2 An introduction to wetlands

Wetland types and their distribution in northern Australia

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Abstract

The Wet-Dry tropics of northern Australia are sparsely populated. There are few large towns with many small settlements scattered across a vast area. The climate is strongly seasonal with two broad seasons – a cool/warm Dry season and a warm/hot Wet season. As a consequence of the climate, flow in the rivers is strongly seasonal and many cease to flow during the Dry season. The knowledge of wetland types and their distribution is very uneven and a comprehensive inventory does not exist. Generalised wetland maps have been compiled and show a pattern of small permanent lakes and swamps inland and extensive floodplains near the coast. Seasonally or intermittently flooded swamps are located along the coast with intermittent or episodic wetlands inland. At a broad scale these wetlands have been described. The general ecological features of the broad categories of wetlands – coastal salt flats, mangrove swamps, freshwater lakes, floodplains, and freshwater ponds and swamps – are summarised in order to illustrate their immense diversity and ecological values.

1 Introduction

The region considered in this overview of wetland types of northern Australia is shown in figure 1. It comprises the Kimberley in Western Australia (WA), the Top End and Barkly Tableland of the Northern Territory (NT), and the Gulf Plains and Cape York Peninsula of Queensland (Qld). In a general sense, the ecological character of the wetlands has been described and the major threats and management problems identified (Arthington & Hegerl 1988, Finlayson et al 1988, 1991, 1997, Finlayson & von Oertzen 1993, Blackman et al 1993, Fleming 1993, Jaensch & Lane 1993, Jaensch 1994, Singer & Wright 1985, Storrs & Finlayson 1997).

This vast region contains many wetlands, particularly along the coast, and many of these have great conservation value and, compared to wetlands elsewhere in Australia, have retained many of their natural features (Finlayson & von Oertzen 1993, Finlayson et al 1997, Storrs & Finlayson 1997). An account of the major wetland types and their distribution is presented as a background for further analysis of their ecological features and management issues. Before considering the major types of wetlands a brief description of the geographical region, population, climate and drainage pattern is presented.

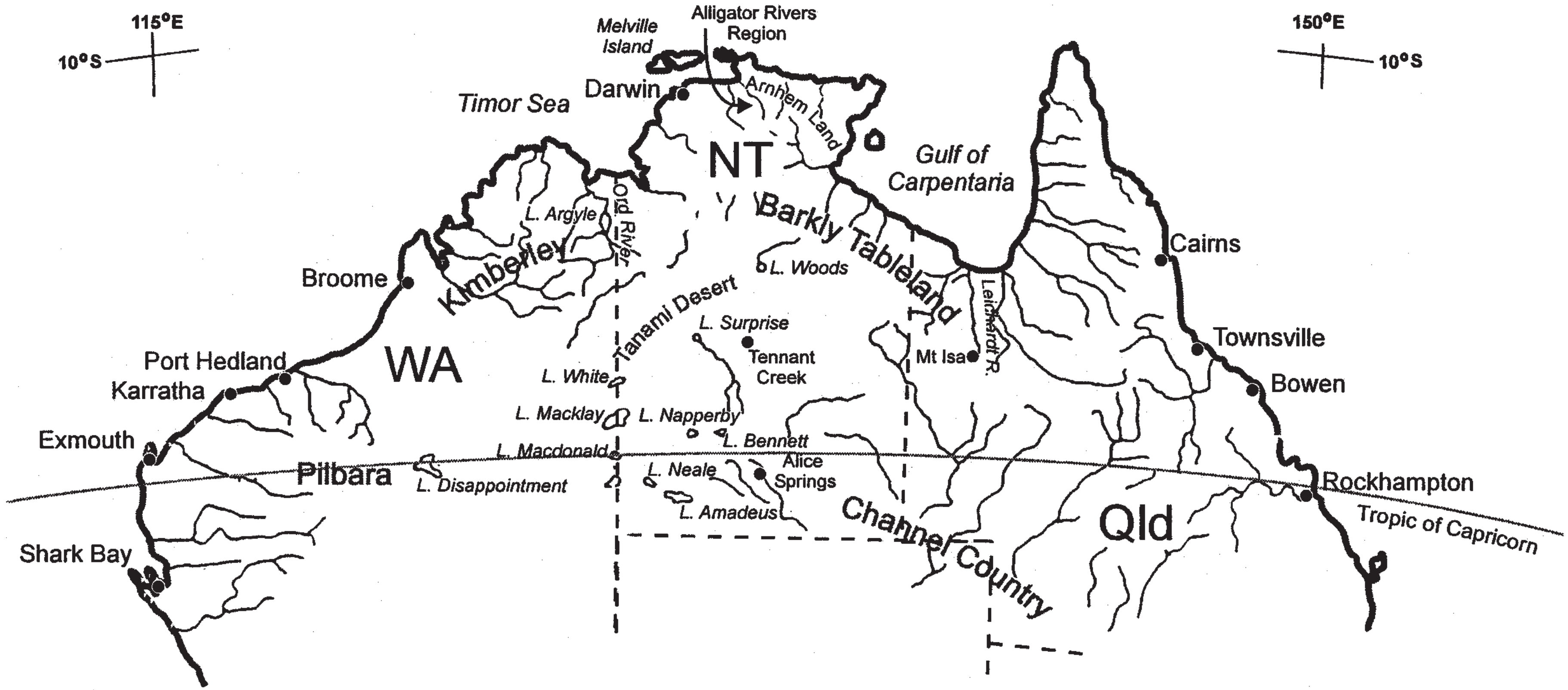

Figure 1 Geographical setting of northern Australia showing major rivers and lakes and population centres (from Finlayson & von Oertzen 1993)

2 Geographical region

The region being considered (fig 1) roughly corresponds to the Wet-Dry tropics of northern Australia. Landsberg et al (1966) defined the Wet-Dry tropics as those areas with an annual rainfall of 600–1600 mm spread over 4–7 months. Within the Australian context this corresponds to the northern-most part of the continent with a south-eastern extension along the western side of the Great Dividing Range (fig 2). Recent efforts to divide Australia into biogeographical regions (Thackway & Cresswell 1995) have provided a further breakdown of the broad region being considered (the south-eastern extension of the Wet-Dry tropics has not been included).

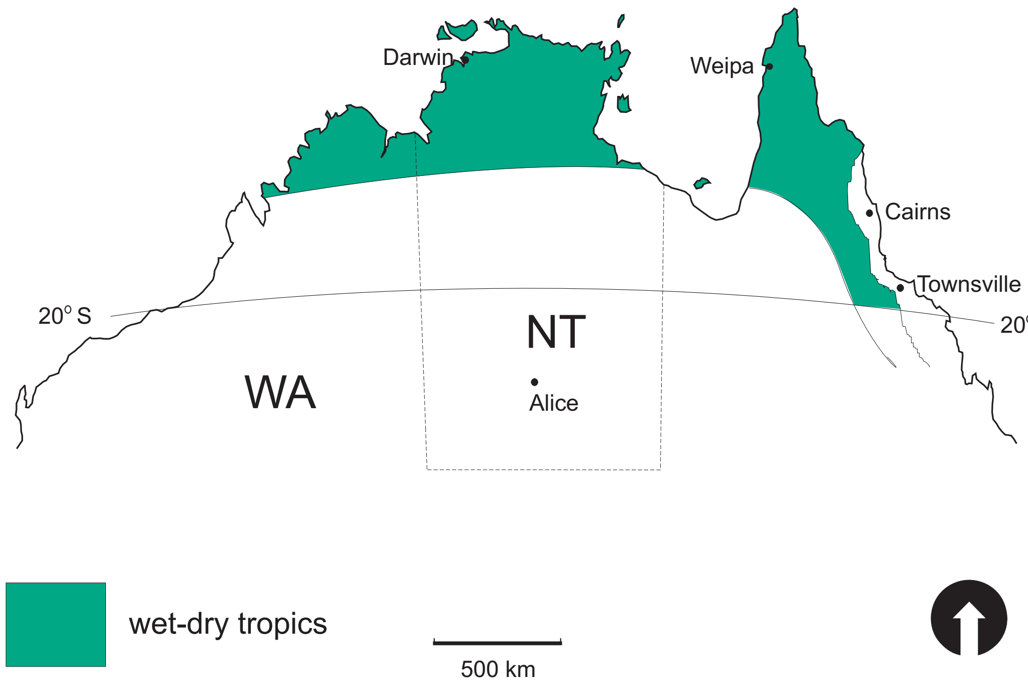

Figure 2 Location of the Wet–Dry tropics in northern Australia (from Finlayson 1995)

The interim biogeographical regions (IBRA) were delineated on the basis of climate, lithology/geology, landform, vegetation, flora and fauna, land use and, where necessary, other attributes. The biogeographical regions covered in this review are shown in figure 3 and listed in table 1. Combined they cover more than 2 x 10^6 km^2.

3 Population

Northern Australia is relatively sparsely populated compared with the eastern and south-eastern regions of Australia. The largest population centre is Darwin (70 250) which is also the administrative centre of the Northern Territory. Smaller population centres include Broome (11 370), Derby (3240) and Kununurra (4880) in Western Australia, Palmerston (12 233) and Katherine (7979) in the Northern Territory and Weipa (2200) in Queensland (Australian Bureau of Statistics 1996 Census). A large proportion of the population resides in urban areas (70% in the NT). Many smaller settlements are located along major transport routes and in association with pastoral, tourist and recreation and mining activities. Aboriginal people have also established many small settlements known as outstations.

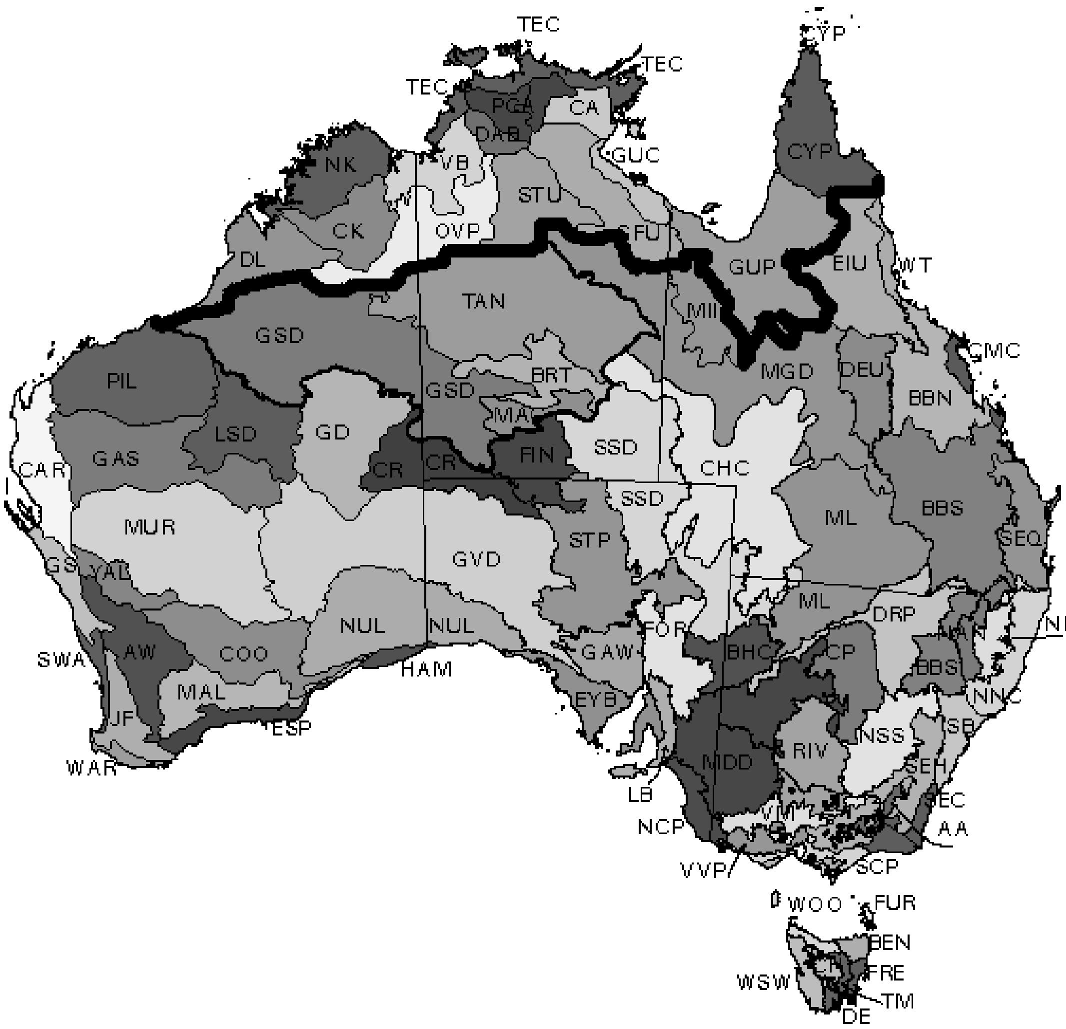

Figure 3 Biogeographical regions (above the dark line) considered in this review of wetland issues in northern Australia (from Thackway & Cresswell 1995). An explanation of the codes used for the regions is given in table 1.

4 Climate

The climate of tropical Australia has been described by Ramage (1971) and Lee and Neal (1984). In general, there are two seasons. The Wet season commences late in the year (November–December) and lasts for 3–4 months; both the onset and duration vary from year to year. Relatively low atmospheric pressure systems develop over northern Australia and the resulting inflow of warm air from the surrounding tropical ocean leads to a hot rainy season. The most significant features of the Wet season are thunderstorms, tropical cyclones, rain depressions and higher humidity. Cyclones occur along the coast during the Wet season and can bring destructive winds, torrential rain, flooding, and sometimes ‘storm-surges’. The build-up to the Wet is heralded by thunderstorms with localised, but very heavy rain. Thunderstorms during March–April do not produce prolonged rain and indicate the approach of the Dry season which is characterised by the dry south-east trade winds.

The region has warm to hot temperatures all year round. These temperatures are accompanied by high relative humidity of about 80% in the Wet season. Cloud cover is greatest over the coast during the warm Wet season, decreasing over the dry interior and allowing overnight radiative cooling. The range of temperatures and day length throughout the year are relatively small. Average annual effective evaporation often exceeds rainfall.

Table 1 Biogeographical regions within the area of northern Australia known as the Wet–Dry tropics (information from Thackway & Cresswell 1995)

Biogeographical region	Codes	Area (km^2)	Description
Burt Plain	BRT	71809	Plains of low rocky ranges of Pre-Cambrian granites with mulga and other acacia woodlands.
Central Arnhem	CA	36898	Gently sloping terrain and low hills on Cretaceous sandstones and siltstones and laterised Tertiary material; yellow earthy sands and shallow stony sands; open forest and woodland with grass understorey.
Central Kimberley	CK	76907	Hilly to mountainous with skeletal sandy soils supporting hummock grasses and scattered trees.
Cape York Peninsula	CYP	115477	Low hills and plains, tropical humid/marine; woodlands.
Daly Basin	DAB	20921	Gently undulating plains and scattered low plateau remnants on Palaeozoic sandstones, siltstones and limestones; neutral loamy and sandy red earths; open forest with perennial and annual grass understorey.
Dampierland	DL	89595	Mix of sandplains, coastal and alluvial plains and limestone with a dry hot tropical climate. Vegetation includes hummock grasses, samphire and scattered woodland.
Gulf Fall and Upland	GFU	118975	Undulating with scattered low hills with skeletal soils and shallow sands. Woodland to low woodland with spinifex understorey.
Great Sandy Desert	GSD	394599	Mainly tree steppe with open hummock grass and scattered trees and shrubs. Undulating uplands with shrubs.
Gulf Coastal	GUC	27807	Gently undulating plains with scattered rugged areas. Woodland with spinifex understorey.
Gulf Plains	GUP	211584	Marine and terrestrial deposits of the Carpentaria and Karumba basins; plains, plateaus and outwash plains; woodlands and grasslands.
MacDonnell Ranges	MAC	36986	High relief ranges and foothills covered with spinifex hummock grassland, sparse acacia shrublands and woodlands along watercourses.
Northern Kimberley	NK	87017	Dissected plateau with savanna woodland and riparian closed forests. Mangal in estuaries and closed embayments.
Ord–Victoria Plains	OVP	125177	Level to gently undulating plains with scattered hills. Skeletal soils with grasses and scattered trees.
Pine Creek Arnhem	PCA	51576	Hilly to rugged with skeletal soils. Woodland with sorghum understorey.
Sturt Plain	STU	99719	Gently undulating plains on laterised Cretaceous sandstones; neutral sandy red and yellow earths; woodland with spinifex understorey.
Tanami	TAN	316656	Sandplains with hills and ranges. Mixed shrub steppe with hummock grasses.
Top End Coastal	TEC	68681	Gently undulating with low plateaux. Open forest and woodland with sorghum understorey. Mix of soils.
Victoria Bonaparte	VB	72970	Marine sediments with samphire–sporobolus grassland and mangal. Red earth plains with open savanna of high grasses.

5 Drainage pattern

About two thirds of total run-off from Australia occurs in northern Australia (Australian Water Resources Council 1976). The two drainage regions that closely correspond to the Wet-Dry tropics (as defined for this overview) are shown in figure 2. Estimated run-off from these is 91 000 ML y^{-1} from the Timor Sea region and 131 000 ML y^{-1} from the Gulf of Carpentaria region. Both regions have coordinated external drainage to the Timor/Arafura Seas and Gulf of Carpentaria respectively.

The rivers have highly seasonal and variable flows. Many cease to flow during the Dry season and tidal influences can extend some 80–100 km upstream. Some are little more than a chain of elongated waterholes for much of the year. The Gregory and Lawn Hill Rivers in Queensland are perennial. As a consequence of the water releases from Lake Argyle and Lake Kununurra the downstream portion of the Ord River in Western Australia is also now perennial.

A number of dams and reservoirs have been constructed to conserve surface water. The largest is Lake Argyle on the Ord River which has a volume of 5672M m^3 and a flood storage capacity of 34 655M m^3.

6 Wetland types

The Ramsar Convention for Internationally Important Wetlands defines wetlands as:

> areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which does not exceed six metres.

This definition has attracted a large amount of debate and dissatisfaction within Australia (see McComb & Lake 1988) and internationally (see Finlayson & van der Valk 1995). However, given that definitions are derived for specific purposes and that the Ramsar definition is purposefully broad it has been generally more accepted in recent years both within Australia (ANCA 1996) and internationally with deliberate modification for specific purposes (Finlayson & van der Valk 1995).

Within Australia Paijmans et al (1985) have defined wetlands as:

> land permanently or temporarily under water or waterlogged. Temporary wetlands must have surface water or waterlogging of sufficient frequency and/or duration to affect the biota. Thus, the occurrence, at least sometimes, of hydrophytic vegetation or the use by waterbirds are necessary attributes.

This definition does not contain a depth criterion, but is otherwise similar to that used by the Ramsar Convention.

Paijmans et al (1985) considered the frequency and regularity of inundation as an important feature of Australian wetlands. Based on flooding patterns they derived four general groups of wetlands (see below), although the hydrological information base may not always be adequate to accurately differentiate between such wetlands on all occasions.

- Permanent – annual inflow exceeds the minimum annual loss in 90% of years
- Seasonal – alternately wet and dry every year according to season
- Intermittent – alternately wet and dry, but less frequently and regularly than seasonal
- Episodic – dry most of the time with rare and very irregular wet phases

In view of the uneven information base for wetlands in northern Australia the wetland categories used by Paijmans et al (1985) are not used in this overview. Rather, a simplified system is used in line with similar approaches used by Finlayson et al (1998), Fleming (1993) and Finlayson and von Oertzen (1993). Thus, the wetland categories used are coastal salt marshes, mangrove swamps, freshwater lakes, floodplains, and freshwater ponds and swamps. These terms are acknowledged to be imprecise and for some purposes (eg detailed biodiversity analyses) may not be suitable.

7 Wetland distribution

It is not possible, based on current inventory information, to accurately depict the extent of wetlands across northern Australia. Concerted inventory work has occurred in some areas, such as the Gulf of Carpentaria and Cape York Peninsula in Queensland (Blackman et al 1993), but a standardised inventory approach has not been adopted across the entire region. (Whether or not such an approach is warranted is not discussed here, but see Blackman et al (1995) for a discussion on this subject.)

Paijmans et al (1985) summarised information derived from 1:250 000 topographical maps and presented this on 1:250 000 000 maps of the entire continent. The maps give a broad indication of wetland distribution but contain many uncertainties and are described by the authors as 'too large, too detailed and too inaccurate'. They do not specifically illustrate individual wetlands nor depict all wetland categories, but they do illustrate a number of key points about the distribution of wetlands in northern Australia that reflect the general geographic setting:

- there is a general low occurrence of permanent freshwater lakes and swamps
- intermittent freshwater swamps are widespread
- permanent and near permanent wetlands are widespread
- episodic lakes and land subject to inundation by freshwater are not common
- generally dry wetlands are not common.

Further south (outside of this region) the wetlands are drier for longer periods and episodic flooding occurs.

Without a complete inventory that includes much better mapping of wetlands, management for conservation and sustainable utilisation of wetlands will continue on an *ad hoc* basis. The recent directory of important wetlands in Australia (ANCA 1996) lists many wetlands across Australia, but does not provide a base for accurate mapping. Remote sensing has been used for wetland inventory (eg Taylor et al 1995), but it has not been used to produce a comprehensive map of wetlands of Australia.

The wetland types shown in figure 4 give a generalised pattern of wetland distribution in the region that reflects the topography, drainage pattern and rainfall. Along the Queensland coast the upland areas contain permanent and seasonal wetlands – floodplains, lakes, billabongs (oxbow lakes) swamps, waterholes, and river flats liable to flooding. There are also extensive tidal flats and mangroves, some backing on to seasonal swamps. Floodplain lakes, billabongs, and waterholes occur in major deltas. On Cape York Peninsula seasonal swamps in shallow depressions are common while some volcanic craters contain permanent lakes and swamps.

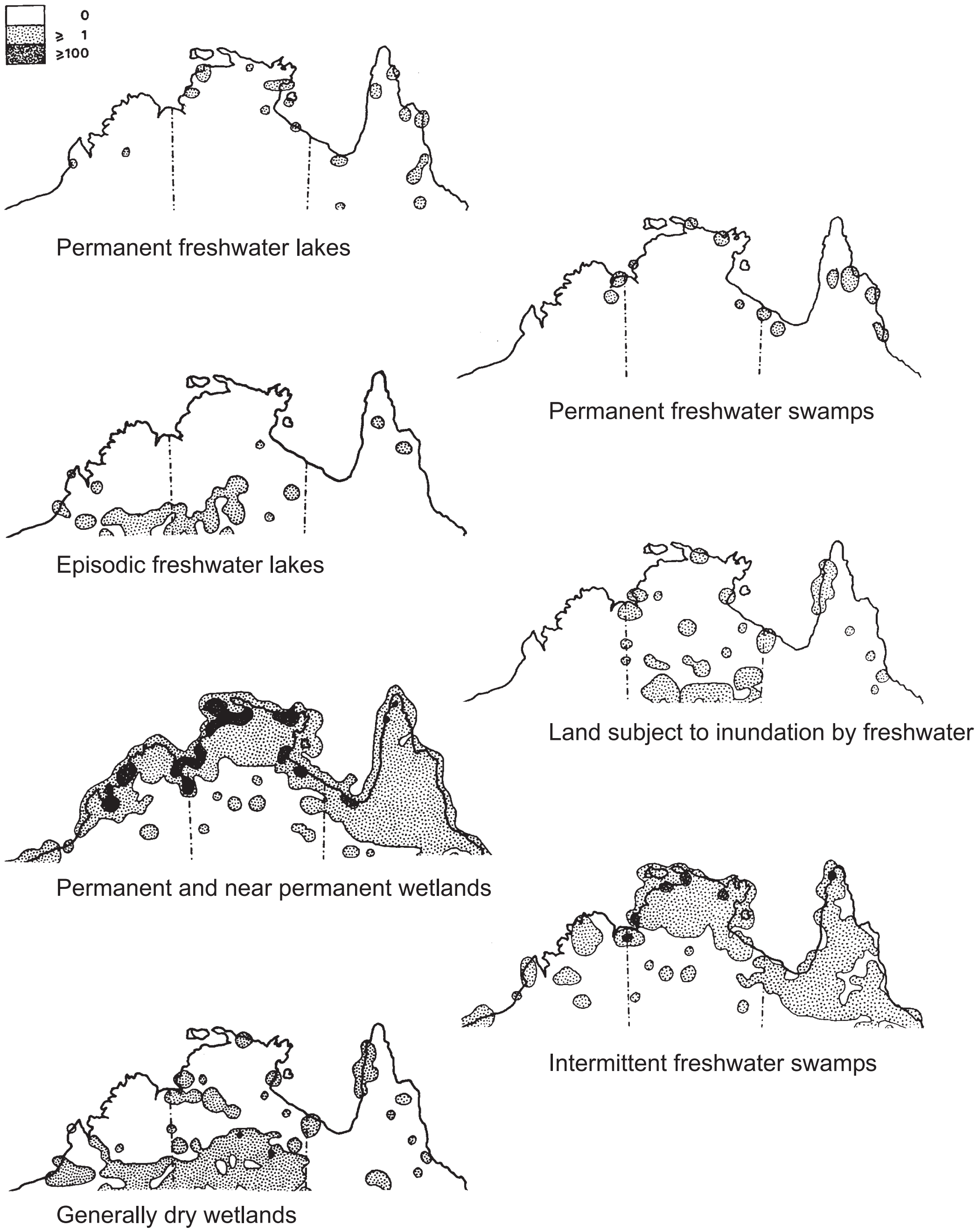

Figure 4 Distribution of wetlands in northern Australia based on Paijmans et al (1985). The code shows the frequency of wetland occurrence on 1:250 000 maps.

The lowlands along the Gulf of Carpentaria contain intermittent or seasonal swamps in shallow pans, permanent waterholes in channels, seasonal billabongs, lakes and swamps on the upper portions of rivers that drain to the Gulf of Carpentaria. Supratidal flats, up to 30 km inland and with very little vegetation, and narrow intertidal flats with a fringe of mangroves, occur along the coast.

The lowlands surrounding the Arnhem Land Plateau have numerous floodplain lakes, waterholes and swamps along the major rivers, and permanent or seasonal swamps on alluvial plains near the sea. The coastal plains to the east of Darwin contain extensive floodplains along rivers originating from the Arnhem Land Plateau. Coastal wetlands include intertidal flats with mangroves and supratidal flats, either bare or with sparse vegetation. The Kimberley coast is very rugged and coastal wetlands are confined to supratidal flats near large rivers.

8 Wetland characteristics

Much of the information presented below is taken from past reviews of northern Australian wetlands (eg Finlayson et al 1988, Blackman et al 1993, Finlayson & von Oertzen 1993, Jaensch 1994, Finlayson 1995, Jonauskas 1996, Finlayson et al 1998, Storrs & Finlayson 1997).

8.1 Coastal salt marshes

Coastal salt marshes encompass intertidal salt marshes and supratidal salt flats that can extend some 30–40 km inland (Blackman et al 1993). The marshes may be separated from inland salt flats by sand dunes and chernier ridges. Salt marshes occur along the coast and in embayments such as Cambridge Gulf and King Sound in the Kimberley (Semeniuk 1993) and extensively along the Arnhem Land/Gulf of Carpentaria coast (Love 1981, Galloway 1982, Blackman et al 1993). They are characterised by macro-tides (often 5–7 m range) that rise and fall across broad expanses of mudflats or seagrass meadows.

Plant diversity is not high. Overall, tropical salt marshes contain considerably fewer plant species than those in temperate areas (Stanton 1975, Saenger et al 1977, Specht 1981). Salt flats lacking vegetation are more common (Macnae 1966) and are found alongside many of the coastal mangrove communities.

Information on the fauna of these marshes and flats is sparse with the exception of migratory shorebirds. These birds also utilise the mudflats that are exposed at low tide. Watkins (1993) presents population numbers and identifies the south-east Gulf of Carpentaria in Queensland and Roebuck Bay and Eighty Mile Beach in Western Australia as three of the most important areas. These areas have the highest concentrations of waders in the East Asian/Australasian flyway and are important staging sites for migratory birds that go even further afield.

8.2 Mangrove-swamps

Mangroves are halophytic trees or shrubs which dominate sheltered, muddy, intertidal environments along tropical and subtropical shorelines. They range from a narrow coastal fringe to extensive forests and extend more than 40 km inland along rivers, covering about 4120 km^2 in the Northern Territory, 2520 km^2 in Western Australia (Galloway 1982) and a further 1140 km^2 (approx) in the Gulf of Carpentaria and northern part of Cape York (Dowling & McDonald 1982).

The distribution of mangroves along the northern coastline has been investigated reasonably thoroughly with broadscale mapping for much of the coastline and relationships with environmental factors identified (Hegerl et al 1979, Dames & Moore 1984, Semeniuk 1993, Blackman et al 1993). The Alligator Rivers Region and Darwin Harbour have received possibly the greatest amount of attention (Hegerl et al 1979, Wells 1985, Dames & Moore 1984, Davie 1985, Finlayson & Woodroffe 1996) in the Northern Territory. Semeniuk (1993) provides an overview of much of the information for the Kimberley coast while in the Gulf of Carpentaria and Cape York Peninsula much of the data are either incomplete or not collated (Blackman et al 1993).

The mangroves of the Kimberley coast are species rich with similar species assemblages to those in the Northern Territory (Semeniuk 1993). For example, on muddy tidal flats there may be a zone of *Sonneratia alba*, then *Avicennia marina*, *Camptostemon schulzii*, *Rhizophora stylosa* and finally a landward mixed zone of *Avicennia marina*, *Aegialitis annulata*, *Bruguiera exaristata* and sometimes pure stands of *Ceriops tagal*. Semeniuk (1993) also describes the geomorphic differences between habitats such as Cambridge Gulf, King Sound and the remainder of the Kimberley coast. Blackman et al (1993) identifies the major mangrove sites along the Gulf of Carpentaria and Cape York Peninsula coast. These include the Nicholson River delta and the Mitchell River Fan aggregation in the Gulf, and the Jardine River wetlands and the Newcastle Bay complex on the Cape.

In general, mangrove forests vary from having distinct vegetation zones to being completely mixed, with the frequency of inundation by tidal water, fresh-water flow, soil type and drainage being important controlling factors (Bunt et al 1982, Semeniuk 1993). Probably the most common species is *Avicennia marina* which can tolerate a wide salinity range (Macnae 1966) and is a pioneer species commonly found on newly formed mudbanks in estuaries or on riverbanks. Semeniuk (1993) reports that there is a gradation from forests in the seaward parts of mangrove formations to scrub and heath in landward parts. Regional factors (coastal setting, climate and tidal range) that are inter-related influence the nature of mangrove habitats in any location.

Mangroves are very productive, but except for Darwin harbour (see Woodroffe & Bardsley 1988, Woodroffe et al 1988) there is little information on the primary productivity of these communities in northern Australia.

The mangrove fauna, especially the macroinvertebrates, are not as well known as the flora (Hanley 1995). Relatively few surveys have been undertaken across the range of habitats. The larger animals are better known, but not necessarily in a quantitative manner. The saltwater or estuarine crocodile (*Crocodylus porosus*), a number of snakes, lizards, geckos, skinks and turtles plus mammals such as the fruit and insect-eating bats, water rats, feral buffaloes, pigs and cattle are known to utilise mangrove habitats (Hegerl et al 1979, Milward 1982). List of biota in Australian mangrove-swamps are given by Saenger et al (1977) and Hutchings and Recher (1983) while Hanley (1995) discusses the invertebrate fauna of a few sites in northern Australia. The best known animal species is the estuarine crocodile.

8.3 Freshwater lakes

Finlayson and von Oertzen (1993) report that the classification and delineation of permanent waterbodies in tropical Australia is confused. The terms billabongs, waterholes, lagoons and ponds are used interchangeably. Further, there is a strong temporal pattern associated with such habitats that is not fully understood. The permanent waterholes that are features of many northern rivers – eg the Nicholson and Gregory Rivers, Queensland (Blackman et al 1993) – are not considered with the lakes, but with the freshwater ponds (see below).

Permanent and seasonal lakes are rare in northern Australia (fig 4), only occur near the coast and are often associated with floodplain and dune ecosystems (Paijmans et al 1985, Blackman et al 1993). Artificial lakes are an important feature of the region. They vary in size from small stock-watering dams (or tanks) to the extremely large Lake Argyle on the Ord River. Fogg Dam is a permanent lake near Humpty Doo in the Northern Territory that was built to retain water for the ill-fated rice development scheme (Mollah 1982). It is relatively shallow and contains many water plants, including the alien weed *Eichhornia crassipes*. To a large extent the flora and fauna of Fogg Dam is similar to that described for the permanent swamps and floodplains along the northern coastal zone.

Lake Argyle has great conservation value (Graham & Gueho 1995) in what was otherwise a fairly dry environment. The Ord River downstream from the lake now flows all year round. Along with Lake Kununurra it has become a significant drought refuge for waterbirds and a migration stop-over for many species (Jaensch & Lane 1993).

8.4 Floodplains

8.4.1 General Information

Seasonally and intermittently flooding plains occur along most rivers that are influenced by monsoonal rains and have a very pronounced seasonal inundation cycle. The floodplains vary in size and occur across all of northern Australia. Those between Darwin and Arnhem Land have probably been the centre of more investigation and controversy than the others due to conservation, mining, weed and saline intrusion problems (Fox et al 1977, Finlayson et al 1988, Finlayson & von Oertzen 1993, Jonauskus 1996).

The northern climate and hydrology have a strong influence on the floodplains. The permanent waterholes (often inaccurately called billabongs) have fairly uniform physico-chemical conditions during periods of stream flow and a progressive increase in solute concentrations during the Dry season. Detailed accounts are presented in Walker and Tyler (1984), Bishop and Forbes (1986) and Morley et al (1984) and summarised in Finlayson et al (1990).

8.4.2 Plants

Detailed vegetation surveys have been undertaken on the floodplains between Darwin and the East Alligator River (eg Story 1976, Williams 1979, Burgman & Thompson 1982, Sanderson et al 1983, Taylor & Dunlop 1985, Bowman & Wilson 1986, Finlayson et al 1989, 1990, Whitehead et al 1990). In the Northern Territory a broadscale vegetation survey of the major floodplains between the Moyle River in the west and the Glyde River in the east was undertaken in 1990 (Wilson et al 1991). A detailed floristic survey of the Arafura Swamp has recently been undertaken, however, other areas of Arnhem Land have not been surveyed in detail. Further surveys and collation of data are required for the Gulf of Carpentaria and Cape York Peninsula to supplement the information reported by Blackman et al (1993). Jaensch and Lane (1993) have reported on the floodplains of the Kimberley region.

General descriptions of the distribution of the major plant species on the floodplains in the Northern Territory can be made from various surveys (Wilson et al 1991). *Oryza rufipogon (meridionalis)* grasslands and *Melaleuca* spp woodlands are extensive and spread across most, if not all of the floodplains. The sedges *Eleocharis* spp and *Fimbristylis* spp and the water lilies *Nymphaea* spp and *Nymphoides* spp are also common. The grass *Pseudoraphis spinescens* is not common outside of the Adelaide-Alligator Rivers floodplains. The weeds *Mimosa pigra* and *Salvinia molesta* have become prominent features of some floodplains.

A detailed analysis of aquatic plant distribution is available for the Magela Creek floodplain in the Northern Territory (Morley 1981, Williams 1979, Sanderson et al 1983, Finlayson 1988, 1993, Finlayson et al 1989, 1990). The general classification presented by Finlayson et al (1989) is listed as an example of the diversity of habitats that occur on these plains: *Melaleuca* open forest and woodland; *Melaleuca* open woodland; *Nelumbo* swamp; *Oryza* grassland; *Hymenachne* grassland; *Pseudoraphis* grassland; *Hymenachne-Eleocharis* swamp; mixed grassland and sedgeland; *Eleocharis* sedgeland; and open-water community. Whilst not as rigorous as that proposed by Sanderson et al (1983) this classification allows for seasonal and annual changes in vegetation associations and dominance.

An outstanding feature of the floodplain vegetation is the variation in floristic composition and foliar cover during the Wet and Dry seasons (Finlayson et al 1989, 1990). The success of the majority of species relies on mechanisms that enable them to survive the Dry season drought (Finlayson et al 1989, 1990, Finlayson 1993).

8.4.3 Animals

Examination of available data reveals that the Northern Territory floodplains hold high numbers of animals (Finlayson et al 1988). These include freshwater and saltwater crocodiles (Bayliss et al 1986, Messel & Vorlicek 1986), other large reptiles such as the file snake (Shine 1986) and freshwater turtles, freshwater fish (Bishop et al 1986), freshwater mussels (Humphrey & Simpson 1985) and a wide assortment of water birds (Morton & Brennan 1986, Morton et al 1993a,b). When taken in conjunction with the sizes of the animals, these data convey the reality of a high standing biomass. It is expected that the same reality will apply to floodplains across northern Australia given reports on populations of at least some sectors of the fauna (Blackman et al 1993, Jaensch & Lane 1993).

The floodplains have a relatively low mean nutrient availability (Morley et al 1984) and are temporally and spatially variable. They are, however, dynamic with plant standing crops developing very rapidly at the start of the Wet season and senescing and decomposing at the beginning of the Dry season (Finlayson 1990). Large long-lived animals exploit the wetlands by using a high level of mobility and/or by having mechanisms that allow them to withstand periods of little or no nutrient intake.

Animals lacking the mobility to be successful in exploiting sequences of highly productive periods are faced with food shortages, at least on a seasonal basis. Large aquatic reptiles in the region exhibit either or both a physiology of periodic or constant low metabolism and slow growth rates, or food habits that lower their dependence on foods provided by the aquatic environment (Seymour et al 1981). *Crocodylus johnstoni* (freshwater crocodile) eats less during the Dry season than during the Wet season, particularly when the temperature is lower (Webb et al 1982) and approximately 40% of their food comes from the terrestrial environment. Freshwater turtles and adult *Crocodylus porosus* (saltwater crocodile) also depend heavily on foods of terrestrial origin. Smaller *Crocodylus porosus* are opportunistic feeders and mainly eat invertebrates (Taylor 1979). The Arafura file snake (*Acrochordus arafurae*) reproduce less frequently than other snakes (Shine 1986) and possess a metabolic rate that is lower than most other reptiles (Seymour et al 1981, Shine 1986).

Morton and Brennan (1986) and Morton et al (1990a,b, 1993a,b) provide a biogeographical description of the birdlife of monsoonal Australia. The freshwater wetlands are the prime habitat for 68 species, the adjacent grass/sedgelands for 26 species and the *Melaleuca*-dominated riparian forests for 20 species, which together comprise 45% of the Top End bird species. The numerically dominant species on the floodplains are *Anseranas semipalmata* (magpie goose), *Dendrocygna arcuata* (wandering whistling duck), *Ardea intermedia* (intermediate egret) and *Plegadis falcinellus* (glossy ibis). There are also an additional 18 species of migratory birds from the Charadriidae and Scolopacidae families, though few are resident. Unlike other habitats the wetlands have a predominance of piscivores, herbivores and species that consume aquatic invertebrates.

Seasonal movement of waterbirds is very pronounced with species migrating between wetlands on a seasonal basis (Morton & Brennan 1986, Jaensch 1995) and from and to both the northern hemisphere and southern Australia. The magpie goose is the best known and most abundant of the waterbirds and the complex interactions that determine its migratory pattern are discussed by Morton and Brennan (1986). In broad terms, they move to swamps that supply their nesting requirements in the Wet season, and during the Dry season they are influenced by the availability of food and water. Broad scale, seasonal changes in distribution occur for other wetland birds, such as *Tadorna radjah* (radjah shelduck) and *Dendrocygna arcuata* and *Dendrocygna eyloni* (the whistling ducks) (Morton et al 1990b, 1993a,b).

Some freshwater fish are dependent on food entering the aquatic environment from terrestrial sources. These include surface feeding species like *Melanotaenia splendida inornata* and *Melanotaenia nigrans* (chequered and black-striped rainbow fish) as well as such highly specialised species as *Toxotes chatareus* and *Toxotes lorentzi* (the archer and primitive archer fish). Other species, such as *Hephaestus fuliginosus* (black bream) and *Syncomistes butleri* (sharp-nosed grunter), scavenge on material of terrestrial origin, while the fork-tailed catfish (*Arius leptaspis*) is omnivorous.

Of the larger species, *Lates calcarifer* (barramundi) exhibits great mobility, breeding in sea water at the mouth of the river system and then either staying in the salt water or swimming upstream to the fresh water. The juveniles spend their early weeks in brackish coastal swamps, some migrating upstream to the freshwater floodplains. Fish migration occurs during the Wet season (Bishop et al 1995). Recolonisation of the lowland sandy creeks and backflow billabongs in the early-Wet results in the most obvious seasonal changes in fish community structure. Movement occurs in both an upstream and downstream direction from Dry season refuge areas on the floodplains and upper escarpment areas.

8.5 Freshwater ponds and swamps

The uncoordinated drainage lines characteristic of the Barkly Tableland terminate in or have associated with them wetlands which are flooded frequently enough to support distinctive swamp communities. The Barkly Tableland lies on the southern edge of the monsoonal belt and contains intermittently flooded swamps that receive some rain in most years. Freshwater swamps also occur in the Kimberley (eg Lake Kununurra, Parry floodplain – Jaensch & Lane 1993), Gulf of Carpentaria (eg along the Nicholson and Gregory Rivers) and Cape York Peninsula (along the Archer and Jardine Rivers) (Blackman et al 1993).

Detailed descriptions of these areas are not available, though general reports such as that by Perry and Christian (1954), Jaensch and Lane (1993), Blackman et al (1993) and Jaensch (1994) list plant species and provide general information on seasonal changes and hydrology. In general, the drier areas are treeless except for small areas of *Eucalyptus microtheca* (coolibah) woodland, while the stream channels are fringed with *Muehlenbeckia cunninghamii* (lignum). The larger swamps contain assemblages of plants and animals similar to those described for the floodplains.

The summer filling of the swamps provides breeding areas for water birds such as *Anseranas semipalmata* (magpie goose), *Malacorhynchus membranaceus* (pink-eared duck) and *Dendrocygna eytoni* (plumed whistling duck), ‘staging’ grounds for migratory waders and ‘summering’ areas for *Glareola maldivarum* (oriental pratincole). The bird populations are immense and vary spatially and temporally. The long-haired rat *Rattus villasissimus* utilises the intermittent swamps as refugia and during good seasons will rapidly breed to plague proportions (Carstairs 1976).

9 Conclusion

The major wetland types of northern Australia have not been well mapped. The only comprehensive maps available are generalised and show wetland distribution derived from topographical maps. There is a general low occurrence of permanent freshwater lakes and swamps, intermittent freshwater swamps are widespread, permanent and near permanent wetlands are widespread, episodic lakes and land subject to inundation by freshwater are not common, and generally dry wetlands are not common. Given the uncertain information base the following categories of wetlands are used, whilst recognising the imprecise nature of many of the terms – coastal salt marshes, mangrove swamps, freshwater lakes, floodplains, and freshwater ponds and swamps.

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Some important ecological features of wetlands in the Wet-Dry tropics of northern Australia

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Abstract

The coastal fringe of the Northern Territory is dominated by a vast area of seasonally-inundated wetlands, formed only about 2000 years ago and subject to the climatic extremes of the Wet-Dry tropics. The Wet season extends from October to April. This is followed by a long Dry season during which many creeks cease to flow and dry out. Whether a wetland is permanent (retains surface water) or seasonal (dries out completely) has important ecological consequences. The implications for species distribution and diversity, endemism and the reproductive and survival strategies of aquatic biota in the Wet-Dry tropics are important background information for wetland managers.

1 Introduction

The purpose of this paper is to provide wetland management students with some background to the ecology of wetlands in the Wet-Dry tropics and to flag some management issues that may not be addressed elsewhere in the course. It is, of necessity, brief and therefore cursory, but we hope it is also useful in giving students a feel for the dramatic ecological dynamics of these wetlands and a helpful starting point for inquiry into these special places.

The vast area of seasonally inundated wetlands that is such a prominent feature of the coastal zone of the Top End of the Northern Territory is a very recent development in terms of geological and evolutionary time scales. At the time of the last glacial maximum, about 20 000 years BP, the sea level was 130 m lower than today (Williams 1991). The coastline was well out to sea from most places and surrounded New Guinea (fig 1). At that time, there was a large lake in the Gulf of Carpentaria into which drained rivers from New Guinea and Australia. The present lowlands probably then contained few extensive lentic wetlands. As sea levels rose with the glacial decline, the coastline moved inland, presumably with an advancing fringe of marine wetlands, reaching its maximum extent approx 6000 BP. These events are mirrored in the rock art of the Arnhem Land region (Chaloupka 1983): prior to 6000 BP the art depicts only freshwater fish species and magpie geese are absent. Barramundi and fork-tailed catfish appear after that, indicating the breaching of dispersal barriers to euryhaline and diadromous species in the rivers by rising seawater. More recently, about 2000 BP, magpie geese appeared in the art and this coincides with the development of the present freshwater wetlands. This change to freshwater wetlands was caused by sediment deposition raising the bottom of inundated areas, development by fluviatile processes of levees along the estuary to impound freshwater and attenuation of tidal height by coastal processes at creek mouths. The present threat to these wetlands from saltwater intrusion appears to be a reversal of these processes.

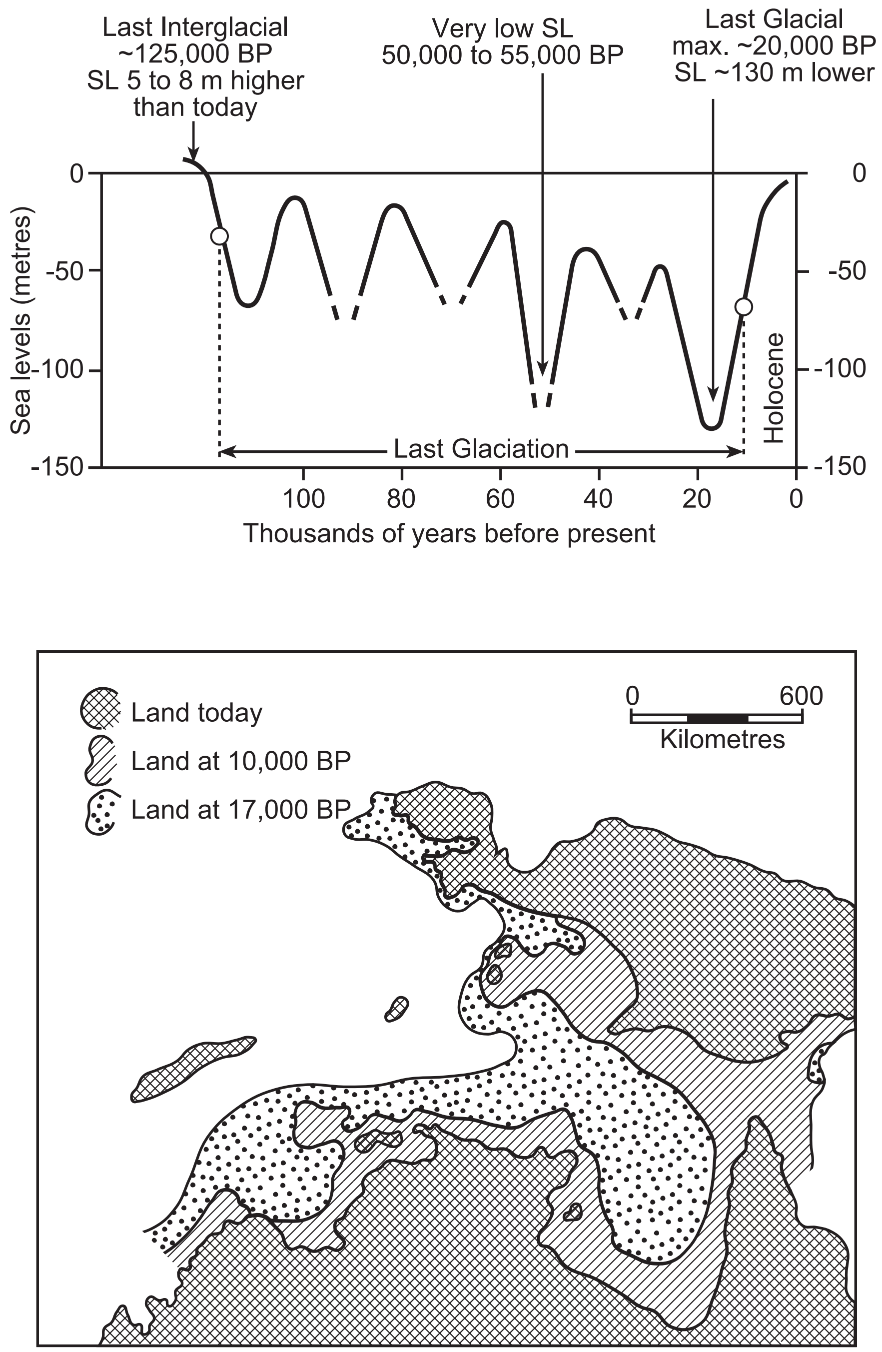


Figure 1 Sea level fluctuations during the past 125 000 years, and some associated changes in the coastline of northern Australia and Papua New Guinea (Source: Williams 1991, figure 5, slightly modified from Chappell 1976, figures 1 & 3)

Extensive coastal freshwater wetlands such as these in the Northern Territory occur also on Cape York in Queensland and most likely have similar origins. Freshwater wetlands are less well developed on the rivers of the lower Gulf and the Kimberley region. This may in part be a result of lower rainfall but in the Kimberley region the topography is also not conducive to floodplain development.

2 Climate and hydrology in the Wet-Dry tropics: Some biotic responses

The highly seasonal rainfall pattern of the Wet-Dry tropics is the major feature influencing the ecology of wetlands of the region. The typical pattern of rainfall and runoff is shown for the Top End in figure 2. The rainfall period here extends from September to June. The runoff period starts 2–3 months later in late November to mid December. The 4–5 month Dry season with very little or no rain results in only seasonal inundation of the floodplain and seasonal flow in many rivers in the region.

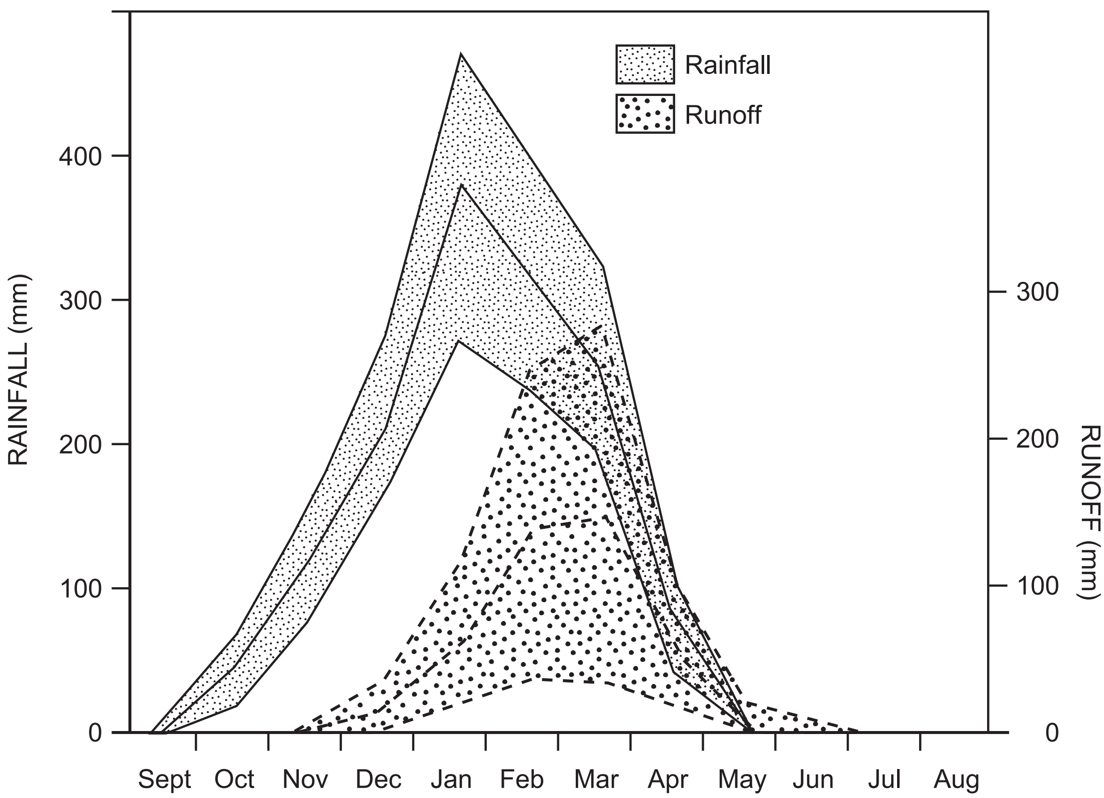


Figure 2 Runoff in the Adelaide River basin in relation to rainfall (rainfall for Darwin; runoff regionalised for 6 stations in the Adelaide River basin; zones show range from 30% to 70% probability of occurrence), from Kingston (1991)

Stream flow continues for some months after rain ceases but at a steadily declining rate. This period is termed locally as the 'tapering-flow' or 'recessional-flow' period. The 'runoff season' referred to by barramundi anglers is quite different to that referred to above and is the period from the middle of the Wet season (late February) to the early Dry (early May) when floodplain water drains from the floodplains into the tidal river channels.

Inundation of the floodplains occurs by both direct rainfall and runoff from feeder streams. Inundation by direct rainfall can start occurring as soon as the cracking clay soils are moistened and sealed and this may occur well before runoff starts. In general, the floodplains closer to the coast are inundated by direct rainfall and the more inland floodplain reaches by runoff.

The timing of rainfall events and the amount of rain can vary considerably among years but there is always some rain, unlike many other parts of the continent (fig 3). The period for which the floodplain remains inundated can, therefore, vary greatly from year to year and also between sites depending on topography (fig 4). This spatial and temporal variation has enormous consequences for the wetland biota, determining both the plant assemblage composition and the production and recruitment success of floodplain fauna. Examples of this are:

- Griffin (1995) has shown that recruitment of barramundi is greater in years of high rainfall;
- At ***eriss*** the recruitment of chequered rainbowfish (as measured by upstream migration) has been shown to be related to the amount of discharge in December in Magela Creek, ie how early the floodplain is inundated and is therefore available as breeding, feeding and nursery grounds (see ***eriss***, Annual Research Summary 1992–1994) (fig 5);
- The year class strength of freshwater mussels is related to total Wet season discharge (Humphrey & Simpson 1985) (fig 6);
- And the breeding success of saltwater crocodiles and magpie geese can be greatly influenced by flood events affecting nests and eggs.

Clearly, both the pattern of rainfall and the total amount of rain have important consequences for the biota. Being able to interpret these relationships, and even predict outcomes from them, would be an important aid for wetland managers.

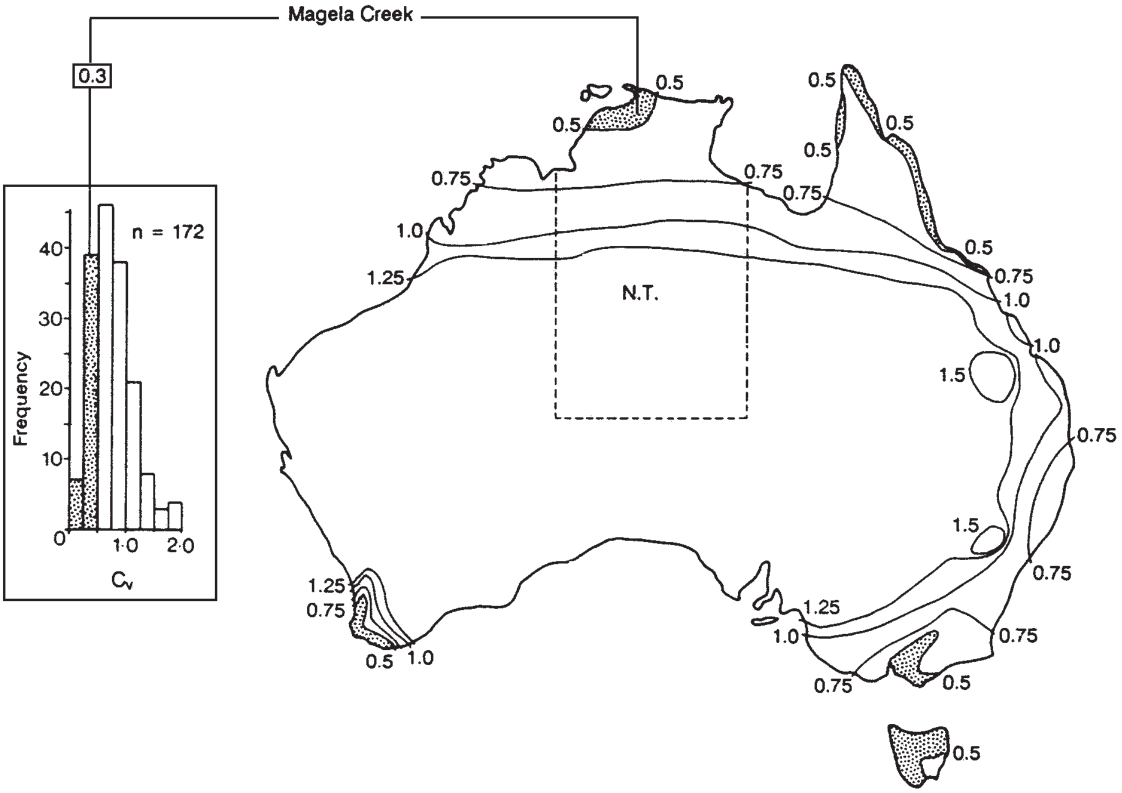


Figure 3 Map of Australia showing contours of coefficients of variation (C_v) of annual discharge of rivers (Source: Humphrey et al 1990, drawn after McMahon (1979) who examined hydrological data from 172 rivers (see frequency histogram of C_vs for these rivers to the left). The NT contours have been modified following data supplied by NT Water Division. Stippled areas have $C_v < 0.5$.)

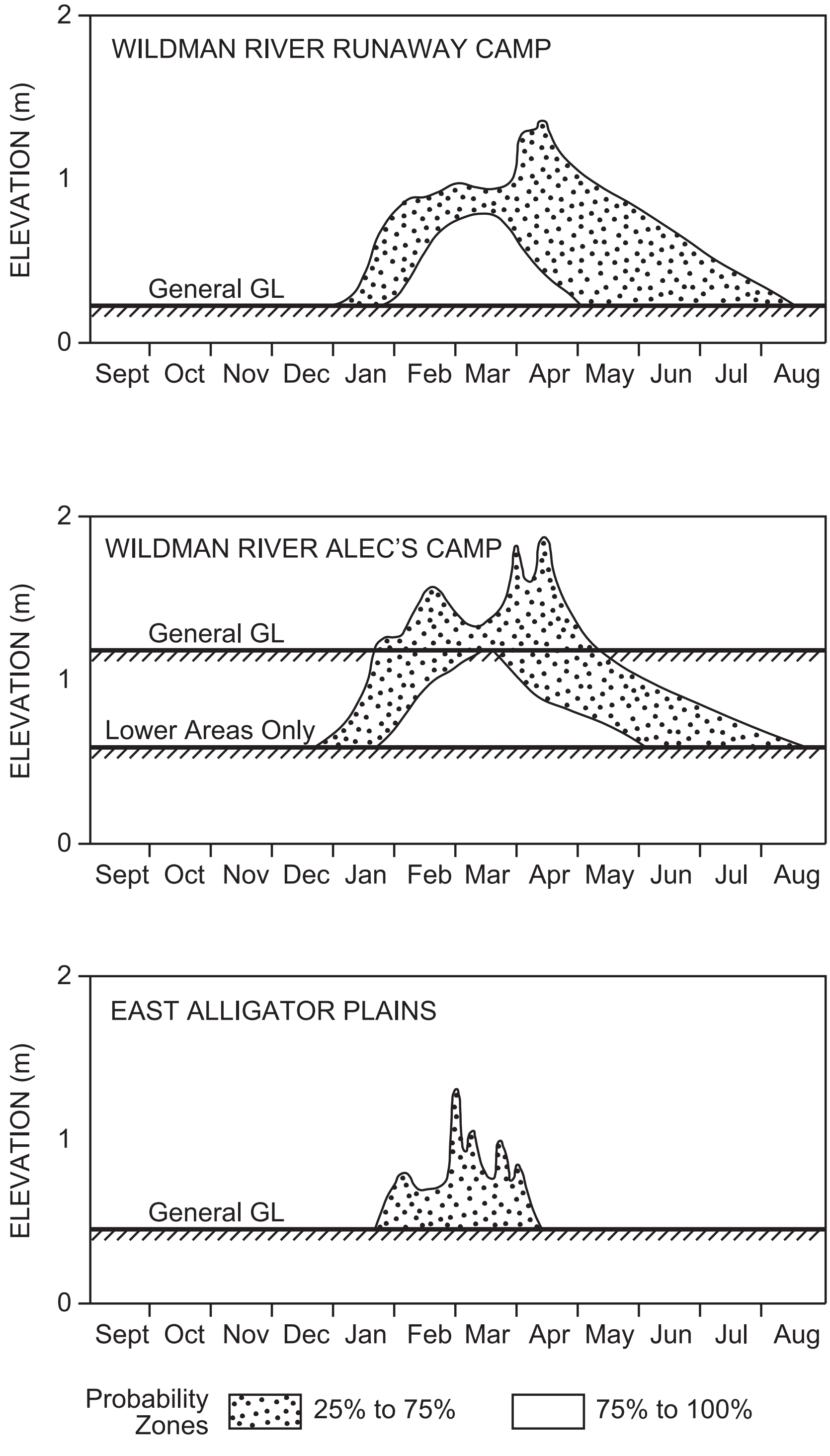


Figure 4 Seasonal inundation patterns (flooding probability) on different floodplains showing spatial and temporal variation (from Purich 1965 in Kingston 1991)

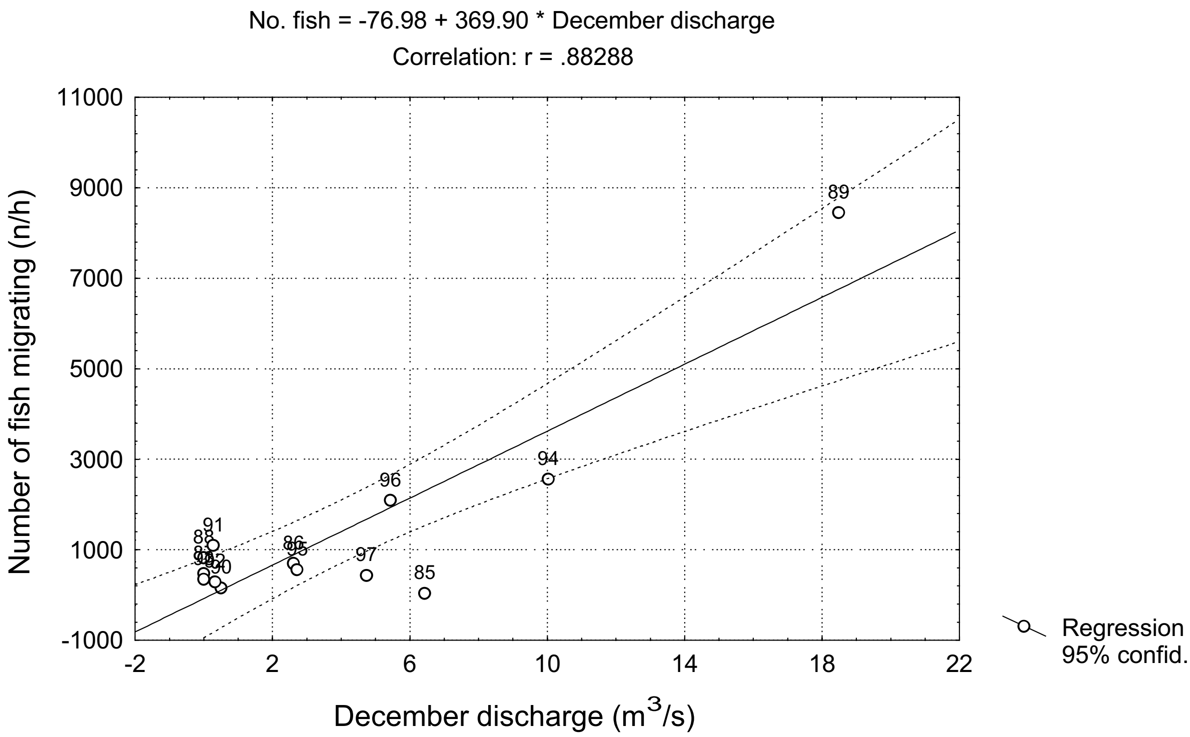


Figure 5 Annual mean migration rate of chequered rainbowfish (*Melanotaenia splendida inornata*) in Magela Creek in relation to the discharge in the first month of flow, December (symbol numbers indicate years)

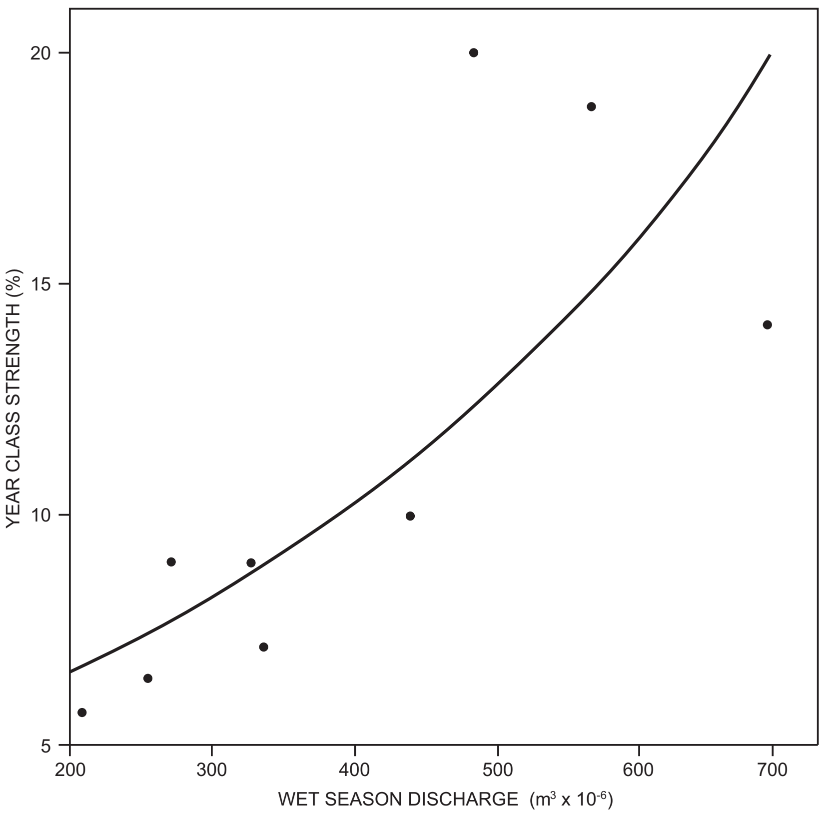


Figure 6 Exponential relationship between year class strength of mussels (*Velesunio angasi*) in the floodplain billabongs of Magela Creek, NT, and Wet season discharge (from Humphrey 1984)

An idea of the natural inter-annual variation in populations and communities can assist in deciding whether any changes detected in monitoring programs are of any real concern. A measure of this variability is the 'persistence' of the community. *Persistence* is the tendency for the species composition of a community to remain the same (Giller et al 1994). Increased temporal variability in stream flow and large fluctuations in annual rainfall and water availability all lead to reduced persistence in macroinvertebrate communities. With the reliable occurrence of rainfall in the Wet-Dry tropics it might be expected that persistence would be higher than for the semi-arid regions of southern Australia.

An example of extreme persistence, which might support this idea, was found with fish in one permanent pool in the upper reaches of Gulungul Creek, near Jabiru Northern Territory. Species abundance data gathered in the mid-Wet season each year for 8 years were very highly correlated ($P < 1/200\,000$) (Humphrey et al 1990). Unfortunately there were no data from elsewhere in Australia to compare with this.

However, a recent examination of persistence of macroinvertebrates in streams around Australia has been undertaken by Humphrey et al (1997) (table 1). This showed that, as might be expected, persistence of macroinvertebrate communities is significantly and positively correlated with permanence of stream flow, and negatively correlated with interannual variability of annual stream discharge. However, there is also a tendency (only) for macroinvertebrate communities of permanent streams in temperate Australia to be more persistent than those in tropical regions. It is possible that this is related to individual life spans being much shorter in the tropics (many insects live for only a month in tropical waters whereas lifespans of 6 months to 3 years are common in temperate waters). The longer life spans increase the probability that at least some of the species may survive a disturbance, such as inadequate flow, in isolated refugia.

3 Major wetland habitats

The broad classification of wetland habitats in the Wet-Dry tropics includes coastal saltflats, mangrove swamps, freshwater lakes, floodplains, freshwater ponds and swamps. Adding rivers to this list covers all the components present in a wetland system that are, at some time, inter-connected. From an ecological point of view, the most important subdivision of these categories is into permanent and seasonal water bodies. Most of the floodplains and lowland stream channels are inundated seasonally and dry out each Dry season, leaving only small areas of permanent water for aquatic organisms to survive in. These permanent water bodies are the deeper billabongs of the floodplain zone and the lowland stream channels, and the pools and shallow channel sections of permanently flowing headwaters of streams rising from rocky plateaux such as Arnhem Land and Litchfield. In the Magela Creek system, a tributary of the East Alligator River, there are 210 km^2 of seasonal habitat and, in some years, only about 3 km^2 of permanent water to act as refuges for biota that require surface water to survive.

On a temporal scale, many wetlands spend more of their time as dryland systems than as wetlands. Consequently, dryland processes such as fire and grazing will be important considerations in the management of these areas.

Table 1 Persistence of stream macroinvertebrate communities across different bioregions of Australia (after Humphrey et al 1997). Level of persistence is indicated by three 'inconstancy' indices where high persistence = low inconstancy index. Calculations based on family level, presence-absence data.

Region	Flow status	Inconstancy index (%dissim>0.35)	Inconstancy index (mean threshold)	Inconstancy index (mean dissimilarity)	CV of annual flow	Latitude (°; decimal minutes)	Comments on persistence and mechanism for relative lack of persistence
Temperate (VIC-Latrobe)	Permanent	4.5	1.1	0.266	0.32	38.0	High persistence (to some degree an artefact of combined seasons and habitat data).
Temperate (SW WA)	Permanent	6.5	1.6	0.244	0.49-0.73	32.3	High persistence (predictable pattern of flow)
Temperate (TAS)	Permanent	7.5	1.9	0.204	0.47	41.3	High persistence (predictable pattern of flow)
Wet-dry tropical (SAR, NT)	Permanent	13.5	4.0	0.234	0.58	13.35	High persistence (predictable pattern of flow)
Wet tropical (NE QLD)	Permanent	15.0	6.3	0.256	0.5	18.1	High late dry season persistence; cause of low early dry season persistence unknown (cyclonic disturbance/opening of canopy in early 1990s?)
Wet-dry tropical (RMC, NT)	Seasonal	17.0	4.3	0.237	0.58	13.35	Lower taxa richness in 1992 associated with low wet season rains and discharge
Subtropical (SE QLD)	Permanent	19.0	13.0	0.293	1.04-1.07	26.3	High autumn persistence; low persistence in spring associated with drought (1995)
Temperate-dry (VIC-Wimmera)	Seasonal	19.5	8.3	0.257	0.58-0.98	36.3	Seasonal flow (pools in dry season)
Wet-dry tropical (Magela, NT)	Seasonal	21.0	9.8	0.279	0.56	12.4	Seasonal flow (little or no surface water by end of dry season)
Temperate (SW WA)	Seasonal	24.0	11.4	0.264	0.49-0.73	32.3	Seasonal flow (little or no surface water by end of summer 'dry season')
Temp. semi-arid (Flinders, SA)	Permanent (riffle)	25.0	8.3	0.290	1.25	31.1	Reasonably high persistence (sites of permanent flow)
Sub-alpine (NSW)	Permanent	27.5	12.3	0.268	0.5-0.75	36.3	High summer persistence; low persistence in spring associated with snow-melt floods (eg 1992).
Temp. semi-arid (Flinders, SA)	Permanent (macro, pool)	51.7	30.9	0.387	1.25	31.1	Low persistence of pool and macrophtye fauna compared with that in riffles. 'Flashiness', and occasional severe floods characteristic of these streams may affect fauna of the habitats differently.
Dry tropics (Pilbara, WA)	Seasonal	93.0	60.0	0.431	1.4	21.3	

4 Annual cycle of ecological processes

The natural wetland habitats of the Top End that have been most intensively studied to describe their ecological character (biotic structure and processes and environmental processes) are the floodplain and lowland billabongs. The following account is based largely on this work on those water bodies in the Alligator Rivers Region.

4.1 Water chemistry

After the first flush of water in the Wet season, surface waters in the region generally have very low levels of dissolved solids reflecting the highly leached land surface of the region (EC range 5–20 uS/cm). The waters are slightly acidic (pH 5.2) with a very low buffering capacity and generally very clear with low levels of suspended solids (5–60 mg/L). The soft, acidic water probably contributes to a low diversity of molluscs in the region (C Humphrey, pers comm). With each flood event, there is a further general decline in the concentration of solutes (Hart et al 1987a). Most of the surface water at this time is derived from surface runoff (or direct precipitation on parts of the floodplain) rather than ground water. Consequently, the proportions of major ions of surface waters closely resembles that of local rainwater (fig 7). Plants and soil remove over 90% of P, NH_4 and NO_3 from rainwater (Hart et al 1987b).

During the Dry season the water chemistry changes and the pattern of change varies with different kinds of waterbodies. The spring-fed permanent headwaters and the deep channel billabongs change very little over the year. On the other hand, the standing waters of the shallower floodplain billabongs and backflow billabongs of the lowlands evaporate to some extent and concentrate their dissolved salts steadily during the season. In some billabongs the addition of ground water from seepage may cause the solutes to increase ten-fold or more. As the waters concentrate there is a steady progression towards the composition of seawater (Walker & Tyler 1982). In some billabongs there is a sudden marked rise in EC at the end of the Dry season (fig 8). pH also rises slightly over the Dry.

When flow begins early in the Wet season the composition of the first flush water depends on the manner in which it arises. When the downstream progression is at a steady pace the advancing water may develop a front with high solute concentrations leached from the soils over which it passes and the pH may also be quite low (3.5–4.5). Consequently, when this mixes with the water in the billabongs, the water quality for the biota may be very unfavourable for a time until it is diluted by following, more dilute, waters. In some floodplain areas with jarosite soils, oxidation of sulphide to sulphate occurs after the soil becomes wet again after drying out during the Dry season and allowing aeration of the soil. This causes very acidic conditions in the soil water and this allows aluminium to dissolve. High levels of aluminium and sulphate can then be leached from the soil by the slowly advancing water and transported to billabongs. When this happens the water is potentially toxic to fish and mass fish kills may occur (Noller 1983). These kills are invariably associated with very low oxygen levels in the water which is probably also caused by the influx of organic matter with the new water. Fish kills can also occur at this time solely from oxygen depletion resulting from influx of organic matter with storm events (Townsend 1994).

When, as often happens, the first flush occurs as a large flood with rapid progression across the floodplain, there is less potential for these harmful conditions to arise.

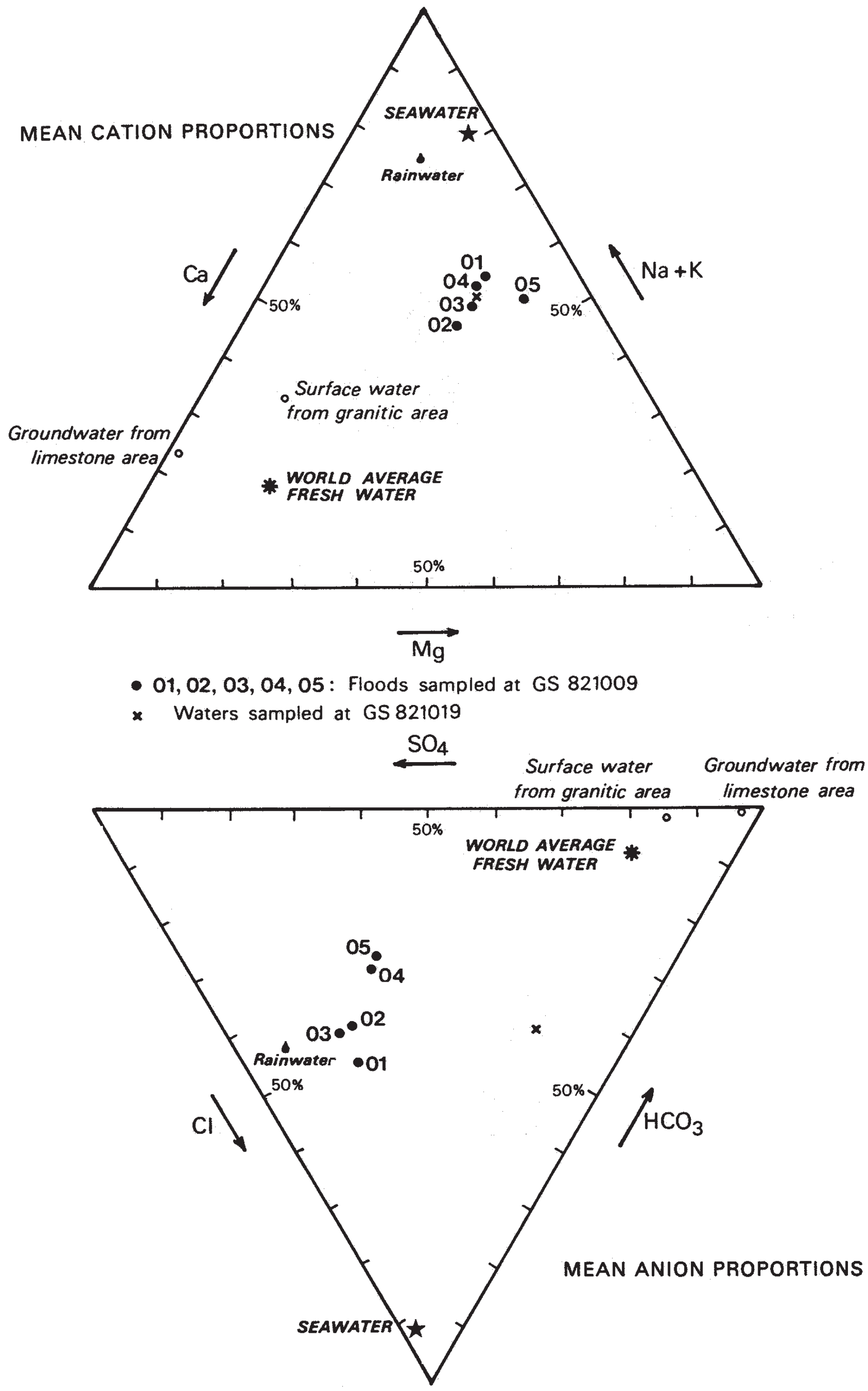


Figure 7 Relative ionic composition of Magela Creek water (flood events 01–05) and rainwater, both collected at GS821009. For comparison, ionic composition of seawater, 'world average fresh water', and two different fresh waters are also shown. (From Hart et al 1987)

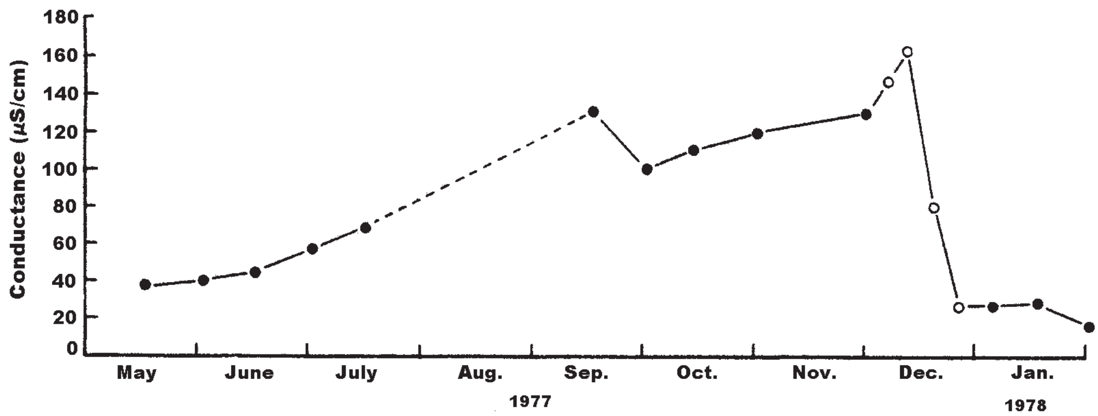


Figure 8 Conductivity in Jabiluka Billabong from May 1977 to February 1978. Data obtained from Water Division, NT Department of Transport and Works (●) and this study (○)

4.2 Primary production patterns and nutrient cycling

With the exception of an initial short-lived pulse of algal production at the start of the Wet (Humphrey & Simpson 1985), during the Wet the combination of low nutrients and flushing flows prevents development of large populations of phytoplankton (Walker & Tyler 1983). As flows cease and the Dry season commences, nutrient levels rise (from about June). Primary production consequently increases until water levels drop enough to allow wind induced resuspension of fine sediments. In some billabongs, this results in a high turbidity from tripton (non-living suspended fine particles) which in turn reduces the amount of light penetration and primary production.

In seasonal water bodies growth and production of submerged and emergent aquatic macrophytes begins in the early Wet season each year when dry ground becomes saturated by rain or floodwater. Maximum biomass of the dominant grasses occurs in the late Wet–early Dry season (Finlayson 1991). With the senescence of these plants there is a large increase in decomposing detritus. In some billabongs this decomposition results in the water becoming anoxic for a period (Walker & Tyler 1983) and this can also be a cause of fish kills.

4.3 Oxygen and temperature

Surface water temperature averages around 30°C but may range from 25°C to 38°C depending on location and time of year. Highest temperatures are recorded late in the Dry season. Thermal depth gradients are typically absent during the Wet season but frequently develop during the Dry. There is some diurnal variation in this gradient as surface waters cool at night. However, even small temperature differences of 1–2°C may be sufficient for stratification to occur (fig 9) and this can cause deoxygenation of deeper waters (Hart & MacGregor 1980). This happens in many billabongs.

Dissolved oxygen levels are generally at their lowest levels at dawn after a night of steady oxygen consumption by respiration by the aquatic community and before any photosynthesis has occurred to produce more oxygen in the water. Oxygen levels typically then begin to rise soon after sunrise and reach maximum levels around mid afternoon. There are not many data on the frequency with which total oxygen depletion occurs by this process, but it has been observed on a number of occasions. When it occurs many fish species can be seen gulping at the water surface flushing their gills with the oxygenated surface film of water.

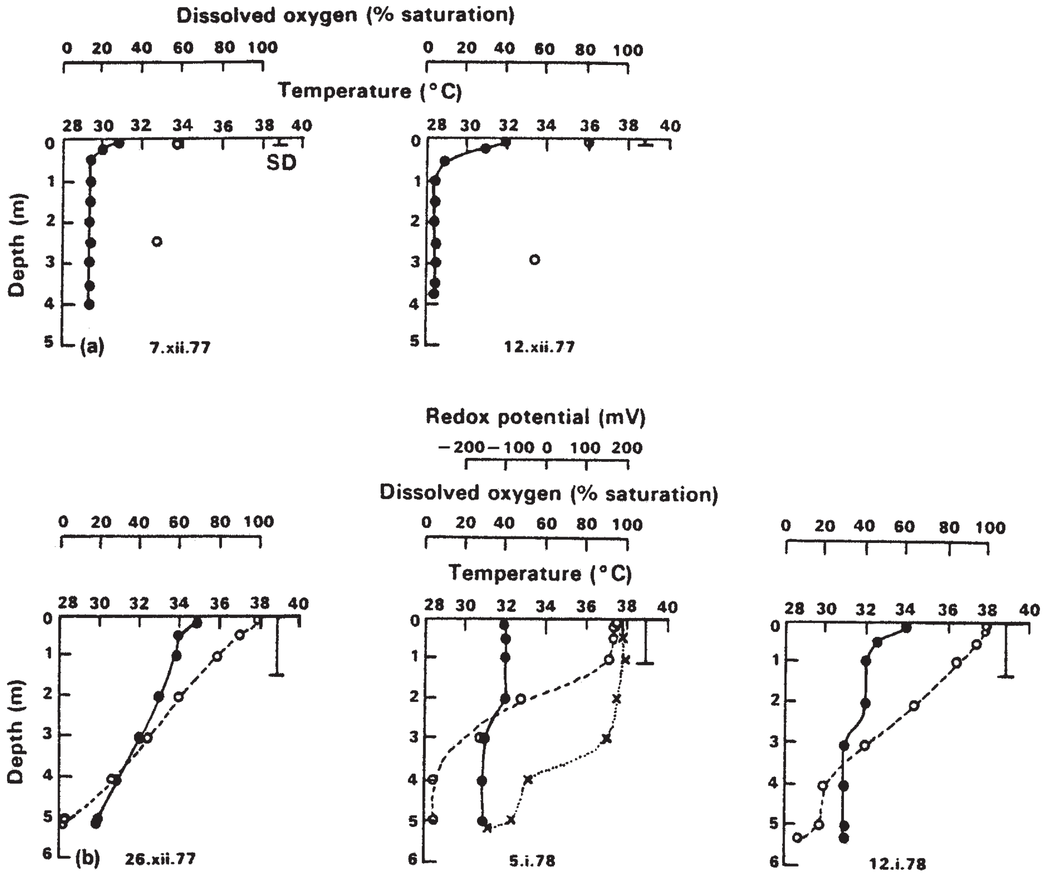


Figure 9 Temperature and oxygen depth profiles in Jabiluka Billabong before (December) and after (January) the first flush of Wet season water (from Hart & MacGregor 1980)

The effect of these short periods of anoxia on fish have not been examined in detail. Fish can recover from short periods of this stress but more frequent and prolonged periods may have more harmful effects. Barramundi have been observed to jump out of the water and strand themselves on fringing vegetation in response to this oxygen depletion (Pidgeon et al 1997).

4.4 Nutrient budgets

As well as the intrinsic aesthetic value of their vegetation and bird life, floodplain wetlands have been considered to play a major role in the 'economy' of the entire river system. The 'flood-pulse' concept proposed by Junk et al (1989) stemmed from observations that the most productive riverine fisheries in Africa were on rivers with extensive floodplains. The concept suggests that the seasonal pulsing of floods over dry ground results in a more rapid recycling of nutrients and organic matter than occurs in permanently wet or dry areas and hence results in much higher productivity than would occur from the increased area of habitat alone. Obviously many fish species in the tropics have adapted to taking advantage of this production.

The applicability of this concept to Australian river systems has not been widely considered to date. Direct evidence from water chemistry may be difficult to obtain as nutrients are rapidly taken up by the biota so that evidence would have to come from biotic responses.

Some support is offered by the observation by Griffin (1995) on barramundi. The past commercial barramundi catch rate in the Mary River system, which is dominated by extensive coastal floodplains with prolonged periods of freshwater inundation, was much higher than in rivers such as the Adelaide River, where the floodplain inundation period is relatively brief.

Freshwater mussels in Magela Creek display a bimodal pattern of change in condition over the year. There is a major increase related to the plankton production of the Dry season and a second peak occurring soon after the first flush of water in the early Wet season (fig 10) (Humphrey & Simpson 1985). This second peak in condition appears to be such a flood pulse response.

If this nutrient pulse can be shown to be important for the function of Australian floodplain wetlands then it has implications for the construction of ponded pastures, a controversial issue in Queensland at present, and for adequate provision of environmental flows where river regulation for irrigation occurs (almost everywhere).

A chemical budget for nutrients, nitrogen and phosphorus, entering and leaving the Magela floodplain (Hart et al 1987b) suggested that the floodplain acted as a net sink for these nutrients entering from the catchment. However, a similar budget for metals (Finlayson 1994) showed that the floodplain probably acts as a net source of major ions (sodium, potassium, calcium and magnesium) and a net sink for trace metals (table 2). Thus, there is an indication of net export of material from the Magela floodplain to the main channel of the East Alligator River estuary; the vast herbaceous swamps do not simply function as a sponge soaking up nutrients washed in and filtering out particulate matter. However, none of these studies considered transport of nutrients by migratory fauna. Up-stream migration for spawning by salmon and other fish species has been shown to be a major source of nutrients for the aquatic community in Northern Hemisphere rivers. It could also be a significant pathway in other river systems.

Table 2 Chemical budget for the floodplain basin of Magela Creek, NT (from Finlayson 1994)[1]

	Material load of							
	Runoff		Rainfall		Output		Net load	
Sodium (t)	370	(90)	33	(13)	630	(150)	-220	(180)
Potassium (t)	120	(50)	13	(16)	200	(55)	-60	(75)
Calcium (t)	120	(150)	4	(11)	310	(72)	-180	(170)
Magnesium (t)	170	(46)	4	(7)	390	(110)	-220	(120)
Iron (t)	230	(230)	a		680	(190)	-450	(300)
Manganese (t)	6	(3)	1	(1)	2	(1)	+4	(3)
Copper (kg)	410	(610)	89	(50)	65	(35)	+440	(610)
Lead (kg)	83	(35)	67	(65)	22	(12)	+130	(75)
Zinc (kg)	250	(250)	910	(930)	87	(47)	+1100	(970)
Uranium (kg)	42	(240)	18	(9)	11	(6)	+48	(240)

1 Calculation of material loads entering and transported from the Magela floodplain during the 1982–1983 wet season. Error estimates are given in brackets. See Hart et al (1987) for sampling methods and the estimation of errors.

a Missing value

4.5 Energy flux and food webs

The ecological energetics of tropical freshwater wetlands in Australia has received little attention until recently. Much work has been done on mangrove swamps in north Queensland, however. Dietary studies of vertebrates provide some idea of energy pathways at the higher consumer levels but little work has been done on the invertebrates which comprise much of the lower parts of the consumer food chain (fig 11) (Bishop & Forbes 1991). An interesting feature among the freshwater fish is a high incidence of omnivorous species that are rare in temperate waters.

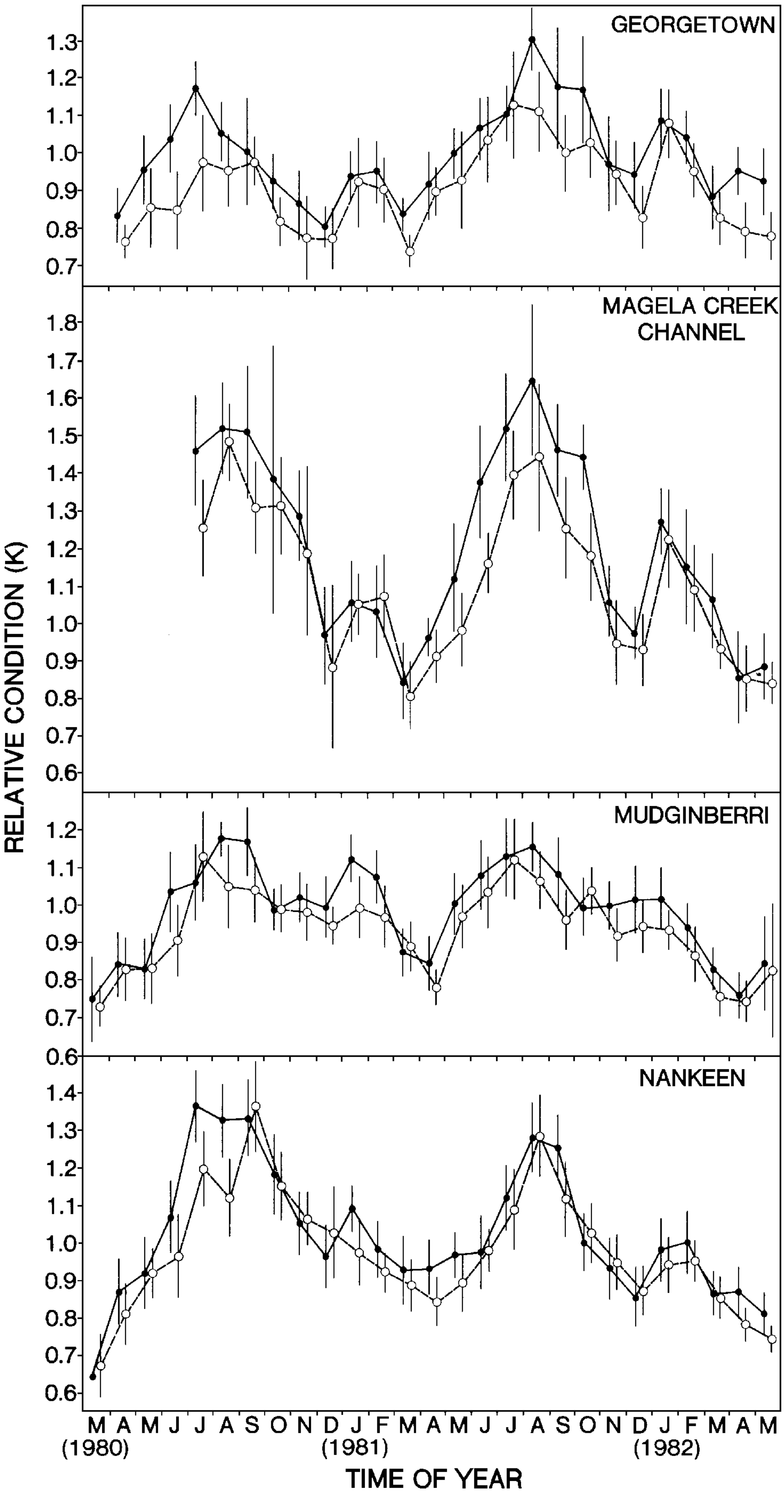


Figure 10 Mean relative condition (K) of male (solid circles) and female (open circles) mussels (*Velesunio angasi*) in selected waterbodies of Magela Creek, NT. 95% confidence limits are indicated by vertical lines (from Humphrey 1984).

The characterisation of trophic and nutrient processes in tropical wetlands remains a challenge. Fundamental to the management of natural ecosystems is knowledge of what are the major carbon sources that 'drive' it. In rivers and streams knowledge of the relative importance of inputs autochthonous sources (algae and macrophytes) and allochthonous sources (terrestrial detritus and fauna) has important implications for land-use management, especially of the riparian zone. Where autochthonous primary production is important (most lentic wetlands and many streams) the role of algae and macrophytes in food webs needs clarification. Whilst there are many planktonic and benthic invertebrates that 'graze' on algae there are very few that directly consume macrophytes. Until recently, macrophytes were assumed to enter the food web after death as detritus and this material was thought to flow through food chains via decomposers and detritivores. However, carbon and nitrogen isotope studies that trace carbon sources have shown that for some swamp grasses this detrital pathway to higher level consumers may not exist. In these cases the trophic function of the grasses may be to simply provide a substrate near the water surface for periphytic algae to grow on. This information has implications for evaluating management practices such grazing and the ecological impact of weed species. Some work along these lines has been undertaken in north Queensland (Bunn et al 1997). Isotope studies are also part of a current study of the impact of paragrass on the Magela Creek floodplain in the Northern Territory.

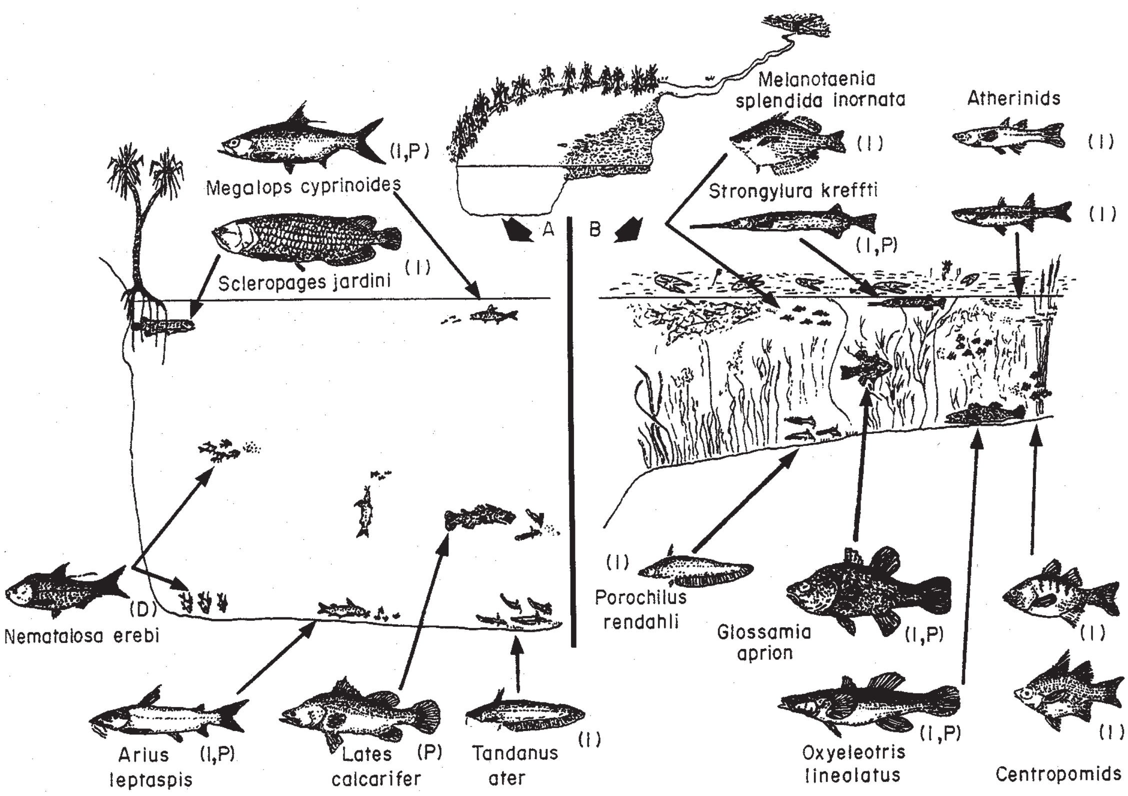


Figure 11 A simplistic food web for fish in Top End billabongs (from Bishop & Forbes 1991)

Where a range of different types of wetland are inter-connected, it may also be very important to examine the exchange of energy/carbon and nutrients between the different sections of the wetland system. This occurs largely by passive stream transport (nutrients as dissolved and suspended solids, detritus, algae and invertebrates). However, there may also be significant active transport by the migration of fish and birds. Both processes, but particularly the latter, can be seriously affected by human activities. Consequently, knowledge of its presence and ecological significance is important for planning purposes.

5 Biogeography of fauna and flora

Coastal wetlands can wax and wane rapidly with changes in climate and many of their inhabitants are, of necessity, highly vagile species that are widespread. Also, the freshwater wetlands of the Northern Territory's coastal floodplains are very young (2–3000 y) (Woodroffe et al 1985). Hence it is unlikely that these wetlands would contain many specialised endemic biota. Sediments of the seasonally-flowing portions of the streams in the lowlands are comprised of unstable, shifting sands and are also relatively young (<6000 y) as the result of infilling of deep (10 m) Holocene channels (Roberts 1991). In contrast, the Arnhem Land escarpment is very ancient (Mesozoic). The permanent streams associated with the sandstone massif and outliers are, therefore, likely to have been present for a very long time so that endemic elements in their biota may be present, either as relict species or through local speciation. Consequently, these areas should be targeted in future survey and monitoring work where conservation of biodiversity is the management target.

The possibility of endemism is supported by the freshwater fish. Two freshwater fish species (Mariana's hardyhead *Craterocephalus marianae* and the black anal-fin grunter *Pingala midgleyi*) have a very restricted distribution, occurring only in the headwaters and lowland streams of the ARR and nearby western Arnhem Land, and appear to be associated with the sandy substrates derived from the sandstone plateau. Also, several fish species (*Melanotaenia exquisita, M. trifasciata, Toxotes lorentzi* and *Hephaestus carbo*) have a very disjunct occurrence among the permanent escarpment streams (Bishop & Forbes 1991, Larson & Martin 1990) indicating that quite strong isolating mechanisms may occur, even among streams on the same river system. In contrast, most fish species in the floodplain zone are relatively widespread species.

The absence of exotic species of freshwater fish in the ARR is worthy of mention, as it is an increasingly rare situation on a national and global scale.

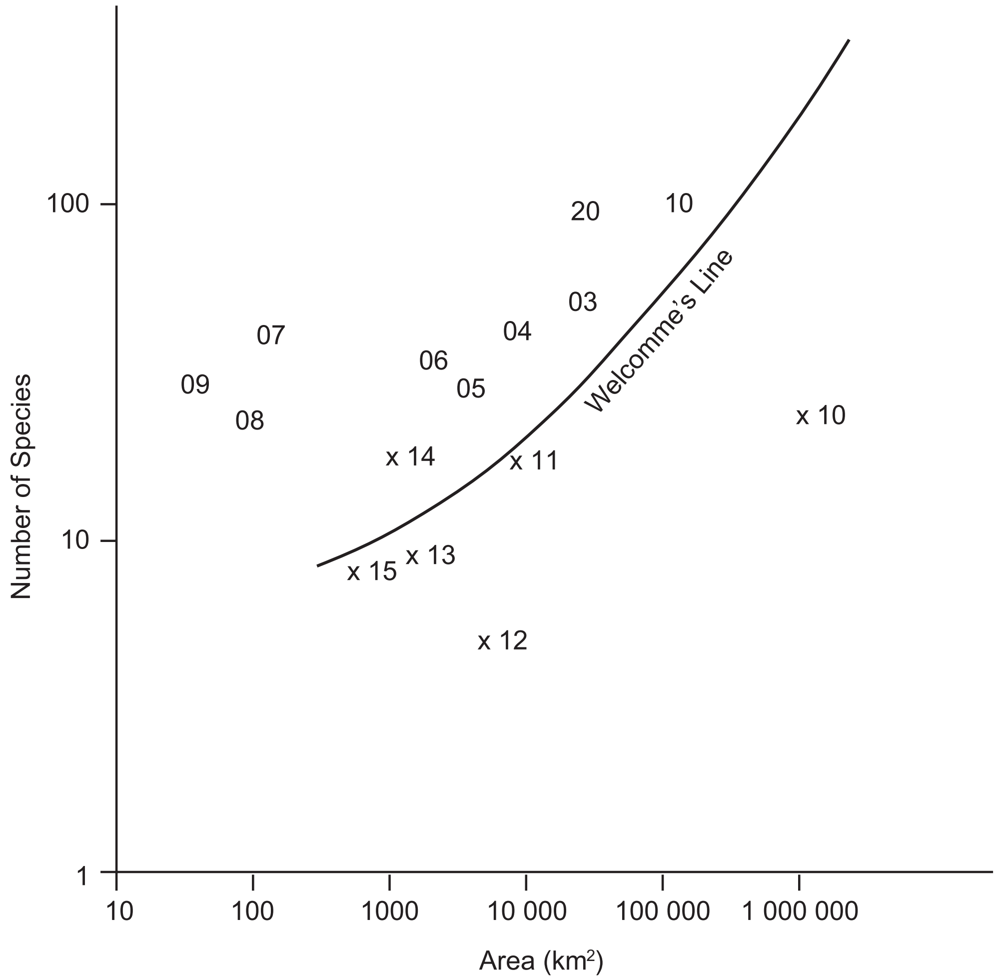
The biogeographic situation for invertebrates is not well known. However, there are several, described and undescribed, species of macrocrustaceans inhabiting permanent escarpment waters for which there are only one or a few site records at this stage (Humphrey & Dostine 1994).

5.1 Latitudinal and other spatial effects on taxa richness

One of the most accepted patterns in ecology is the increase in species diversity from the poles to the tropics. Most frequent explanations for this pattern invoke concepts of climatic stability, geological age, habitat heterogeneity, high productivity, predator-prey relationships, and comparative interactions (Shiel & Williams 1990). When these authors examined this pattern for different groups of freshwater biota on the Australian continent, different patterns were observed. Species richness is generally depressed in zooplankton and littoral microfaunal species in the tropics; for fish and macroinvertebrates tropical species richness is either higher or not lower than for comparable temperate systems; the situation for algae and macrophytes is unknown. This situation casts doubt on the value of this pattern as a useful construct for management planning. This is probably largely a result of inadequate knowledge at present and it may be a useful question to readdress in the future.

Bishop and Forbes (1991) made some interesting analyses of species-area relationships that relate to this question. They found that, although the total freshwater fish fauna of Australia is very species poor for a continent of this size, when the Australian tropical streams are compared with relationships for floodplain rivers on other continents they have as many or more species (fig 12). Also, in relation to the size of the catchment, tropical streams in Australia contain more species than temperate streams. More recently Pusey and Kennard (1996) demonstrated that, over a much smaller latitudinal range, a latitudinal change in the species-catchment area relationship occurs in coastal streams in north Queensland (fig 13).

In the Northern Territory, water softness, seasonality of flow, recency of ecosystem formation and lack of significant habitat heterogeneity (especially vast tracts of sand substrate and lack of altitudinal gradients) mitigate against significant speciation in many freshwater invertebrate groups.



Tropical:0			Temperate:X		
Code	System	Source	Code	System	Source
1	Fly R.	Roberts (1978)	9	Baroalba Ck.	Bishop & Harland (1981)
2	Purari R.	Haines (1979)	10	Murray-Darling	Lake (1979)
3	Alligator Rvs.	Bishop *et al* (1982)	11	Shoalhaven R.	Bishop (1979)
4	Laloki R.	Berra *et al* (1975)	12	Ironstone Ck.	Lake (1982)
5	Jardine R.	Allen & Hoese (1980)	13	Parson's Ck.	Lake (1982)
6	Magela Ck.	Bishop *et al* (1982)	14	Tweed R.	Richardson (1984)
7	Black-Alice R.	Buemer (1980)	15	Seven Creeks	Cadwallader (1979)
8	Gulungul Ck.	Bishop & Harland (1981)			

Figure 12 Relationship between catchment area and number of fish species for Australian rivers compared with the relationship indicated by Welcomme's line based on 45 rivers on other continents (from Bishop & Forbes 1991)

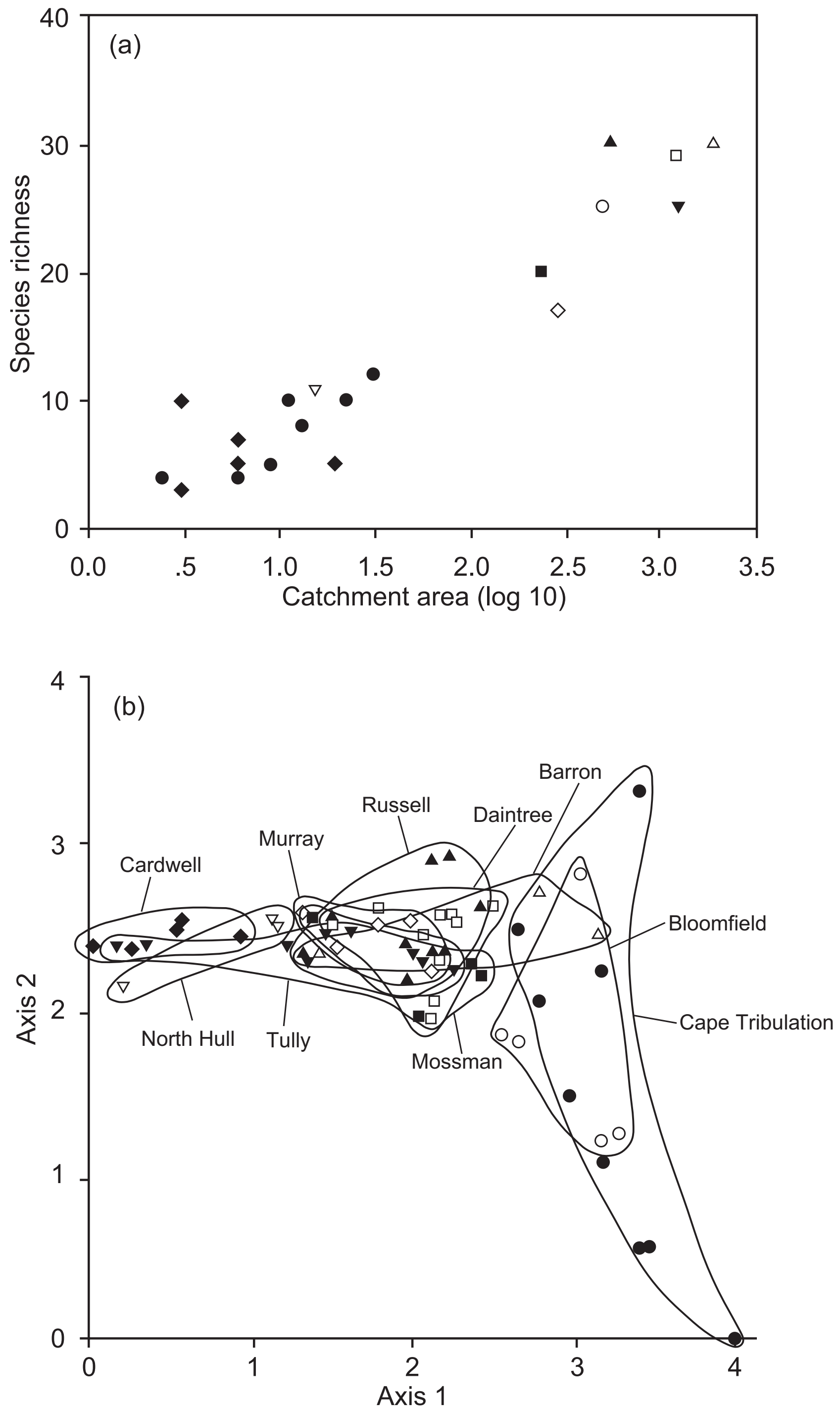


Figure 13 Biogeographic relationships of freshwater fish in coastal rivers of north Queensland. (a) The relationship between catchment area (km^2, log transformed) and fish species richness. Drainage basins are distinguished by the following symbols: ○ Bloomfield River; ● Cape Tribulation area; □ Daintree River; ■ Mossman River; △ Barron River; ▲ Russell River; ▽ North Hull River; ▼ Tully River; ◇ Murray River; ◆ Cardwell area. (b) The distribution of study sites in ordination space as defined by DECORANA Axes 1 and 2 of an ordination of weighted species abundance data from which all sites located above major discontinuities in river profile were omitted. Drainage basins are distinguished by the same symbols as in (a). (from Pusey & Kennard 1996)

6 Life history strategies

6.1 Breeding cycles

The reproductive cycle of most vertebrate species in the Wet-Dry tropics is timed to take advantage of seasonal abundance of resources offered by the Wet season. Thus the gonads of most fish species mature at the end of the Dry season in readiness for spawning when the rains come and provide a vast increase in available habitat for them and their progeny. A few species, rainbowfish and hardyheads, appear to spawn to some extent year round. Food resources for waterbirds are most abundant later in the Wet season and breeding occurs from the mid-Wet to early-Dry seasons, depending on seasonal rainfall, when floodplain grasses start seeding. Saltwater crocodiles start nesting early in the Wet season. Freshwater crocodiles and turtles, however, reproduce in the Dry season, presumably to avoid flooding of their buried eggs.

The reproductive strategies of invertebrates are no doubt extremely varied. Many have short and continuous breeding cycles and seasonal flooding provides opportunities for extensive colonisation and high production in lowland waterbodies. The familiar mass emergence of dragonflies at the end of the Wet season is not necessarily an indication of a general pattern. For example, the cherubin (*Macrobrachium rosenbergi*), a very large prawn, migrates to sea during the early-mid Wet season for spawning and their small progeny migrate upstream towards the end of the Wet season.

6.2 Survival strategies

For the aquatic biota of highly seasonal habitats, strategies have evolved for taking advantage of the seasonally-available resources in the Wet season and persistence through harsh Dry season conditions. Many plants, and some invertebrates, remain on site in the dry sediments as desiccation-resistant and/or dormant stages of the life cycle. However, some species die out in these areas and recolonise them by stream or aerial transport from populations surviving the Dry season in permanent habitats (Paltridge 1992). The strategy used by birds (Morton & Brennan 1991), fish (Bishop & Forbes 1991) and possibly some reptiles (such as filesnakes and crocodiles) is to undertake a regular migration of some form between seasonal and permanent water habitats (fig 14).

Fish migration between the floodplain and lowland stream channels of Magela Creek has been studied for 10 years by ***eriss*** as a potential method for detecting effects of mining (Bishop et al 1995, Pidgeon et al, in press). Rainbowfish (*Melanotaenia splendida inornata*) and perchlets (*Ambassis* spp) comprise over 90% of the migrants. The upstream migration of these species is much (at least 9 times) greater than the downstream migration (Pidgeon & Boyden 1993). As well as being a potential survival strategy for reaching permanent upstream habitats, this migration represents a significant net transfer of energy from the floodplain systems to the lowland/headwater sections of streams. On several days during the 1995 Wet season, it was estimated that there was 0.5–1.0 tonnes (wet weight)/day of rainbowfish leaving the floodplain; these fish would contribute substantially to the diet of upstream predators. This information should be of relevance to environmental managers planning the construction of any in-stream or riverbank structures. Further information on movements of other fish species between seasonal floodplain swamps and permanent billabongs would be useful for evaluating land-use practices and fisheries management.

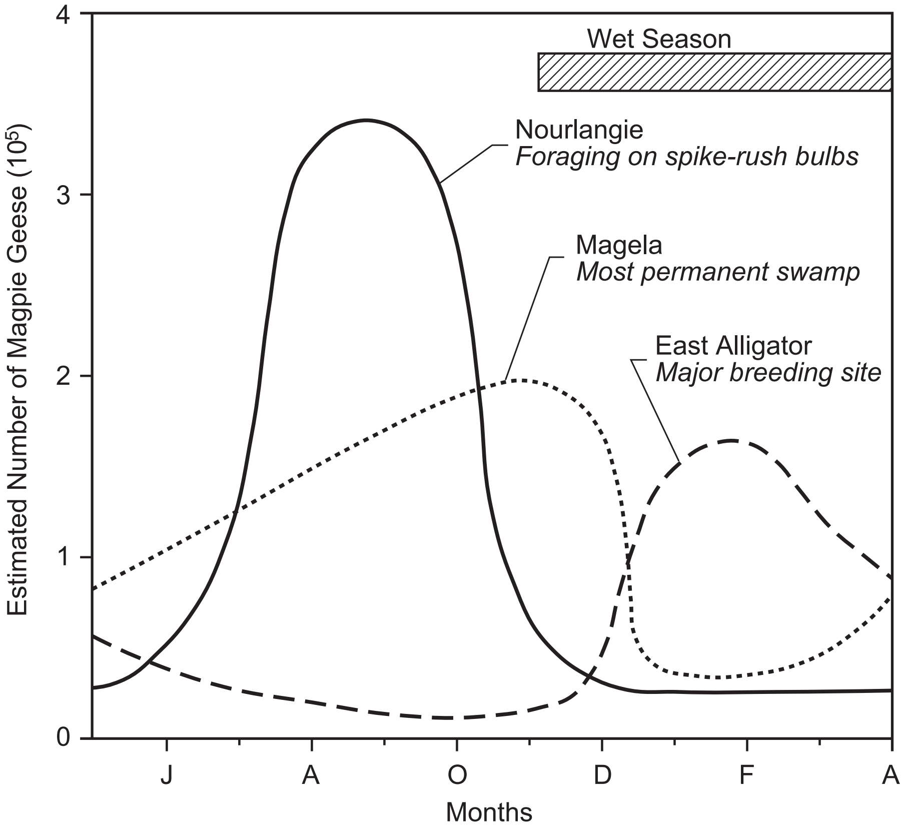


Figure 14 Seasonal changes in the numbers of Magpie Geese occurring on three floodplains in the Alligator Rivers region. The estimates are based on aerial surveys during 1981–1984. (SR Morton, KG Brennan & MD Armstrong, unpubl data)

In seasonal stream channels, most macroinvertebrates die out during the dry phase and recolonise the stream by downstream drift from permanent headwaters (Paltridge et al 1992). Information on the survival strategies used by invertebrates in seasonal floodplain habitats is needed and is currently being examined by staff at ***eriss***.

It is clearly important for conservation management to have some understanding of these survival strategies. The most intensively studied wetland animal species in the Wet-dry tropics are the economically important barramundi (*Lates calcarifer*), saltwater crocodile (*Crocodylus porosus*) and magpie goose (*Anseranas semipalmata*) (Bayliss & Yeomans 1990, Morton et al 1990, Griffin 1995, Webb et al 1987). The migratory movements and population dynamics of these species are quite well understood and management strategies are in place to ensure their sustainable harvesting and conservation. Whilst other species are not exploited to the same extent, similar information on many other species would be useful to provide an ecological basis for reserve design and management.

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Wetland classification and inventory in northern Australia

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Abstract

Wetland classification is still the subject of debate in Australia with several national programs using different systems. The classification systems used for an overview of Australian wetlands and the LWRRDC scoping review of Australian wetlands, and that used for the directory of important wetlands are described. These are compared with a recently prepared geomorphic-based system of classification. An inventory of Australian wetlands does not exist, although an overview was provided in the 1980s as part of a national program. The recent directory of important Australian wetlands has compiled much of the existing information base and led to moves to consider a process for developing a national wetland inventory. Currently, the status of wetland inventory information in northern Australia is uneven and incomplete.

1 Introduction

A comprehensive inventory of the wetlands of northern Australia does not exist (Finlayson et al 1998, Storrs & Finlayson 1997), although it is much further advanced in Queensland (Blackman et al 1992, 1993, 1996) than in Western Australia (Lane et al 1996) or the Northern Territory (Whitehead & Chatto 1996). The recently compiled *Directory of Important Wetlands in Australia* (ANCA 1996) provides an invaluable description of the inventory information held by governmental agencies, but it is not intended as a comprehensive inventory. It does, however, provide the basis of a systematic collation of information on wetlands and could lead to the development of a national inventory. Thus, it could lead to a national inventory with active processes in place to obtain further information and be regularly updated.

A recent recommendation from the ANZECC Wetlands Network (encompassing representatives from all state/territory conservation agencies and several federal bodies) supports this intention. Under the auspices of the federally funded National Wetlands Program the Environmental Research Institute of the Supervising Scientist has been asked to liaise with appropriate agencies to develop a draft proposal for a national wetlands inventory. These moves are encouraging and could lead to a greatly enhanced information base for wetlands in northern Australia. The importance of a comprehensive wetland information base has been promoted by the Ramsar Wetland Convention and various wetland conservation fora (Dugan 1990, Blackman et al 1992, Finlayson 1996).

The extent of existing wetland classifications and inventory effort in northern Australia is outlined below, with a particular emphasis on national approaches. Hence, the classification systems used by Paijmans et al (1985) and ANCA (1996) are described along with the newly promoted approach of Semeniuk and Semeniuk (1995, 1997). The ‘inventories’ described are the national directory project (ANCA 1996) and the overview provided by Paijmans et al (1985) which was used as the basis for the LWRRDC scoping review of R&D for wetlands (Bunn et al 1997).

2 Classification

Finlayson and von Oertzen (1993) reported five wetland classification systems that had been used in northern Australia. In addition, ANCA (1996) proposed a further system for the Directory of Important Wetlands in Australia, and Semeniuk and Semeniuk (1995, 1997) have proposed a completely different approach using geomorphic features. Given their current status the latter two systems are briefly described along with the Paijmans et al (1985) system for a generalised overview of Australian wetlands. Unfortunately, there is no general acceptance of one or the other of these systems. For example, the National Wetland Program is supported by both LWRRDC and the Biodiversity Group of Environment Australia (encompassing ANCA), but both have adopted different classification systems. The difficulties with applying the classifications have also led Storrs and Finlayson (1997) and Finlayson et al (1997) to adopt a much simplified, but not accurate (*sensu* Semeniuk & Semeniuk 1995, 1997), set of wetland categories for northern Australia which is largely based on geographic location. These categories are given below.

Wetland categories in northern Australia
Coastal marshes
Mangrove swamps
Freshwater lakes and swamps
Floodplains
Freshwater ponds and swamps

The above example reinforces the case for determining and field testing a national classification of wetlands and, if needed, the inclusion of regional differences or modifiers. It is also stressed that local names for various wetland types should not be discouraged and the means of including these in the classification (eg cross-referencing) should be investigated. The rationale for this is based principally on the need to encourage local association with the classification, and hence its use; foreign names may do little to promote ownership of the classification.

2.1 Generalised overview of Australian wetlands

Paijmans et al (1985) adopted a loosely defined classification that was lacking in detail compared to the system developed by the United States Fish and Wildlife Service (Cowardin et al 1979). The latter was not adopted as it was regarded as too detailed for use in Australia where many wetlands lacked detailed descriptions. Whilst recognising these issues Paijmans et al (1985) acknowledged that problems of gradation between wetland types, lack of seasonal information, and inconsistent and indefinite terms still had not been fully resolved in the system they proposed. Finlayson and von Oertzen (1993) also point out that in northern Australia the degree of permanence and salinity of many inland lakes also needed further consideration.

The classification system adopted was simple and loosely hierarchical with categories, classes and sub-classes (table 1) based on hydrologic and vegetation characteristics. There are six categories – lakes, swamps, land subject to inundation, rivers and creeks, tidal flats, and coastal inshore waters. As a rule these were fairly identifiable on topographic maps although there was some confusion between swamps and land subject to inundation. The key features of the six categories are given below.

Wetland category	Hydrologic and/or vegetation features
Lakes	Open water bodies generally more than 1m deep when full
	Permanent emergent vegetation, when present, is confined to the margins
	Differences between classes of lakes are not clear-cut
Swamps	Generally less than 1 m deep when full
	Dominated by emergent vegetation
Land subject to inundation	Seasonally or intermittently flooded but not usually long enough for hydrophytic vegetation to develop
	Terrestrial vegetation can be common
River and creek channels	Channels for the conveyance of surface runoff
	Many intergrades between the classes recognised
Tidal flats	Areas subject to tidal inundation at least once per year
	Frequency and nature of inundation varies from daily by high tides to rarely and associated with freshwater flooding
Coastal water bodies	Water bodies with varying degree of access to the open sea

The classes used in this classification are based on permanency of water and frequency of flooding (table 1). Thus they reflect the hydrologic, climatic and tidal features of the region. The sub-classes reflect the geologic and geomorphic context and location in the hydrologic basin. As such they tend to be rather *ad hoc* and many others could be added if more detailed landscape information was available.

2.2 Directory of important wetlands in Australia

The classification system adopted for the Directory is based on that used by the Ramsar Wetland Convention (Scott & Jones 1995) which was in turn modelled on the hierarchical system used in the USA (Cowardin et al 1979, Wilen & Bates 1995). The latter is divided into systems, sub-systems, classes and sub-classes (table 2) together with a series of modifiers concerning water regime, water chemistry (salinity, pH) and soil. The basic unit of the hierarchy is the 'system', of which five are distinguished (table 2). After being in use for more than a decade Cowardin and Golet (1995) reviewed the USA system, and despite recommending some changes were generally happy that it had served a useful purpose. The Ramsar Convention classification (table 3) is simpler than that used in the USA with three systems – marine and coastal, inland and human-made (Scott & Jones 1995).

The classification used in the Australian Directory is shown in table 4. It uses the same three hierarchical 'systems' as that used in the Ramsar Convention classification. To reflect the Australian situation three further wetland types were added – non-tidal forested wetlands, rock pools, and karst systems. In 1996 subterranean karst systems were included in the Ramsar classification after representation from Australia. A similar classification was developed for Queensland as the basis of a state-wide wetland inventory (Blackman et al 1992).

2.3 Geomorphic classification of Australian wetlands

A global approach to wetland classification combining attributes of landform setting and hydroperiod was proposed by Semeniuk and Semeniuk (1995). The categories of landform and hydroperiod used in this classification are given below.

Landform setting categories	Hydroperiod (water availability) categories
Basins	Permanently inundated
Channels	Seasonally inundated
Flats	Intermittently inundated
Slopes	Seasonally waterlogged
Highland/Hills	

Combining the landforms and hydroperiods generates 13 wetland categories that can be further described systematically and hierarchically using descriptors to denote wetland shape and size, soils, vegetation, and water salinity and its consistency throughout the year. The system is referred to as a geomorphic one as landforms form the first stage in the hierarchy. That is, wetland geomorphic geometry is noted first and then divided further on hydroperiod. The first stages of this classification are shown in table 5.

Semeniuk and Semeniuk (1997) list four stages for the acquisition of data for the classification of wetlands. This entails progressively obtaining more detailed information on the wetlands and establishing the hierarchical separations in the classification. The descriptors within the classification allow for a rigorous, systematic discrimination of the array of wetlands. Whilst Semeniuk and Semeniuk (1995, 1997) present a set of names for the wetland types discriminated they do not encourage the abandonment of local terms, but encourage their use in parallel with a standardised globally accepted set of terms in order to facilitate further communication.

Stages for acquiring data for the classification of wetlands
• Assessment of geomorphic setting from aerial photographs
• Preliminary field survey to determine hydroperiods, soils, biota
• Field survey to determine more detailed hydroperiods, water chemistry, soils and biota
• Field survey to determine more detailed information on seasonal, and long-term dynamics

3 Inventory

Noting the above comments about the absence of comprehensive wetland inventories in northern Australia details of two recent 'inventory' approaches are given. The first is the generalised overview of Australian wetlands undertaken by Paijmans et al (1985) and the second the collation of existing information on wetlands under the national *Directory of Important Wetlands in Australia* (ANCA 1996).

3.1 Generalised overview of Australian wetlands

Paijmans et al (1985) record that in 1973 a proposal was put forward for a survey of the wetland habitats of Australian waterbirds and then expanded to provide information for the management and conservation of Australian wetlands. Feasibility studies were undertaken and the extent of knowledge in each state/territory assessed, but a national wetland inventory did not eventuate. Paijmans et al (1985), however, did proceed with an attempt to classify and map Australia's wetlands on a continental scale. The study was not completed, but a dyeline map of wetlands at a scale of 1:250 000 000 was prepared by analysing published 1:250 000 topographical maps.

The classification used was the same as that shown in table 1 except that all wetlands less than 1000 m across were combined as 'waterholes', seasonal and intermittent wetlands were not distinguished and combined as intermittent, flat-floored depressions more than 1000 m across that occasionally held water were classed as 'dry lake' rather than as 'episodic', and an attempt was made to distinguish between saline and non-saline wetlands. Copies of the map were made available, but were not published. The map was too large, too detailed and too inaccurate. An overview with regional descriptive information was provided (Paijmans et al 1985).

Further computer analysis of the data on the 1:250 000 000 map was made to produce frequency data for the main wetland types. An analysis of wetland assemblages was not as successful.

3.2 Directory of Important Wetlands in Australia

The *Directory of Important Wetlands in Australia* (ANCA 1996) has evolved from an earlier edition (Usback & James 1993) and is supported by the ANZECC Wetlands Network and the National Wetlands Program. As such, it represents the input of information on Australian wetlands as provided by governmental agencies; it does not represent the complete extent of information held by such agencies (Blackman et al 1996, Lane et al 1996, Whitehead & Chatto 1996). The inventory is coordinated by the National Wetlands Program with the state/territory agencies taking responsibility for collecting and collating the information. In this respect it does not provide an even information base given differences in the information resources and the extent to which this has been collated.

Wetlands are included in the directory on the basis of six criteria agreed by the ANZECC Wetlands Network (Phillips 1996).

Criteria for determining wetlands of national importance
• It is a good example of a wetland type occurring within a biogeographic region in Australia.
• It is a wetland which plays an important ecological or hydrological role in the natural functioning of a major wetland system/complex.
• It is a wetland which is important as the habitat for animal taxa at a vulnerable stage in their life cycles, or provides a refuge when adverse conditions such as drought prevail.
• The wetland supports 1% or more of the national populations of any native plant or animal taxa.
• The wetland supports native plant or animal taxa or communities which are considered endangered or vulnerable at the national level.
• The wetland is of outstanding historical or cultural significance.

Application of these criteria is subjective due to differences in interpretation and the extent of available information. Adoption of a biogeographical region approach has reduced the difficulty of determining whether or not a site is unique or representative, although this may not apply where these regions straddle state/territory borders.

A format for a 'minimum dataset' for describing wetlands in the Directory was also agreed (table 6). It was acknowledged that in many instances more information may be available for particular wetlands, but that this would be made available through an accompanying reference list and contact with the responsible state/territory agency. The current edition of the Directory contains information on 698 wetlands or wetland complexes of national importance. Further analysis of the information in the Directory is underway.

Information provided in the Directory covers 30 sites in the Northern Territory, with a further 19 noted in a supplementary list. Whitehead and Chatto (1996) reject the concept of relative importance of individual wetlands and strongly support the development of a comprehensive inventory of all substantial wetlands. The Queensland information base is comprehensive and covers some of the most important sites in the Gulf Plains, Wet Tropics and Cape York Peninsula bioregions of northern Australia (Blackman et al 1996). Lane et al (1996) also report a very uneven information base for wetlands in Western Australia and support moves to obtain a more systematic and even information base. A list of the wetlands of the biogeographical regions that comprise the Wet-Dry tropics was derived from the Directory by Finlayson et al (1997) and presented in table 7. The overall area of these wetlands is not accurately known but exceeds, based on available estimates, 65 000 km^2.

4 Conclusion

Wetland classification is beset with difficulties of terms and inconsistencies in attributes used to separate wetland types. There is still no agreement on the acceptance of a wetland classification system in Australia. That used for the Directory of Important Wetlands in Australia is broadly based on that developed in the USA and adapted by the Ramsar Wetland Convention. In contrast, a more general classification was used for an overview of Australian wetlands approx 15 years ago and formed the basis of a recent national review of wetland R&D needs.

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Table 1 Categories, classes and sub-classes of the hierarchical wetland classification proposed by Paijmans et al (1985)

Categories	Classes	Sub-classes
Lakes	Permanent and near-permanent	• Floodplain lakes including billabongs and waterholes in channels • Lakes of coastal dunes and beach ridge plains • Lakes in terminal drainage basins • Lakes associated with lava flows • Crater lakes • Karst lakes • Glacial lakes • Man-made lakes
	Seasonal	• Floodplain lakes • Terminal drainage basin lakes
	Intermittent	• Floodplain lakes • Coastal dune lakes • Lakes in terminal drainage depressions • Man-made lakes
	Episodic	• Lakes in terminal drainage depressions • Lakes on present or former floodplains
Swamps	Permanent	• Floodplain swamps • Swamps of coastal dunes and beach ridge plains • Swamps in terminal drainage depressions • Swamps associated with lava flows • Crater swamps • High mountain swamps • Swamps fed by springs
	Seasonal	• Floodplain swamps
	Intermittent	• Floodplain swamps • Swamps in terminal drainage depressions
	Episodic	
Land subject to inundation	Seasonal	• Floodplains • River and creek banks
	Intermittent	• Floodplains • River and creek banks

Table 1 continued

Categories	Classes	Sub-classes
River and creek channels	Permanent and near-permanent	• Rocky • Sandy • Silty/clayey
	Seasonal	• Rocky • Sandy • Silty/clayey
	Intermittent	• Rocky • Sandy • Silty/clayey
	Episodic	• Rocky • Sandy • Silty/clayey
Tidal flats	Daily inundation	• Intertidal flats of open coasts • Intertidal estuarine flats • Intertidal stream banks
	Spring tidal and less frequent inundation	• Supratidal surfaces • Supratidal stream banks • Saline pools
	Spring tidal and less frequent flooding and seasonal freshwater flooding	• Supratidal flats • Brackish pools and billabongs
Coastal water bodies	Permanently open to the sea Intermittently open to the sea Rarely open to the sea	

Table 2 Hierarchy of wetlands and deepwater habitats in the wetland classification used in the USA (Cowardin et al 1979, Wilen & Bates 1995), showing systems, subsystems and classes

System	**Sub-system**	**Class**
Marine	Subtidal	• Rock bottom • Unconsolidated bottom • Aquatic bed • Reef
	Intertidal	• Aquatic bed • Reef • Rocky shore • Unconsolidated shore
Estuarine	Subtidal	• Rock bottom • Unconsolidated bottom • Aquatic bed • Reef
	Intertidal	• Aquatic bed • Reef • Stream bed • Rocky shore • Unconsolidated shore • Emergent wetland • Scrub-shrub wetland • Forested wetland
Riverine	Tidal	• Rock bottom • Unconsolidated bottom • Aquatic bed • Stream bed • Rocky shore • Unconsolidated shore • Emergent wetland
	Lower perennial	• Rock bottom • Unconsolidated bottom • Aquatic bed • Rocky shore • Unconsolidated shore • Emergent wetland
	Upper perennial	• Rock bottom • Unconsolidated bottom • Aquatic bed • Rocky shore • Unconsolidated shore
	Intermittent	• Streambed

Table 2 continued

System	Sub-system	Class
Lacustrine	Limnetic	• Rock bottom • Unconsolidated bottom • Aquatic bed
	Littoral	• Rock bottom • Unconsolidated bottom • Aquatic bed • Rocky shore • Unconsolidated shore • Emergent wetland
Palustrine		• Rock bottom • Unconsolidated bottom • Aquatic bed • Unconsolidated shore • Moss-lichen wetland • Emergent wetland • Scrub-shrub wetland • Forested wetland

Table 3 Wetland classification used by the Ramsar Wetland Convention (Scott & Jones 1995)

Marine and Coastal	Marine	Subtidal		Shallow marine waters Marine beds Coral reefs
			Aquatic bed	
			Reef	
		Intertidal	Rocky	Rocky marine shores
			Unconsolidated bed	Sand/shingle beaches
	Estuarine	Subtidal		Estuarine waters
		Intertidal	Unconsolidated bed	Intertidal mudflats
			Emergent	Salt marshes
			Forested	Mangrove, tidal forest
	Lacustrine/Palustrine	Permanent/seasonal		Brackish/saline lagoons
				Coastal fresh lagoons
Inland	Riverine	Perennial		Permanent rivers/streams
			Emergent	Inland deltas Intermittent rivers/streams
		Intermittent	Emergent	Floodplain wetlands
	Lacustrine	Permanent		Permanent freshwater ponds
		Seasonal		Seasonal freshwater lakes
		Permanent/seasonal		Permanent/seasonal saline lakes and marshes

Table 3 continued

Inland (cont)	Palustrine	Permanent	Emergent	Permanent freshwater ponds and marshes Open peat bogs and fens Alpine/tundra wetlands
			Shrub dominated	Shrub-dominated swamps
			Forested	Freshwater swamp forest Peat swamp forest
		Seasonal	Emergent	Freshwater springs/oases Seasonal freshwater marsh
	Geothermal			Geothermal wetlands
Human-made	Aquaculture			Fish/shrimp ponds
	Agriculture			Farm ponds, small tanks Irrigated land, rice fields Seasonal-flooded arable land
	Salt exploitation			Salt pans, salines
	Urban and industrial			Reservoirs, barrages Gravel pits Sewage farms

Table 4 Wetland classification used in the *Directory of important wetlands in Australia* (ANCA 1996)

Marine and coastal wetlands	Inland wetlands	Peatlands
Marine waters	Permanent rivers and streams	Alpine and tundra wetlands
Subtidal aquatic beds	Seasonal and irregular rivers and streams	Freshwater springs, oasis and rock pools
Coral reefs	Inland permanent deltas	Geothermal wetlands
Rocky marine shores	Riverine floodplains	Inland subterranean karst wetlands
Sand, shingle or pebble beaches	Permanent freshwater lakes	Human-made wetlands
Estuarine waters	Seasonal/intermittent freshwater lakes	Water storage areas
Intertidal mud, sand or saltflats	Permanent saline/brackish lakes	Farm/stock ponds, and small tanks
Intertidal marshes	Seasonal/intermittent saline lakes	Aquaculture ponds
Intertidal forested wetlands	Permanent freshwater ponds, marshes and swamps on inorganic soils	Salt pans
Brackish-saline lagoons	Seasonal/intermittent freshwater ponds and marshes on inorganic soils	Excavation pits
Freshwater lagoons	Permanent saline/brackish marshes	Wastewater treatment ponds
Non-tidal freshwater forested lagoons	Seasonal saline marshes	Irrigated land and channels
	Shrub swamps	Seasonally flooded arable land
	Freshwater swamp forest	Canals

Table 5 Classification of wetlands using geomorphic and hydroperiod characteristics (Semeniuk & Semeniuk 1997)

	Landform				
Hydroperiod	**Basin**	**Channel**	**Flat**	**Slope**	**Highland**
Permanent Inundation	Lake	River	–	–	–
Seasonal Inundation	Sumpland	Creek	Floodplain	–	–
Intermittent Inundation	Playa	Wadi	Barlkarra	–	–
Seasonal Waterlogging	Dampland	Trough	Palusplain	Paluslope	Palusmont

Table 6 Information categories used in the *Directory of important wetlands in Australia* (ANCA 1996)

Information category	**Comments**
Name of wetland	Commonly used name of the site
Reference number	Each wetland has been allocated an individual number in alphabetical order and cross referenced to the biogeographical region and the state/territory where it occurs.
Location	Latitude and longitude at the centre of the site.
Area	Hectares
Elevation	Metre above sea level (m asl)
Other wetlands in same aggregation	Listed by reference number
Wetland type	Coded against the classification system
Criteria for inclusion	Coded against the criteria used to justify inclusion as a site of national importance.
Site description	Description of the important characteristics of the site under subheadings – physical, hydrological, and ecological features.
Significance	Significance of the site within the bioregion under the subheadings – notable flora, fauna, and social and cultural values.
Land tenure	Ownership of the site and surrounding land.
Current land use	Human uses of the site and surrounding land.
Disturbances or threats	Current and/or potential direct or indirect human activities at the site or in the catchment that may have a detrimental effect on the ecological character of the wetland.
Conservation measures taken	Details of management plans and conservation listings.
Management authority and jurisdiction	Management agency
Compiler and date	Name of individuals and organisation that supplied the information.

Table 7 Wetlands in the biogeographical regions used by Finlayson et al (1997) as the basis of a review of wetlands of the Wet-Dry tropics. The information is derived from the *Directory of important wetlands in Australia* (ANCA 1996).

Biogeographical Region		**Wetland name**	**Area (ha)**
Name	**Code**		
Burt Plain	BRT	NA	NA
Central Arnhem	CA	NA	NA
Central Kimberley	CK	Tunnel Creek	NA
		Windjana Gorge	20
Cape York Peninsula	CYP	Archer Bay Aggregation	29 911
		Archer River Aggregation	149 761
		Bull Lake	26
		Cape Flattery Dune Lakes	44 034
		Cape Grenville Area	7 304
		Cape Melville – Bathurst Bay	5 480
		Harmer River – Shelburne Bay Aggregation	31 751
		Jardine River Wetland Aggregation	81 740
		Lloyd Bay	15 682
		Marina Plains – Lakefield Aggregation	392 333
		Newcastle Bay – Escape River Estuarine Complex	42 307
		Northeast Karumba Plain Aggregation	182 418
		Northern Holroyd Plain Aggregation	1 114 324
		Olive River	17 609
		Orford Bay – Sharp Point Dunefield	17 239
		Port Musgrave Aggregation	52 685
		Princess Charlotte Bay Marine Aggregation	87 835
		Silver Plains – Nesbitt River Aggregation	44 834
		Skardon River – Cotterell River Aggregation	63 194
		Somerset Dunefield Aggregation	8 095
		Temple Bay	4 424
		The Jack Lakes Aggregation	35 054
		Violet Vale	1 896
Daly Basin	DAB	Daly River Middle Reaches	NA
Dampierland	DL	Bunda Bunda Mound spring	22
		Camballin Floodplain (Le Lievre Swamp System)	30 000
		Eighty Mile Beach	40 000
		Geikie Gorge	130
		Roebuck Bay	50 000
		Roebuck Plains System	48 340
		Willie Creek Wetlands	20
Gulf Fall and Upland	GFU	Lawn Hill Gorge	1 133
		Mataranka Thermal Pools	<100

(NA – no information available)

Table 7 continued

Biogeographical Region		Wetland name	Area (ha)
Great Sandy Desert	GSD	Dragon Tree Soak	5
		Lake Dora (Rudall River) System	32 000
		Mandora Salt Marsh	80 000
		Rock Pools of the Breaden Hills	NA
		Karinga Creek Palaeodrainage System	30 000
		Lake Amadeus	103 700
Gulf Coastal	GUC	Borroloola Bluebush Swamps	80
		Limmen Bight (Port Roper) Tidal Wetlands	184 400
		Port McArthur Tidal Wetlands Systems	119 000
Gulf Plains	GUP	Bluebush Swamp	879
		Buffalo Lake Aggregation	1 909
		Dorunda Lakes Area	6 801
		Forsyth Island Wetlands	6 388
		Lignum Swamp	282
		Macaroni Swamp	258
		Marless Lagoon Aggregation	167 009
		Mitchell River Fan Aggregation	714 886
		Musselbrook Creek Aggregation	45 157
		Nicholson Delta Aggregation	63 640
		Smithburne – Gilbert Fan Aggregation	250 320
		Southeast Karumba Plain Aggregation	336 233
		Southern Gulf Aggregation	545 353
		Stranded Fish Lake	67
		Wentworth Aggregation	82 430
MacDonnell Ranges	MAC	NA	NA
Northern Kimberley	NK	Drysdale River	5 100
		Mitchell River System	NA
		Prince Regent River System	NA
Ord-Victoria Plains	OVP	Birrindudu Waterhole and Floodplain	19 000
		Nongra Lake	6 000
Pine Creek Arnhem	PCA	Katherine River Gorge	NA
Sturt Plain	STU	NA	NA
Tanami	TAN	Lake Gregory System	38 700
		Lake Surprise (Yinapaka)	800

(NA – no information available)

Table 7 continued

Biogeographical Region		Wetland name	Area (ha)
Top End Coastal	TEC	Adelaide River Floodplain System	134 800
		Kakadu National Park	234 450
		Arafura Swamp	71 400
		Blyth-Cadell Floodplain and Boucat Bay System	35 500
		Cobourg Peninsula System	84 000
		Daly-Reynolds Floodplain-Estuary System	159 300
		Finniss Floodplain and Fog Bay System	81 300
		Mary Floodplain System	127 600
		Moyle Floodplain and Hyland Bay System	48 100
		Murganella-Cooper Floodplain System	81 500
		Port Darwin	48 800
Victoria Bonaparte	VB	Lake Argyle	74 000
		Lake Kununurra	2 500
		Ord Estuary System	94 700
		Parry Floodplain	9 000
		Legune Wetlands	5 000

(NA – no information available)

The role of GIS and remote sensing technology

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Abstract

The role of this paper is to present a broad overview of the current capabilities of natural resource inventory, spatial analysis and modelling using geographic information systems (GIS) and remote sensing (RS) technologies with particular reference to wetland environments in northern Australia. The underlying theme is that advances in technology continue to facilitate the study of large, relatively unpopulated and inaccessible areas like wetlands and savannas in northern Australia and these provide valuable information for tropical environmental management information and decision support systems.

1 Introduction

Wetlands in northern Australia are extensive, play a major role in the environment, and are in many cases relatively unspoilt by human impact. Their importance as a natural resource is highlighted in the papers that accompany this one. In order to maintain and enhance wetlands as a natural resource, environmental managers need information on which to base their decisions. Some of this information is political, legal, and socio-economic but in many respects the most significant component is environmental. Managers need to know the current status of natural resources, to monitor changes in these resources over time, and to predict and evaluate the impact of proposed courses of action.

1.1 GIS provides a framework

Geographic information systems provide the necessary framework to input, manipulate, analyse, and retrieve spatial data and related attributes of spatial features. They can store data collected from a variety of sources and bring it together in a way that enhances the information that can be gleaned from it. The enhancement may simply take the form of a map of a particular area with specified information included in it, or may involve spatial analysis and modelling. Data stored may be relatively static, such as soils maps, or dynamic, such as fire scars. An important source of dynamic data is remotely sensed data from spaceborne or airborne platforms as it can provide a synoptic view of large areas.

1.2 Wetland inventory, monitoring and modelling

Effective management of wetlands in northern Australia therefore requires information from a GIS which in turn provides a framework for data from many sources including remotely sensed data. In the first instance, the application of these technologies is required to provide baseline information for wetland inventory. When this baseline information has been collated it is possible to begin monitoring change and model alternative management scenarios. This paper provides an introduction to GIS and remote sensing technology and their integration for wetland.

2 Geographic Information Systems

There are as many definitions of geographic information systems as there are authors and an exhaustive definition will not be attempted here. The important characteristics of a GIS in the context of wetland inventory are that it provides a framework for the collation and analysis of spatial data from disparate sources as well as information for input to management decision support systems. The requirements for a GIS with a particular emphasis on data are briefly discussed hereafter as well as the outcomes necessary for a successful GIS implementation.

2.1 GIS components

The essential components of a GIS are easily identified – hardware, software, data and people. Hardware includes computing power, data storage and backup facilities, and output in the form of monitors or hard copy plots or reports. Software provides a means for the user to easily use the hardware to manipulate, analyse and visualise the underlying data. Data, not to be confused with information, an obvious prerequisite to any wetland GIS application, is discussed further below. People, perhaps the most important component, need knowledge, understanding and skill in both wetland environmental management and GIS to enable useful outcomes from the system. It is the responsibility of the manager to assemble these components in a way that produces useful information for decision making.

In general, the cost, availability, and complexity or depth of knowledge of each of these components is inter-related and dependent on the scope and complexity of the task at hand. This relationship can be visualised using a graph with four axes, each representing a component (fig 1). An arrow on each axis indicates increasing cost and complexity. For example, low-end hardware and software might be a PC with Windows 95 and desktop mapping software, whereas a high-end system might be a Unix workstation or supercomputer with specialised GIS software. Low-end data requirements might be readily available vector or raster data whereas high-end requirements could be a comprehensive digital elevation model for an area. People skills can range from a PC end user with limited or no training in GIS/RS to experienced and highly qualified professionals.

The bottom line of this section is to emphasise that to achieve a successful GIS implementation where cost and benefits are balanced, management generally need to keep operational activities at the low end of these scales. High-end activities should be entered into sparingly, perhaps through out-sourcing or consultancies, to achieve specific one-off tasks or develop protocols for operational activities that once determined can be migrated to a less complex and more cost-effective environment.

2.2 GIS data

GIS data can come in digital or analogue forms. Analogue data can be an important source of information since most information collected in the past was recorded and mapped using analogue techniques. Currently, with the notable exception of aerial photography, most information is recorded in a digital format. Historical information is important when attempting to establish baseline data or determine whether change has taken place and it should not therefore be overlooked. It does need to be converted to a digital form before it can be integrated into a GIS and this can be an expensive exercise.

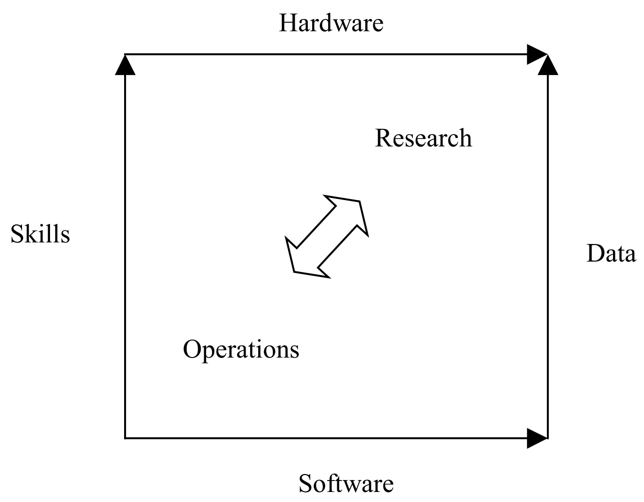

Figure 1 The relationship between the components of a GIS and operational/research activities

Geographic information has location, time and attributes. Location is generally expressed in a coordinate system often 2-dimensional but sometimes 3-dimensional (for example, digital elevation data). Time is not a dimension that is well handled at present by conventional GIS and is usually the date of data collection. Attributes include any information relating to the spatial features in the GIS (including dimension, images, text, video, sound etc). It is important to bear in mind that data is only a representative sample of the real world that is being modelled in the GIS.

Data is generally recorded and stored in one of three formats:

- Vector data are represented by coordinate pairs that on their own are point features (for example, bores or sample sites). A series of coordinate pairs is a line feature (for example a road or river), and a series of coordinate pairs that start and finish at the same point is a polygon or area feature (for example, vegetation types or land use). This method of recording and manipulating spatial information works well for some data and is efficient in terms of storage space.
- Raster data are stored in a grid cell or pixel format the size of which can vary. This variation in cell size is called the spatial resolution and may be dictated by the resolution of the data available or the task for which the data is required. Digital remotely sensed data is stored in this manner (discussed separately below) and it is often used where continuous surfaces are of interest (eg digital elevation models).
- Attribute data are conventionally stored in a relational database management system (RDBMS). Each spatial object in the raster or vector spatial database has a unique identifier that is used to provide a key to the related aspatial or attribute data associated with those features. The key can be used either way – spatial features can be selected by attribute selection in the RDBMS or attributes can be listed for spatial features identified through a spatial selection.

An important aspect of all spatial data is that they must be registered to a common coordinate system if it is to be useful. Commonly, a map projection such as AMG (Australian Map Grid) or geographic latitude and longitude is used to register all data. This is a necessary prerequisite to any comparison or overlay analysis. Although space precludes their discussion it should be noted that spatial resolution and scale are important issues to consider when collating and analysing data in a GIS.

2.3 GIS outcomes

It is particularly important from a management perspective to have a clear picture of what might be expected to come out of a GIS implementation. In the first instance, a GIS can provide the efficient storage and retrieval of data with spatial characteristics that might otherwise be difficult to manipulate. The retrieval can take the form of maps and reports that contain selected themes for areas of interest and characteristics of the spatial features can be found. These may be spatial characteristics (area, length, perimeter etc) or aspatial attributes (description, address, owner etc). There are many advantages over traditionally prepared maps including the ability to generate updated maps quickly and easily when new information comes to hand.

These factors alone are enough for many people and organisations to implement GIS but once the system is in place and baseline data has been collated users begin to look for answers to more complex questions which require some analysis of the data. Typically these will include questions relating to suitability of specific areas for a defined use, risk analysis, and the monitoring of change over time. As the database matures in terms of quantity and quality of data it becomes possible to use the GIS to assist in simulations, and the evaluation of alternative courses of action. Modelling may be done within the GIS or involve the integration of external models (for example, hydrological models).

A GIS is a tool for the use of management and the outcomes need to be integrated with other sources of information. GIS can provide useful ways for managers to visualise impacts of various courses of action and demonstrate these to others (perhaps their managers or funding bodies). A map can be worth a thousand words!

3 Remote sensing technology

The extent and remoteness of many of the wetlands in northern Australia combined with their inherent inaccessibility make remotely sensed imagery the only viable option for collecting synoptic data on a regular basis. After processing, these data then become input to the GIS and contribute to the flow of information available to environmental managers.

Remotely sensed data are a surrogate for the actual features of interest on the ground and are collected in a manner that suits integration in GIS. Satellite data contain attribute information (a spectral response) about a particular location on the ground at a particular time.

Remotely sensed data offer significant advantages in that they presents a synoptic view of the earth at periodic intervals, are (with some limitations outlined below) readily available and accessible, and they provide a relatively economical means to build a spatial database. They also offer the possibility of visiting and revisiting the past through the use of archived data. Aerial photographs provide the longest lived historical record of most areas but even satellite imagery can be obtained for the last twenty years.

Like most new technologies, remote sensing brings challenges as well as advantages. The large number of variables that play a role in the data collection can make it hard to interpret and use in a consistent manner. For example, features of interest such as vegetation will appear markedly different between seasons. These changes (for example, greening and browning) can come about over very short time periods. They can also consume large amounts of storage space and processing capacity.

3.1 Remotely sensed data

Remotely sensed imagery is generally collected through measurement of the electromagnetic spectrum. The signals may be passively generated through the reflection of light energy from objects on the surface of the earth such as aerial photographs or optical satellite imagery. Alternatively, signals may be actively generated from airborne or spaceborne platforms using radar or laser technology. The data collected are stored in raster format as an image made up of one or more bands (the wavelengths measured) each of which has pixels (grid cells) with a measured value (usually between 0–255) which is the attribute of the pixel. This information is then processed and interpreted to identify objects and/or areas of interest using digital image processing techniques.

3.2 Digital image processing

Digital satellite imagery contains huge amounts of data that generally need to be reduced in order to be useful as input to a GIS and consequently provide information for environmental managers. For example, a Landsat Thematic Mapper (TM) image has 7 bands of information at a spatial resolution of 30 metres (for 6 bands and 120 metres for the seventh). Techniques for data reduction are well established and a number of computer software applications are available to assist in this process. A brief description of the standard method follows.

Each pixel represents a location on the ground at a particular time and an attribute that is a measurement of the average reflectance of the spatial objects on the ground in that cell. Since the energy reflected, absorbed and transmitted by different objects varies it is possible to differentiate between objects and identify those of interest. After pre-processing (eg eliminating atmospheric effects), enhancement techniques can be used to highlight areas or features of interest. Once identified, the spectral characteristics can be described as a spectral signature. This signature can then be used to identify other similar features in the image using classification functions available in image processing software.

Following classification, post-processing techniques are required to make the data suitable for integrating into a GIS. The most important of these are smoothing the classified image to create a thematic map and registering the image to known coordinates on the ground. Ground truthing of the results of this data reduction process is absolutely essential. This involves going out into the field to sites identified on the image (usually located using a GPS receiver) and ensuring that the classification is accurate. Without an evaluation of this nature the quality of the data cannot be relied upon by managers. There are other techniques for verification of results within a GIS which can augment or reduce the need for field work which may be particularly difficult and/or expensive in wetlands during the Wet season.

4 Integration of GIS/RS/MIS

Management requires information to make decisions. This information is normally the synthesis of information integrated into a management information system from a number of sources, a significant one of which is the GIS. The GIS, in turn, also integrates data from a number of disparate sources including remotely sensed data. The GIS also provides information to aid the data reduction process for remotely sensed data. For example, a digital elevation model may be used to reduce the area to be classified for mangrove vegetation by masking out areas above a certain elevation in the image. This reduces the chance of an overlap in spectral signatures of different vegetation types.

The integration path for the application of these techniques to wetland environmental management should now be clear. Remote sensing data provide synoptic and dynamic data at varying spatial and temporal resolutions which after digital image processing are used as input to a GIS where analysis and modelling can be performed. The output of the GIS is then fed up the line directly to management or into a management information or decision support system.

5 Conclusion

A summary of how these technologies have been and can be used in wetland management follows.

Wetland information that may be derived from remotely sensed imagery includes:

- extent of wetlands
- type of wetland
- characterise wetland land cover type
- identify submergent/emergent wetlands
- provide information about quality

When this information is added to a GIS and integrated with data from other sources the following applications are possible:

- inventory (eg what is the extent of wetlands in northern Australia?)
- analysis (eg what changes have occurred in that extent over the past X years?)
- modelling (eg predicting flood levels given certain parameters)

The authors have prepared a comprehensive bibliography of GIS, remote sensing and wetlands which is published as a companion to this paper. The reader is urged to turn to this for detailed discussion and examples of wetland applications. There is also a wealth of material on the Internet, particularly relating to the North American continent, much of which is germane to the application of these technologies in northern Australia.

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