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Grazing pressure by the tammar (*Macropus eugenii* Desm.) on the vegetation of Garden Island, Western Australia, and the potential impact on food reserves of a controlled burning regime

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Abstract

Tammar (*Macropus eugenii* Desm.) populations occur in a restricted number of Western Australia mainland locations and two offshore islands. From faecal pellet epidermal remnants and analysis of stomach contents, eleven plant species were documented as dietary species of the tammar population of Garden Island. Of special preference were the dominant shrub *Acacia rostellifera*, introduced herbaceous species *Asphodelus fistulosus* and *Asparagus asparagoides*, and the native grass *Stipa flavescens*. Grazing damage to these species was generally restricted to localized sites thus assuring their continued survival on the island. Exclosure studies demonstrated a marked impact of grazing on *Asparagus asparagoides*, *Geranium molle* and *Stipa flavescens*. Two small ground herbs, *Parietaria debilis* and *Galium murale* showed increases in cover in areas where larger species were removed by grazing. The tammar was generally attracted to areas of new growth regenerating after disturbance. This suggests that a planned fire management programme incorporating a system of fire breaks, fire protection access routes and low fuel buffers should meet the perceived objectives of protecting the naval installations, maintenance of the food resource and hence, continued survival of the tammar populations on the island. The remaining areas of long-unburnt vegetation should be retained to provide cover for the tammars and to conserve the native vegetation of the island, especially fire sensitive species.

Introduction

The tammar (*Macropus eugenii* Desm.) is a herbivore from the family Macropodidae. Its present range in Western Australia is restricted and includes only Garden Island, West Wallabi Island, and a few isolated pockets on the mainland in the south-west. In the early 1970s the number of tammars on Garden Island was estimated at 2 000 (Bakker 1973) where as current sampling suggests the population is around 1700 (A. Bradley, pers. comm.). This small wallaby is also found in South Australia and more particularly on Kangaroo Island (Kelsall 1965). Its distribution patterns in south-west Australia have been associated with a range of site factors, but of special importance are dense thickets of vegetation which provide protection from predators and associated grass species thought to be a preferred food resource (Christensen 1981).

Other studies on the tammar have concentrated on physiological factors (Kelsall 1965, Kinnear *et al.* 1968, Bakker *et al.* 1982). Any reference to the dietary habits of the tammar in these studies was based on observation of grazing damage and extrapolations from other marsupial studies. Christensen (1981) studied the biology of the tammar in relation to fire and listed several major characteristics which might contribute to the adaptation of the tammar to a fire-prone habitat. These include: (1) seasonal breeding, (2) lack of repression of juveniles, (3) group territoriality, (4) wide dispersal, (5) absence of panic during fire, and (6) some fidelity to home range. It is, however, the direct effects of fire on the plant communities of Garden Island which will ultimately affect this population since fire protection is an important requirement of the recently established naval facilities on this island.

Currently the W.A. Bushfires Board, W.A. Department of Conservation and Land Management, the Department of Defence (Navy) and the University of Western Australia Departments of Zoology and Botany are cooperating in a research effort to understand the ecology of the tammar and to develop an appropriate fire management plan that will both protect life and property and ensure the short- and long-term health and survival of this endangered species. The objective of this study was to determine the plant species important in the tammar diet and to make preliminary comments on the potential impact that a fire management plan might have on the population.

Metbods

Garden Island (115°40'E, 32°16'S) is a near-shore island centred approximately 35 km southwest of Perth and southward of Rottnest and Carnac Islands. It measures 9.5 km from north to south and 2 km at its widest point. The islands are estimated to have been separated from the Western Australian mainland for 6 000-7 000 (Main 1961). The major plant formations are dense stands of shrub scrub dominated by *Acacia rostellifera* and low forests dominated by *Callitris preissii* and *Melaleuca lanceolata*. For a more detailed discussion of the major landforms and the vegetation associations of the island, refer to McArthur and Bartle (1981).

Exclosure studies

Four tammar grazing exclosures measuring 10 x 25 m with 1.5 m high fences of 2 cm wire mesh were established in a range of plant communities and regions of Garden Island in May 1983 (Fig. 1). Selection of the exclosure sites was based on evidence of local grazing by tammars, time since the last fire, and proximity to the Zoology Department's population sampling sites. The Beacon Head Site, on the most northern portion of the island, was situated in an area classified as *Acacia rostellifera* Open Scrub; the Cliff Point Site near the central western coastline in an area of *Melaleuca lanceolata* Open Heath; the Denham Road Site in the centre of the southern half of the island in *Melaleuca lanceolata—Acacia rostellifera* Low Open Forest, and the Quarry Road Site near the southeastern tip of the island in *Melaleuca lanceolata* Open Scrub. The Beacon Head Site was burnt in December 1982. The Cliff Point and Denham Road Sites probably last burned in the disasterous fire of January 1956 which burned most of the island north of Careening Bay (Baird 1958). The Quarry Road Site lies in a region which has probably remained fire-free for more than 40 years.

Percentage cover values for all vascular species were visually estimated from permanently marked transects of ten 1 m^2 quadrats. One transect was situated inside and one immediately adjacent but outside the exclosure at each site. Cover values for selected species were estimated in August 1983 and a full survey of all species was made in September 1985. From these estimates mean percentage cover values for species in each transect were determined.

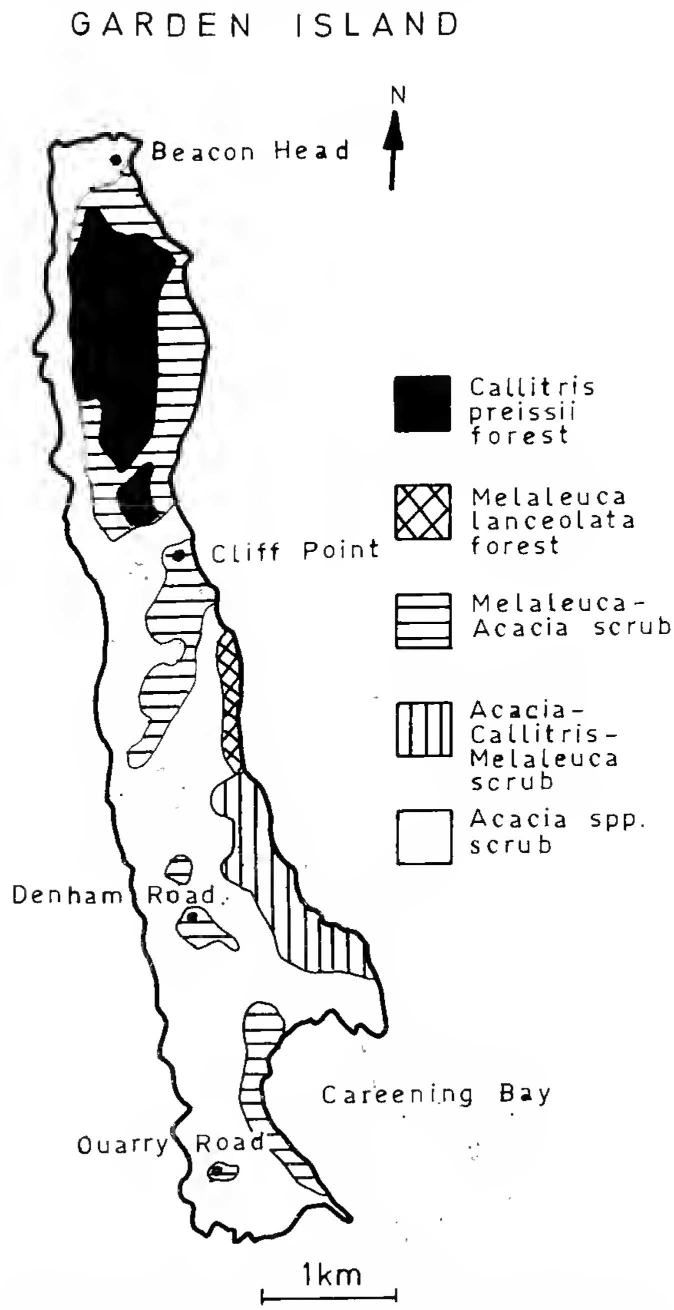

Figure 1.—Map of Garden Island showing locations of grazing exclosures (●) and major vegetation types (modified from McArthur and Bartle 1981).

Tammar diet studies

The dietary preferences of the tammar were determined by analysing the epidermal remnants from faecal pellets and from the stomach contents of two road-killed animals. A total of 40 faecal pellets were collected; 5 from outside each of the tammar grazing exclosure areas and 20 from a range of habitats generally distant from the Naval installations. The emphasis on native areas was made to reduce likely grazing by tammars of the irrigated lawns and domestic gardens within the settlement area which is known to occur (McArthur and Bartle 1981). One series of samples was obtained prior to the onset of winter rains (April, 1983) and a second in late winter (August, 1983). The road-killed animals were obtained during April 1983 from an area just north of the North Gate of the Naval installation. The stomach contents were removed immediately upon collection and frozen for later analysis.

The identification of epidermi in the faecal pellet and stomach content materials followed the methods of Halford *et al.* (1984a) which were modified from the original techniques reported by Storr (1961) and Jain (1976). Comparisons of faecal pellet epidermal remnants to epidermal samples prepared from plant tissue provided information on tammar diet preferences. Frequencies of the proportions of the epidermal fragments from microscopic analysis provided an estimate of dietary preference (Halford *et al.* 1984b).

Direct grazing observation and re-establishment response

Plants throughout the island were checked for direct signs of grazing and, where tammars could be observed grazing or browsing particular shrubs, these species were recorded. Plant species were also categorized for re-establishment strategy. Disturbance to a plant community can result from fire damage, animal grazing or the mechanical removal of vegetation such as occurs in firebreaks or alongside roads. Post-fire modes of re-establishment have been widely documented (Specht *et al.* 1958, Keeley and Zedler 1978, Keeley and Keeley 1981, Malanson and O'Leary 1982, Bell *et al.* 1984). In contrast there is a paucity of information concerning re-establishment strategies following grazing damage and mechanical disturbance. In relation to fire, species can be described as ephemerals, obligate seeders and sprouters (Bell *et al.* 1984), although re-establishment strategies may vary within a particular species as well as between species. Mode of re-establishment may also vary depending upon the intensity of the fire or the degree of damage sustained from non-pyric disturbances. In the main, fire prone environments are high in the proportion of resprouting species (Siddiqi *et al.* 1976, Bell *et al.* 1984). Similarly, areas subjected to repeated mechanical disturbance might favour resprouters, although obligate seeders with a bradysporous habit may also survive clearing operations (Griffin and Hopkins 1981). Similar information is not available for grazed plants, but it might be assumed that resprouting species would, in the long term, have a greater chance of survival than obligate seeding species. The collection of re-establishment data allowed the prediction of changes which might occur following an imposed controlled-burning regime.

Results

Exclosure studies

Twenty-nine species of vascular plants were identified in and adjacent to the four tammar exclosure study sites (Table 1). Only *Acanthocarpus preissii* and *Phyllanthus calycinus* occurred in every transect and only eight species occurred in more than half of the study transects. Of these common species, those showing major differences between the inside and the outside of the exclosures were *Acanthocarpus preissii, Asparagus asparagoides, Geranium molle* and *Stipa flavescens*, which were much more common inside, and *Galium murale, Parietaria debilis* and *Phyllanthus calycinus*, which showed consistently higher cover values outside the grazing exclosures. The most obvious effect of the grazing exclosure occurred at the recently burned Beacon Head site where *Asparagus asparagoides* averaged 78.9% under protection and only 1.8% where exposed to grazing.

Comparisons of mean cover values of the common species after about four months grazing protection (1983) and after more than two years protection (1985) showed an increase in the difference between protected and unprotected samples for those species with greater cover inside the exposures (Fig. 2).

Faecal and stomach content studies

Eleven different species of vascular plants were identified in the tammar faecal pellet material and stomach contents (Fig. 3). The most common were *Asphodelus fistulosus, Acacia rostellifera* and *Asparagus asparagoides*. The August faecal pellet samples included a greater variety of species (11 species) compared to either the April faecal pellet sample (5 species) or the April stomach contents sample (8 species).

Re-establishment following grazing or fire

Direct observations of tammar grazing proved difficult although seven plant species were confirmed as dietary species. These seven species, however, had already been identified from faecal pellets or stomach content analyses. Of significance was that the tammars seemed to prefer young shoots of the resprouting species or seedlings.

Of the forty-seven species identified from the 1983 and 1985 samplings, only ten are known to re-establish from existing rootstocks following intense fires with the remainder either ephemerals (16 species) or obligate seeders (20 species) (Table 2). Of this total sample, 26% (12 species) were introduced, and, of the eleven dietary species, 27% (3 species) were introduced.

Table 1.

Mean percentage cover values for transects inside and outside the Garden Island Tammar exclosure study sites for data measured September 1985.

Species	Beacon Head		Cliff Point		Denham Road		Quarry Road	
	In	Out	In	Out	In	Out	In	Out
Acacia rostellifera	—	3.1	0.1	0.3	2.0	43.7	—	—
Acanthocarpus preissii	5.8	1.9	12.5	7.4	24.0	13.7	86.0	62.4
Anagallis spp.*	5.2	1.4	—	1.7	1.1	—	—	0.1
Asparagus asparagoides	78.9	1.8	12.7	0.2	—	0.2	—	—
Asphodelus fistulosus	—	1.4	1.3	10.1	—	0.8	—	—
Carduus pycnocephalus	—	1.1	—	—	—	—	—	—
Clematis microphylla	—	—	2.7	—	—	—	36.1	0.1
Crassula colorata	—	—	7.3	0.4	—	—	—	—
Daucus glochidiatus	—	0.1	—	—	—	—	—	0.1
Eremophila glabra	0.7	22.4	—	—	—	—	—	0.4
Galium murale	4.6	48.8	6.8	28.2	—	0.2	—	—
Geranium molle	—	0.4	23.7	0.1	16.1	—	1.0	0.8
Guichenotia ledifolia	—	—	1.9	—	—	—	—	—
Hardenbergia comptoniana	—	—	—	—	—	—	6.9	—
Leucopogon insularis	—	—	9.5	—	—	—	8.1	—
Leucopogon parviflorus	—	—	—	—	—	—	0.1	2.1
Oxalis pes-caprae	—	—	—	—	—	—	0.1	—
Poranthera microphylla	—	0.1	—	—	—	—	—	0.1
Parietaria debilis	—	0.1	—	—	6.2	56.1	3.4	4.2
Phyllanthus calycinus	0.5	6.5	0.9	8.8	0.4	1.1	0.2	7.8
Rhagodia baccata	—	—	—	—	—	—	0.4	—
Senecio lautus	—	—	—	—	0.3	—	0.4	—
Solanum symonii	—	0.7	—	—	—	—	—	—
Sonchus oleraceus	3.6	0.2	0.5	—	—	—	0.3	—
Spyridium globulosum	—	—	—	—	0.1	—	0.5	—
Stipa flavescens	—	—	10.2	0.1	5.8	0.1	—	1.0
Thomasia cognata	—	—	0.2	—	—	—	—	—
Trachyandra divaricata	—	—	—	0.5	—	—	—	1.3
Zantedeschia aethiopica	—	—	—	—	2.6	0.2	3.2	0.6

*Includes both *Anagallis arvensis* and *A. foemina*

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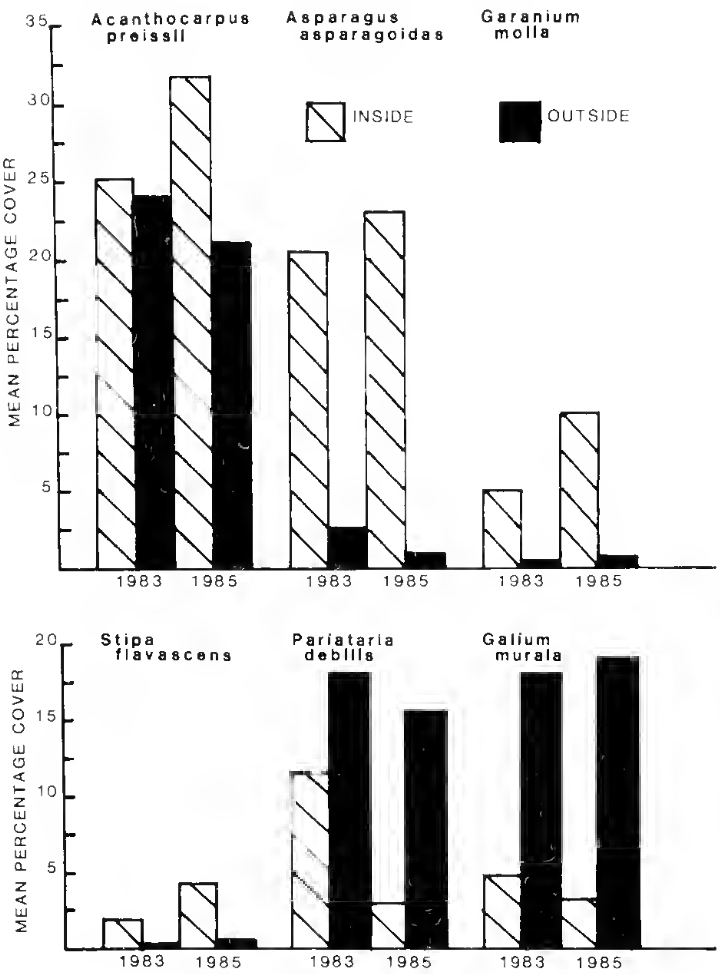

Figure 2.—Mean percentage cover values from the four exclosure sites for selected species sampled inside and outside the exclosure during August 1983 and September 1985.

Discussion

The tammar wallabies on Garden Island appear to be versatile feeders. Preferred plants generally included young shoots from resprouting species (*Stipa flavescens, Asparagus asparagoides*), seedlings (*Solanum symonii, Thomasia cognata*) or short-lived ephemeral species (*Asphodelus fistulosus*). Results obtained from the examination of faecal and stomach material indicated that the introduced ephemeral, *Asphodelus fistulosus*, dominated the diet of the tammar. This species is now particularly widespread over the island, although differences in cover values were not particularly apparent in the exclosure studies due to a tendency of this species to be concentrated in disturbed areas such as along road verges and in fire breaks. At the Cliff Head site in the grazed area surrounding the exclosure, many individuals appeared to have invaded the area following an initial period of grazing. Grazing observations suggested that the tammar preferred areas where recent mowing or ploughing stimulated the production of new shoots or seedlings.

The presence of *Acacia rostellifera* in both faecal and stomach material indicated a strong preference for this species. Other authors have reported various species of *Acacia* in the diet of the tammar and other Macropods (Storr 1961, Kelsall 1965, Christensen 1981, Halford *et al.* 1984b). Probably because of the high density and widespread distribution of *Acacia rostellifera* on Garden Island, direct grazing evidence was not apparent. Kelsall (1965) noted that the tammar preferentially grazed this species in the dry season. In this study no seasonal preference for *Acacia rostellifera* occurred between the late Autumn first sampling period and the late Winter second sampling when water would be readily available. During summer the thick central parenchymatous tissue of the phyllods of this species could be an important source of moisture. Preference for legume species could also relate to greater foliar nitrogen levels (Halford *et al.* 1984b).

Previous research established that grasses were a dietary preference in mainland populations of the tammar (Christensen 1981). *Stipa flavescens* has a relatively wide but discontinuous distribution over Garden Island occurring in higher densities in scrub communities where *Acanthocarpus preissii* was either absent or present in low densities. In these regions *Stipa flavescens* tussocks often showed evidence of grazing damage. The limited evidence for this species in the faecal and stomach content analyses, however, could be mainly an artifact of the laboratory technique. The nitric/chromic acid maceration technique entirely digests the epidermi of grasses and the digestion processes of the tammar could duplicate this process. Cautionary procedures regarding grass epidermal remnants have been pointed out previously (Storr 1961, Halford 1984a).

The Beacon Head exclosure site located in a small experimental burn area showed vigorous regrowth of *Asparagus asparagoides*. The major cover differences between areas inside and outside the fences and the common occurrence of this plant species in both the faecal and stomach content samples implicate *Asparagus asparagoides* as a favoured dietary component. Evidence of near complete digestion of epidermi of young leaves

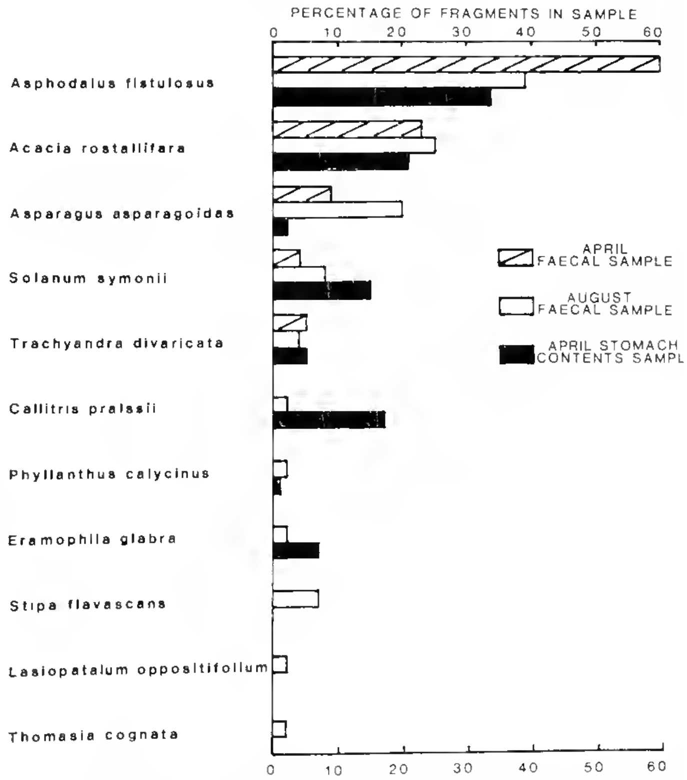

Figure 3.—Proportions of fragments separated by species from the April and August, 1983 faecal pellet samples and the April, 1983 stomach content samples.

of this species in the preparation of the voucher slides suggests that fragments noted from the faecal pellet and stomach content analyses probably underestimate the actual proportions ingested.

Grazing damage to *Rhagodia baccata* on Garden Island has been previously documented (McArthur 1957, Kelsall 1965, McArthur and Bartle 1981). The absence of this species in the dietary preferences noted in this study, however, is probably due to the particular location of the exclosure sites in respect to the occurrence of *Rhagodia baccata*. Other inconsistencies arising between the direct observation of grazing pressure and the quantitative evidence may also be explained by the distribution and density patterns of individual species and/or relatively low number of pellets analysed. For example, *Callitris preissii*, which did not occur in the transects, was identified from the stomach contents of the road-killed animals.

In the twelve years since completion of the new naval facilities the tammar population has remained relatively constant; the difference of 300 animals between the pre-1973 and current estimates could be attributed to the general difficulty of accurately sampling animal populations. Given the feeding preference for young shoots and seedlings, combined with the known behaviour of the tammar during fires (Christensen 1981), a controlled burning regime on Garden Island could benefit the population of this rare marsupial by increasing the areas of regenerating vegetation. However, the large proportion of species requiring seedling re-establishment indicates that the vegetation of Garden Island does not normally have a regime of frequent natural burns and, therefore, it would be irresponsible to suggest that large areas of the native vegetation be burned to provide greater feeding areas for the tammar. In fact, the greater availability of preferred food following large area burns could result in unacceptably large population increases in the tammar population. Frequent fires could also increase the already considerable invasions of introduced species into the native plant communities of the island as has been noted elsewhere in small 'island-like' bushland reserves within metropolitan Perth (Baird 1977, Loneragan *et al.* 1984, Wycherley 1984). The present proportion of introduced species on the island (26%) is similar to that included in the Star Swamp Bushland Reserve (25%) (Bell *et al.* 1979) even though the mainland reserve includes a greater diversity of habitats, communities and species. What could prove beneficial to both the tammars and the human population on Garden Island would be a series of control burns to

Table 2.

Characteristics of Garden Island vascular plants relating to grazing, re-establishment strategy, tammar diet, and floral affiliation.

	Observed grazing damage	Re-establishment strategy	Faecal pellet	Stomach content	Floral affiliation
Acacia cochlearis	—	Resprouter	—	—	Native
Acacia rostellifera	Yes	Resprouter	Yes	Yes	Native
Acanthocarpus preissii	—	Resprouter	—	—	Native
Anagallis arvensis	—	Ephemeral	—	—	Introduced
Anagallis foemina	—	Ephemeral	—	—	Introduced
Asparagus asparagoides	Yes	Resprouter	Yes	Yes	Introduced
Asphodelus fistulosus	Yes	Seeder	Yes	Yes	Introduced
Beyeria viscosa	—	Seeder	—	—	Native
Boronia alata	—	Seeder	—	—	Native
Callitris preissii	—	Seeder	Yes	Yes	Native
Carduus pycnocephalus	—	Ephemeral	—	—	Introduced
Carpobrotus aequilaterus	—	Seeder	—	—	Native
Centaurium erythraea	—	Ephemeral	—	—	Introduced
Clematis microphylla	—	Resprouter	—	—	Native
Crassula colorata	—	Ephemeral	—	—	Native
Crassula pedicellosa	—	Ephemeral	—	—	Native
Diploleana dampiera	—	Seeder	—	—	Native
Daucus glochidiatus	—	Ephemeral	—	—	Native
Eremophila glabra	—	Seeder	Yes	Yes	Native
Exocarpus sparteus	—	Resprouter	—	—	Native
Galium murale	—	Ephemeral	—	—	Introduced
Geranium molle	—	Ephemeral	—	—	Introduced
Guichenotia ledifolia	—	Seeder	—	—	Native
Hardenbergia comptoniana	—	Resprouter	—	—	Native
Melaleuca huegelii	—	Seeder	—	—	Native
Melaleuca lanceolata	—	Seeder	—	—	Native
Lasiopetalum oppositifolium	—	Seeder	Yes	—	Native
Leucopogon insularis	—	Seeder	—	—	Native
Leucopogon parviflorus	—	Seeder	—	—	Native
Olearia axillaris	—	Seeder	—	—	Native
Oxalis pes-caprae	—	Ephemeral	—	—	Introduced
Parietaria debilis	—	Ephemeral	—	—	Native
Poranthera microphylla	—	Seeder	—	—	Native
Phyllanthus calycinus	Yes	Resprouter	Yes	Yes	Native
Rhagodia baccata	—	Seeder	—	—	Native
Scaevola crassifolia	—	Seeder	—	—	Native
Scirpus nodosus	—	Resprouter	—	—	Native
Senecio lautus	—	Ephemeral	—	—	Native
Solanum symonii	Yes	Seeder	Yes	Yes	Native
Sonchus oleraceus	—	Ephemeral	—	—	Introduced
Spyridium globulosum	—	Seeder	—	—	Native
Stipa flavescens	Yes	Resprouter	Yes	—	Native
Thomasia cognata	Yes	Seeder	Yes	—	Native
Trachyandra divaricata	—	Seeder	Yes	Yes	Introduced
Trachymene caerulea	—	Ephemeral	—	—	Native
Trachymene pilosa	—	Ephemeral	—	—	Native
Zantedeschia aethiopica	—	Ephemeral	—	—	Introduced

create low flammable fuel regions around the Naval facilities and to break up the length of the island into units to prevent large areas burning as occurred during the summer of 1956 (Baird 1958).

Garden Island has been largely free of wild fires during the history of European settlement on the mainland. Indications from growth ring analyses from a small stand of *Callitris preissii* located in the northern end of the island which escaped the fire of 1956 showed that the trees were not much older than 50 years (Pearman 1971). This stand would now be around 65 years old. Although growth is generally slow, fuel build up during fire free periods can be considerable. McArthur (1957) reported that after 18 years of accumulation litter depths were of the order of 5 cm in the *Callitris* Forest, 3 cm in *Acacia rostellifera*-Mixed Scrub, and 1 cm in *Melaleuca heugelii* Scrub. His description of the vegetation at the time 4yr prior to the 1956 fire also indicated that *Stipa flavescens* occurred in most of the plant communities and would have contributed to the flammability of the litter.

Small spot fires accidentally lit by island visitors have occurred since the 1956 fire but documentation of these fires is unavailable. Controlled burning trials carried out by the W.A. Bush Fires Board in conjunction with the Department of Botany in April 1982 and December 1982 in the Beacon Head region were the first documented fires for 27 years. Estimates following these small experimental control burns indicated that only about 50% of the lit area actually burnt, and indeed, on both occasions some difficulty was experienced in keeping the fires alight. These controlled burns were carried out under mild temperatures and in the absence of strong winds; in marked contrast to the conditions under which the 1956 fire burned when temperatures in the two weeks preceeding the wild fire averaged 38°C and strong south-westerly winds had prevailed.

The ability to impose a controlled burning regime in a region which normally only rarely receives a fire should not be the only management decision for the regions of native vegetation on Garden Island. As was noted by Krinitskii (1974), 'Man's help should be thoroughly worked out; he should not lightly and arrogantly recarve nature'. The protection of the Naval installations from wild fires could be achieved by a system of fire breaks and reduced fuel-load buffers, rather than the burning of large tracts of the native plant communities of the island which has the additional disadvantage of destroying most of the cover for the tammars. If the fire-breaks were of a firm-base construction (e.g. limestone) rather than ploughed annually, there would be minimal disturbance and, hence, greater probability of controlling weed invasion. Changes in the tammar population numbers that result from the increased areas of preferred food resources could then indicate further considerations for the management of the island.

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Wetlands of the Darling System—A geomorphic approach to habitat classification

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Abstract

A classification utilising the 2 primary components of wetlands, the "wetness" and "landform" components, is proposed here. The water component distinguishes wetlands from other terrestrial habitats and also influences biological response by its presence, permanence or longevity, depth, chemistry, and movement. The landform determines wetland size, shape and depth. Using subdivisions of cross-sectional landform geometry there are recognised: basins, channels, and flats. Within the category of water longevity, there are recognised: permanent inundation, seasonal inundation, and seasonal waterlogging. Combining these "wetness" and landform attributes provides 7 categories of common wetlands: 1. permanently inundated basin = *lake;* 2. seasonally inundated basin = *sumpland;* 3. seasonally waterlogged basin = *dampland;* 4. permanently inundated channel = *river;* 5. seasonally inundated channel = *creek;* 6. seasonally inundated flat = *floodplain;* and 7. seasonally waterlogged flat = *palusplain.* Water and landform descriptors/modifiers are used to further augment the nomenclature of the primary units. Modifiers for water include salinity and its consistency. Modifiers for landform include size and shape. Since there are only seven primary wetland types, the classification provides a practicable number of categories for mapping. The addition of more precise or detailed information as modifiers/descriptors increases the ability to discriminate individual wetlands from each other.

Introduction

This paper presents a geomorphic classification of wetlands in the Darling System (Swan Coastal Plain and Darling Plateau; Fig. 1), an area occurring in the subhumid and humid region of southwestern Australia and encompassing coastal plains and dissected plateau. Many classifications of wetlands to date in Western Australia and elsewhere have been based on vegetation and water quality but it is considered that a geomorphic classification best provides the *initial framework* to understanding the various types of wetlands, their distribution and their relationship to biota. The rationale of the geomorphic approach is that ultimately wetlands are related fundamentally to landform development and water maintenance.

The classification presented here may be used for recognising the varied wetland types that occur in the Darling System. Information such as this is needed to establish a geographic, stratigraphic, hydrological and biological pattern in the distribution of wetland types, to determine regional and local significance of wetlands, to determine conservation strategies and to manage wetlands.

It has long been recognised that wetlands range from: permanent lakes, small to large seasonal lakes, small to large areas of seasonally water-logged soils, fluviatile systems, estuarine systems, and marine systems, and that these categories can be intergradational. Figure 2 illustrates the intergradational relationship between, and attributes of, the various wetland systems, recognising that there are land-based, marine-based and intermediate (estuarine) categories. This paper deals with the land-based wetlands. Estuarine systems and marine systems will be the subject of a later study. The approach of this paper is to provide a review of international literature on wetland classification and nomenclature followed by a review of local studies that deal with wetlands of the Darling System. This is in turn followed by a description of the classification adopted here.

Review of international literature on classification and terms for land-based wetlands

Definition of wetland

In the more recent literature the definition of wetlands encompasses lakes, water-saturated basins, estuaries and fluvial systems (UNESCO 1971, Bayly and Williams 1973, Cowardin *et al.* 1979, Department of Conservation and Environment 1980, Adam *et al.* 1985). However in the older literature the concept of wetland was more rigidly confined to encompass only lakes and water-saturated basins.

A variety of wetland definitions from the international literature is presented here to indicate the wide range of concepts of what constitutes a wetland. The Ramsar Convention defined 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 at low tide does not exceed 6m" (UNESCO 1971). Zoltai and Pollet (1983) define wetlands as areas where wet soils are prevalent, having a water table near or above the mineral soil for most of the thawed season, supporting a hydrophilic vegetation, and pools of open water (< 2m deep). This includes shallow open water. It does not include areas that become temporarily flooded, but remain relatively well drained for most of the growing season. Hill (1978) identifies

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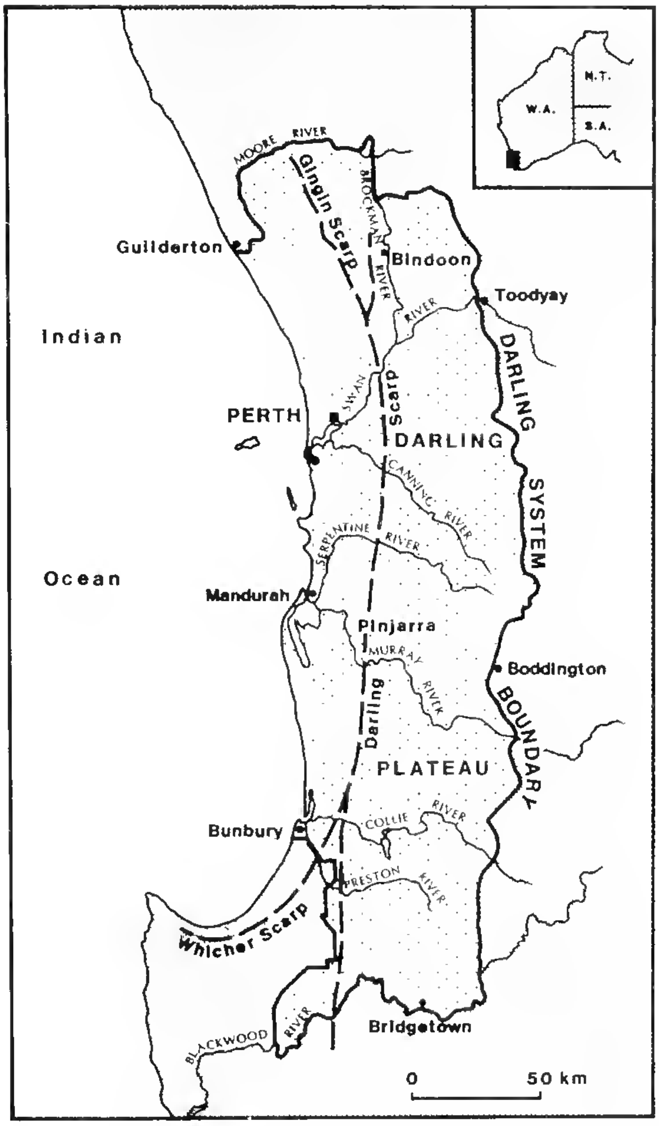

Figure 1.—Location of the study area, the System Six Region in southwestern Australia.

wetlands by the presence of vegetation typically adapted to life in areas inundated or saturated by water with the appropriate duration and frequency to promote that vegetation. Cowardin *et al.* (1979) define wetlands as lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. Cowardin *et al.* (1979) define wetlands as having one or more of the following attributes: 1) at least periodically the land supports hydrophytes, 2) the substrate is predominantly undrained hydric soil 3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year. Bates and Jackson (1980) define wetland as a general term for a group of wet habitats and include areas that are permanently wet and/or intermittently water covered, such as coastal marshes, tidal swamps and flats, and associated pools, sloughs and bayous.

A consensus of Western Australian workers define wetlands as:

> "Areas of seasonally, intermittently or permanently waterlogged soils or inundated land, whether natural or otherwise, fresh or saline, e.g. waterlogged soils, ponds, billabongs, lakes, swamps, tidal flats, estuaries, rivers and their tributaries" (Wetlands Advisory Committee 1977).

The definition is adequately encompassing and is adopted herein.

Wetland classifications

Wetlands have been examined and/or classified from a number of disciplines: biologically (e.g. mires, swamps; Ivanov 1981, Gore 1983); physically (e.g. riverine lakes, glacial lakes, tectonic lakes; Hutchinson 1957); biologically/chemically (e.g. fens, bogs; Tansley 1939, Gorham 1957, Reeves 1968, Moore and Bellamy 1974, Ruttner 1975, Gore 1983); chemically (e.g. minerotrophic, ombrotrophic etc.; Kulczynski, 1949; Hakanson and Jansson 1980, Wetzel 1983); ontogenetically; and others. It is not proposed to present a historical review of all the terms nor is it intended to explore the meanings of terms which are not widely used. Rather this review documents current terminology, discusses the relevance of those terms to the present classification, and assesses their applicability to the wetlands in the Darling System.

Terms for types of wetlands

Currently inland water bodies can be separated into 4 types: rivers, lakes, mirelands and marshlands. Rivers refer to channelled surface water. Lakes, mirelands, and marshlands are "basin-like" or flat wetlands which are differentiated on the basis of plant colonisation. The recent distinction between running water (Lotic environment) and standing water (Lentic environments) basically identifies the broader categories of riverine

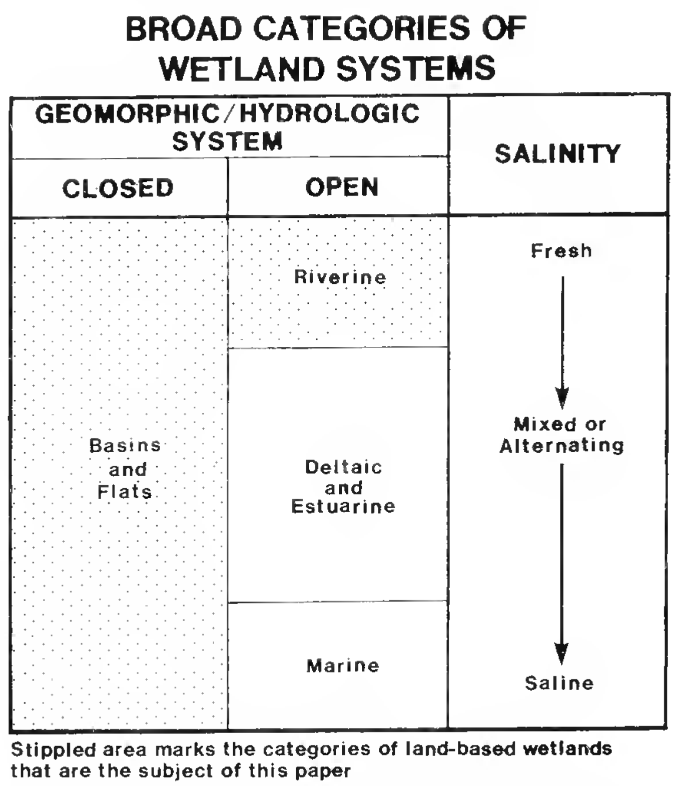

Figure 2.—Conceptual summary of types of broad wetland categories and their inter-relationships in terms of geomorphic/hydrologic setting and their salinity.

versus "basin-type" of wetlands. The fluvial systems (encompassing rivers, streams, creeks and all other forms of established surface water flow) generally in the past were not considered to be wetlands. Since the documentation and analysis of fluvial systems have been separated traditionally from that of other types of wet habitats, the approaches to their classification have been variable (Schumm 1977, Leopold *et al.* 1964, Twidale 1968, Fairbridge 1968, Bloom 1978).

Fluvial wetland systems

Fluvial systems already have been described and categorised according to geomorphic principles (Gilluly and Waters 1951, Schumm 1977, Leopold *et al.* 1964, Chorley 1969, Bloom 1978, Strahler 1978, Cant 1982, Leeder 1982). Both land and water criteria have been combined to identify and nominate the features of a fluvial system. The recognised geomorphic features of fluvial systems include channels, flood basins and floodplains, levees, crevasses, swamps, and ox-bow lakes (op cit).

Fluvial channel patterns have been subdivided by workers using the criteria of 1) genetic relationship to landform, 2) channel size and position in relationship to branching pattern, 3) sinuosity, 4) water permanence and 5) sediment load. The genetic classification used terms such as subsequent, consequent, obsequent and insequent, and the terms "first order stream", "second order stream", etc were used to categorise relationship of channel to branching pattern. Several classes of channel are recognised on the basis of sinuosity (i.e. the ratio of channel length to valley length); these include straight, transitional, regular, irregular, tortuous, sinuous, meandering, straight-and-braided, and anastomosing (Schumm 1977, Leopold *et al.* 1964, Miall 1977, Cant 1982, Smith 1983); some of these terms are synonymous. Channels occupied by water for different periods of time are referred to as permanent, intermittent, and ephemeral. Predominant sediment transport mode also has been used to classify channels (Schumm 1977) resulting in a similar set of classes as those derived from sinuosity criteria, but with the additional information on channel stability i.e. whether the channel is stable, eroding, or depositional.

Basin wetland systems and flats

Research into "basin-type" inland water bodies or wetlands, has been largely concentrated in the areas of the Temperate, Boreal and Arctic zones of the Northern Hemisphere, particularly Europe, where precipitation is greater than evaporation and/or drainage. The wetlands of these regions are permanently inundated or waterlogged areas and the terms derived from these areas tend to describe only this limited range of wetlands. Examples of wetland terms from these regions are (Gore 1983): lake and mireland (English), moor, see (German), myr (Swedish), suo (Finnish), boloto (Russian), veen (Dutch), myri (Icelandic) and muskeg (Canadian).

Basins were divided, on the presence or absence of emergent vegetation, into 2 water depth types, i.e. those deeper than 2m and those shallower than 2m. The current terms used to distinguish these types are *lake* and *mireland*. Lake has been defined as an "inland body of standing water occupying a depression in the earth's surface, generally of appreciable size (larger than a pond) and too deep to permit vegetation (excluding subaqueous vegetation) to take root completely across the expanse of water; the water may be fresh or saline" (Bates and Jackson 1980). Mireland refers to any area which remains waterlogged and is vegetated (Ivanov 1981).

Lakes have been classified for specific purposes, according to dissolved mineral content, or thermal properties, but the most widely used classification is according to origin (Hutchinson 1957, Reeves 1968, Hakanson 1980, and Jansson 1983, Wetzel 1983). Thus tectonic, glacial, volcanic, solution lakes etc., have been distinguished.

Mirelands have been subdivided into mires and swamps. Mires are permanently waterlogged areas which must include a minimum thickness of peat (Gorham 1957, Moore and Bellamy 1974, Ivanov 1981). They are further divided into two types: bog and fen. A bog is domed, raised above the level of the surface of the surrounding terrain, often with a steep marginal bank (rand). Bogs are oligotrophic, because they rely on atmospheric precipitation, and as a result support a typical vegetation of *Sphagnum* mosses. A fen occurs in hollows or depressions, is minerotrophic and as a result supports a variety of vegetation including mosses, graminoids, or trees. Swamps are permanently waterlogged seasonally inundated, or permanently inundated, vegetated areas. Swamps have alternatively been identified or defined as peat-forming, and non-peat forming (Holmes 1944, Golet and Larson 1974, Ivanov 1981). Swamps are subdivided into numerous different types according to the physiognomy of plant cover (Hofstetter 1983, Anderson 1983, Gore 1983, Denny 1985, and others), e.g. conifer swamps, hardwood swamps, reed swamps, and Ti-tree swamps.

Wetlands other than mirelands, lakes and rivers, are fewer in number in the Northern European climatic zones, but they exhibit enough common similarities in terms of biotic and water parameters to be classified collectively as *marshlands*. Marshlands have been defined as seasonally inundated or waterlogged, with or without a well developed peat, and supporting a graminoid or herb plant cover (Gorham 1953, Riggert 1964-1966, Zoltai and Pollet 1983, Golet and Larson 1974, Campbell 1983, Hofstetter 1983, Denny 1985). The term has also been applied to vegetated peripheral flats of estuaries. Marshlands may be "basin-like" or flats. The types of marshlands are: 1) marshes, 2) swamps, 3) meadows, and 4) wetlands. The range and inconsistency in terms have been brought about by the variability in marshlands occurring outside Europe. Authors describing areas which satisfy only part of the marshland definition (e.g. the seasonal waterlogging of soils) but have different vegetation structure, often use an alternative term or a modifying term to avoid confusion.

Marshes are subdivided on basis of saline and fresh water, geographical distribution (e.g. coastal and inland), and water depth during the growing season (Martin *et al.* 1953, Golet and Larson 1974). The term swamp, used in the sense of, and as a synonym of marsh (Zoltai 1983, Junk 1983, Hofstetter 1983, Howard-Williams and Gaudet 1985) as distinct from a subdivision of mireland is defined as an area intermittently or permanently covered with water, supporting woody plants and essentially lacking peat development. In fact, marsh, swamp, and wetland are sometimes used interchangeably and the general term wetland has been used to describe all land/water interfaces.

General classifications

A variety of classifications have been produced by a number of workers. Some have been comprehensive and generally exhaustive (Cowardin *et al.* 1979) whereas some have concentrated mainly on limnologic wetlands or some specialised aspect of wetlands (Martin *et al.* 1953, Hutchinson 1957, Bayly and Williams 1973, Ivanov 1981, Wetzel 1983, Ruttner 1963). Two of these classifications are outlined below.

Martin *et al.* (1953) produced a classification of wetlands based on 1) geographical position 2) water quality 3) period of flooding 4) depth of water during the growing season and 5) vegetation type within the wetland. The freshwater wetlands were then divided into meadows, marshes, swamps, open water and flats, and were differentiated on the criteria of water depth and/or vegetation cover. Similar wetland categories were proposed for inland and coastal areas and again for saline wetlands. An example from Martin *et al.* (1953) is as follows: "Fresh Inland Meadow: No standing water, but saturated within a decimeter of the soil surface. Shallow depressions. Communities dominated by graminoids and herbs". Within the classification by Martin *et al.* (1953), however, criteria were not applied consistently. In the case of "wooded swamps" the period of flooding is omitted whereas in the categories of "salt flat", "salt meadow" and "irregularly flooded salt marshes", it becomes the distinguishing factor. The use of salinity is another problem with the classification. Salinity was noted to be either fresh or saline. There is no class of wetland which is gradational or dynamic. The cross sectional shape of the wetlands was not differentiated in each class. The terminology does not allow for wetlands with variegated vegetation pattern. Also, the water levels are too specific and in cases, where this is the only differentiating factor, it is too precise for use in Australia.

The classification by Cowardin *et al.* (1979) is a hierarchial one based on recognition of classes, orders and progressively lower levels of taxonomic differentiation. The classification at the onset denotes 5 systems of wetlands that "have certain homogeneous natural attributes"; these are the marine, estuarine, riverine, lacustrine and palustrine systems. Each system is composed of subsystems of littoral and limnetic habitats. The systems are divided into classes and then dominance types, and finally modifying terms are added. The class to which a wetland belongs is determined by the dominant life form of the vegetation (or in the absence of vegetation, the attributes of the substrate): the dominance type refers to the dominant plant or animal species present; the modifiers refer to soil and water attributes of the wetland. The classification was designed so that it could be applied at all levels of data collection. As the information on a wetland increases, the classification may be refined so that two objectives were satisfied: the wetland could be classified immediately within a regional framework, and secondly the wetland could be finally described and differentiated on important individual characteristics.

A number of classifications for wetlands also have been devised by workers in Australia. These classifications are intended mainly for local use (Goodrick 1970, Cowling 1977, Jacobs 1983). Many generally appear to utilize existing overseas schemes and amend them where appropriate for the local system (e.g. Riggert 1964-66, see later). More recently Paijmans *et al.* (1985) provided an overview of Australian wetlands and proposed 6 categories of wetlands (lakes, swamps, land subject to inundation, channels, tidal flats and coastal water bodies). Their approach however is too broad for this study and their categories are based on a variety of mixed criteria.

Application of international classifications to the Darling System

Wetlands of the Darling System are quite variable in shape, size, vegetation, soil, peat, water quality and water maintenance. Wetlands with permanently or seasonally inundated soils have been predominantly described in the literature, but those with seasonally, waterlogged soils generally have been neglected. According to the current international literature most of the wetlands of the Darling System would fall into the categories of 1) channels, 2) lakes, 3) mirelands (fens and swamps) and 4) marshlands. There are no bogs as found in Northern Europe. Marshlands, however, are the most dominant but there are types of marshlands which do not conform to the definition presented above e.g. there are open bodies of water which are fringed by a range of vegetation types, and there are areas of seasonally waterlogged soils supporting variable vegetation.

Use of riverine terms

The genetic and quantitative classifications for rivers and streams (Twidale 1968, Fairbridge 1968) are considered inappropriate for channels of the Darling System because they do not provide precise information on the important features of shape, size and permanence, factors that are considered to be important in the identification of the wetland habitat. The terms of these classifications furthermore have neither ecological nor descriptive geomorphic implication. The classification involving sediment load relates to stream function and also does not convey the necessary descriptive information useful to identify the various channel wetlands. The terms used to describe sinuosity are appropriate to describe wetland channels because they convey geometric impressions of the channel system particularly if used in conjunction with size terms. However it is necessary only to use a limited range of these terms to convey channel sinuosity; these are: straight, anastomosing, irregular and sinuous.

Use of vegetation in classification

Vegetation (using features of floristics or structure, or both) has been used to classify wetlands (Martin *et al.* 1953, Goodrick 1970, Cowardin *et al.* 1979, Briggs 1981, Campbell 1983, Sjors 1983, Pisano 1983, and others). In some cases vegetation has even been used to unravell the edaphic features of wetlands. For instance, Ivanov (1981) deduces hydrology, stratigraphy, origin and development from the use of restricted plant habitats in mire ecology and uses species presence and structure in relation to micro-relief to determine the structure of mire formations. Vegetation has been used to differentiate types of mires and swamps (e.g. spruce swamp, pine bog).

It is considered here, however, that vegetation should not be used as a primary criterion to classify wetlands of the Darling System. The vegetation structure is dependent upon hydrological and geomorphological factors such as water maintenance, water quality, micro-relief and soils, so that the primary classification of wetlands solely based on vegetation structure may not allow any differentiation of other wetland properties. Also, because of the relatively limited species pool that dominantly contribute to the vegetation of wetlands, the use of vegetation as a primary criterion would result in many different wetlands being classified into one group. Consider for example paperbark forests and woodlands which occur on deltas, along river banks, on flood plains, along the edge of basins, in blow outs, in interdune depressions and fringing the shores of estuaries; the use of this vegetation in classification would not bring out the various and different primary wetland categories.

Use of water quality in classification

Wetlands have been subdivided variably on the basis of different water types, such as ombrotrophic and minerotrophic, or aspects of salinity (Tansley 1939, Martin *et al.* 1953, Bayly and Williams 1973, Moore and Bellamy 1974, Gore 1983) and in some cases it forms the primary criterion for classification. More usually the subdivision of water categories merely provides a secondary subdivision of wetland types.

Since most of the wetlands in the Darling System are maintained by groundwater, it must be concluded that they are to some extent minerotrophic. However, the input of rain during the wet season shifts wetlands to the ombrotrophic end of the spectrum. Although this simple division based on dissolved mineral content cannot be used successfully, the division according to salinity or to the presence of one or more minerals may be attempted. The use of water quality is considered important at lower hierarchial levels but not at a primary level. Accordingly salinity terms such as freshwater, brackish water, subsaline, hyposaline, saline water and hypersaline water become applicable (Davis and DeWiest 1966, Logan *et al.* 1974, Cowardin *et al.* 1979, Dreva 1982, Hammer *et al.* 1983). An excellent review of the problems of terminology of categories of water quality is provided by Hammer (1986). The consistency of water quality also is considered here to be relevant in classification at lower hierarchial levels, because of the seasonal variation in water quality of many wetlands of the Darling System.

Use of peat/stratigraphy in classification

The secondary classification of mirelands into fens and bogs is based on the presence/absence of peat and essentially underscores botanical and shallow stratigraphic aspects of wetlands. Taken to conclusion the stratigraphic approach would result in wetlands being categorised on the origin of their surficial soils such as peat, carbonate mud, diatomite, gypsum deposits, etc. Wetland shallow stratigraphy in the Darling System is primarily determined by the vegetation type, the geomorphic unit in which the wetland is situated, and the developmental history of the wetland. This shallow stratigraphy is often complex and necessitates detailed analysis. Thus although it is very important in understanding wetland formation, stratigraphic information is considered to be inappropriate at the higher hierarchial levels of classification.

An additional complication relates to the age of peat units. Peat and peaty sand occur in many of the wetlands in the Darling System and are forming under present conditions; they are young and often less than a metre thick. In some places, however peat has been buried to some depth and is essentially a "fossil" deposit. The buried peat horizons may be relics of a different climatic or wetland regime and should form no part of a classification dealing with modern processes.

Use of internal morphology in classification

Morphological criteria such as internal relative relief is used by a number of authors for basin wetlands (Moore and Bellamy 1974, Ivanov 1981, Gore 1983) but its use has tended to be subtly introduced at all stages of classification. Where not directly mentioned, the wetland internal morphology often is implied in the use of vegetation structure and the water quality. For instance with bogs and fens, use is made of vegetation structure to infer the varieties of depressions, hollows, basins, flats or slopes. In essence the use of internal morphology in the international literature is merely a variation of the use of vegetation criteria.

Use of external morphology in classification

The morphology of fluvial systems has been successfully classified by a number of authors and according to these approaches fluvial wetlands of the Darling System could be classified as to channel shape and water permanence. The external shape of basin-wetland landform, however, generally is not directly considered in the international literature even though it is one underlying factor for the presence and extent of the wetland itself and therefore should be a primary factor in the classification of wetlands. In the Darling System the morphological components of the landforms produce definite, recognisable types of wetlands, and small scale sedimentological features of wetlands can also be used for more detailed categorisation. The larger morphological components are considered to be crucial in the primary classification of wetlands from a geomorphic viewpoint as will be discussed later in the paper.

Discussion

The review of international literature shows that classifications and nomenclature of wetlands have been based on amost every edaphic or ecological aspect of the system: water supply, water chemistry, type of landform, morphological structures within the wetland, shape of wetlands, vegetation cover, and occurrence/types of peat. There have been integrated approaches such as the genetico-geotopic classification of Ivanov (1981), the wetland classes of Zoltai *et al.* (1983), and the five major systems of Cowardin *et al.* (1979). There also have been numerous classifications based on a single feature, the most common being vegetation.

The primary classification of wetlands into lake, mireland and marshland is inconsistently based on the duration and depth of water supply and shows no clear demarcation between wetlands with different water levels and longevity. Three types of water longevity are explicitly recognised by authors: 1) permanent inundation, 2) permanent waterlogging, 3) seasonal inundation or waterlogging, but the terms lake, mireland and marshland clearly do not mirror these categories; for example:

- Permanently inundated areas may be termed lake or swamp
- Permanently waterlogged areas may be termed mire, swamp, marsh

- Seasonally inundated or waterlogged areas are termed wetland, marsh, meadow, swamp.

There is no term other than marsh to refer to seasonally waterlogged areas, as opposed to seasonally inundated surfaces.

It is also clear that most classifications of wetland rely heavily on categorisation using vegetation (which is presumed to reflect water longevity and quality) at a primary or secondary level. The classification of wetlands where landform is linked to water permanence/longevity generally is not an approach adopted in the literature. For instance, wetlands divided into lake or mireland then are subdivided according to biotopes (i.e. the presence or absence of peat and, on the physiognomy of the plant cover). The third major factor in categorising wetlands appears to be the use of water quality. This may be based simply on aspects such as minerotrophism, or specific salt content, or acidity.

Further subdivisions or classifications of wetlands have been based on the genetic morphologic relationships of the entire wetland systems at a regional scale, or on vegetation-related internal morphological components of the wetland and the resulting structure of the vegetation, or the presence of specific vegetation (Moore and Bellamy 1974, Cowardin *et al.* 1979, Ivanov 1981, Gore 1983, Ruuhijarvi 1983, Sjors 1983).

The terms available in the literature that are useful in classifying wetlands at a primary level therefore are:

the term *wetland* itself,
the term *lake*,
riverine geomorphic nomenclature such as river, creek, channel sinuosity terms, etc.

A wide variety of wetland categories or terms therefore are considered inapplicable for the Darling System because they are genetic, or they have imprecise definition, or have strong vegetation connotation, or soil/stratigraphy connotation, or they should be at lower stage levels of hierarchy in classification, or because they do not fully extend across the range of wetlands available in the Darling Systems; these are:

1. *genetic chemical categories* such as ombrotrophic, minerotrophic etc.;
2. *morphogenetic categories* such as volcanic lake, glacial lakes;
3. *floristic categories* such as swamp, meadow, marsh, muskeg;
4. *chemical-floristic* or *soil-floristic* categories such as mire, swamp, moor, fen, bog etc.;
5. *geologic/geographic* base categories such as paludal, continental;
6. the terms lake, swamp, marsh as used in a *sedimentologic* sense.

Previous local classification of wetlands

There have been previous classifications of the wetlands of the Swan Coastal Plain and Darling Plateau of the Darling System, notably by Serventy, Owen and Pirrott (cited by Clarke *et al.* 1971), Riggert (1964-1966), Tingay and Tingay (1976) the Wetlands Advisory Committee (1977), and Allen (1980). All these classifications devised to date have useful purposes since each was developed for a specific task. These systems of classification are briefly discussed below.

Classification adopted by Serventy, Owen and Pirrott

Serventy *et al.* (1971) (cited by Clarke *et al.* 1971) in an unpublished document probably provided the first classification of wetlands in the Darling System. Three genetic types of lakes or swamps were distinguished: 1) isolated portions of the ocean; they cited examples such as Preston-Clifton Lakes; 2) relic abandoned river courses of which Herdsman and Perry Lakes are cited as examples and 3) chance depressions.

Classification adopted by Riggert

As part of a study into wetlands of Western Australia by the Department of Fisheries & Fauna, Riggert (1964-1966) classified and evaluated wetlands of Western Australia (including the Darling System) (see Fig 1). The study was oriented to evaluating the utilisation of wetlands by waterfowl. Riggert postulated that the presence or absence of waterfowl provided an indication of the physical state of a wetland. The wetlands were classified on criteria developed by Martin *et al.* (1953) into 22 types. These were A. *INLAND FRESH AREAS* 1. Seasonally flooded basins or flats 2. Flooded Agricultural Land 3. Inland fresh meadows 4. Inland shallow fresh marshes 5. Inland deep fresh marshes 6. Inland open fresh water 7. Permanent Open Water (Reservoirs) 8. Shrub swamps 9. Wooded swamps and 10. Bogs: B. *INLAND SALINE AREAS* 11. Inland saline flats 12. Inland saline marshes and 13. Inland open saline water: C. *COASTAL FRESH AREAS* 14. Coastal shallow fresh marshes 15. Coastal deep fresh marshes and 16. Coastal open fresh water; and D. *COASTAL SALINE AREAS* 17. Coastal salt flats 18. Coastal salt meadows 19. Irregularly flooded salt marshes 20. Regularly flooded salt marshes 21. Sounds and bays 22. Mangrove Swamps.

Examples of these categories of wetlands in Western Australia were described in an inventory approach by Riggert noting size, depth, total surface area and vegetation. The wetlands were also categorised and evaluated on the basis of utilisation by waterfowl, in terms of numbers of waterfowl per year, and types of utilisation (e.g. breeding, feeding, migration and loafing).

The approach by Riggert (1964-1966) indicated that there was much variability in wetland types. However, it did not distinguish between the many types of wetlands that exist in the Darling System that can be separated on the basis of geometry, vegetation, degree of water permanence and other faunal groups apart from avifauna. For instance, riverine wetlands were not distinguished.

Classification adopted by Tingay and Tingay

As part of a study into wetlands of the Darling System prepared for the Environmental Protection Authority, Tingay and Tingay (1976) classified and compiled an inventory of wetlands in the southwest of Western Australia. They adopted the classification of Hutchinson (1957) and Bayly and Williams (1973), wherein wetlands in the first instance are classified into lentic and lotic. Tingay and Tingay (1976) utilised schemes that subdivided the lentic categories into 1) lakes: tectonic, volcanic, landslide, glacial, solution, fluviatile, wind action or coastal types, and 2) shallow water bodies: underground water, springs, water associated with terrestrial vegetation, puddles, rock pools and ponds, either permanent or temporary. Lotic categories were sub-divided as permanent, temporary or episodic, and also on features such as unidirectional flow, fluctuation in flow rates, linear morphology, etc.

Tingay and Tingay applied the classification to the Darling System and noted that *lentic* wetlands dominate the Bassendean, Quindalup, Spearwood and Pinjarra geomorphic systems of McArthur and Bettenay (1960), and that each wetland type within a geomorphic system may have similarity in terms of origin, nature and biota. Tingay and Tingay classified the lakes at Yanchep for instance, as lentic solution lakes, and the wetlands of the Bassendean system as lentic wind action dune water table lakes. They further subdivided the lentic wetlands of the coastal plain on the basis of soil elements and series (i.e. they adopted soil associations as environmental indicators) and they devised an acronym symbol system to distinguish them. The lotic wetlands were subdivided by Tingay and Tingay on a geographic basis into Moore, Swan, Peel, Leschenault, Capel and Hardy types with no further subdivision.

The approach of Tingay and Tingay (1976) constituted a useful categorisation of wetlands for inventory purposes. The categories provided a checklist of features to be determined for each wetland and highlighted the variability of wetlands. However, the system adopted is too genetic in the first instance, as well as too complicated both for classification purposes and for mapping. It involves a worker having to determine a wide range of factors such as soil mosaics and landform origin before a classification is possible. Yet a simpler classification is possible based on readily-available features gathered from maps and short field surveys. It should be noted, however, that many of important features of wetlands used by Tingay and Tingay are utilised in the classification developed herein.

Classification adopted by Wetlands Advisory Committee (1977)

The Wetlands Advisory Committee (1977) in a report to the Environmental Protection Authority also devised a classification of wetlands in the Darling System. The main subdivisions adopted by the committee were: 1) Lentic (non-flowing), 2) Lotic (flowing), 3) Estuarine, and 4) Artificial. Thereafter the wetlands were subdivided on criteria of size, salinity, permanence, and degree of vegetation cover. These criteria were considered important to determine the potential value of a wetland for particular uses (e.g. waterfowl drought refuge; or use for aquatic recreation). This approach produced a total of 15 potential types of lentic wetlands, which together with the lotic, estuarine and artificial types identified a total of 18 wetland types throughout the Darling System region.

Wetlands classified by the Wetlands Advisory Committee were allocated symbols (similar to Tingay and Tingay 1976) to distinguish them. Thus Lake Jandabup at Wanneroo was designated LE.f.1.p.sc (lentic, fresh, large, permanent, semi-closed vegetation cover), the Swan River upper reaches were designated LO (lotic); the Swan River at Fremantle was designated E (estuarine) and ornamental lakes in Kings Park were designated A (artificial).

The classification of the Wetlands Advisory Committee (1977) provided a useful categorisation of various types of wetlands. It addressed many of the major attributes of wetlands and clearly showed their variability and complexity in the Darling System. However the classification did not utilise wetland shape, only distinguished between two sizes of wetland (small and large), did not separate types of Lotic systems and did not distinguish between various "basin-type" wetlands or identify wetland flats.

Classification by Allen

As part of a geohydrology study of the Swan Coastal Plain, Allen (1976, 1981) identified wetlands as lakes and swamps and further categorised them into six types on the basis of age, inferred origin, and geographic location. Allen identified the following: 1) Bambun type, 2) Gnangara type, 3) Forrestdale type, 4) Joondalup type, 5) Gwelup type and 6) Cooloongup type. These categories 1-6 were listed in order of inferred decreasing age.

Other studies

In addition to the works cited above in which classification of wetlands was a primary or important motive, there are other works in which some form of wetland classification or wetland vegetation classification was utilised. These works include Evans and Sherlock (1950), McComb and McComb (1967), Seddon (1972), Bell *et al.* (1979), Watson and Bell (1981); Muir (1983), Pen (1983), Speck and Baird (1984), Congdon and McComb (1976) and Baird (1984). Each of these works utilised established international classification schemes. Thus the Yanchep wetland system was termed a swamp and fen formation (McComb and McComb 1967), Star Swamp and Yeal Swamp were termed swamp and swampy flat, respectively (Watson and Bell 1981, Baird 1984), and Seddon (1972) utilised terms such as wetland, swamp, lake.

Discussion

All classifications devised to date have not provided an approach that enables categorisation of the variety of wetlands across the whole Darling System. Only 3 of the classifications have attempted to be comprehensive. These are the works of Riggert (1964-66), Tingay and Tingay (1976), and the Wetland Advisory Committee (1977). However, even the most detailed of these classifications use an essentially similar primary subdivision of lentic and lotic types (Tingay and Tingay 1976, Wetlands Advisory Committee 1977). The distinction between still-standing water and flowing water (which is the basis of the lentic and lotic subdivision and essentially attempts to separate fluvial from lacustrine wetlands) however becomes indefinite in some systems, e.g. some channels are slow flowing, and in fact, have slower flow rates than some lakes, that are part of a groundwater drainage system. The approach to classifying lakes by Tingay and Tingay (1976) is too genetic to be of use and secondly only considers part of the range of wetlands available, since many wetlands may have no free-standing water at any time of year. A classification that separates the wetland into numerous types as proposed by Riggert (1964-1966) serves as a useful function in identifying wetlands for use of avifauna but does not provide the adequate distinction for additional purposes between the many varied wetland types existing in the Darling System.

All the above classifications to date however have not adequately addressed the identification and nomenclature of waterlogged soils, or types of water saturation/inundation or the full range of cross-sectional and plan geometry of wetlands, or the range of sizes of wetlands.

Classification—this study

Philosophical approach to classification

Ideally classifications should initially be non-genetic and then with additional information the non-genetic categories should relate to genetic categories. Landform/geomorphic and water/wetness criteria are non-genetic and the proposed classification of wetlands is based fundamentally on the two major features which determine the existence of wetlands i.e. the water and landform components. The water component is the major feature that distinguishes the wetland habitat from other terrestrial habitats and also the component which influences biological response by its presence, depth, chemistry, and movement. The landform essentially is the "water container" and thus it determines the size, shape and depth of a wetland. Any wetland classification thus should reflect variability or attributes of these two components (Figure 3). In combination, the variables or attributes of these two components result in a wide spectrum of possible wetland types. As a prerequisite to examining these combinations, a fuller explanation of the types of subdivision of water and landform is presented below.

The water component

The component of water in a wetland may be viewed from 4 inter-related aspects: 1) its persistence or longevity, 2) its quality, 3) the consistency of water quality, and 4) the mechanism by which water maintains the wetland.

The longevity of water residing in a wetland, i.e. its permanence or intermittency, is directly related to the precipitation and evaporation, mechanisms of water supply, the permeability of underlying sediments, and the shape of the wetland. Three types of longevity are distinguished: 1) permanent inundation 2) seasonal or intermittent inundation 3) seasonal or intermittent waterlogging (without inundation).

Water quality referring to the dissolved solids, rather than pH or coloration, may be subdivided into categories of: fresh, brackish (or mixosaline), saline and hypersaline. However, there is inconsistent use of terms and definitions for categories such as brackish, saline, hypersaline (Davis and Dewiest 1966, Drever 1982, Cowardin *et al.* 1979, Logan *et al.* 1974, Hammer *et al.* 1983, Hammer 1986). The category terms and boundaries adopted in this paper are presented in Table 1. It also should be pointed out that many wetlands vary in salinity during the year due to variable input of water sources and evapo-transpiration. Wetlands that are seasonally variable in salinity are categorised by the salinity state in which the wetland exists for the major part of each year e.g. a wetland that ranges from freshwater for most of the year, to brackish during the season of reduced water supply, would be classified as freshwater. However, a term is introduced to denote whether salinity is constant or variable. Water quality that is consistent throughout the year (i.e. it remains totally within a given salinity field, e.g. the freshwater field or saline water field) is termed *stasohaline**; water quality that markedly fluctuates throughout the year is termed *poikilohaline**. For instance a wetland that alternates seasonally from freshwater to saline is described herein as poikilohaline. In areas of seasonal inundation and seasonal waterlogging, the determination of salinity throughout the year will necessitate sampling the shallow groundwater for part of the year.

Table 1

Classification of water salinity based on total dissolved solids

Salinity mg/l	Water Category*
less than 1,000	Fresh
1,000—3,000	Subhaline
3,000—20,000	Hyposaline
20,000—50,000	Mesosaline
50,000—100,000	Hypersaline
100,000 and greater	Brine

*The terms and boundaries for fresh, subhaline, hyposaline mesosaline and hypersaline are from Hammer 1986; the term "brine" is delineated by Davis and Dewiest 1966.

The mechanisms by which water maintains the wetland are variable and include direct precipitation, groundwater seepage, surface inflow, ponding etc. However the mechanisms of water maintenance will not be considered further here.

Landform component

The landform component of a wetland can be categorised on the basis of cross sectional geometry, plan geometry and scale. The cross sectional geometry subdivides a wetland into basins, flats and channels. Basins and flats have no external surface drainage system. Basins range from flat bottomed to concave, from steep to gentle sloping sides, from shallow to deep and are represented by many of the common and ubiquitous lakes and "swamps" of the Swan Coastal Plain. They have clearly defined centres or depressions but may have sharp or broad margins. Cross sectional shapes of basins include: broad u-shape, steep u-shape, saucer, and slightly concave depressions. It is on the basis of a topographic depression that an individual basin is recognised. This factor is particularly important when a number of basins may form a nearly coalescing network; the local central depressions define each basin even though the littoral zones of adjacent basins may merge or overlap. Flats are marked by little or no marginal relief, and have diffuse lateral boundaries. Flats in the Darling System commonly occur on the tributary interfluves of creeks and rivers, as overbank floodplains, and on broad alluvial flats and slopes in front of foothills of the Darling Scarp.

Channels refer to any incised water course, or reach, including those connecting basin-type bodies of water. Channels have clearly defined margins and may be bedrock confined or alluvial and this distinction may result in deeply incised channels as opposed to shallowly incised channels. The alluvial channels vary according to their hydraulic characteristics which are determined by their stability, channel and valley slope gradients, the mode of transport, and composition of their load (suspended vs. bedload).

*staso ....after Greek Stasimos (=constant)
*poikilo ....after Greek Poikilos (=variable)

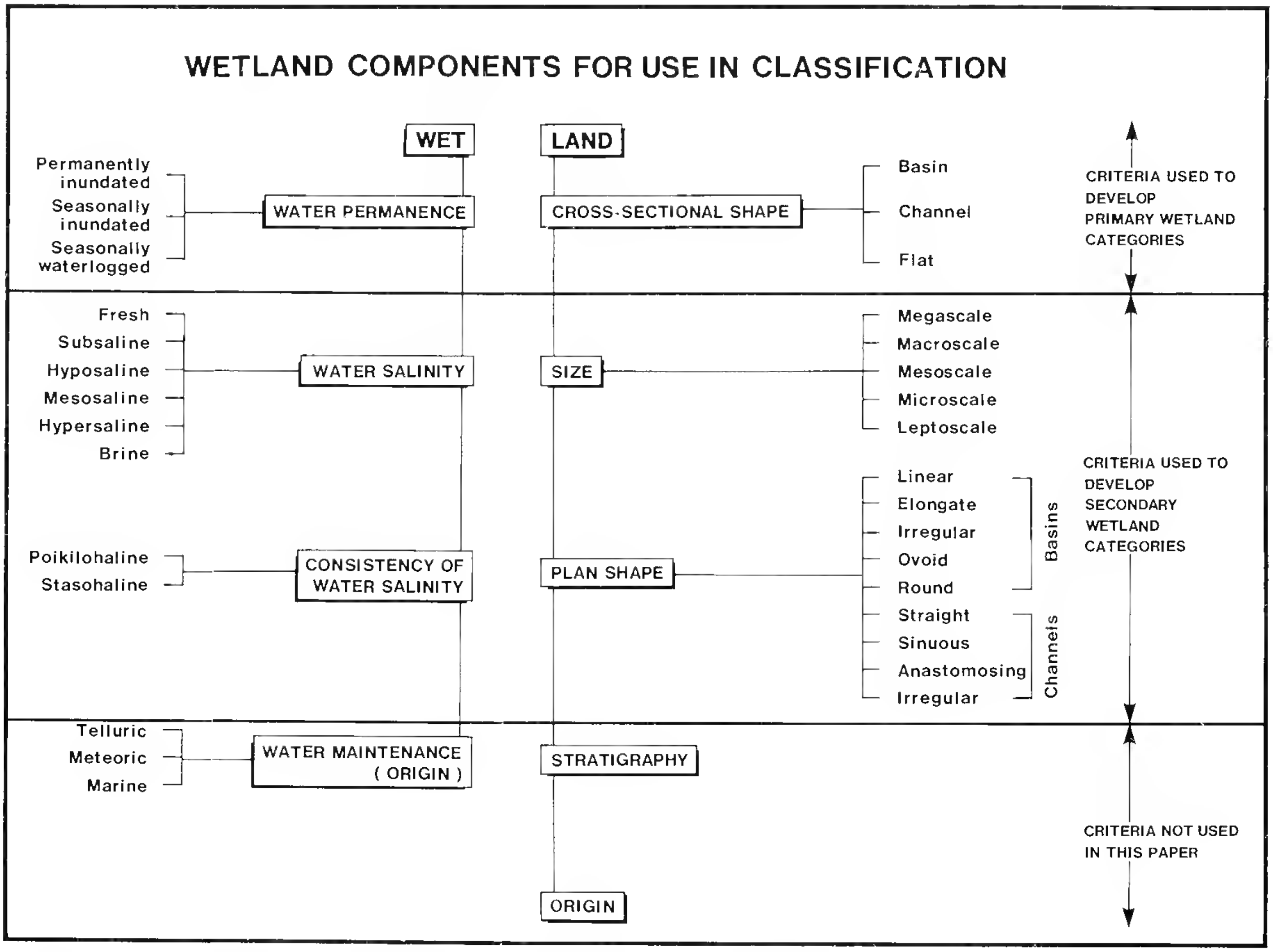

Figure 3.—Components or attributes of wetlands and their terminology used in the proposed classification.

Channel terms include rivers, streams, brooks, creeks, drainage lines or troughs. Only the terms rivers and creeks are used in this classification.

In plan form, encompassing the limnetic and littoral zones (Hutchinson 1957, Cowardin *et al.* 1979), wetland shapes are easily discernible and may be described as linear, elongate, irregular, ovoid or round, for basins; and straight, sinuous, anastomosing, or irregular for channels (Fig. 4).

Wetlands may be further categorised according to scale. For basins and flats the categories of geomorphic scale (modifed from Semeniuk 1986) are:

Megascale: Very large scale wetlands larger than a frame of reference 10km x 10km

Macroscale: Large scale wetlands encompassed by a frame of reference 1000m x 1000m to 10km x 10km

Mesoscale: Medium scale wetlands encompassed by a frame of reference 500m x 500m to 1000m x 1000m

Microscale: Small scale wetlands encompassed by a frame of reference 100m x 100m to 500m x 500m

In the case of channels, a definitive width to length relationship is used:

Macroscale: Large scale channels 1km and greater wide, by several to tens of kilometres long.

Mesoscale: Medium scale channels hundreds of metres wide, by thousands of metres long.

Microscale: Small scale wetlands tens of metres wide, hundreds of metres long.

Leptoscale: Fine scale channels several metres wide, tens of metres long.

The suggested order of importance to classification for the components of landform is presented in Figure 3.

The proposed classification

The classification of wetlands proposed here has been developed by combining the various components of water and landform. Using primary subdivisions of cross-sectional landform geometry there are recognised:

- basins
- channels
- flats

Within the category of basin, using primary subdivision of water there are recognised:

- permanently inundated types
- seasonally inundated types
- seasonally waterlogged types.

Within the category of channels there are:

- permanently inundated types
- seasonally, or intermittently, inundated types.

Within the category of flats there are:

- seasonally, or intermittently, inundated types
- seasonally, or intermittently, waterlogged types.

This categorisation then allows recognition of 7 main wetland types:

Water Longevity	Landform		
	Basin	Channel	Flat
Permanent inundation	Permanently inundated basin	Permanently inundated channel	—
Seasonal (or intermittent) inundation	Seasonally inundated basin	Seasonally inundated channel	Seasonally inundated flat
Seasonal (or intermittent) waterlogging	Seasonally waterlogged basin	—	Seasonally waterlogged flat

These basic 7 categories require nomenclature so that they may form the primary units of wetland differentiation. Permanently inundated flats and seasonally waterlogged channels are not common wetlands.

The proposed terms for the basic wetland units are:

1. Permanently inundated basin =LAKE
2. Seasonally inundated basin =SUMPLAND
3. Seasonally waterlogged basin =DAMPLAND
4. Permanently inundated channel =RIVER
5. Seasonally inundated channel =CREEK
6. Seasonally inundated flat =FLOODPLAIN
7. Seasonally waterlogged flat =PALUSPLAIN

Some of the terms above are established and well defined previously in the literature and hence have been re-utilised. Others (i.e. sumpland, dampland, palusplain) have been coined in this paper. The rationale for, the definition of, and the origin of the terms are described in Table 2. A comparison of the proposed wetland terms with other previously established terms is provided in Table 3. It should be noted that the terms river and creek are used to denote permanence and intermittency of water flow, respectively; the size of the river or creek is indicated by the use of the scale modifier.

Areas such as damplands and palusplains which are rarely or infrequently inundated do not necessarily qualify to be termed sumplands and floodplains. The characteristic of seasonal waterlogging should be a prevailing, recurring feature and this is the deciding factor in determining the categorisation of a wetland by the longevity and type of its "wetness". The occasional or infrequent flooding of terrain can take place anywhere during torrential rainfall or sheet flooding but such phenomena do not categorise the temporarily inundated land surface as a wetland. An example illustrating how a basin cross sectional geometry interacts with a varying water level to develop 3 categories of wetland (i.e. lake, sumpland and dampland) is presented in Figure 5.

Further uses of water and landform descriptors/modifiers are implemented to elaborate and ornament the nomenclature of the primary units. For example, the Swan Coastal Plain contains numerous examples of freshwater large scale ovoid, permanently inundated basins, that remain fresh throughout the year; these would be simply and obviously termed freshwater, stasohaline macroscale, ovoid lakes. Lake Coogee for instance is a hyposaline, stasohaline, macroscale, ovoid lake; Lake Joondalup is a freshwater, stasohaline macroscale lake; Lake Pinjar is a freshwater, stasohaline megascale sumpland.

The full range of descriptors/modifiers are listed in Figure 3. A variety of wetland types developed by various combinations of water and landform features are listed in Table 4 together with some examples of each. Figure 6 illustrates a typical range in geometry and size of various wetlands in the Darling System.

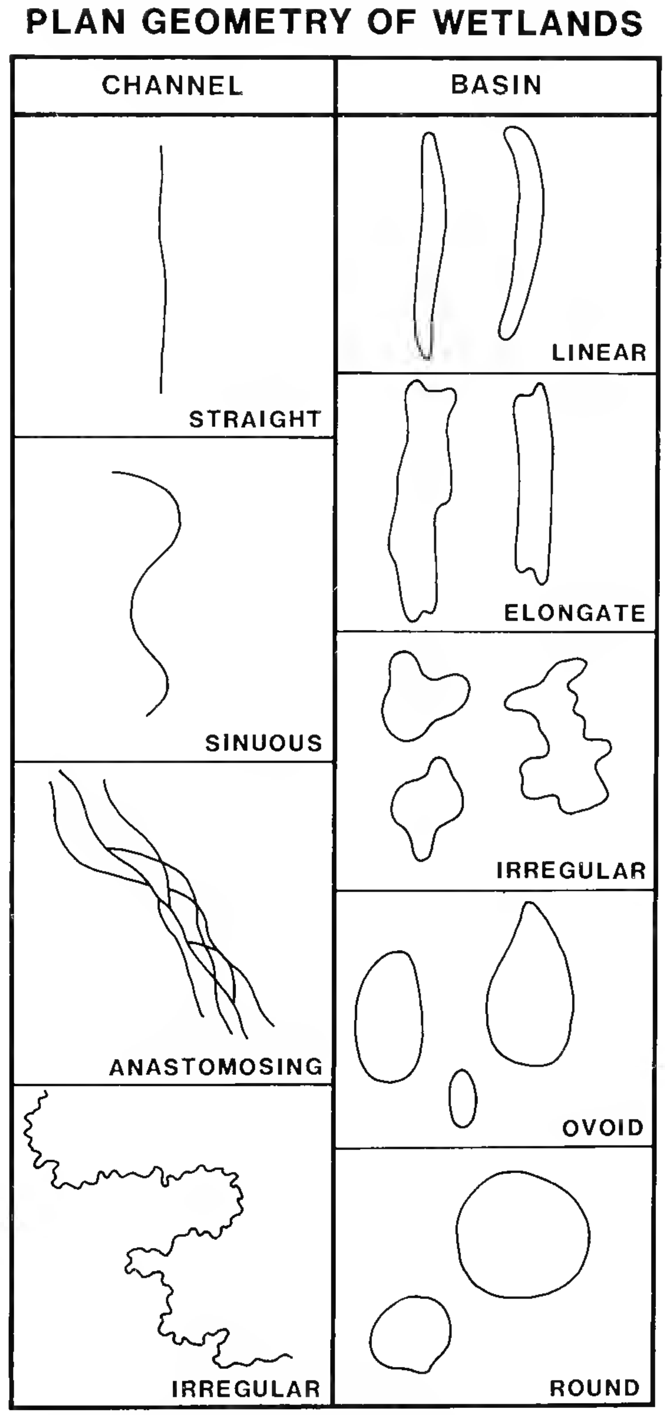

Figure 4.—Plan geometry of basin and channel wetlands.

Table 2

Definition and origin of terms

Wetland term	Definition	Defined by	Origin of term	Usage in this paper
Lake	Permanently inundated basin of variable size and shape	Mill (1900-1910) Monkhouse (1965) Bates & Jackson (1980) Fairbridge (1968) Ruttner (1953)	Established term, from Latin *lacus*, a hollow.	The usage in this paper does not distinguish between shallow lakes and deep lakes.
Sumpland	Seasonally inundated basin of variable size and shape	This paper	After "sump" meaning site of water retention or ponding or accumulation; The term is fortuitously similar to "sumpf" the German term for swamp	As defined.
Dampland	Seasonally waterlogged basin of variable size and shape	This paper	After "damp" meaning moist or wet. Thus it refers to a dampness or waterlogging of soils of some basin wetlands	As defined.
River	Permanently inundated channel of variable size and shape	Swayne (1956) Trowbridge (1962) Morisawa (1968)	Established term from Latin of most *rivus*, a stream (Shipley 1982)	This usage conforms with the concept of other authors that a river is defined as channelled water flow, but is different to most authors in its necessity for permanence of water. The permanence of water, also generally implies a channel of large rather than small size.
Creek	Seasonally inundated channel of variable size and shape	Whittow (1984) Monkhouse (1965) Trowbridge (1962) Bates and Jackson (1980)	Established term	This usage generally conforms with that of Australia and southwestern U.S.A.
Floodplain	Seasonally inundated flat	Mill (1900-1910) Monkhouse (1965) Moore (1949)	Established term	This differs from other authors in that inundation of the plain need not be linked to a river; in general however a floodplain is associated with a river or creek.
Palusplain	Seasonally waterlogged flat	This paper	After latin *palus* meaning "marshy"; thus the term refers to flats which are similar to dampland basins.	As defined.
Stasohaline	Water of relatively constant salinity remaining in a given salinity field	This paper	After staso (Greek) meaning constant	As defined.
Poikilohaline	Water of variable salinity fluctuating from one salinity field to another	Originally defined Dahl (1956)	After poikilo (Greek) meaning variable	As defined.
Waterlogged	Area in which water stands near, or at the land surface		Established term	Usage conforms with Golet and Larson (1974), Martin *et al.*, (1953) and most other authors.

The use of vegetation in describing and classifying wetlands has always been accepted by wetland workers. Vegetation has been viewed in previous work in terms of: 1) structure, 2) life form, 3) species dominance, 4) percentage cover of area, and 5) zonation. Each of these parameters significantly increase understanding of an individual wetland, and its uniqueness or similarity to other wetlands. The methods for describing vegetation have been thoroughly documented by numerous authors, as have interrelationships with physical chemical and biological variables. Vegetation also becomes important when correlating or establishing ecological linkage for chains or series of wetlands in the same physiographic settings, but because it is a dynamic, responsive and mutable feature, it is suggested that the use of vegetation should only be employed in a later stage description of individual wetlands as opposed to initial stage regional descriptions of wetlands. It is suggested that the use of vegetation be applied in a tertiary or quaternary modifier capacity. As such, it is suggested that vegetation be used as an adjectival modifier to the wetland classification by utilising floristic and structural terms with a primary wetland class. However it should be pointed out that categorisation/classification of wetland vegetation becomes a difficult task where vegetation is not a simple extensive unit but rather concentrically zoned, or in the form of complex mosaics.

The use by many limnologists and biologists (Hutchinson 1957, Wetzel 1983, Ruttner 1953, Bayly

Table 3

Comparison of wetland terms used in this paper with established classifications

This paper	Martin *et al.* (1953)	Cowardin *et al.* (1979)	Golet & Larson (1974)	Paijmans *et al.* (1985)	General European	General N. American
Lake	Open fresh water Deep fresh marshes Open saline water	Lacustrine	Open water Shrub swamp Deep marsh	Lakes Swamp Coastal water bodies	Lake Swamp	Lake Swamp
Sumpland	Wooded swamp Seasonally flooded Basins Shallow fresh marshes Deep fresh marshes Saline marshes Open saline water	Palustrine	Deep marsh Shallow marsh Shrub swamp Wooded swamp Open water	Lakes Swamp	Marsh	Marsh Meadow
Dampland	Fresh meadows Wooded swamp	Palustrine	Meadow	—	—	Meadow
River	—	Riverine	—	River and creek channels	River Stream Creek Brook	River Stream Creek Brook
Creek	—	Riverine	—	River and creek channels	—	Arroyo
Floodplain	Shrub swamp Wooded swamp	—	Seasonally flooded flats	Land subject to inundation	Floodplain	Floodplain Seasonally Flooded flat
Palusplain	Wooded swamp Saline flat Salt meadow?	Palustrine	—	—	—	—

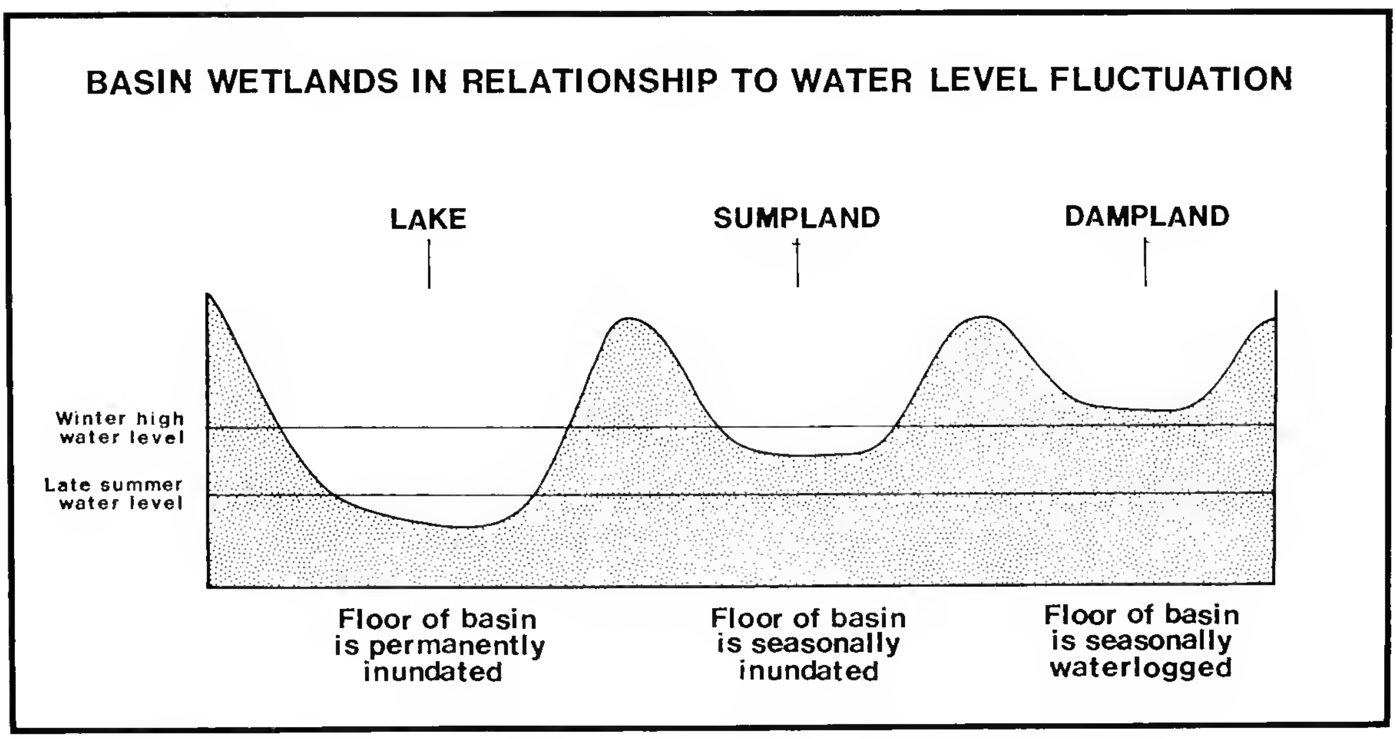

Figure 5.—The development (based on permanence of water) of the 3 basin wetland categories, which in this example are related to landform position with respect to fluctuating water level.

and Williams 1973, Cowardin *et al.* 1979) of the terms limnetic and littoral to denote physical regions of a basin wetland is important in this classification. By denoting these separate zones, a wetland can be viewed in its entirety rather than as two or more separate wetlands e.g. the gradation from inundated surface to waterlogged soil may be seen as a continuous system. Thus the exposed marginal zone of a lake need not be viewed as a sumpland, but rather as a littoral zone.

Application of the proposed classification to wetlands of the Darling System

Several areas in different physiographic regions have been selected to indicate the practical use of the proposed classification and to display the range of wetlands occurring throughout the Darling System in their variability of geometry, size, and salinity. Figure 7 presents maps from four different geomorphic settings on the Swan Coastal Plain (McArthur and Bettenay 1960) and illustrates a range of wetland types in each selected area. Figure 8 presents hydrographs of selected wetlands from these areas to illustrate their hydrologic properties. The areas selected are:

1. Gnangara area
2. Ballajura area
3. Coogee area
4. Pt. Becher area

Table 4

Classification of some typical wetlands in the Darling system

Wetland	Primary Category	Full Classification *
Lake Joondalup	lake	macroscale, elongate fresh, stasohaline, lake.
Lake Bambun	lake	mesoscale, round subsaline stasohaline, lake.
Lake Coogee	lake	mesoscale, elongate hyposaline stasohaline, lake.
Lake Bibra	lake	macroscale, irregular fresh, poikilohaline, lake
Lake Cooloongup	lake	macroscale, ovoid hyposaline poikilohaline, lake.
Carine Swamp	sumpland	mesoscale, ovoid fresh, stasphaline, sumpland.
Lake Pinjar	sumpland	macroscale, ovoid fresh, stasphaline, sumpland.
Bollard Bullrush Swamp	sumpland	macroscale, round fresh, poikilohaline, sumpland.
Melaleuca Park	sumpland	microscale, ovoid fresh, poikilohaline, sumpland.
Stable Swamp	sumpland	microscale, linear fresh, stasohaline, sumpland.
Lake Bindiar	dampland	mesoscale, round fresh, stasohaline, dampland.
Lake Adams	dampland	macroscale, ovoid fresh, poikilohaline, dampland.
Yalbanberup Pool	river	mesoscale, sinuous hypersaline, poikilohaline, river.
Ellen Brook	creek	microscale, sinuous fresh, poikilohaline, creek.
Collie River tributory at Schotts	creek	microscale, straight fresh, stasohaline, creek

* Information for this classification based on 3 years of seasonal surveys.

The Gnangara area (Fig. 7) set in the Bassendean Dune system of McArthur and Bettenay (1960) is dominated by numerous unnamed microscale, round stasohaline, freshwater, sumplands and damplands. Lake Gnangara itself was an isolated macroscale, round, stasohaline freshwater lake; in recent years it has changed to being a sumpland. Snake Swamp is a mesoscale, ovoid, stasohaline, freshwater dampland. Badjerup Lake is a mesoscale, ovoid, stasohaline, freshwater sumpland.

In contrast, the Ballajura area set in the Bassendean Dune system and Pinjarra Plain alluvial system of McArthur and Bettenay (1960), contains wetlands that are mesoscale, straight and sinuous stasohaline creeks, a mesoscale, freshwater, poikilohaline river, mesoscale to macroscale floodplains which are poikilohaline, and microscale, freshwater, stasohaline sumplands and damplands.

The Lake Coogee area set in the Spearwood Dune System of McArthur and Bettenay (1960) has the following wetlands: Lake Coogee North is a mesoscale, elongate, poikilohaline, mesosaline sumpland; Lake Coogee South is a mesoscale elongate, stasohaline, hyposaline lake; the Henderson wetland complex is comprised of mesoscale, elongate, poikilohaline, freshwater sumplands; and Brownman's Swamp is a mesoscale ovoid, poikilohaline freshwater sumpland.

The Pt. Becher area, set in the Quindalup Dune system of McArthur and Bettenay 1960, is one in which microscale, ovoid, linear to irregular shaped, poikilohaline freshwater sumplands and damplands predominate.

Discussion

Wetlands are inherently complex ecological habitats but their analysis is simplified somewhat by a classification which brings into prominence the important wetland components of water and landform. Since there are only seven basic geomorphic wetland types, to which are added modifiers/descriptors of scale, plan geometry, and water properties, the classification enables one to distinguish a practicable number of wetland types. The basic wetland categories can then be ornamented/embellished to illustrate further variability with the addition of more detailed field information. But even without the more detailed studies a given wetland still can be readily classified into the primary categories with a minimum of field surveys. Thus the approach provided here has the advantages when additional detailed information becomes available of increasing the discrimination of individual wetlands from each other and from their surrounding areas; with less precise information available, categorisation at a broader level into a regional physiographic setting is also feasible.

The proposed classification also can provide useful mapping units since the various wetland types may be readily identified and mapped as categories. The regional differences and similarities between wetlands also would emerge more clearly and may be linked to other types of mapping parameters, e.g. contours, climate, geology. The "dry" wetland types in the Darling System, i.e. the damplands, which in the past were in some cases excluded, or included as wetlands on the basis of mixed criteria, can now be consistently identified as a category of wetland.

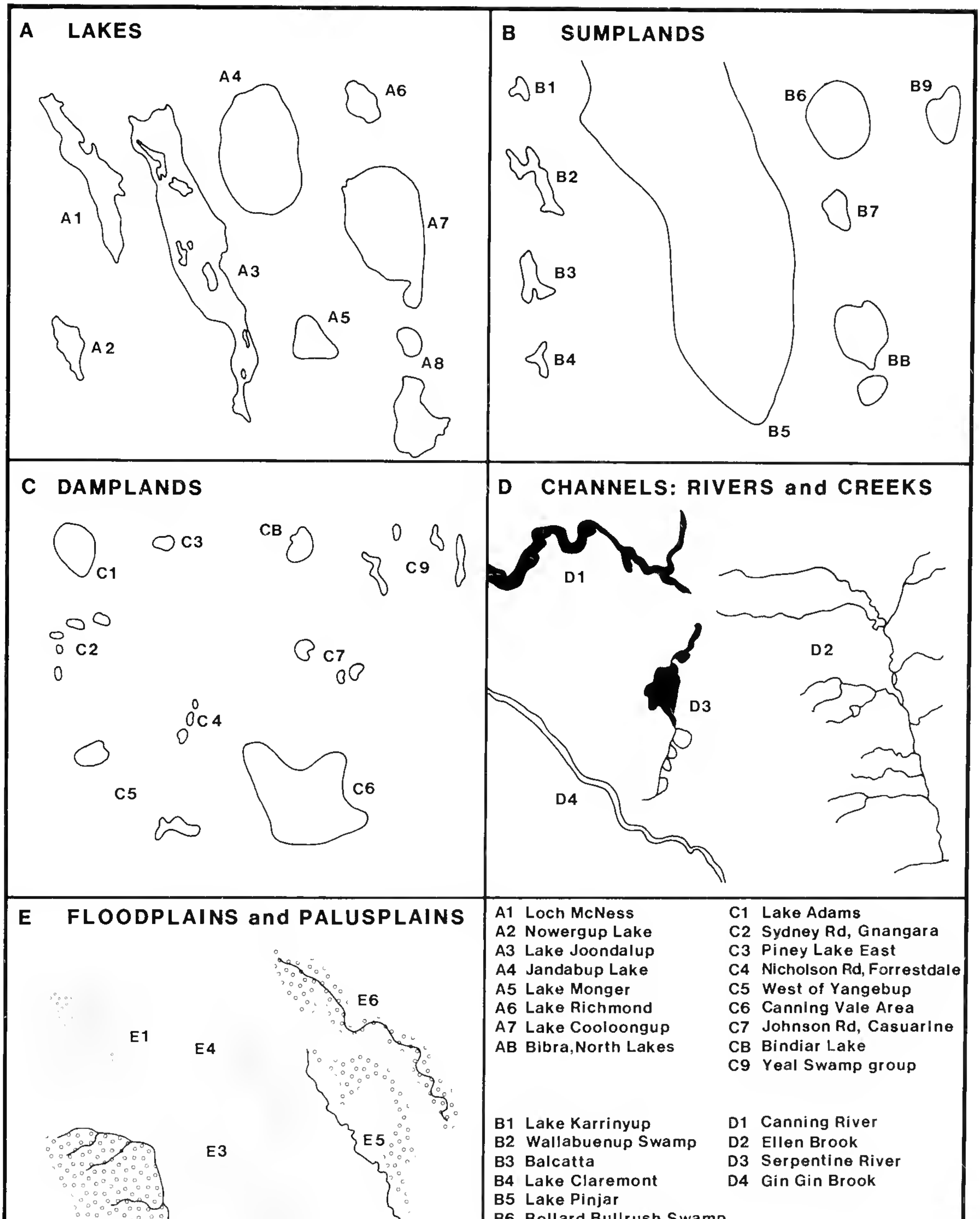

Figure 6.—Typical range of wetland categories in the Darling System.

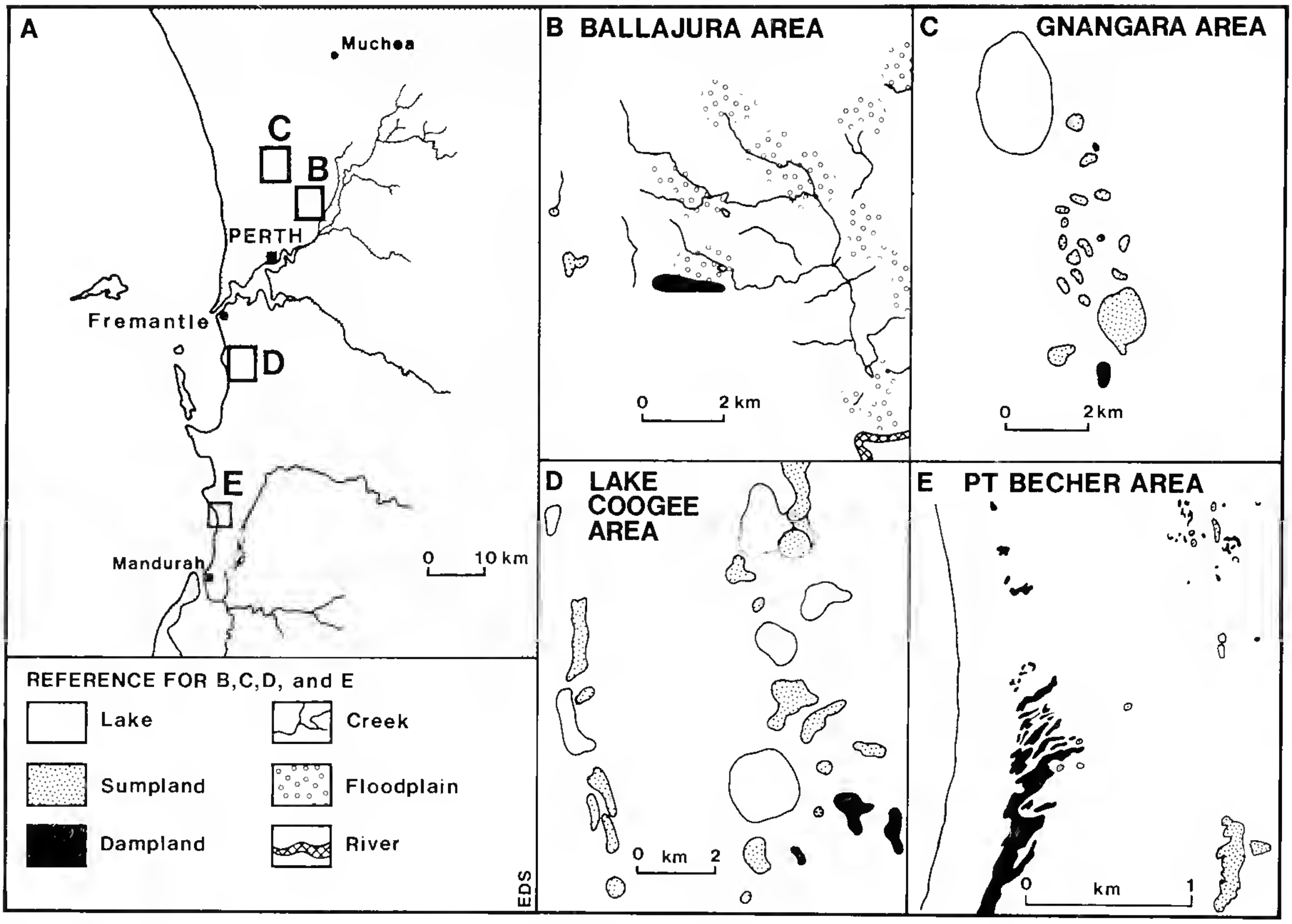

Figure 7.—Maps showing types and distribution of wetland categories for four selected areas.

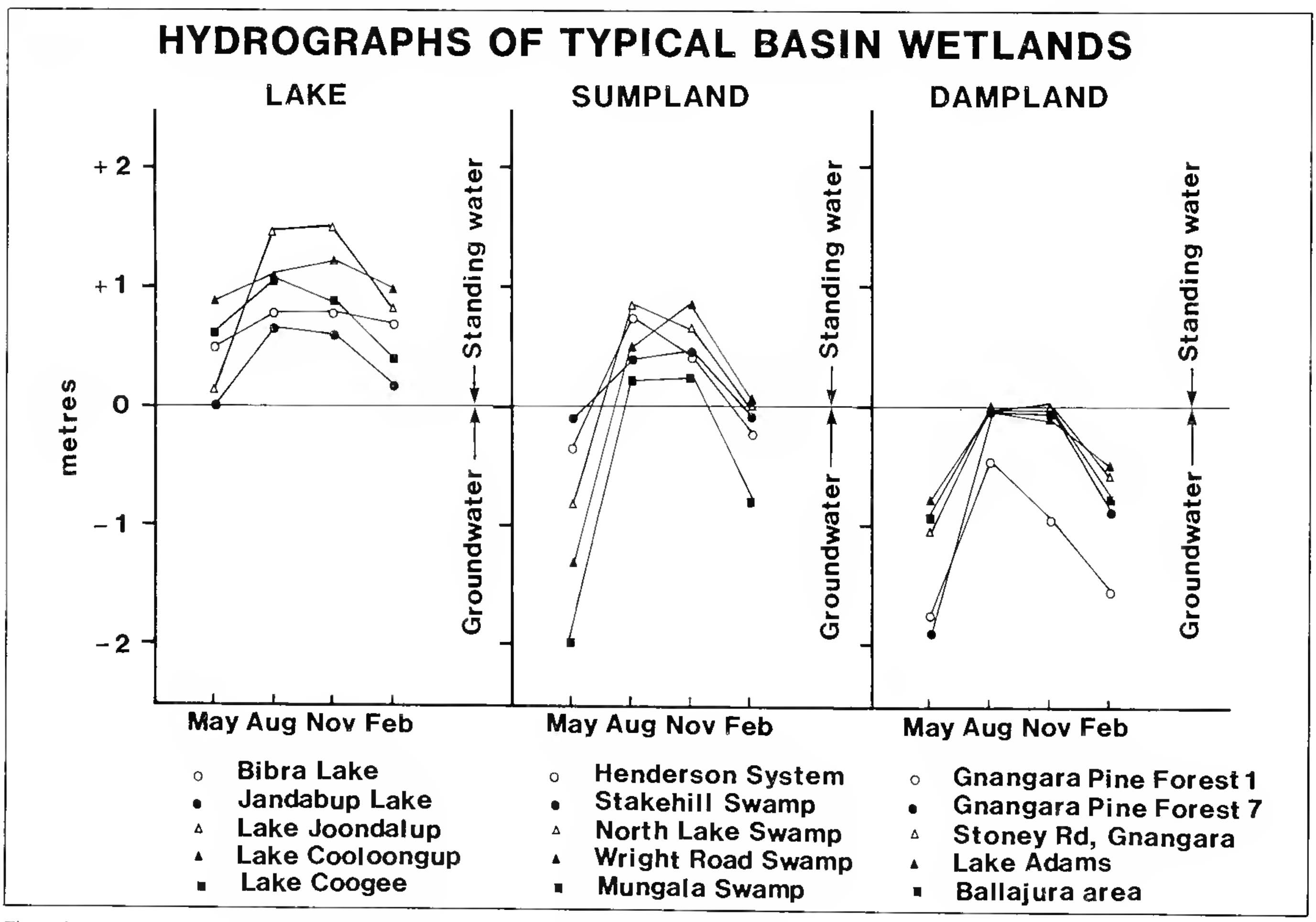

Figure 8.—Hydrographs of some typical basin wetlands on the Swan Coastal Plain.

Various wetland categories have a range of multifarious ecological functions and the proposed classification may parallel these functional delineations. For instance lakes, damplands and creeks are utilised by fauna in different ways because each of these wetlands are essentially different habitats as determined by the longevity and type of water input. For example some avifauna and reptiles use open water lakes for a specific range of purposes, whereas the vegetated sanctuary of many typical damplands may be utilised by mammals and other species of avifauna in a different capacity. Nutrient pathways and trophic inter-relationships also may be fundamentally distinct between these various primary wetland types. Botanists, zoologists, educationalist, recreational and land use planners may be able to make preliminary assessments of the diversity, dependence, complexity etc. of wetlands from the class to which it belongs. The advantage of the proposed classification also is that it can be used as a basis for any wetland study regardless of the ultimate discipline of the study (e.g. hydrology, stratigraphy, botany, zoology), and so circumvents the problem of a proliferation of nomenclature arising from specific applications/studies. Thus it provides a non-genetic framework upon which to base further detailed work.

Finally it is apparent that with the proposed classification a wetland can still be placed in its appropriate category even if it has been substantially altered by clearing of vegetation and disturbance of soils. As long as the mechanisms of water maintenance and basic geometry have not been destroyed then the inherent geomorphic wetland entity remains and can be identified and named.

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Rb-Sr Geochronology of granitoids from Mount Mulgine, Western Australia

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Abstract

The Mulgine Granite is highly fractionated with greisen sheets containing tungsten-molybdenum mineralisation. The Mulgine Granite forms a dome-shaped body which has been intruded by an unmineralised discordant porphyritic-biotite adamellite.

The best estimate of the Rb-Sr whole rock age and initial $^{87}Sr/^{86}Sr$ ratio of the Mulgine Granite is 2684 ± 79 Ma and 0.701 ± 0.005 respectively. It is unlikely that it had an extended crustal pre-history. The cross-cutting porphyritic-biotite adamellite has a Rb-Sr whole rock age of 2596 ± 35 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.704 ± 0.004. Although the experimental errors do not show a significant difference in the ages, the isotopic data indicate that the porphyritic-biotite adamellite is younger than the Mulgine Granite; a result consistent with the field relationships. A subset of the samples of the porphyritic-biotite adamellite gives an approximate Rb-Sr whole rock age of 2330 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.713. Two Rb-rich samples of granitoid from the Mulgine Granite give similiar model Rb-Sr ages which indicate that a later thermal event has affected both granitoid suites.

Introduction

The Yilgarn Block in Western Australia is one of the largest segments of Archaean crust in the world. Gee *et al.* (1981) subdivided the Yilgarn Block into three granitoid-greenstone provinces (the Murchison, Southern Cross and Eastern Goldfields provinces), and a predominantly gneissic terrain (the Western Gneiss Terrain), which occupies an area around the western periphery of the granitoid-greenstone province.

Granitoids account for about 70 per cent of the crustal exposure of the Yilgarn Block, which has an area of approximately 650,000 km^2 (Gee *et al.* 1981). Older synkinematic granitoids have been described by Archibald and Bettenay (1977) and Watkins and Tyler (1985) in the Kalgoorlie and Cue districts of the Yilgarn Block respectively. Younger post-tectonic granitoid batholiths intrude these foliated rocks.

The most common compositional types in both synkinematic and post-tectonic plutons are adamellite and granodiorite in contrast to many other granitoid-greenstone terrains where more tonalite and trondjemitic rocks predominate (Libby 1979).

In the Murchison Province the greenstone belts are intruded by a number of discrete or coalescing ovoid plutons (Muhling 1969). The synkinematic granitoids are emplaced prior to deformation and metamorphism within the greenstone belts (Watkins and Tyler 1985), each commonly containing co-planar foliation. Deformation and metamorphism in the synkinematic granitoids and greenstone belts are consequently often co-eval.

From an extensive Rb-Sr whole-rock study of granitoids and gneisses across most of the Yilgarn Block, Arriens (1971) found three distinct episodes between 3100-2900 Ma, 2700-2550 Ma and 2300-2200 Ma. Arriens pointed out that many of the granitoids which had Rb-Sr ages between 2700 and 2600 Ma have an initial $^{87}Sr/^{86}Sr$ ratio of approximately 0.704 suggesting a crustal pre-history for these samples. Arriens (1971) estimated that these granitoids could not have existed for longer than 120 Ma as crustal materials, assuming an average Rb/Sr ratio for the granitoids of 0.85. However, Gee *et al.* (1981) argue that this period of crustal prehistory may be 200 to 400 Ma in duration. Oversby (1975) considers that the high μ values recorded in some Eastern Goldfields granitoids indicates that these rocks had existed as crustal material for at least 300 Ma before the ~ 2600 Ma tectono-thermal event. On the other hand Bickle *et al.* (1983) argue that Pb-Pb whole rock isotopic data from synkinematic plutons in the Diemals area indicate that the crustal history of the precursor material is less than ~ 200 Ma.

De Laeter *et al.* (1981a) have reviewed the geochronological data in the Yilgarn Block. Few results from the Murchison Province have been reported. Granitoids from the Cue-Mount Magnet-Paynes Find region give a Rb-Sr whole-rock age of 2706 ± 264 Ma (Arriens 1971). Two muscovites from Mount Mulgine give model Rb-Sr ages of 2632 and 2614 Ma (Arriens, 1971). Muhling and De Laeter (1971) also reported Rb-Sr whole-rock ages for granite-adamellite and granodiorite from the Poona batholith (a complex granitoid body east of Cue), of 2535 ± 23 Ma and 2550 ± 51 Ma respectively. Fletcher (Pers. Comm.) has obtained Sm-Nd model ages of 2820 Ma and 2730 Ma on two of these samples.

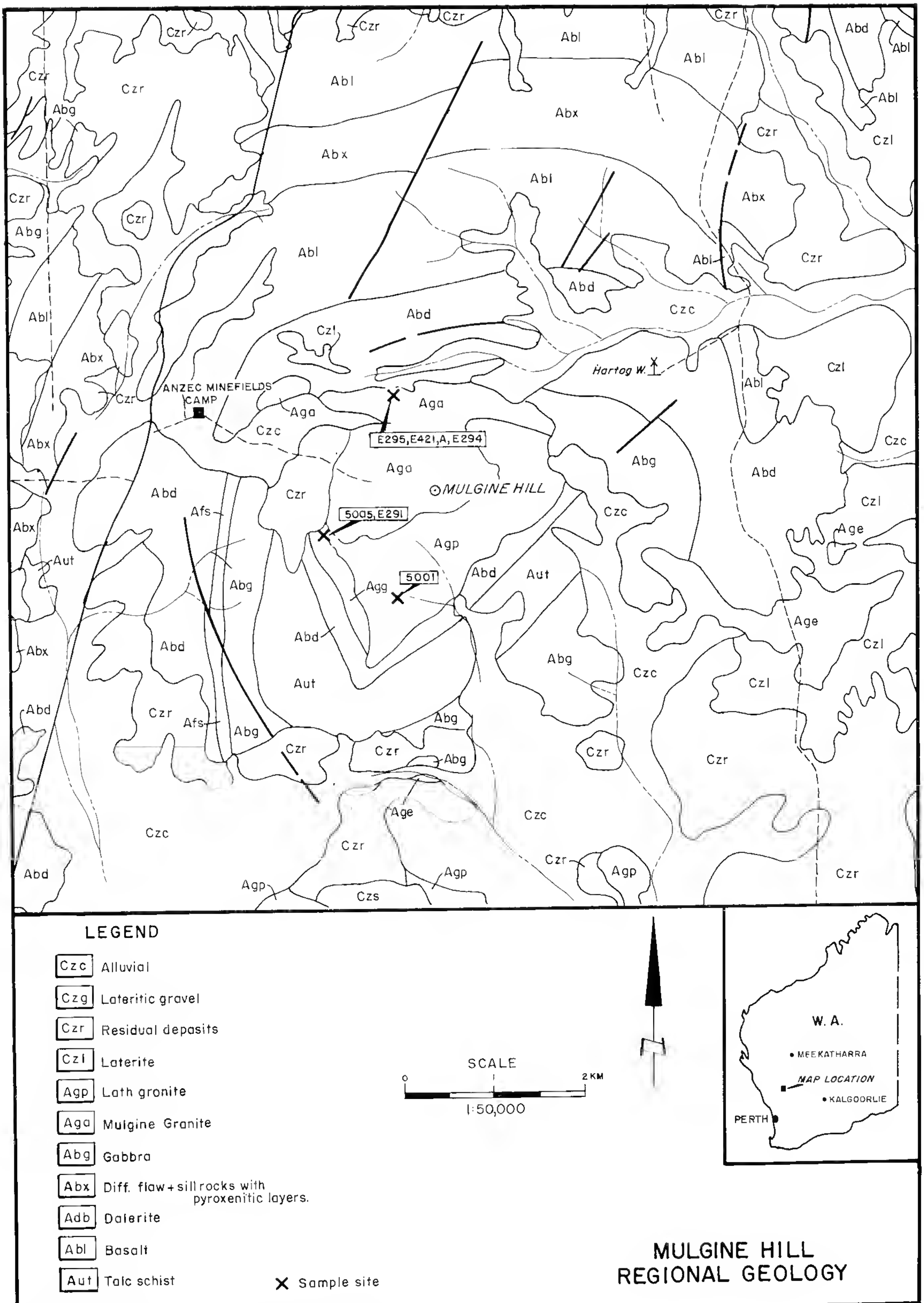

Figure 1.—Regional map of Mount Mulgine in the Murchison Province of Western Australia.

Geology of the area

The Mt. Mulgine district contains a mafic volcanic supracrustal succession intruded by the synkinematic Mulgine Granite and a discordant porphyritic (lath granite) adamellite (Fig. 1). Both granitoid suites are unusually highly fractionated with Rb-Sr ratios ranging from 0.88 to 49.5.

The Mulgine Granite is a 1 km diameter ovoid stock near the axis of a regional anticline. The northern, eastern and western margins of the stock are parallel to layering in the adjacent volcanic sequence (Baxter 1979). Foliation and lineation in the volcanic rocks and the granite are parallel. Greisen sheets intrude the volcanic sequence along the northern perimeter of the stock. The greisen has induced polymetallic scheelite-molybdenite-fluorite mineralisation in potassium metasomatized ultramafic rocks in the adjacent volcanic sequence. Pegmatites and greisen sheets associated with the Mulgine Granite occur up to 2 km from the stock contact. The volatile rich nature of the Granite is indicated by the wide halo of hydrothermal alteration around the stock.

Porphyritic-biotite adamellite intrudes the southern margin of the Mulgine Granite (Fig. 1). This is an apophysis of a batholith of coarse-grained porphyritic and even-grained adamellite lying to the south and east of Mulgine Hill.

Experimental procedures

Samples were reduced to -200 mesh using a jaw crusher and an agate Tema-type mill. After chemical extraction, the samples were analysed in a 30.5 cm radius of curvature, 90° magnetic sector field, solid source mass spectrometer. Techniques are essentially those reported by De Laeter *et al.* (1981b).

The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard was 0.7102 ± 0.0001 normalised to a $^{87}Sr/^{86}Sr$ value of 8.3752. A value of $1.42 \times 10^{-11} yr^{-1}$ was used for the decay constant of ^{87}Rb. All the Rb-Sr ages quoted in this paper have been corrected where necessary, to this decay constant. The data have been regressed using the least squares programme of McIntyre *et al.* (1966). All errors are given at the 95% confidence level.

Results and discussion

Two suites of samples were available for analysis—the Mulgine Granite and the postkinematic discordant porphyritic-adamellite. Isotopic data are listed in Tables 1 and 2 for these two granitoids.

Mulgine Granite

Initially nine samples of the Mulgine Granite were collected and subsequently analysed. Seven of the nine samples form an isochron with an age of 2694 ± 30 Ma and initial $^{87}Sr/^{86}Sr$ ratio (R_I) of 0.7000 ± 0.0018 (Fig. 2). The mean square of weighted deviates (MSWD) is 6.3, indicating that there is a real dispersion in the data greater than the experimental errors associated with the measurements. A better estimate of the age, initial ratio and associated errors is 2684 ± 79 Ma and R_i = 0.7007 ± 0.0053. This Model 4 age implies a real scatter in age and initial ratio. Taking into account the average Rb/Sr ratios of these samples, it is unlikely that there was an extended period of crustal pre-history for these samples. The remaining two samples (numbers 255 and 247) have a much higher Rb/Sr ratio with respect to the group, and give model ages of 2362 Ma and 2282 Ma respectively. The choice of initial ratio does not affect the model ages to any significant extent.

Subsequently, another five drill-core samples of the Mulgine Granite were obtained, and if these are combined with the original seven samples, a Rb-Sr whole rock age of 2644 ± 17 Ma and R_i = 0.7026 ± 0.0012 is obtained with a MSWD of 28. Thus the effect of the additional samples is to increase the scatter in the data, and to lower the age slightly. A Model 2 assessment of the age, initial ratio and errors is 2643 ± 87 Ma and R_i = 0.7026 ± 0.0061 respectively.

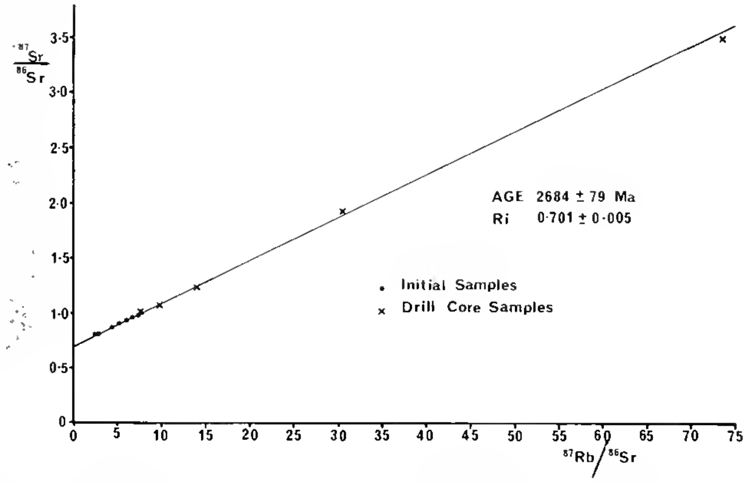

Figure 2.—$^{87}Sr/^{86}Sr$ vs $^{87}Rb/^{86}Sr$ isochron diagram for the Mount Mulgine Granite.

It is of interest to note that the average age for the two muscovite samples reported by Arriens (1971) is 2623 Ma. These two samples, presumably from pegmatites associated with the Mulgine Granite, were obtained from drill-core by Newmont Pty Ltd, who held leases for molybdenum prospecting at Mount Mulgine. The Rb/Sr values for these muscovites are exceptionally high.

Porphyritic Adamellite

Ten samples of the porphyritic-biotite adamellite were originally analysed and the results are displayed in Figure 3. Six of the ten samples fall on an isochron of age 2570 ± 65 Ma and R_i = 0.7055 ± 0.0071 with a MSWD

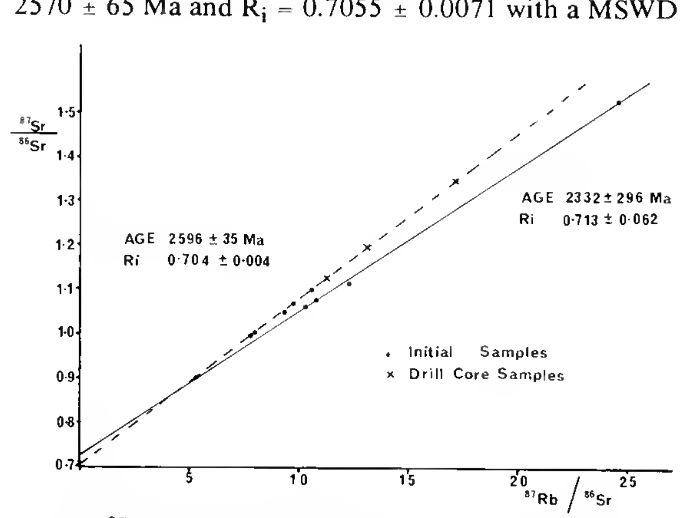

Figure 3.—$^{87}Sr/^{86}Sr$ vs $^{87}Rb/^{86}Sr$ isochron diagram for the porphyritic-biotite granitoid from Mount Mulgine.

of 2.4. Subsequently three additional samples were analysed, and if the resulting nine samples are fitted to an isochron, an age of 2596 ± 35 Ma and R_i = 0.7039 ± 0.0043, with an improved MSWD of 1.8 is obtained.

The remaining four samples (numbers 270, 266, 267 and 271) give a poorly fitted isochron with a Model 3 age and initial ratio of 2332 ± 296 Ma and 0.7133 ± 0.062 respectively. This age, despite its large error, is in good agreement with the average model age 2322 Ma, of samples 255 and 247 from the Mulgine Granite.

Conclusion

The Rb-Sr whole rock analyses of two suites of granitoids from the Mount Mulgine district indicate that the Mulgine Granite is older than the discordant porphyritic-biotite adamellite, thus supporting the field relationships. The low initial ratio of the Mulgine Granite suggests that the rocks were derived from the mantle, with a relatively short crustal history prior to the Rb-Sr isochron age. The best estimate of this whole-rock age is 2684 ± 79 Ma with an initial ratio of 0.701 ± 0.005. However if one takes into account all the isotopic evidence available, it could be argued that an age of approximately 2650 Ma and an initial ratio of 0.702 is more appropriate for the Granite.

The discordant porphyritic biotite adamellite gives a younger age of 2596 ± 35 Ma with an initial ratio of 0.704 ± 0.004. In terms of the errors associated with the two sets of samples, it is not possible to state that the ages and initial ratios are significantly different, although the isotopic data are consistent with the field evidence.

A subset of the porphyritic adamellite suite gave an approximate age of 2330 Ma with a high initial ratio of 0.713. This younger age is in good agreement with model ages from two Rb-rich samples from the Mulgine Granite, and reflects a younger Proterozoic metamorphic event which has reset some of the samples from each granitoid suite. It is possible that this event could be associated with the basic magmatic emplacement of Proterozoic dykes in the Yilgarn Block.

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