# BIOREGIONAL FRAMEWORKS FOR ASSESSMENTS OF FRESHWATER BIODIVERSITY IN AUSTRALIA.

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**Abstract**

Criteria such as species richness, endemism, rarity, comprehensiveness, adequacy, representativeness and refugia are often used to assess biodiversity values and priorities for protected area networks. Bioregional frameworks are essential for the application of most of these criteria. Although hierarchical biogeographic units from regional ecosystems (Sattler and Williams 1999) to bioregions have been defined for terrestrial (Thackway & Creswell 1995) and marine and coastal (Thackway & Creswell 1998) biodiversity in Australia, lack of agreed bioregional frameworks currently hinders assessment of freshwater biodiversity values. This particularly applies in relation to representativeness criteria used for protected area planning (Nevill 2001, 2002).

Different components of freshwater biodiversity form bioregional relationships at different scales in response to different biogeographic features, the distribution abilities of biota and river basin/geological histories. Consequently no one bioregional framework may have application across all components of freshwater biodiversity (Wells and Newall 1997). Substantial data collection and research is needed to progress toward the possible definition of universally applicable Australian freshwater 'bioregions'. Meanwhile, prudent and pragmatic approaches involving the use of existing regionalisations and data are required to serve current freshwater biodiversity assessment and conservation planning needs.

This paper considers the potential for applying spatial frameworks provided by terrestrial bioregions, river basins, riverine ecological process zones (Whittington *et al*



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2001), geographic patterns of aquatic biota including findings from phylogenetic studies, to freshwater biodiversity conservation evaluation and protected area planning. The role and potential of assessments of aquatic ecosystem condition (eg, the Assessment of River Condition (NLWRA 2002)) in relation to defining the areal status of defined biogeographic units is also discussed.

**Introduction**

Biogeographic regions, also known as bioregions or ecoregions, are defined as units of land with relatively homogeneous ecological systems or relationships between organisms and their environment (Omernik 1987). In Australia, bioregions have been developed at a continental scale for terrestrial ecosystems (*Interim Biogeographic Regions of Australia* (IBRA) (Thackway & Cresswell 1995,1998)), and marine ecosystems (*Interim Marine and Coastal Regionalisation of Australia* (IMCRA)), but not for freshwater ecosystems.

The definition of bioregions is considered an essential step for nature conservation planning particularly for the design of an ecologically or biogeographically representative system of protected areas (Thackway & Cresswell 1998). Bioregions and subregions are used for two main biodiversity conservation planning applications: as a framework to assess biological resource condition (figure1); and to define progress toward representative protected area networks (figure 2) (NLWRA 2001).

Most jurisdictions in Australia have made commitments to the development of representative protected area networks for freshwater biodiversity, particularly riverine ecosystems (Nevill 2002). The need for such commitments has been realised within the context of established protected area networks, which have been primarily based on terrestrial ecosystems and biota, and where inclusion of riverine ecosystems has generally been by default rather than design.

Previous assessments have found terrestrially defined bioregions wanting in terms of application for freshwater biota (Wells and Newall 1997, Turak et al 1999), and the need to develop a biogeographic regionalisation of Australian inland waters is well recognised as a national priority for the protection and management of freshwater biodiversity (Georges and Cottingham 2002).

Figure 1. Percentage of IBRA bioregion, subregion in conservation reserves (Source NLWRA 2001).

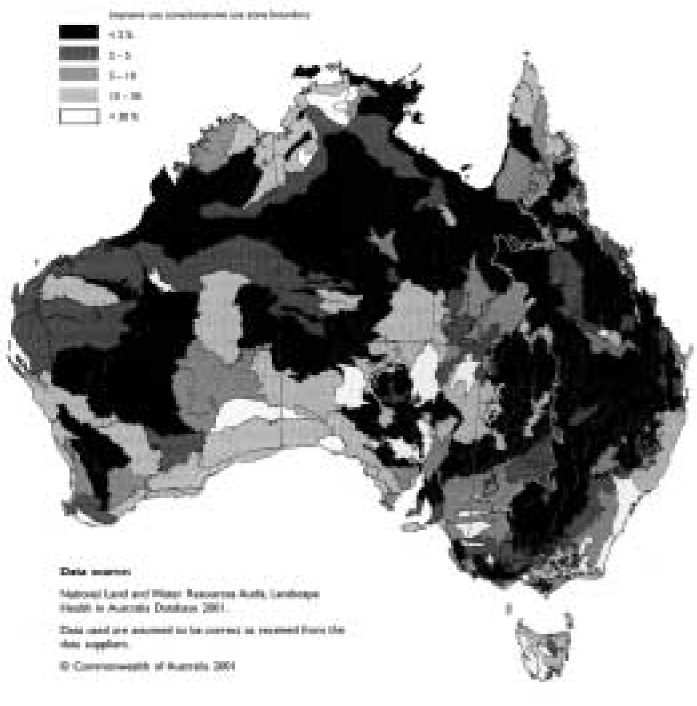
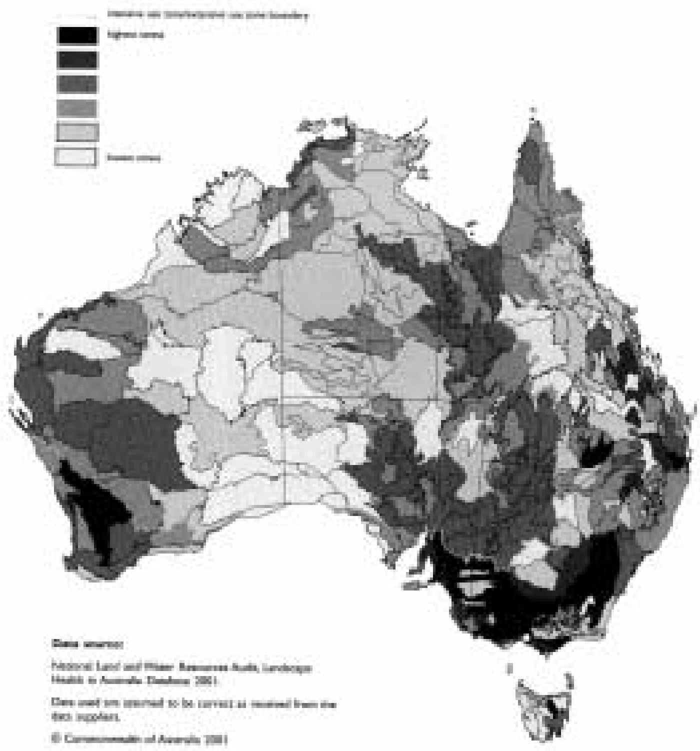



Figure 2. Continental landscape stress of IBRA bioregion, subregions (Source NLWRA 2001).



In the absence of bioregions that can be used to assess freshwater biodiversity, proponents of riverine protected areas (eg, Cullen 2002) have proposed that river basins in better ecological condition be primarily considered for ‘Heritage River’ protection. While ecological condition is a legitimate criterion for protected area selection (Dunn 2000), without a bioregional assessment framework and the application of associated criteria such as representativeness, there is a risk that only river basins less affected by development pressures will be protected. This contrasts with bioregional-based assessments of freshwater biodiversity (eg, Whitting et al 2000), that identify high values in terms of diversity, endemicity, critical species, representativeness and complimentarity in regions with substantially modified catchments and high land use pressures. While more challenging to implement and manage protected areas in these catchments they are potentially more crucial for the protection of biodiversity values.

One of the primary constraints limiting the development of a freshwater bioregional framework in Australia is our ignorance of aquatic species and their distribution patterns, with the exception of a few well-studied groups (Choy and Marshall 2000, Georges and Cottingham 2002, Wells, et al 2002). However, in the last decade there has been a number of developments that contribute toward the working definition of such a framework, including: national scale sampling of macroinvertebrates for the National River Health Program (Davies 2000); biogeographic reviews of key taxa including fish (Unmack 2001), molluscs (Ponder and Walker 2001) and turtles (Georges and Thomson 2002); the development of molecular tools for mapping phylogeographic regions (Hughes at al 1996, Avise 2001, Hurwood et al 2001, Georges et al 2001, Ponder & Walker 2001); further refinement of existing terrestrial bioregions (eg IBRA version 5.1 (Environment Australia 2001)); and new biophysical classification frameworks for rivers and wetlands (Blackman, Spain and Whitely 1992, Semeniuk & Semeniuk 1995, Calvert, Eskine & Junor 2001, Thoms et al 2001, Thoms and Parsons in press).

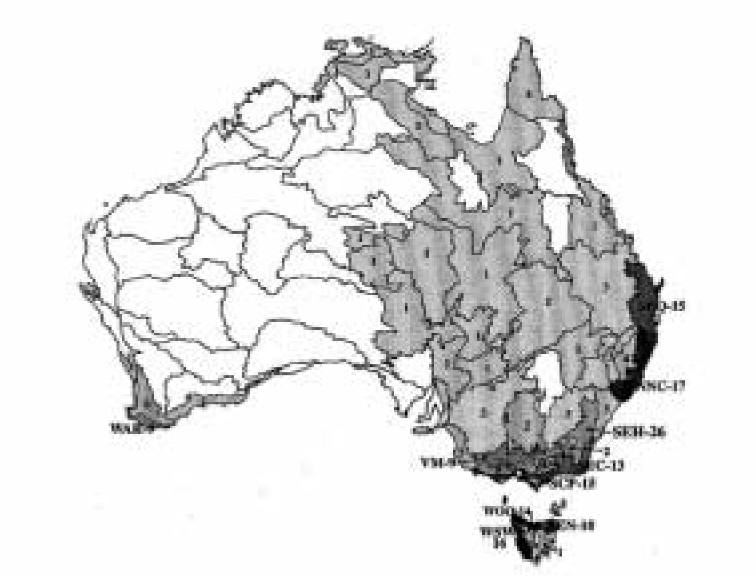
### Previous work - *a priori* regionalisation

The various approaches to the definition or application of bioregions for inland waters in Australia have been driven by their intended application. This has ranged from predicting water quality characteristics (Tiller and Newall 1995), assessing ecological condition (Turak et al 1999, Choy and Marshall 2000, Choy et al 2002) and biodiversity conservation planning (Whiting et al 2000). While several studies described below have utilised regions defined *a priori* on geomorphic and climatic data for freshwater applications, this paper recommends that for biodiversity conservation planning the distribution of aquatic biota should have precedence in the definition of bioregions and that the primary regional framework should be provided by drainage units and within drainage position.

It is only recently that the development of bioregions based specifically on aquatic ecosystems has been progressed in Australia (Wells and Newall 1997). This work followed the example of North American workers (Omernik 1987) in developing *a priori* regionalisations using largely terrestrial attributes (eg climatic surfaces, physiography (altitude and landform) and pre-European vegetation). Defined regions were then 'tested' against observed water quality characteristics, macroinvertebrate assemblages and other biophysical regionalisations. A key limitation of this work was that natural boundaries provided by watersheds were not considered in the definition of regions, despite the recognition that drainage network and positioning were likely to explain much of the observed subregional variation (Wells and Newall 1997). Also, while intrinsic regions evident in the biota (macroinvertebrate) data were acknowledged as an appropriate means of defining the scale of regions they were not proposed as a primary protocol for the definition of aquatic ecoregions.

Whiting et al (2000) provide another recent example of the application and limitations of *a priori* defined terrestrial bioregions for defining aquatic conservation priorities. They quantify biodiversity values for freshwater crayfish taxa in terms of diversity, endemicity, critical species, and complementarity within IBRA regions (Interim Biogeographic Regions of Australia (Thackway & Creswell 1995)). As the concordance of individual crayfish species and community distributions with the applied IBRA regions was not assessed, the resolution of defined regional conservation values is limited (figure 3). For example resultant conservation planning would still need to make reference to individual species distribution data to select between regions and identify priority catchments or sites to protect representative examples of the crayfish community. One important finding of this study was that regional biodiversity conservation values defined in terms of species richness were distinct for different taxa with northern Australia tropical regions most important for amphibians (Tyler, Watson and Martin 1981), and subtropical and temperate regions most significant for crayfish.

Figure 3. Species Richness of Australian Freshwater crayfish taxa within IBRA bioregions (source Whiting et al 2000).



**Intrinsic biota regionalisation**

Defining intrinsic regional patterns in aquatic biota particularly macroinvertebrates has been progressed by many workers involved with the Australia-wide sampling underpinning the National River Health Program (Davies 2000). This program has developed a RIVPACS-type predictive modelling capacity for regional and reach scale macroinvertebrate assemblages. The primary use of this data has been assessment of riverine ecological condition through the comparison of observed and expected values (Turak et al 1999, Huong et al 2000). However this national data set does have substantial potential for regionally based biodiversity assessment and protected area planning (Wells, et al 2002). One limitation of much of the data is that macroinvertebrates have been described only to family level. While a predictive capacity for macroinvertebrate family assemblages has served riverine condition assessment (NLWRA 2002), defined regions are broad and often do not recognise distinct biogeographic boundaries such as drainage divides (Wells and Newall 1997, Turak et al 1999). In some jurisdictions where macroinvertebrate data has been defined to species level, its potential for defining bioregions has been recognised (Doeg 2001, Wells et al 2002).

**Organism vagility**

Within Australian states, Victoria has made the greatest progress toward the definition of representative riverine regions using both invertebrate and vertebrate biota (Doeg 2001). An important consideration in the use of biota for the definition of aquatic biogeographic regions illustrated by the Victorian work is the vagility of different taxa, particularly of totally aquatic organisms versus those with terrestrial life stages or distributional abilities.

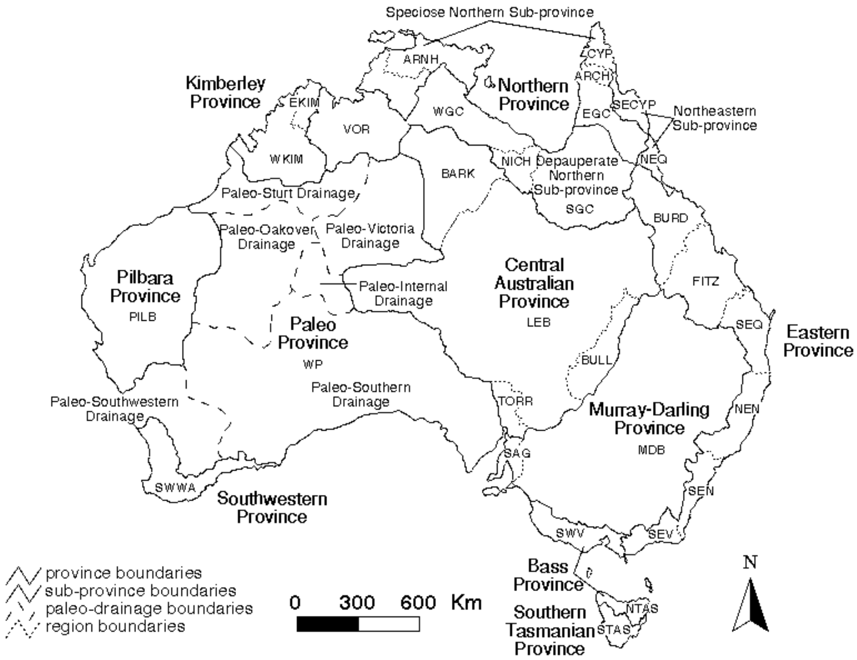
In contrast to vagile terrestrial organisms, organisms that are restricted to freshwater (eg. freshwater fishes) suffer unique biogeographic constraints (Unmack 2001). Their ability to distribute to suitable habitats or move in response to climate change or geological events is limited to patterns of connectivity of freshwater bodies which is usually catchment constrained but does includes rare events such as drainage rearrangements, changes in continental shelf width and depth and major pulses of freshwater into oceans (Unmack 2001).

**The case for drainage basins as a primary framework**

Drainage basins have been considered the most meaningful regionalisations for inland waters as surface waters 'are arranged spatially as a network throughout the landscape effectively controlled by topography' (Georges and Cottingham 2002). Recognition of drainage network boundaries and their current and historical connectivity is perhaps one of the most important considerations for the definition of freshwater bioregions.

Unmack's (2001) work on the biogeography of Australia's freshwater fishes provides one of the most substantial developments toward the definition of freshwater bioregions in Australia. It restricts its analysis to only fish with life histories restricted to freshwater and uses drainage units as the starting point for the definition of regions (figure 4) based on discontinuities of fish community distributions using a range of methods.

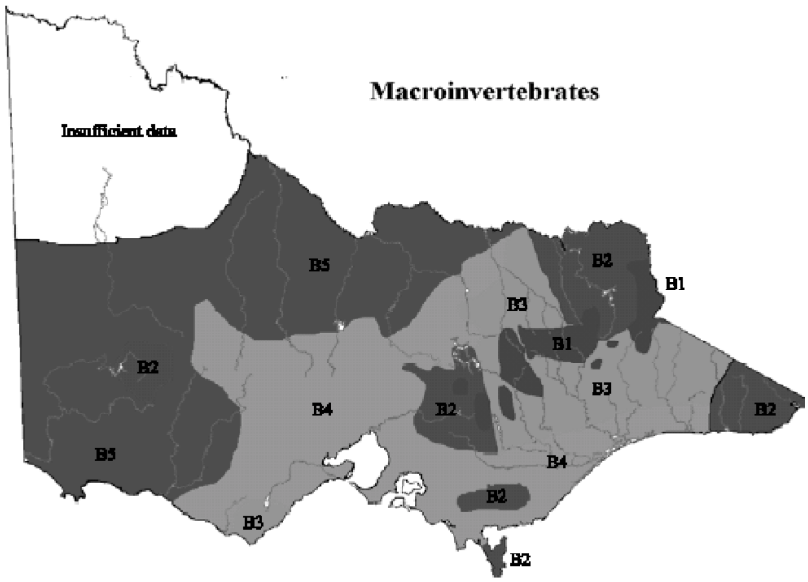
Figure 4. Freshwater fish biogeographic provinces proposed for Australia (Source Unmack 2001)




Where the vagility of individual aquatic taxa species is not considered, the resolution of defined regions is poorer for example, even at species level, macroinvertebrate associations used to define Victoria's river regions (Doeg 2001) are board and cross major drainages (see figure 5). With the inclusion of purely aquatic taxa (i.e. freshwater fish) the bioregions more closely define drainages (see figure 6) recognising major catchment divides (Doeg 2001). Interestingly, associations of both invertebrate and vertebrate biota typical of steep gradient upper catchment areas defined for Victorian regions appear less affected by catchment divides occurring in low order streams both sides of the dividing range and define a riverine region that straddles both coastal and inland drainage systems (Doeg 2001).

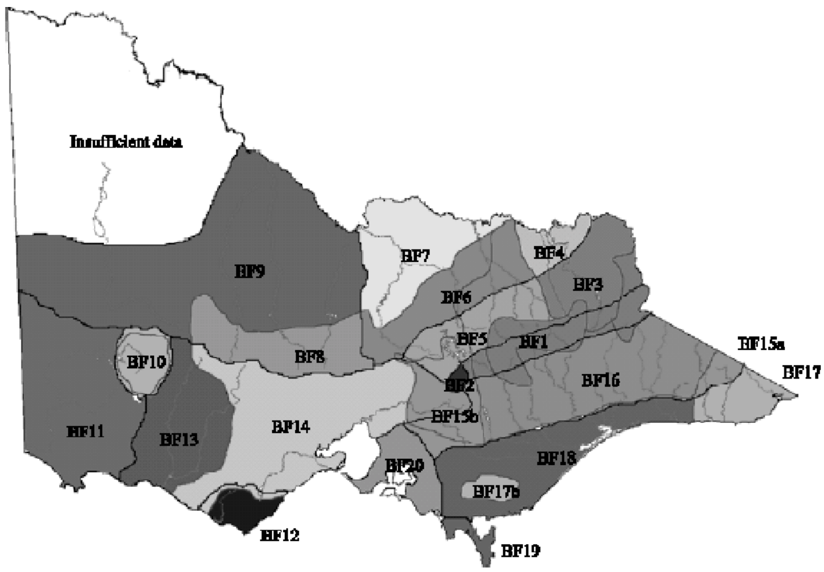
We propose that after drainage boundaries, the second most important consideration in the definition of freshwater bioregions is within drainage position. The recognition of within-drainage regional associations reflecting upper, mid and lower catchment areas is a significant finding of the Victorian work (Doeg 2001) and earlier fish-based assessments (Pusey, Arthington and Read 1993 & 1995, Gehrke 1997).

Figure 5 Macroinvertebrate regions defined for Victorian rivers. (Source Doeg 2001)



Aquatic macroinvertebrate regionalisation (from EPA data)

Figure 6. Riverine Biological regions defined for Victorian rivers using both macroinvertebrate and fish biota data. (Source Doeg 2001)



Riverine Biological Regions of Victoria

## Physical river classification

Freshwater ecologists have long recognised that invertebrate and fish community composition is strongly influenced by drainage position and catchment area. This is related to the range of physical habitat settings and associated biophysical processes that influence riverine systems from upper to lower catchment areas (Calvert, Eskine

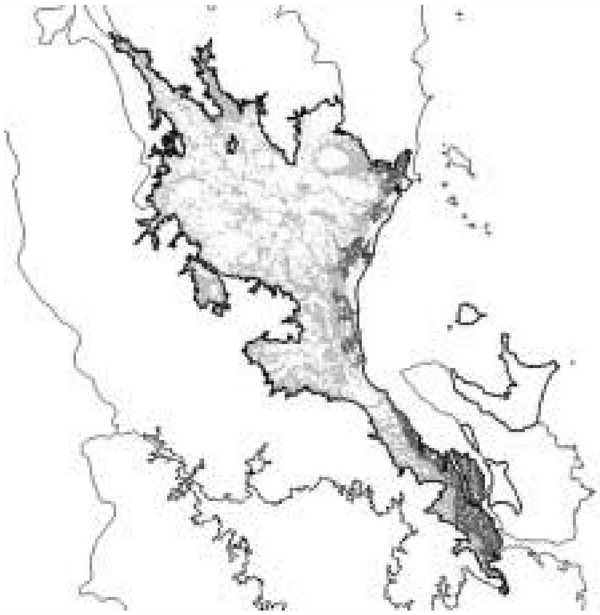
& Junor 2001, Thoms et al 2001, Thoms and Parsons in press). Compared to the distinct breaks in aquatic habitat connectivity, and hence aquatic biota community, that exist between drainages, within-drainage distinctions in biota composition are likely to be less well demarcated except where major biogeographic boundaries and discontinuities exist such as waterfalls and lakes. Analysis of intrinsic patterns observed within Australia aquatic vertebrate and invertebrate biota does suggest that upper, middle and lower catchment species associations and, hence, regionalisation can be defined (Pusey, Arthington and Read 1993 & 1995, Wells and Newall 1997, Gehrke 1997, Doeg 2001, Georges and Thomson 2002).

The demonstration of concordance between within-drainage biota associations and physical river classifications (eg Choyet al 2000) would present the opportunity to divide aquatic bioregions defined on the basis of drainage units (eg Unmack 2001) into upper and lower catchment sub units with some confidence where detailed biota data is lacking. The recent definition of riverine process zones (Whittington *et al* 2001, Thoms et al 2001, Thoms and Parsons in press) which integrate both physical and ecological process attributes may distinguish more ecologically meaningful boundaries reflected by the aquatic biogeography. Biotic interactions such as competition and predation could also be considered as additional attributes but data would often be lacking.

**Are terrestrial bioregions useful?**

Workers in aquatic biogeography have generally dismissed the suitability of terrestrially defined bioregions for explaining patterns in freshwater biota (Georges and Cottinham 2002). Some of this is related to the perception that the original 80 bioregions defined for Australia (Thackway & Creswell 1995), were too broad for the scale of patterns observed in freshwater biota (Marchant et al 1997, Turak et al 1999). However, recent developments in hierarchical terrestrial bioregional frameworks have resulted in finer scale units including subregions (Environment Australia 2001) and regional ecosystems (Sattler and Williams 1999). These regionalisations have not been tested for their application to freshwater biodiversity but given that they 'capture' some of the key geomorphic drivers affecting aquatic habitats and ecological processes we hypothesise that they would have a legitimate application particularly for more vagile or terrestrially associated components of freshwater biodiversity such as riparian vegetation communities and associated fauna. Where detailed riparian community information is available indicative assessments show there to be major stratifications of riparian community types across subregion boundaries (figure 7). We also hypothesise that aquatic biota with terrestrial adult stages particularly those that can fly (eg, many aquatic insects) are likely to have distributions associated more with terrestrial regional ecosystems and not be constrained by drainage boundaries. This would be particularly true for insects that have a relatively long adult flying stage and are strong flyers (eg. dragonflies).

Figure 7. Remnant vegetation within the Tully Subregion of the Wet Tropics Bioregion. Different shades represent four different land zones. Distinct riparian communities are observed to stratify across the different land zones (Source Qld EPA).



Ultimately the suitability and scale of freshwater or terrestrial regionalisations that may be applied for describing the distribution of aquatic biota will be related to the biota's vagility, particularly its ability to distribute across drainage divides, and the extent to which its life cycle is restricted to aquatic habitats. Figure 8 presents a generalised relationship between the vagility of aquatic organisms and the suitability of freshwater versus terrestrial regionalisations.

Figure 8. Generalised relationship between the vagility of aquatic organisms and the suitability of freshwater versus terrestrial regionalisations.

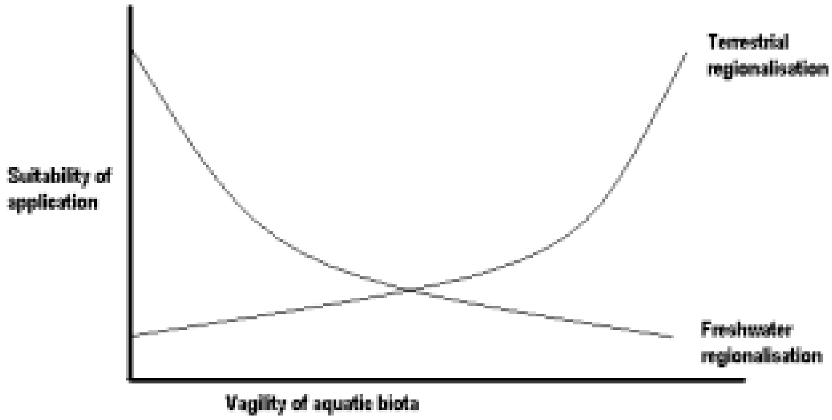



Table 1 presents hypothesised scales of association & applicable bioregional frameworks for components of freshwater biodiversity with differing vagility.

**Wetlands other than riverine ecosystems**

Much of this paper has focussed on riverine ecosystems and associated biota. In considering bioregional frameworks for the assessment of freshwater biodiversity it is important to recognise that much of it occurs in wetland ecosystems other than the linear drainage networks of river systems. Subterranean and groundwater associated ecosystems are a particularly unique class of wetland that also host much biota. While no attempt is made to address the particular bioregional associations of these systems here, the observation can be made that even subterranean systems are often contained within the hydrological systems of individual catchments and are likely to exhibit some level of bioregional distinction between drainage systems.

Patterns of surface wetland biodiversity is likely to reflect both terrestrial and aquatic derived bioregions. The primary means often used to classify surface wetlands are the landform setting in which they are hosted and associated vegetation types (Blackman, Spain, and Whiteley 1992, Semeniuk & Semeniuk 1995) both being largely governed by attributes reflected in terrestrial bioregionalisations. Some existing approaches to wetland classification recognise the distinct bioregional drivers of wetland form, function and biodiversity and classify them within the nested hierarchy provide by the existing terrestrially based bioregions (Blackman, Spain, and Whiteley 1992). However, less vagile aquatic biota within freshwater wetlands will most likely be drainage basin constrained in terms of distribution and hence will be best served by assessment frameworks using bioregions defined by drainage based frameworks.

**Table 1: Hypothesised scales of association & applicable bioregional frameworks for components of freshwater biodiversity with differing vagility**

| **Component of Freshwater Biodiversity** | **Distributional patterns, associations & constraints** | **Applicable bioregional framework** |
|---|---|---|
| Completely aquatic macroinvertebrates and vertebrates (eg freshwater fish) | Distributions generally constrained by drainage boundaries and prior connection history, within basin distributions controlled by river process zone / wetland type and finer scales of hydrological / habitat. stratification | 'Provincial' (Unmack 2001) drainages (eg those with shared history of biota exchange), stratified by riverine process zones, or valley scale physical habitats. |
| Aquatic macroinvertebrates with terrestrial adult phase | Depending on length of adult phase and flying strength, adult distributions associated with suitable terrestrial habitats independent of catchment divides, within basin distributions controlled by river process zone / wetland type and finer scales of habitat. | Riverine process zone / wetland type / regional ecosystems stratifications within IBRA bioregions. |
| Semi- aquatic vertebrates (ie amphibians, reptiles, birds, mammals) | Distributions associated with suitable terrestrial, riparian & wetland habitats relatively independent of catchment divides (exceptions noted for freshwater turtles Georges pers comm.>) | Riverine process zone or wetland type / regional ecosystem stratifications within IBRA bioregions or grouped 'Provincial' (Unmack 2001) drainages. |
| Aquatic plants | Dependent upon distribution abilities of species, pattern of distributions relatively less constrained by catchment boundaries and histories than fauna, within basin distributions controlled by river process zone / wetland type and finer scales of habitat stratification | Riverine process zone or wetland type / regional ecosystem stratifications within IBRA bioregions or grouped 'Provincial' (Unmack 2001) drainages. |
| Emergent and terrestrial (riparian) plants | May exhibit some level of catchment bounded distribution but generally associated with suitable terrestrial / riparian / wetland habitats– can cross catchment divides | Riverine process zone or wetland type / regional ecosystem stratifications within IBRA subregions - bioregions |

## Discussion

**Proposing a framework for an *Interim Freshwater Biogeographic Regionalisation for Australia***

Based on the preceding review of work that has contributed toward defining freshwater bioregions in Australia, the following principles and approaches are suggested as a way forward to the development of an *Interim Freshwater Biogeographic Regionalisation for Australia)*:

1. For defined bioregions to serve biodiversity conservation planning, distribution of aquatic biota should have precedence over physical attributes in the definition of bioregions (eg. Wells et al 2002), while recognising a legitimate though secondary role for physical attributes in helping to define subdivisions in broadly defined freshwater bioregions,
2. The framework should be hierarchical to enable biodiversity assessments and planning to be made at a number of scales,
3. The macro-regions (top of the hierarchy) for a freshwater bioregional framework should be based on riverine drainage systems and various scale aggregations of drainage systems defined by shared aquatic biota demonstrating historical connectivity. The drainage based freshwater fish regions and provinces defined Australia-wide by Unmack (2001) form a robust starting point.
4. The second level of the framework hierarchy should be defined within drainages, with sub-drainage units defined for upper, middle and lower catchment areas. These sub-regions ultimately should be defined on the basis of distinctive sub-drainage associations of aquatic biota particularly recognising natural biogeographic boundaries such as escarpment waterfalls, lakes and major breaks in slope with associated changes in hydraulic power reflected in valley scale instream changes in habitat and associated biota. In the absence of available biota data we suggest that for defining the first interim bioregionalisation, physical and 'river process zone' valley classifications be utilised (Calvert, Eskine & Junor 2001, Thoms et al 2001, Thoms and Parsons

in press). Subsequent research effort could then be directed toward identifying the existence and scale of concordance with within-basin biogeographic patterns as defined for both vertebrate and invertebrate biota (Pusey, Arthington and Read 1993 & 1995,Gehrke 1997, and Doeg 2001, Choy et al 2000).

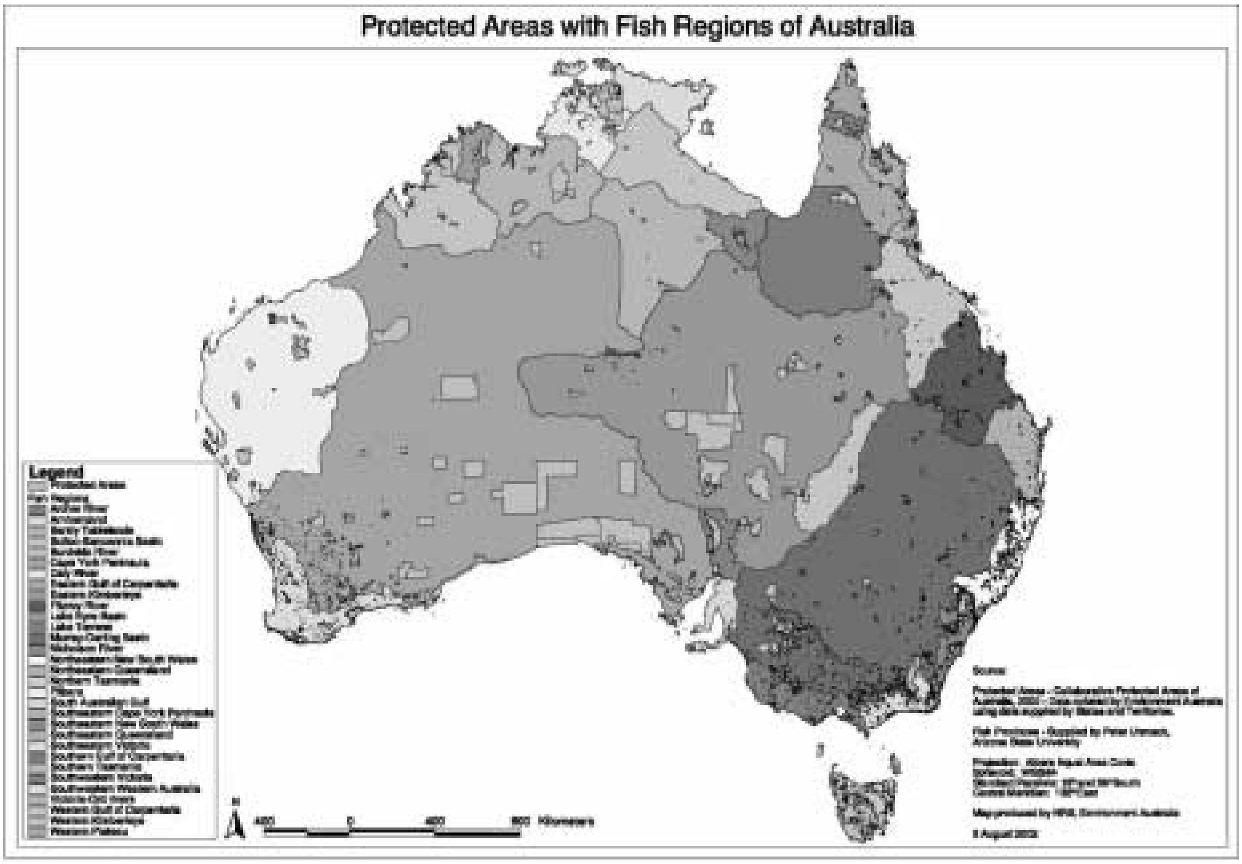
5. Two lower spatial scales of the bioregional framework hierarchy equivalent to the riverine 'reach' and 'habitat patch' scale association recognised by both geographer and ecological workers in aquatic ecosystems (Calvert, Eskine & Junor 2001, Thoms et al 2001) may also be defined. These associations will in most instances form discontinuous units and their application would primarily be for within basin site assessment rather than national, state or regional applications envisaged for an *Interim Freshwater Biogeographic Regionalisation for Australia*. More detailed analysis of macroinvertebrate data at a species level and constrained to particular taxa are likely to provide a biogeographic basis for defining some of these smaller spatial scale regional associations.
6. The variable vagility of different components and taxa groups comprising freshwater biodiversity should be recognised in the choice of bioregional frameworks used for conservation assessments. This approach acknowledges that more than one bioregional framework are needed to serve conservation assessments for all components of what is recognised as 'freshwater biodiversity' and that a legitimate case can be made for the application of both terrestrial and freshwater based bioregionalisations in assessing the status of biodiversity for conservation planning.
7. Where elements of freshwater biodiversity (eg, freshwater wetlands) are recognised to reflect both terrestrial and freshwater bioregional patterns one regionalisation be used to stratify assessments within the other with precedence based on spatial scale and the vagility of the biota being examined.

**Example application of a freshwater bioregional planning framework**

*Representativeness of freshwater fish regions in protected areas.*

For many Australian freshwater conservation biologists, the potential for applying bioregional frameworks for biodiversity conservation planning is not well recognised because such approaches have largely been the reserve of terrestrial workers. To illustrate such an application, the freshwater fish regions of Unmack 2001, have been intersected with the Australian protected area database (Hardy 2001), figure 9. As these protected areas largely contain terrestrial ecosystems, the AUSLIG 250K Australian Drainage Coverage was also intersected to assess the percentage of defined drainage network within each fish region that is included in existing protected areas. The results of this analysis are presented in table 2.

Figure 9. Overlay of Australian Freshwater fish regions (Unmack 2001) with existing protected areas in Australia (Source Environment Australia, National Reserve Section)




Although the analysis is relatively crude and includes a fallible assumption that riverine systems within terrestrial reserves are protected, there are several significant findings:

1. There are very few protected areas in Australia that are sufficiently large to encompass entire river catchments, exceptions being in Tasmania and

Arnhemland. Victoria is the only jurisdiction in Australia that has specifically developed linear protected area systems to protect the riparian ecosystems of Heritage River basins (Doeg 2001).

2. Even where relatively large percentages of a fish region's drainage network is included in protected areas (eg, Archer River, South eastern NSW, South Eastern Victoria (all ~25%)), examination of the distribution of the protected areas within the drainage network indicates that they predominantly cover upper catchment areas and do not include lower gradient mid-catchments or lower catchment floodplains. This has major implications for components of freshwater biodiversity such as freshwater fish communities which increase in species diversity with increasing catchment area (Pusey, Arthington and Read 1993 & 1995,Gehrke 1997), and for some species which are diadromous (and may not be able to traverse more impacted reaches), and highlights the importance of defining regions within basins to help focus more representative conservation planning.
3. Many of the fish regions with low percentages of their drainage network in protected areas represent Australia's more intensively used river basins (i.e. Fitzroy, Murray Darling Basin, South eastern Queensland, Burdekin River (all less that 5% of drainage network within protected areas)). While opportunities for establishing protected areas within these systems may be limited, they are also the systems under the greatest landuse stress where protected area declaration may provide a legislative impetus for improved catchment management.

*Ecological Condition Status of Freshwater Fish Regions*

Areal representation of fish regions within protected areas is only one approach to defining conservation priorities. The other major input for biodiversity conservation priority decision making is resource condition. In terrestrial conservation assessments, GIS based analyses of the status of individual bioregions is often undertaken by intersecting bioregions with vegetation clearing coverages or other measures of biodiversity loss or degradation (NLWRA 2001). With riverine and wetland ecosystems such analyses are confounded by the fact that the ecosystems may continue to remain physically in the landscape in a range of condition states. Recent

Australia-wide integrated assessments of river ecological condition (NLWRA 2002) http://audit.ea.gov.au/ANRA/coasts/docs/estuary_assessment/River_Findings.cfm provide a means to assess the condition status of defined aquatic bioregions. Analyses which intersect Unmack's defined fish regions with the national assessment of river condition reach scale output highlights some useful biodiversity conservation planning contexts. These include identifying where opportunities to

**Table 2.** Percent of AUSLIG 1:250000-drainage network within each Australian freshwater fish region (Unmack 2001) that is included in existing terrestrial reserves

| **Fish Region Name** | **%** |
|---|---|
| Southern Tasmania | 45.2 |
| Archer River | 29.2 |
| South eastern New South Wales | 26.3 |
| South eastern Victoria | 23.6 |
| North eastern Queensland | 16.3 |
| North eastern New South Wales | 16.2 |
| South eastern Cape York Peninsula | 16.0 |
| Arnhemland | 15.8 |
| Cape York Peninsula | 13.6 |
| Northern Tasmania | 12.8 |
| Eastern Kimberleys | 11.9 |
| Daly River | 9.6 |
| South western Western Australia | 9.3 |
| Nicholson River | 9.1 |
| Victoria-Ord rivers | 8.2 |
| South western Victoria | 7.9 |
| South Australian Gulf | 5.1 |
| Barkly Tablelands | 4.9 |
| Lake Eyre Basin | 4.7 |
| Western Kimberleys | 4.7 |
| Western Plateau | 4.6 |
| Pilbara | 4.4 |
| Bulloo-Bancannia Basin | 3.9 |
| Fitzroy River | 3.7 |
| Murray-Darling Basin | 3.6 |
| Southeastern Queensland | 3.0 |
| Lake Torrens | 2.9 |
| Southern Gulf of Carpentaria | 2.0 |
| Burdekin River | 1.6 |
| Eastern Gulf of Carpentaria | 1.0 |
| Western Gulf of Carpentaria | 0.1 |

secure the protection of better condition river reaches in Australia's more intensively used basins (and more ecologically impacted fish regions) still exist, opportunities for lower catchment / floodplain protection in coastal fish regions and the prevalence of entire river drainages in relatively good ecological condition in northern and inland Australia. These provide substantial opportunities for large scale protective management.

**Ways Forward**

An *Interim Freshwater Biogeographic Regionalisation of Australia* established using some of the ideas developed in this paper would be a 'work in progress' limited by available data. However, it would provide an interim framework with which to progress assessment and planning initiatives for the development of a representative network of inland aquatic protected areas Australia-wide. An example of the application of freshwater fish bioregional frameworks defined by Unmack (2001) for protected area planning is presented below.

There are a number of key areas in which targeted research could further develop an interim framework.

*Closer assessment of existing terrestrial regionalisations*

Much more work needs to be done to assess the concordance of freshwater biota and ecosystems with the finer scale terrestrially-based regionalisations that have been developed in many jurisdictions eg, Sattler and Williams 1999, Environment Australia 2001. Hypothetically these regionalisations should have application for more vagile aquatic biota and freshwater ecosystems with substantial terrestrial components (eg floodplain wetlands). They may also have a useful application as secondary classifiers of defined freshwater regions particularly for biota that form biogeographic patterns at finer spatial scales in relation to terrestrial vegetation of landforms.

*More distributional data for aquatic biota*

Our current ability to define bioregions is constrained by our limited knowledge of aquatic biota. This is demonstrated by the many dedicated surveys of various aquatic taxa that continue to unearth undescribed species, even for conspicuous vertebrate taxa such as fish (eg, Pusey, Arthington and Read (1995), Unmack (2001)). To refine biogeographic boundaries and identify regional concordance between taxa further dedicated surveys of freshwater aquatic biota are required.

*Examining concordance between biophysical and biogeographic patterns*

Given that Australia is a very large country and that resources are not readily available to undertake comprehensive inventory across all taxa, effort needs to be made to examine the surrogacy value of geomorphic and physical classification approaches for defining biogeographically meaningful boundaries in the absence of available data for biota.

*More detailed analysis of macroinvertebrate data sets*

The Australia-wide macroinvertebrate sampling efforts of the National Monitoring River Health initiative provide us with one of the only national data sets for aquatic biota. This data set has been primarily used for riverine condition assessment and has not been utilised to its full potential for defining bioregional associations and biodiversity values. Assessment of species level data where it exists and bioregional definitions using less vagile more strictly aquatic taxa may prove most useful (eg, Wells et al 2002).

*Use of molecular tools to define phylogenetic boundaries*

Traditionally bio-geographers have defined bioregional boundaries on the basis of concordant cross-taxa discontinuities in the distributions of species defined using a range of methods (eg Unmack (2001)). One of the key limitations of this approach is the influence of physiological tolerances of individual aquatic species and stochastic events on their occurrence and continued persistence in particular areas, which affects the resolution of defined regional boundaries (A. Georges pers comm). Phylogenetic approaches to biogeography examine the flow of genetic material between individuals within species (Hughes et al 1996, Avise 2001, Hurwood et al 2001, Georges et al 2001, Ponder & Walker 2001). Using these methods, biogeographic boundaries are indicated where there is marked separation in genetic profiles between populations. The advantage of this approach is that biogeographic barriers can be defined confidently where genealogical evidence concurs across a number of taxa avoiding the confounding influences of stochasism and variable vagility. Phylogenetic research on a range of key aquatic taxa offers perhaps the most robust method by which to refine an *Interim Freshwater Biogeographic Regionalisation of Australia.*

## Conclusion

While efforts to develop a freshwater bioregionalisation in Australia are recent in comparison to advances made for terrestrial and marine ecosystems, advancement in the study of freshwater biogeography puts us in a position to establish an *Interim*

*Freshwater Biogeographic Regionalisation of Australia.* This framework would most logically be based on the natural biogeographic units provided by river basins, which would form the macro-regions of a hierarchical framework with the second scale of the hierarchy defined by sub-drainage regions. Biota distribution and phylogeography using molecular techniques should form the primary tools for defining regions across drainages on the basis of demonstrated past connectivity. The variable vagility of different components of aquatic biodiversity should also be recognised as key determinant of appropriate bioregional frameworks for conservation assessment which in some cases will legitimately include terrestrial based bioregionalisations.

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