addition, to check if both approaches assigned the highest conservation values to similar sets of planning units we carried out a Principal Component Analysis (PCA) on the scores obtained through each criteria (n=6) and frequency of selection for each conservation feature (n=7). The analysis was therefore based on a matrix with 13 variables and 5612 rows (one for each planning unit). PCA is commonly used to reduce the dimensionality of a data set consisting of a large number of interrelated variables and to identify new underlying axes that retain and integrate as much as possible of the variation present in the original data set. This is achieved by summarizing the original set of variables into a new set of synthetic variables, or Principal Components (PCs), which are uncorrelated (Jollife, 1986). If all the criterion scores and frequency of selection for each conservation feature were correlated we would expect PCA to produce a single PC that explains most of the variability in the distribution of the conservation values across both methods. However, if both approaches were not concordant, at least two PCs would be needed to ordinate the conservation values. PCA will also allow us determine the internal coherence of criteria and frequency of selection for each conservation feature (e.g. whether different criteria show the same information).

10.3 Results

10.3.1 Spatial connectivity

The spatial connectivity rules applied in this study (longitudinal and lateral) enhanced the internal connection of the high conservation value areas identified using the systematic approach (Fig. 10.3).

The longitudinal connectivity rule helped to identify hydrologically connected planning units within catchments. Incorporation of longitudinal connectivity is an effective way to address the protection of conservation features from impacts received from upstream or downstream areas (Hermoso et al., 2010). The full protection against these impacts was efficiently achieved through the use of a gradual decay in the longitudinal penalty.

The use of lateral connectivity also favoured the selection of whole lakes and wetlands (within lake and wetland connectivity) in clustered groups (between lakes and wetlands connectivity) (Fig. 10.3). In addition, the combination of both components of connectivity resulted in the selection of the immediate upstream contributing catchments to those lake or wetlands (Fig. 10.3). In this way we also accounted for potential upstream perturbations that could affect those groups of high conservation value areas as explained above.

10.3.2 Frequency of selection

Using the averaged frequency of selection across different target levels we reduced uncertainties derived from the subjective selection of conservation targets. Increasing targets forced the selection of broader areas, as expected (Fig. 10.4). A reduced number of planning units were necessary to represent all the conservation features even when a moderate connectivity penalty was used. However, when the target level was high (over 10,000 km^2) vast areas received high conservation values. The main purpose of this approach is to show how different areas might be necessary depending on the conservation targets required.

Due to differences in the total range of the spatial distribution of each conservation feature, the frequency of selection was more widely distributed for birds, macroinvertebrates or river classes than for the remaining. These conservation features were predicted to occur in broader areas in general (e.g. the average distribution of waterbird species was four times greater than for fish species), so the selection process for these taxa was more flexible and many different combinations of planning units achieved the same conservation targets. For conservation features with narrower distribution areas (e.g. fish or turtles) some planning units were necessarily included all the time. These areas contained species with a restricted distribution range according to the predictive models and were selected most of the time to achieve the conservation targets.

We found areas with similar average frequency of selection across all the conservation features (Fig. 10.5, Fig. 10.6). These were basically centred in three different areas: the northern area of Northern Territory (NT), especially in the Arnhem Land area, the lower Daly River basin and the Moyle River, the Kimberley (Berkeley River) in Western Australia, and the northern portion of western Cape York Peninsula in Queensland. Accordingly, these areas are highly irreplaceable, and are needed to achieve the adequate representation of all the conservation features in an efficient way.

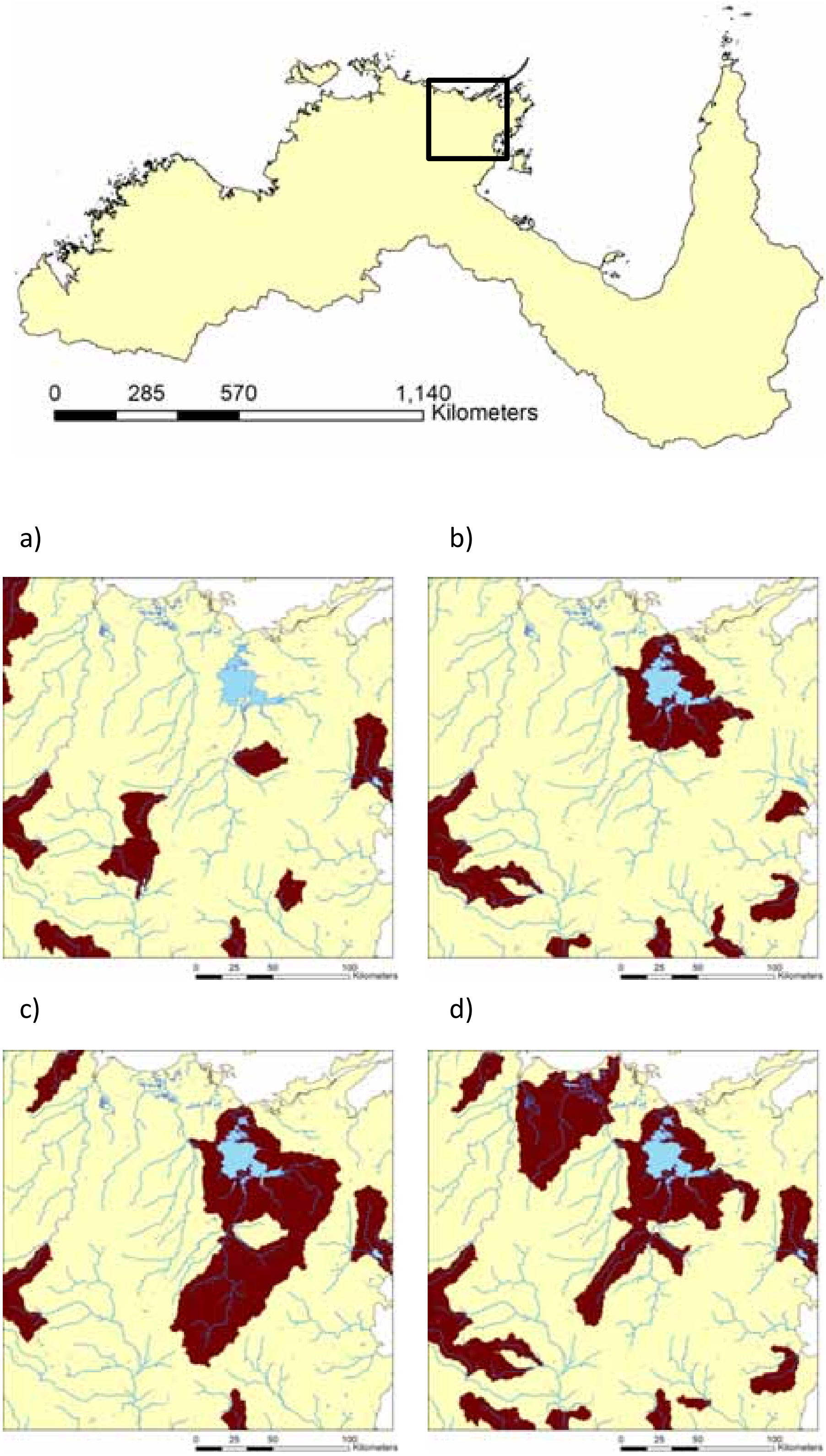

Figure 10.3. Example of spatial connectivity achieved by using increasing connectivity penalties (from a to d, a connectivity penalty of 0.01, 0.1 and 1 and 2 was used respectively) to enhance longitudinal and lateral connectivity. When increasing the penalty whole lake or wetlands, their neighbours and respective upstream contributing catchments were selected (d).

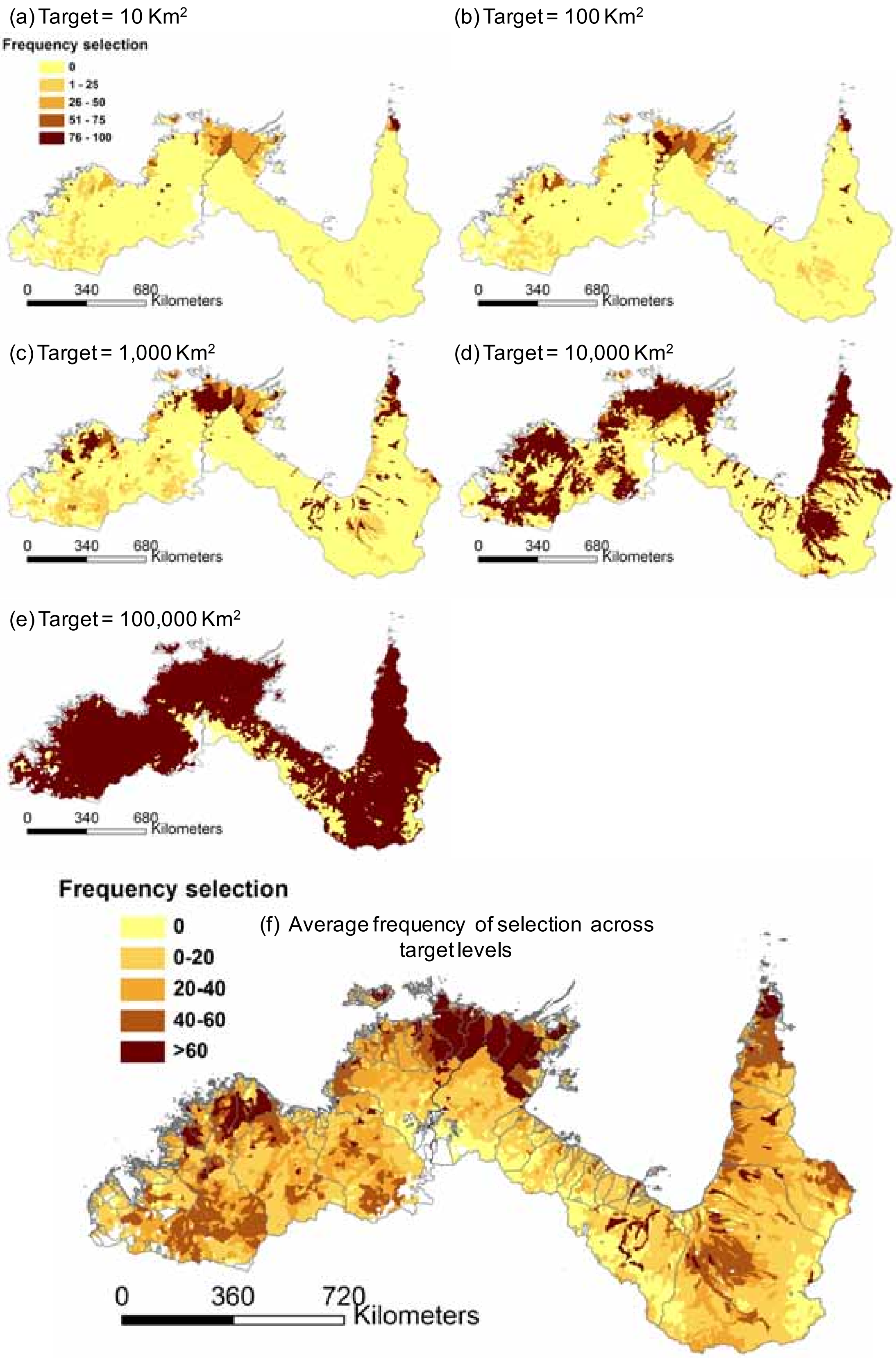

Figure 10.4. Frequency of selection for the five different target levels used in this study and averaged value for fish. The selection frequency at each target represents the number of times that each planning unit was included in the best solution after 100 runs. High values indicate highly irreplaceable areas, which were necessary most of the time to achieve the conservation goals.

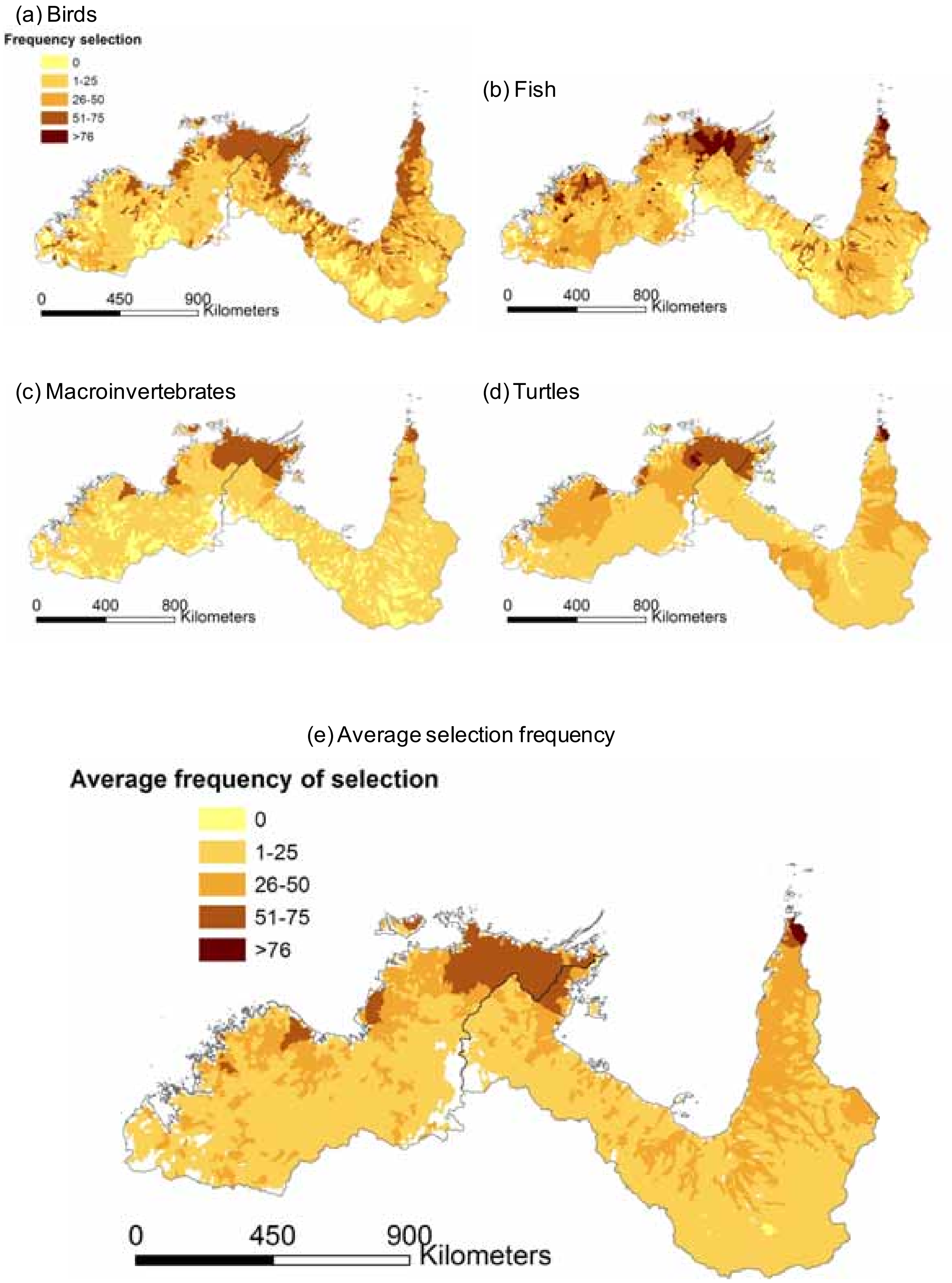

Figure 10.5. Average frequency of selection after 100 runs across five target levels for the biological conservation features used in this study (a-d). The average value for all the conservation features is also shown in (e).

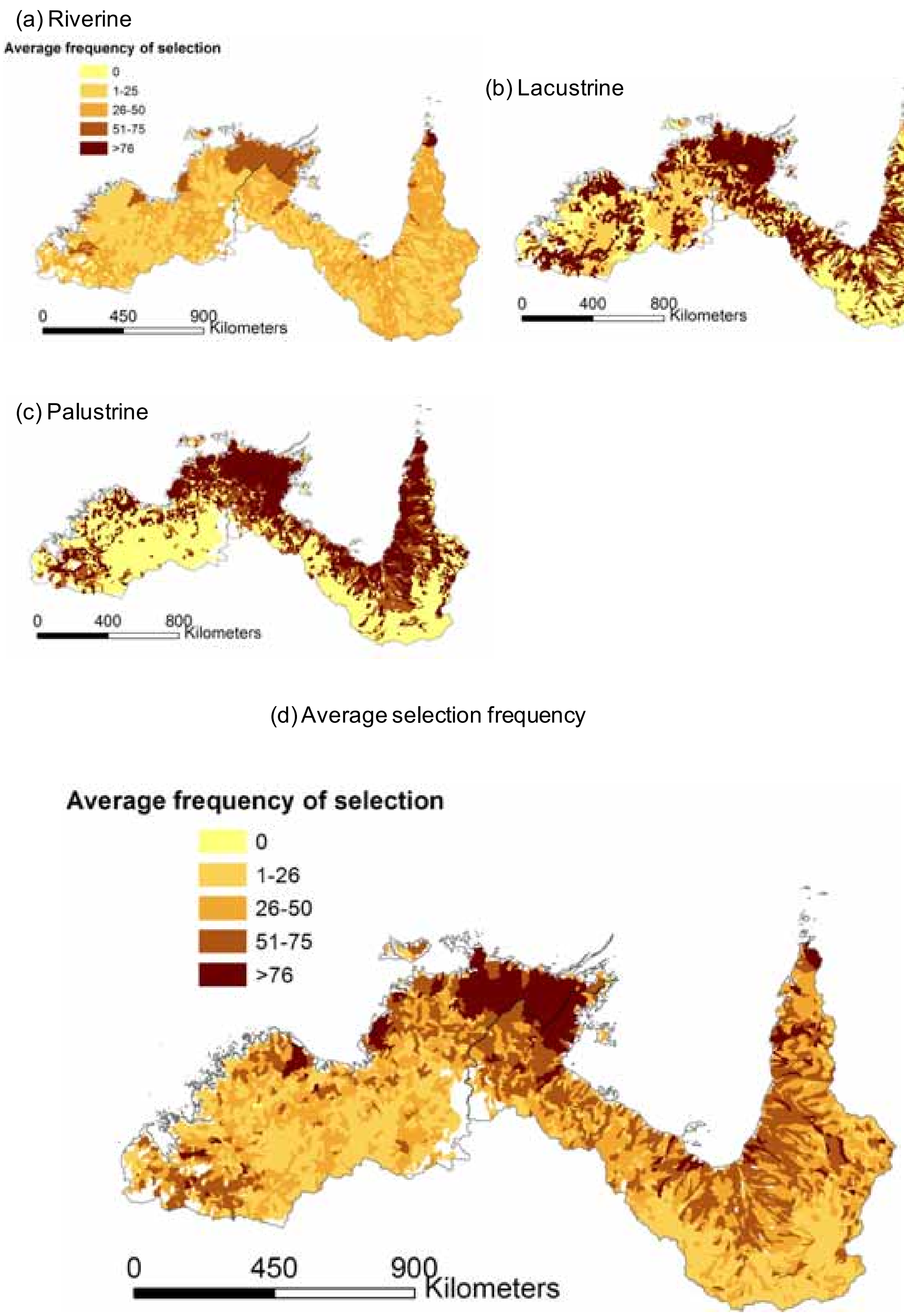

Figure 10.6. Average frequency of selection after 100 runs across five target levels for the environmental classes used in this study (a-c). The average value for all the conservation features is also shown in (d).

10.3.3 Are current reserves the most efficient way of representing freshwater biodiversity and do they represent all the freshwater biodiversity?

The current reserve system did not overlap with the areas previously identified of high conservation value according to their frequency of selection in the systematic conservation planning approach. As an example, some of the basins in the Arnhem Land area (e.g. Liverpool River, Blyth River or Goyder River) with a high frequency of selection are not included in the current reserve system. This could simply mean that the current reserve system is not the most efficient way of representing the conservation features addressed in this study (they could contain all the freshwater biodiversity, although not in the most efficient way). However, current reserved planning units included only part of the freshwater biodiversity (Table 9.1). They included at least one occurrence for all the waterbirds, macroinvertebrates and wetland types, but they failed to represent all fish, turtles, river and lake types at least once (some of these conservation features never appeared within the current reserve system).

The frequency of selection of planning units under the two alternative scenarios (with and without reserves) was clearly different (Fig. 10.7, Fig. 10.8). Reserves were only highly selected when we forced their inclusion for most of the conservation features. This supports the assertion made above and highlights the inefficiency of the current reserve system to represent freshwater diversity. Only some areas in Kakadu National Park in the Northern Territory received an intermediate frequency of selection although it was never included in the top conservation value areas when reserves were ignored.

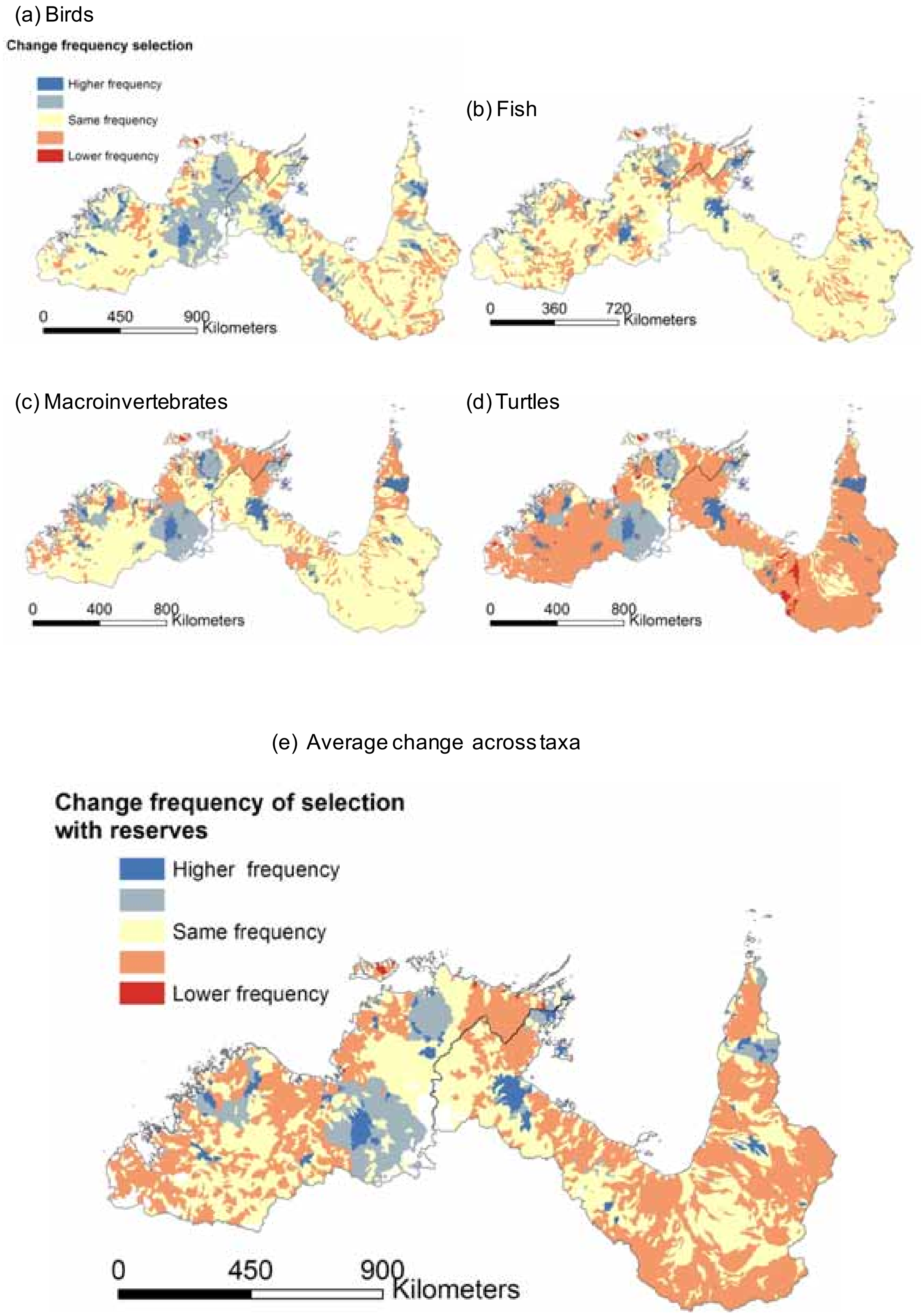

Figure 10.7. Change in the average frequency of selection of each planning unit when forcing the inclusion of current reserves in the selection process for each biological conservation feature (a-d) and the average across them (e). For each conservation feature the average frequency of selection across five target levels was used.

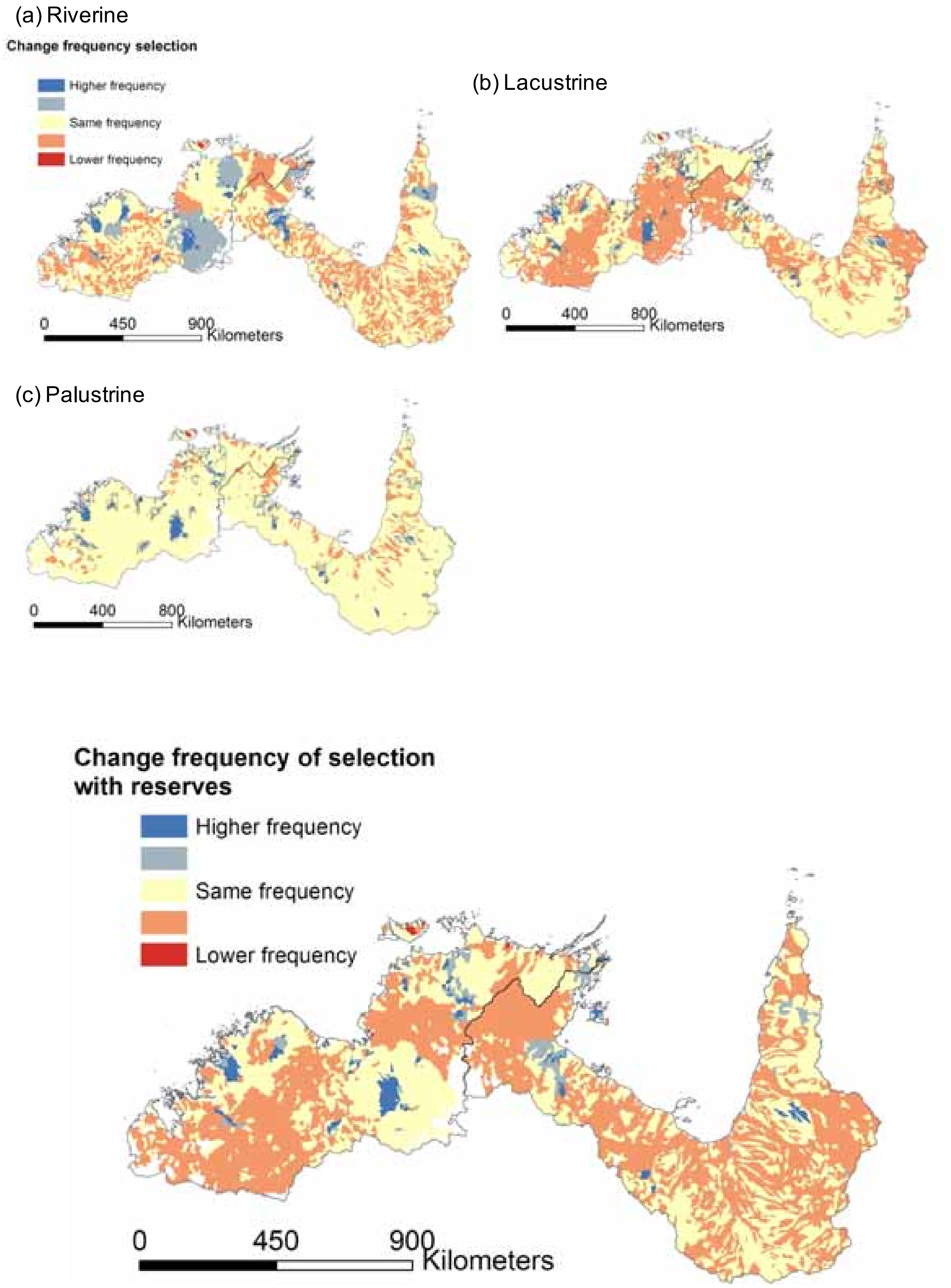

Figure 10.8. Change in the average frequency of selection of each planning unit when forcing the inclusion of current reserves in the selection process for each environmental class (a-c) and the average across them (d). For each conservation feature the average frequency of selection across five target levels was used.

10.3.4 COMPARISON OF SCORING CRITERIA AND SYSTEMATIC PLANNING.

Systematic conservation planning was more efficient than the Framework scoring approach representing conservation features (Fig. 10.9). For example, using the systematic approach it was necessary to include 11% of all the planning units or 12% of total area to represent at least once all the fish species, while these values were 85% and 87% respectively when using the scoring approach. Similarly turtle species were represented at least once using less than 5% or the planning units and total area using the systematic approach while the scoring approach needed 28% of planning units or 24% of the total area to do the same.

The differences between both approaches were more reduced for birds, macroinvertebrates or river types (Fig. 10.9). These conservation features are broadly distributed through the study area, so selecting planning units to represent them adequately was not a problem for either approach.

Using a similar area to that currently reserved (5%) we could represent all the conservation features except fish species (99%) and river types (75%) at least once using a systematic approach, compared to 80% and 85%, respectively, using scoring criteria.

The ordination (PCA) of the conservation values obtained using each criteria (n=6) and the selection frequency for each conservation feature (n=7) showed that each approach assigned the highest conservation values to different planning units (Fig. 10.10). The first two PCs explained 59.3% of the total variance (31.9% and 27.4% for the first and second PC, respectively). Both approaches had high and similar loadings in PC1, except scoring Criterion 5. However, they showed opposite loading values on PC2. Systematic solutions were positively related to PC2 while the scoring criteria did it negatively. Moreover, the spatial proximity of scoring or systematic solutions in the ordination indicated that conservation values were consistent within each approach. The within-approach coherence shows that the same set of planning units tended to receive high conservation values when the systematic or the scoring approach was used. The only exception to this general pattern was showed by scoring Criterion 5, which produced high conservation value areas not similar to the remaining scoring criteria or the systematic approach (Fig. 10.10). So the information offered by the two alternative approaches was not concordant between them though consistent within each approach (excluding Criterion 5). A further exploration showed the number of coincident high conservation value planning units between both approaches to be extremely low (10 planning units out of the 300 top ranked ones in both approaches, Fig. 10.10).Given that three different conservation plans would be delivered if using scoring criteria or systematic approaches, care must be paid to the approach used to identify high conservation value areas.

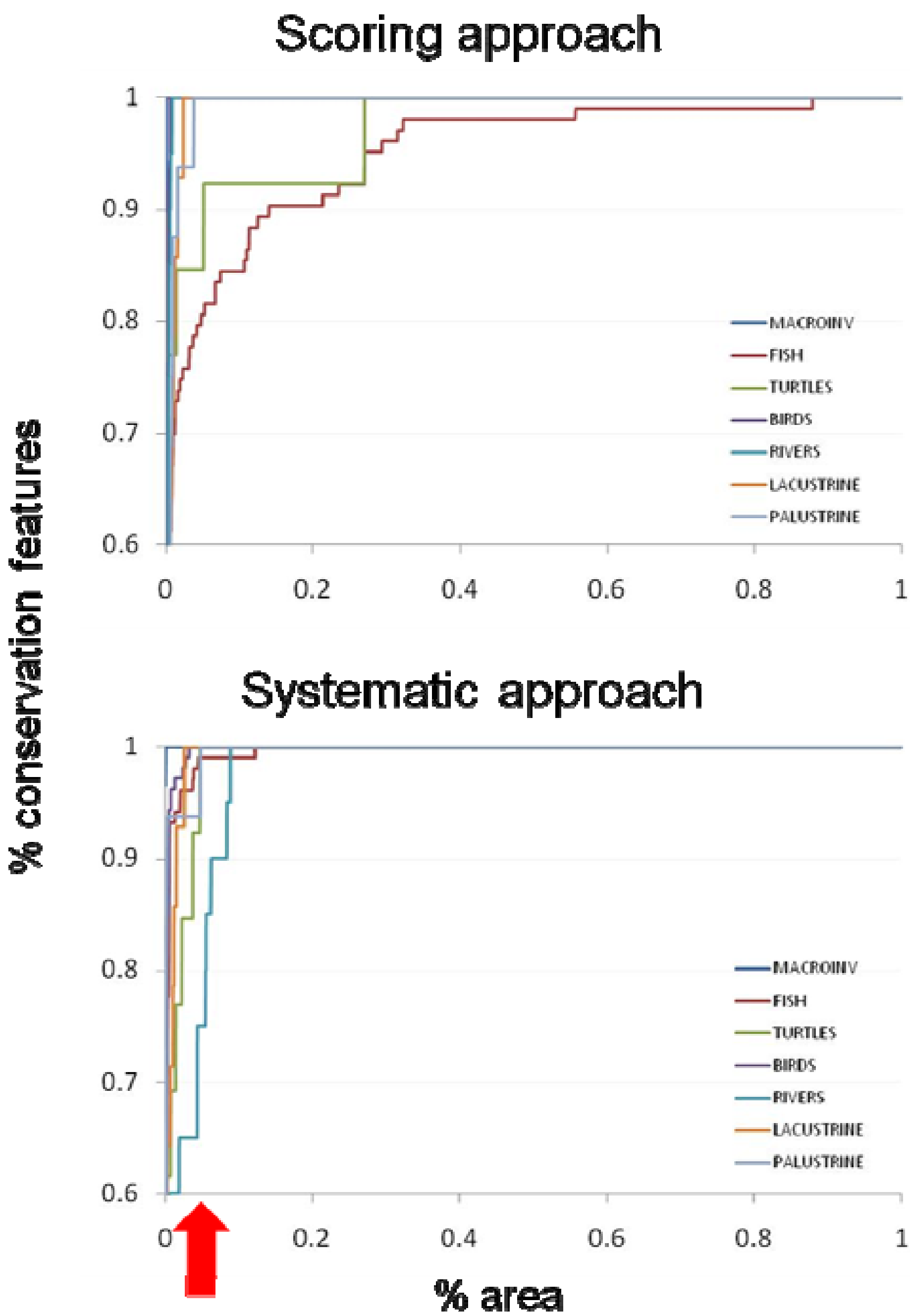

Figure 10.9. Accumulation rate of species representation across planning units ranked according to their conservation value. The current proportion of total area reserved is also indicated with an arrow (5%).

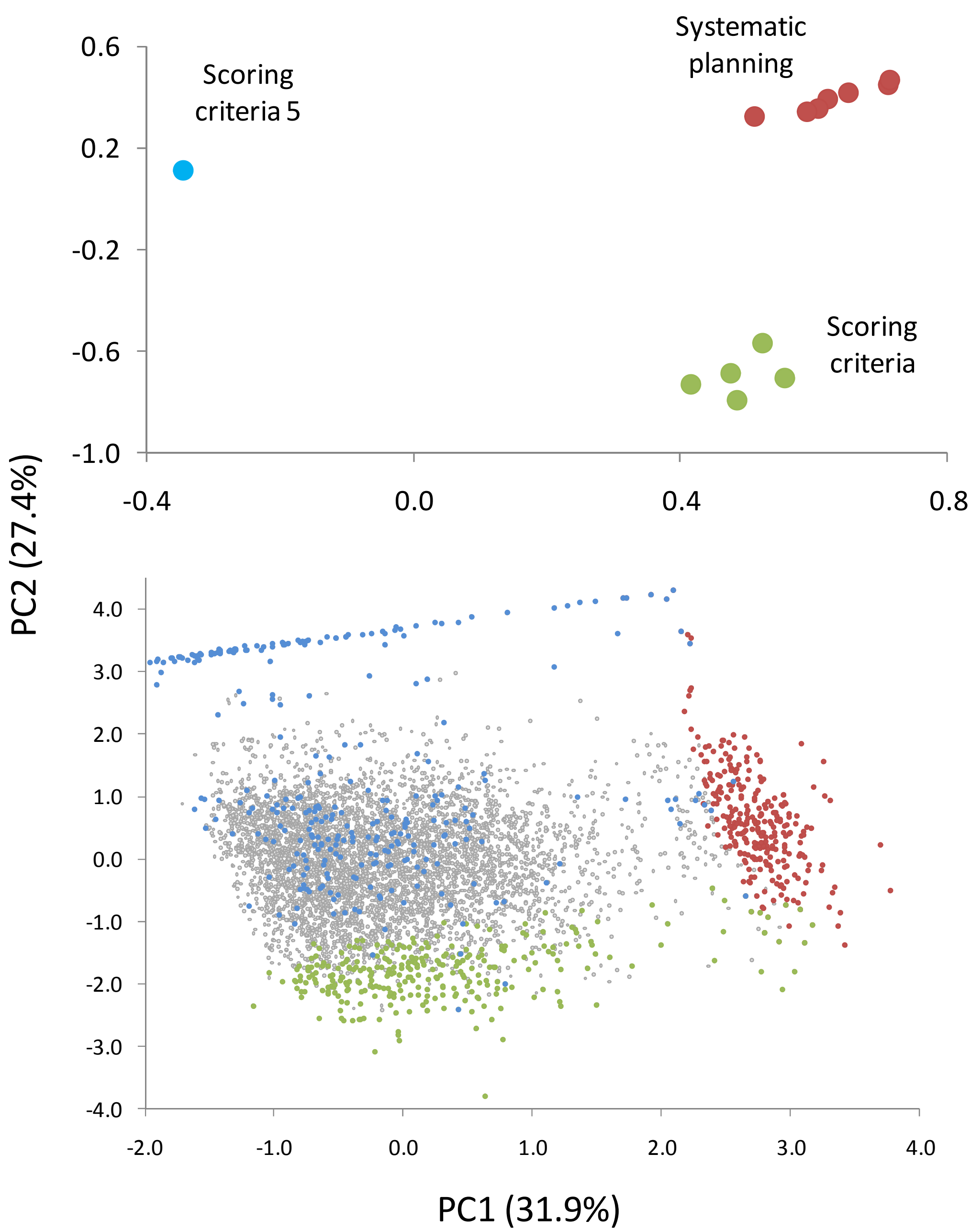

Figure 10.10. Biplot of Factor loadings obtained from a Principal Component Analysis carried out on a conservation values x planning unit matrix (upper plot). Conservation values were obtained using different scoring criteria (n=6 criteria) and frequency of selection for each conservation features (n=7 conservation features). Spatial ordination of the 5,612 planning units according to their conservation value for each criteria and frequency of selection in the systematic approach in the first two PCs (lower plot). The 300 top ranked planning units for each approach are represented in different colours (systematic planning in red, scoring criteria in green and Criterion 5 in blue). Average values across criteria or conservation values were used to rank planning units.

10.4 Discussion and knowledge gaps/next steps

Systematic conservation planning aims to select a set of areas that efficiently ensures the representation and long-term persistence of all conservation features under consideration (Margules & Pressey, 2000). Complementarity based methods, such as the optimization algorithm used in this study, overcome hidden deficiencies in other spatial prioritisation methods based on scoring and ranking approaches (Williams et al., 1996; Margules et al., 2002). We showed how the systematic approach outperformed the scoring criteria at assigning high conservation values in a more efficient way. This is a key issue, given the limited resources devoted to conservation. For the same "budget" (measured as proportion of area in this case) we can achieve better representation of our conservation features using systematic approaches. Moreover, when using systematic planning we also accounted for some important aspects in conservation, such as potential conservation costs or spatial connectivity, which are ignored in scoring methods.

Spatial connectivity is a major consideration in systematic conservation planning in general (Cabeza, 2003) and particularly relevant in freshwater applications. The success of conservation actions in any part of a river catchment will be greatly influenced by longitudinal connectivity within the catchment. Pringle (2001) refers to four main processes related to connectivity which have important implications for the location and management of freshwater priority areas: (i) deterioration of lower watersheds; (ii) deterioration and loss of riverine floodplains; (iii) deterioration of irrigated lands and connecting surface waters; and (iv) isolation of upper watersheds. All these issues can seriously limit the capacity of a set of freshwater priority areas to maintain biodiversity values. The occurrence of perturbations upstream or downstream of the boundaries of a set of freshwater priority areas will have clear consequences on the processes within it and its ability to ensure the long-term persistence of its biodiversity. Flow regime changes and barriers to movement caused by dams, and deterioration of water quality due to wastewater disposals in a basin are just two examples of how freshwater communities apparently protected within exisiting reserves can be seriously threatened by processes operating far away in the river network. Hence, the consideration of connectivity and its importance in maintaining natural ecological processes and biodiversity in fresh waters is a key for systematic conservation planning in these systems (Fausch et al., 2004; Ward et al., 2004; Grantham et al., 2010). Here we have addressed two kinds of connectivity to enhance the protection of high conservation value areas from perturbations and facilitate the maintenance of ecological processes and movements within and between high conservation value areas.

Further studies are needed to evaluate systematically the opportunities that the current reserve system offers and their limitations in efficiently representing the full range of aquatic biodiversity features. Existing protected areas did not fulfil the representativeness principle, so some freshwater conservation features are not protected at all or are not represented at an adequate level. Systematic planning could help to identify a set of areas that complement the current network of protected areas including economic aspects or future vulnerability to make them more resilient.

Finally, the systematic conservation planning solutions presented in this chapter are only meant to be a tool to help in the decision making process in identifying high conservation value areas. The incorporation of expert and stakeholders' knowledge, needs and interests is a fundamental next step at achieving the implementation of an efficient and realistic conservation plan. This information should be seen as an additional tool to guide future decisions on conservation management rather than a rigid and strict conservation plan itself.

There are some aspects of current systematic approaches that could be improved to bring more objectivity to the planning and decision making process, and hence should be further considered in future studies:

1. The incorporation of uncertainties that arise at multiple phases of the conservation planning process. There are a number of uncertainties that could compromise the identification of high conservation value areas, such as those derived from the accuracy of the predictions used to estimate the spatial occurrence of conservation features. The inclusion of these uncertainties in the selection process (e.g. penalizing areas where the occurrence of the conservation features is highly uncertain) will produce more robust solutions.

2. Better informed selection of conservation targets. Systematic planning allows considering explicitly conservation goals by using target levels that guide the identification of high conservation value areas. The establishment of adequate conservation goals led by the needs of each conservation feature would bring objectivity and more certainty to the selection process (we could ensure the complete cover of ecological needs or minimum areas to sustain healthy and viable populations, for instance).
3. Additional information on real conservation costs is also needed. As explained above the use of surrogates of cost, or penalties to the selection, in the absence of real economic cost is a common practice. This approach has been proved to be an efficient way to avoid giving high conservation values to areas that cannot or should not be protected given their degradation status for instance. However, better informed selection processes using more accurate estimates of real economic cost would facilitate the posterior decision making or even the selection of affordable conservation targets.
4. Considerations of vulnerability aspects in the selection process. Future changes might compromise the current value of an area for the conservation of biodiversity. Even though a particular area could currently be in good condition, be cheap and contain certain amounts of conservation features, which makes them suitable for conservation, the likelihood of change could recommend avoiding it and centre the high conservation value areas in less vulnerable zones, where the conservation features have a higher likelihood of occurrence. This applies especially to vulnerability derived from future changes in land uses or climate change.
5. The consideration of conservation features beyond the traditional approach based on species or environmental classes. The incorporation of community level surrogates and measures of functional and phylogenetic diversity as targets for conservation planning would bring new benefits that have not been prospected yet, such as maintaining long-term demographic processes and genetic integrity.
6. The integration of species-specific directional connectivity to enable the maintenance of key processes for freshwater biogeography (e.g. allowing migrations to the ocean for catadromous species or to spawning areas in headwater for anadromous ones).
7. The incorporation of all the conservation features (i.e. all species and environmental types) in a single conservation plan rather than in separate plans for eacxh set of biodiversity surrogates as we did. This will help identify high conservation value areas for freshwater biodiversity in general, avoiding particular differences in solutions for each set of conservation feature and the problem of averaging across solutions.
8. The integration of expert and stakeholders' knowledge and needs in the decision making process. Taking the solutions that we provide here as a baseline for the identification of priority areas for the conservation of freshwater biodiversity will help achieve conservation goals in the most efficient way, while minimizing socioeconomic costs.

10.5 References

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11. KEY FINDINGS, KNOWLEDGE GAPS AND RECOMMENDATIONS FOR FUTURE DEVELOPMENT OF THE HCVAE FRAMEWORK

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11.1 INTRODUCTION

This project has made important advances in identifying high conservation value aquatic ecosystems in northern Australia. The project has also identified a number of key knowledge gaps that, if addressed, could substantially improve the ability to accurately and efficiently identify those aquatic ecosystems of highest conservation value that should be the focus of ongoing management to sustain their values. Key findings and knowledge gaps based on our implementation of the draft HCVAE Framework are listed below, together with recommendations for future improvements to the ANAE scheme and the HCVAE Framework.

11.2 RECOMMENDATIONS

11.2.1 APPLYING THE DRAFT AUSTRALIAN NATIONAL AQUATIC ECOSYSTEM CLASSIFICATION SCHEME

1. The draft ANAE Classification Scheme (Auricht, 2010) describes different aquatic ecosystems and the attributes which could be used to define "habitat" types across Australia within an integrated regional and landscape setting. While the current version of the ANAE scheme provides some implementation guidelines further development is recommended. Ideally, the ANAE scheme should offer further guidance on choice of appropriate attributes, methods of measurement or derivation, applicable spatial and temporal scales and so on to ensure consistent application across jurisdictions.
2. We employed bottom-up (i.e. data-driven) ecotope classifications to generate environmental surrogates for biodiversity for the HCVAE assessment. We recommend this approach when consistent high quality datasets are available (rather than top-down classifications as described in the ANAE scheme.
3. Further development of the ANAE scheme will be required to ensure that all integral components of aquatic ecosystems are effectively recognized across spatial scales, perhaps as emergent properties (i.e. bottom-up classifications as employed in the preset study) of the currently separate classifications of hydrosystems.

11.2.2 Improvements to aquatic ecosystem mapping

4. The draft ANAE scheme to delineate hydrosystems was successfully implemented for the northern Australia HCVAE trial area. However, time constraints of the project meant that further development of the Geodata Estuarine, Lacustrine and Palustrine hydrosystem delineation is required. Further delineation of the estuarine ecosystems could be undertaken by using existing mangrove mapping, and the location of barrages to delineate the transition zones between Estuarine and Riverine hydrosystems. Further validation of the Geodata derived hydrosystems (e.g. the Lacustrine hydrosystem) could be undertaken using existing hydrosystem delineation such as the Queensland Wetland Mapping and Classification data set.
5. Remotely sensed information on flood frequency, extent and duration, available for a number of catchments in northern Australia could be generalised and used to update the existing attribution of hydrosystem inundation frequency. With suitable resourcing, the remote sensing archive could be used to evaluate and update the hydrosystem perenniality attribute.

11.2.3 Improvements to aquatic biodiversity data

6. Fundamental knowledge of the distribution of many freshwater dependent flora and fauna is lacking for much of northern Australia. We considered but did not assemble datasets other water-dependent fauna (i.e. frogs, crocodiles, lizards, snakes, riparian birds) or aquatic, semi-aquatic and riparian flora due to resource and/or data constraints. Whilst this project assessed molecular-level, phylogeographic data for a selected number of taxa, there remain substantial sampling gaps (particularly in the Kimberley region) for these species and many other species. More extensive phylogeographic data sets (in terms of both completeness of spatial coverage and greater number of taxa) would be very useful in future efforts to delineate freshwater bioregions and would enable more rigorous assessments of molecular-level patterns of biodiversity at a range of spatial scales.
7. Improved knowledge of the macroinvertebrate biodiversity of subterranean systems, springs and off-channel floodplain habitats is required. Limited data meant that the conservation values of these hydrosystems were not assessed with respect to macroinvertebrate biodiversity, despite the high likelihood that such habitats are of conservation significance.
8. Future research efforts that apply molecular data to freshwater biodiversity assessments in northern Australia should consider within- and between- river basin scale patterns of genetic-level biodiversity. Landscape genetic approaches could be coupled with phylogeographic analyses to identify the key landscape features (e.g. flow regime, river structure, landscape topography) that subdivide populations of freshwater species, thereby providing key information about genetic connectivity (or isolation) among populations. This would enable molecular-level patterns of biodiversity to be considered at the planning unit scale and allow measures of population connectivity to be applied in conservation planning assessments.
9. We used predictive models of species distributions to mitigate the problem of incomplete sample coverages. Greater confidence in the outputs from the predictive models could be obtained by improving the model validation process using true presence/absence data for all faunal groups. Therefore a research priority should be to collect these data in the future. The use of multiple predictive modelling methods and generation of consensus predictions would allow better quantification of uncertainty in the extrapolation of species distributions for use as biodiversity surrogates in conservation assessments.

11.2.4 Identifying high conservation value areas using the draft HCVAE Framework

10. We feel that implementing the draft HCVAE Framework criteria goes some way to identifying areas that are of potentially high conservation value. However, greater clarity as to the purpose of the HCVAE identification may further increase the efficient investment of resources to manage these areas effectively. The Framework criteria are not specifically designed to identify which management options are most appropriate for a particular area and require further development in this regard.
11. The lack of clear objectives as to the purpose of the HCVAE identification meant that it was difficult to select a subset of the most import attributes to characterise the criteria. Instead there was the strong temptation to characterise each criterion in as many ways as possible. We recommend that this temptation be resisted. Our overall philosophy was to only apply attributes that could be calculated from the biodiversity surrogates datasets, rather than applying attributes based on other data which was of variable quality and spatial extent and that would therefore potentially yield large gaps and uncertainties in the outcomes of an HCVAE assessment.
12. The nature of the Framework (i.e. a multi-criteria scoring approach) means that the method combines potentially numerous individual attributes that by themselves can be (and often are) used to assess conservation value. However, the integration process ultimately means a potential loss of transparency, in that it is unclear how many attributes (and which ones) contribute greatly to the integrated score for each criterion. It is important however that this integrative approach remains fully transparent; that is, it must be clear how many and which attributes contribute most to the integrated score for each criterion.
13. It is unclear which components of biodiversity (the fundamental currency of conservation assessments). contribute most to the final rankings based on criterion scores. Although it is certainly possible to interrogate the underlying data and maps to understand why a particular area scored highly for a particular criterion or set of criteria, this is not a simple process. One solution to this issue is to greatly reduce the number of attributes used to characterise the Framework criteria to only a few key ones that are deemed by experts to be most important indicators of conservation value (though this is obviously not a simple task). We suggest that the use of more attributes does not necessarily provide a better or more interpretable conservation assessment. In fact, the converse appears to be true.
14. The draft HCVAE Framework states that an ecosystem meeting any one of the criteria could be considered an HCVAE, but that appropriate thresholds for nationally significant HCVAE are yet to be determined. It is unclear what threshold should be used to discriminate those planning units that "meet" each criterion (i.e. that their criterion score exceeds the threshold and therefore could be considered to be of high conservation value based on that criterion). The choice of threshold is a somewhat arbitrary decision, but can have potentially important consequences for identifying which and how many planning units are considered of high conservation value.
15. It is unclear whether some criteria should be considered more important than others for identifying HCVAEs and whether particular planning units that meet a greater number of criteria are concordantly of higher conservation value. We agree with the approach taken in the Lake Eyre Basin trial (Hale, 2010) that the lack of a specified purpose, for the identification of HCVAE, means that the criteria be considered to be equally important. We assumed that conservation value increased with increasing number of criteria met (i.e. a planning unit that met all six criteria had a greater potential for containing an HCVAE than a planning unit that met only one criterion).

11.2.5 PROMOTING EFFICIENCY IN THE IDENTIFICATION AND MANAGEMENT OF HIGH CONSERVATION VALUE AREAS

16. A fundamental goal of conservation assessments should be to efficiently identify sets of areas that need to be managed to conserve species and the processes that sustain them. The draft HCVAE Framework may be limited in the extent to which it can efficiently contribute to this conservation goal and ideally will require complementary approaches such as systematic planning, that specifically address biodiversity representation in a more efficient way.
17. There are some key challenges that, if addressed, would lead to greater objectivity in systematic conservation planning. The incorporation of uncertainties in the distribution of conservation features or the vulnerability to future change of candidate high conservation value areas (e.g. due to land use or climate change) would increase the ability to assess the resilience of these areas and the likelihood of long-term persistence of the conservation values that they contain. Setting scientifically defensible conservation targets (e.g. the number of populations or areas required to maintain species) would help improve the efficiency of the resilience of high conservation value areas to future changes.
18. Estimates of the socioeconomic costs of different conservation management actions (e.g. threat mitigation, restoration, stewardship, acquisition) should ideally be incorporated into the conservation assessment process. Here, the aim is to optimize the set of management actions and the places where they should be implemented, required to achieve biodiversity conservation goals with the minimum cost (or impact in local economies). This would provide the first step in developing a strategic, efficient and effective approach to identify high conservation value areas and guide on-the-ground management actions to conserve freshwater biodiversity.
19. Finally, we view the application of systematic planning as a tool to help in the decision making process in identifying high conservation value areas. The incorporation of expert and stakeholders' knowledge, needs and interests is a fundamental next step at achieving the implementation of an efficient and realistic conservation plan. This information should be seen as an additional tool to guide future decisions on conservation management rather than a rigid and strict conservation plan itself.

12. APPENDICES

APPENDIX 1.1 HIGH CONSERVATION VALUE AQUATIC ECOSYSTEMS DRAFT NATIONAL FRAMEWORK

APPENDIX 1.2 DRAFT GUIDELINES FOR APPLYING THE CRITERIA FOR THE HCVAE ASSESSMENT PROCESS

APPENDIX 4.1. ASSESSMENT OF GEODATA HYDROGRAPHY FEATURE CLASSES AND FEATURE INTERPRETATION

APPENDIX 4.2. METHODS FOR DELINEATING ESTUARINE, LACUSTRINE AND PALUSTRINE HYDROSYSTEMS

APPENDIX 4.3. MAPPING OF NVIS VERSION 3.1 MAJOR VEGETATION SUB-GROUPS (AUSTRALIAN GOVERNMENT DEPARTMENT OF THE ENVIRONMENT AND WATER RESOURCES, 2006) TO NORTHERN AUSTRALIA HCVAE TRIAL VEGETATION CLASSES

APPENDIX 4.4. Boxplots showing the distribution of environmental attribute values among the 20 riverine ecotopes. Ecotopes are arranged in dendrogram order (Fig. 4.2). The boxes indicate the inter-quartile range with the central bar signifying the median value. Whiskers are drawn to include all data points that are not more than 1.5 times the inter-quartile range from the box. Outliers are portrayed as separate points in red.

APPENDIX 4.5. Barcharts and boxplots showing the distribution of environmental attribute values among the 14 Lacustrine ecotopes. Ecotopes are arranged in dendrogram order. The barcharts indicate the frequency of occurrence for binary attributes such as perenniality and inundation frequency. The boxes indicate the inter-quartile range with the central bar signifying the median value. Whiskers are drawn to include all data points that are not more than 1.5 times the inter-quartile range from the box. Outliers are portrayed as separate points in red

APPENDIX 4.6. Barcharts and boxplots showing the distribution of environmental attribute values among the 16 Palustrine ecotopes. Ecotopes are arranged in dendrogram order. The barcharts indicate the frequency of occurrence for binary attributes such as perenniality and inundation frequency. The boxes indicate the inter-quartile range with the central bar signifying the median value. Whiskers are drawn to include all data points that are not more than 1.5 times the inter-quartile range from the box. Outliers are portrayed as separate points in red.

APPENDIX 5.1. List of macroinvertebrate (MIV) taxa compiled for use in the development of species distribution predictive models. The inclusion of each taxa from AusrivAs collection lists provided by each jurisdiction is also shown.

APPENDIX 5.2. List of fish species compiled for use in the development of species distribution predictive models.

APPENDIX 5.3. List of turtle species compiled for use in the development of species distribution predictive models.

APPENDIX 5.4. List of waterbird species compiled for use in the development of species distribution predictive models.

APPENDIX 5.5. Waterbirds data & related environmental datasets collated by SSD for the Northern Australian Water Futures Assessment (Ecological assets sub-project), March 2010. Compiled By James Boyden

APPENDIX 6.1 Mean and standard error of environmental variables for groups based on distribution in ordination space shown in Figure 6.3. Group one basins were located negatively to axis 1 scores <0.65 and group 2 were located positively to axis 1 scores >1.0 (i.e. no overlap). Only those variables significantly different at p<0.01 or greater (paired t-test) are shown. Definitions are included only for attributes uncommonly encountered in the literature. . The final eight variables relating to floodplain habitats were significantly correlated (r = 0.503) with the pattern of dissimilarity determined using all landscape scale variables as determined by the BIOENV procedure in PRIMER statistical analysis software.

APPENDIX 6.2. Waterbird species present in at least 90% of drainages within at least one of the aggregated NASY regions. X denotes that a species present in the region. Species highlighted in bold type are migratory species as listed under the CAMBA, JAMBA or ROKAMBA migratory bird international treaties.

APPENDIX 6.3. Proportion of the total waterbird fauna of northern Australia found in one or more aggregated NASY regions (solid bars) and proportion of widely distributed birds within a region (i.e. >90% drainages of a region) also found in other drainages (open bars).

APPENDIX 6.4. Turtle species contributing to within region distinctiveness. Also shown is the frequency of incidence within each region in parentheses and total contribution (in bold face) to within-region similarity.

APPENDIX 6.5. Results of SIMPER analysis highlighting turtle species contributing greatest to between region dissimilarity. Species names are abbreviated to first letter of genus and species respectively. Proportion (%) contribution to overall dissimilarity is shown in parentheses.

APPENDIX 6.6. Freshwater fish species contributing to the distinctiveness of individual aggregated NASY regions. FOI = frequency of incidence, % contribution = extent to which species contributes to within region similarity.

APPENDIX 9.1. Planning units identified as having met one or more criteria at the 99th percentile threshold for each reporting scale. The numeric code of each planning unit (PU), and the drainage division (DD) and NASY region (R) in which they occur is listed. Also shown are the major named hydrosystems occurring within each planning unit. Hydrosystem codes are: riverine (R), lacustrine (L), palustrine (P) and springs (S). For each planning unit and each reporting scale, the individual criteria met (1) and the total number met (∑) are also shown.

APPENDIX 1.1

HIGH CONSERVATION VALUE AQUATIC ECOSYSTEMS

DRAFT NATIONAL FRAMEWORK

November 2009

Context

The Natural Resources Policies & Programs Committee (NRPPC) established the Aquatic Ecosystems Task Group (AETG) in 2005 to develop a draft national framework for the identification, classification and management of High Conservation Value Aquatic Ecosystems (HCVAE).

The key driver for the Framework was to ensure that jurisdictions were using consistent approaches in meeting the requirement of the National Water Initiative (NWI) clause 25x that *parties agree that 'their water access entitlements and planning frameworks will…identify and acknowledge surface and groundwater systems of high conservation value, and manage these systems to protect and enhance those values..*' 'Aquatic ecosystems' include rivers, estuaries, lakes, wetlands, saltmarsh, karst and other groundwater ecosystems. Such ecosystem types are described generically as 'aquatic ecosystems' in Ramsar documentation and also in the national Directory of Important Wetlands in Australia.

Jurisdictions are using a variety of tools to identify HCVAEs within their boundaries, and the work of the AETG has found that these approaches are resulting in suitably consistent approaches to the identification of HCVAE. This consistency is demonstrated through the six criteria for the identification of HCVAE used by this Framework. These criteria capture the core criteria used by jurisdictions in their systems i.e. the essential criteria used by jurisdictions fall within these six. In these circumstances, there is no requirement for a mandated national Framework that jurisdictions would need to apply to management areas that fall exclusively within jurisdictional boundaries. However, there is a need for a tool that will enable jurisdictions to identify and classify HCVAEs in regions that are managed across jurisdictional boundaries, for example the Murray-Darling Basin and the Lake Eyre Basin.

There is also a need to identify a set of nationally significant HCVAE that would serve a number of purposes, including to assist the Australian Government to focus and prioritise its natural resource management investments.

The lack of an agreed approach at the national level has made it difficult to comprehensively assess the conservation significance of Australia's aquatic ecosystems and to manage them, in keeping with international agreements to conserve biodiversity.

Australia's Strategy for the National Reserve System 2009–2030 endorsed by the Natural Resource Management Ministerial Council in June 2009 recommended that aquatic ecosystems need to be better protected in the National Reserve System. The *Australian Guidelines for Establishing the National Reserve System* (ANZECC 1999) are planned to be reviewed to better account for the needs of aquatic ecosystems including their water requirements, the impact of climate change and integrated landscape management. A national HCVAE Framework will assist this process.

To assist the jurisdictions in the management of HCVAE for natural resource management outcomes beyond their water management obligations under the NWI, the Australian Government has aligned a number of its investment programs (Caring for Our Country, Northern Australia Water Futures Assessment and Great Artesian Basin Sustainability Initiative 3) to the HCVAE process. The national Framework will assist governments to jointly identify HCVAEs and the threats to them as a basis for determining priorities for investment.

The need for a set of nationally significant HCVAE is not serviced through either the set of internationally important (Ramsar) Australian wetlands, nor through the assets identified in the Directory of Important Wetlands in Australia (DIWA). The set of Ramsar assets in Australia is small and is unlikely to expand to the extent necessary to fulfill HCVAE needs. The compilation of the DIWA list was based on self-assessment at the jurisdictional level, with limited quality assurance at the national level.

This Framework has been developed as a tool to identify a set of nationally significant HCVAE, and Guidelines for the application of the criteria have been developed to assist the process. The HCVAE framework will complement and build on existing jurisdictional initiatives, and take into account threats to aquatic ecosystems, including climate change.

The Framework addresses the identification and classification of HCVAE. Management responsibilities will remain with the appropriate land managers.

Objectives

To provide a practical policy tool to assist jurisdictions meet their NWI commitments by enabling a nationally consistent approach to the identification and classification of HCVAE in regions that cross jurisdictional boundaries; and to provide a vehicle to facilitate the management of HCVAE for natural resource outcomes beyond the water management obligations identified through the NWI.

The national framework will be used to:

1. establish a core set of ecological criteria for identifying aquatic ecosystems of high conservation value;
2. differentiate between HCVAEs of national and regional importance;

3. improve knowledge of the extent, distribution and characteristics of HCVAE;
4. guide planning, investment and management decisions;
5. improve cross-jurisdictional coordination and cooperation;
6. improve information sharing between NRM bodies, governments and other stakeholders; and
7. assist in meeting national and international obligations for protection of aquatic ecosystems.

DEFINITION

For the purposes of the national framework:

- "Aquatic ecosystems", are those that depend on flows, or periodic or sustained inundation/waterlogging for their ecological integrity (e.g. wetlands, rivers, karst and other groundwater dependent ecosystems, saltmarshes and estuaries) but do not generally include marine[2] waters.
- "High conservation value aquatic ecosystems" (HCVAEs) are those having ecological values that meet one of the criteria outlined in this framework.

HCVAE Criteria

Six core biophysical criteria have been agreed as appropriate for the identification of nationally significant HCVAE, and draft Guidelines have been developed for applying the criteria. In developing the HCVAE Framework, trials to test the applicability of the criteria in different ecosystem types were conducted as well as trials of the Framework itself and the draft Guidelines.

The criteria are as follows:

- 1. Diversity - It exhibits exceptional diversity of species or habitats, and/or hydrological and/or geomorphological features/processes.
- 2. Distinctiveness - It is a rare/threatened or unusual aquatic ecosystem; and/or it supports rare/threatened species/communities; and/or it exhibits rare or unusual geomorphological features/ processes and/or environmental conditions.
- 3. Vital habitat - It provides habitat for unusually large numbers of a particular species of interest; and/or it supports species of interest in critical life cycle stages or at times of stress; and/or it supports specific communities and species assemblages.
- 4. Evolutionary history - It exhibits features or processes and/or supports species or communities which demonstrate the evolution of Australia's landscape or biota.
- 5. Naturalness - The aquatic ecosystem values are not adversely affected by modern human activity to a significant level.
- 6. Representativeness – It contains an outstanding example of an aquatic ecosystem class, within a Drainage Division (It is expected that this criterion will be applied only after the previous five criteria have been applied and a potential HCVAE identified).

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[2] Defined as **areas of marine water the depth of which at low tide exceeds six metres**, but to be interpreted by jurisdictions. Note that the Ramsar Convention classifies marine waters less than six metres, as wetlands.

While an ecosystem meeting any one of these criteria could be considered to be an HCVAE, further trials of the Framework to determine appropriate thresholds for a site to be considered an HCVAE of national significance, are underway.

Assets that have international recognition through Ramsar listing or listing as an Australasian-East Asian Flyway site will be automatically recognised as nationally significant HCVAEs, the presumption being that the criteria for those listings are comparable with the HCVAE criteria. World Heritage sites where aquatic criteria form a basis for listing will be assessed on a case-by-case basis.

While not specifically referenced in the criteria, it would be consistent with the general approach to consider bioecological ecosystem services (e.g. water regulation, flood control, soil retention) when assessing nationally significant HCVAE.

Additional criteria may also be used by jurisdictional agencies, regional bodies and local councils, in conjunction with these core criteria, should they wish to use the Framework for identifying HCVAEs at the State/Territory or other level, but would not be used in identifying HCVAEs of national importance.

Detailed draft guidelines for applying the criteria have been developed and are being tested.

Representativeness

In order to apply the representativeness criterion, a nationally agreed approach to both aquatic ecosystem regionalisation and classification have been developed.

Regionalisation

The approach for regionalisation of HCVAE at a national level is the Australian Drainage Divisions system (together with Integrated Marine and Coastal Regionalisation of Australia for marine ecosystems – where the site extends into the marine environment). However, it is recognised that some HCVAE, particularly groundwater dependent ecosystems may cross some of these boundaries. The Drainage Division regionalisation is applicable at the national scale. It is recognised that where assessments are undertaken on other levels, the approach to regionalisation may differ, eg catchments or sub-catchments.

Classification

[TEXT TO BE PROVIDED – REFER TO LATEST DRAFT ANAE CLASSIFICATION SCHEME]

Ecosystem delineation

HCVAEs are spatially delineated around ecological functioning rather than simply geographical areas that represent the main identified values. HCVAEs will include those areas needed for effective management of the core ecosystem and the threats to it, where these threats can be managed as part of the ecosystem. In some cases, this will mean that HCVAEs will have different boundaries from ecological assets identified through other processes.

Spatial scale and level of analysis

The scale of the system being managed needs to be recognised. Aquatic ecosystems occur on a variety of scales in terms of both spatial distribution within the landscape and in physical area or size. The HCVAE criteria are designed to be used at a variety of scales, with aquatic ecosystems ranging in size from small, discrete systems, such as rainfed rock pools in arid landscapes, to whole river systems and to aggregations of ecosystems. A pragmatic approach to scale, using recognised classifications and a scale appropriate for management purposes, will be used for assessment purposes.

Asset Identification

Assets will be identified through the application of the criteria and classification scheme to locally/regionally generated inventories rather than through undertaking a census of aquatic ecosystems. Where locally generated inventories are absent or data poor, some form of census may need to be undertaken as a preliminary step. The criteria and classification scheme provide tools to systematically identify aquatic ecosystems of differing levels of significance for a range of purposes. There is therefore no public mechanism for 'nomination' of ecosystems specifically for identification and listing as an HCVAE.

Expert Reference Panels

Cross-jurisdictional coordination and technical support will be provided through the establishment of Expert Reference Panels in relevant drainage divisions, established by the Australian Government and jurisdiction(s) in question, and comprising relevant jurisdictional and Australian Government technical and policy officers as well as outside experts. Expert Reference Panels will provide guidance in the evaluation of ecosystems against the criteria, and consider 'whole of drainage division' issues as they relate to representativeness and levels of significance.

This process will assist jurisdictions in meeting their NWI obligations through improving the consistency of approach amongst jurisdictions for the identification of HCVAE, improving inter-jurisdictional coordination and cooperation in the management of HCVAE, and acting as a conduit for the exchange of information between jurisdictions.

Reporting Obligations

The identification and management of HCVAE is an NWI obligation. As such, jurisdictions are required to report on progress in implementing this commitment through the National Water Commission's (NWC) Biennial Assessments. No additional reporting arrangements are therefore proposed.

The draft NWI Performance Indicator relating to HCVAEs requires jurisdictions to report on the number and proportion of water systems for which:

- HCVAE have been identified
- plans or other instruments addressing high conservation value components have been completed
- actions consistent with the plan have been undertaken.

The NWC considers that other instruments may include any relevant state or territory policies, legislation or strategic plans that recognise high conservation systems and provide for their management.

Review of the HCVAE Framework

The Framework will be reviewed periodically. The outcomes of the Review will be reported to the NRMMC, and any appropriate action undertaken through NRMMC processes.

APPENDIX 1.2

DRAFT GUIDELINES FOR APPLYING THE CRITERIA FOR THE HCVAE ASSESSMENT PROCESS

November 2009

CRITERIA FOR IDENTIFYING HIGH CONSERVATION VALUE AQUATIC ECOSYSTEMS

This document lays out guidelines for application of the HCVAE criteria. The six criteria provide a clear basis for data analysis and offer examples of how standards might be applied.

The HCVAE Framework captures the core criteria that are used at all levels to identify HCVAE, but these guidelines are designed to be used for identifying ecosystems significant at a national level.

These guidelines draw upon elements of the Ramsar guidelines, and upon thresholds for significance from Ramsar, the National Heritage List and *Environment Protection and Biodiversity Conservation Act 1999 (EPBC 1999)* listing for threatened species and communities. This will provide commonalities between these identification processes and consistency in thresholds for national significance.

USING THE CRITERIA

This document outlines the six criteria to be used in regard to identifying high conservation value aquatic ecosystems.

It is intended to be used:

a) as a guide for jurisdictions to determine what assets they will select for further assessment as nationally significant and

b) to guide the Panels for each drainage division in determining whether assets meet the requirements for identification of Nationally Significant HCVAE.

Each jurisdiction will determine which ecosystems may be potential nationally significant HCVAE. This will be influenced by the Australian National Aquatic Ecosystem Classification and data across the full range of assets of that type.

Criteria may be selected according to appropriateness and data availability. For example, a potential asset may be considered because of its diversity of ecosystem types, naturalness and critical habitat, even though detailed data at species level is not available to assess its significance under Criterion 3.

Criteria will be applied by jurisdictions to the analysis of data relating to particular ecosystem classes. Criteria will be selected on the basis of available data. All criteria will not necessarily be used. Where the data is patchy, surrogacy or modelling may assist in ecosystem-by-ecosystem analysis.

Testing of HCVAE criteria has indicated that a number of the criteria will need to be met for an ecosystem to be considered as nationally significant. Current and future trials of the HCVAE Framework are intended to inform this issue.

Data quality – information regarding data quality to be added after the trials.

ECOSYSTEM FOCUS

Aquatic ecosystems are delineated around ecological functioning rather than simply those 'sites' or geographical areas that represent the main identified values. In some cases, this will mean that HCVAEs will have different boundaries from similar assets identified through other processes, such as Wetlands of International Importance (Ramsar sites) and the Directory of Important Wetlands in Australia.

Further guidance on the spatial delineation of HCVAE is available in the document 'Design Guidelines for HCVAE Sites'.

International Recognition

Ecosystems that already have recognition as being of international significance will be recognised as a nationally significant HCVAE, subject to the provisos discussed below. Ecosystems added in future to any of these registers will also be recognised as nationally significant.

Ramsar

As of November 2008, 65 places in Australia are listed under the Ramsar convention (see Appendix 1). The significance of these aquatic ecosystems has been assessed against the Ramsar criteria and supported by the International Ramsar bureau. The Ramsar criteria have common elements and standards with HCVAE criteria. All Ramsar sites that may be classed as an 'aquatic ecosystem' within the definitions of the HCVAE framework classification will be recognised automatically.

East Asian-Australasian Flyway Site Network

As of November 2008, 17 sites are included on the East Asian-Australasian Flyway Site Network. These sites must meet any one of the three Ramsar criteria related to migratory shorebirds:

- it regularly supports > 20 000 migratory shorebirds; or,
- it regularly supports > 1 % of the individuals in a population of one species or subspecies of migratory shorebird; or,
- it supports appreciable numbers of an endangered or vulnerable population of migratory shorebird

These flyway sites meet HCVAE Criterion 4 (Vital habitat). Most are already included under the category of Ramsar and /or World Heritage listing, others that meet the Ramsar migratory shorebird criteria above and fall within the scope of HCVAE aquatic ecosystem types may also be recognised as nationally significant. Any Flyway site that is considered to be exclusively a 'marine' ecosystem is excluded.

World Heritage List

Areas already listed as World Heritage and that have specific aquatic ecosystems listed within their world heritage values will be recognised as a nationally significant HCVAE.

As some World Heritage places will only have parts of that area which meet HCVAE criteria or encompass several separate locations, the entire area of a World Heritage Area may not necessarily be considered as a HCVAE.

Aquatic ecosystem values that would meet national HCVAE criteria and thresholds may not be documented in a World Heritage site's listing details. In this case a specific assessment using HCVAE criteria must be conducted to assess whether the site has merit as an HCVAE using the full scope of HCVAE assessment, rather than automatic inclusion on the basis of its WH listing.

Assessing internationally listed assets

Determination of HCVAEs will be conducted by the Australian Government in consultation with the relevant jurisdiction. Potential HCVAE assets will be assessed on a case-by-case basis. The following decision rules will apply:

- the proposed ecosystem must be of an ecosystem type within the scope of the HCVAE definition, therefore entirely marine sites will be excluded,
- the aquatic values of the ecosystem must meet international standards for those values and these components must be included in the relevant listing documentation,
- noting that the values do not necessarily have to match the HCVAE criteria provided they are (a) aquatic values and (b) have been assessed according to the international listing process,
- For World Heritage Areas, HCVAE boundaries will be determined according to identified aquatic values, i.e. not necessarily all of a World Heritage Area will be included.

Any asset listed under:

- Ramsar Convention
- East-Asian-Australasian Flyway Site Network
- World Heritage Convention (on a case-by-case basis)

will be included, as a whole or in part, as an HCVAE provided it meets the specifications as detailed above.

1 DIVERSITY

The asset exhibits exceptional diversity of species or habitats, and/or geomorphological features/processes

Places with a high diversity of species are particularly important in maintaining regional biodiversity. The diversity of an individual asset may be attributable to a diversity of habitats or its location in a centre of speciation.

Diversity includes diversity of ecosystem types (rivers, aquatic ecosystems, etc) and diversity of geomorphic features and processes. Diversity of geomorphic features and habitats within an ecosystem is significant in itself and may act as a surrogate for diversity of biota where data is limited. However, data limitations may impact on the ability to apply this criterion to geomorphic diversity.

Species diversity includes the full range of biota including microscopic taxa. Ecosystems identified through systematic and extensive survey for a particular taxonomic group may meet this Criterion based on that group alone, rather than the entirety of the biota at that ecosystem.

Documentation of diversity must be set with reference to classification of aquatic ecosystem. Diversity will be assessed in the context of regionalisation by Drainage Division and by aquatic ecosystem class as discussed under Criterion 2.

A ecosystem with several different types of aquatic ecosystem class within its boundaries - for example river reach, floodplain aquatic ecosystems, estuary and saltmarsh or a suite of aquatic ecosystems of different sub-classes – may be considered of particularly high value.

Key research reference documents:

2 DISTINCTIVENESS

The asset is a rare/threatened or unusual aquatic ecosystem; and/or

The asset supports rare/threatened species/communities and/or

The asset exhibits rare or unusual geomorphological or hydrological features/ processes and/or environmental conditions, and is likely to support unusual assemblages of species adapted to these conditions

The Distinctiveness criterion includes not only threatened species and communities but also rare, threatened or unusual aquatic ecosystem types, habitats and geomorphological features and processes.

Maintaining the biodiversity of species and communities is a familiar issue in conservation. The concept of rare geomorphic and hydrological features and processes is less familiar. Such attributes are key components of aquatic ecosystems and, if lost, the possibility of regenerating such features within human time scales is unlikely. Where such features occur, there may be an unusual assemblage of species that is able to exploit the conditions, although the individual species may not be rare or threatened.

Ecosystems with typically low species diversity may qualify under this criterion where the species present are adapted to particular environmental conditions.

The *EPBC Act 1999* classes species and communities as 'vulnerable', 'endangered' or 'critically endangered' according to the extent of pressures upon that species or community, its geographic extent or population numbers and rates of decline. In the discussion that follows, the term 'threatened' is used to include all of these risk categories.

Spatial definitions of distribution used under *EPBC Act 1999* may need review for some aquatic ecosystems, such as rivers where linear connectivity confers particular constraints on species distributions. Where necessary, other thresholds using spatial or other measures more appropriate to aquatic ecosystems may be argued from ecological principles.

RARE/THREATENED OR UNUSUAL AQUATIC ECOSYSTEM

Uncommon habitats or ecosystems demanding particular adaptations of their biota are a feature of Australia's biodiversity. Defining what constitutes 'rare', 'unusual' or 'threatened' requires a clear understanding of the full range of habitats and classes or ecosystem. An irreplaceability analysis will highlight systems that are rare or unusual while a risk assessment will indicate systems that are vulnerable or threatened.

Threatened habitats may be identified by articulating the processes that are threatening that particular aquatic ecosystem type, whether by human activity or by climate change. Impacts of these threatening processes across a national scale as well as the rate at which change is progressing and the scale of impact will be considered. An estimate of the pre-1790 condition and extent of such classes can be used as a reference point for comparative purposes. Aquatic ecosystem types and classes are vulnerable to a range of different threats and the impacts of those threats can vary across the country. Nationally threatened aquatic ecosystems and communities should be articulated and key locations for conservation identified. Identification of threatened ecosystems is a precautionary approach to biodiversity conservation where detailed community and species data is lacking.

An unusual aquatic ecosystem may also be one that is important for providing one of only a few known habitats of an organism of unknown but apparently limited distribution.

SUPPORTS RARE/THREATENED SPECIES /COMMUNITIES

Rare and threatened species and communities fall under legislation at both national and state level. Other frameworks also provide indications of species and communities that are distinctive and of conservation value but do not necessarily fall under legislative provision. These frameworks include some Regional Forest Agreements and some agreements supporting non-forest vegetation conservation. An expert reference panel approach may be one way to verify the claims for inclusion under the Distinctiveness criterion. To avoid individual interests being promoted, the decision will not lie with a single expert.

A mechanism for defining what constitutes 'threatened' is provided by the Environment Protection and Biodiversity Conservation Act,

http://www.environment.gov.au/biodiversity/threatened/pubs/nominations-form-species.doc#Guidelines. (See Appendix 4)

These guidelines provide criteria for identifying level of threat and estimating species 'rarity' in a semi-quantitative manner. These guidelines provide a useful starting point for analysis but there may need to be other means of estimating, numerically or spatially, due to the difference in natural distribution patterns for aquatic species and communities. The guidelines provide tables showing calculation of the level of threat (vulnerable, endangered or critically endangered), under each criterion. The guidelines are applied to occurrence at national level within a Drainage Division. If the HCVAE framework is used at different scales, the thresholds will need to be adjusted accordingly by individual jurisdictions.

RARE OR UNUSUAL GEOMORPHOLOGICAL OR HYDROLOGICAL FEATURES/ PROCESSES/ ENVIRONMENTAL CONDITIONS

The hydro-geomorphological context of aquatic ecosystems conspicuously defines their character. The kinds of features and processes that are included under this criterion include:

- Geomorphic features of limited occurrence at continental scale
- Geomorphic features that are fragile (responsive) and vulnerable to threats
- Aquatic habitats that are uncommon or specialised in form, character, hydrology
- Hydro-geomorphology that is uncommon or limited in distribution
- Extreme or unusual environmental conditions that affect the biota inhabiting the ecosystem (eg. water chemistry or temperature) and the biota have adapted to this.

Key research reference documents:

3 VITAL HABITAT

An asset provides vital habitat for flora and fauna species if it supports:

- unusually large numbers of a particular natural species; and/or
- maintenance of populations of specific species at critical life cycle stages; and/or
- key / significant refugia at times of stress.

THE NOTION OF VITAL HABITAT IS PARTICULARLY IMPORTANT IN AQUATIC ECOSYSTEM ECOLOGY AS FLORA AND FAUNA ARE OFTEN HIGHLY DEPENDENT UPON THE PATTERNS OF WATERING, OR FLOW, OR SALINITY AT VARIOUS STAGES OF THEIR LIFE CYCLES. MANY ICONIC AQUATIC ECOSYSTEM SPECIES, ESPECIALLY BIRDS, ARE MOBILE AND MAY BE RELIANT UPON MORE THAN ONE LOCATION OR HABITAT TYPE DURING THEIR LIFE-CYCLE. VITAL HABITAT MAY BE CHARACTERISE D BY PARTICULAR SALINITY, TIDAL REGIMES, HYDROLOGY, SEASONAL PATTERNS OF DRYING AND WETTING, EXTENT AND NATURE OF VEGETATIVE COVER OR SUBSTRATE.

HABITAT FOR AN UNUSUAL ABUNDANCE OF PARTICULAR SPECIES

Large numbers of individual species will gather at some assets where the conditions are particularly favourable for feeding, breeding, nesting, or roosting. Ramsar criteria set the threshold for this criterion at 20 000 waterbirds. This number is appropriate for assessment at national scale, lesser numbers may be appropriate at regional scale. An alternative calculation may be as percentage of the total population, or highest numbers in region or catchment. Clearly this can only be used where population counts are reliable.

Ramsar includes multi-species counts. To ensure consistency multi-species counts will be included under this criterion.

SUPPORTS SPECIES OF INTEREST IN CRITICAL LIFE CYCLE STAGES

Aquatic ecosystems provide resources required for particular fauna at certain seasons or at critical stages in their life cycle, notably breeding. Such habitats are particularly critical in arid zones. Less obviously, habitats that are subject to periodic dehydration can be critical for other species, such as some invertebrate taxa and flora which depend on dry periods to develop resting stages or spores for recolonization or distribution.

Habitats with requisite characteristics – such as temperature, depth, chemistry, microhabitats, vegetation – will attract large numbers of species of interest. They may be key ecosystems in the wider region for species renewal and maintaining genetic diversity. Fish species may spawn under quite specific conditions in key locations and provide stock for areas beyond the immediate spawning grounds. Significant spawning grounds will apply where required conditions are uncommon or threatened, or fish species are of particular concern.

Aquatic ecosystems, notably riverine systems, can be critical to colonization and extension of range. Under this criterion, importance for distribution and colonization should only consider species that are directly dependent on the aquatic ecosystem, not incidental flora and fauna.

Aquatic biota, especially birds, must be opportunistic in accessing necessary resources in a variable landscape. Habitats may be critical in some years, but apparently not so in other years. Habitats may be identified as 'vital' on the basis that they provide links in a landscape chain of habitats required to maintain populations under a variety of environmental conditions and over a number of seasons.

Stopover or seasonal ecosystems for migratory birds meet this criterion. Assets need to be visited on a regular basis by substantial numbers of birds to meet this criterion.

REFUGES IN TIMES OF STRESS

Drought and unpredictable weather patterns characterise Australia's natural environment. Significant aquatic ecosystems will provide a refuge under these conditions as a result of their biophysical features and hydrology. They can sometimes be identified by the increase in number and diversity of species located at the ecosystem at times of stress such as drought, as well as persistence of water and vegetation.

Loss of habitat through fire can also affect certain types of aquatic ecosystems. Ecosystems which as a consequence of topography tend to be less fire-prone are important refuges in the event of wildfire.

Key research reference documents:

4 EVOLUTIONARY HISTORY

Exhibits features or processes and/or supports species or communities which are important in demonstrating key features of the evolution of Australia's landscape, riverscape or biota, especially in a world context.

Both the National Heritage List and the National Strategy for the Conservation of Australia's Biological Diversity http://www.environment.gov.au/biodiversity/publications/strategy/index.html acknowledge the significance of Australia's evolutionary history. This recognition applies to both physical and biological elements of aquatic ecosystems. The landforms, soils, geological history and palaeoclimates have shaped our landscapes and hence our aquatic ecosystems.

The biota, like the biota of Australia's terrestrial environments, is often distinctive, demonstrating ancient and relict components of Pangaean and Gondwanan origin and adaptations to special conditions including salinity, ephemeral water and variable hydrology. Many species and genera, even numerous families, are endemic. This endemism can be quite localized and reinforces the evolution of Australia's landscapes revealed in the geomorphology.

Key research reference documents:

5 NATURALNESS

The ecological character of the aquatic ecosystem is not adversely affected by modern human activity

Systems in natural condition are important for aquatic conservation. Not only are all aspects of the ecosystem intact and functioning but poorly known or unknown features or species will also be conserved.

Naturalness will also include aquatic ecosystems functioning in an almost, or near, natural way. This will allow the identification of assets that are not pristine but retain values making them significant. (drawn from Ramsar clarification of 'near natural').

In some areas, most aquatic ecosystems will meet the naturalness criterion. In these circumstances, greater weighting may be given to other criteria in assessing an ecosystem's environmental values.

Key research reference documents:

6 REPRESENTATIVENESS

> The asset is an outstanding example of an aquatic ecosystem class to which it has been assigned, within a Drainage Division

In order to assess 'representativeness' of ecosystems there are three key requirements:

- an agreed regionalisation or set of regionalisations
- a classification for each ecosystem type, and
- defined spatial scale and level of analysis.

REGIONALISATION

Drainage Divisions and the Integrated Coastal and Marine Regionalisation of Australia (IMCRA) will be used as the Regionalisation for HCVAE analysis.

CLASSIFICATION

In order to support the assessment of the representativeness criteria, *the Australian National Aquatic Ecosystem (ANAE) Classification scheme* provides several levels of evidence.

Any particular candidate HCVAE should be compared to all current HCVAE identified within the same region (eg – Drainage Division). If the system is the best in its class in the drainage division or contains habitats that are under-represented, it will fulfil the Representativeness Criteria.

Refer to *the ANAE Classification scheme* for details of how to establish the ecosystem's classification.

SPATIAL SCALE AND LEVEL OF ANALYSIS

The selection of an appropriate spatial scale will depend on the purposes of the assessment. Aquatic ecosystems occur on a variety of scales in terms of both spatial distribution within the landscape and in physical area or size. The HCVAE criteria are designed to be used at a variety of scales.

A pragmatic approach to scale, using recognised classifications and a scale appropriate for management purposes will be used for assessment purposes.

Integrity

HCVAE assets proposed under this criterion will, as far as possible, be among the 'best' or 'outstanding' examples of that aquatic ecosystem within the Drainage Division. That, is, they should be typical of the class and retain the key ecosystem components and functions of that class, or is a rare example of the class on a continental scale.

National Moderation

The Expert Reference Panel process will also be used to moderate nationally to ensure representativeness and completeness at the national scale.

Application of Criterion

Application of this criterion can only be undertaken if the full dataset for an aquatic ecosystem class is available within a drainage division. It is anticipated that this criterion would be applied at the end of the aquatic ecosystem identification process, and as a means of confirming that all classes that occur in the drainage division are captured.

Key research reference documents:

DEFINITION OF TERMS AS USED IN THE HCVAE FRAMEWORK

Aquatic ecosystems are those that depend on flows of fresh water, or periodic or sustained inundation/waterlogging for their ecological integrity (e.g. aquatic ecosystems, rivers, karst and other groundwater dependent ecosystems, saltmarshes and estuaries) but do not generally include marine waters.

HCVAE list is the list of aquatic ecosystems that meet the criteria and thresholds outlined in these guidelines and are therefore considered to have national significance. The list will not include assets that are entirely marine.

High conservation value aquatic ecosystems (HCVAE) are those having ecological values that meet at least three of the criteria outlined in the framework, achieving appropriate thresholds or standards

Conservation value: natural value of aquatic asset worthy of protection

Ecosystem type: an aquatic ecosystem included under the definition above, e.g. rivers, lakes and other waterbodies, aquatic ecosystems, karst and other ground-water dependent ecosystems, saltmarshes and estuaries.

Attribute: A particular expression of the criterion that provide the basis for data collection. Attributes may not be applicable to all types or features of every aquatic ecosystem.

Standard/threshold: A qualitative description or quantitative statement set to determine whether the criterion has been met and, for a multi scale assessment, at what level.

Classification: allocation of an aquatic ecosystem to a particular type or class

Level of significance: meets the criterion for a specified standard or threshold

Site: Area within the boundary of the nominated HCVAE place. It may be composed of one or several ecosystem types, or may be several spatially discrete areas connected hydrologically.

Table 1 Criteria and thresholds for High Conservation Value Aquatic Ecosystems and examples of attributes

Criterion	Description	key attributes for significance as a HCVAE at national level	Attributes – selected examples
1. Diversity	The asset exhibits exceptional diversity of species or habitats, and/or geomorphological features/processes.	• diversity of aquatic ecosystem classes or types ➢ incorporate at least x % of aquatic ecosystem classes, habitats or types within a drainage division that are hydrologically connected and interdependent, usually large scale and with high integrity. • species diversity ➢ have a natural species diversity that significantly exceeds the expected diversity within the Drainage division or ➢ have a high natural diversity of taxa at higher taxonomic levels (genus, family) • diversity of communities ➢ include several or many of the communities typical of that ecosystem class including a diversity of communities significantly above expected diversity for that ecosystem class. • Diversity of geomorphology ➢ includes several geomorphic features that could provide habitats supporting a species diversity that significantly exceeds the expected diversity within the Drainage division.	• High diversity of habitats, communities or species • Important for sustaining significant floodplain habitats and diversity • Diversity of geomorphological features or processes • Important for bio- or geo-diversity at regional or local scales
2. Distinctiveness	The asset is a rare/threatened or unusual aquatic ecosystem; and/or supports rare/threatened species/communities and/or exhibits rare or unusual geomorphological or hydrological features/ processes and/or environmental conditions, and is likely to support unusual assemblages of species adapted to these conditions	• Rare, unusual and/or threatened aquatic ecosystem classes ➢ Threatened aquatic ecosystem classes or habitats will be identified by analysis of key threatening processes with impacts across a national scale, the rate of progress of change and scale of impact, together with an assessment of pre 1790 distribution of these classes or features. • To meet national level of significance as HCVAE under this criterion, threatened ecosystem classes or habitats must ➢ have been lost to a significant degree within the Drainage Division or ➢ be an uncommon type that is specifically under threat, resulting in decline in occurrence or condition within the Drainage Division • Support rare and threatened species and communities ➢ These must meet national thresholds for listing under EPBC, either by their listing under the EPBC Act or by rigorous application of the EPBC guidelines	• Species listed under respective legislation as rare, threatened, vulnerable or at risk • Geomorphic features of limited occurrence and/or fragile and vulnerable to stressors • Habitats that are uncommon or specialised in form, character, hydrology • Rare or threatened geomorphic, hydrological or ecological features or processes • Conservation dependent (priority) flora and fauna species

Criterion	Description	key attributes for significance as a HCVAE at national level	Attributes – selected examples
		(Criteria and indicative thresholds). • Contain rare or threatened geomorphological or hydrological features. ➢ These will be assessed by expert opinion using available data sets. In future, these attributes will be assessed systematically through a regional and classification analysis. To meet the national level of significance under this criterion, the ecosystem classes and features must be rare within the Drainage Division at national level.	
3. Vital habitat	An asset provides vital habitat for flora and fauna species if it supports unusually large numbers of a particular natural species; and/or maintenance of specific species at critical life cycle stages; and/or key / significant refugia times of stress.	• a major location for very large numbers of individuals (e.g. 20 000 waterbirds), either of one species or numbers of species • is a location for intensive breeding activity, notably for birds or fish. It may attract species that do not inhabit the area in all life stages but use the area solely for breeding • a place that is the most utilised by migratory birds at a regional scale • considered significant for life cycle of some species if it maintains a natural regime of drying and wetting that is critical for the existence of those species and/or communities. • a location that typically sustains aquatic ecosystem species under conditions of stress, as shown by the large numbers of individuals that are attracted to that asset under conditions such as drought • Habitat for large numbers and/or diversity of migratory species (esp. EPBC listed)	• Provides resources for large numbers of birds for feeding, breeding • Important site for fish breeding, nursery area • Habitat for priority species or communities • Refugium in time of stress eg drought, habitat loss • Stopover or seasonal sites for migratory species • Critical corridor, dispersal or re-colonization route • Habitat for unusually large numbers of particular species
4. Evolutionary history	Exhibits features or processes and/or supports species or communities which are important in demonstrating key features of the evolution of Australia's landscape, riverscape or biota, especially in a world context.	• Habitat for an unusually high diversity of endemic taxa with limited geographical distribution • Habitat for a diversity of taxa endemic at higher taxonomic levels (genus or above) • Habitat for a group of endemic species suggesting a centre of speciation • Habitat for a sequence of related taxa indicative of evolutionary processes • Habitat for iconic species recognized as 'living fossils', relictual species that appear as key links in evolution • Species that are endemic at high taxonomic level (eg order or above) • Habitat for large number of individual endemic species, including hot spots of diversification • Species of worldwide evolutionary significance as apparently of great antiquity, having Pangaean or Gondwanan origins • Ecosystem morphology or hydrology that demonstrates evolution of Australia's	• High percentage of endemic species; • Species with Gondwanic affinities or of taxonomic significance; • Species demonstrating biogeographic patterns for Australia • Demonstrates hydrological and geomorphological processes important in Australia's landscape history and development

Criterion	Description	key attributes for significance as a HCVAE at national level	Attributes – selected examples
		continental landscape	
5. Naturalness	The ecological character of the aquatic ecosystem is not adversely affected by modern human activity	• Most components and process that describe the ecological character of its ecosystem class, or classes, remain close to pre-European condition or in outstanding condition for the drainage division. • An asset with all or most of the components and processes that define its ecological character in outstanding condition for the Drainage Division	• Components of the ecosystem are intact and • Processes are maintained without modification by human intervention • Exotic species absent or do not appear to alter balance or health of biota • Connectivity maintained between ecosystem and its water supplies and corridors
6. Representativeness	The asset is an outstanding example of an aquatic ecosystem class to which it has been assigned, within a Drainage Division	• A asset that is assessed as an outstanding representative example of a particular aquatic ecosystem type when compared with similar aquatic ecosystems of the same classification in the Drainage Division . • A asset may be recognized as a representative HCVAE aquatic ecosystem at national scale if it is of a spatial scale that illustrates the full characteristics of its class, for example a river intact from headwater to ocean or major convergence, or an aquatic ecosystem that responds periodically to cycles of water availability and is either,: ➢ in natural or near-natural condition with the processes that sustain it intact or ➢ a rare example of such a system on a continental scale.	• Representative examples of ecosystem types, selecting those in best condition at appropriate spatial scale • Representative examples of ecosystem types demonstrating particular adaptations to Australian conditions (variable hydrology, ephemeral systems, salinity)

APPENDIX 5.1. List of macroinvertebrate (MIV) taxa compiled for use in the development of species distribution predictive models. The inclusion of each taxa from AusrivAs collection lists provided by each jurisdiction is also shown.

Phylum/ Division	Class	Order	Suborder	Family	Subfamily	MIV number	Jurisdictional inclusion		
Annelida	Hirudinea			Glossiphoniidae		MIV0001	QLD	NT	WA
Annelida	Hirudinea			Erpobdellidae		MIV0002	QLD		WA
Annelida	Hirudinea			Richardsonianidae		MIV0003	QLD	NT	WA
Annelida	Oligochaeta			Oligochaete		MIV0006	QLD	NT	WA
Arthropoda	Arachnida	Acariformes		Acarina		MIV0007	QLD	NT	WA
Arthropoda	Crustacea	Branchiopoda	Conchostraca			MIV0018	QLD	NT	WA
Arthropoda	Crustacea	Decapoda		Atyidae		MIV0021	QLD	NT	WA
Arthropoda	Crustacea	Decapoda		Hymenosomatidae		MIV0022		NT	WA
Arthropoda	Crustacea	Decapoda		Parastacidae		MIV0023	QLD	NT	WA
Arthropoda	Crustacea	Decapoda		Palaemonidae		MIV0024	QLD	NT	WA
Arthropoda	Crustacea	Decapoda		Sundatelphusidae		MIV0025	QLD	NT	WA
Arthropoda	Crustacea	Isopoda		Oniscidae		MIV0032	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Brentidae		MIV0039	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Carabidae		MIV0040	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Chrysomelidae		MIV0041	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Curculionidae		MIV0042	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Dytiscidae		MIV0043	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Elmidae		MIV0044	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Gyrinidae		MIV0045	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Haliplidae		MIV0046	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Heteroceridae		MIV0047	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Hydraenidae		MIV0048	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Hydrophilidae		MIV0049	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Hygrobiidae		MIV0050	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Limnichidae		MIV0051	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Microsporidae		MIV0052			WA
Arthropoda	Insecta	Coleoptera		Noteridae		MIV0053	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Psephenidae		MIV0054	QLD		
Arthropoda	Insecta	Coleoptera		Ptilodactylidae		MIV0055	QLD		
Arthropoda	Insecta	Coleoptera		Scirtidae		MIV0056	QLD	NT	WA
Arthropoda	Insecta	Coleoptera		Staphlynidae		MIV0057	QLD	NT	WA
Arthropoda	Insecta	Diptera		Athericidae		MIV0060	QLD		WA
Arthropoda	Insecta	Diptera		Ceratopogonidae		MIV0061	QLD	NT	WA
Arthropoda	Insecta	Diptera		Chaoboridae		MIV0062	QLD	NT	WA
Arthropoda	Insecta	Diptera		Chironomidae(L)	Aphroteniinae	MIV0063	QLD	NT	WA
Arthropoda	Insecta	Diptera		Chironomidae(L)	Chironominae	MIV0064	QLD	NT	WA
Arthropoda	Insecta	Diptera		Chironomidae(L)	Orthocladiinae	MIV0065	QLD	NT	WA
Arthropoda	Insecta	Diptera		Chironomidae(L)	Tanypodinae	MIV0066	QLD	NT	WA
Arthropoda	Insecta	Diptera		Culicidae		MIV0068	QLD	NT	WA
Arthropoda	Insecta	Diptera		Dolichopodidae		MIV0069	QLD	NT	WA
Arthropoda	Insecta	Diptera		Empididae		MIV0070	QLD	NT	WA
Arthropoda	Insecta	Diptera		Ephydridae		MIV0071	QLD		WA
Arthropoda	Insecta	Diptera		Muscidae		MIV0072	QLD		WA
Arthropoda	Insecta	Diptera		Psychodidae		MIV0073	QLD	NT	WA
Arthropoda	Insecta	Diptera		Sciomyzidae		MIV0074	QLD	NT	WA
Arthropoda	Insecta	Diptera		Simulidae		MIV0075	QLD	NT	WA
Arthropoda	Insecta	Diptera		Stratiomyidae		MIV0076	QLD	NT	WA
Arthropoda	Insecta	Diptera		Syrphidae		MIV0077	QLD		WA
Arthropoda	Insecta	Diptera		Tabanidae		MIV0078	QLD	NT	WA
Arthropoda	Insecta	Diptera		Tipulidae		MIV0080	QLD	NT	WA
Arthropoda	Insecta	Ephemeroptera		Ameletopsidae		MIV0082	QLD		
Arthropoda	Insecta	Ephemeroptera		Baetidae		MIV0083	QLD	NT	WA
Arthropoda	Insecta	Ephemeroptera		Caenidae		MIV0084	QLD	NT	WA
Arthropoda	Insecta	Ephemeroptera		Leptophlebiidae		MIV0085	QLD	NT	WA
Arthropoda	Insecta	Ephemeroptera		Prosopistomatidae		MIV0087	QLD		
Arthropoda	Insecta	Hemiptera		Belostomatidae		MIV0088	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Corixidae		MIV0089	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Gelastocoridae		MIV0090	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Gerridae		MIV0091	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Hebridae		MIV0092	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Hydrometridae		MIV0093	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Leptopodidae		MIV0094	QLD		
Arthropoda	Insecta	Hemiptera		Mesoveliidae		MIV0095	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Naucoridae		MIV0096	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Nepidae		MIV0097	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Notonectidae		MIV0098	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Ochteridae		MIV0099	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Pleidae		MIV0100	QLD	NT	WA
Arthropoda	Insecta	Hemiptera		Saldidae		MIV0101	QLD		WA
Arthropoda	Insecta	Hemiptera		Veliidae		MIV0102	QLD	NT	WA
Arthropoda	Insecta	Lepidoptera		Pyralidae		MIV0103	QLD	NT	WA

Phylum/ Division	Class	Order	Suborder	Family	Subfamily	MIV number	Jurisdictional inclusion		
Arthropoda	Insecta	Megeloptera		Corydalidae		MIV0104	QLD		WA
Arthropoda	Insecta	Megeloptera		Sialidae		MIV0105	QLD	NT	
Arthropoda	Insecta	Neuroptera		Osmylidae		MIV0107	QLD		
Arthropoda	Insecta	Neuroptera		Sisyridae		MIV0108	QLD		WA
Arthropoda	Insecta	Odonata	Epiproctophora	Aeshnidae		MIV0109	QLD	NT	WA
Arthropoda	Insecta	Odonata	Epiproctophora	Austrocorduliidae		MIV0110			WA
Arthropoda	Insecta	Odonata	Epiproctophora	Corduliidae		MIV0111	QLD	NT	WA
Arthropoda	Insecta	Odonata	Epiproctophora	Gomphidae		MIV0112	QLD	NT	WA
Arthropoda	Insecta	Odonata	Epiproctophora	Hemicorduliidae		MIV0113	QLD		WA
Arthropoda	Insecta	Odonata	Epiproctophora	Libellulidae		MIV0114	QLD	NT	WA
Arthropoda	Insecta	Odonata	Epiproctophora	Lindeniidae		MIV0115	QLD		WA
Arthropoda	Insecta	Odonata	Epiproctophora	Macromiidae		MIV0116	QLD		WA
Arthropoda	Insecta	Odonata	Epiproctophora	Urothemistidae		MIV0119	QLD		WA
Arthropoda	Insecta	Odonata	Zygoptera	Coenagrionidae		MIV0121	QLD	NT	WA
Arthropoda	Insecta	Odonata	Zygoptera	Diphlebiidae		MIV0122	QLD		
Arthropoda	Insecta	Odonata	Zygoptera	Isosticidae		MIV0123	QLD	NT	WA
Arthropoda	Insecta	Odonata	Zygoptera	Lestidae		MIV0124	QLD		WA
Arthropoda	Insecta	Odonata	Zygoptera	Protoneuridae		MIV0126	QLD	NT	WA
Arthropoda	Insecta	Plecoptera		Eustheniidae		MIV0128	QLD		
Arthropoda	Insecta	Plecoptera		Gripopterygidae		MIV0129	QLD		WA
Arthropoda	Insecta	Trichoptera		Antipodoeciidae		MIV0130	QLD		
Arthropoda	Insecta	Trichoptera		Calamoceratidae		MIV0131	QLD	NT	WA
Arthropoda	Insecta	Trichoptera		Calocid/Helicophidae		MIV0132	QLD		
Arthropoda	Insecta	Trichoptera		Conoesucidae		MIV0133	QLD		
Arthropoda	Insecta	Trichoptera		Dipseudopsidae		MIV0134	QLD	NT	
Arthropoda	Insecta	Trichoptera		Ecnomidae		MIV0135	QLD	NT	WA
Arthropoda	Insecta	Trichoptera		Helicopsychidae		MIV0136	QLD	NT	WA
Arthropoda	Insecta	Trichoptera		Hydrobiosidae		MIV0137	QLD		WA
Arthropoda	Insecta	Trichoptera		Hydropsychidae		MIV0138	QLD	NT	WA
Arthropoda	Insecta	Trichoptera		Hydroptilidae		MIV0139	QLD	NT	WA
Arthropoda	Insecta	Trichoptera		Leptoceridae		MIV0140	QLD	NT	WA
Arthropoda	Insecta	Trichoptera		Odontoceridae		MIV0141	QLD		
Arthropoda	Insecta	Trichoptera		Philopotamidae		MIV0142	QLD	NT	WA
Arthropoda	Insecta	Trichoptera		Polycentropodidae		MIV0144	QLD	NT	WA
Arthropoda	Insecta	Trichoptera		Psychomyiidae		MIV0145		NT	
Cnidaria	Hydrozoa	Hydroida		Hydridae		MIV0147	QLD		WA
Mollusca	Bivalvia	Unionoida		Hyriidae		MIV0148	QLD	NT	WA
Mollusca	Bivalvia	Veneroida		Corbiculidae		MIV0149	QLD	NT	WA
Mollusca	Bivalvia	Veneroida		Sphaeriidae		MIV0150	QLD	NT	WA
Mollusca	Gastropoda	Architaenioglossa		Viviparidae		MIV0151	QLD	NT	WA
Mollusca	Gastropoda	Basommatophora		Ancylidae		MIV0152	QLD	NT	WA
Mollusca	Gastropoda	Basommatophora		Lymnaeidae		MIV0153	QLD	NT	WA
Mollusca	Gastropoda	Basommatophora		Physidae		MIV0154	QLD		WA
Mollusca	Gastropoda	Basommatophora		Planorbidae		MIV0155	QLD	NT	WA
Mollusca	Gastropoda	Neotaenioglossa		Bithyniidae		MIV0156	QLD	NT	WA
Mollusca	Gastropoda	Neotaenioglossa		Hydrobiidae		MIV0157	QLD	NT	WA
Mollusca	Gastropoda	Neotaenioglossa		Thiaridae		MIV0158	QLD	NT	WA
Mollusca	Gastropoda	Neotaenioglossa		Pomatiopsidae		MIV0159			WA
Nematoda				Nematoda		MIV0160	QLD	NT	WA
Platyhelminthes	Turbellaria	Seriata	Tricladida	Dugesiidae		MIV0164	QLD	NT	WA
Platyhelminthes	Turbellaria	Temnocephalida		Temnocephalidae		MIV0165	QLD	NT	WA
Porifera	Demospongiae			Spongillidae		MIV0166	QLD		WA

APPENDIX 5.2. List of fish species compiled for use in the development of species distribution predictive models.

Family	Genus	Species
Osteoglossidae	*Scleropages*	*jardinii*
Anguillidae	*Anguilla*	*bicolor*
Anguillidae	*Anguilla*	*obscura*
Anguillidae	*Anguilla*	*reinhardtii*
Clupediae	*Nematalosa*	*erebi*
Engraulidae	*Thryssa*	*scratchleyi*
Ariidae	*Neoarius*	*berneyi*
Ariidae	*Neoarius*	*graeffei*
Ariidae	*Neoarius*	*leptaspis*
Ariidae	*Neoarius*	*midgleyi*
Ariidae	*Neoarius*	*paucus*
Ariidae	*Cinetodus*	*froggatti*
Plotosidae	*Anodontiglanis*	*dahli*
Plotosidae	*Neosilurus*	*ater*
Plotosidae	*Neosilurus*	*brevidorsalis*
Plotosidae	*Neosilurus*	*hyrtlii*
Plotosidae	*Neosilurus*	*pseudospinosus*
Plotosidae	*Porochilus*	*spFLINDERS*
Plotosidae	*Porochilus*	*obbesi*
Plotosidae	*Porochilus*	*rendahli*
Hemiramphidae	*Arramphus*	*sclerolepis*
Hemiramphidae	*Zenarchopterus*	*spp*
Belonidae	*Strongylura*	*krefftii*
Atherinidae	*Craterocephalus*	*helenae*
Atherinidae	*Craterocephalus*	*lentiginosus*
Atherinidae	*Craterocephalus*	*marianae*
Atherinidae	*Craterocephalus*	*munroi*
Atherinidae	*Craterocephalus*	*stercusmuscarum*
Atherinidae	*Craterocephalus*	*stramineus*
Melanotaeniidae	*Iriatherina*	*werneri*
Melanotaeniidae	*Melanotaenia*	*australis/solata*
Melanotaeniidae	*Melanotaenia*	*exquisita*
Melanotaeniidae	*Melanotaenia*	*gracilis*
Melanotaeniidae	*Melanotaenia*	*maccullochi*
Melanotaeniidae	*Melanotaenia*	*nigrans*
Melanotaeniidae	*Melanotaenia*	*pygmaea*
Melanotaeniidae	*Melanotaenia*	*splen inornata*
Melanotaeniidae	*Melanotaenia*	*trifasciata*
Pseudomugilidae	*Pseudomugil*	*gertrudae*
Pseudomugilidae	*Pseudomugil*	*tennellus*
Synbranchidae	*Ophisternon*	*spp*
Chandidae	*Ambassis*	*spFITZROY*
Chandidae	*Ambassis*	*spKINGEDWARD*
Chandidae	*Ambassis*	*spNORTHWEST*
Chandidae	*Ambassis*	*agrammus*
Chandidae	*Ambassis*	*elongatus*
Chandidae	*Ambassis*	*macleayi*
Chandidae	*Denariusa*	*bandata*
Chandidae	*Parambassis*	*gulliveri*
Centropomidae	*Lates*	*calcarifer*
Terapontidae	*Amniataba*	*percoides*
Terapontidae	*Hannia*	*greenwayi*
Terapontidae	*Hephaestus*	*carbo*
Terapontidae	*Hepahestus*	*epirrhinos*
Terapontidae	*Hephaestus*	*fuliginosus*
Terapontidae	*Hephaestus*	*jenkinsi*
Terapontidae	*Variicthys*	*lacustris*
Terapontidae	*Leiopotherapon*	*macrolepis*
Terapontidae	*Leiopotherapon*	*unicolor*
Terapontidae	*Pingalla*	*gilberti*
Terapontidae	*Pingalla*	*lorentzi*
Terapontidae	*Pingalla*	*midgleyi*
Terapontidae	*Scortum*	*neili*
Terapontidae	*Scortum*	*ogilbyi*
Terapontidae	*Syncomystes*	*butleri*
Terapontidae	*Syncomystes*	*kimberleyensis*
Terapontidae	*Syncomystes*	*rastellus*
Terapontidae	*Syncomystes*	*trigonicus*
Apogonidae	*Glossamia*	*aprion*
Toxotidae	*Toxotes*	*chatareus*
Toxotidae	*Toxotes*	*kimberleyensis*
Toxotidae	*Toxotes*	*lorentzi*
Mugilidae	*Liza*	*ordensis*
Gobiidae	*Chlamydogobius*	*ranunculus*
Gobiidae	*Glossogobius*	*aureus*

Family	Genus	Species
Gobiidae	*Glossogobius*	*concavifrons*
Gobiidae	*Glossogobius*	*giuris*
Gobiidae	*Glossogobius*	*sp2MUNROI*
Gobiidae	*Glossogobius*	*sp3DWARF*
Eleotridae	*Bostrichthys*	*zonatus*
Eleotridae	*Giurus*	*margaritacea*
Eleotridae	*Hypseleotris*	*burrawayi*
Eleotridae	*Hypseleotris*	*compressa*
Eleotridae	*Hypseleotris*	*ejuncida*
Eleotridae	*Hypseleotris*	*kimberleyensis*
Eleotridae	*Hypseleotris*	*regalis*
Eleotridae	*Kimberleyeleotris*	*hutchinsi*
Eleotridae	*Kimberleyeleotris*	*notata*
Eleotridae	*Mogurnda*	*mogurnda*
Eleotridae	*Mogurnda*	*oligolepis*
Eleotridae	*Oxyeleotris*	*aruensis*
Eleotridae	*Oxyeleotris*	*fimbriata*
Eleotridae	*Oxyeleotris*	*nullipora*
Eleotridae	*Oxyeleotris*	*lineolatus*
Eleotridae	*Oxyeleotris*	*selheimi*
Soleidae	*Leptochirus*	*Sp. (polylepis and darwiniensis*)
Soleidae	*Leptachirus*	*triramus*
Soleidae	*Synaptura*	*salinarum*
Soleidae	*Synaptura*	*selheimi*
Soleidae	*Cynoglossus*	*spp*
Kurtidae	*Kurtus*	*gulliveri*
Megalopidae	*Megalops*	*cyprinoides*
Kuhliidae	*Kuhlia*	*marginata*

APPENDIX 5.3. List of turtle species compiled for use in the development of species distribution predictive models.

Family	Genus	Species	Race	Common name
Carettochelydidae	*Carettochelys*	*insculpta*		
Chelidae	*Chelodina*	*burrungandjii*		
Chelidae	*Chelodina*	*canni*		
Chelidae	*Chelodina*	*rugosa*		
Chelidae	*Elseya*	*dentata*	dentata	
Chelidae	*Elseya*	*dentata*	Arnhem clade	
Chelidae	*Elseya*	*lavarackorum*		
Chelidae	*Myuchelys*	*latisternum*		
Chelidae	*Emydura*	*Subglobosa*	spp	
Chelidae	*Emydura*	*victoriae*		
Chelidae	*Emydura*	*tanybaraga*		
Chelidae	*Emydura*	*worrelli*		
Chelidae	*Emydura*	*australis*		

APPENDIX 5.4. List of waterbird species compiled for use in the development of species distribution predictive models.

Order	Family	Genus	Species	Common name
Anseriformes	Anatidae	*Anas*	*acuta*	Northern Pintail
Anseriformes	Anatidae	*Anas*	*castanea*	Chestnut Teal
Anseriformes	Anatidae	*Anas*	*gracilis*	Grey Teal
Anseriformes	Anatidae	*Anas*	*querquedula*	Garganey
Anseriformes	Anatidae	*Anas*	*rhynchotis*	Australasian Shoveler
Anseriformes	Anatidae	*Anas*	*superciliosa*	Pacific Black Duck
Anseriformes	Anatidae	*Aythya*	*australis*	Hardhead
Anseriformes	Anatidae	*Biziura*	*lobata*	Musk Duck
Anseriformes	Anatidae	*Cereopsis*	*novaehollandiae*	Cape Barren Goose
Anseriformes	Anatidae	*Chenonetta*	*jubata*	Australian Wood Duck
Anseriformes	Anatidae	*Cygnus*	*atratus*	Black Swan
Anseriformes	Anatidae	*Cygnus*	*olor*	Mute Swan
Anseriformes	Anatidae	*Dendrocygna*	*arcuata*	Wandering Whistling-Duck
Anseriformes	Anatidae	*Dendrocygna*	*eytoni*	Plumed Whistling-Duck
Anseriformes	Anatidae	*Dendrocygna*	*guttata*	Spotted Whistling-Duck
Anseriformes	Anatidae	*Malacorhynchus*	*membranaceus*	Pink-eared Duck
Anseriformes	Anatidae	*Nettapus*	*coromandelianus*	Cotton Pygmy-Goose
Anseriformes	Anatidae	*Nettapus*	*pulchellus*	Green Pygmy-Goose
Anseriformes	Anatidae	*Oxyura*	*australis*	Blue-billed Duck
Anseriformes	Anatidae	*Stictonetta*	*naevosa*	Freckled Duck
Anseriformes	Anatidae	*Tadorna*	*radjah*	Radjah Shelduck
Anseriformes	Anatidae	*Tadorna*	*tadornoides*	Australian Shelduck
Anseriformes	Anseranatidae	*Anseranas*	*semipalmata*	Magpie Goose
Charadriiformes	Burhinidae	*Burhinus*	*grallarius*	Bush Stone-curlew
Charadriiformes	Burhinidae	*Esacus*	*neglectus*	Beach Stone-curlew
Charadriiformes	Charadriidae	*Charadrius*	*asiaticus*	Caspian Plover
Charadriiformes	Charadriidae	*Charadrius*	*dubius*	Little Ringed Plover
Charadriiformes	Charadriidae	*Charadrius*	*hiaticula*	Ringed Plover
Charadriiformes	Charadriidae	*Charadrius*	*leschenaultii*	Greater Sand-plover
Charadriiformes	Charadriidae	*Charadrius*	*mongolus*	Lesser Sand-plover
Charadriiformes	Charadriidae	*Charadrius*	*ruficapillus*	Red-capped Plover
Charadriiformes	Charadriidae	*Charadrius*	*veredus*	Oriental Plover
Charadriiformes	Charadriidae	*Elseyornis*	*melanops*	Black-fronted Dotterel
Charadriiformes	Charadriidae	*Erythrogonys*	*cinctus*	Red-kneed Dotterel
Charadriiformes	Charadriidae	*Pluvialis*	*apricaria*	Eurasian Golden Plover
Charadriiformes	Charadriidae	*Pluvialis*	*fulva*	Pacific Golden Plover
Charadriiformes	Charadriidae	*Pluvialis*	*squatarola*	Grey Plover
Charadriiformes	Charadriidae	*Vanellus*	*miles*	Masked Lapwing
Charadriiformes	Charadriidae	*Vanellus*	*tricolor*	Banded Lapwing
Charadriiformes	Glareolidae	*Glareola*	*maldivarum*	Oriental Pratincole
Charadriiformes	Glareolidae	*Stiltia*	*isabella*	Australian Pratincole
Charadriiformes	Haematopodidae	*Haematopus*	*fuliginosus*	Sooty Oystercatcher
Charadriiformes	Haematopodidae	*Haematopus*	*longirostris*	Pied Oystercatcher
Charadriiformes	Jacanidae	*Irediparra*	*gallinacea*	Comb-crested Jacana
Charadriiformes	Laridae	*Anous*	*minutus*	Common Noddy
Charadriiformes	Laridae	*Chlidonias*	*hybridus*	Whiskered Tern
Charadriiformes	Laridae	*Chlidonias*	*leucopterus*	White-winged Black Tern
Charadriiformes	Laridae	*Larus*	*novaehollandiae*	Silver Gull
Charadriiformes	Laridae	*Sterna*	*albifrons*	Little Tern
Charadriiformes	Laridae	*Sterna*	*anaethetus*	Bridled Tern
Charadriiformes	Laridae	*Sterna*	*bengalensis*	Lesser Crested Tern
Charadriiformes	Laridae	*Sterna*	*bergii*	Crested Tern
Charadriiformes	Laridae	*Sterna*	*caspia*	Caspian Tern
Charadriiformes	Laridae	*Sterna*	*dougallii*	Roseate Tern
Charadriiformes	Laridae	*Sterna*	*fuscata*	Sooty Tern
Charadriiformes	Laridae	*Sterna*	*hirundo*	Common Tern
Charadriiformes	Laridae	*Sterna*	*nereis*	Fairy Tern
Charadriiformes	Laridae	*Sterna*	*nilotica*	Gull-billed Tern
Charadriiformes	Laridae	*Sterna*	*striata*	White-fronted Tern
Charadriiformes	Laridae	*Sterna*	*sumatrana*	Black-naped Tern
Charadriiformes	Recurvirostridae	*Cladorhynchus*	*leucocephalus*	Banded Stilt
Charadriiformes	Recurvirostridae	*Himantopus*	*himantopus*	Black-winged Stilt
Charadriiformes	Recurvirostridae	*Recurvirostra*	*novaehollandiae*	Red-necked Avocet
Charadriiformes	Rostratulidae	*Rostratula*	*benghalensis*	Painted Snipe
Charadriiformes	Scolopacidae	*Actitis*	*hypoleucos*	Common Sandpiper
Charadriiformes	Scolopacidae	*Arenaria*	*interpres*	Ruddy Turnstone
Charadriiformes	Scolopacidae	*Calidris*	*acuminata*	Sharp-tailed Sandpiper
Charadriiformes	Scolopacidae	*Calidris*	*alba*	Sanderling
Charadriiformes	Scolopacidae	*Calidris*	*alpina*	Dunlin
Charadriiformes	Scolopacidae	*Calidris*	*canutus*	Red Knot
Charadriiformes	Scolopacidae	*Calidris*	*ferruginea*	Curlew Sandpiper
Charadriiformes	Scolopacidae	*Calidris*	*fuscicollis*	White-rumped Sandpiper
Charadriiformes	Scolopacidae	*Calidris*	*himantopus*	Stilt Sandpiper
Charadriiformes	Scolopacidae	*Calidris*	*melanotos*	Pectoral Sandpiper

Order	Family	Genus	Species	Common name
Charadriiformes	Scolopacidae	*Calidris*	*minuta*	Little Stint
Charadriiformes	Scolopacidae	*Calidris*	*ruficollis*	Red-necked Stint
Charadriiformes	Scolopacidae	*Calidris*	*subminuta*	Long-toed Stint
Charadriiformes	Scolopacidae	*Calidris*	*tenuirostris*	Great Knot
Charadriiformes	Scolopacidae	*Gallinago*	*hardwickii*	Latham's Snipe
Charadriiformes	Scolopacidae	*Gallinago*	*megala*	Swinhoe's Snipe
Charadriiformes	Scolopacidae	*Heteroscelus*	*brevipes*	Grey-tailed Tattler
Charadriiformes	Scolopacidae	*Heteroscelus*	*incanus*	Wandering Tattler
Charadriiformes	Scolopacidae	*Limicola*	*falcinellus*	Broad-billed Sandpiper
Charadriiformes	Scolopacidae	*Limnodromus*	*semipalmatus*	Asian Dowitcher
Charadriiformes	Scolopacidae	*Limosa*	*lapponica*	Bar-tailed Godwit
Charadriiformes	Scolopacidae	*Limosa*	*limosa*	Black-tailed Godwit
Charadriiformes	Scolopacidae	*Numenius*	*madagascariensis*	Eastern Curlew
Charadriiformes	Scolopacidae	*Numenius*	*minutus*	Little Curlew
Charadriiformes	Scolopacidae	*Numenius*	*phaeopus*	Whimbrel
Charadriiformes	Scolopacidae	*Phalaropus*	*lobatus*	Red-necked Phalarope
Charadriiformes	Scolopacidae	*Philomachus*	*pugnax*	Ruff
Charadriiformes	Scolopacidae	*Tringa*	*glareola*	Wood Sandpiper
Charadriiformes	Scolopacidae	*Tringa*	*guttifer*	Nordmann's Greenshank
Charadriiformes	Scolopacidae	*Tringa*	*nebularia*	Common Greenshank
Charadriiformes	Scolopacidae	*Tringa*	*ochropus*	Green Sandpiper
Charadriiformes	Scolopacidae	*Tringa*	*stagnatilis*	Marsh Sandpiper
Charadriiformes	Scolopacidae	*Tringa*	*totanus*	Common Redshank
Charadriiformes	Scolopacidae	*Tryngites*	*subruficollis*	Buff-breasted Sandpiper
Charadriiformes	Scolopacidae	*Xenus*	*cinereus*	Terek Sandpiper
Ciconiiformes	Ardeidae	*Ardea*	*alba*	Great Egret
Ciconiiformes	Ardeidae	*Ardea*	*intermedia*	Intermediate Egret
Ciconiiformes	Ardeidae	*Ardea*	*modesta*	Eastern Great Egret
Ciconiiformes	Ardeidae	*Ardea*	*pacifica*	White-necked Heron
Ciconiiformes	Ardeidae	*Ardea*	*picata*	Pied Heron
Ciconiiformes	Ardeidae	*Ardea*	*sumatrana*	Great-billed Heron
Ciconiiformes	Ardeidae	*Botaurus*	*poiciloptilus*	Australasian Bittern
Ciconiiformes	Ardeidae	*Bubulcus*	*ibis*	Cattle Egret
Ciconiiformes	Ardeidae	*Butorides*	*striatus*	Striated Heron
Ciconiiformes	Ardeidae	*Egretta*	*garzetta*	Little Egret
Ciconiiformes	Ardeidae	*Egretta*	*novaehollandiae*	White-faced Heron
Ciconiiformes	Ardeidae	*Egretta*	*sacra*	Eastern Reef Egret
Ciconiiformes	Ardeidae	*Gorsachius*	*melanolophus*	Malay Night Heron
Ciconiiformes	Ardeidae	*Ixobrychus*	*flavicollis*	Black Bittern
Ciconiiformes	Ardeidae	*Ixobrychus*	*minutus*	Little Bittern
Ciconiiformes	Ardeidae	*Nycticorax*	*caledonicus*	Nankeen Night Heron
Ciconiiformes	Ciconiidae	*Ephippiorhynchus*	*asiaticus*	Black-necked Stork
Ciconiiformes	Threskiornithidae	*Platalea*	*flavipes*	Yellow-billed Spoonbill
Ciconiiformes	Threskiornithidae	*Platalea*	*regia*	Royal Spoonbill
Ciconiiformes	Threskiornithidae	*Plegadis*	*falcinellus*	Glossy Ibis
Ciconiiformes	Threskiornithidae	*Threskiornis*	*molucca*	Australian White Ibis
Ciconiiformes	Threskiornithidae	*Threskiornis*	*spinicollis*	Straw-necked Ibis
Coraciiformes	Alcedinidae	*Alcedo*	*azurea*	Azure Kingfisher
Coraciiformes	Alcedinidae	*Tanysiptera*	*sylvia*	Buff-breasted Paradise-Kingfisher
Coraciiformes	Alcedinidae	*Todiramphus*	*macleayii*	Forest Kingfisher
Coraciiformes	Alcedinidae	*Todiramphus*	*pyrrhopygia*	Red-backed Kingfisher
Coraciiformes	Alcedinidae	*Todiramphus*	*sanctus*	Sacred Kingfisher
Falconiformes	Accipitridae	*Circus*	*approximans*	Swamp Harrier
Falconiformes	Accipitridae	*Haliaeetus*	*leucogaster*	White-bellied Sea-Eagle
Falconiformes	Accipitridae	*Haliastur*	*indus*	Brahminy Kite
Gruiformes	Gruidae	*Grus*	*antigone*	Sarus Crane
Gruiformes	Gruidae	*Grus*	*rubicunda*	Brolga
Gruiformes	Otididae	*Ardeotis*	*australis*	Australian Bustard
Gruiformes	Rallidae	*Amaurornis*	*olivaceus*	Bush-hen sp2
Gruiformes	Rallidae	*Eulabeornis*	*castaneoventris*	Chestnut Rail
Gruiformes	Rallidae	*Fulica*	*atra*	Eurasian Coot
Gruiformes	Rallidae	*Gallinula*	*tenebrosa*	Dusky Moorhen
Gruiformes	Rallidae	*Gallinula*	*ventralis*	Black-tailed Native-hen
Gruiformes	Rallidae	*Gallirallus*	*philippensis*	Buff-banded Rail
Gruiformes	Rallidae	*Lewinia*	*pectoralis*	Lewin's Rail
Gruiformes	Rallidae	*Porphyrio*	*porphyrio*	Purple Swamphen
Gruiformes	Rallidae	*Porzana*	*cinerea*	White-browed Crake
Gruiformes	Rallidae	*Porzana*	*fluminea*	Australian Spotted Crake
Gruiformes	Rallidae	*Porzana*	*pusilla*	Baillon's Crake
Gruiformes	Rallidae	*Porzana*	*tabuensis*	Spotless Crake
Gruiformes	Rallidae	*Rallina*	*tricolor*	Red-necked Crake
Passeriformes	Artamidae	*Cracticus*	*nigrogularis*	Pied Butcherbird
Passeriformes	Hirundinidae	*Petrochelidon*	*nigricans*	Tree Martin
Passeriformes	Maluridae	*Malurus*	*coronatus*	Purple-crowned Fairy-wren
Passeriformes	Pachycephalidae	*Pachycephala*	*melanura*	Mangrove Golden Whistler
Pelecaniformes	Anhingidae	*Anhinga*	*melanogaster*	Darter
Pelecaniformes	Anhingidae	*Anhinga*	*novaehollandiae*	Australasian darter
Pelecaniformes	Fregatidae	*Fregata*	*ariel*	Lesser Frigatebird

Order	Family	Genus	Species	Common name
Pelecaniformes	Pelecanidae	*Pelecanus*	*conspicillatus*	Australian Pelican
Pelecaniformes	Phaethontidae	*Phaethon*	*rubricauda*	Red-tailed Tropicbird
Pelecaniformes	Phalacrocoracidae	*Microcarbo*	*melanoleucos*	Little Pied Cormorant
Pelecaniformes	Phalacrocoracidae	*Phalacrocorax*	*carbo*	Great Cormorant
Pelecaniformes	Phalacrocoracidae	*Phalacrocorax*	*sulcirostris*	Little Black Cormorant
Pelecaniformes	Phalacrocoracidae	*Phalacrocorax*	*varius*	Pied Cormorant
Pelecaniformes	Sulidae	*Sula*	*leucogaster*	Brown Booby
Podicipediformes	Podicipedidae	*Podiceps*	*cristatus*	Great Crested Grebe
Podicipediformes	Podicipedidae	*Poliocephalus*	*poliocephalus*	Hoary-headed Grebe
Podicipediformes	Podicipedidae	*Tachybaptus*	*novaehollandiae*	Australasian Grebe
Podicipediformes	Podicipedidae	*Tachybaptus*	*ruficollis*	Eurasian Little Grebe

APPENDIX 5.5

WATERBIRDS DATA & RELATED ENVIRONMENTAL DATASETS COLLATED BY SSD FOR THE NORTHERN AUSTRALIAN WATER FUTURES ASSESSMENT (ECOLOGICAL ASSETS SUB-PROJECT), MARCH 2010

Compiled By James Boyden

TABLE OF CONTENTS

1 Introduction

This brief report provides background reference material on waterbird distribution datasets (and associated environmental records) that were collated and standardised for the Northern Australian Water Futures Project (ecological assets subproject). Waterbirds survey data covering either part or the entire NAWFA study area were sourced from relevant State, Territory, and Commonwealth Agencies, and the University of New South Wales. James Boyden (SSD) coordinated the acquisition and collation of datasets. While every effort was made to consolidate datasets made available to SSD over the project time-line, some of the datasets (e.g. those acquired from the Parks & Wildlife Service of the NT) were incomplete at the time of compiling this report.

2 Data Storage

Collated data have been supplied on DVD accompanying this report and are organised according to the directory structure outlined by Fig. 1. To cite original data files named in this report, please refer to the relevant ‘rawdata’ directory for each dataset. Additional metadata supplied with raw data files are stored under relevant subfolders in the “rawdata” directory. . Further details are summarised in Table 1.

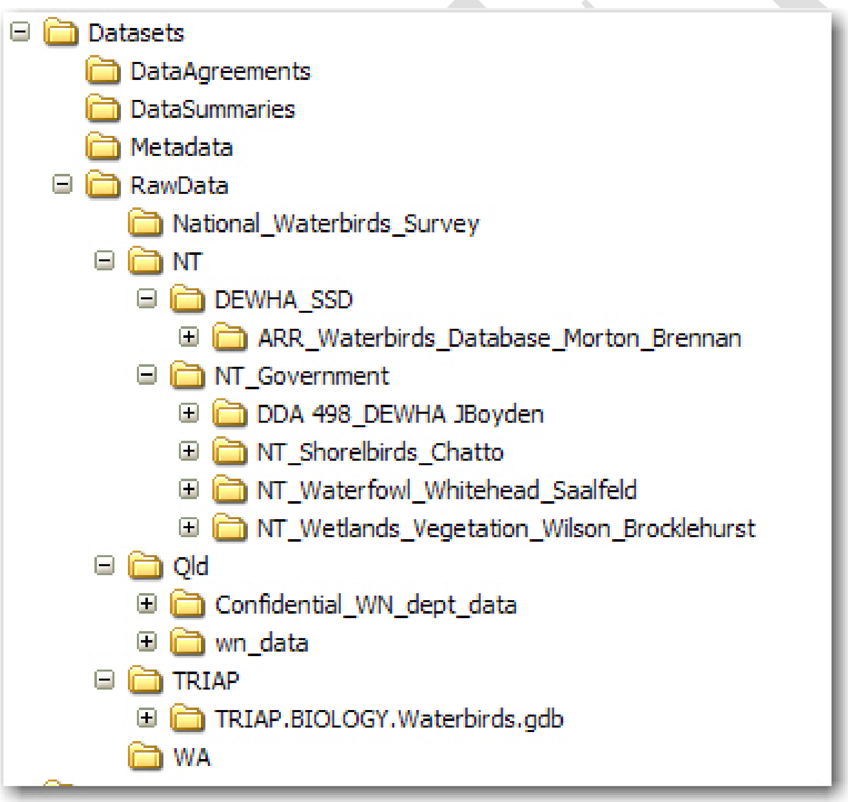

Figure 1. Directory structure for datasets provided on distribution DVD for this project

3 DATA SOURCES

Specific datasets included:

8. The National Water Birds Survey (NWBS), 2008, sourced through John Porter of the University of New South Wales. Ancillary environmental data include information on associated wetland names and area. The dataset is complete for the NAWFA coverage area.
9. Presence-only distribution records collated for the Tropical Rivers Inventory and Assessment Project (TRIAP) from Australian Bird Atlas records- see (Franklin 2008). Data cover the entire NAWFA area.
10. Quantitative aerial surveys (1984-2000) of waterfowl (Magpie Geese) for the Top End of the Northern Territory (NT), sourced from the Parks and Wildlife Service of the Northern Territory (PWSNT). At time of collating this report, some gaps were apparent in the data provided.
11. Quantitative ground and aerial surveys of shorebirds, and significant breeding colonies for the Top End of the Northern Territory (NT), sourced from the Parks and Wildlife Service of the Northern Territory (PWSNT). At time of collating this report, some gaps were apparent in the data provided. Data exist from 1990-1999, but records from 2000-2003 are missing.
12. Quantitative waterbird surveys over seasonal wetlands of the Alligator Rivers Region (ARR) of the NT, provided by the Supervising Scientist Division (SSD) of the Commonwealth Department of the Environment, Water, Heritage and the Arts (DEWHA). These data include:
    a. Systematic aerial survey, conducted monthly from June 1981 to August 1984. Environmental information on dominant cover types is also included (Wet Plain, Dry Plain, Wet Melaleuca, Dry Melaleuca, Open Water, Dry Woodland, Mud);
    b. For the same period and sampling frequency above, systematic ground surveys from 30 sites on the Magela Floodplain, Kakadu National Park;
    c. For the same period and sampling frequency above, ground and aerial surveys at 17 billabongs within the Magela Creek catchment. Environmental information includes structural classification of each billabong surveyed; .
13. Presence-only distribution records sourced from the WildNet database through the Queensland Department of Environment and Resource Management (DERM).
14. Miscellaneous waterbird records for WA from provided from various sources through Peter Bayliss

Wetland Vegetation Characterisation of NT Wetlands. Please refer to technical report on DVD (Wilson et al 1991) for description of vege4tation attributes contained on associated shapefile.

Table 1 Summary of waterbird datasets supplied in this report on DVD.

Custodian	Dataset	Coverage Area	Summary Data[1] for NAWFA	Raw Data	Completeness
DEWHA -SSD	**TRIAP Waterbirds (presence only)**	National (TRIAP area)	TRIAP_Franklin_2008 Table of NAWFA_Waterbirds_Summary_B.mdb	File Geodatabase: TRIAP.BIOLOGY.Waterbirds.gdb	Complete
NT NRETA – Saalfeld & Whitehead	**Magpie Geese & waterfowl (quantitative)**	Welland's between the Moyle River Catchment and East Alligator and Cooper Creek Catchments	*Not summarised any further*	NT_TopEnd_WaterbirdSurveys_Saalfeld_etal.mdb (original data supplied to Peter Bayliss and collated by James Boyden) Raw data containing a few additional; years was re-supplied as shapefiles in the directory DDA 498_DEWHA JBoyden	Western Arnhemland coverage appears complete for survey years 1984-84, 1996-97, and 2000. Top-End wide survey coverage's (conducted in 1984, 1985 and 1986) are missing
NT NRETA – Chatto	**Shorebirds & Sea Birds (Semi-quantitative)**	Coastal wetlands of the NT	Tables[2]: NT_SeaBirdColonies_Group_summary, NT_SeaBirdColonies_Species_summary, NT_WaterbirdColonies_Group_summary, and NT_WaterbirdColonies_Species_summary of NAWFA_Waterbirds_Summary_B.mdb	Raw Data_Cstdata_Access2003.mdb	Incomplete temporal coverage (data only supplied from 1990 to 1999. According to Ray Chatto, further data exist in database form up until 2003.
NT NRETA – Wilson & Brocklehurst	**Wetland vegetation of the NT**	Coastal wetlands of the NT	*Not summarised any further*	Listed under RawData\NT\NT_Government\NT_Wetlands_Vegetation_Wilson_Brocklehurst	Complete for 1990
DEWHA -SSD	**ARR_Waterbirds_Database_Morton_Brennan (Quantitative systematic survey records**	Wetlands of the Alligator Rivers Region, NT	Tables ARR_AerialSurveys_Crosstab__estimated_density_with_Zeros, ARR_MagelaBillabongs_Counts, and ARR_MagelaGroundCounts of NAWFA_WaterBirds_Summary_A_corrected.mdb *Environmental data not summarised any further*	Morton_Brennan_ARR_Bird_Surveys_20100309.mdb	Monthly records complete for 1981-1984
Qld DERM	**WildNet waterbirds data (Presence only records)**	Queensland	Table Qld_WildNet_WaterBirdSummary of NAWFA_Waterbirds_Summary_B.mdb *(filtered for waterbirds)*	dept_data.DBF (selected confidential records) & wn_data.dbf (publicly available records)	Incomplete (3rd party confidential records not supplied by DERM)
WA	**-**	WA	-	- miscellaneous records	-unknown

1. Note that species list names have been normalised according to the CAVs taxon list used in the National waterbird surveys. Species have also been groups according to two separate 'Guild' attributes used by UNSW & Don Franklin (TRIAP).
2. Note that species level counts are provided in tables containing 'Species' in the name while counts in 'Group' data tables refer to additional independent counts of generic bird groups, eg waders, egrets

3 DATA STANDARDISATION

Standardised summaries were produced from each dataset, listed in Section 1, with the exception of datasets under point 7. Selected spatially referenced count records of waterbirds were collated in a Microsoft Access database from original datasets supplied in various formats (PDF, Text, DBF, XLS and MDB formats). Species names were standardised to the CAVS (Census of Australian Vertebrate Species) list[3]. Two guild-grouping attributes (used for the NWBS and the TRIAP) were also linked to the waterbird data summaries. Standardisation and linking of guild categories was undertaken using the Species Coding Access file (See metadata directory on supplied DVD). Original attributes for each dataset were preserved in the supplied raw data tables.

For the ARR summary dataset only, raw count data from aerial surveys were converted to density/Km^2 estimates. Raw count records were retained in all other data summaries. In the case of the NT waterfowl datasets, metadata supplied in the NT Goose Surveys DataSummary.xls spreadsheet may be used to calculate density estimates from raw data.

4 DATA LICENSE AGREEMENTS

Data agreements were arranged for the datasets supplied from NT Government., and a PDF copy is provide with the data supplied on DVD. For DEWHA data acquired through SSD (Alligator Rivers Waterbirds dataset) no digital data agreement was arranged as the NAWFA project is a DEWHA funded project. Mark Kennard acquired data license agreements for remaining datasets from other custodians, however these were not cited at the time of compiling this report (WA, Qld and National Waterbirds survey datasets).

[3] See http://www.environment.gov.au/biodiversity/abrs/online-resources/fauna/cavs/index.html for more information on CAVS

5 METADATA

Metadata supplied in this section was compiled only for selected datasets. Metadata summaries are not included for NT Wetland vegetation, NT Shorebirds, and WA datasets. However additional metadata and PDF reports relating to these datasets are provided with the original datasets and these files reside in the relevant Raw Data directory with the supplied DVD.

5.1 TRIAP - THE WATERBIRDS OF AUSTRALIAN TROPICAL RIVERS AND WETLANDS (FRANKLIN 2008)[4]

Note: Refer to Franklin 2008 for full bibliographic details of the citations listed in this section

Location: Server=nt01app01; Service=esri_sde; Database=ssdp1; User=TRIAP; Version=SDE.DEFAULT

Coordinate system: GCS_GDA_1994

Theme keywords: FAUNA_Mapping, FAUNA Native_Conservation, FAUNA Native_Classification, FAUNA Native_Distribution, FAUNA Native_Indicators, FAUNA Native_Mapping, FAUNA Native_Monitoring, FAUNA Native_Surveys

ISO AND ESRI METADATA:

- Resource Information
- Spatial Representation Information
- Reference System Information
- Data Quality Information
- Distribution Information
- Metadata Information

Metadata elements shown with blue text are defined in the International Organization for Standardization's (ISO) document 19115 *Geographic Information - Metadata.* Elements shown with green text are defined by ESRI and will be documented as extensions to the ISO 19115. Elements shown with a green asterisk (*) will be automatically updated by ArcCatalog.

Resource Information:

Title: TRIAP - The waterbirds of Australian tropical rivers and wetlands (Franklin 2008)
Alternate title(s): TRIAP.FAUNA_BIRDS

Abstract:
1) As part of the Tropical Rivers Inventory and Assessment Project (TRIAP), a database of 94,148 waterbird records was assembled, comprising 82,596 records from the TRIAP area and 11,552 records from a surrounding 10 km buffer. These records were sourced from databases for Atlas1 and Atlas2 provided by Birds Australia, 99.1% of which are from the Historical Atlas (pre-1977), the first Field Atlas (1977-1981) or the second Field Atlas (1997-2002).

2) Waterbirds were defined to include species of freshwater and coastal wetlands including in-shore but not off-shore marine species. The TRIAP waterbird fauna

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[4] ISO 19115 metadata summary extracted from ArcSDE from SSDs GIS data storage system

comprises 145 species from twenty families, of which 112 species are represented in the database by more than ten records.

3) One TRIAP waterbird species – the Australian Painted Snipe – is listed as threatened under the Environment Protection and Biodiversity Conservation Act 1999 (EPBCA). Eighty-seven species are listed as "migratory" under the EPBCA, 44 species are listed under the Japan-Australia Migratory Bird Agreement and 53 species under the China-Australia Migratory Bird Agreement. The geographical characteristics of all listed species are summarised for the TRIAP area.

4) In the TRIAP area, the Australian Painted Snipe is an infrequent visitor or perhaps rare resident found more frequently in the more arid south. Its preferred habitat of ephemeral wetlands with a mix of mud-flats and dense low vegetation does not closely match habitats recorded for the species in the TRIAP area, which may reflect the marginal nature of its occurrence in this area. Breeding records in the TRIAP area have been in flooded grasslands.

5) A foraging guild classification based on a classification of foraging substrate, foraging methods and food types is presented in this dataset. Twelve foraging guilds are recognised as occurring in the TRIAP area.

6) No waterbirds are endemic to the TRIAP area. However, the TRIAP area represents a major proportion of the range of the Chestnut Rail, and a major proportion of the Australian range of the Great-billed Heron.

7) A biogeographic classification of TRIAP waterbirds is developed based on breeding distributions. Four classes are recognised: a. species for whom TRIAP is a core breeding area; b. Australasian species for whom TRIAP is marginal to their main distribution; c. Palaearctic / Nearctic migrants – these do not breed in Australia; and d. Non-migratory species with a distribution centre in Asia, or Malaysia including New Guinea. Few species other than vagrants have restricted ranges within the TRIAP area, but there is a weak declining gradient in species richness from east to west.

8) The distribution of waterbird families, foraging guilds and threatened species were compared qualitatively with a 1:250 000 classification of waterbodies into seven units. Although the results are "noisy", groups associated with deep water and saline habitats were clearly identifiable. A geomorphic classification of rivers provides only linear data and poor spatial correspondence with waterbird records. Neither classification provides a direct measure of the wetland features most relevant to most species, and whilst quantitative analysis could be pursued, it appears unlikely to identify many definitive habitat relationships.

See Table 6, section 3.3 of (Franklin 2008) for an explanation of foraging guilds. Note that "herbivore" includes the possibility of also being extensively insectivorous, whereas "insectivore" implies that herbivory is not a major component of the diet.

See lineage for more details or refer to:

Franklin DC. 2008. Report 9: The waterbirds of Australian tropical rivers and wetlands. In A Compendium of Ecological Information on Australia's Northern Tropical Rivers. Sub-project 1 of Australia's Tropical Rivers – an integrated data assessment and analysis (DET18). A report to Land & Water Australia, ed. GP Lukacs, CM Finlayson. National Centre for Tropical Wetland Research: Townsville.

Note: Metadata not published in Australian Spatial Data Directory (ASDD) as of October 2009- No ANZLIC Unique Identifier assigned.

Creation Date: 2008-05-01

***Presentation format:** digital map

Unique resource identifier: ISOCW0501006695

Custodian Organisation: Australian Government Department of the Environment and Heritage
Contact's position: GIS Manager

Contact information:
Phone:

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Country: Australia

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Online resource:

Online Location: http://www.deh.gov.au/

Publisher Organisation: Australian Government Department of the Environment, Water, Heritage and the Arts

Contact's position: Metadata Publisher

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Online resource:

Online Location: http://www.environment.gov.au/

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Themes or categories of the resource: biota

Theme keywords:

Keywords: FAUNA_Mapping, FAUNA Native_Conservation, FAUNA Native_Classification, FAUNA Native_Distribution, FAUNA Native_Indicators, FAUNA Native_Mapping, FAUNA Native_Monitoring, FAUNA Native_Surveys

Dataset language: English

Dataset character set: utf8 - 8 bit UCS Transfer Format

Update Status: completed
Update frequency: not planned

Resource constraints:
Access constraints:

The data are subject to Commonwealth of Australia Copyright. A licence agreement is required.

Limitations of use:

Since most statements about the waterbody units from which a taxon or guild was recorded are based on sampling, statements such as 'was not recorded' should not be interpreted as absolute. Statements about positive or negative associations or lack of association with waterbody units are qualitatively equivalent to goodness-of-fit tests in which patterns of association with waterbody units of the taxon or guild are compared with that for all waterbirds.

Methodological issues:

The data and analysis is both qualitative and broad-brush. For a number of reasons, it cannot be expected to produce strong or definitive results.

The first reason is that there is a fundamental and often severe mismatch of scales between the waterbody and waterbird data. Waterbird surveys are rarely point surveys, often of necessity. Wetlands frequently comprise a mosaic of habitats even at the large scale measurable by remote sensing. Thus, general waterbird surveys such as Atlas data frequently do not discriminate between elements of the mosaic which the waterbody classification does. Indeed, the precision of much Atlas data is often measured in kilometres rather than metres.

Secondly, the waterbody classification is not specifically designed to reflect features of relevance to waterbirds. For example, there appears to be no discrimination between treed and treeless floodplain vegetation nor between brackish and freshwater lakes. Relevant features may also be at a scale far too fine to be measured by remote sensing, for example in the structure of wetland margins. Relevant wetland characteristics may also change over time, for example in degrees of salinity or the state of margin vegetation. Thirdly, the habitat requirements of a species are not necessarily unitary. Optimal habitat may change from the breeding to non-breeding season, and a species may utilise several sets of habitat characteristics more or less simultaneously, for example alternately for foraging and nesting.

Finally, habitat requirements are most characteristic of species, whereas these analyses are pitched at families and foraging guilds. This may be particularly problematic in families where divergence has occurred though gross habitat specialisation, as for instance is particularly the case within the Ardeidae. It may thus be anticipated that families with only one or a few species within the TRIAP area will show greater habitat definition than speciose families, and this was often the case. Furthermore, foraging guilds may show clearer habitat definition than families because the classification is in itself a partial description of habitat requirements, and this also was often the case.

There are particular problems with both the waterbodies and geomorphic datasets. A major problem with the waterbodies dataset is that it does not indicate watercourses less than 250 m wide, a problem avoided by the geomorphic datasets. The entirely linear nature of the geomorphic datasets is problematic, though this could be overcome by incorporating buffers into the GIS or attributing all records to the geomorphic unit in nearest proximity. There are therefore, possibilities for further and more quantitative analysis of these datasets. However, given the series of constraints detailed in the above paragraphs, it is not envisaged that such analyses will offer great enhancement to the definition of waterbird / habitat relationships.

Also refer to data quality reports

***Spatial representation type:** vector

Resource format:

Format name: SDE Feature Class

Resource's bounding rectangle:

*__Extent type:__ Full extent in decimal degrees

*__Extent contains the resource:__ Yes

*__West longitude:__ 122.0389

*__East longitude:__ 145.5

*__North latitude:__ -10.69472

*__South latitude:__ -21.66667

Supplemental information:

not to be published

Dataset point of contact:

Organisation: Australian Government Department of the Environment and Heritage

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Administrative area: NT

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Country: Australia

e-mail address: enquiries_ssd@deh.gov.au

Online resource:

Online Location: http://www.deh.gov.au/

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Spatial Representation - Vector:

***Level of topology for this dataset:** geometry only
Geometric objects:

***Name:** TRIAP.FAUNA_BIRDS

***Object type:** point

***Object count:** 82708

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Reference System Information:

Reference system identifier:
***Value:** GCS_GDA_1994

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Data Quality Information:

Lineage:
The following is an extract from the Franklin 2008 report:

The two source databases provided by the Commonwealth for this project were BA_ATLAS1.mdb and Bird Australia_97.mdb. These are the Atlas1 and Atlas2 datasets compiled by Birds Australia (Blakers et al. 1984, Barrett et al. 2003), although in both cases the datasets extend beyond the Field atlas data (section 2.2 of Franklin 2008).

Relevant fields were extracted from the source databases, merged and cropped to include only those in the TRIAP area and a surrounding 10 km buffer. The buffer records were retained because of location inaccuracies in the databases (discussed in section 2.2) and in particular that a substantial portion of coastal records and species would be lost without the buffer. Atlas1 records were vetted to exclude those coded as other than "normal" or "confirmed", i.e. the categories "doubtful" and "escapee" and several codes for which metadata are not available, although there it appears that records published by Blakers et al. (1984) have been vetted further. Atlas2 records had previously been vetted by Bellio (unpublished).

The resultant database is hereafter referred to as the master database (file: TRIAP_waterbirds_master.dbf). It contains 82,596 records for the TRIAP area and 11,552 records from the buffer, 94,148 in total. Study area and buffer records are distinguished in the database, as is the TRIAP catchment of each study area record. Metadata for the database and its derivate sub-set databases are provided in Appendix 3 (Franklin 2008).

SOURCES OF ATLAS DATA

Atlas1 and Atlas2 records were obtained from a variety of sources, eleven of which are represented in the master database (see Table 1 of Franklin 2008). However, 99.1% of records were derived from three sources, the Historical Atlas and the Atlas1 and Atlas2 field atlases. The Historical Atlas is a more or less exhaustive database of published and unpublished records along with specimen records from museum and private collections around the world - Blakers et al. (1984, p. xxv) describe it as "a comprehensive catalogue of the distribution of Australian birds from the time of European settlement". The two field atlases are extensive datasets for the periods 1977–1981 and April 1997 to April 2002 respectively, as reported by Blakers et al. (1984) and Barrett et al. (2003).

Metadata for other Atlas2 sources not been provided. The "Nest Record Scheme" refers to the Birds Australia project of that name (Marchant 1987-1989). "Parks & Wildlife Commission NT" records presumably refer to the Biological Records Scheme for which no metadata have evidently been published. "QPWS WildNet" refers to the Queensland Parks & Wildlife Service's wildlife database (e.g. Anon. 2002). "Birds on Farms" was a Birds Australia project, the methods for which are presented by Barrett (2000).

For current purposes, precision and accuracy are problematic. These datasets are all extensive in nature and individual search areas were often large (Table 2). For example, in the Atlas1 field survey, records were attributed to map grids of either 10' or 1º in area for which the coordinates were the centre of the grid cell. The two hectare searches of the Atlas2 field survey are by definition the most precise, with accuracy enhanced by the availability of

Global Positioning Systems in recent times, but the alternate larger search areas are more generally applicable to the often-extensive wetlands of tropical areas. Thus, although the proportion of Atlas2 surveys that were 2 ha searches varied greatly between IBRA bioregions (Barrett et al. 2003, p729-730), these data are unlikely to be particularly relevant to waterbirds.

A GIS was prepared for the TRIAP area in which the following hierarchy could be superimposed:

1. Atlas1 records for the specified taxon or foraging guild

2. Atlas2 records for the specified taxon or foraging guild

3. all waterbird records

4. the waterbodies classification.

The distinction between Atlas1 and Atlas2 was maintained in recognition of the lower precision and accuracy associated with the latter (Table 2 - Franklin 2008).

As the relevant datasets are extremely detailed, it was possibly only to consider a sample of the TRIAP area. For this purpose, the TRIAP area was divided into 17 compartments (Table 9). Because mangrove habitat occupies such a small portion of the TRIAP landscape and most mangrove areas were poorly surveyed for birds in the Atlas datasets, an additional two compartments featuring well-surveyed mangrove areas were identified and included (Table 9- Franklin 2009).

For each compartment, I zoomed in on one or more focus areas (usually two or three) containing records of the taxon or foraging guild or containing numerous records of waterbirds but notably lacking records of the taxon or foraging guild, and noted the waterbody units utilised along with any evidence of differential use of waterbody units.

Records that were within a few kilometres of a waterbody unit were attributed to the nearest unit. The patterns noted in each compartment were aggregated across all compartments to provide a qualitative synthesis of the patterns of habitat use observed. I also noted evidence of habitat selection at the level of aggregations of units into coastal wetland complexes, major floodplains or river/billabong systems.

For the focus catchments, the exercise was repeated , zooming in on a minimum of ten selections within each catchment.

Further metadata relating to database structure and explanation of terms and codes can be found in Appendix 3 of Franklin (2009)

Source data acknowledgements:

See Franklin DC. 2009.

Data quality report - Absolute positional accuracy:

Extract from Table 2 of Franklin 2008

Historical Atlas Data:

These represent 11% of the Master Dataset (for the pre-1977 Survey Period). Precision & Accuracy is variable and frequently very low

Atlas1 field records: These represent 34.4% of the Master Dataset (for the Jan. 1977 – Dec. 1981 Survey Period). These records were derived from grid-based recording; (grid cell were either 10' or 1-degree cells- averaging c. 18.5 x 18 km or 110.5 x 107.5Km in the TRIAP area.

Atlas2 field records:

These represent 53.7% of the Master Dataset (for the April 1997 – April 2002 Survey Period). Precision of records was derived from either GPS or map-based, point centred records and was either 2ha, 500m radius, or 5km radius)

Data quality report - Attribute accuracy:

Historical Atlas Data:

These represent 11% of the Master Dataset (for the pre-1977 Survey Period). Records from literature and diaries, often with only very general locational information and with lists of species for large areas. Many records attributed to cells in excess of 100 x 100 km

Data quality report - Conceptual consistency:

Unknown

Data quality report - Completeness:

Complete for the data collated:

Given the remoteness of much of the TRIAP area, coverage is surprisingly substantial and well-dispersed (Fig. 2). Nevertheless, there are major gaps and considerable unevenness. Coverage is particularly heavily concentrated in the Darwin-Kakadu-Katherine region of the Northern Territory and the Kununurra-Ord River region of Western Australia, along with other smaller foci such as Broome and Cloncurry-Mt Isa. In remoter areas, the path of main roads is clearly traceable in the record even at the coarse scale of Figure 2. The unevenness of coverage is related primarily to accessibility and proximity to major settlements. Furthermore, because a high proportion of records are contributed to visitors and access is limited during the wet season, seasonal coverage is both uneven and geographically biased. In the Atlas1 Field atlas, almost every degree cell received some coverage during "winter", but much of Cape York Peninsula, Arnhemland and the north Kimberley received no coverage at all during "summer" (illustrated by Blakers et al. 1984: pp. xxx – xxxi).

Catchment totals varied by more than two orders of magnitude (Table 3). Whilst considerable unevenness can be attributed to variation in the size of catchments and in particular the area of wetlands they contain, coverage of less than 100 records (eight catchments) is by any definition very poor coverage. On the other hand, eighteen catchments are represented by more than 1,000 records and the three focus catchments each by more than 2,500 records.

Of more concern for the issues under consideration here are unevenness in coverage of habitats due to variation in accessibility. This effect varies greatly amongst catchments. For example, coasts of the TRIAP area are often remote, swampy and accessible, but this is markedly not the case in the Cape Leveque Coast (Broome) and Finniss River Darwin) catchments. Even at quite local scales, the accessibility of habitats to observers can vary substantially – as an example, not the accessibility of sandstone watercourses in Litchfield National Park and the contrasting inaccessibility of floodplain wetlands in the nearby Reynolds River floodplain. Observers also tend to focus on landscape features such as lakes or rivers at the expense of floodplains and extensive swamps, and mangrove and saline coastal flats are particularly poorly sampled.

As a result, it would be spurious and seriously misleading to assume that waterbird records represent a random sample of habitat. However, there is a simple solution which is generally robust when considering the habitat relationships of elements of the waterbird fauna separately - to use the distribution of all waterbird records as the baseline against which the distribution of sub-sets may be compared. This is a variation of the method employed by Franklin (1998) to characterise changes in abundance of granivorous bird species from Atlas and other historic data.

Distribution Information:

Distributor's name: Australian Government Department of the Environment, Water, Heritage and the Arts

Distribution format:

Format name: ArcView shapefile

Transfer options:

***Online Location:** Server=nt01app01; Service=esri_sde; Database=ssdp1; User=TRIAP; Version=SDE.DEFAULT

Available As: Departmental Data

Metadata Information

***Metadata language:** English
***Metadata character set:** utf8 - 8 bit UCS Transfer Format

Last update: 2009-10-09

Metadata contact:
Organisation: Australian Government Department of the Environment and Heritage

Contact's position: GIS Manager

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City: Darwin

Administrative area: NT

Postal code: 0801

Country: Australia

e-mail address: enquiries_ssd@deh.gov.au

Online resource:

Online Location: http://www.deh.gov.au/

*Scope of the data described by the metadata: dataset

*Scope name: dataset

Name of the metadata standard used: ISO 19115 Geographic Information - Metadata
Version of the metadata standard: Australian Government

5.2 National Waterbird Survey Dataset, 2008

These data were collected by aerial survey methods outlined by Richard Kingsford –Smith and John Porter at http://www.wetrivers.unsw.edu.au/docs/rp_nws_home.html. Semi-quantitative bird counts are included with ancillary information on wetland name and extent, described under the tblWetLand_Area attibute). The dataset provided was clipped to the NAWFA project area which includes all Timor Sea and Gulf of Carpentaria (Fig. 2).

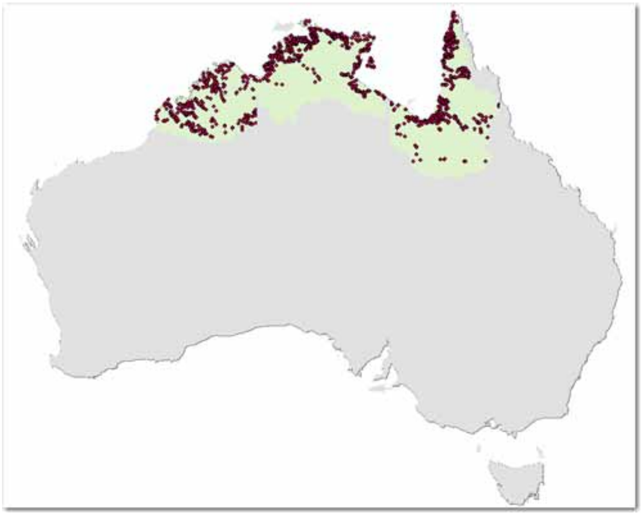


Figure 2. Coverage of data records provided from the NWBS, 2008, for the NAWFA project area (green shading).

James Boyden liaised with John Porter to acquire these data. Brief metadata are provided with the raw data spreadsheets. For further information please also refer to:

http://www.wetrivers.unsw.edu.au/docs/rp_nws_home.html

5.3 Aerial surveys of Waterfowl (Magpie geese) conducted in the Top End Region from 1984-2000 by Parks and Wildlife Service of the Northern Territory

Monitoring waterfowl populations, including the Magpie goose, has been undertaken by the PWSNT across the Top End since 1983. Data represent systematic aerial counts along predetermined transect lines on wetlands at either 2.4 or 5.4km transect intervals. Sampling generally occurred in the late wet season and sometimes included nest counts for Magpie Geese. Please refer to the NT Goose Surveys DataSummary.xls spreadsheet for further technical details on individual surveys. The key purpose of the monitoring is to detect changing trends in the distribution and abundance of major species. The seasonal timing of surveys is variable although most occur during the Magpie goose nesting period (late Wet season to early Dry season).

Data were collated for the Western Top End Region for the period 1984-2000. These data, cover Top End wetlands between Moyle River (to the west) and the East Alligator River-Cooper Creek catchments generally, however in some years selected wetlands, only, were surveyed in this region. In addition to bird counts, nest counts are included for Magpie Goose, Brolga, & Jabiru in some years.

Surveys conducted in 1984, 1985 and 1986 apparently covered a larger area of the Top End, compared to the Western Top End region (Delaney 2008). However data extending outside of t Western Top End Region were not included in those collated with this report. Additional data from 2001- 2007, cited in metadata spreadsheets are also absent from this report.

Data were provided to Peter Bayliss by Peter Whitehead (NRETAS), for surveys conducted between 1984 and 1996; and Keith Saalfeld (NRETAS-PWSNT) for the 2000 survey for data. Data was provided as separate files for selected species and each survey year and season. These data were collated in an Access (see table 1). More recently data for the years 1991 to 2006 was re-supplied by Keith Saalfeld. Compared to data that was originally supplied, these data were found to have some anomalies in terms the number of records in each year. (see table 2)

Additional information on these datasets (pre-2000) and survey methodology standards have been documented in various reports and publications (Bayliss and Yeomans 1990a; Bayliss and Yeomans 1990b; Chatto 2000; 2006; Colley 1999; Saalfeld 1990).

Table 2. Anomalies noted between magpie goose datasets previously provided through Peter Bayliss and datasets re-supplied by Keith Saalfeld

Year	Season	Coverage	Number of records	
			Previous	Re-supplied
1984	wet	Moyle to East Alligator (Top End Extent missing?)	1376	x
1984	dry	Moyle to East Alligator (Top End Extent missing?)	2064	x
1985	wet	Moyle to East Alligator (Top End Extent missing?)	2064	x
1986	wet	Moyle to East Alligator (Top End Extent missing?)	2064	x
1987	wet	Complete coverage Moyle to East Alligator	1980	x
1988	wet	Complete coverage Moyle to East Alligator	2064	x
1989	wet	Complete coverage Moyle to East Alligator	2063	x
1990	wet	Moyle to East Alligator (Sth Alligator missing)	2808	x
1991	wet	Complete coverage Moyle to East Alligator	5616	6174
1992	wet	Complete coverage Moyle to East Alligator	4482	3779
1993	wet	Complete coverage Moyle to East Alligator	1242	5183
1994	dry	Kakadu & Murganella FPs only	X	329
1995	not surveyed	not surveyed	X	X
1996	dry	Western floodplains (excluding Kakadu & Murganella FPs)	538	538
1997	dry	Moyle to East Alligator	X	228
1998	not surveyed	not surveyed	X	X
1999	not surveyed	not surveyed	X	X
2000	wet	Moyle to East Alligator	1552 + 469	2689

Two observers were used to count birds, one from RHS & the other from LHS of aircraft. Records usually consisted of two separate count records for each grid point along a transect, therefore. However, for the data provided for 1990-91 only one record per grid point was provided. In these cases it may be assumed that data are a summary calculation from both observers, however and explicit explanation on how these calculations were made is currently absent from metadata. These differences have been summarised in the Observer LUT of the Access database used to collate the raw files (with an additional code ‘assumed sum of 2 observers’ assigned for cases where two separate observer counts were not present.

Specific dates for survey records were not always provided with the supplied datasets. Instead data were indexed by ‘year’ and ‘season’ (Wet/Dry). When specific dates were provided data had not been coded by year and season, and these attributes had to be populated. In this case data observations from March to April were coded as “wet” season data.

There were some duplicate count anomalies (for same location, time, species, and observer) for 1992 (148 duplicates, each usually only have one additional record) with ranging associated count values.

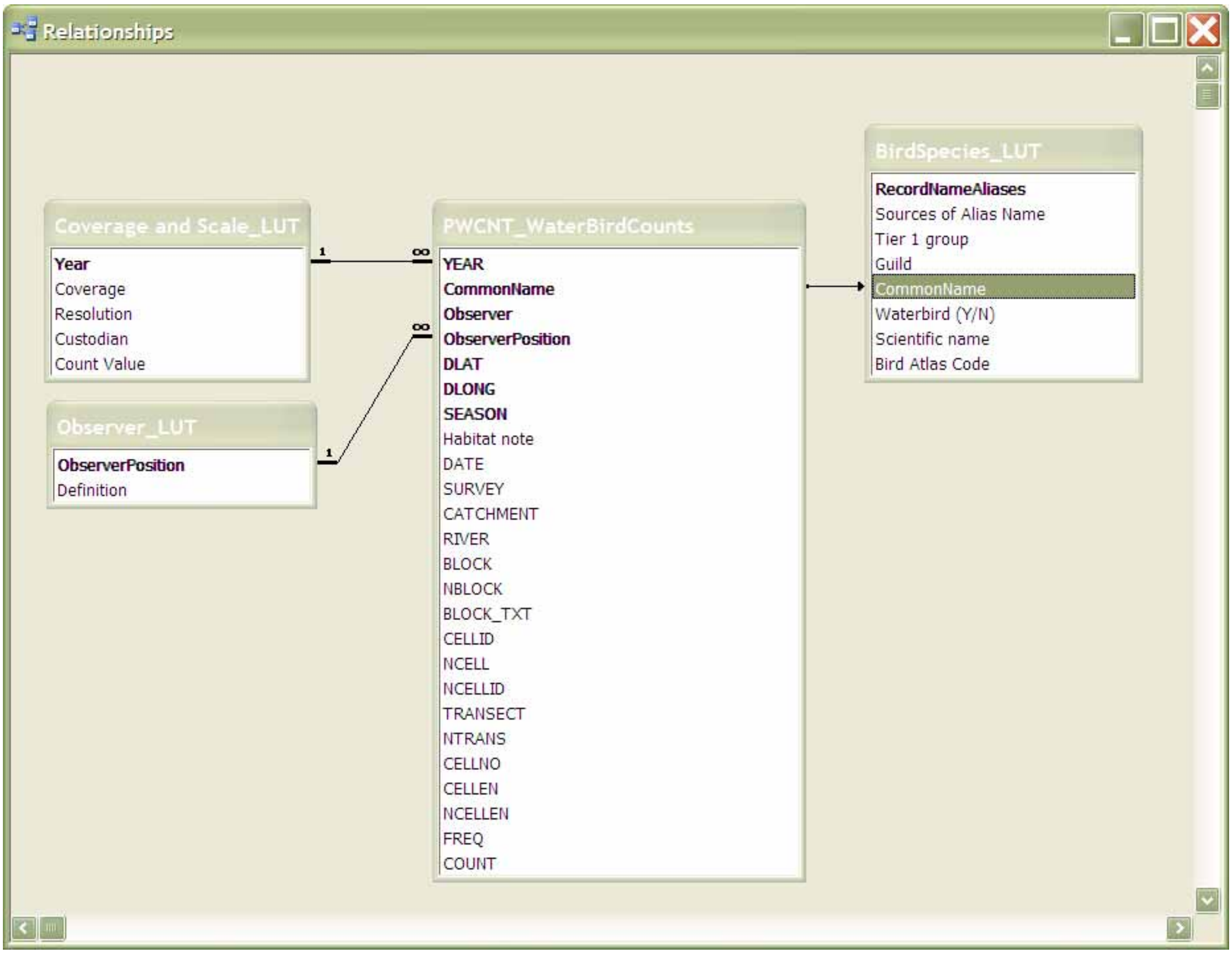


Figure 3. Table relationships within the PWSNT TopEnd aerial waterbirds surveys (primarily Magpie Goose) database.

5.4 Aerial & Ground surveys of waterbirds conducted in the Alligator Rivers Region from 1981 to 1984 by Morton and Brennan

These data relate to a monitoring study on waterbird populations of major wetlands in the ARR conducted between June 1981 and August 1984 by Morton et al (1991). Three sampling methods were used: a) systematic aerial counts, repeated monthly, along predetermined transect lines at approximately 1.2 km intervals and covering major wetlands of the region (some 1161 km^2); b) ground counts repeated monthly at 30 predetermined locations on the Magela Creek floodplain of the ARR ; and c) a combination of ground counts and low altitude aerial counts repeated monthly at 17 selected billabongs on the Magela Creek floodplain. See Appendix 1 for excerpts from Morton & Brennan summarising the methods in detail

The study aimed to assess seasonal trends in abundance and distribution for all waterbird species and used a combination of aerial & ground surveys techniques to assess abundance, distribution, and habitat preference (including vegetation) for specific species, resulting in a number of scientific publications (see also (Morton et al. 1993a; b; 1991; 1990a; b). An extract from OFR 086 outlining the methods for aerial and ground surveys of waterbirds in the ARR is provided in Appendix 1.

From 2007 the complete original hardcopy transcripts of the aerial, ground, and billabong survey datasets were digitised to MS Excel. Sites including Magela, Nourlangie, Cooper Creek, East Alligator River, and Boggy Plain – were collated in separate Excel workbooks, except for Boggy Plain that was combined with the Nourlangie workbook.

Spreadsheets for the ground survey and aerial component were rationalised for database design and then migrated and collated in a consistent format in Access by James Boyden.

QAQC tests for duplication undertaken in Access and by visual inspection of the attributes. Checks for positional errors were done by projection of the data within a GIS and when anomalies were detected by comparing (and correcting where appropriate) coordinates published in OFR 086.

1.4.1 Spatial Information:

Original Coordinates:

Published coordinates were scanned and digitised from OFR 086 (PDF) then corrected for logical consistency by checking point locations and coordinates in ArcMap against the original reported figures and tables. Reported map grid coordinates for transect start and end points, were assumed to be in the AGD 66 MGA zone 53 datum/projection, and were reprojected to WGS84 geographic coordinates.

Interpolated sample points locations

For each transect count location records for each species and time interval were interpolated using: the known *start* location of the transect; the calculated bearing between this point and the known *end* point of the transect; and a assumed a constant (average) distance between each 30 second count interval of 1.2 km (as indicated in OFR086). A geostatistical formulae was applied to do these calculations in Excel (See Appendix 1.4 for details). The first count location was taken as the midpoint of the first 1.2 km interval (0.6 km from the start), and subsequent points were generated at 1.2 km intervals from this point.

It is recognised that some spatial error resulted from these calculations given that 30-second count intervals did not necessary equate to a distance of 1.2 km (aircraft speed varied). Some indication of the degree of spatial error can be determined by comparing these interpolated points with those generated for the Magela floodplain site, independently, using different calculation criteria: where average airspeed per transect was determined using records of the total time taken to fly each transect, as well as aircraft direction.

Latitude and longitude coordinates were attributed in shapefiles by calculating them in ArcGIS using XTools Pro and then exported to Access ‘location’ lookup tables in.

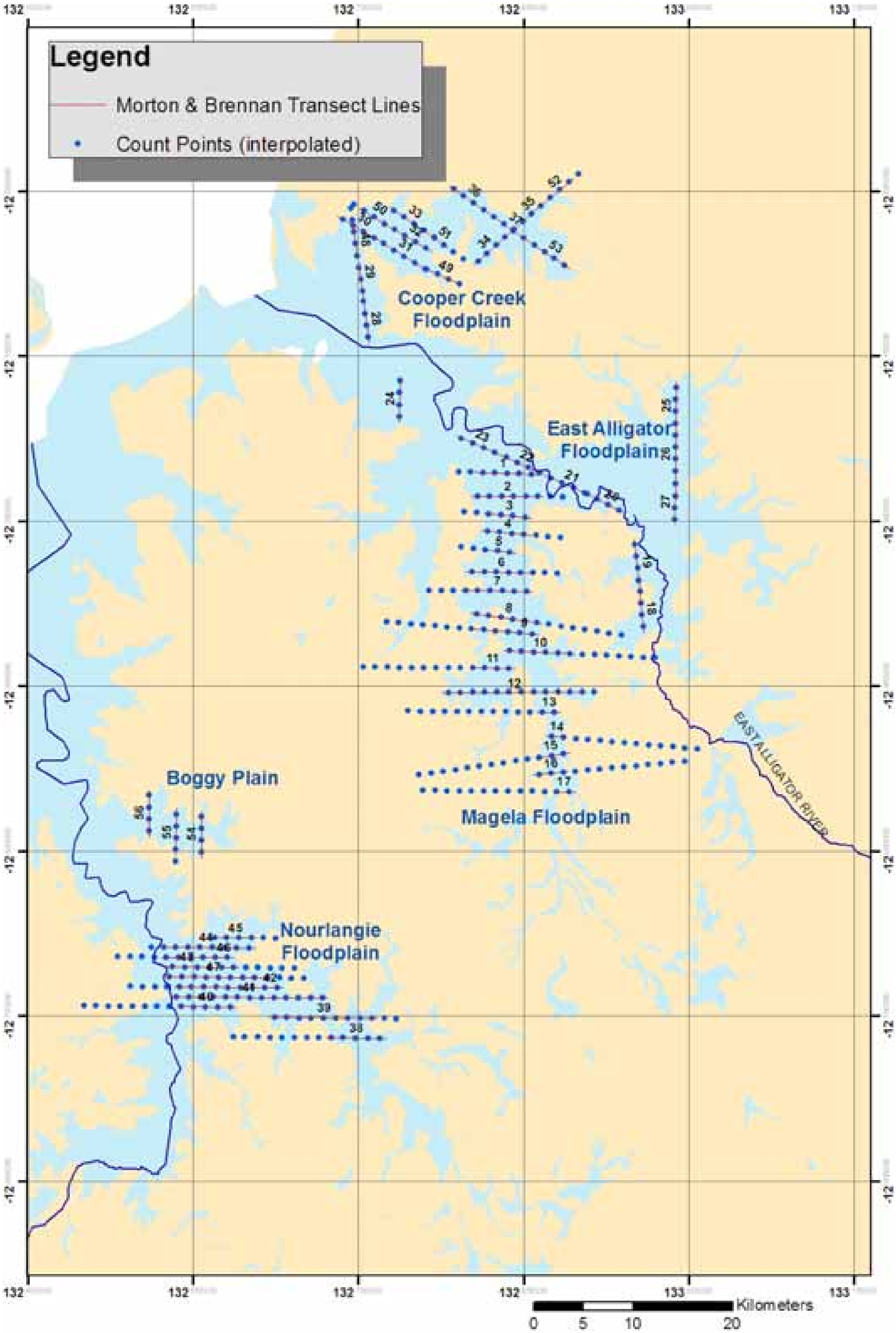


Figure 1. Location of transect lines for repeated aerial surveys of waterbirds undertaken in the Alligator Rivers Regions (Kakadu National Park) by Morton & Brennan between June 1981 and August 1984.

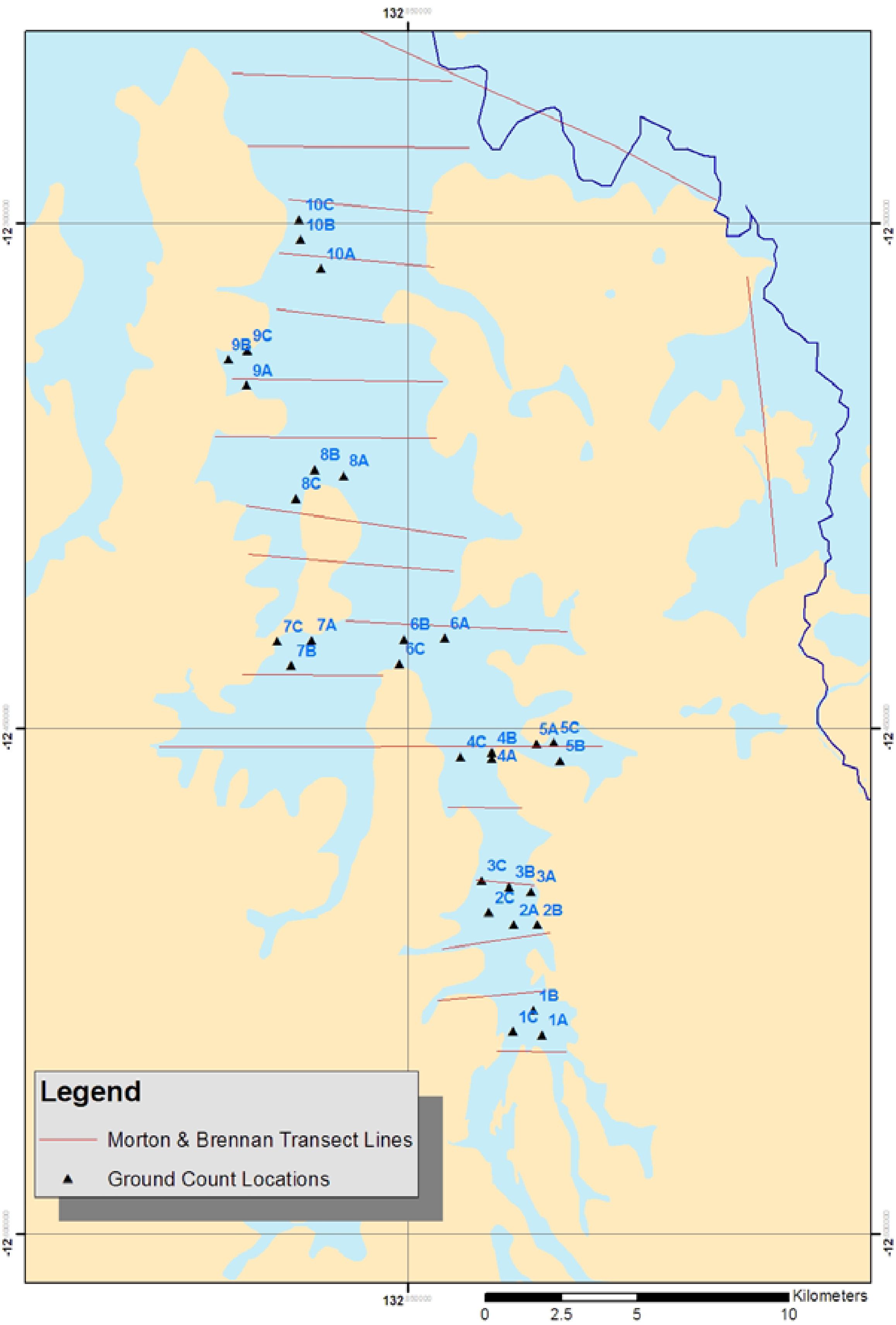


Figure 2. Location of ground count sites on the Magela Creek Floodplain in relation to the position of aerial transect lines

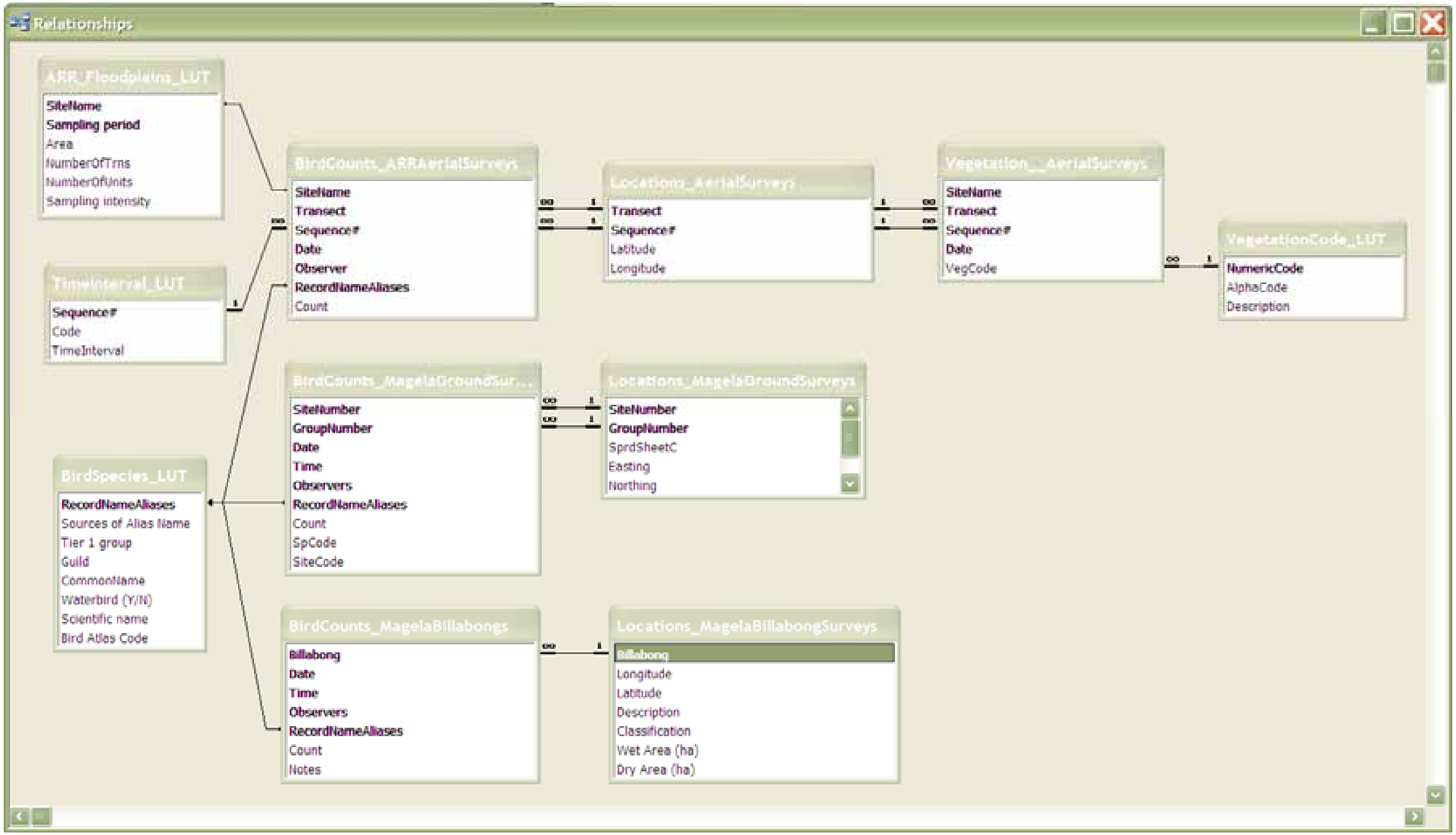


Figure 3. Table relationships within the Morton & Brennan database for aerial and ground surveys of waterbirds. Note all ground count & billabong survey data relates to the Magela Floodplain area only.

BirdCounts_AerialSurveys : Table

Field Name	Data Type	Description
SiteName	Text	General wetland location name within Alligator Rivers Region (cited from OFR - Morton & Brennan)
Transect	Number	Unique Transect Number (cited from Open File Record -Morton & Brennan)
Sequence#	Number	Time segment sequence number for each transect
Date	Date/Time	Date of observation
Observer	Number	Observer code (1 = Steve Morton, 7 = Kym Brennan). 2 observers were used for most aerial counts, except on a few occasions when only Steve Morton counted
RecordNameAliases	Text	The common name of bird species (including a number of name aliases). Refer to BirdSpecies_LUT to group named aliases
Count	Number	The numbe of birds of a particualr species counted by each observer at each time and location

BirdCounts_GroundSurveys : Table

Field Name	Data Type	Description
SiteNumber	Number	Site Number (corresponds to that published in OFR 086)
GroupNumber	Number	Group Number (corresponds to that published in OFR 086)
Date	Date/Time	Date of Observation
Time	Number	Time of observation (hh.mm)
Observers	Text	Bird count observers (Kym Brennan or Steve Morton)
RecordNameAliases	Text	Common name of Bird (Aliases have been compiled in Species LUT)
Count	Number	Number of birds counted by each observer for each site location, time, and species
SpCode	Number	Believed to be Australian Bird Atlas Code (not confirmed)
SiteCode	Text	Spreadsheet site code (from original data)

BirdSpecies_LUT : Table

Field Name	Data Type	Description
RecordNameAliases	Text	All bird names, codes or aliases used in the original imported datasets – these have been cross-refereced with official Australian common name, scientific name, and Australian Bird Atlas numeric codes for waterbird species only as compiled in this table
Sources of Alias Name	Text	The source(s) of data where the RecortNameAliases were used (sometimes several names were used for the same bird in the same dataset)
Tier 1 group	Text	This field has not been completely populated. James Boyden began placing family or genus of waterbirds birds
Guild	Text	This field has not been populated. The field was provided such that ecological feeding guilds for waterbirds can be designated
CommonName	Text	The general group (eg egret spp, duck spp.) OR official Australian common name as determined from the RAOU website and the Australian Bird Atlas in 2009. Populated for waterbirds only as of 2009.
Waterbird (Y/N)	Text	A 'y' assigned to all waterbirds for data filtering purposes. Non-waterbird species have been left blank
Scientific name	Text	The official scientific name of the waterbird species as determined from checklist on the RAOU website, 2009. Note that this field has been left blank when only the bird group is cited in RecordNameAliases (eg egrets, duck spp.).
Bird Atlas Code	Number	The official numeric species code used in the Australian Bird Atlas, 2009. Note that this field has been left blank when only the bird group is cited in RecordNameAliases (eg egrets, duck spp.) Has been populated for waterbirds only as of 2009

BirdCounts_MagelaBillabongs : Table

Field Name	Data Type	Description
Billabong	Text	Billbong Name (refer to Location_MagelaBillabong_LUT)
Date	Date/Time	
Time	Number	Time of day hh.mm (24hr format)
Observers	Text	Observer(s)
RecordNameAliases	Text	Generally the common name of teh bird species. However use BirdSpecies_LUT to derive standardised common and scientific name
Count	Number	Total number counted at a particular time/place
Notes	Text	additonal field notes (when they exist)

Figure 4. Attribute descriptions for tables contained within Morton & Brennan Access database for aerial and ground surveys of waterbirds

ARR_Floodplains_LUT : Table

Field Name	Data Type	Description
SiteName	Text	Name of floodplain location (cited from OFR 086)
Sampling period	Text	Period over which monthy samples undertaken
Area	Number	Estimates area in square Kms (cited from OFR 086)
NumberOfTrns	Number	Number of transects
NumberOfUnits	Number	Number of 30 second interval sample units
Sampling intensity	Number	Estimated sampling intensity (cited from OFR 086)

TimeInterval_LUT : Table

Field Name	Data Type	Description
Sequence#	Number	Sample sequence number (from beginning of each transect)
Code	Text	Time interval code: Sequential number from transect start point
TimeInterval	Text	Time interval (30 second increments) in seconds from transect start point

BirdSpecies_LUT : Table

Field Name	Data Type	Description
RecordNameAliases	Text	All bird names, codes or aliases used in the original imported datasets - these have been cross-refereced with official Australian common name, scientific name, and Australian Bird Atlas numeric codes for waterbird species only as compiled in this table
Sources of Alias Name	Text	The source(s) of data where the RecorNameAliases were used (sometimes several names were used for the same bird in the same dataset)
Tier 1 group	Text	This field has not been completely populated. James Boyden began placing family or genus of waterbirds birds
Guild	Text	This field has not been populated. The field was provided such that ecological feeding guilds for waterbirds can be designated
CommonName	Text	The general group (eg egret spp, duck spp.) OR official Australian common name as determined from the RAOU website and the Australian Bird Atlas in 2009. Populated for waterbirds only as of 2009.
Waterbird (Y/N)	Text	A 'y' assigned to all waterbirds for data filtering purposes. Non-waterbird species have been left blank
Scientific name	Text	The official scientific name of the waterbird species as determined from checklist on the RAOU website, 2009. Note that this field has been left blank when only the bird group is cited in RecordNameAliases (eg egrets, duck spp.).
Bird Atlas Code	Number	The official numeric species code used in the Australian Bird Atlas, 2009. Note that this field has been left blank when only the bird group is cited in RecordNameAliases (eg egrets, duck spp.) Has been populated for waterbirds only as of 2009

Locations_AerialSurveys : Table

Field Name	Data Type	Description
Transect	Number	Unique Transect Number (cited from Open File Record -Morton & Brennan)
Sequence#	Number	Time segment sequence number for each transect
Latitude	Number	Latitude WGS84 (decimal degrees). Locations interpolated at 1.2 km (30 second) intervals from given transect start location and bearing
Longitude	Number	Longitude WGS84 (decimal degrees). Locations interpolated at 1.2 km (30 second) intervals from given transect start location and bearing

Figure 4 (cont) Attribute descriptions for tables contained within Morton & Brennan Access database for aerial and ground surveys of waterbirds

Locations_MagelaGroundSurveys : Table

Field Name	Data Type	Description
SiteNumber	Number	Site Number (corresponds to that published in OFR 086)
GroupNumber	Number	Group Number (corresponds to that published in OFR 086)
SprdSheetC	Text	Spreadsheet data cpde (assocaited with original datasheets digitised by Gary Fox)
Easting	Number	Easting coordinate, assumed to be AGD66 AMG zone 53
Northing	Number	Northing coordinate, assumed to be AGD66 AMG zone 53
Longitude	Number	Longitude (Decimal degrees) WGS 84
Latitude	Number	Latitude (Decimal degrees) WGS 84

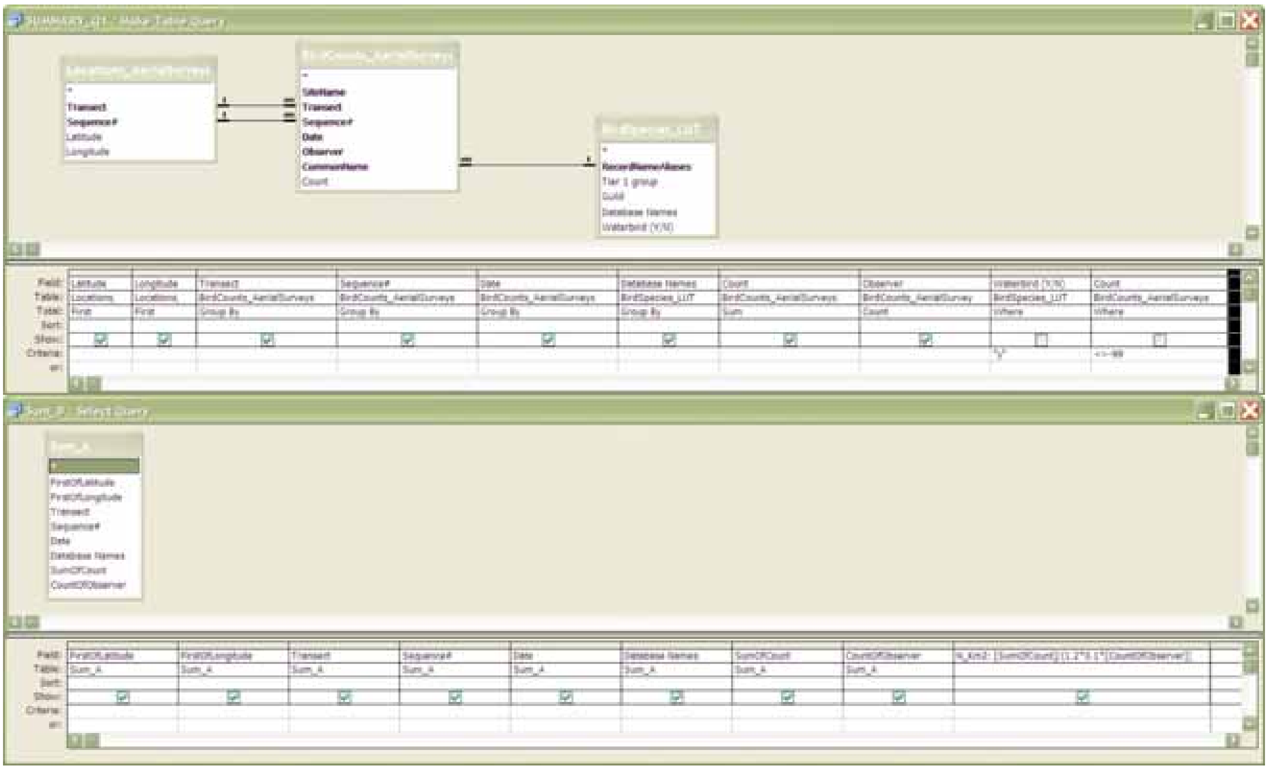
Locations_MagelaBillabongSurveys : Table

Field Name	Data Type	Description
Billabong	Text	
Longitude	Number	
Latitude	Number	
Description	Text	
Classification	Text	Billbong classification following Hart & McGregor (1982): See Morton & Brennan, Open File Record 086, for reference
Wet Area (ha)	Number	Estimated wet season area (cited from OFR 086)
Dry Area (ha)	Number	Estimated dry season area (cited from OFR 086)

Vegetation__AerialSurveys : Table

Field Name	Data Type	Description
SiteName	Text	
Transect	Number	Unique Transect Number (cited from Open File Record -Morton & Brennan)
Sequence#	Number	Time segment sequence number for each transect
Date	Date/Time	Date of observation.
VegCode	Number	Vegetation code assigned for aerial characterisation of vegetation. Refer to VegetationCode_LUT for definitions

Figure 4 (cont) Attribute descriptions for tables contained within Morton & Brennan Access database for aerial and ground surveys of waterbirds



Access queries used for calculating waterbird density estimates for ARR aerial surveys..

5.5 Queensland Sources (WildNet data)

Data was sourced through Dr Mark Kennard who liaised with Qld Department of Environment and Resource Management. Publicly available and selected confidential records were included. Third party confidential records were excluded. Summary data were filtered to waterbirds only.

Scientific names listed in this dataset differed substantially from the CAVs taxonomic list. Scientific names were changed to appropriate name in the CAVs register in order to generate a standardised species/guild lists from raw data.

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APPENDICES

APPENDIX 1 BACKGROUND INFORMATION RELATING TO THE ALLIGATOR RIVERS WATERBIRDS DATASET

A1.1 WATERBIRD SAMPLING PROCEDURES - MORTON & BRENNAN (EXCERPTS FROM OFR 086)

A1.1.1 ARR AERIAL SURVEYS: EXCERPT TAKEN FROM CHAPTER 3.1, PAGERS 9-10, OF OFR86:

3.1 Aerial survey

(1) Sampling procedures. It was possible to fly close to predetermined transect lines on each sampling occasion by navigating according to natural features. However, the floodplains are of irregular shape, and so in most cases the transects used for estimating numbers of waterbirds were of unequal length (co-ordinates specifying the locations of all transects are given in Appendix 1, and maps indicating the transects are shown in Appendices 2 to 6). Parallel transects from 1-2 km apart were used on the Magela and Nourlangie flood plains, and sampling intensities were similar (Table 2). Due to the curved shape of the Cooper flood plain (Appendix 5), transects were not parallel and in one case crossed each other. After the first 13 samples, we increased the number of transects on the Cooper to improve the sampling intensity (Table 2). We had insufficient resources to sample the much larger East Alligator to the same extent as the other flood plains, and in addition we needed to maximise the range of geographical regions of this large plain that could be sampled. Hence, we surveyed along four lines that encompassed sections of the flood plain in its southern, northern, eastern and western reaches. The lines on both the Cooper and East Alligator were broken into sections 4.8 km long (three on the Cooper were only 3.6 km), which we designated as transects. Although the sampling intensity on the East Alligator flood plain was lower than on the other plains (Table 2), most of the major habitat types, including portions of two of the largest backswamps, were sampled. Only three transects from 1-2 km apart could be surveyed on Boggy Plain, but because of the relatively small size of this wetland the sampling intensity was similar to that on other flood plains (Table 2).

The survey team consisted of the pilot, a navigator (M.D.A.), a back-right observer (S.R.M.) and a back-left observer (K.G.B.). The transects were flown in a Cessna 206 at a height of 30 m (100 ft) and at a ground-speed of 140 km h^{-1} (75 knots). Width of transect was demarcated for the observers by two marks on each wing strut; when looking between these, each observer viewed a strip of ground 100 m wide. The observers estimated the numbers of birds of all species seen on the transect as the plane moved along it, noting the counts on a cassette recorder. On most occasions the birds were seen in groups, so it was necessary to estimate the numbers in groups of 10, 50, 100 or sometimes even 500 (estimates in large groups were particularly necessary for Magpie Geese).

Resolution of the surveys was improved by division of each transect into units 1.2 km long. It was not possible for the units to be identified from natural features during sampling; rather, the navigator in the survey team timed the flight on each transect, and called out every 30 sec. The observers left their cassette recorders turned on for the entire transect, and the call enabled the sightings to be divided into segments of 30 sec.

On return to the laboratory, the navigator transcribed the counts onto data sheets. While doing so, he adjusted the timing of the segments so that each transect was composed of the appropriate number of units of identical time, and thereby ensured that counts for each unit were based on a ground distance of 1.2 km. This process of adjustment negated the problem caused by differing wind speeds, which altered the ground-speed at which transects were flown and thereby made it difficult to specify location of each unit when the plane was in the air. Adjustment was especially important on the East Alligator and Cooper flood plains, where one particular flight path was frequently broken into more than one transect.

Each transect therefore comprised a series of units each 1.2 km long. For the purposes of calculating densities of waterbirds the unit counts were pooled and analysed per transect, but for certain purposes the unit data were utilized. In particular, the navigator noted whether the flood plain was wet or dry in every unit along each transect.

Surveys were conducted every month from June 1981 on the Magela and Nourlangie flood plains, from August 1981 on the East Alligator and Cooper flood plains, and from August 1982 on Boggy Plain, until August 1984. In December 1983, only one observer (S.R.M.) was able to count. Surveys were conducted over three days; in general, the Magela was surveyed on one morning, the Nourlangie and Boggy Plain on the next, and the East Alligator and the Cooper on the third morning. All surveys began about 1 hr after dawn, and usually took about 1.5 hr to complete.

Table 2. Areas of the flood plains surveyed by air, and sampling intensities.

Flood plain	Area (km^2)	No. of transects	No. of units	Sampling intensity (%)
Magela	188	17	80	4.8
Nourlangie	160	10	81	5.7
East Alligator	437	10	40	1.1
Cooper August 1981- June 1982	171	10	40	2.8
July 1982- August 1984	171	16	58	4.0
Boggy Plain	34	3	12	4.2

TRANSECT NUMBER	BEGINNING		END	
	EASTING	NORTHING	EASTING	NORTHIN
MAGELA FLOOD PLAIN				
1	267400	8643850	260300	8644050
2	260850	8641650	26800	8641650
3	266800	8639500	262150	8639900
4	261900	8638150	266900	8637750
5	265300	8635900	261800	8636300
6	260400	8634000	267200	8633950
7	267000	8632100	259850	8632100
8	260900	8629850	268000	8628850
9	267600	8627750	260950	8628250
10	264150	8626100	271300	8625800
11	265350	8624300	260800	8624300
12	258150	8621900	272450	8622050
13	269850	8620000	267450	8620000
14	268400	8617600	270300	8617450
15	270800	8615900	267300	8615350
16	267200	8613650	270700	8614000
17	271350	8612000	269100	8612000
EAST ALLIGATOR				
18	278000	8628000	277550	8632700
19	277550	8632700	277000	8637500
20	276000	8640000	272600	8641800
21	272600	8641800	268100	8643800
22	268100	8643800	263700	8645800
23	263700	8645800	259300	8647700
24	253700	8649000	253700	8653700
25	281000	8653300	281000	8648500
26	281000	8648500	281000	8643600
27	281000	8643600	281000	8638900
COOPER CREEK FLOOD PLAIN				
28	250600	8657000	250000	8661600
29	250000	8661600	249300	8666400
30	247400	8669700	251500	8667300
31	251500	8667300	255700	8664700
32	256700	8666300	252600	8668700
33	252500	8670700	256500	8668000
34	260900	8664900	264400	8668100
35	264400	8668100	268000	8671400
36	258400	8672900	262400	8670100
37	262400	8670100	266400	8667300
48	249300	8666400	248800	8669800
49	255700	8664700	259700	8662900
50	252600	8668700	249500	8670600
51	256500	8668000	258400	8666600
52	268000	8671400	270800	8673800
53	266400	8667300	270500	8664600
NOURLANGIE FLOOD PLAIN				
38	252900	8587000	246900	8587000
39	241300	8589000	252100	8589000
40	238100	8590000	232200	8590000
41	231600	8591000	247200	8591000
42	242700	8592000	231900	8592000
43	231200	8594000	238400	8594000
44	239900	8596000	230300	8596000
45	235300	8597000	240100	8597000
46	237800	8595000	230600	8595000
47	230900	8593000	241700	8593000
BOGGY PLAIN				
54	234500	8605000	234500	8609800
55	232000	8610000	232000	8605200
56	229300	8607100	229300	8611900

A1.1.2 ARR Ground Surveys: Excerpt taken from Chapter 3.2, pages 11-12, of OFR86:

3.2 Ground surveys

(1) Sampling procedures. Ten groups of sites were selected along the Magela flood plain (Fig. 2; co-ordinates for the sites are given in Appendix 7), and were randomly placed with respect to vegetation association except for two factors. First, we avoided *Melaleuca* forest because waterbirds are less likely to use forest than open flood plain; and secondly, we placed four groups in the southernmost section of the flood plain (which comprises only about 3,100 ha) and sited six in its remaining bulk (about 15,700 ha). This was done because we felt it important to obtain most information about that portion of the flood plain closest to the Ranger and Jabiluka deposits. Although we did not sample all major vegetation associations of the Magela flood plain, the sites encompassed all but two of the communities (*Melaleuca* forest and *Nelumbo* swamp; see Finlayson et al. 1985).

Each of the ten groups consisted of three sites each 6 ha in area (300 x 200 m) and placed within about 600 m of each other. One site was placed at the edge of the flood plain, another in the deepest section in the near vicinity, and the third in between. The corners of the sites were marked by tall pegs. Every month from April 1981 until May 1984 we visited the sites by airboat, three-wheeled tricycle or on foot and counted waterbirds of all species. In many cases the abundance of the birds forced us to estimate numbers in groups of 10 or 50. Counts were usually completed between 0700 hrs and 1100 hrs, but when sites had to be reached on foot during the dry season some counts were not finished until 1230 hrs. Most counting was done by S.R.M. The monthly counts generally took two days to complete; groups 1-6 were usually visited on the first morning and groups 7-10 on the second. Water depth and vegetational composition were measured at each site during every visit (see Morton & Brennan 1989).

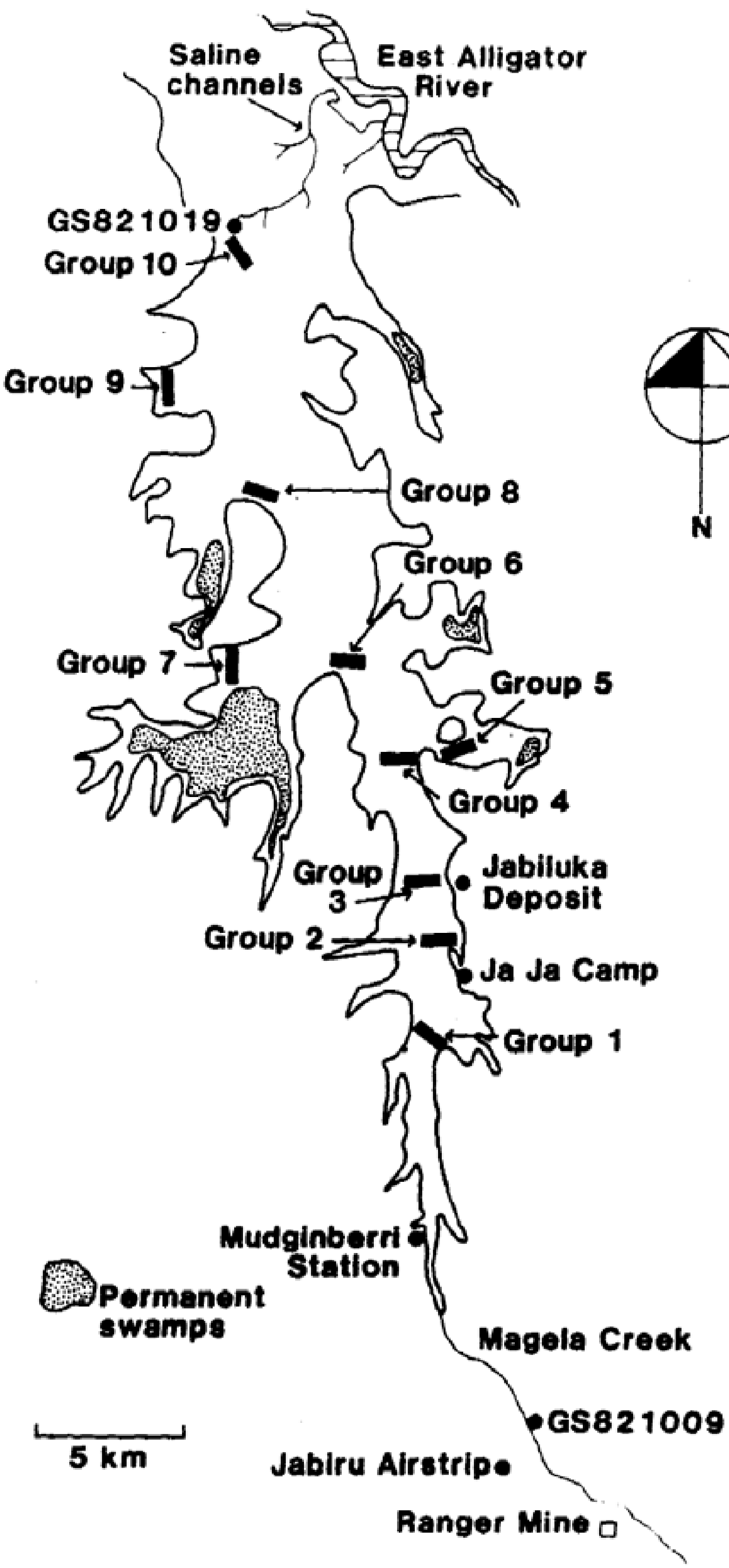


Figure 2 Map of the Magela flood plain showing location of the ten groups of sites at which waterbirds were counted.

A1.1.3 ARR BILLABONG SURVEYS (GROUND & HELICOPTER): EXCERPT TAKEN FROM CHAPTER 3.3, PAGERS 12-13, OF OFR86:

3.3 Surveys of billabongs

(1) Sampling procedures. Waterbirds were counted on 18 billabongs along the Magela Creek system once a month from April 1981 to March 1984; location of each billabong is depicted in Fig. 3. Surveys of Winmurra Billabong did not begin until January 1983. Each billabong was classified, according to the division proposed by Hart and McGregor (1982), as either a channel, a backflow or a floodplain billabong. Estimates of the areas of each billabong during wet and dry seasons are shown in Table 3, together with their classifications.

All channel and backflow billabongs were surveyed from a low-flying helicopter. Two observers sat in the rear seats of a Jetranger (S.R.M. on the right and K.G.B. on the left) and recorded estimates of numbers as waterbirds flew either right or left away from the flight path of the helicopter. Data were spoken into a cassette recorder. In many cases it was necessary to estimate numbers of birds in groups of 10 or 50. Surveys were conducted about mid-morning, and took about three-quarters of an hour to complete.

Floodplain billabongs were surveyed at the same times as groups 1 to 6 were visited for ground counts of waterbirds. Thus, estimates were made from airboat, three-wheeled tricycle or foot, depending on the season. As before, it was often necessary to estimate numbers in units of 10 or 50.

Table 3. Classification of each billabong of the Magela Creek system on which waterbirds were surveyed, together with estimates of their areas during Wet and Dry seasons.

Billabong	Classification	Estimated area (ha) Wet	Dry
1. Georgetown	Backflow	3.2	2.1
2. Djalkmarra	Backflow	1.7	1.1
3. Coonjimba	Backflow	3.7	3.7
4. Goanna	Channel	4.5	3.0
5. Gulungul	Backflow	6.1	4.1
6. Corndorl	Backflow	85	26
7. Mudginberri	Channel	8.7	8.7
8. Buffalo	Channel	2.1	2.1
9. Boomerang	Backflow	12	12
10. Island	Channel	25	25
11. Y-shaped	Channel	11	11
12. Hidden	Channel	9.2	9.2
13. Three-croc	Channel	17	17
14. Winmurra	Backflow	1.8	1.8
15. Ja Ja	Floodplain	3.7	3.7
16. Leichhardt	Floodplain	8.9	8.9
17. Jabiluka	Floodplain	17	17
18. Nankeen	Floodplain	22	22

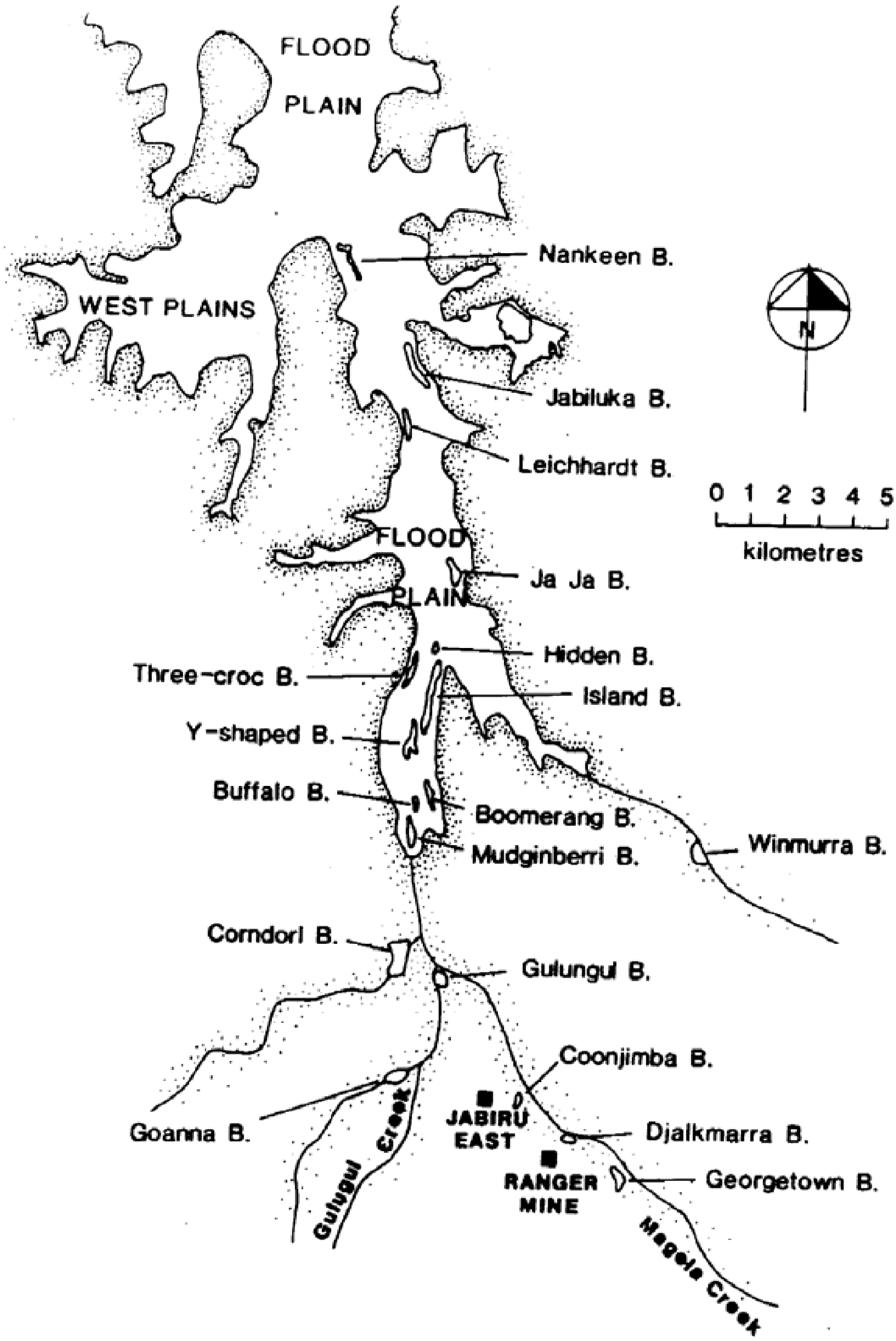


Figure 3 Map of the Magela Creek system showing the location of billabongs surveyed during the study.

A1.2 Software - Excel Geometry Functions

These functions were used to interpolate aerial survey count points using known start location of the transect, the calculated bearing between this point and the known end point of the transect, and assuming an average 1.2km distance for each 30 second count interval. The first count point along a transect was taken as the midpoint of the first 30 second interval (or 0.6km from the start point), while each subsequent count point was at 1.2km intervals.

Microsoft's spreadsheet software EXCEL is used to manipulate and analyse all types of data. However, the product is oriented to business so most of the built-in functions are specific to business and include only basic math/science functions. Fortunately, Microsoft developed EXCEL to be extendible through the Visual Basic for Applications (VBA) language. This capability allows the user to develop their own functions and subroutines and to incorporate them easily into EXCEL. In response to my own needs with the analysis of marine mammal survey data and other types of data, I have written various EXCEL functions that perform trigonometric calculations for plane and spherical geometry and a number of other related calculations. I have compiled these functions into a single EXCEL add-in file - after downloading, double-click on the Geofunc.exe icon to extract geofunc.xla file! (Download self extracting zip file here). Functions within EXCEL such as Solver and wizards are add-in files. You can use this add-in file by simply copying the file to the appropriate XLSTART sub-directory or in the AddIns sub-directory and use Add-in under the Tools menu item. Or you download the text file and paste them into the VB editor. By examining the text file you can see the code used to make the computations and more complete documentation. The text file should also work for a Mac but I've not tested it. For complete instructions consult EXCEL help.

Each time EXCEL loads, it will load the Geofunc.xla file and all of the functions it contains will be available. The functions can be used like any other EXCEL built-in function by typing them into a formula with the appropriate arguments. If you use functions through the fx icon, the functions in Geofunc will be listed in alphabetical order under the User-defined category.

The Visual Basic code for each function is listed below with comments that describe what the function does and the assumed input and output measurement units. The functions are organized alphabetically as follows:

Spherical (Earth) Geometry: Angle & Distance Measurements

The earth is approximately spherical, so trigonometric relationships between positions on the earth's surface can be approximated with spherical trigonometry. The appropriate formulas were used from pages 176-177 in the Standard Mathematical Tables 24th edition, CRC Press. All units for latitude and longitude and bearing are in decimal degrees [e.g., 100 degrees, 30 minutes and 50 seconds corresponds to 100.5139 = 100 + (30 + 50/60)/60 in decimal degrees]. Distance units are nautical miles (1 nautical mile = 1852 meters). Northern latitudes and eastern longitudes are specified as positive values and their counterparts are negative.

1. Bearing(Lat1, Lon1, Lat2, Lon2)
2. NewPosLat(Lat1, Lon1, Bearing, Distance)
3. NewPosLon(Lat1, Lon1, Bearing, Distance)
4. Posdist(Lat1, Lon1, Lat2, Lon2)

Update Notice March 22, 2000: Update Notice: Two minor changes listed below were made to the routines on 22 March 2000. If you obtained a prior copy, you should update with the new version.

1) The Bearing and NewPosLat functions were incorrectly handling degrees of 90 and 270. Both were mistakenly

being used as a constant latitude which only holds at the equator. The effect of this on previous calculations should have been minor except for large distances (>100 nm).

Disclaimer: The add-in file is provided as a courtesy to others that may find it useful. I have checked these functions reasonably well but I make no claims about their accuracy. As with any computer software, check to make sure the answers you get make sense and are accurate. That will ensure that you understand their use. **Please pay particular attention to the measurement units.** If you find any errors, please notify me via email (Jeff.Laake@Noaa.Gov).

http://www.afsc.noaa.gov/nmml/software/downloads/

APPENDIX 6.1 – 6.6

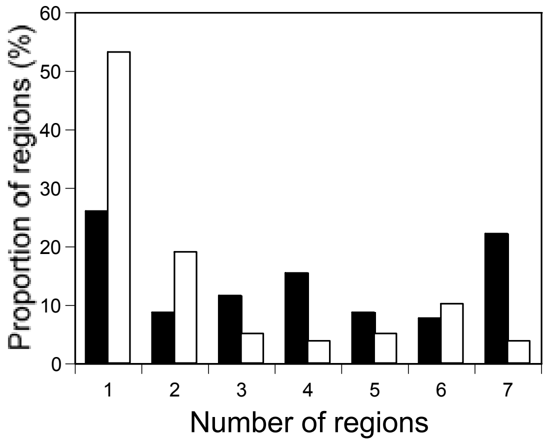
APPENDIX 6.1 Mean and standard error of environmental variables for groups based on distribution in ordination space shown in Figure 6.3. Group one basins were located negatively to axis 1 scores <0.65 and group 2 were located positively to axis 1 scores >1.0 (i.e. no overlap). Only those variables significantly different at p<0.01 or greater (paired t-test) are shown. Definitions are included only for attributes uncommonly encountered in the literature. . The final eight variables relating to floodplain habitats were significantly correlated (r = 0.503) with the pattern of dissimilarity determined using all landscape scale variables as determined by the BIOENV procedure in PRIMER statistical analysis software.

			Ordination groups			
			1 (negatively arrayed on axis 1)		2 (positively arrayed on axis 1)	
		Definition	mean	SE	mean	SE
Catchment area	km^2		3949.4	947.97	135.82	11.58
CATRELIEF		mean upstream elevation-pour point elevation) /(max upstream elevation-pour point elevation	0.32	0.01	0.38	0.01
CONFIN	%	Percentage of stream reach grid cells and their immediate neighbours that are not valley bottoms as defined by mrVBF and mrRTF indices	41.8	2.8	58.0	3.5
UPSDIST	km	Maximum flow path length upstream to the reach pour-point, grid cell downstream in the direction of flow.	93.1	9.0	23.9	0.9
CATSLOPE	%	Elevation/stream length	0.87	0.059	2.08	0.18
CATSTORAGE		?	23.5	1.4	14.1	1.6
CATMELALEU		?	4.4	0.5	1.3	0.5
CATCOASTAL		?	2.1	0.2	4.1	0.4
STRDENSITY	km/km^2	Stream density, total length of stream /catchment area	0.52	0.01	0.63	0.019
SUM_P_PE	km^2	palustrine area perrennial	344.5	112.5	0	0
SUM_P_NPE	km^2	palustrine area non-perrennial	14743.8	4005.9	0.3	0.3
SUM_P_IFH	km^2	palustrine area inundation frequency high	9545.2	3482.5	0	0
SUM_P_IFL	km^2	palustrine area inundation frequency low	5543.1	1174.3	0.3	0.36
SUM_L_PE	km^2	lacustrine area perrennial	2284.8	534.4	0	0
SUM_L_NPE	km^2	lacustrine area non-perrennial	1968.6	688.8	0	0
SUM_L_IFH	km^2	lacustrine area inundation frequency high	1458.7	492.4	0	0
SUM_L_IFL	km^2	lacustrine area inundation frequency low	2794.7	788.346.3	0	0

APPENDIX 6.2. Waterbird species present in at least 90% of drainages within at least one of the aggregated NASY regions. X denotes that a species present in the region. Species highlighted in bold type are migratory species as listed under the CAMBA, JAMBA or ROKAMBA migratory bird international treaties.

	NASY Region								NASY Region						
Species	1	2	3	4	5	6	7	Species	1	2	3	4	5	6	7
Actitis hypoleucos					x	x		*Grus rubicunda*		x					
Anas gracilis		x						*Haematopus fuliginosus*						x	x
Anas superciliosa		x						*Haematopus longirostris*	x	x	x		x	x	x
Anseranas semipalmata				x				*Heteroscelus brevipes*	x						x
Ardea alba	x	x						*Himantopus himantopus*		x					
Ardea intermedia		x						*Larus novaehollandiae*	x	x	x			x	x
Ardea pacifica		x						***Limosa lapponica***	x	x	x		x	x	x
Ardea sumatrana				x	x	x		***Limosa limosa***	x	x					
Ardeotis australis		x						***Numenius madagascariensis***	x	x	x	x	x	x	
Arenaria interpres	x	x	x		x	x	x	***Numenius minutus***		x		x	x		
Aythya australis		x						***Numenius phaeopus***	x	x	x	x	x	x	x
Burhinus grallarius	x	x						*Pelecanus conspicillatus*		x					
Butorides striatus	x	x	x	x		x		*Phalacrocorax carbo*		x					
Calidris acuminata	x	x						*Phalacrocorax sulcirostris*		x					
Calidris canutus		x					x	*Phalacrocorax varius*		x					
Calidris ferruginea		x						*Platalea flavipes*		x					
Calidris ruficollis	x	x						*Platalea regia*		x					
Calidris subminuta		x					x	*Plegadis falcinellus*		x					
Calidris tenuirostris	x	x	x		x	x	x	*Pluvialis apricaria*	x						
Charadrius leschenaultii	x	x	x	x	x	x		***Pluvialis squatarola***	x	x				x	x
Charadrius mongolus	x	x	x	x			x	*Podiceps cristatus*		x					
Charadrius ruficapillus	x	x					x	*Poliocephalus poliocephalus*		x					
Charadrius veredus		x					x	*Porphyrio porphyrio*		x					
Chenonetta jubata		x						*Porzana fluminea*		x					
Chlidonias hybridus		x						*Recurvirostra novaehollandiae*		x					
Chlidonias leucopterus	x	x						***Rostratula benghalensis***		x					
Cygnus atratus		x						***Sterna albifrons***		x					
Dendrocygna eytoni		x						***Sterna bergii***	x		x	x	x	x	x
Egretta garzetta	x	x		x				*Sterna caspia*		x					
Egretta sacra	x	x						***Sterna hirundo***		x					
Elseyornis melanops		x						*Sterna nilotica*	x	x					
Ephippiorhynchus asiaticus		x	x		x			***Sterna sumatrana***	x	x					
Erythrogonys cinctus		x						*Stiltia isabella*		x					
Esacus neglectus	x					x		*Tachybaptus novaehollandiae*		x					
Eulabeornis castaneoventris		x		x	x	x		*Tadorna tadornoides*	x			x			
Fulica atra		x						*Threskiornis molucca*	x	x	x	x	x		
Gallinago hardwickii	x							***Tringa glareola***		x					
Gallinula ventralis		x						***Tringa nebularia***	x	x					
Gallirallus philippensis		x						***Tringa stagnatilis***	x	x					
Glareola maldivarum		x						***Xenus cinereus***	x	x	x		x	x	x
Grus antigone		x													

APPENDIX 6.3. Proportion of the total waterbird fauna of northern Australia found in one or more aggregated NASY regions (solid bars) and proportion of widely distributed birds within a region (i.e. >90% drainages of a region) also found in other drainages (open bars).



APPENDIX 6.4. Turtle species contributing to within region distinctiveness. Also shown is the frequency of incidence within each region in parentheses and total contribution (in bold face) to within-region similarity.

aggregated NASY region						
1	2	3	4	5	6	7
C. rugosa (100)	*C. rugosa* (100)	*C. rugosa* (100)	*C. rugosa* (100)	*C. rugosa* (100)		
				C. burrungandjii (66)	*C. burrungandjii* (64)	*C. burrungandjii* (100)
	C. canni (100)	*C. canni* (81)				
M. latisternum (89)						
						E. victoriae (100)
	E. worreli (64)					
				E. dentata (67)	*E. dentata* (79)	*E. dentata* (64)
97.6	**98.8**	**98.1**	**96.4**	**93.2**	**92.1**	**92.1**

APPENDIX 6.5. Results of SIMPER analysis highlighting turtle species contributing greatest to between region dissimilarity. Species names are abbreviated to first letter of genus and species respectively. Proportion (%) contribution to overall dissimilarity is shown in parentheses.

	Aggregated NASY regions					
	1	2	3	4	5	6
2	C.c (34) M.l (31) E.w (22)					
3	M.l (42) C.c (37)	E.w (43) C.c (19) M.l (19)				
4	M.l (37) C.b (30)	C.c (35) C.b (22) E.w (20)	C.c (38) C.b (30) M.l (13)			
5	M.l (28) C.b (20) E.d (20)	C.c (29) C.b (17) E.d (17) E.w (16)	C.c (29) C.b (23) E.d (22) E.v (13)	E.d (30) C.b (26) E.v (18)		
6	C.b (24) M.l (20) C.r (20) E.d (17)	C.b (21) C.c (21) C.r (17) E.d (15)	C.b (25) C.r (21) C.c (19) E.d (17)	C.r (31) E.d (25) C.b (15)	C.r (34) E.d (18) E.v (17) C.b (17)	
7	E.v (24) C.r (23) M.l (20)	C.c (21) E.v (21) C.r (20)	E.v (26) C.r (26) C.c (19)	E.v (29) C.r (28) C.b (15)	C.r (33) E.v (23) C.b (18) E.d (16)	E.v (30) C.b (29) E.d (20)

APPENDIX 6.6. Freshwater fish species contributing to the distinctiveness of individual aggregated NASY regions. FOI = frequency of incidence, % contribution = extent to which species contributes to within region similarity.

	Species	FOI	% contribution	Cumulative %
aggregated NASY 1	*Oxyeleotris nullipora*	1	11.87	11.87
	Hypseleotris compressa	1	11.87	23.74
	Glossamia aprion	0.96	10.39	34.13
	Melanataenia trifasciata	0.96	10.39	44.52
	Pseudomugil gertrudae	0.93	9.25	53.77
	Iriatherina werneri	0.89	8.19	61.96
	Mogurnda mogurnda	0.81	6.54	68.5
	Denariusa bandata	0.74	5.31	73.81
aggregated NASY 2	*Glossamia aprion*	0.9	20.44	20.44
	Glossogobius aureus	0.8	13.05	33.49
	Hypseleotris compressa	0.8	13.05	46.54
	Craterocephalus stercusmuscarum	0.8	12.56	59.1
	Melanoatenia splendida inornata	0.7	7.5	66.6
	Ophisternon spp.	0.5	4.58	71.18
aggregated NASY 3	*Glossamia aprion*	0.92	20.07	20.07
	Hypseleotris compressa	0.86	19.21	39.28
	Craterocephalus stercusmuscarum	0.81	14.02	53.3
	Leiopotherapon unicolor	0.69	8.67	61.97
	Mogurnda mogurnda	0.67	8.3	70.27
aggregated NASY 4	*Hypseleotris compressa*	1	14.13	14.13
	Mogurnda mogurnda	0.99	13.62	27.75
	Melanotaenia nigrans	0.99	13.62	41.37
	Pseudomugil gertrudae	0.93	11.5	52.87
	Glossamia aprion	0.93	11.26	64.13
	Neosilurus ater	0.85	9.02	73.15
aggregated NASY 5	*Melanotaenia australis*	1	19.93	19.93
	Mogurnda mogurnda	0.94	16.08	36.01
	Leiopotherapon unicolor	0.94	16.08	52.1
	Glossamia aprion	0.82	10.95	63.04
	Hypseleotris compressa	0.79	10.51	73.55
aggregated NASY 6	*Leiopotherapon unicolor*	1	16.67	16.67
	Melanotaenia australis	1	16.67	33.34
	Ambassis sp.NW	0.95	14.58	47.92
	Glossamia aprion	0.95	14.46	62.39
	Hypseleotris compressa	0.9	12.27	74.66
	Oxyeleotris selheimi	0.86	11.58	86.24
	Amniataba percoides	0.6	4.69	90.93
aggregated NASY 7	*Hypseleotris compressa*	1	25.38	25.38
	Melanotaenia australis	1	25.38	50.76
	Oxyeleotris selheimi	0.98	24.23	75

APPENDIX 9.1

Planning units identified as having met one or more criteria at the 99th percentile threshold for each reporting scale. The numeric code of each planning unit (PU), and the drainage division (DD) and NASY region (RG) in which they occur is listed. Also shown are the major named hydrosystems occurring within each planning unit. Hydrosystem codes are: riverine (R), lacustrine (L), palustrine (P) and springs (S). For each planning unit and each reporting scale, the individual criteria met (1) and the total number met (∑) are also shown. Criteria are: (1) Diversity, (2) Distinctiveness, (3) Vital habitat, (4) Evolutionary history, (5) Naturalness, (6) Representatieness.

				Entire study region							Drainage Divisions							NASY Regions						
				Criteria							Criteria							Criteria						
PU	DD	RG	NAME	1	2	3	4	5	6	∑	1	2	3	4	5	6	∑	1	2	3	4	5	6	∑
4	GC	1	JARDINE RIVER(R),				1			1				1			1		1		1			2
3	GC	1	SANAMERE LAGOON(L), BIFFIN SWAMP(P), COWAL CREEK(R), ELIOT CREEK(R), JARDINE RIVER(R),	1		1	1			3	1		1	1			3		1	1	1			3
7	GC	1	ELIOT CREEK(R),				1			1				1			1							
6	GC	1	JARDINE RIVER(R),				1			1				1			1		1		1			2
13	GC	1						1		1					1		1					1		1
16	GC	1	DOUGHBOY RIVER(R),																			1		1
29	GC	1	MACDONALD RIVER(R),																			1		1
170	GC	1	GIBSON WATERHOLE(P), WENLOCK RIVER(R),	1		1				2	1		1				2			1				1
181	GC	1	MOONLIGHT CREEK(R), WENLOCK RIVER(R),										1				1							
583	GC	1	TIMINIE CREEK(L), ARCHER RIVER(R), EAST ARCHER RIVER(R), WEST ARCHER RIVER(R),	1		1				2	1		1				2	1		1				2
617	GC	1	COEN RIVER(L), VARDONS WATERHOLE(L), COEN RIVER(R),	1						1	1						1	1						1
696	GC	1	ARCHER RIVER(L), LEICHHARDT SWAMP(P), ARCHER RIVER(R),								1						1							
721	GC	1	ARCHER RIVER(L), BOUYEL LAKE(L), TEA TREE LAGOON(L), ARCHER RIVER(R),	1		1				2	1		1				2							
791	GC	1	KIRKE RIVER(R),										1				1							
992	GC	1	HOLROYD RIVER(R), KENDALL RIVER(R),	1		1				2	1		1				2	1						1
994	GC	1	BIG BIN SWAMP(P), KENDALL RIVER(R),				1			1														
1042	GC	1	PRETENDER CREEK(R), THE BIG SPRING(R),																				1	1
1059	GC	1	FERRIS SWAMP(P), HOLROYD RIVER(R),	1						1	1						1						1	1
1109	GC	1	CHRISTMAS CREEK(L), HOLROYD RIVER(R),	1						1	1						1						1	1
4376	GC	2	BROWN CREEK(R),																			1		1
4399	GC	2																				1		1
4884	GC	2																				1		1
5166	GC	2																				1		1
5378	GC	2																				1		1
1232	GC	2	EDWARD RIVER(R),			1	1			2			1	1			2			1				1
1168	GC	2	EDWARD RIVER(R),																		1			1
1364	GC	2	COLEMAN RIVER(R),				1			1				1			1				1			1
1362	GC	2	COLEMAN RIVER(R),				1		1	2				1		1	2				1		1	2
1391	GC	2	CATTLE SWAMP(L), COLEMAN RIVER(R), STAN LAGOON(R),	1			1		1	3	1			1		1	3	1			1			2
1376	GC	2	THOMAS LAGOON(L),										1				1			1				1
1328	GC	2	BULL LAKE(L), LIGHTNING CREEK(R), THE OVERFLOW(R),	1						1	1						1	1						1
1433	GC	2	MALAMAN CREEK(R),	1			1			2				1			1							
1410	GC	2	SWORDFISH HOLE(L), COLEMAN RIVER(R), LIGHTNING CREEK(R), MALAMAN CREEK(R),	1	1					2	1	1					2	1	1					2
1498	GC	2	COLEMAN RIVER(R),	1			1			2	1			1			2	1						1
1650	GC	2	BOTTLE CREEK(R),			1				1			1				1							
1688	GC	2	RACECOURSE SWAMP(P), BOSWORTH CREEK(R), MAGNIFICENT CREEK(R), SOUTH MITCHELL RIVER(R),	1						1	1						1	1						1
1704	GC	2					1			1														
1705	GC	2	ALICE RIVER(R), MITCHELL RIVER(R),				1			1				1			1							
1732	GC	2	ALICE RIVER(R),										1				1							
1695	GC	2	MOSQUITO WATERHOLE(L), CROSBIE CREEK(R), EIGHT MILE CREEK(R),	1					1	2	1					1	2	1						1
1834	GC	2	DOG LAGOON(L), EVERGREEN WATERHOLE(P), MAGNIFICENT CREEK(R), TOPSY CREEK(R),				1			1				1			1							
1896	GC	2					1			1														
1901	GC	2	KILLPATRICK CREEK(R), KILPATRICK CREEK(R), MAGNIFICENT CREEK(R),	1						1	1						1	1						1
1933	GC	2	FLYING FOX SWAMP(P),				1			1				1			1				1			1
1905	GC	2	MAGNIFICENT CREEK(R), MITCHELL RIVER(R),	1						1	1						1	1						1
1958	GC	2					1			1														
2026	GC	2	BURRUM CHANNEL(R), MITCHELL RIVER(R),	1			1			2	1			1			2	1						1
1978	GC	2	FIVE MILE WATERHOLE(L), POPPY LAGOON(L), THREE MILE WATERHOLE(P), DIAMOND CREEK(R), SCRUTTON RIVER(R),	1						1	1						1	1						1
2022	GC	2	SCRUTTON RIVER(R),				1			1				1			1							
2036	GC	2	CHRISTMAS WATERHOLE(L), SCRUTTON RIVER(R),	1			1			2	1			1			2							
2130	GC	2	NASSAU RIVER(R),				1			1														
2054	GC	2	SWAN HOLE(L), NASSAU RIVER(R),				1			1				1			1							
2151	GC	2	KILLARNEY WATERHOLE(L), NASSAU RIVER(R), SCRUTTON RIVER(R), TEA-TREE CREEK(R),	1						1	1						1	1						1
2297	GC	2	DIAMOND CREEK(R), MITCHELL RIVER(R), TEA-TREE CREEK(R),	1						1	1	1					2	1						1
2125	GC	2	NASSAU RIVER(R), STATION CREEK(R),				1			1														
2263	GC	2	BURKES LAGOON(L), FLYING FOX LAGOON(L), BRANDYS LAGOON(P), MITCHELL RIVER(R),						1	1						1	1							
2384	GC	2											1				1							
2473	GC	2	DINGO SWAMP WATERHOLE(P), OASIS DAM(P), SALT ARM CREEK(R), SURPRISE CREEK(R),	1						1	1						1	1						1
2692	GC	2	JACKYS LAGOON(L), TEN MILE LAGOON(L), TWELVE MILE LAGOON(L), ALBERTS LAGOON(P), MITCHELL RIVER(R),	1						1	1						1	1						1
2630	GC	2	LESLIE SWAMP(P), MITCHELL RIVER(R),													1	1							
2704	GC	2	STAATEN RIVER(R), VANROOK CREEK(R),				1			1														
2645	GC	2	MENTANA CREEK(R),																		1			1
2725	GC	2	STAATEN RIVER(R),																		1			1
2754	GC	2	WYAABA CREEK(R),			1				1			1				1			1				1
2844	GC	2	HENDERSON LAGOON(L), TWO MILE SWAMP(P), BROWN CREEK(R), WILLIAMSTOWN CREEK(R),	1						1	1						1	1						1

				Entire study region							Drainage Divisions							NASY Regions						
				Criteria							Criteria							Criteria						
PU	DD	RG	NAME	1	2	3	4	5	6	∑	1	2	3	4	5	6	∑	1	2	3	4	5	6	∑
2855	GC	2																				1		1
3000	GC	2	WOMBIES DAM(L), BARRAMUNDI WATERHOLE(P), VANROOK CREEK(R),		1					1		1					1							
3081	GC	2	WALSH RIVER(R),						1	1						1	1							
3176	GC	2	EMU CREEK(R),																	1				1
3158	GC	2	GILBERT RIVER(L), REVOLVER SWAMP(P), GILBERT RIVER(R),		1					1														
3326	GC	2	RIDGE LAGOON(L), HORSE LAGOON(P), JACKS LAGOON(P), ROWDIES LAGOON(P), LYND RIVER(R), TATE RIVER(R),						1	1														
3325	GC	2	BANCROFT WATERHOLE(L), BIRD WATERHOLE(L), BLACKFELLOW LAGOON(L), BULLOCKY LAGOON(L), COBBLE LAGOON(L), WOMBIES LAGOON(L), BULL_SWAMP_DAM(P), FOUR_MILE_SWAMP(P), FREDS_LAGOON(P), GALAH_WATERHOLE(P), GREEN_SWAMP_DAM(P), NINE_MILE_LAGOON(P), OLD_STATION_WAT	1	1					2	1	1					2	1	1					2
3369	GC	2	GILBERT RIVER(R),				1			1				1			1							
3442	GC	2	SWORDFISH WATERHOLES(L), WHITE WATER WATERHOLES(P), GILBERT RIVER(R), SMITHBURNE RIVER(R),		1					1		1					1		1					1
3465	GC	2	H LAGOON(L), GILBERT RIVER(R), SMITHBURNE RIVER(R),		1					1		1					1		1					1
3432	GC	2	WATSONS WATERHOLE(L), EMU CREEK(R), RED RIVER(R),			1				1			1				1			1				1
3425	GC	2	ACCIDENT INLET(R),																	1				1
3501	GC	2	FITZMAURICE CREEK(L), ACCIDENT INLET(R), FITZMAURICE CREEK(R),				1			1				1			1							
3533	GC	2	PICKLE LAGOON(L), VELOX LAGOON(L), EINASLEIGH RIVER(R), GILBERT RIVER(R), MAXWELL CREEK(R), WALKER CREEK(R),		1					1		1	1				2			1	1			2
3634	GC	2	HORSE LAGOON(P), LYND RIVER(R), TATE RIVER(R),													1	1							
3696	GC	2	WHITE WATER LAGOON(L), YELLOW DINNER CAMP LAGOON(L), CROCODILE WATERHOLE(P), DINGO WATERHOLES(R), MIRANDA CREEK(R), WALKER CREEK(R),		1					1		1					1							
3732	GC	2	TWO MILE DAM(L), BULLOCK CREEK(R), ROCKY TATE RIVER(R),																	1				1
3629	GC	2	BLUE LAGOON(L), EINASLEIGH RIVER(R), VANROOK CREEK(R), , , , , , , , , , , , ,		1					1		1					1		1					1
3763	GC	2	DICKSON CREEK(R), LYND RIVER(R),													1	1							
3786	GC	2	JENNY LIND CREEK(R), NORMAN RIVER(R), WALKER CREEK(R),			1				1			1				1			1				1
3813	GC	2	FISH HOLE CREEK(R),																	1				1
3843	GC	2	ALBERT NYANZA LAGOON(L), EINASLEIGH RIVER(R),,						1	1						1	1							
3833	GC	2	GIN ARM CREEK(R), NICHOLSON RIVER(R),	1			1			2	1			1			2	1			1			2
3823	GC	2	NORMAN RIVER(R), WILLS CREEK(R),																		1			1
3840	GC	2	DESERT CREEK(R), LYND RIVER(R),			1				1			1				1			1				1
3864	GC	2	SHELL RIDGE WELL(P), FLINDERS RIVER(R),			1				1			1				1							
3868	GC	2	HAWK NEST LAGOON(L), BARE LAGOON(P), GOOSE LAGOON(P), GIN ARM CREEK(R), GREGORY RIVER(R), NICHOLSON RIVER(R),	1						1														
3930	GC	2	PIDGEON WATERHOLE(L), UHRS LAGOON(L), BYNOE WATERHOLE(P), BYNOE RIVER(R), FLINDERS RIVER(R),	1	1					2	1	1					2	1	1					2
3931	GC	2	BYNOE RIVER(R), SALTWATER CREEK(R),			1				1			1				1			1				1
3947	GC	2	CARRON RIVER(R),		1					1		1					1							
3935	GC	2																				1		1
3946	GC	2	BRUMBY WATERHOLE(L), DUCK HOLE(L), MCDONALD LAGOON(L), ROPE HOLE(L), SHADY LAGOON(L), SIX MILE LAGOON(L), SNAKE_HOLE_WATERHOLE(P), CARRON_RIVER(R), NORMAN_RIVER(R),		1					1		1					1							
4028	GC	2	SHADY WATERHOLE(P), FLINDERS RIVER(R),			1				1			1				1			1				1
3997	GC	2	WOODS LAKE(L), ALBERT RIVER(R),				1			1				1			1				1			1
4057	GC	2	EINASLEIGH RIVER(R), GALLOWAY CREEK(R), PARALLEL CREEK(R),													1	1				1			1
4046	GC	2	SCOTCHMANS WATERHOLE(L), NORMAN RIVER(R),																	1				1
4048	GC	2	FORK LAGOON(L), SWEET SWAMP(P),			1				1			1				1			1				1
4074	GC	2	ALBERT RIVER(R), BARKLY RIVER(R), ONE MILE CREEK(R),																		1			1
4127	GC	2																			1			1
4090	GC	2																		1				1
4120	GC	2	BEAMES BROOK(R), ONE MILE CREEK(R),				1		1	2				1		1	2				1		1	2
4131	GC	2	FIVE MILE WATERHOLE(L), NICHOLSON RIVER(R),		1					1		1					1		1					1
4079	GC	2							1	1						1	1						1	1
4329	GC	2	NORMAN RIVER(L), CASHMANS SWAMP(P), EIGHTY MILE SWAMP(P), MULDOON SWAMP(P), GREEN CREEK(R), NORMAN RIVER(R), SILVERFISH_CREEK(R), SILVERFISH_WATERHOLE(R), , , , , , , ,	1						1	1						1	1						1
4177	GC	2	ROPE WATERHOLE(L), BLUE BUSH WATERCOURSE(R),						1	1						1	1						1	1
4188	GC	2	LAST HOPE WATERHOLE(P), LEICHHARDT RIVER(R),						1	1						1	1							
4139	GC	2																				1		1
4239	GC	2	GREGORY RIVER(R), ONE MILE CREEK(R),																		1			1
4258	GC	2	NADJABARRA LAGOON(P), NICHOLSON RIVER(R),									1					1			1				1
4271	GC	2				1				1			1				1							
4294	GC	2	SOUTH NICHOLSON CREEK(R),																			1		1
4300	GC	2																				1		1
4308	GC	2																				1		1
4282	GC	2	GUM HOLE(P), ELIZABETH CREEK(R), MUSSELBROOK CREEK(R),																	1				1
4353	GC	2	BEAMES BROOK(R), CARTRIGE CREEK(R), FOUR MILE CREEK(R), GREGORY RIVER(R), MACADAM CREEK(R), MILLAR CREEK(R), RUNNING_CREEK(R),	1	1					2	1	1					2	1	1		1			3
4347	GC	2	ARCHIE CREEK(R), GREGORY RIVER(R), WILLIS WATERHOLE(R),		1		1			2		1		1			2		1		1			2
4330	GC	2	POLEYS LAGOON(L), LAWN HILL CREEK(R),						1	1														
4356	GC	2	PELICAN WATERHOLE(L), POLEYS LAGOON(L), BLUEBUSH SWAMP(P),						1	1						1	1				1			1
4387	GC	2																				1		1
4378	GC	2																				1		1
4416	GC	2																				1		1
4427	GC	2	GORGE WATERHOLE(L), ALEXANDRA RIVER(R), BLUE BUSH WATERCOURSE(R), LEICHHARDT RIVER(R),						1	1						1	1						1	1
4430	GC	2	WASHPOOL WATERHOLE(L), BULLRING SWAMP(P), DINNER HOLE(P), BLUE BUSH WATERCOURSE(R), FIERY CREEK(R), LEICHHARDT RIVER(R),						1	1						1	1						1	1
4434	GC	2	SIX MILE WATERHOLE(P), WASHPOOL WATERHOLE(P), EIGHT MILE WATERHOLE(R), FLINDERS RIVER(R), SAXBY RIVER(R),						1	1						1	1						1	1
4433	GC	2	HETZERS LAGOON(L), GOOSE LAGOON(P), PELICAN WATERHOLE(P), FLAT HOLE CHANNEL(R), FLINDERS RIVER(R), PADDYS LAGOON(R),		1					1		1					1		1					1
4478	GC	2										1					1							

				Entire study region							Drainage Divisions							NASY Regions						
				Criteria							Criteria							Criteria						
PU	**DD**	**RG**	**NAME**	**1**	**2**	**3**	**4**	**5**	**6**	**∑**	**1**	**2**	**3**	**4**	**5**	**6**	**∑**	**1**	**2**	**3**	**4**	**5**	**6**	**∑**
4509	GC	2	ARMSTRONG CREEK(R), MAGOWRA SPRING(S), MARGARET VALE SPRING(S),			1				**1**			1				**1**			1				**1**
4495	GC	2																				1		**1**
4516	GC	2	BLACK TAR WATERHOLE(P), COBBS WATERHOLE(P), FINCH CREEK(R), JUMBLE HOLE CREEK(R), ROCKY CREEK(R),						1	**1**						1	**1**						1	**1**
4577	GC	2	CAULFIELD CLAY FLATS(L),																			1		**1**
4585	GC	2																				1		**1**
4603	GC	2																				1		**1**
4612	GC	2	ROCKY WATERHOLE(L), LEICHHARDT RIVER(R),						1	**1**						1	**1**						1	**1**
4619	GC	2																				1		**1**
4620	GC	2																				1		**1**
4633	GC	2	FLAT HOLE CHANNEL(R), FLINDERS RIVER(R),		1				1	**2**		1				1	**2**		1				1	**2**
4739	GC	2	WILSONS LAGOON(L), CLARA RIVER(R), MAY LAGOON(R), NORMAN RIVER(R),		1				1	**2**		1				1	**2**						1	**1**
4707	GC	2	NUNDA CREEK(R), YAPPAR RIVER(R), EMPRESS SPRING(S),						1	**1**						1	**1**						1	**1**
4688	GC	2	TWELVE MILE WATERHOLE(L), WONDOOLA CREEK(L), FOUR MILE WATERHOLE(P), THREE MILE WATERHOLE(P), SAXBY RIVER(R), WONDOOLA CREEK(R),		1					**1**		1					**1**		1					**1**
4689	GC	2	SAXBY RIVER(R),		1					**1**		1					**1**		1				1	**2**
4694	GC	2	PELICAN WATERHOLE(L), SIX MILE SWAMP(P), SINGLE CREEK(R),						1	**1**						1	**1**						1	**1**
4693	GC	2	EIGHT MILE WATERHOLE(L), PELICAN WATERHOLE(L), EIGHT MILE SWAMP(P), LILY WATERHOLES(P), SIX MILE SWAMP(P), LEICHHARDT RIVER(R),						1	**1**						1	**1**						1	**1**
4730	GC	2	TEATREE WATERHOLE(L), CLONCURRY RIVER(R), FLINDERS RIVER(R), SANDY CREEK(R), IANS SPRING(S),		1				1	**2**		1				1	**2**						1	**1**
4732	GC	2	FLAGSTONE WATERHOLE(L), MCDOUGALLS WATERHOLE(L), MONKEY WATERHOLE(L), FLINDERS RIVER(R),		1		1			**2**		1		1			**2**		1					**1**
4750	GC	2	IFFLEY LAGOON(L), THREE MILE WATERHOLE(L), FOREST CREEK(R), NORMAN RIVER(R), SPEAR CREEK(R), STOCK ROUTE CREEK(R),		1					**1**		1					**1**		1					**1**
4748	GC	2	WILSONS WATERHOLE(P), CLARA RIVER(R),											1			**1**							
4774	GC	2							1	**1**						1	**1**						1	**1**
4379	GC	2	CARTRIGE CREEK(R), MILLAR CREEK(R),		1					**1**		1					**1**		1					**1**
4825	GC	2	CHARLO WATERHOLE(L), CLONCURRY RIVER(L), BRANCH CREEK(R), CLONCURRY RIVER(R),		1					**1**		1					**1**		1				1	**2**
4858	GC	2	DINNER CAMP WATERHOLE(P), LAKE EYRE(P),				1			**1**				1			**1**							
4873	GC	2	POLICEMANS SWAMP(P), NORMAN RIVER(R),				1			**1**				1			**1**				1			**1**
4953	GC	2	SPEAR CREEK(R),		1					**1**		1					**1**		1					**1**
5047	GC	2	COCKATOO WATERHOLE(L), EARLES CAMP WATERHOLE(L), FISHERIES WATERHOLE(L), LYRIAN WATERHOLE(L), SAXBY RIVER(R),		1					**1**		1					**1**		1	1				**2**
5071	GC	2	SHINBONE WATERHOLE(P), DISMAL CREEK(R),											1			**1**							
5162	GC	2	TEN MILE WATERHOLE(L), GARDENER WATERHOLE(P), CLONCURRY RIVER(R), SANDY CREEK(R),				1			**1**				1			**1**							
5271	GC	2	FIFTY FOUR WATERHOLE(L), WASHPOOL LAGOON(L), CAROLINE CREEK(R), CLONCURRY RIVER(R), FLINDERS RIVER(R),,		1		1			**2**		1		1			**2**		1					**1**
5519	GC	2	STAWELL (CAMBRIDGE CREEK) RIVER(R),													1	**1**						1	**1**
5574	GC	2	ALMA WATERHOLE(L), BLUE LAGOON(L), FLINDERS RIVER(R),																				1	**1**
1377	GC	3													1		**1**							
1424	GC	3													1		**1**							
1769	GC	3													1		**1**							
2048	GC	3													1		**1**							
2049	GC	3													1		**1**							
2097	GC	3													1		**1**							
2098	GC	3													1		**1**							
2148	GC	3													1		**1**							
424	GC	3						1		**1**					1		**1**					1		**1**
446	GC	3	KOOLATONG RIVER(R),					1		**1**					1		**1**					1		**1**
478	GC	3													1		**1**					1		**1**
337	GC	3	DURABUDBOI RIVER(R),			1				**1**			1				**1**			1				**1**
471	GC	3	WILTON RIVER(R),												1		**1**					1		**1**
526	GC	3	MATTA MURTA RIVER(R),												1		**1**					1		**1**
530	GC	3													1		**1**					1		**1**
560	GC	3													1		**1**					1		**1**
620	GC	3													1		**1**					1		**1**
640	GC	3													1		**1**					1		**1**
643	GC	3													1		**1**							
682	GC	3													1		**1**							
766	GC	3													1		**1**							
663	GC	3	BULMAN WATERHOLE(L), WILTON RIVER(R),															1						**1**
763	GC	3													1		**1**							
798	GC	3													1		**1**							
816	GC	3	ROSE RIVER(R), WASHAWAY CREEK(R),												1		**1**							
828	GC	3	ANGURUGUBIRA LAKE(L),			1				**1**			1				**1**			1				**1**
850	GC	3													1		**1**							
818	GC	3	PHELP RIVER(R),												1		**1**							
824	GC	3	MAINORU RIVER(R),						1	**1**								1					1	**2**
879	GC	3													1		**1**							
855	GC	3	PHELP RIVER(R),												1		**1**							
910	GC	3													1		**1**							
948	GC	3													1		**1**							
924	GC	3	WONGALARA WATERHOLE(L), WILTON RIVER(R),															1						**1**
1051	GC	3	AH CUP WATERHOLE(L), WILTON RIVER(R),						1	**1**													1	**1**
1092	GC	3	PANIPANIN WATERHOLE(L), WONMURRI WATERHOLE(L), WARIEJAL WATERHOLE(P), PHELP RIVER(R),	1					1	**2**	1						**1**	1					1	**2**
1116	GC	3													1		**1**							
1132	GC	3	MANGKARDANYIRANGA CREEK(R), PHELP RIVER(R),																1					**1**
1093	GC	3	LAKE ALLEN(L), BRIGHT CREEK(R), WILTON RIVER(R),															1	1					**2**
1180	GC	3	PHELP RIVER(R), WUNGGULIYANGA CREEK(R),																	1				**1**
1183	GC	3	NAMALURI WATERHOLE(L), ROPER RIVER(R), TURKEY LAGOON CREEK(R), WUNGGULIYANGA CREEK(R),						1	**1**			1			1	**2**	1					1	**2**
1243	GC	3	PHELP RIVER(R), ROPER RIVER(R), WUNGGULIYANGA CREEK(R),										1				**1**			1				**1**
1251	GC	3	ROPER RIVER(R),			1				**1**			1				**1**			1				**1**
1268	GC	3	ROPER RIVER(R),			1				**1**			1				**1**			1				**1**

				Entire study region							Drainage Divisions							NASY Regions						
				Criteria							Criteria							Criteria						
PU	**DD**	**RG**	**NAME**	**1**	**2**	**3**	**4**	**5**	**6**	**∑**	**1**	**2**	**3**	**4**	**5**	**6**	**∑**	**1**	**2**	**3**	**4**	**5**	**6**	**∑**
1295	GC	3	ROPER RIVER(R),																	1				**1**
1211	GC	3	ROPER RIVER(R),						1	**1**													1	**1**
1282	GC	3	YALWARRA LAGOON(P), HODGSON RIVER(R), ROPER RIVER(R),			1				**1**			1				**1**			1				**1**
1314	GC	3	MOUNTAIN CREEK(R), ROPER RIVER(R),															1						**1**
1318	GC	3	LOMARIEUM LAGOON(L), NULLAWUN LAGOON(P), ROPER RIVER(R),			1			1	**2**			1	1			**2**	1		1				**2**
1381	GC	3	HODGSON RIVER(R),						1	**1**									1					**1**
2192	GC	3	MCARTHUR RIVER(R),																		1			**1**
2233	GC	3	BATTEN CREEK(R),						1	**1**						1	**1**						1	**1**
2338	GC	3	WARBY LAGOON(P), WEARYAN RIVER(R),																				1	**1**
2434	GC	3	FOELSCHE RIVER(L), LILY LAGOON(L), FOELSCHE RIVER(R), WEARYAN RIVER(R),															1						**1**
2395	GC	3	GOOSE LAGOON(L), MCARTHUR RIVER(R),																1					**1**
2571	GC	3	BIG STINKING LAGOON(L), LITTLE STINKING LAGOON(P), CALVERT RIVER(R),						1	**1**													1	**1**
2970	GC	3	CAMEL CREEK(R), SETTLEMENT CREEK(R),																		1			**1**
3161	GC	3	PEACOCK WATERHOLE(L), BALLYS LAGOON(P), PEACOCK LAGOON(P), STONEBALL WATERHOLE(P), CLIFFDALE CREEK(R),				1			**1**									1		1			**2**
3168	GC	3	IRANINDJINA CREEK(R), KARNS CREEK(R),						1	**1**						1	**1**						1	**1**
3169	GC	3	BUNDELLA WATERHOLES(L), CLIFFDALE CREEK(R),																1		1			**2**
3428	GC	3	EIGHT MILE CREEK(R),																		1			**1**
3143	GC	3	CLIFFDALE CREEK(R),																		1			**1**
3626	GC	3																			1			**1**
3745	GC	3	KNOBS LAGOON(P), CLIFFDALE CREEK(R),		1					**1**		1					**1**		1					**1**
3838	GC	3	CLIFFDALE CREEK(R),																1		1			**2**
3802	GC	3	BAMADJINA CLAYPAN(L), DJUMBARANA CLAYPAN (CALVERT LAKE)(L), LILIGI CREEK(R),																1		1			**2**
8	TS	4						1		**1**					1		**1**					1		**1**
11	TS	4	DONGAU CREEK(R),					1		**1**					1		**1**					1		**1**
17	TS	4	JOHNSTON (TUANUNGKU) RIVER(R),					1		**1**					1		**1**					1		**1**
25	TS	4	JOHNSTON (TUANUNGKU) RIVER(R),					1		**1**					1		**1**					1		**1**
24	TS	4	JOHNSTON (TUANUNGKU) RIVER(R),					1		**1**					1		**1**					1		**1**
49	TS	4						1		**1**					1		**1**							
46	TS	4	MURGENELLA CREEK(R),			1				**1**														
67	TS	4	KING RIVER(R),					1		**1**					1		**1**							
68	TS	4						1		**1**					1		**1**							
79	TS	4						1		**1**					1		**1**							
78	TS	4	COOPER LAGOON(L), COOPER CREEK(R),			1				**1**			1				**1**							
98	TS	4	DJIGAGILA CREEK(R),					1		**1**					1		**1**							
108	TS	4	BLYTH RIVER(R), CADELL RIVER(R),			1				**1**			1				**1**							
107	TS	4	LIVERPOOL RIVER(R), TOMKINSON RIVER(R),			1				**1**			1				**1**							
124	TS	4	LUCY LAKE(L), NO 1 BILLABONG(L), TWIN SISTERS LAGOONS(P),			1				**1**			1				**1**							
125	TS	4				1				**1**														
130	TS	4						1		**1**					1		**1**							
149	TS	4	ARAFURA SWAMP(P), GLYDE RIVER(R),			1				**1**														
141	TS	4	GARDEN SPRINGS(P), IRONSTONE BILLABONG(P), MARANGARRAYU (WEST ALLIGATOR RIVER)(R), WEST ALLIGATOR RIVER(R),			1				**1**														
148	TS	4				1				**1**			1				**1**							
174	TS	4	QUAMBI LAGOON(P), ADELAIDE RIVER(R),			1				**1**			1				**1**							
162	TS	4	GUNBALANYA LAGOON(L),																				1	**1**
156	TS	4	MANJDJALANJARRK (UNAWAHLURK BILLABONG)(L), WOELK (RED LILY LAGOON)(L), EAST ALLIGATOR RIVER(R),	1		1				**2**	1		1				**2**	1						**1**
184	TS	4	WOOLEN RIVER(R),					1		**1**					1		**1**							
157	TS	4	LAKE EVELLA(L), BUCKINGHAM RIVER(R), KALARWOI RIVER(R), WARAWURUW0I RIVER(R),,			1				**1**			1	1			**2**							
228	TS	4	BEN HOLE(P), CALF BILLABONG(P), DIRTY WATER BILLABONG(P), HORN BILLABONG(P), TWIN BILLABONG(P), ADELAIDE RIVER(R),			1				**1**			1				**1**			1				**1**
229	TS	4	STUMP BILLABONG(P), ADELAIDE RIVER(R),			1				**1**														
223	TS	4	MANN RIVER(R),	1						**1**	1						**1**							
163	TS	4	LIVERPOOL RIVER(R),						1	**1**														
167	TS	4	CADELL RIVER(R),	1						**1**	1						**1**							
173	TS	4	DEEP LAKE(L), LUCY LAKE(L), SHADY CAMP BILLABONG(L), MARY RIVER(R), SAMPAN CREEK(R), LITTLEJOHN SPRINGS(S),			1				**1**			1				**1**							
186	TS	4	COONJIMBA BILLABONG(L), GURNDURRK (CORNDORL WATERHOLE)(P), MAGELA CREEK(R),	1	1		1			**3**	1	1		1			**3**		1		1			**2**
192	TS	4	BENHAMS LAGOON(L), BLACK JUNGLE SWAMP(P), ADELAIDE RIVER(R),			1				**1**			1				**1**							
197	TS	4	TOMMY POLICEMAN LAGOON(L), LAMBELLS LAGOON(P), ADELAIDE RIVER(R),			1				**1**														
209	TS	4	GOOMADEER RIVER(R),					1		**1**					1		**1**							
206	TS	4						1		**1**					1		**1**							
207	TS	4	GOOMADEER RIVER(R),					1		**1**					1		**1**							
172	TS	4	PALM LAGOON(L), MARY RIVER(R),			1	1			**2**			1	1			**2**			1				**1**
198	TS	4	TIN CAMP CREEK(R),	1		1				**2**	1		1				**2**	1						**1**
222	TS	4	EAST ALLIGATOR RIVER(R),	1				1		**2**	1			1	1		**3**							
227	TS	4						1		**1**					1		**1**							
242	TS	4	ARAFURA SWAMP(P), ARAFURA SWAMP (MUCKANINNIE PLAINS)(P), GOYDER RIVER(R), GULBUWANGAY RIVER(R),			1				**1**			1				**1**							
253	TS	4	BLYTH RIVER(R),					1		**1**					1		**1**							
255	TS	4						1		**1**					1		**1**							
271	TS	4						1		**1**					1		**1**							
270	TS	4						1		**1**					1		**1**							
290	TS	4	ARAFURA SWAMP(P), GOYDER RIVER(R),	1						**1**	1						**1**							
281	TS	4	EAST ALLIGATOR RIVER(R),					1		**1**					1		**1**							
280	TS	4						1		**1**					1		**1**							
279	TS	4						1		**1**					1		**1**							
285	TS	4	DONALDS LAGOON(L), RED LILY WATERHOLE(P), ADELAIDE RIVER(R),	1						**1**	1						**1**	1						**1**
282	TS	4	ARAFURA SWAMP(P), ARAFURA SWAMP (MUCKANINNIE PLAINS)(P),,					1		**1**					1		**1**							
289	TS	4	EAST ALLIGATOR RIVER(R),					1		**1**					1		**1**							
300	TS	4		1		1				**2**	1		1				**2**							
305	TS	4						1		**1**					1		**1**							
299	TS	4	EAST ALLIGATOR RIVER(R),					1		**1**					1		**1**							

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PU	DD	RG	NAME	1	2	3	4	5	6	∑	1	2	3	4	5	6	∑	1	2	3	4	5	6	∑
311	TS	4	GURDURUNGURANJDJU (ALLIGATOR BILLABONG)(L), UNG.GURLINJ (LEICHHARDT BILLABONG)(L), AMBARRAWARRKU(P), DJUNDA (RED LILY BILLABONG)(P), NGARRABABA (BUCKET BILLABONG)(P), SOUTH ALLIGATOR RIVER(R),	1	1	1	1			**4**	1	1	1	1			**4**			1				**1**
301	TS	4	MARY RIVER(R),										1				**1**							
312	TS	4						1		**1**														
314	TS	4	LIVERPOOL RIVER(R),					1		**1**														
313	TS	4						1		**1**														
324	TS	4	NOURLANGIE CREEK(R),		1					**1**		1					**1**							
327	TS	4			1					**1**		1					**1**						1	**1**
328	TS	4	NOURLANGIE CREEK(R),	1	1		1			**3**	1	1		1			**3**				1		1	**2**
341	TS	4	EAST ALLIGATOR RIVER(R),					1		**1**														
338	TS	4	ADELAIDE RIVER(R), MANTON RIVER(R),											1			**1**							
336	TS	4	BLYTH RIVER(R),					1		**1**														
342	TS	4						1		**1**														
339	TS	4	LAKE BENNETT(L), HEATHERS LAGOONS(P), ADELAIDE RIVER(R),	1					1	**2**	1						**1**	1						**1**
340	TS	4	EAST ALLIGATOR RIVER(R),					1		**1**														
348	TS	4	NOURLANGIE CREEK(R),	1	1		1			**3**	1	1					**2**							
349	TS	4						1		**1**														
346	TS	4						1		**1**														
366	TS	4						1		**1**														
357	TS	4	EAST ALLIGATOR RIVER(R),					1		**1**														
375	TS	4	NAMARRGON CREEK(R), NOURLANGIE CREEK(R),		1				1	**2**		1				1	**2**		1				1	**2**
356	TS	4	DEAF ADDER CREEK(R), NOURLANGIE CREEK(R),	1	1		1		1	**4**	1	1		1			**3**		1					**1**
360	TS	4	BLYTH RIVER(R),					1		**1**														
359	TS	4						1		**1**														
363	TS	4	JIM JIM BILLABONG(L), JIM JIM CREEK(R), SOUTH ALLIGATOR RIVER(R),	1	1		1			**3**	1	1		1			**3**				1			**1**
373	TS	4	YIRRIRRI(L), BARRAMUNDIE CREEK(R), SOUTH ALLIGATOR RIVER(R),		1		1			**2**		1		1			**2**							
365	TS	4	EAST ALLIGATOR RIVER(R),					1		**1**														
364	TS	4						1		**1**														
358	TS	4	GURDURUNGURANJDJU (ALLIGATOR BILLABONG)(L), JIM JIM CREEK(R), SOUTH ALLIGATOR RIVER(R),		1		1			**2**		1		1			**2**							
372	TS	4	SOUTH ALLIGATOR RIVER(R),		1		1			**2**		1		1			**2**							
362	TS	4	MOWZIE BILLABONG(L), SWEETS LAGOON(L), FINNISS RIVER(R),			1				**1**			1				**1**			1				**1**
381	TS	4	ADELAIDE RIVER(R), MARGARET RIVER(R),	1						**1**	1						**1**							
378	TS	4						1		**1**														
385	TS	4						1		**1**														
391	TS	4						1		**1**														
406	TS	4	GALURRUYU(L), JIM JIM CREEK(R),		1					**1**		1					**1**							
394	TS	4	JIM JIM CREEK(R),		1					**1**		1					**1**							
395	TS	4						1		**1**														
393	TS	4	JIM JIM CREEK(R),		1					**1**		1					**1**							
397	TS	4	GUYUYU CREEK(R),					1		**1**														
402	TS	4	BARRAMUNDIE LAGOON(P), BARRAMUNDIE CREEK(R), SOUTH ALLIGATOR RIVER(R),		1		1			**2**				1			**1**							
401	TS	4	SOUTH ALLIGATOR RIVER(R),		1		1			**2**		1		1			**2**							
407	TS	4	ANBALAWALA(L), GALURRUYU(L), JIM JIM CREEK(R),	1	1		1			**3**	1	1		1			**3**		1					**1**
416	TS	4	DEAF ADDER CREEK(R),		1		1	1	1	**4**		1		1			**2**				1			**1**
413	TS	4	KUNKAMOULA BILLABONG (GUNKUMULU)(L), SOUTH ALLIGATOR RIVER(R),				1			**1**														
417	TS	4	EAST ALLIGATOR RIVER(R),					1		**1**														
418	TS	4						1		**1**														
444	TS	4	MCKINLAY RIVER(R),	1					1	**2**	1					1	**2**							
516	TS	4	LONG BILLABONG(P), COIRWONG (GOWONJ) CREEK(R), SOUTH ALLIGATOR RIVER(R),	1	1		1		1	**4**	1	1		1			**3**	1	1					**2**
445	TS	4	COIRWONG (GOWONJ) CREEK(R), SOUTH ALLIGATOR RIVER(R),		1					**1**		1					**1**							
454	TS	4						1		**1**														
451	TS	4	DEAF ADDER CREEK(R),					1		**1**														
457	TS	4			1			1		**2**		1					**1**							
434	TS	4	DEAF ADDER CREEK(R),					1		**1**														
470	TS	4	JIM JIM CREEK(R),		1				1	**2**		1				1	**2**							
456	TS	4	ADELAIDE RIVER(R), BURRELLS CREEK(R),						1	**1**	1						**1**							
469	TS	4			1					**1**		1					**1**							
452	TS	4	SHERIDAN CREEK(R),					1		**1**														
528	TS	4	MARGARET RIVER(R), SAUNDERS CREEK(R),						1	**1**														
506	TS	4			1				1	**2**		1				1	**2**							
508	TS	4	JIM JIM CREEK(R),				1			**1**				1			**1**				1			**1**
512	TS	4																					1	**1**
493	TS	4	REYNOLDS RIVER(L), REYNOLDS RIVER(R),			1				**1**			1				**1**			1				**1**
585	TS	4												1			**1**							
589	TS	5	DALY RIVER(R),																			1		**1**
608	TS	5	MOON BILLABONG(L), CLEANSKIN SWAMP(P), DALY RIVER(R),																	1				**1**
626	TS	5																				1		**1**
678	TS	5	DALY RIVER(R),																1		1			**2**
707	TS	5	NANCAR BILLABONG(L), RED LILY LAGOON(L), CHILLING CREEK(R), DALY RIVER(R),	1	1	1	1			**4**	1	1	1	1			**4**	1	1	1	1			**4**
706	TS	5	YARRA BILLABONG(L), HORSESHOE BILLABONG(P), DALY RIVER(R),																1					**1**
715	TS	5	FISH BILLABONG(L),																		1			**1**
722	TS	5	KATHERINE RIVER(R),																			1		**1**
664	TS	5	GREEN ANT CREEK(R),						1	**1**											1			**1**
750	TS	5																	1					**1**
826	TS	5																1						**1**
767	TS	5	CHILLING CREEK(R), DALY RIVER(R), MULDIVA CREEK(R),	1	1		1		1	**4**	1	1		1		1	**4**	1	1		1		1	**4**
811	TS	5	HOT WATER BILLABONG(L), DALY RIVER(R), FISH RIVER(R),	1	1		1			**3**	1	1					**2**	1	1		1			**3**
794	TS	5	BAN BAN LAGOON(L), RUBY BILLABONG(L), DALY RIVER(R), DOUGLAS RIVER(R),															1			1			**2**
793	TS	5	ANWOOLLOLLA LAGOON(L), NULLI BILLABONG(L), DALY RIVER(R), GREEN ANT CREEK(R),																1					**1**
812	TS	5	ANWOOLLOLLA LAGOON(L), DALY RIVER(R),													1	**1**	1	1					**2**
817	TS	5	BAMBOO (MOON BOON) CREEK(R), BAMBOO CREEK(R),																1					**1**
822	TS	5	ALLIA CREEK(R), MULDIVA CREEK(R),																1					**1**

				Entire study region							Drainage Divisions							NASY Regions						
				Criteria							Criteria							Criteria						
PU	DD	RG	NAME	1	2	3	4	5	6	∑	1	2	3	4	5	6	∑	1	2	3	4	5	6	∑
821	TS	5	ALLIGATOR LAGOON(L),		1					1		1					1	1	1					2
815	TS	5	HOT WATER BILLABONG(L), BAMBOO CREEK(R), DALY RIVER(R), PEGGY SPRING(S),																1		1			2
861	TS	5	MOYLE RIVER(R),			1				1			1				1			1				1
899	TS	5	DALY RIVER(R),																1					1
893	TS	5	MOYLE RIVER(R), TOM TURNERS CREEK(R),			1				1			1				1			1				1
946	TS	5	EJONG WATERHOLE(L), TURKEY HOLE(P), DALY RIVER(R), STRAY CREEK(R),																1					1
802	TS	5	FISH WATERHOLES(L), STRAY CREEK(R),															1						1
1031	TS	5																				1		1
1041	TS	5																				1		1
1212	TS	5																				1		1
1216	TS	5																				1		1
1264	TS	5																				1		1
1194	TS	5	CUI-ECI CREEK(R),																			1		1
1241	TS	5	FITZMAURICE RIVER(R),																			1		1
1215	TS	5	FITZMAURICE RIVER(R),																			1		1
1279	TS	5	FITZMAURICE RIVER(R),																			1		1
1223	TS	5																				1		1
1225	TS	5																				1		1
1442	TS	5	ANGALARRI RIVER(R),																		1			1
1514	TS	5				1				1										1				1
1558	TS	5	CAMERA POOL(L), FORREST RIVER(R),						1	1						1	1						1	1
1698	TS	5	ANGALARRI RIVER(R), VICTORIA RIVER(R),						1	1						1	1						1	1
1644	TS	5	ANGALARRI RIVER(R), IKYMBON RIVER(R),																		1			1
1684	TS	5	VICTORIA RIVER(R),			1				1			1				1			1				1
1736	TS	5	BROLGA SWAMP(P), BULLO RIVER(R), VICTORIA RIVER(R),			1				1										1				1
1740	TS	5	BUFFALO SPRING(P), THE ELBOW WATERHOLE(P), ANGALARRI RIVER(R), VICTORIA RIVER(R),						1	1						1	1	1					1	2
1809	TS	5	ORD RIVER(R), REEDY CREEK(R),															1						1
1830	TS	5	MOOCHALABRA DAM(L), KING RIVER(R), WEST ARM(R),	1		1			1	3	1		1			1	3	1		1			1	3
1844	TS	5							1	1						1	1						1	1
1839	TS	5																		1				1
1857	TS	5	ORD RIVER(R),						1	1						1	1						1	1
1877	TS	5	ORD RIVER(R),	1						1	1						1	1						1
1870	TS	5	BULLO RIVER(R),										1				1			1				1
1897	TS	5	OLD STATION BILLABONG(P), ORD RIVER(R),	1					1	2	1					1	2	1					1	2
1909	TS	5	BAINES RIVER(R), DICK CREEK(R), WEST BAINES RIVER(R),																				1	1
2050	TS	5	KING RIVER(R),															1					1	2
2014	TS	5	PENTECOST RIVER(R),																		1			1
2078	TS	5	DUNHAM RIVER(R), ORD RIVER(R),						1	1						1	1						1	1
2109	TS	5	DUNHAM RIVER(R),			1				1			1				1			1				1
2115	TS	5	FLYING FOX WATERHOLE(L), DUNHAM RIVER(R),						1	1						1	1						1	1
2170	TS	5																		1				1
2174	TS	5	EAST BAINES RIVER(R),																		1			1
2187	TS	5	DURACK RIVER(R), ELLENBRAE CREEK(R), FINE POOL(R),																		1			1
2453	TS	5	SNAKE CREEK(R), WEST BAINES RIVER(R),						1	1						1	1						1	1
2896	TS	5	BOW RIVER(R), ORD RIVER(R),																		1			1
2926	TS	5	O'DONNELL BROOK(R), WILSON RIVER(R),																				1	1
3690	TS	5	ORD RIVER(R),																	1				1
3810	TS	5				1				1			1				1			1				1
835	TS	6	KING GEORGE RIVER(R),													1	1	1	1				1	3
989	TS	6	MONGER CREEK(R),																1					1
1025	TS	6	DRYSDALE RIVER(R), JOHNSON CREEK(R),				1			1				1			1	1	1		1		1	4
1060	TS	6	CASUARINA CREEK(R),																			1	1	2
1073	TS	6	BERKELEY RIVER(R),			1				1										1				1
1120	TS	6	MOOL MOOL LAGOON(L), CARSON RIVER(R), KING EDWARD RIVER(R), MORGAN RIVER(R),															1						1
1130	TS	6	KING EDWARD RIVER(R),											1			1	1						1
1144	TS	6	BERKELEY RIVER(R),																			1		1
1145	TS	6	BERKELEY RIVER(R),																			1		1
1148	TS	6	BERKELEY RIVER(R),																			1		1
1247	TS	6	DRYSDALE RIVER(R), JOHNSON CREEK(R),																1					1
1329	TS	6	MORGAN RIVER(R											1			1							
1674	TS	6	ROE RIVER(R),																		1			1
1866	TS	6	PRINCE REGENT RIVER(R),																				1	1
1867	TS	6	CASCADE CREEK(R), PRINCE REGENT RIVER(R), QUAIL CREEK(R),											1			1							
1935	TS	6	PRINCE REGENT RIVER(R), YOUWANJELA CREEK(R),											1			1				1			1
2062	TS	6	PRINCE REGENT RIVER(R), YOUWANJELA CREEK(R),											1			1							
2017	TS	6	GLENELG RIVER(R),																	1				1
2132	TS	6	PRINCE REGENT RIVER(R),											1			1				1			1
2808	TS	6	ISDELL RIVER(R),																	1				1
2917	TS	6	TARRAJI RIVER(R),																	1				1
3422	TS	7																				1		1
3423	TS	7	MILLE MILLE LAKE(P),																			1		1
3741	TS	7																				1		1
3754	TS	7																				1		1
3936	TS	7																				1		1
4030	TS	7	WILLIES CREEK(R),																			1		1
4031	TS	7																				1		1
4534	TS	7			1					1														
3082	TS	7	FIRST YARP(L),																	1				1
3250	TS	7																		1				1
3571	TS	7	MAY RIVER(R), MEDA RIVER(R),															1						1
3569	TS	7	ORANGE POOL(P), HAWKSTONE CREEK(R), MEDA RIVER(R),													1	1							
3586	TS	7	FRASER RIVER(R),																	1				1
3641	TS	7	POULTON POOL(L), CAMIARA CREEK(R), LENNARD RIVER(R), MAY RIVER(R), MEDA RIVER(R),															1						1
3972	TS	7	JORDAN POOL(L), LAKE ALMA(L), LAKE SKELETON(L), LULIKA POOL(L), FITZROY RIVER(R), MINNIE RIVER(R),	1			1			2	1						1	1	1					2
3971	TS	7	COCKATOO CREEK(R),																		1			1
4121	TS	7	(R), MINNIE RIVER(R),													1	1		1				1	2
4077	TS	7	MUNSTERS POOL(L), FITZROY RIVER(R),													1	1						1	1
3948	TS	7	DUCK HOLE(L), NAMELESS DAM(P), BLIND CREEK(R), SANDY CREEK(R),													1	1							

				Entire study region							Drainage Divisions							NASY Regions						
				Criteria							Criteria							Criteria						
PU	**DD**	**RG**	**NAME**	**1**	**2**	**3**	**4**	**5**	**6**	**∑**	**1**	**2**	**3**	**4**	**5**	**6**	**∑**	**1**	**2**	**3**	**4**	**5**	**6**	**∑**
4319	TS	7	URALLA CREEK(L), YALLAMUNGIE POOL(L),																		1			**1**
4280	TS	7	FITZROY RIVER(R),																		1			**1**
4366	TS	7	FITZROY RIVER(L), TRAGEDY POOL(L), FITZROY RIVER(R), SNAKE CREEK(R),	1						**1**	1						**1**	1			1			**2**
4240	TS	7				1				**1**			1				**1**			1				**1**
4263	TS	7	SIX MILE CREEK(L), UPPER LIVERINGA POOL(L), SIX MILE CREEK(R),													1	**1**							
4339	TS	7	FITZROY RIVER(L), NINE MILE POOL(L), SIX MILE CREEK(L), LOONGADDA POOL(P), SIX MILE POOL(P), FITZROY RIVER(R),				1			**1**								1	1		1			**3**
4343	TS	7																		1				**1**
4119	TS	7	TROYS LAGOON(L), MOUNT WYNNE CREEK(R),															1			1			**2**
4324	TS	7	FITZROY RIVER(L), SIX MILE CREEK(L), MANAROO POOL(P), FITZROY RIVER(R),			1				**1**										1				**1**
4390	TS	7	CARRIGAN POOL(L), FITZROY RIVER(L), WOOLABUDDA POOL(L), JUNEDELLA WATERHOLE(P), FITZROY RIVER(R), NERRIMA CREEK(R),																	1				**1**
4359	TS	7	FITZROY RIVER(L), FITZROY RIVER(R),																		1			**1**
4253	TS	7	ALLIGATOR POOL(L), FITZROY RIVER(R), MARGARET RIVER(R),																1					**1**
4411	TS	7	FITZROY RIVER(L), FITZROY RIVER(R),																1					**1**
4403	TS	7	FITZROY RIVER(L), FITZROY RIVER(R),																1					**1**
4418	TS	7	FITZROY RIVER(L), COOGABING POOL(P), ROCKY HOLE(P), FITZROY RIVER(R),															1	1					**2**
4468	TS	7	CAROL WATERHOLE(L), MARGARET RIVER(R),													1	**1**						1	**1**
4563	TS	7	MARGARET RIVER(L), POWDER SPRING(P), MARGARET RIVER(R),													1	**1**						1	**1**
4592	TS	7	LOUISA RIVER(R)													1	**1**						1	**1**
4709	TS	7	BALWYNAH POOL(L), ONE TREE HOLE(P), FITZROY RIVER(R),						1	**1**						1	**1**						1	**1**
4704	TS	7	FITZROY RIVER(R), PANDANUS SPRINGS(S),													1	**1**							
4711	TS	7	7 MILE BILLABONG(L), PELICAN BILLABONG(L)													1	**1**						1	**1**