Dependence of Ecosystems on Groundwater and its Significance to Australia

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Occasional Paper No 12/98

Land & Water Resources
Research & Development Corporation

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Published by:

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Publication data:

'Dependence of Ecosystems on Groundwater and its Significance to Australia' by Tom Hatton and Richard Evans, LWRRDC Occasional Paper No 12/98.

ISSN 1320-0992

ISBN 0 642 26725 1

Typesetting: Mastercraft, Canberra

Printing: The Communication Station, Canberra

August 1998

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Executive Summary

The role which groundwater plays in controlling ecosystems in Australia is very poorly understood. With a few notable exceptions, there is virtually no literature specific to this very important topic. As an unseen and poorly understood resource, groundwater nonetheless fundamentally controls the health of major ecosystems across Australia. To help ensure the continued health of these ecosystems, LWRRDC has commissioned this report to provide a basis upon which to identify issues where further research and investigation are required.

This report is aimed at identifying ecosystems which are dependent on groundwater for all of Australia. Groundwater is defined, for the purpose of this report, as that water which has been below ground and would be unavailable to plants and animals where it to be extracted by pumping. This relatively narrow definition is to avoid having to consider many other types of water found in the biosphere. Four major types of ecosystems are considered with respect to groundwater dependency:

1. Terrestrial Vegetation

   Terrestrial vegetation may depend to varying degrees on the diffuse discharge of shallow groundwater, either to sustain transpiration and growth through a dry season or for the maintenance of perennially lush ecosystems in otherwise arid environments. Note that in such cases the vegetation itself may induce groundwater discharge to the atmosphere.

2. River Base Flow Systems

   Stream flow may have a component of base flow whose origin is groundwater discharge; this base flow may be vital to the character and composition of in-stream and near-stream ecosystems.

3. Aquifer and Cave Ecosystems

   Hypogean life exists in a continuum through different types of karstic, cave, porous and fissured aquifers.

4. Wetlands

   For the purposes of this report, we only consider those wetland systems with a known or likely component of groundwater discharge in their hydrologic cycle. We also include mound spring vegetation in this category.

Fauna that have a dependence on groundwater that is not linked to vegetation is acknowledged as being important. However this topic is largely undocumented and although not discussed in detail in this report, identified examples are cited.

The principal criterion adopted in this report is that the degree of the dependence on groundwater is proportional to the fraction of the annual water budget that ecosystem derives from groundwater. Other criterion such as uniqueness and vulnerability are seen as of secondary importance. Technical methods and approaches to assess dependence are discussed.

An extensive literature search has been undertaken to describe all those cases throughout Australia where a dependence, or lack thereof, on groundwater has been demonstrated or inferred. Knowledge regarding the response of Australian ecosystems to groundwater level changes is limited.

Cases of both a reduction in groundwater availability to support ecosystems and an increase in groundwater availability (for example, salinity), are presented.

The literature is presented both by region (using the Jennings and Mabbutt (1977) geographic classification system for Australia) and by vegetation type. The diverse range of ecosystems identified throughout Australia are grouped as follows:

- Ecosystems entirely dependent on groundwater
- Ecosystems highly dependent on groundwater
- Ecosystems with proportional dependence on groundwater
- Ecosystems which may only use groundwater opportunistically or to a very limited extent
- Ecosystems with no apparent dependence on groundwater

Ecosystems which are entirely dependent on groundwater represent less than 1% of the land area of Australia, and a similar fraction is occupied by ecosystems highly dependent on groundwater. Those systems which are proportionally dependent on groundwater cover less than 5% of the nation. However, given the low rainfall characteristic of most of Australia, these relatively well-watered ecosystems have an importance far in excess of their geographic extent.

The systems identified as entirely dependent on groundwater are also often unique, viz Great Artesian Basin Mound Springs, lakes of the Swan Coastal Plain, Exmouth Cape Karst Groundwater Ecosystems, and water holes of the Central Australian Ranges. Perhaps the only exception to this are the stream side red gum stands in the interior of the country; these are extensively distributed.

Many highly dependent ecosystems are identified. Some are local and specific, others cover large areas and are general. For example, most streams originating from the Great Dividing Range in South-Eastern Australia show a base flow which is highly dependent on groundwater discharge.

Even through the primary focus for assessing the dependence of ecosystems was related to groundwater development, nonetheless where appropriate, pollution and land use changes, as they relate to possible changing water levels, have also been considered.

Wetlands in general are more vulnerable to changes in groundwater level compared with the other three ecosystem classes in this report.

Dealing with the four major ecosystem classes this project concludes:

1. Vegetation

   The extent and degree of dependence of non-wetland vegetation on groundwater is only just beginning to be understood. There is a relatively poor understanding of how adaptive vegetation is with respect to changing the depth, quality and regime of groundwater and how opportunistic vegetation can access groundwater.

2. Base Flow Systems

   There is no national data for comparison and prioritisation of the groundwater contribution to streams across Australia. On the basis of Victoria alone, base flow comprises, for the greatest number of natural catchments, between 40% to 50% of the total stream flow. Some fraction of this is groundwater in origin. In arid and semi-arid regions, it is likely that base flow will be much less but perhaps of greater ecological significance. Ecosystem dependence is not solely related to the amount of base flow but perhaps more importantly to the variability and predictability of flow.

3. Aquifer Ecosystems

   Virtually nothing is known about Australia's aquifer ecosystems, their importance in terms of biodiversity, and their importance to the systems into which they discharge.

4. Wetlands

   Few groundwater dependent wetland ecosystems have been extensively studied, except for some systems on the Swan Coastal Plain and mound group of the Great Arterian Basin. Most of the wetlands with likely high dependence have been subject to little or no investigation in this regard. Clearly, groundwater plays a role in most of Australia's wetlands. This role may vary, however, from minor to essential. Not all wetlands are groundwater dependent.

Three maps are produced which attempt to describe terrestrial vegetation, wetlands and river base flow systems. The vast majority of dependent ecosystems have a relatively small local extent which cannot be shown at the scale of 1:5,000,000.

The general level of understanding of the role of groundwater in maintaining ecosystems throughout Australia is very low. Groundwater resource managers and investigators tend to underestimate ecosystem vulnerability with respect to groundwater development, pollution and land use change, although there is greater awareness in some regions such as South-Western Western Australia.

The translation of the COAG (1996) concept of provision for the environment, in a groundwater sense, is poorly defined. Planning must recognise ecosystem dependence on groundwater and related processes. This is perhaps best achieved through the development of groundwater management plans.

Introduction: Scope and Definition

Aim

The role which groundwater plays in controlling ecosystems in Australia is very poorly understood. With a few notable exceptions, there is virtually no literature specific to this very important topic. Groundwater movement is unseen and poorly understood. Exploitation of groundwater resources for irrigation and many other uses, has the potential to significantly alter groundwater levels and groundwater behaviour. In addition, many land use practices also change groundwater behaviour. These groundwater processes, it is postulated, may fundamentally influence and control the health of many ecosystems, at both a local and regional scale, across Australia.

To ensure the continued health of these ecosystems, LWRRDC has commissioned this report to provide a basis upon which to identify issues where further research and investigation is required.

Geographic Scope of the Assessment

This report examines ecosystem dependence on groundwater for all of mainland Australia, Tasmania, and near-shore islands (eg. Kangaroo, Fraser Islands). It also considers estuarine and near-shore marine ecosystems which may have a dependency of groundwater from terrestrial sources.

Definition of Groundwater

The meaning of the term *groundwater* was defined with respect to this report in a somewhat more narrow way than the meaning it may have to the wider community. Were we to take its widest possible meaning *(water in the ground*, or even, *water in the ground in a saturated state*), then it becomes impossible to distinguish among Australia's ecosystems with respect to dependency. All terrestrial systems have soils which saturate at one time or another due to perching, saturation-excess rainfall, or deeper and/or more regionalised processes which we traditionally associate with *groundwater*. This report focusses on this latter notion of an extensive and persistent aquifer system, but even then it is hard to explicitly define.

For the purposes of identifying ecosystem dependence, we define groundwater as that water in the system which would be unavailable to plants and animals were it to be extracted by pumping. Thus, we exclude for example transient shallow (soil), perched systems including shallow throughflow down hillslopes. We include systems which may operate only in the vertical dimension with a watertable which seasonally fluctuates only as a function of point recharge and discharge processes, on the basis that if the water levels were lowered by pumping then supplies to the vegetation would be reduced.

Definition of Ecosystem

The immense complexity and diversity of Australia's biota argues for broad groupings of organisms into units which sufficiently characterise this diversity but at the same time represent the huge array of taxonomic, physiological and ecological information (unevenly) available in a general but appropriate way. The usual nomenclature of ecosystems employed (eg. *savanna woodlands*) typically adopts a phyto-centric view, but is of too coarse of scale to adequately differentiate Australian systems. At the other extreme, this report could not discuss the potential groundwater dependency of each organism in the Australian environment.

The compromise reached was to adopt broad vegetation classes as in Briggs' (1981) treatment of Australian wetlands, recognising that associated with these plant communities are zoological and fungal components. Herein, these assemblages are termed *ecosystems*. We based our approach on the assumption that as the vegetation and waterbodies goes, so goes the fauna. Where it was recognised that this assumption does not necessarily hold, the direct dependence of fauna or microbes was addressed.

Framework for Relating Australian Ecosystems' Groundwater Dependence

Ecosystem Classification Schemes in Australia—Relating these to Groundwater Dependence

The survey, description and discussion of Australian ecosystems dependent on groundwater requires some classification of the diverse ecological and hydrological systems in which the biota and groundwater interact. This is in part necessary due to the fact that in many systems this dependence is either subtle or cryptic, extending beyond the ephemeral or permanent expressions of groundwater at the surface which we might characterise as *wetlands* (*sensu* Paijmans *et al.* 1985). In this report, we adopt and expand the broad nomenclature for wetlands employed by Briggs (1981) to cover the wider range of groundwater dependent ecosytems. Where possible, we identify locally specific, significant biological components as well. Thus, we define four major types of ecosystems with respect to groundwater dependency:

Vegetation

Terrestrial vegetation may depend to varying degrees on the diffuse discharge (root uptake) of shallow groundwater, either to sustain transpiration and growth through a dry season (eg. tropical woodlands) or for the maintenance of perennially lush ecosystems in otherwise arid environments (eg. streamside vegetation like river red gums along usually dry river beds in interior Australia). There are groundwater-dependent forests and woodlands which lack the surface expressions of water normally associated with wetlands, and thus we add to Briggs (1981) classification two additional vegetation types (*upland woodlands, upland forests*). In this regard we also consider tree plantations which may extract groundwater.

River Base Flow Systems

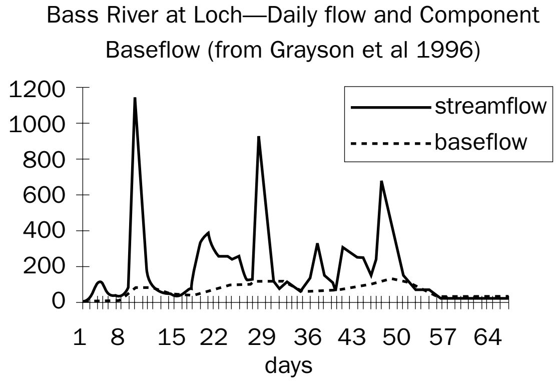
Stream hydrographs may have a component of base flow (*sensu* Boughton 1988) whose origin is groundwater discharge; this base flow may be vital to the character and composition of in-stream and near-stream ecosystems.

Base flow is a purely conceptual quantity resulting from statistical or graphical methods of breaking up a stream hydrograph into components of quick and slow responses to rainfall. These are not directly equivalent to the amount of surface and subsurface (groundwater discharge) flow. Baseflow is made up of several components, such as groundwater discharge, bank storage and lateral unsaturated flow. However, baseflow is generally considered to arise to some significant degree from groundwater discharge to streams. A method used to extract baseflow is a statistical algorithm that provides credible baseflow estimates. It is impossible to identify groundwater discharge from stream flow data alone. Grayson et al (1996) present a brief, cogent treatment of baseflow calculation methods.

It is emphasised that fauna may be especially dependent on rivers that 'dry up' as a result of consumptive use of groundwater resources.

In considering the significance of groundwater processes influencing ecosystems in rivers, it is postulated that several key factors dominate the relative significance of rainfall (and hence runoff) as compared with groundwater discharge, and the differing effects of fractured rocks as compared with porous media aquifers. This consideration leads to several key hypotheses:

Figure 1
Example of base flow derived from streamflow using the method of Nathan and McMahon (1990).



Thesis 1

A key determinant of the dependence of ecosystems on groundwater is the volume of baseflow and its temporal variability, not the mean annual flow of the river.

Thesis 2

In local fractured rock systems, groundwater development and land use changes will be highly variable with respect to impacts on base flow volume and hence ecosystem dependence. In contrast, in regional porous aquifer systems, groundwater development and land use change will be likely to impact on base flow, and hence dependent ecosystems in a more predictable manner.

Thesis 3

Where base flow is maintained in areas of relatively low rainfall (eg. the Broughton River in South Australia) and the base flow is a high proportion of the mean annual flow, it is presumed that there is a greater dependence by the ecosystem on this base flow. That is, a unit change in base flow in a low rainfall region will cause significantly greater effect on ecosystem health than in areas where rainfall is higher and/or the dry season is shorter.

Aquifer Ecosystems

Hypogean life exists in a continuum through different types of karstic, cave, porous and fissured aquifers. Gibert (1996) asserted that life there is as diversified as in the surface biotic milieu, and that aquifers form the most extensive array of freshwater ecosystems on our planet. That these ecosystems exist within the groundwater makes the nature of their dependence absolute, albeit poorly understood and appreciated.

Wetlands

We adopt the basic definition of wetlands from Paijmans *et al.* (1985): land permanently or temporarily under water or waterlogged, with temporary wetlands having surface water or waterlogging of sufficient frequency and/or duration to affect the biota. This is substantially the same as the definition for wetlands in Western Australia (Wetlands Advisory Committee 1977), adopted by Semeniuk (1987) and Hill *et al.* (1996). Note that these do not clearly include the Vegetation and Aquifer ecosystem categories above. For the purposes of this report, however, we only consider those systems with a known or likely component of groundwater discharge in their hydrologic cycle. These ecosystems potentially include all of those systems discussed by Paijmans *et al.* in their extensive review, but also tidal flat and coastal inshore waters whose ecosystems may be dependent on the flux of groundwater either as direct discharge or through base flow discharge at mouths of rivers, and in-stream ecosystems themselves.

There are numerous schemes for classifying wetlands. Paijmans *et al.* (1985) and Semeniuk and Semeniuk (in Hill *et al.* 1996) together give a fairly comprehensive overview of classification schemes and their criteria. For the purposes of this report, the geomorphic classification of wetlands based on landform and water permanence of Semeniuk (1987), as expanded by Semeniuk *et al.* (1990) and Semeniuk and Semeniuk (in Hill *et al.* 1996), provides the clearest link to the role of groundwater in the maintenance of these systems. While it was not within the brief of this study to apply this mapping and classification approach to the entirety of Australia, it is perhaps a useful example or model for such an activity and certainly provides a sound basis for the interpretation and discussion of groundwater-dependant ecosystems in Western Australia. The latest and best description of the approach, supported by a broad literature survey, is in Hill *et al.* (1996); note that these authors provide the equivalent terminology for each of their classes with several other schema including Paijmans *et al.* (1985). In this report, we attempt, in so far as possible, to adopt and apply the Hill *et al.* (1996) terminology to the discussion of Australian wetland ecosystems generally. To wit:

	Landform				
Water Longevity	**Basin**	**Channel**	**Flat**	**Slope**	**Highland**
Permanent Inundation	lake	river			
Seasonal Inundation	sumpland	creek	floodplain		
Intermittent Inundation	playa	wadi	barlkarra		
Seasonal Waterlogging	dampland	trough	palusplain	paluslope	palusmont

(adapted from Hill *et al.* 1996)

Not all of these features involve groundwater in a direct or significant way. As well, these features do not necessarily capture groundwater-dependent ecosystems in aquifers or in upland landscapes. To discuss the latter, additional terminology is invoked. Finally, understanding the nature of the distribution, dependence and vulnerability of ecosystems on groundwater requires the definition of the aquifer systems as local or regional (*sensu* Evans *et al* 1996); in this report, we make this distinction where possible.

The classification described above provides the physical background. Within each of these geomorphic classes, different floristic assemblages (and their associated faunal components) occur. Thus, permanent water in a river may support streamside red gum communities in Southern Australia, but support cajeput communities in the Pilbara.

Briggs (1981) did not identify *mound springs* systems within the classification. While it may have structural and floristic similarity to one or more of the above classes, we add them as an additional vegetation type for completeness and convenience given the inordinate amount of literature available on these systems.

Geography

It is not, however, easy to organise a national assessment strictly on the basis of types of ecosystems as described above. As Paijmans *et al.* (1985) and Semeniuk (1987) both point out, the regional climate and geomorphology control the water balance and movement through ecosystems, and thus it is useful to structure this assessment on a regional basis, at least as far as examples of terrestrial, wetland and river base flow ecosystems are concerned (so little is known about aquifer ecosystems in Australia that it is not necessary to characterise them regionally). The regions used by Paijmans *et al.* (1985) for this purpose, based on Jennings and Mabbutt (1977), are used herein. This regional classification is as follows:

1. **Tropical Northern Australia**
   North-Eastern Uplands
   Carpentaria Lowlands
   North Australian and Kimberley Plateaux

2. **Temperate Uplands**
   South-Eastern Uplands
   South Australian Peninsulas and Kangaroo Island
   South-West of Western Australia
   Tasmania

3. **Murray and Central Lowlands**
   Murray Lowlands
   Central Lowlands
   South Australian Ranges

4. **North-West**
   Pilbara
   Coastal Lowlands

5. **Arid Areas of Uncoordinated Drainage**
   Sandland
   Yilgarn Plateau
   Nullarbor Plain
   Lander–Barkly Plains
   Central Australian Ranges

6. **Coast Zone**
   East coast South of Brisbane
   North of Brisbane
   Coastlands of the Gulf of Carpentaria
   Northern Territory coast
   Kimberley coast
   North-West coasts of Western Australia
   West coast of Western Australia
   South coast of Western Australia
   Coastal Bight
   South Australian Gulfs
   South-East of South Australia
   Victorian coasts
   Tasmanian coasts

Hydrogeological Framework

Groundwater Processes

The processes of groundwater recharge, throughflow and discharge are well-understood in a general way, and locally in Australia may be quantified. Ecosystems may interact with all three of these processes, but will be locally dependent on only the latter two. That is, where through flow systems are near the land surface or at the land surface (lakes, rivers), ecosystems will develop to exploit this water, probably in a dependent way. Where surface waters in a permanent or ephemeral lake are in a recharge mode and develop a local groundwater mound, it is presumed that the ecosystems of that lake are not locally dependent on the groundwater. The magnitude and variation in groundwater processes will depend on the seasonality of recharge processes (rainfall, drought) and water use (natural and through groundwater and surface water management). Note that as a consequence, some sites which are normally in a discharge mode may at times become recharge sites to the aquifer.

Local vs Regional

To understand the importance of groundwater to various ecosystems, it is frequently helpful to be able to separate local from regional groundwater processes. This distinction is useful because the temporal nature of groundwater discharge may vary significantly depending upon the scale of the groundwater process.

Local processes are frequently those involving recharge and discharge occurring within hundreds or thousands of metres of each other. Cause and effect with respect to hydrogeological response are relatively easy to define. These local processes may be strongly influenced by recent climate and land use patterns and hence may exhibit large temporal variability. Ecosystems may develop a more opportunistic dependency on groundwater in such local systems.

At the other extreme, regional processes operate over many kilometres (up to thousands of kilometres). These processes tend to be more temporally invariant , and hence ecosystem dependence may be more complete (the best-known example of such complete ecosystem dependence on a regional system is the mound springs of the Great Artesian Basin).

In practice there is a continuum of scales, from local through intermediate to regional, and hence ecosystem dependence can scale, all other factors aside, along the same continuum. The identification of hydrogeological scale can be a useful indicator of ecosystem dependence.

A related distinction, at a broad level, is the recognition of two basic types of aquifer: one based on porous media and one based on fractured rock. The former are characteristic of large sedimentary basins, and the latter are characteristic of cratons. From the perspective of this report, a functional distinction may be made between these two types. Considering all of Australia, at a broad scale porous media which are exploitable commonly will have a less variable transmissivity than fractured rock. Hence porous media are perhaps more likely to transmit changes in groundwater levels or quality in a more predictable manner than would fractured rock systems. However it should be noted that there will be many local exceptions to this generalisation.

Groundwater Dependence and Ecosystem Significance Criteria

It is a general property of ecosystems that, should a physical resource be available within the biosphere, it will be exploited. This is true for light, for nutrients, and for water. Further, where that resource is at all limiting, there will develop some functional dependence on the timing and extent of its availability. Most of Australia has either seasonal drought or a semi-arid to arid climate, and if groundwater exists within the reach of organisms, ecosystems will develop which are to some extent reliant upon it.

Two corollaries of the above are perhaps less obvious. The first of these is that in some cases, reducing the availability of groundwater may result in a gradual, proportional decrease in the health or aerial extent of a given ecosystem; in other cases, a threshold of availability may be reached at which the entire system collapses. As will become apparent on reading the literature review, knowledge regarding this response for particular Australian ecosystems is limited.

Secondly, like all other resources, superabundance can be harmful to ecosystems. That is, just as extreme solar radiation can burn leaves, and excess micronutrients become toxic, many ecosystems are dependent on groundwater not becoming *too* available. In much of Australia, changes in land use have increased groundwater discharge, especially saline discharge, and as a consequence pose a major threat to a wide variety of terrestrial and aquatic ecosystems. For example, in Western Australia, there are a large and extensive number of ecosystems either already degraded by, or under threat from, rising saline watertables and associated saline discharge to streams (EPA 1994). In other systems such as the Darling–Barwon, the relative discharge of groundwater with respect to surface flows may be directly proportional to the risk of algal blooms through a complex sequence of chemical, physical and biological reactions (Donnelly *et al.* 1996). In this report, we emphasise the ecosystem dependence on the supply (quantity) and quality of groundwater, as opposed to vulnerability to increasing groundwater discharge. Nonetheless, these secondary aspects are considered not to be fundamental to the assessment of significance.

Thus it is unlikely that there are ecosystems in Australia that exist in the presence of groundwater that have no dependence upon it, and were groundwater to be made less available, would not suffer. Were it to be shown that a woodland derived only 10% of its annual transpiration from groundwater, it may be unsafe to assume that denial of this resource would have only a trivial impact. Nevertheless, we do assume in this report that the magnitude of the dependence on groundwater is proportional to the fraction of the annual water budget that ecosystem derives from groundwater. *This aspect of dependence is the principal criterion used to assess and rank significance in this report.*

We note that the above criteria reflect a vegetation-oriented bias in the report. We defend this bias on the basis that vegetation health generally underpins the health of an ecosystem. However, we recognise that some systems have faunal components with a more direct dependence on groundwater. For instance, fauna may rely directly on groundwater as a source of drinking water in the dry season via seepages, springs, etc, or as the direct source of habitat in the case of aquatic animals (eg. crocodiles, turtles, fish, macro-invertebrates). Where possible, we have identified these faunal dependencies. Nonetheless, the role of groundwater in maintaining and supporting fauna which are not related to vegetation per se is very poorly known and understood. Of particular importance is the role of groundwater in supporting Aboriginal communities throughout much of Central Australia.

Secondary aspects used as significance criteria are (a) uniqueness and (b) vulnerability. The former criterion addresses how well-represented the system, or critical components of the system, is nationally. This entails not only biodiversity considerations, but cultural and aesthetic ones as well. The latter criterion is also applied and discussed where appropriate, and is an attempt to consider not just the degree of dependence as defined above, but the expected sensitivity to changes in the availability of groundwater.

Methods to Assess Dependence

Methods for assessing the dependence of ecosystems on groundwater are largely indirect, or based on the (reasonable) assumption that groundwater use by plants and animals is *prima facie* evidence of dependence. Few, if any, *in situ*, controlled and replicated manipulative experiments have ever been performed in this regard.

In the case of terrestrial or streamside vegetation, the development of techniques based on the ratios of the naturally-occurring, stable isotopes of oxygen and hydrogen (White *et al* . 1985, Sternberg and Swart 1987, Ehleringer and Dawson 1992, Lin and Sternberg 1992, Thorburn *et al.* 1992b) has lead to major insights into if and when vegetation accesses different sources of water including groundwater. In Australia, this technique has helped to define the dependence of natural vegetation on groundwater on the floodplain of the River Murray (Thorburn *et al.* 1993a, 1994b; Thorburn and Walker 1994) and in *Melaleuca* stands in the Upper South-East of South Australia (Mensforth *et al.* 1994). The technique is currently finding application to similar questions of ecosystem dependence on groundwater in studies of the *Banksia* woodlands of the Swan Coastal Plain (Ray Froend, Waters and Rivers Commission) and in the tropical woodland systems near Darwin (Derek Eamus and Peter Cook of the Northern Territory University and CSIRO Land and Water, respectively). Pilot work by the CSIRO Land and Water, CSIRO Forest and Forest Products, Mines and Energy (South Australia) and the Department of Natural Resources and Environment (South Australia) has also been completed in the application of isotope techniques to the question of radiata pine plantation groundwater use, although there is as yet only indirect evidence that such use occurs.

It is recognised that the application of stable isotope techniques to the problem of discriminating plant water sources has limitations. First and foremost, it requires a difference in the isotopic signatures of soil water and groundwater. Such differences do not always exist. Secondly, these techniques are most effective when combined with flux measurements (eg. Thorburn et al 1993); this allows the degree of use or dependence to be better assessed.

Because the stable isotope technique is not universally suitable for determining the source of plant water, more indirect means have been employed to assess groundwater dependence. Most of these are based on an explicit or implicit water balance, with discrepancies between annual rainfall and actual (evapo-) transpiration ascribed to the discharge of local or regional groundwater. In practice, such inferences are rarely made explicit through long-term measurement, but inferred indirectly from arguments based on potential evaporation and annual rainfall and the persistence of water at or near the surface of wetlands. Paijmans *et al.* (1985) give the best national-scale treatment of regional water balances together with a discussion of wetlands as anomalies in this respect. Other approaches rely on associated changes in surface water or groundwater levels with observed changes in flora and fauna (eg. Froend *et al.* 1987, 1993; Water Authority of Western Australia 1992, Froend and van der Moezel 1994).

Perhaps the most obvious expression of wetlands and other groundwater-dependent surface ecosystems is their relative greenness. That there is a hydrologic equilibrium between climate, soil, and biomass (or leaf area index, LAI) has been so repeatedly hypothesised and sufficiently tested globally and in Australia (see Hatton *et al.* 1996 for review) that there is little doubt that LAI is a strong indicator of water availability in semi-arid to arid environments.

At a broad scale, this notion has been implicit in most assertions of groundwater-dependence in Australian ecosystems. More formal treatments exist, however. Specht (1972) developed an empirical relationship between climate indices and LAI, with wetlands identifiable outliers within this framework. Williams and Holmes (1978) inferred discharge from mound springs in the Great Artesian Basin on the basis of the biomass they supported. Sheriff *et al.* (1996) used a calibrated biophysical model of forest water use and growth to identify the anomalous growth performance of *Pinus radiata* stands in South Australia, which they hypothesised was due to access to fresh local groundwater.

Ascertaining the importance of groundwater to in-stream and estuarine ecosystems is far more difficult. In many cases, even the magnitude or relative proportion of waters in these systems originating from aquifers is difficult to assess. Information on characterisation of low flows of Australian streams at a National level is not available. For comparative assessment of the importance of groundwater in river base flow across different ecosystems in Australia, the necessary processed information is not available. Flow duration analyses and estimates of base flow contributions have not been derived nationally, although they were undertaken for Victoria (Nathan and Weinmann 1993) based on objective analytical techniques (Nathan and McMahon 1990). In the Nathan and Weinmann report, it is important to recognise that the base flow index can only be used for comparative purposes, as the index reflects a range of processes contributing to streamflow other than groundwater discharge including bank storage, capillary fringe effects, attenuated unsaturated zone flow, and delayed surface flow. Nonetheless, base flow indices do provide an objective, if relative, basis for comparison across different catchments and does reflect to some degree groundwater contribution.

Nathan and Weinmann (1993) analysed hydrographs for 117 catchments in Victoria and concluded that the base flow for the greatest number of catchments comprised between 40% and 50% of the total stream flow. It was believed that the two major variables influencing base flow are climate and geology. Dealing with geology, of the 117 catchments, 91 were in a fractured rock environment and the remainder were in alluvial sediments. As the majority of Australian streams are in alluvial environments, it may be concluded that in a similar climate, the base flow component of many Australian streams would be expected to be at least the 40% to 50% recorded for Victorian streams. It would be expected that in different climatic regions of Australia, different conclusions would result. Lacey (1996) examined the importance of vegetation and geology to baseflow in 114 catchments in Victoria, and reported variations in the base flow index due to rock types and climate but not to topographic indices.

It is considered that the base flow index provides an objective basis for comparison across different catchments and that it is an index that reflects groundwater contribution. The significance with which ecosystems depend on base flow is more complex. It is considered that ecosystem dependence is not solely related to the base flow index, but that the variability and predictability of flow are likely to be of key importance in influencing ecosystem dependence. A particular ecosystem may evolve because of a given degree of variability.

Attempts to quantify groundwater discharge have been made for waterbodies like Port Philip Bay (Anderson 1988, Hall 1992, Leonard 1992, Otto 1992, Hydrotech 1993, O'Rourke 1995), but O'Rourke concluded that it was not as yet possible to separate the ecosystem effects of surface water from groundwater, and no work on the specific ecological impacts of groundwater discharge has been done. In most cases, the maintenance of base flow or river pools in semi-arid to arid environments, or through a dry season, by means of groundwater discharge is taken (justifiably, it is considered) as an *a priori* dependence of the local biological systems.

Literature Survey and Identification of Dependent Ecosystems

There is virtually no literature specific to the dependence of Australian ecosystems on groundwater, apart from the mound springs of the Great Artesian Basin, the wetlands of the Swan Coastal Plain, and a small but growing body of work on woodlands. Indeed, most of the environmental water allocation literature in Australia ignores groundwater components of the water balance. For instance, *Stream Hydrology: An Introduction for Ecologists* (Gordon *et al.* 1992), which was written by and largely for Australians, does not reference groundwater in its index nor does it mention groundwater processes in discussions of aquatic ecosystem protection specifically nor dependence in general. While the methods described for environmental flow requirements (eg. Hoppe 1975, Tennant 1976) are based on hydrographic analysis, they involve no identification of groundwaters' role.

Thoms *et al.* (1996) *Scientific Panel Assessment of Environmental Flows for the Barwon–Darling River* makes no mention of groundwaters' role in that system, nor even invokes the term base flow. To their credit, one of their recommendations was that, in the future, a hydrologist be part of such expert panel assessments. Similar deficiencies exist within the much of the Australian vegetation-focused overviews. For instance, in Australian Vegetation (Ed. Groves, 1981), none of the chapters covering the vegetation types of Australia make reference to the role of groundwater, not does the term appear in the index. In *Ecology of Estuaries* by Kennish (1986), there is not mention made of groundwater or the role discharge plays in the maintenance of such systems; in *Estuaries and Enclosed Seas* (Ed. Ketchum 1983), there is no mention made of groundwater, although there is a passing reference to river plumes maintaining brackish waters. Bardsley *et al.* (1984) discuss the geomorphology of coastal systems in *Coastal and Tidal Wetlands of the Australian Monsoon Region*, but make no reference to groundwater. In *Aquatic Life in Estuaries and Man's Effect Upon It: Plant Life*, Harris (1982) provides a long list of man's impacts but does not include anything related to groundwater. Only Paijmans *et al.* (1985) have attempted to provide a synoptic view of groundwaters' importance in wetland system water balances, although these observations are spotty and incomplete.

In a paper prepared for the Prime Minister's Science and Engineering Council (Anon. 1996), *Managing Australia's Inland Waters. Roles for Science and Technology*, the need for a better understanding of hydrogeological processes operating in native environments was identified. However, in Chapter 1, *Threats and Challenges, and Environmental Allocation*, by L. Russell (Department of Primary Industries and Energy), no linkage is made between groundwater extraction and ecosystem health; the impacts of uncontrolled bore drains on the great Artesian Basin were limited to subsequent overgrazing. Chapter 3, *The Ecological Imperatives* (Cullen *et al.)* does not recognise groundwater abstraction as potential impact on aquatic systems, and discounted minimum flow criteria as ecologically important (this may be more true for *inland* water systems than other aquatic habitats in Australia, however).

Thus, we are in general forced to assume a dependency between the surface (or near-surface) presence of local and regional groundwater and the ecosystems associated with them. Two largely independent sources of information were drawn upon: (a) literature on the ecosystems of Australia and (b) literature on the hydrogeological and hydrological systems of Australia.

Overview of Groundwater Dependent Ecosystems in Australia

There are a number of national and regional compendia of ecosystem descriptions which encompass wetlands in general, and a few which cover other kinds of ecosystems under consideration in this report. The literature on the hydrological and hydrogeological aspects of the ecosystems under consideration are far more dispersed, and are identified in the literature review for each region and ecosystem. This review may be found in Appendix A. This appendix is organised first by the regions of Jennings and Mabbutt (1977) and thence by the ecosystem classification described above.

This study accessed the following sources for the biological components of Australian ecosystems (complete citations in bibliography):

Wetlands and Terrestrial Systems

Aston, H.I. (1973) Aquatic Plants of Australia.

Bardsley *et al.* (1984) Coasts and Tidal Wetlands of the Australian Monsoon Region

Beadle (1981a) The Vegetation of Australia.

Beadle (1981b) The vegetation of the arid zone.

Briggs (1981) Freshwater wetlands.

Campbell (1983) Mires of Australasia.

Connor and Clifford (1972) The vegetation near Brown Lake, North Stradbroke Island.

Congdon and McComb (1976) The nutrients and plants of Lake Joondalup, a mildly eutrophic lake experiencing large seasonal changes in volume.

Costin (1981) Vegetation of high mountains in Australia.

Deluca and Williams (1992) Wetlands of the National Estate in Victoria. 1. Statewide Inventory and Update of Significance for South-Eastern Victoria.

Department of Environment and Planning (1983) Wetland Conservation in South Australia.

Ecologic & Associates (1988) Wetlands of the Bakers Range and Marcollat Watercourses: Environmental Characteristics.

Giblett and Webb (1996) Western Australian Wetlands: The Kimberley and the South-West.

Hill *et al.* (1996a). Wetlands of the Swan Coastal Plain. Volume 2A. Wetland Mapping, Classification and Evaluation, Main Report.

Hill *et al.* (1996b). Wetlands of the Swan Coastal Plain. Volume 2B. Wetland Mapping, Classification and Evaluation, Wetland Atlas.

Ketchum (1983) Estuaries and Enclosed Seas.

Lintermans and Ingwersen (1996). Important Wetlands of the Australian Capital Territory.

Love (1981) Mangrove swamps and salt marshes.

Masini (1988a) Inland Waters of the Pilbara, Western Australia. Part 1. A Report of a Field Study Carried Out in March–April, 1983

Masini (1988b) Inland Waters of the Pilbara, Western Australia. Part 2. A Report of a Field Study Carried Out in October–November, 1984.

McComb and McComb (1967) A preliminary account of the vegetation of Loch McNess, a swamp and fen formation in Western Australia.

Miles, J.T. (1975). A review of literature and other information on New South Wales wetlands.

Mitchell *et al.* (1981) A botanical survey of remnant vegetation and wetlands in the Central and North-Eastern Mount Lofty Ranges.

Paijmans *et al.* (1985). Aspects of Australian Wetlands.

Richardson and Beiharz (1994) Wetlands of the National Estate in Victoria. 2. Update of Significance Information for Victorian Wetlands.

Saenger *et al.* (1977) Mangal and coastal salt-marsh communities in Australasia.

Seminiuk (1987) Wetlands of the Darling system—A geomorphic approach to habitat classification.

Seminiuk (1988) Consanguineous wetlands and their distribution in the Darling system, South-Western Australia.
Semeniuk *et al.* (1990). Wetlands of the Darling System, South-Western Australia: a descriptive classification using vegetation pattern and form.

Smith, A.J. (1975a). A review of literature and other information on Victorian wetlands.

Smith, A.J. (1975b). A review of literature and other information on South Australia wetlands.

Smith, A.J. (1975c). A review of literature and other information on Western Australia wetlands.

Smith, A.J. (1975d). A review of literature and other information on Tasmanian wetlands.

South-Eastern Wetlands Committee (1985) Wetland Resources of the South-East of South Australia. Volume 1: Conduct of Investigation and Findings of the Committee.

Sparrow (1991) A Geobotanical study of the remnant natural vegetation of temperate South Australia.

Specht (1979a). Heathlands and related shrublands of the world.

Specht (1979b) The sclerophyllous (heath) vegetation of Australia: the Eastern and Central states.

Specht (1981) Major vegetation formations in Australia.

Specht (1986) Forested wetlands in Australia.

Story, R. (1969). Vegetation of the Adelaide–Alligator River area.

Thompson (1986) River Murray Wetlands, their Characteristics, Significance and Management.

Warcup (1982) Wetlands of South Australia: a selective bibliography of their natural history.

Mound Springs Ecology

Badman (1985) Birds of the mound springs and bores South and West of Lake Eyre with special reference to the Coward Springs area.

Badman (1987) Boredrains and the Birds of Inland South Australia; a Study of the Relationships of Boredrains and Native Bird Populations in the Far North of South Australia. Nature Conservation Society of South Australia, Adelaide.

Badman (1991a). Mound springs.

Badman (1991b) Birds.

Boyd (1989). Late holocene vegetation changes at Dalhousie Springs, Northern South Australia—an interim report.

De Deckker (1979) Ostracods from the mound springs area between Strangways and Curdimurka, South Australia.

Fatchen and Fatchen (1993) Dynamics of Vegetation on Mound Springs in the Hermit Hill Region, Northern South Australia.

Glover (1989). Fishes.

Greenslade *et al.* (1985) South Australia's Mound Springs.

Harris (1992) Mound springs: South Australian conservation initiatives.

Kinhill Stearns Roger (1982). Olympic Dam project. Draft Environmental Impact Statement.

Kinhill Stearns Roger (1983). Olympic Dam project. Supplement to the Draft Environmental Impact Statement.

Knoack (1993) The mound springs of South Australia.

Lange and Fatchen (1990). Vegetation.

Ling *et al.* (1989) Micro-algae.

Mollemans (1989). Terrestrial and semi-aquatic plants.

Ponder (1985). South Australian mound springs: relict faunas in the desert.

Ponder (1989). Mollusca.

Robinson and Casperson (1986) The Biology of Dalhousie Springs Complex, Witjira National Park.

Smith (1989). Mammals from the Dalhousie Springs area, with notes on some reptiles and frogs.

Social and Ecological Assessment (1985). Biological assessment of South Australian mound springs.

Symon (1984). A checklist of plants at Dalhousie Springs and their immediate environs.

Symon (1985). Botanical notes on mound springs and bores.

Thompson (1985). Reptiles of the mound springs area.

Tyler (1978) Amphibians of South Australia.

West (1985). Mammals of the mound springs area.

Zeidler (1989) Crustacea.

Zeidler and Ponder (1989b) Natural History of Dalhousie Springs.

Aquatic Systems

Gehrke *et al.* (1995) River Regulation and Fish Communities in the Murray–Darling River System, Australia.

Harris (1995). Fish/Habitat Associations in NSW Rivers.

Hillman (1995b) Flow Regimes of Rivers in the Murray–Darling Basin: Ecological Characteristics and Ecological Consequences.

Lake (1995b) Of Floods and Droughts—River and Stream Ecosystems of Australia.

Aquifer and Cave Systems

Botosaneanu (1986) Stygofauna Munid. A faunistic, distributional, and ecological synthesis of the world fauna inhabiting subterranean waters (including marine interstitial).

Camacho (1992) The natural history of biospeleology.

Gibert *et al.* (1994) Groundwater Ecology.

Jasinska and Knott (1991) Stability of root mat ecosystems in a groundwater stream, Cabaret Cave, Yanchep National Park, W.A.

Matthews, P.G. (1979) Check-List of Australian Caves and Karst.

Details of the above references as applied to groundwater dependent ecosystems, either directly or by inference, are discussed in Appendix A.

National Assessment of Ecosystems Dependence

Summary of Australian Ecosystem Dependence on Groundwater

Given the large uncertainties regarding the role of groundwater in the diverse ecosystems identified above, we classify the ecosystems of Australia by their probable degree of dependence based on the above review. We repeat the introductory thesis, however, that given the availability of (fresh) groundwater, an ecosystem will use it and likely become dependent upon it, and a reduction of this resource necessarily means a subsequent impact on the ecosystem.

In the following classification of systems according to their degrees of dependency on groundwater, we recognise that many vegetation types are distributed over a range of hydrological conditions, and in places may have developed a dependency that does not exist elsewhere in its range. Perhaps the best understood example of this are *Banksia* woodlands on the Swan Coastal Plain; some stands are clearly (monotonically) dependent and others have apparently no access to groundwater.

Ecosystems Entirely Dependent on Groundwater

The following systems are undoubtedly dependent on groundwater, and were groundwater to diminish or be modified only slightly, either below a threshold like the ground surface or such that a surface water system stops flowing, then the ecosystem would essentially cease to be:

- mound spring ecosystems in the Great Artesian Basin and elsewhere
- karstic groundwater ecosystems of Exmouth Cape, Yanchep Caves, the Nullarbor and elsewhere
- channel waterholes in the Central Australian Ranges
- saline discharge lakes of the Western Murray Basin (eg. Pink Lakes) and most other playa lakes
- streamside eucalypt and related vegetation (eg. *E. camaldulensis*) along inland (frequently dry) rivers and streams in the arid zone
- permanent lakes and associated ecosystems on the Swan Coastal Plain
- spring ecosystems of the Pilbara
- the inland stand of mangrove near Eighty Mile Beach

Ecosystems Highly Dependent on Groundwater

In such systems, moderate changes to groundwater discharge or water tables would lead to substantial decreases in the extent or health of the ecosystem. There is some significant chance that the ecosystem would collapse, but this is not entirely certain.

- mesophyll palm vine-forests in the tropical North
- swamp sclerophyll woodlands and swamp scrub in solution hollows on the Eyre and Yorke Peninsulas
- karst ecosystems including those on the Nullarbor
- permanent water holes on the rivers of the Central Lowlands and South Australian Ranges (such as those on the Cooper, Warburton, Kallakoopah and Strezlecki Creeks), and lakes in this region such as Goyder Lagoon and Coongie Lakes, which support swamp sclerophyll woodlands, Lignum swamps, Carex sedgelands, canegrass grasslands, submerged and emergent herbfields and floating herbfields

- river pool ecosystems of the rivers of the Pilbara
- the near-shore stromatolite systems of coastal Western Australia
- RAMSAR-listed wetlands in the basalt plains of the Western District of Victoria
- *Melaleuca* spp. stands in the Upper South-East of South Australia
- paperbark swamp forests and woodlands in the tropical North, North-Eastern uplands and Pilbara
- base flow systems of the South-Eastern uplands
- damplands on the Swan Coastal Plain

Ecosystems with Proportional Dependence on Groundwater

For a number of systems, it is likely that a unit change in the amount of groundwater will result in a proportional change in the health or extent of that ecosystem. In other words, were groundwater discharge cut by half, one might expect some equivalent diminution of the ecosystem.

- river pools and billabongs supporting herblands on the floodplains of the tropical North
- base flow and herbland ecosystems of the North-Eastern uplands, and the North Australian and Kimberley Plateaux
- lake ecosystems on the Lower Burdekin and similar rivers in the North-Eastern uplands and Carpentaria lowlands
- volcanic crater lakes and swamps of the Cape York Peninsula
- perennially green river plain grasslands on the floodplains of the North Australian Plateau
- tropical sclerophyll forests and woodlands on the North Australian Plateau
- base flow systems in the South-Eastern uplands
- permanent coastal lakes of dunes and beachridge plains supporting sedgelands, paperbark swamp forests and swamp scrub in the South-Eastern uplands (eg. on Stradbroke Island, Fraser Island, and on the coast of Northern New South Wales)
- permanent glacial lakes supporting wet tussock and *Carex* grasslands and *Sphagnum* swamps in the South-Eastern uplands
- swamp heaths on the Hawkesbury Sandstone in the South-Eastern uplands
- Swamp sclerophyll forests on the inland floodplains of the South-Eastern uplands
- *Eleocharis* and *Baumea* sedgelands in lagoons of the inland rivers of the South-East.
- permanently flooded swamps and lakes of inland portions of the South-Eastern uplands, supporting *Phragmites* and *Typha* grasslands (eg. the permanently flooded portions of the Macquarie Marshes)
- permanent swamps and river pools supported by local base flow on Kangaroo Island
- swamp forests, swamp woodlands, swamp heaths, peat swamps, *Carex* sedgelands and *Baumea* sedgelands along riparian areas of the Mount Lofty Ranges
- damplands and sumplands supporting paperbark and *Banksia* woodlands on the Swan Coastal Plain
- base flow ecosystems in South-Western Western Australia
- lake ecosystems supporting *Baumea* sedgelands and swamp heaths in Tasmania
- sedgelands and Sphagnum bogs on the fringes of Tasmanian rivers
- swamp heathlands, button-grass sedgelands, *Carex* sedgelands and Phragmites grasslands in Tasmania, where waterlogging is dependent on groundwater levels

- swamp scrub and *Eleocharis* and *Baumea* sedgelands in the near-coastal dune systems of the Upper South-East of South Australia
- alpine bogs in South-Eastern highlands on local groundwater flow systems
- ecosystems fringing the Gippsland Lakes in Eastern Victoria

Ecosystems which may only use Groundwater Opportunistically or to a very limited extent

Groundwater may only play a significant role in the water balance of some ecosystems in times of extreme drought or briefly at the end of a dry season. This role of groundwater may be critical in the longer term, but the immediate impacts of substantial reductions in groundwater may be muted.

- swamp sclerophyll forests on the coastal floodplains of the South-Eastern uplands, and of the Lander–Barkly Tablelands
- the jarrah forest and *Banksia* woodlands of South-Western Western Australia
- lignum shrublands on inland river systems
- the ecosystems of the Coorong
- the ecosystems of permanent lakes and swamps at the termini of inland rivers in the Central Lowlands and South Australian Ranges (eg. Lake Eyre exclusive of mound spring systems)
- intermittent floodplain lakes of the Central Lowlands
- Major ocean embayments such as Port Phillip Bay
- coastal mangrove and salt marsh ecosystems

Ecosystems with No Apparent Dependency on Groundwater

There are a number of wetland ecosystems which do not depend on groundwater in any significant way. For most of the Australian systems below, we cannot state this with certainty but only as a strong likelihood.

- seasonal floodplain lakes on minor creek systems in the tropical North.
- *Phragmites* grasslands at the Murray Mouth
- instream ecosystems of the Murray and Darling Rivers, at least with respect to the amount that base flow contributes to the maintenance of the natural ecosystems
- terminal drainage basin lakes in the Central Lowlands such as Cobham Lake and Lake Bancania, which are almost certainly surface water-driven
- intermittent and episodic wetlands of the arid zone with uncoordinated drainage
- the episodic lakes of the Sandland and the Yilgarn Plateau
- the rockpools and solution hollows of the Nullarbor Plain
- Southern rainforests

Background and Interpretation to National-Scale Maps of the Dependence of Ecosystems on Groundwater

National maps of the occurrence and distribution of groundwater-dependent ecosystems were prepared to complement the content of this report; details of their preparation appear in Appendix B. Maps related to vegetation, wetlands and base flow systems accompany this document. Due to the lack of any description of aquifer ecosystems at the national level, no such map could be prepared.

The most salient spatial feature of dependent ecosystems is their small, local extent. That is, most of the dependent ecosystems identified above cannot be revealed at a scale of 1:5,000,000. Rather, mapping units and other features related to their occurrence can be identified which are associated with their distribution and location. For instance, in the case of vegetation, large areas of Australia have been typified as *Acacia*; while mulga and related shrubs dominate and are not reliant on groundwater, within this region there are vegetation types such as streamside red gums with strong dependencies. Such associations are identified on the map.

The wetlands map attempts to characterise the nature of wetland features (eg. permanent lakes, ephemeral swamps, etc.) regionally. The consequence of this generality is that the detail of the diverse types of wetlands may be lost within a particular region of Australia. Nevertheless, there are characteristic, dominant wetland types from region to region in Australia. As was done for the vegetation map, dependent ecosystems within each of these mapping units were identified on the wetlands map.

As previously noted, there is no synoptic picture available for river base flow (or the groundwater contribution to base flow) for Australia. Therefore, no compendium of ecosystem dependence on base flow exists either and cannot be mapped as such. However, given the three base flow theses outlined on page 7, we can map the themes of annual rainfall, aquifer rock type, and Australia's river systems. Within this framework, rivers can be assessed against geographic zones in which ecosystems dependent on base flow, *if base flow exists*, may be expected to have greater or lesser dependence and vulnerability. For instance, the biota associated with base flow in a stream flowing through a region with less than 400 mm of annual rainfall is far more likely to be dependent on base flow than in a case where rainfall is greater than 1,000 mm. Similarly, base flow-dependent ecosystems may be more vulnerable to changes in the groundwater system within porous media than in fractured rock. Thus, with this interpretation methodology clear, it is possible to use the map to indicate regions where ecosystem dependence on base flow (and hence groundwater) is likely to be higher or lower.

National Perspective and Relative Significance

From a national perspective, strongly groundwater-dependent ecosystems occupy only a small fraction of the continent. Ecosystems which are entirely dependent on groundwater represent less than 1% of the land area of Australia, and a similar fraction is occupied by ecosystems highly dependent on groundwater. Those systems which are proportionally dependent on groundwater cover less than 5% of the nation. However, given the generally aridity (or strong seasonality and variability in rainfall) characteristic for most of Australia, these relatively well-watered ecosystems have an importance far in excess of their geographic extent. Indeed, it has been noted that many of the ecosystems associated with groundwater discharge form the bases of many of Australia's national parks, particularly in the arid and semi-arid zones.

The systems identified as entirely dependent on groundwater are also quite unique, in that they are localised phenomena with a high public profile in terms of biodiversity, tourism, cultural heritage, etc. Perhaps the only exception to this are the streamside red gum stands in the interior of the country; these are extensively distributed and are dependent on groundwater recharge arising from flood events.

Much is known about the Great Artesian Basin mound springs, particularly in terms of their vulnerability; they are clearly vulnerable to local changes in groundwater pressure. The surface water-groundwater interactions maintaining the lakes of the Swan coastal plain are also relatively well-understood, and their vulnerability to changing this regime and to pollution is clear. Much less is known about the vulnerability of the karstic groundwater ecosystems of Exmouth Cape; their distance from major centres and other development may make this less moot. The channel waterholes and their catchment areas in the Central Australian Ranges are generally within conservation parks and thus may to some extent be considered less vulnerable.

The saline discharge lakes of the Western Murray Basin are regional groundwater features, and thus would be vulnerable to changes in groundwater levels resulting from pumping from this aquifer. The streamside eucalypt woodland along the interior rivers of the arid zone depend on local channel recharge–discharge phenomena, and we would expect only local impacts due to local changes in the groundwater levels in these systems.

The highly dependent systems of the tropical far North (mesophyll vine forests, paperbark swamps) are currently under assessment with respect to their vulnerability to groundwater development. These systems occur in local patches across much of the top end of Australia, and must be seen as less unique from place to place than other highly dependent systems in this report. By contrast, river pool and spring ecosystems of the Pilbara are generally unique to their regions, and their confinement along rivers make them more vulnerable to changes in the hydrologic regime.

It is well appreciated that many streams from the Great Dividing Range in South-Eastern Australia are base flow streams and are highly dependent on groundwater discharge.

Not enough is known regarding stromatolite formations to assess their vulnerability, but they are clearly unique biological features with a high public profile.

Of the many systems identified in this report as being proportionally dependent on groundwater, a few are noteworthy with respect to uniqueness or vulnerability. The permanent coastal lakes of dunes and beachridge plains in Eastern Australia are subject to a variety of pressures from development of the groundwater resources as well as pollution including acid sulphate runoff. The systems are not locally unique, but their proximity to urban and tourism centres gives them a high public profile, and their potential importance to fisheries is noted.

Base flow, herbland, river pool and billabong communities in Northern Australia are notable in terms of their biodiversity and biological importance to the region. The systems are potentially vulnerable to groundwater development, particularly where demand for water resources is high such as in Northern Queensland.

Conclusions

1. The majority of Australia supports ecosystems with little dependence on groundwater, at least as defined in this report with an emphasis on vegetation. However, there are many localised or extensive ecosystems in Australia with at least a high dependence, and which would suffer or cease to exist in its absence. These systems tend to have high ecological and social significance. This is particularly true for Aboriginal communities in Central Australia. Had we considered the unsaturated zone and transient perched aquifer systems, then a much broader, more extensive portion of Australia would have ecosystems considered dependent on groundwater. Were we to emphasise the faunal component alone, then a wider variety of ecosystems have components with groundwater dependencies. Description and understanding of these faunal dependencies is generally very poor.
2. The general level of understanding of the role of groundwater in maintaining ecosystems throughout Australia in both the scientific community and the general community is low. This perception is based on a general lack of investigations into this relationship at a national level, and is reflected in the preponderance of 'likely' as opposed to 'certainly' ratings in our assessments of particular systems. It is also reflected in the lack of consideration of groundwater in a number of recent assessments of ecosystems which, from a hydrogeological perspective, probably involve groundwater. A notable exception to this generality is the scientific understanding and community awareness of these processes on the Swan Coastal Plain. It should be noted that the impetus for this assessment is shared by the Republic of South Africa, which commissioned a similar national assessment of ecosystem dependence on groundwater almost simultaneously to this report.
3. We have endeavoured, where possible, to assess the significance of groundwater dependent ecosystems not only in terms of degree of dependence but in terms of uniqueness and vulnerability. The former is relatively easy to assess in biological or cultural terms. The latter is rather open-ended, in that inherent vulnerability to a complex array of potential impacts must also be combined with a consideration of the likelihood of such impacts (ie. proximity to urban centres or other developments). The specific impacts we considered in this report included (a) groundwater development, (b) pollution, and (c) land use changes associated with a change in water levels, as mitigated by proximity to development.
4. Rising groundwater levels and associated stream salinisation is having a large impact on wetland, terrestrial and base flow ecosystems across Southern Australia, particularly in upland catchments. Wetlands in general are more vulnerable to changes in groundwater levels compared with the other three ecosystem classes in this report, largely because a small change in groundwater levels can cause significant changes in water availability to vegetation, given the highly non-linear behaviour in evaporation with depth to groundwater. For most wetlands and terrestrial ecosystems, we do not know what the critical depth to the water tables is, and its characteristic dynamics. Aquifer ecosystems, by contrast, may as a class be the most susceptible to groundwater pollution. Although highly site specific, the potential for ecosystem damage or degradation through groundwater development and other impacts is high.
5. We conclude that vulnerability is too complex an issue to be treated meaningfully and comprehensively at a national level. Suffice to say, many of Australia's groundwater dependent ecosystems are vulnerable to the above kinds of impacts, but groundwater resource managers and investigators tend to underestimate ecosystem vulnerability with respect to groundwater development, pollution and land use change.

6. The translation of the COAG (1996) concept of provision for the environment, in a groundwater sense, is poorly defined. Recommendation Six of the COAG report, *Groundwater Allocation and Use: A National Framework for Improved Groundwater Management in Australia*, states that groundwater management plans must include identification of the sustainable yield of systems, and should include an identification of environmental water provisions in accordance with the principles set out in the joint ARMCANZ and ANZECC *National Principles for the Provision of Water for Ecosystems.* This process requires a scientifically-based underpinning which is not, in general, available across Australia. Planning, from the EIS level down to the local level, must recognise ecosystem dependence on groundwater and related processes. This should, in principle, include the processing of the 17,000 bore licences in Australia each year. However in practice it might be better undertaken as part of the development of groundwater management plans for significant groundwater resources.

7. Groundwater development of shallow aquifer systems especially will in many cases cause lowering of groundwater levels and consequently impact on ecosystems. Depending upon how the COAG 'provision for the environment' requirements are interpreted, this could have a major impact across Australia on restricting current and new groundwater development. The economic impacts could be very significant. Hence it is desirable to agree at a national policy level what are considered to be acceptable impacts on ecosystems due to groundwater development.

Vegetation

8. It has only been in the last two decades that Australian science has begun to appreciate the extent and degree of dependence of non-wetland vegetation on groundwater. Due to advances in research methods, particularly those based on isotope and transpiration measurement techniques, this understanding is developing rapidly. In fact, the methodology available in this area in already more advanced and robust than that available for other ecosystem classes.

9. Gaps remain, however. We have a relatively poor understanding of how adaptive vegetation is with respect to changing the depth, quality and regime of groundwater. We have a limited understanding of how opportunistic vegetation can be in accessing groundwater, particularly in the plantation context. For instance, how dependent are agroforestry/forestry systems on groundwater, in the short and longer term? The issues have major implications to ecosystem vulnerability as well as the potential for landscape restoration.

Base Flow Systems

10. There is no national data for comparison and prioritisation of the groundwater contribution to streams across Australia. On the basis of Victoria alone, base flow comprises, for the greatest number of natural catchments, between 40% to 50% of the total stream flow. Some fraction of this is groundwater in origin. It is likely that the above conclusion will be very different for other climatic regions in Australia. In arid and semi-arid regions, base flow will be much less. It is also clear that hydrogeological characteristics can override climate with respect to base flow (eg. the large base flow in the Daly River arising from a limestone aquifer). Although we have mapped these two themes at a broad, national, level generalisations regarding base flow are difficult.

11. Although assertions exist regarding the importance to ecosystems of the hydrogeochemical interactions of discharging groundwater with surface waters, this is a relatively unresearched topic in Australia.

12. Ecosystem dependence is not solely related to the amount of base flow, but variability and predictability of flow are likely to be important. Generally, if there is base flow, then ecosystems will tend to be more dependent and vulnerable in lower rainfall zones, and where this base flow arises from porous media aquifer systems. There is no established methodology for assessing base flow (especially of groundwater origin in particular) dependence of ecosystems. Even the relatively well-established statistical hydrographic techniques for assessing base flow *per se* are virtually unapplied at a national level.

Aquifer Ecosystems

13. Virtually nothing is known about Australia's aquifer ecosystems, their importance in terms of biodiversity, and their importance to the systems into which they discharge. The whole topic is so new that it is hard to judge as to whether or not it is just a research fad or if there are substantial issues to be addressed. Insufficient data exists in Australia to provide any scientifically rigorous assessment of the significance and nature of aquifer and cave ecosystems. Nonetheless, based solely on overseas (principally European) experience, it is expected that these ecosystems, at least those associated with shallow or karstic aquifers, represent a key part of the food chain and ecological processes which emerge as river base flow and flow into wetlands.

Wetlands

14. The Register of Wetland Restoration Projects in Australia and New Zealand (de Jong 1997) provides an overview of the priorities and issues associated with wetlands in this region. In this regard, we note that of the wetland restoration projects listed, the effort was roughly evenly divided among swamps, lakes and estuarine waters/mangroves. By far the largest fraction of these sites (53%) had suffered primarily from altered hydrologic flows, with the second largest impact being salinisation (18%). While the role of groundwater was not isolated, clearly the linkage is likely enough in most cases to emphasise the important dependence of these systems on below-ground hydrology. Note also that in this same analysis, however, 'low groundwater' was a potential impact which they did not associate with any of the sites; this emphasises the necessity to include hydrogeologists in such assessments.

15. A very few groundwater dependent ecosystems have been extensively studied and are well-understood (eg. Swan Coastal Plain Lakes, Great Artesian Basin mound springs). Most of the wetlands with likely high dependence have been subject to little or no investigation in this regard. For instance, the dependence of estuarine and near-shore systems on groundwater discharge is largely unknown or undemonstrated apart from unique features such as stromatolites. The methods available for such assessments generally rely on classic hydrological analyses of potentials and fluxes, and are relatively well-developed.

16. Clearly, groundwater plays a role in most of Australia's wetlands. This role may vary, however, from minor to essential. Not all wetlands are groundwater dependent. It may also range from a typically positive role to one in which increasing groundwater levels may have adverse impacts. There is no comprehensive national assessment of the relative volumes of surface water and groundwater in wetlands. Groundwater hydrology must become part of standard wetland assessments and investigations.

Recommendations

1. Groundwater dependent ecosystems should be recognised as a key component in planning and groundwater allocation processes in Australia. This should involve an assessment of ecosystem susceptibility, analogous perhaps to vulnerability mapping for groundwater pollution.
2. Establish a clear methodology at a national level for assessing groundwater dependence of ecosystems and hence agree, at a policy level, on a process to define acceptable impacts on ecosystems resulting from groundwater development, pollution and land use change.
3. Identify an agreed criterion (such as a base flow index) that can be used across Australia for comparative analyses, or adopt the base flow index as a national indicator of the importance of groundwater to total river flow.
4. Undertake comparative analysis of available historic stream gauging data across Australia to determine the relative importance of groundwater contribution to total stream flow.
5. We do not recommend a large investment in aquifer ecosystems investigations. There may be some worth in assessing the potential of aquifer organisms to serve as indicators of ecosystem health.
6. We do recommend an emphasis of research investment on base flow ecosystems and wetland ecosystems.

Case Studies

To highlight the biophysical, social and economic complexities involved in evaluating the significance of ecosystem dependence on groundwater, the following case studies are offered.

Groundwater Resource Development in a Tropical Savanna

The city of Darwin relies upon surface water impoundments for most of its supply (eg. Darwin and Manton Dams), but more local and higher quality resources below the tropical woodland and swamp systems of the coastal plain surrounding the Howard River Basin were identified as a more attractive source since the early 1960s. Since then, this groundwater system has been exploited to a limited degree by both urban and rural developments; this development of supply bores is concentrated on the Western side of the Howard Basin, an area with a relatively high degree of subdivision and rural development. Further development of this supply is forecast for the groundwater systems Howard East Basin, which underlies “significant stands of natural vegetation” (Pidsley *et al.* 1994) including swamp sclerophyll forests and woodlands, swamp paperbark forests, and monsoon vine forests. In order to promote the sustainable development of this resource, a series of studies has been undertaken to assess the dependence of these ecosystems on groundwater, and the likelihood that exploitation of the aquifer will adversely affect their health.

The key issue is the degree to which these ecosystems use water in the surface aquifer system, and whether or not this supply would be diminished or restricted if water were pumped from the higher yielding layers at depth. Thus, an understanding of the water balance of the Basin, and in particular the balance between tree water use and lateral throughflow in the deeper system, is crucial. In other words, the 6–9 m recession in water levels in the surface aquifer during the dry season can be due to groundwater throughflow, evapotranspiration, or both. If it is largely the former, then much of this volume could be sustainably extploited. If, however, the transpiration component is dominant, then there could be grave consequences to pumping. Standard approaches to hydrography have only limited value in this regard, for evaporation and net recharge in this system are difficult to determine because of the large fluxes involved, the strong seasonality of rainfall, the large amplitude (9 m) in water levels, the lack of correspondence between the surface catchment and groundwater catchment boundaries, the difficulty in determining the profile of specific yield and conductivity of the aquifer, and the uncertain gauging of the Howard River in the wet season. There is even conceptual uncertainty in how water moves through these systems.

Toward resolving these issues, it was determined that direct measurement of the transpiration and evaporation components of the water balance were necessary, complemented by detailed characterisation of the regolith profile, the water level behaviour, and indirect inferences on throughflow using isotopes and other tracers such as chlorofluorocarbons. The first ecosystem examined was the sclerophyll woodland, which is the most widespread vegetation type on in the region. Studies by the Power and Water Authority, CSIRO and the Northern Territory University indicate that the trees use approximately 400–500 mm of water over the dry season, leaving approximately 0–200 mm of throughflow (these figures are under current review by CSIRO). These figures are supported by isotope and CFC profile analyses. Although the transpiration term seems to dominate the dry season water balance and thus flag concern over woodland health given pumping, it is estimated that the unsaturated profile may hold enough water in the upper 6–9 m to supply the trees with the water they need.

In addition to the evidence provided through the investigations referred to above, there is not yet any qualitative evidence of a decline in sclerophyll woodland health in the vicinity of existing supply bores in the Howard West Basin. In itself this would be a dangerous observation to rely on, given the length of time these bores have operated and the confounding effects of rural development on the woodland.

Having established an initial estimate of woodland dependence on groundwater, the subsequent determination of risk must consider the significance of this ecosystem. There are vast tracts of sclerophyll woodland of this type in Northern Australia, the woodland of the Howard East Basin is not unique, nor is it protected from frequent disturbances like fire, vehicular traffic, livestock. It is probably only its proximity to Darwin that raises its profile in the eyes of the community and land managers. In summary, the biological, cultural and economic risks to groundwater development are relatively small.

In contrast, the paperbark woodlands and monsoon vine forests dotted about the same landscape are far more limited in extent, less understood with respect to groundwater dependence, more likely to be dependent, and at least in the case of vine forests, more biologically diverse and significant. Although currently under investigation, indirect inferences based on leaf area index suggest that these relatively dense canopies reflect a better supply of water than enjoyed by the sclerophyll woodland. The general uncertainty regarding how groundwater moves through these systems, the extent of vegetation dependence, and their likely response to groundwater pumping, combined with their higher biological and cultural significance, urge greater caution in resource development. These factors also demand local research and investigation aimed at reducing these uncertainties.

Groundwater Resource Development in a Temperate Woodland

The city of Geelong in Victoria uses several major storages as its primary water supply. Barwon Water Authority has, however, also developed a major groundwater resource to act as a drought security supply and to reduce the need for new surface water storages to meet peak summer demands. As such it is a very effective conjunctive use scheme.

The groundwater bore field is located in the Barwon Downs Graben and four major production bores of 400 m depth are able to pump approximately 12,000 ML/year if required. The graben is recharged from several regions where the key aquifers outcrop or subcrop. The major recharge area is about 5 km to the North of the bore field where a tributary of the Barwon River, Boundary Creek, flows. It is well known that Boundary Creek has a major base flow component and even during the major 1982/1983 drought this stream continued to flow. Adjacent to the creek are a range of vegetation types, which are shown on Figures 2 and 3. Tea tree stands are well-developed close to the creek, while manna gum and messmate are abundant on the mid slopes). It is postulated that these trees use groundwater (Q. Farmer-Bowers 1986) as a major water source. Higher up the slope the vegetation changes to peppermint and messmate. It is postulated that these trees do not use groundwater.

Figure 2
Diagram of Groundwater Vegetation Relationship—Current Situation

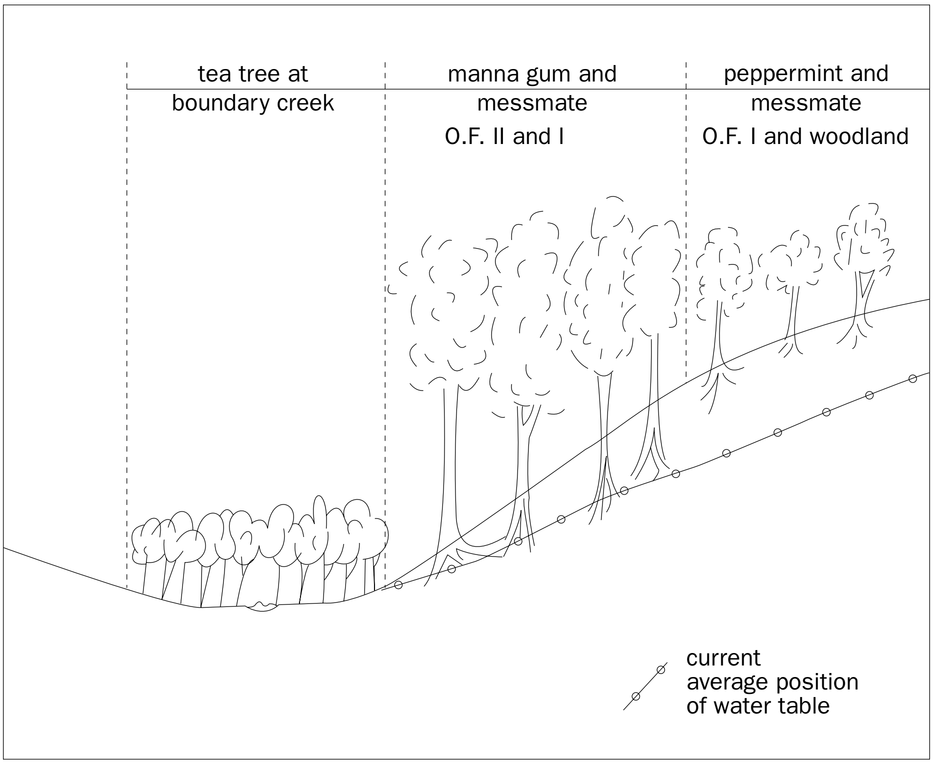
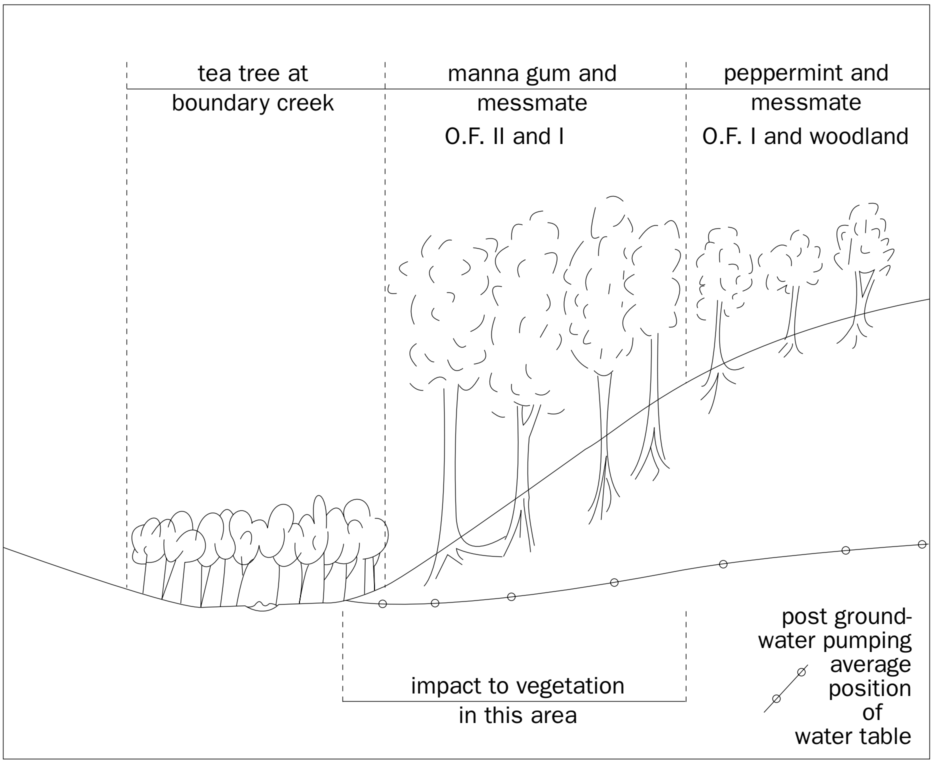


Figure 3
Diagram of Groundwater Vegetation Relationship—Possible Future Situation



As part of proving the sustainable yield of the bore field, a long-term (two year) pumping test was carried out. The key issue influencing the sustainable yield was the effect on the environment, and especially the flow in nearby creeks. Substantial monitoring of the region and especially Boundary Creek was undertaken. Approximately six months after pumping commenced, the flow in Boundary Creek ceased and the observation bores in the region indicated a consistent picture of a regional fall in groundwater level in the recharge area.

It is clear that long term and permanent use at the Barwon Downs borefield would have a significant impact on ecosystems in Boundary Creek and adjacent vegetation. Modelling is currently under way to evaluate a variety of extraction scenarios which, it is postulated, will have lesser impacts on the environment.

Management of Lakes on the Swan Coastal Plain

Concern over the future of sumplands, damplands and lakes on the Swan Coastal Plain grew through the 1970s, in recognition that a very large fraction of the original wetlands had already been lost to development. A sequence of dry years in the late 1970s resulted in declining groundwater levels in the Perth region, and heightened concern for what are important aesthetic and environmental features of the regions. The Perth Urban Water Balance Study (Cageeg *et al.* 1987 a, b) was initiated in 1982 to develop regional scale understanding of the water balance, and the interactions between the hydrological balance and wetland features. A key part of the study indicated the need to identify capture zones, water level management and effective parameters of groundwater models in plan for the flow-through lakes of the Swan Coastal Plain. Such information is necessary for allocating groundwater to development and to the environment, and for protecting the quality of water in environmental flows through the lakes. Research was needed to identify the necessary lake water levels, buffer zones and model parameters for lake management.

These objectives were met by Townley *et al.* (1993), who examined the role of the lakes in the regional, unconfined aquifer system. Through a combination of isotopic, piezometric and modelling investigations, they were able to develop a conceptual model of groundwater flow-through, mixing, and their impact on flow patterns through the regional aquifer. This conceptual model was parameterised as a numerical model of flow and water balance, and was then used to identify opportunities to artificially manage lake levels, minimise the impact of groundwater pumping, understand zonation and stagnation in the lakes themselves, capture zones, and the transport of nutrients from within these zones to and from the lakes.

This case study is perhaps the most detailed and comprehensive examination of surface water-groundwater interactions as they affect a wetland ecosystem in Australia. The corpus of research summarised in Townley *et al.* (1993) was ultimately motivated by the perceived groundwater dependence and uniqueness of lake ecosystems on the Swan Coastal Plain, and ultimately demonstrated the degree and nature of this dependence, and the nature of the system's vulnerability to changes in the groundwater regime, pollution and land use change. Further, the modelling could also show the impact that changes in the lakes would have on the regional groundwater itself.

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Acknowledgements

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APPENDIX A

Review of Australian Ecosystems and Potential Groundwater Dependency

Review By Region

Note that the following regions are indexed on the accompanying maps using numerals which preserve their original indexing in Jennings and Mabbutt (1977).

Tropical Northern Australia

The tropical North of Australia has highly seasonal rainfall with a strong summer maximum ranging between 400 mm inland to 1,600 mm at the coast, generating large river systems that provide sediment and floodwaters to wide coastal plains. Seasonal wetlands based on summer runoff are common, but so are more permanent waterbodies sustained by groundwater-derived base flow from mostly local aquifer systems. These can take the form of lakes, river channels and river pools. These pools typically support a floating and floating-leaved swamp herblands flora including waterlilies (*Nymphaea* spp.), *Ottelia*, *Eichhornia*, *Azolla, Ludwigia, Marsilea* and *Pseudoraphis*. Less ponded systems (submerged and emergent herblands) include *Triglochin, Caldesia, Limnophila, Ludwigia, Ceratophyllum, Monochoria, Utricularia, Myriophyllum, Eriocaulon, Vallisneria, and Chara*. *Phragmites karka* grasslands occur on sub-coastal plains, river floodplains and between coastal sand dunes. *Baumea* sedgelands occur in dune swales. Paperbark swamp forests comprised of *Melaleuca cajuputi, M. viridiflora, M. leucodendron, M. quinquenervia, Barringtonia gracilis* and *Pandanus* spp. occur in lake and sumpland areas with permanent waterlogging (Story 1969, Stocker 1970, Williams 1979). Mesophyll palm vine-forests (*Archontophoenix, Licaula* and rattan) occur in perennially wet patches at over 1,500 sites in the Northern Territory, and in more extensive stands on the Cape York Peninsula.

In systems with permanent water and a fringing zone of more ephemeral water, the tree component can include *Casuarina, Melaleuca, Barringtonia,, Pandanus* and *Terminalia*, as well as species of *Eucalyptus*. Where watertables seasonally drop below the land surface, woodland and forest swamps of *Melaleuca argentia* or *M. cajuputi* develop. The ecology of these swamp systems is further discussed by Specht and Mountford (1958), Williams (1979) and Specht (1981). Pedley and Isbell (1971) and Stanton (1976) describe the various woodland, heath and sedge communities on the Cape Yorke floodplains. which include *Melaleuca* spp., *Sinoga lysicephala, Petalostigma banksii* and *Xanthostemon*. The sedge *Schoenus sparteus* can dominate the ground layer.

North-Eastern Uplands

The North-Eastern uplands extend from the Tropic of Capricorn Northward to the tip of Cape York and inland to the uplands of the Divide. Wetlands are confined to alluvial valleys and include floodplain lakes, river channels (billabongs), sumpland lakes (waterholes) and barlkarras (riverine flats subject to flooding). Permanent lakes also occupy volcanic craters in the South-Eastern part of the Cape York Peninsula.

The rivers of this region sustain significant base flow derived from groundwater, eg. the Jardine River and similar rivers in the Northern Cape York Peninsula. In the basalt areas of the Atherton Tablelands, base flow is also sustained, with streams recharging and discharging at various places along their length. The perennial nature of these systems supports floating herblands with important fauna such as platypus, and streamside woodland and heath communities. Groundwater development in these system has the potential to eliminate discharge to streams (John Hillier, pers. comm.).

The role of groundwater in the maintenance of features like the permanent floodplain lake along Saltwater Creek on the Cape York Peninsula, formed by blockages of its Southern tributaries (Paijmans *et al.* 1985), is not clear. Lagoons on the Lower Burdekin, however, are known to be windows on the regional watertable; the Pelican lakes on the Upper Burdekin may also share a similar dependency on groundwater, but this is not clear. Anabranch Lake, Saltern Lagoon and Lake Louisa are all fresh bodies of water associated with lava flows which disrupted drainage in the Upper Burdekin; Paijmans *et al.* (1985) suggested that Lake Pelican and Lake Agnes may also be associated with basalt blockages to drainage, although in these cases the lakes are saline. *Eucalyptus tereticornis, E. tessellaris*, *E. microtheca*, and *E. alba* form most of the woody shoreline of these lakes. The component of inflow resulting from groundwater is not well-quantified.

The volcanic crater lakes and swamps of the Cape York Peninsula are fed by groundwater and runoff from limited catchment areas. The pollen in these systems has provided a record of vegetation change extending back over 100,000 years (Kershaw 1978, 1981).

There are intermittent coastal dune lakes found locally along the East coast of the Cape York Peninsula, which may be fed by local groundwater systems. Paperbark swamp forests, swamp scrub (*M. nodosa, Leptospermum flavescens*), *Eleocharis* sedgelands, and *Baumea* sedgelands (*B. rubiginosa, Gahnia sieberiana, Fimbristylis ferruginea, Schoenus* spp., and *Cyperus* spp.) may be associated with these sites, similar both structurally and floristically to wet heath systems found more commonly in South-Eastern Queensland and North-Eastern New South Wales.

Carpentaria Lowlands

Permanent lakes (waterholes) exist on the floodplain in channels and billabongs occur on the upper portion of fans that drain to the Gulf and must be considered as largely groundwater-derived. Rivers like the Mitchell and Flinders have a large base flow component. Like most Northern ecosystems, these permanent waters are vital to the maintenance of regional and local biodiversity. The ecosystems associated with the various geomorphic features are similar to those described above.

The North Australian and Kimberley Plateaux

Groundwater-derived wetlands of this region are restricted to river pools in the uplands and numerous waterholes and swamps on the lowlands and rivers, with permanent, base flow-driven wetlands on alluvial plains near the sea. Some of Australia's most notable wetlands occur in the coastal plains East of Darwin where major rivers with sources on the Arnhem Land Plateau reach the sea (Paijmans *et al.* 1985). From the Fitzroy River through to the North-West, including the Victoria, Daly, Adelaide, Mary, South Alligator and East Alligator rivers, base flow increases in magnitude, particularly for those rivers on Cretaceous geology (the latter five). These systems encompass plains along and between river systems which remain green all year, implying (groundwater) sources of water through the dry season. Many of the smaller creek systems (eg. Magela Creek) do not sustain dry season base flow (Vardavas 1988), and the seasonal floodplain lakes that exist (eg. Magela Lagoon), depend only on wet season runoff.

Where permanent water exists in the region, assemblages of floating and emergent herbland vegetation form which include *Chara* spp., *Nelumbo nucifera, Scirpus grossus* and *Hymenachne amplexicaulis*, with fringing *Melaleuca argentia*.

Chin *et al.* (1992) found that the groundwater hydrology of the Mary River Basin is not responsible for the geomorphological changes affecting vegetation patterns on floodplain, but is responsible for the maintenance of freshwater billabongs on the plains due to localised aquifer recharge and discharge into upland creeks. These support floating and emergent herblands as well as swamp paperbark forest.

There is growing evidence that the (upland) tropical savanna woodland, as well as the paperbark swamps and the >15,000 patches of monsoon rainforest in the region, are all dependent on groundwater in the dry season. Tickell (1994) suggested that tree transpiration in these systems was a probable mechanism of dry season groundwater discharge. Investigations are under way through a collaboration among the CRC for Sustainable Development of Tropical Savannas, the Power and Water Authority, the Northern Territory University, and the CSIRO Division of Land and Water Resources to examine the potential impacts on these ecosystems by lowering the watertable as a result of water supply development.

Temperate Uplands

The temperate uplands of Australia enjoy the highest rainfall outside of the tropics. The rivers which drain these regions are generally short, steep, and debouch into coastal estuaries which support wetlands of limited extent (Paijmans *et al.* 1985). Where they drain into the inland river systems of the Murray and Darling Rivers, they provide the largest, freshest source of surface water.

The South-Eastern Uplands

This region extends from just South of the Tropic of Capricorn in South-Eastern Queensland along the Great Dividing range through New South Wales and Victoria to include, for the purposes of this report, the Eight-Mile Creek and Glenelg River systems in the extreme South of South Australia. Major river systems include the Burnett, Brisbane, and Upper Condamine rivers (Queensland); the Clarence, Nymboida, Macleay, Upper Gwydir, Upper Namoi, Manning, Hunter, Upper Goulburn, Upper Castlereagh, Nepean, Hawkesbury, Upper Lachlan, Upper Murrumbidgee, Upper Murray, Shoalhaven and Snowy rivers (New South Wales); the Mitta Mitta, Mitchell, Ovens, Goulburn, La Trobe, Yarra, Mount Emu, Wimmera, Hopkins, Glenelg rivers (Victoria) and Eight Mile Creek (South Australia).

Base flow derived from groundwater discharge can be a large fraction of annual runoff. For example, base flow for the Yarra is 52–60% of the total stream discharge as gauged at Millgrove; tributaries upstream of this point have even a greater base flow component (Little Yarra = 71%, Woori Yallock Creek 57% and Don River 69%) (Nathan and Weinmann 1993).

Wetlands are generally confined to relatively narrow valley floors, with floodplain lakes, billabongs and waterholes in main river channels. In the highest parts of the Snowy Mountain in New South Wales permanent lakes are associated with glacial erosion. Other permanent water features are formed by faulting (Lake George) or in association with basalt flows (Monaro Lakes near Cooma). The extensive basalt sheets in Western Victoria have a dense concentration of fresh, brackish and saline lakes and swamps largely sustained by groundwater inputs (Paijmans *et al.* 1985). Tertiary basalt formations in New South Wales support springs and creek base flow; examples include regions around Mt. Canobolas, Inverell, the Liverpool Ranges, and the Lismore basalts. There are additional permanent water features occupying volcanic craters (Lakes Bullenmeri and Gnotuk in Western Victoria) and in karst topography (notably Blue Lake near Mnt. Gambier); in all of these cases, these features can be considered windows on the regional water table (Currey 1970).

Permanent lakes of coastal dunes and beachridge plains are maintained by outflow seepage from regional and local aquifers operating in deep sands, and are characteristically associated with sedgelands, swamp forests and swamp scrub; these are prominent features below 8m elevation on Stradbroke, Moreton, Fraser and Bribie Islands and at the same elevation range on the mainland coast of South-East Queensland and Northern New South Wales (Blake 1938, Whitehouse 1967, 1968; Baxter 1968, Blake 1968, Campbell 1983)). Conner and Clifford (1972) ascribe the maintenance of vegetation near Brown Lake on North Stradbroke Island to groundwater systems in Pleistocene sands. Similar coastal dune lakes occur in East Gippsland (Bird 1966, Timms 1973) and Central New South Wales (eg. Wooli Lakes like Hiawatha) (Timms 1969).

Permanent glacial lakes in the highest parts of the Snowy Mountains are fed by (very) local groundwater discharge and surface (snowmelt) runoff, and support wet tussock grasslands of *Poa caespitosa, Themeda australis, Festuca muelleri, Juncus* spp. and *Carex* spp, and adjoining *Carex* sedgelands (*C. gaudichaudiana*) or swamp heath. Associated with these systems can be *Sphagnum* swamps which develop below springs at elevations above 1,650 m in New South Wales and on the Bogong High Plains (Campbell 1983). Tussock grasslands occur on waterlogged soils in the region's highlands, often adjacent to Carex sedgelands or swamp heath. On the Hawkesbury Sandstone country of New South Wales, porous sands over impermeable bedrock generate local groundwater seepage which supports the development of swamp heaths with components of *Baeckia, Banksia, Epacris, Kunzea,* and *Leptospermum.*

Paperbark swamp forests (*Melaleuca quinquenerva, M. rhaphiophylla*) occur in the sand-dune country of coastal Queensland and New South Wales, in swamps with a significant component of local groundwater discharge. Swamp sclerophyll forests occur on floodprone soils in coastal Queensland, New South Wales, Eastern Victoria and South-Eastern South Australia, as well as along the Murray River and its tributaries inland, but the role of groundwater in these various systems is unclear. Swamp sclerophyll communities (*Eucalyptus largiflorens, E. camauldulensis*, and *E. microtheca*) are common along inland rivers and on floodplains; there is clear evidence based on isotope and sap flow studies (Thorburn *et al*. 1993, Mensforth *et al*. 1994, Thorburn *et al*. 1994) that groundwater can play a key role in the maintenance of these woodlands by providing a source of water during dry seasons and droughts.

Swamp scrub (*M. nodosa* and *Leptospermum flavescens*) are common in coastal Queensland and are likely dependent on local groundwater systems. Similar systems with *M. ericifolia, M. squarrosa* and *L. lanigerum* occur in coastal New South Wales. Swamp heaths in Southern Queensland and Northern New South Wales include *Banksia serratifolia, B. robur, L. lanigerum* and *Xanthorrhoea* spp. (Briggs 1981), but the role of groundwater in these systems is not known.

Where *Eleocharis* and *Baumea* sedgelands occur in the permanent and semi-permanent wetlands in coastal dune swales (eg. Pidgeon 1940) from Rockhampton South to Northern New South Wales, and along the Victorian coast, groundwater is likely to play a role in their maintenance. Where these *Eleocharis* and *Carex* sedgelands occur in the lagoons of the Murray River or on the tablelands of New South Wales and Southern Queensland, this role of groundwater is no longer clear but it is possible that local groundwater discharge determines their presence. Wet grasslands occur on coastal floodplains, where groundwater discharge may play a role in maintaining surface soil moisture in the dry season.

Typha and *Phragmites* grasslands (*T. domingensis, T. orientalis*, *P. australis*) occur throughout the region, including coastal sites, the Macquarie Marshes, the Gippsland Lakes. They have in common a need for inundation up to one metre depth for at least part of each year.

Since they occur on a variety of soil textures and geographic settings, the role of groundwater is difficult to generalise. In the case of the Macquarie Marshes, a permanent floodplain lake with an intermittent fringing swamp, the more permanent waters are occupied by *Paspalum paspaloides, Phragmites australia* and *Typha domingensis*, with fringing swamp woodland or swamp forest; it is likely that the Macquarie Marshes' permanent water features are maintained by local groundwaters arising out from the river (Paijmans *et al.* 1985). This may also be true for a billabong near Maryborough, Queensland, described by these same authors.

Emergent herblands (fen) occur on Eight Mile Creek in the extreme South of South Australia (Eardley 1943); system is probably base flow (groundwater) dependent (Campbell 1983). Much of the unique ti tree vegetation in the system has been lost to clearing (C. Harris, pers. comm.).

The South Australian Peninsulas and Kangaroo Island

These regions form biogeographical outliers of the South-Eastern Uplands. The Southern and Western Eyre Peninsula (Polder, Calptanna basins) have small seasonal to permanent swamps formed in solution hollows in the calcareous surface layers, with local, fresh aquifer systems supporting swamp sclerophyll woodlands of *Eucalyptus camauldulensis*. Similar features exist on the Yorke Peninsula, which also has local internal drainage features (most notably Pessey Swamp, are likely to be sustained by local groundwaters discharging from shallow, unconfined aquifers and which support swamp scrub communities of *Melaleuca*; some of these features are naturally saline. On Kangaroo Island, there are permanent swamps (lakes) in hollows of the interior lateritic plateau (Murray's Lagoon, Lake Ada, Lashmar's Lagoon, Archway Lagoon), and river pools supported by local groundwater discharge in a few of the major streams such as Cygnet Creek. In the Mount Lofty Ranges and Kangaroo Island, swamp forest and swamp woodlands (*Eucalyptus viminalis* and *E. leucoxylon*) and swamp heaths (*Rubus, Leptospermum, Pteridium, Phragmites, Blechnum* and *Typha*) are associated with local gullies and hollows, which may be local aquifer discharge points. Mitchell *et al.* (1981) provided a botanical survey of remnant vegetation and wetlands in the Central and North-Eastern Mount Lofty Ranges; areas of scientific significance probably involving groundwater discharge include peat swamps in the Upper Finnis River near Mount Compass, and inland freshwater swamps supporting *Carex* and *Baumea* sedgelands. The Department of Environment and Planning (1983) provide an overview of the wetland types and their conservation for this region. In this same document, damming of the Onkaparinga River is blamed for substantial changes in the ecology of its estuary.

The South-West of Western Australia

This region extends South-West from a line from Geraldton to Esperance, and includes a diverse assembly of wetland, base flow, aquifer and upland vegetation systems dependent on groundwater. In part this is due to the highly seasonal rainfall, and in part to the presence of a coastal plain with significant, shallow aquifer systems. The ecosystems of this region, and their dependence on groundwater, are probably the best-documented and understood in Australia. This understanding has not only generated classification systems and complex biophysical models of system interactions, but has been incorporated into municipal and land management(eg. Atwood and Barber 1989, Environmental Protection Authority 1990, 1992, 1993a, 1993b, 1994; Godfrey *et al.* 1992, Balla and Davis 1993, Kite *et al.* 1994, Arrowsmith 1996). Strategies now exist, at least in draft form, for the management of groundwater in the Jandakot and Gnangara regions; these strategies include explicit consideration of ecosystem-groundwater interactions (Jennings and Payne 1996). It is anticipated that abstraction from the Gnangara Mound will increase over the next thirty years to augment water supplies to Perth. Atwood and Barber (1989) identified the major groundwater quality threats to the Swan Coastal Plain as fertiliser use in parks and gardens, unsewered suburbs, leaking storage tanks, rubbish dumps and industrial wastes.

The magnitude and importance of such investigations and management is prompted by the fact that the Swan coastal plain, for example, has lost more than 80% of the original wetlands since settlement (Giblett and Webb 1996), while the situation in the South-West Agricultural Region is even more serious, with many wetlands cleared by farmers and the rest potentially affected by salinity caused by land clearance (EPA 1994). Groundwater-dependent vegetation has been lost due to extraction from the Jandakot and Gnangara borefields (Water Authority of Western Australia 1992). Wetlands in this region are of great national and international significance. For example, they include living examples of some of the world's most ancient life forms (microbialites). This region is one of the major provinces of biodiversity in the world (Jennings and Payne 1996), and much of this diversity is associated with the thousands of wetlands which support a rich abundance of aquatic flora and fauna (Giblett and Webb 1996). The 400 groundwater-fed wetlands on the Gnangara Mound, including permanent lakes and seasonal wetlands, support bird species listed in the Japan (China) Australia Migratory Bird Agreement (JAMBA and CAMBA); some of these wetlands (Peel–Yalgorup system) are also listed, or proposed for listing (Forrestdale and Thomsons Lakes, Vasse–Wonnerup system) under the RAMSAR convention (Hill *et al.* 1996a). The Western portion of the Gangara contains karst features, including streams which support the richest subterranean fauna ever reported (Jasinka and Knott 1991), and are considered to be of high conservation significance (Arrowsmith 1996). Of the 176 taxa found in the region, 30% require permanently wet habitats (Balla and Davis 1993).

Classification and description of wetland ecosystems on the Swan Coastal Plain are documented in detail by Semeniuk (1987), Semeniuk *et al.* (1990), Semeniuk and Semeniuk (1995), and Hill *et al.* (1996a, b). This body of work not only defines the hydrological and hydrogeological regime for the diverse wetlands in the region, and their associated flora and fauna, but also documents wetland evaluation criteria (after Leprovost Semeniuk and Chalmer 1987) and wetlands and rivers of Aboriginal significance. Hill *et al.* (1996a) also proposed preliminary management priorities of conservation, for the region extending from Moore River to Mandurah. Wetlands of the Darling System are similarly described using the classification system documented in Semeniuk (1988) and Semeniuk *et al.* (1990). Mapping of wetlands is available at a scale of 1:25,000.

In summary, the groundwater-dependent systems in the area consist of lake, sumpland, damplands, rivers (including pools), palusplains, and floodplains. All coastal plains wetlands are ultimately groundwater-driven. Permanent lakes like Joondalup and Loch McNess support floating herbland communities with *Najus marina, Lemna minor, Ottelia ovalifolia* and *Myriophyllum propinqua* in deep waters, replaced by an emergent herbland and sedgeland communities of *Baumea articulata, B. juncea, Gahnia trifida, Leptospermum gladiatum, Chara baueri, Nitella congesta*, *Potamogeton pectinatus and P. tricarinatus* in shallower water (McComb and McComb 1967, Aston, H.I. 1973, Congdon and McComb 1976). In lakes receiving fresh groundwater but subject to progressive salinisation over summer (eg.. lakes on Rottnest Island), emergent herblands include *Halosarcia halocnemoides, Sarcocornia quinquefolia* and *Wilsonia humilis*. The exotic*Typha orientalis* is commonly present in coastal lake systems, and its rapid spread is restricting the distribution of the native *T. domingensis* (R. Froend, pers. comm.). Semi-natural impoundments like Lake Leschenault on the Darling Scarp, and Lakes Leake and Tooms are oligotrophic and support emergent and fringing herblands and sedgelands.

Paperbark swamp woodlands are common features associate with damplands and sumplands (coastal dune swales), and consist of *Melaleuca parviflora, M. raphiophylla,* and *Eucalytpus rudis*. Swamp scrubs (*Hypocalymna angustifolium, Leptospermum ellipticum, Banksia littoralis*) can occur on similar geomorphic features; Farrington *et al.* (1990) found that dampland vegetation (*Hypoclymna angustifolium, Kunzea vestita, Regelia ciliata*) used 266 mm of groundwater over summer. Samphire (*Anthrocnemum*) shrublands can colonise the edges of periodically-inundated inland salt lakes, but the role of groundwater in these systems is not clear.

At least two ‘terrestrial’ systems have known dependence on groundwater. There is at least 100 square kilometres of woodlands, consisting primarily of *Banksia*, on the Swan Coastal Plain. While some of these woodlands are xerophytic (no dependency on groundwater), many have root systems down to the water table; this differentiation is not necessarily species-specific but appears to be site-specific. In these latter systems, changes in groundwater levels in the vicinity of production wells has resulted in tree deaths. In 1991, 100 hectares of woodland near two well fields on the Gnangara mound were severely affected following two very hot days coinciding with reduced water levels. In the most significantly affected area, 70% of *B. illicifolia* and 30% of *B. menzesii* died (Arrowsmith 1991). Although Farrington *et al.* (1989) concluded that such woodlands were net recharge sites, more recent work using stable isotopes by Ray Froend (pers. comm.) and associates suggest that this vegetation does use groundwater. It has been inferred that *Banksia* woodlands are most susceptible to alterations in groundwater depth where they grow over watertables within 6 m of the surface, and that the species involved can adapt or tolerate a lowering of the minimum watertable of an average of 0.2 m per year, and a total fall of up to 1.5 m (Water Authority of Western Australia 1992).

The second upland terrestrial system of note is the jarrah (*Eucalyptus marginata*) forest. The presence of forest in such an extremely seasonal environment (long summer dry seasons) suggests a large capacitance for moisture storage. It is known that water levels in the surface aquifer fluctuate widely over the year, and that jarrah trees can extract water to great depth (Carbon *et al.* 1981); it is likely that much of this fluctuation is due to discharge of groundwater to the atmosphere via transpiration. Energy balance and tree water use investigations by Silberstein (1996) suggested that deep stores of (ground) water maintain transpiration at or near equilibrium evaporation rates through most of the dry season. It is problematic as to whether or not to characterise these deep stores as groundwater or not, but in the sense that if they were reduced or removed by pumping they would affect forest health, then this system is probably groundwater-dependent in the sense of this report.

The stability of the hydrological regime on the Swan Coastal Plain can determine the composition of flora and fauna; *fluctuations* of water levels can be important in maintaining systems (Balla and Davis 1993, Froend *et al.* 1993, Froend and van der Moezel 1994). Thus, management of the interactions between surface and groundwaters may, in some cases, be more important than the maintenance of a water table at a given height.

Apart from the Swan Coastal Plain, rivers debouching to the sea in the South-West of the region maintain base flow through groundwater discharge in their lower reaches (eg. the Blackwood, Warren, Margaret, Kalgan Rivers). Although under threat from increasing saline discharge upstream, this base flow maintains streamside (swamp sclerophyll forests (*Eucalyptus rudis* and *Melaleuca* spp.) and in-stream ecosystems.

In one of the few studies of its kind in Australia, Jasinka and Knott (1991) surveyed in detail the cave systems of Yanchep National Park, and found at least one unique species in each cave, and with some species in every cave requiring permanent water. They concluded that the greatest threat to these systems is drying. Caves systems and their hydrology have also been studied South of Katherine in the Northern Territory (Peter Jolly, pers. comm.).

Tasmania

In Tasmania there are permanent lakes and swamps at low and intermediate elevations in alluviated valley floors (eg. Lake Edgar) or in wind-scoured hollows in the North-East of the island (Paijmans *et al.* 1985). Lakes such as Diprose Lagoon also form behind crescentic lunette dunes. The uplands and interior tablelands of the island have a dense network of freshwater lakes in glacially scoured basins and in hollows behind moraines, in addition to lakes formed by hydroelectric works. These systems are all maintained in part by local groundwater systems supporting high river base flows even over extended dry period; such base flow is particularly important in the relatively drier Eastern and South-Eastern parts of the state, as well as on Flinders Island.

Springs occur in some limestone/dolomite areas (known locally as ‘mound springs’), particularly in the area around Smithton in the North-West (eg. Mole Creek–Chudleigh, Smithton, Kimberley, Marrawah, Beaconsfield and Hastings); some have slightly elevated water temperatures. No information is available on associated ecosystems.

The ecosystems associated with lakes such as Lake Edgar on the Huon Plains of South-West Tasmania include *Baumia* sedgelands (*B. rubiginosa*) in water over 0.5 m deep, and swamp heaths (*Lepidosperma longitudinale* and *Chorizandra cymbaria*) in shallower water, and swamp scrubs (*Melaleuca* spp. and *Leptospermum* spp. with *Restio tetraphyllus*) in the swampy surrounds (MacPhail and Shepherd 1973). Glacial lakes generally lack floating herblands, but emergent or fringing herblands include *Montia australica* and *Velleia montana*. *Sphagnum* bogs occur where there is a constant supply of seepage water in the highlands. Other sedgelands and swamp scrubs and heaths occur in a fringe along gently flowing rivers (Campbell 1983).

Swamp heaths occupy waterlogged, acid soils on the tablelands and include *Richea, Epacris* and *Callistemon* (Jackson 1965, Kirkpatrick 1977). *Eleocharis* sedgelands occur in the South-East coastal region, with *Trichlochin* swamps developed at the ends of lakes (eg. near Oatlands and Rushy Lagoon) (Campbell 1983). In the South-West and West, waterlogged, peaty soils on valley floors support button-grass sedgelands of *Gymnoschoenus sphaerocephalus* (Curtis 1969, Paton and Hosking 1970). Where the groundwater levels are permanently at the surface in these sedgelands, *Leptocarpus tenax, Xyris operculata, Lepidosperma longitudinale, L. filiforme, Restio tetraphyllus, Utricularia* and *Drosera* replace *G. sphaerocephalus* (Curtis and Somerville 1947, MacPhail and Shepherd 1973). Other permanently waterlogged sites support Carex sedgelands (Briggs 1981). Estuaries of the Huon and Derwent Rivers support Phragmites grasslands (Briggs 1981).

Submerged and emergent herblands in the higher areas of Tasmania (eg. Lakes Sorrell and Crescent) support *Triglochin procera, Myriophyllum pedunculatum, Liparophyllum, Potamogeton, Claytonia australasica* and *Centrolepis monogyna* (Cheng and Tyler 1976, Briggs 1981), while lowland herblands consist of *Myriophyllum, Hydroctyle, Limosella* and *Liparophyllum* (Specht *et al.* 1974).

Small, near-coastal lagoons occur on Flinders Island and in parts of the Eastern and North-Eastern coasts which depend largely on groundwater for their maintenance.

Murray Lowlands

The Murray Lowlands include Central and South-Western New South Wales, South-Eastern South Australia and North-Western Victoria, and largely include the Murray Basin geological formation. The region has a semi-arid climate, and coordinated drainage of low stream gradients. The East and Centre of the region is composed of the alluvial fans of the Darling, Lachlan, Murrumbidgee, Murray, Goulbourn, Loddon and Wimmera; most of the Western third is porous aeolian sands (Paijmans *et al.* 1985). Many of the wetlands in this regional are caused primarily by the damming of tributary streams by naturally-occurring levees along the main rivers.

Wetlands also occur where dunes systems block former river channels. Wetlands are generally restricted to localities with high water tables or river runoff originating from uplands to the East and South. Other wetlands are associated with river pools, floodplain lakes, and billabongs. The sands of the Western third of the region have few wetlands due to high permeabilities and low water tables, although upstream portions of the Wimmera River have permanent pools. The South-West of the region features old coastal barriers between swamps and lakes (ie. the Coorong) which become progressively more permanent towards the sea.

Swamp sclerophyll forests of *Eucalyptus camauldulensis* are common along the rivers and in floodplains subject to periodic inundation. Swamp sclerophyll woodlands occur in places less frequently inundated (Briggs 1981) and include *E. camauldulensis* and *E. largiflorens* (Moore *et al.* 1970), with the former usually occupying lower ground closer to watercourses than the latter. Although the survival of these ecosystems has been linked to the frequency and duration of flooding (ie. non-base flow discharge), their maintenance during dry periods is also dependent upon the depth and quality of groundwater (Eldridge *et al.* 1993, Thorburn *et al.* 1993, Mensforth *et al.* 1994, Thorburn *et al.* 1994b, 1995; Jolly and Walker 1996). Interestingly, streamside trees may be more dependent on groundwater than previously believed (Thorburn and Walker 1994, Thorburn *et al.* 1994a), but this may be due to a relatively fresh zone of groundwater being maintained through flushing mechanisms associated with changes in river height. The widespread decline in the health of these floodplain woodland and forest systems, associated with decreased flood frequency and high saline water tables, has prompted calls for changes to the surface water regime. River regulation has not only reduced flood frequency, but also raised river levels in downstream portions (ie. the six locks in South Australia) of the Murray leading to a shift in the predominance of temporary to permanent wetlands, and the forcing of saline groundwater into the river due to elevated heads (Thompson 1986).

Lignum shrublands also occur on the floodplains of the Murray and Darling rivers and their tributaries and distributaries, and are often associated with swamp woodland formations as described above, although their dependence on groundwater is unknown.

The other major wetland formation in the region is the Coorong, a series of permanent lakes and swamps on the South Australian coastal plain, formed behind a series of parallel dunes. These lakes are filled either by rainfall or when the unconfined aquifer rises above the lake beds in winter (van der Borch and Lock 1979). Complex interactions between seawater, surface waters and groundwaters of varying salinities has lead to the development of freshwater soaks, saline marches, open water and samphire swamps (Department of Environment and Planning 1983, Jensen and Nicolson 1993). Historically, surface inflows from the South-East occurred only in extremely wet years, so the water balance is very dependent on the quantity and quality of inflows from the Murray River. Groundwater inflows have been reduced by drainage works which intercept groundwater and discharge it elsewhere, so this system is probably less groundwater-dependent than other permanent wetlands (Jensen and Nicholson 1993), although subject to degradation from enhanced saline inflow. Up to 88.8% of the wetlands in the South-East of South Australia have been drained (Jones 1978).

To the East and South of the Coorong is a region locally referred to as the Upper South-East, which consists of an inland extension of the dune systems referred to above. In this system, local aquifers generated on the dune tops discharge into swales, which are also subject to a regional groundwater system arising in Western Victoria. In the swales of both the Coorong and Upper South-East, swamp scrub of *Melaleuca halmaturorum* and *Leptospermum pubescens* occur (Briggs 1981); the survival of this scrub is dependent on the flood frequency of surface waters (Denton and Ganf 1994) and on the salinity and depth of groundwaters (Mensforth and Walker 1996). Ecologic and Associates (1988) maintained that the role that groundwater plays in these systems (specifically the wetlands of the Bakers Range and Marcollat watercourses) is better understood and defined than the role of surface waters.

In the Coorong and South-East regions, freshwater swamps contain *Eleocharis* (*E. pallens* and *E. acuta*) sedgelands; these systems also occur in association with ephemerally flooded depressions on floodplains of rivers. Where flooding is deeper and more permanent, *Baumea* sedgelands occur (Dodson and Wilson 1975). *Phragmites* grasslands occur at the mouth of the Murray (Briggs 1981); *Typha* grasslands are widespread and apparently not associated with specific geomorphological or hydrological systems. Floating and floating-leaved communities are associated with the Murray and Darling Rivers and their tributaries, and include *Azolla filiculoides, A. pinnata, Potamogeton tricarinatus, Lemna minor, Spirodela oligorrhiza* and *Marsilea* spp. (Beadle 1948, Knight and Smith 1961, Briggs 1981).

Given the predominance of the Murray–Darling River with respect to wetland vegetation in the region, it is clearly essential to identify the role that groundwaters play in the hydrologic and hydrogeochemical regime. Groundwater can potentially discharge anywhere along the length of these rivers (Williams 1991), but the magnitude in terms of mass flux is relatively small compared with surface flows from the uplands. It may be very important chemically, however. Donnelly *et al* (1992) noted that the saline groundwater discharging into the Darling–Barwon system is sulphate rich, and indicated the potential to cause significant sediment/water interactions, and Grace *et al* (1996) noted that rapid clay flocculation during low river flow was caused by the influx of saline groundwater, and that this decrease in turbidity removes light limitations on algal growth. Donnelly *et al.* (1996) linked these observations to phosphorus dynamics and subsequent algal blooms, and argued for the maintenance of sufficient river flow to prevent groundwater discharge from markedly influencing the chemistry of water column. Thus, in this system, groundwater discharge may be inversely proportional to ecosystem health.

On the other hand, other authors have argued that it is the maintenance of (more) permanent flow in these systems which has most altered their ecological characteristics (eg. Hillman 1995b, Anon 1996). Regardless, the recent and numerous studies of flow requirements of the inland river systems of South-Eastern Australia (Bailey 1995, Gehrke *et al.* 1995, Harris 1995, Hillman 1995a, Lake 1995a, Lake 1995b, Swales and Harris 1995) have all focused on surface water flows, their frequency, and the effects of their regulation.

The Central Lowlands and the South Australian Ranges

This region is an extensive basin(s) of inland drainage covering Central and South-Western Queensland, North-Eastern South Australia and North-Western New South Wales. From its wetter, Eastern margin, rivers feed permanent lakes and swamps such as the Macquarie Marshes. This region also includes the Channel Country, which has extensive floodplains and barlkarras. Much of the surface water in the South-Western portion drains into the episodic Lake Eyre. Finally, the region contains most of the artesian features of the Great Artesian Basin known as mound springs.

There are few (naturally) permanent lakes. Narran Lake, near Brewarrina, is the terminal drainage basin for the Narran River (a distributary of the Balonne River); it supports canegrass (*Eragrostis australasica*) and *Phragmites* grasslands, and *Lignum* shrublands. The role of groundwater in maintaining this system is not known. Other permanent floodplain lakes occur on along the Lachlan (eg. Lake Waljeers) and support swamp sclerophyll woodlands. Barrenbox Swamp, on the floodplain of Mirrool Creek between the Lachlan and Murrumbidgee Rivers, is now permanently flooded due to human intervention; Typha grasslands dominate the lake to a depth of about 1.5 m, with floating and floating-leaved herblands growing in deeper waters (Braithwaite and Frith 1969). Many such systems have connection to the regional groundwater table, but it is not possible to provide a synoptic assessment of the importance of this connection across the wetlands of the region. Intermittent floodplain lakes are common but are assumed to have no significant dependence on groundwater.

There are deep, permanent water holes in the Cooper, Warburton, Kallakoopah and Strezlecki Creeks. Such features are likely to be part of local recharge–discharge groundwater systems associated with the floodplain and channel. Lakes such as Goyder Lagoon on the Diamantina and Coongie Lakes on the Cooper are also likely to be maintained by local groundwater systems associated with floodplains. Along such permanent features are found swamp sclerophyll woodlands of E. camauldulensis, *Lignum* swamplands, *Carex* sedgelands (with *Cyperus gymnocaulus*), canegrass grasslands, submerged and emergent herbfields (*Myriophyllum verrucosum*). Coongie Lakes supports floating herblands of *Ludwigia peploides, Azolla filiculoides* or *Lemna disperma*, which are largely absent from Goyder Lagoon although the latter supports an equivalent herbland of *Polygonum* sp. in the lower reaches of the Diamantina at Clifton Hills. Given the arid country in which they occur, we infer that these ecosystems are entirely dependent on groundwater. Morton *et al.* (1995) list Goyder Lagoon and the Coongie Lakes as a refuge area for biological diversity in arid and semi-arid Australia, and provides a good review of the biological component of these systems.

Some lakes in terminal drainage basins are almost certainly surface water-driven, such as Cobham Lake and Lake Bancania in Western New South Wales. The most prominent episodic lake in a terminal drainage basin in the region is Lake Eyre, which fills rarely. The heritage values of this basin were assessed by Morton *et al.* (1995). The lake has two hydrological systems: an artesian groundwater system and a surface water system driven by infrequent floods. The former exist as discharging aquifers on the lake's Western margin, and along North–South lines in the lake bed, presumably marking fault zones (Kotwicki 1986). The importance of these discharges to lake ecosystems is not known. Paijmans *et al.* (1985) suggested that groundwater flows issuing from the South Australian ranges furnish some water in addition to runoff to the arc of episodic lakes around their Northern end (Lakes Frome, Torrens, Eyre South). Allison and Barnes (1985) established that significant groundwater discharge to the atmosphere is a feature of Lake Frome and thus it is possible that fringing vegetation may obtain some water from this source.

This region includes the discharge areas of the Great Artesian Basin, and thus a large arc along its Southern and Western edge of discharge features known locally as mound springs. These springs occur where exposed geological strata vent thermally heated water to the surface, and there are perhaps 600 groups of such springs in the region (Habermehl 1982, Ponder and Clark 1990) covering an arc of about 1,000 km. Ponder (1990) identified three major groups of springs in South Australia: the Dalhousie supergroup with 90% of the total spring discharge (Williams 1979); the Lake Eyre supergroup which ranges from Marree to Oodnadatta including the Bubbler, Blanch Cup, Coward, Hamilton Hill Strangways and Elizabeth Springs; and the Lake Frome supergroup which includes springs East of Marree and those in Lakes Frome and Callabonna. Elsewhere in the region, there are eight more aggregations: the Mulligan River, Springvale, Flinders, Barcaldine, Springsure and Eulo groups in Queensland and the Bogon River and Bourke supergroups in New South Wales (Morton *et al.* 1996). Many of these springs outside of South Australia have declined or are extinct (Ponder 1986), but there are active sites in the Springvale, Barcaldine and Springsure supergroups, but information about these springs is not as comprehensive as for those in South Australia.

The major recharge area is along the Eastern edge of the region in the higher rainfall uplands of Queensland; residence time of water in this system may be as great as 2 million years (Habermahl 1980, 1982). The structural geology associated with the formation of mound springs was investigated by Aldam and Kuang (1988). The ages of springs vary from 20,000 to one million years old (Wopfner and Twidale 1967, Boyd 1990).

The rate of discharge varies among springs with a maximum at Dalhousie of 160 l s^{-1} (Smith 1989); many of these discharges are sufficient to form outflow channels with associated wetlands. Many spring wetlands in New South Wales and Queensland have been destroyed by the lowering of the piezometric surface by extraction and development of unregulated bores (Boyd 1990). The springs are the only source of permanent fresh water within a desert environment, and the ecosystems which develop upon them are entirely reliant on the discharge of groundwater and have been so since the late Pleistocene (Krieg 1989). This geographic isolation and dependence has given rise to unusual ecological and evolutionary phenomena (Morton *et al.* 1996).

Most of the springs support sedgelands and grasslands, but some of the larger pools at the Dalhousie complex support *Melaleuca glomerata* swamp woodlands or swamp shrublands (Mollemans 1989). Vegetation at the mound springs tends to be of low species diversity, and high similarity among springs with other wetland systems; what dissimilarity in composition does occur may be related to variations in water chemistry among springs (Lange and Fatchen 1990). Systematic surveys were conducted by Symon (1984), Kinhill Stearns (1984), Mollemans (1989) and Fatchen and Fatchen (1993). There are few endemic or relict species; Morton *et al.* (1996) review the literature on these plants.

The mound springs do not seem to be a significant refuge for birds (Badman 1987), with no known endemics (Morton *et al.* 1996). There is only one species of frog (*Limnodynastes tasmaniensis*) (Tyler 1978, Robinson and Casperson 1986), which is found elsewhere. Fish fauna at Dalhousie consists of six species in five genera from five families (Glover 1989, Crowley and Ivantsoff 1990, Kodric-Brown and Brown 1993, Morton *et al.* 1996); four of these are endemic. The fish fauna of Dalhousie may be the most diverse assemblage of native fish species without exotics in desert mound springs world-wide (Kodric-Brown and Brown 1993). However, all of these families and genera are represented elsewhere in the Lake Eyre Basin (Glover 1989), although there is evidence to suggest that they have been isolated at Dalhousie for at least 10,000 years and it is unlikely that they could now disperse naturally in floodwaters.

It is among the invertebrates that we find the most unique features of mound spring fauna (Morton *et al.* 1996). The only known desert-dwelling isopod (Ponder 1986), the crustacean *Phreatomerus latipes*, is found only in the springs of the Lake Eyre Basin (Mitchell 1985) but is absent from Dalhousie (Zeidler 1989). The ostracod *Ngarawa dirga* is the only member of its subfamily and occurs only in the Lake Eyre supergroup of mound springs (De Decker 1979, Zeidler 1989); other ostracod species have yet to be described taxonomically but are present. One copepod among the 12 species present at Dalhousie may be relictual (Morton *et al.* 1996). There is an endemic blind amphipod *Phreatochiltonia anophthalma* at Dalhousie (Zeidler 1991). There is evidence of differentiation in the yabby *Cherax* sp. and the shrimp *Caridinia* sp. suggesting long isolation in the mound springs in which they occur (Sokol 1987). The mound springs are also rich in previously undescribed species of hydrobiid snails (Ponder 1989, Ponder *et al.* 1989), with two endemic genera *Fonscochlea* and *Trochidrobia*.

Lothian and Williams (1988) listed nine mound springs in South Australia as having special scientific significance. Dalhousie Springs and the Lake Eyre supergroup were listed as highly significant refugia by Morton *et al.* (1995). The mound springs were listed as one of four special wetland areas in Australia with respect to biodiversity by Mummery and Hardy (1994). Social and Ecological Assessment (1985) ranked the springs on their biological value, species diversity, species rarity, naturalness and perceived vulnerability to damage the following descending order of conservation value: Dalhousie, Freeling, Hermit, Old Finniss, West Finniss, Blanche Cup and Bubbler, Strangways, Nilpinna, Bopeechee, The Fountain, Big Cadna-owie, Twelve, Coward, and Davenport.

Harris (1992) provides an excellent review of mound spring values, their history of management and study, and their conservation, including a discussion on their immense importance to Aboriginal and European communities. Morton *et al.* (1996) concluded that two aspects of the aquatic systems of the Lake Eyre Basin are sufficiently unusual within Australia to warrant further assessment against World Heritage criteria: (1) the nature and scale of the endorheic drainage systems reaching Lake Eyre from the East and the ecological responses to that system, and (2) the most unusual nature of the evolutionary radiations which have taken place among the scattered, isolated artesian springs of the Basin. These authors also concluded that while the Australian mound springs are not globally unique, the spatial scale over which they are distributed and their abundance are unusual at the global level.

It should be noted that unregulated artesian flow from bores has lead to the development of desert wetlands similar to, if not equivalent to, mound spring ecosystems. Examples of such human-induced wetlands are associated with Nunn's, Angas' and McEwin's bores (Department of Environment and Planning 1983) and Purni Springs in the Dalhousie supergroup (C. Harris, pers. comm.). While the biological significance of these features is questionable given associated heavy grazing pressure and probable lack of endemics, they can have appreciable cultural significance. For example, Purni Springs is a popular outback destination for campers. Local resistance to regulating these bores and thus drying up these wetlands is one gauge to their cultural value.

The single most important threat to mound spring ecosystems is clearly aquifer drawdown, which at its worst can eliminate the flora and fauna altogether (Ponder 1985, 1986; Ponder and Hershler 1984). Habermahl (1980) believed that a new steady-state between recharge and discharge for the Great Artesian Basin was reached in the 1970s, potential impacts of local groundwater extraction remain. This is underscored by concerns expressed in the environmental impact assessment associated with the Olympic Dam mining development and subsequent monitoring studies to ensure compliance with specified limits (Olympic Dam Operations 1990, 1991, 1992). Among the recommendations for mound spring conservation in Harris (1992) is a call for the continuing research into the ecology and dynamics of plant and animal populations and the systematic monitoring of spring flow rates. The latter is only undertaken at Dalhousie at present. Morton *et al.* (1996) also identified gaps in our knowledge about mound springs as including (1) the distribution of aquatic organisms among the springs, (2) a detailed inventory of springs, and (3) detailed studies of water budgets for outlets of the Great Artesian Basin (human-induced and natural). Addressing this latter gap was considered urgent. Ponder (1986) suggested that the mound spring systems of Queensland required detailed scientific investigation.

The Pilbara

This region of Western Australia includes the Ashburton, Fortescue and De Grey River systems, whose headwaters flow from the Archean granite plains of the Hamersley and Chichester Ranges. The climate is wet-dry tropic with low and variable rainfall of about 200–350 mm yr^{-1}. Surface waters are largely restricted to drainage lines. Springs are fed by local aquifers, and river pools are sustained by local bank storage or the local water table. Masini (1988a, 1988b) provided the most comprehensive study of ecosystems in this region, including an explicit evaluation of the dependence of these systems on groundwater. For instance, river pools in the Fortescue are maintained by discharge from the Millstream Aquifer.

Masini (1988a) maintained that the presence of cajeput *(Melaleuca argentia, formerly leucadendron)*) signifies permanent water, but that in general the majority of the biota of the region depends to some degree on the sparse permanent water sources. This includes the floating herblands of *Marsilea* sp., submerged herblands of *Vallisneria* sp. and *Myriophyllum* sp. and emergent herblands of *Potamogeton* sp. in the pools, *Typha* grasslands on the fringes of pools, and swamp sclerophyll woodlands on the outermost fringes. These woodlands contain *E. camauldulensis* and *E. coolibah* which are almost certainly dependent on groundwater (Masini, pers. comm.). Where E. coolibah grows on floodplains, the watertables are usually more than 20 metres deep, suggesting no dependence on groundwater in these locations (J. Kite, pers. comm.) Masini (1988a) provides a survey of the fauna associated with these ecosystems, and suggests that the springs and permanent river pools probably harbour endemics of aquatic fauna and associated flora, and that these species would be 'vulnerable' to pastoral, mining and recreational activities. He further asserted that the definition of the interrelationships between the biotic and abiotic components of these ecosystems was 'imperative.'

The Coastal Lowlands

This region extends from Kalbarri in the South to Dampier in the North, East to include the sand plains inland from the coast. The region has a similar climate to the Pilbara and is generally sandy, with intermittent or episodic lakes between linear dunes, areas liable to flooding along main rivers (eg. Murchison, Gascoyne, Lyndon) and seasonal river channels. A karst aquifer on the Exmouth Cape supports an important groundwater ecosystem assemblage (R. Humphries, pers. comm.). Similarly, groundwater discharge into Shark Bay is implicated in the maintenance of stromatolite formations such as those in the Hamelin Pool; the nature of this dependency is essentially chemical in the form of the carbonates brought to marine surface from regional or local aquifers (R. Salama, pers. comm.).

Arid Areas of Uncoordinated Drainage

This region covers almost half of the continent and is characterised by low rainfall, high potential evaporation, low topographic gradients and a predominance of porous sands (Paijmans *et al.* 1985). As a consequence, only intermittent and episodic wetlands are commonly found, and most of these are saline. The only reported inland stand of the mangrove *Avicennia marina* exists along a salt creek with no present tidal connection with the ocean, 40 km inland from the Eighty Mile Beach (Beard 1967). There is probably a dependence on groundwater discharge at this site, but it has not been investigated.

Sandland

Sandland covers the deserts which extend from the Nullarbor Plain to the Eighty Mile Beach in Western Australia. The episodic lakes (eg. Lake Disappointment, Lake Carnegie, Lake Auld, Percival Lakes and Lake Mackay) occur between dunes and in the broad, shallow valleys where blocked by sand (Paijmans *et al.* 1985). No systems with known groundwater dependencies are reported.

The Yilgarn Plateau

The Yilgarn Plateau extends from the Western Nullarbor North-West to Karalundi and Meekathera in Western Australia. The region has large, shallow valleys of low gradient occupied by extensive chains of episodic, saline lakes such as Lake Raeside, Lake Barlee, Lake Lefroy, Lake Cowan and Lake Austin. These valleys rarely flow with water. No ecosystems with known groundwater dependencies are reported.

The Nullarbor Plain

The Nullarbor Plain consists of flat-lying limestone with thousands of solution hollows that occasionally hold water for brief periods (Paijmans *et al*. 1985). Along the moister Southern margin there are rockholes which may hold water for more extended periods, but this water is probably of surface origin. There is an extensive series of caves under the Nullarbor (Matthews 1979), and these contain permanent water features (a more complete, general discussion of aquifer and cave ecosystems is presented below).

The Lander–Barkly Plains

These plains extend Northward from Alice Springs to Daly Waters and East from Mt. Isa to the Western Australia–Northern Territory border. According to Paijmans *et al*. (1985), wetlands in this area occur mainly as extensive intermittent or seasonal swamps which broadly correlate with the black soil plains in the North-East of the region. Drainage is internal for both surface and groundwaters (eg. Lake Woods, Tarrabool Lake, Lake Sylvester, Lake De Burgh, Bluebush Swamp), and discharge features are less common and tend to be in the form of playa lakes (Tickell 1994). Sclerophyll swamp woodland in this region may have groundwater dependencies.

The Central Australian Ranges

These ranges include the Musgrave, Macdonnell, Stuart Bluff, Treuer, Harts, Murchison and Davenport Ranges of Central Australia. The terminal playa of Lake Amadeus is a regional groundwater sink, but free water rarely exists here. Surface water features include numerous rockholes and channel waterholes; the latter are generally connected to local aquifer systems (eg. in the Macdonnell Ranges). In some locations, notably Kings Canyon (Watarrka National Park), relict vegetation around these permanent water features is of major ecological and cultural interest.

It is of considerable note that local Aboriginal knowledge of the locations and characteristics of surface water sources (potentially of groundwater origin) far outstrips that documented by agencies. This may be particularly true in this region. The Western Water Study (Toyne Remote Area Consultancies 1995) included consultation with Aboriginal communities in the South-West of the Northern Territory around Yuendumu; in a 6,000 square kilometre area, hundreds of soaks, cave pools, river pools and seepages were identified in an area for which only a fraction of these features would otherwise be known. Many of these traditional sites have deep ceremonial, economic, and social significance.

Coast Zone

As noted by Paijmans *et al*. (1985), Australia's coastal zone extends over a wide range of climates (and geomorphologies) and so many types of wetlands exist including a high proportion of permanent ones. Further, groundwater interactions with the marine environment offshore or in embayments can be significant with respect to ecosystem maintenance.

The coast of Australia is generally a drowned one and consequently valleys form estuaries where they meet the sea unless they are filled in by geologically recent sedimentation. Exceptions include geomorphologically emergent landscapes such as North-West Cape and the Ashburton Delta (J. Kite, pers. comm.). The larger discharges of water (and thus sediment) of the Northern rivers develop extensive tidal flats, with an association with mangroves in the intertidal portions. The combination of strong winds and abundant sand of this zone favours the development of dunes, which in turn provide local groundwater systems and some runoff to maintain permanent lakes and swamps.

It is an arbitrary distinction within Jennings and Mabbutt's (1977) classification system as to what to consider a coastal system and what to consider as part of one of the above terrestrial regions. For the purposes of this report, the distinction is unimportant; where reference is made in one of the above sections to a system perhaps coastal in nature, we indicate so.

East Coast South of Brisbane

This region extends to the Cape Howe in the South. It is characterised by well-developed barriers formed by beach ridges and dunes which close off embayments to form coastal lagoons that range from permanently open to the sea (eg. Wallis Lake) through intermittently open (eg. Coila Lake) to permanently closed (eg. Myall Lake) (Paijmans *et al.* 1985). These coastal lakes are normally associated with permanent swamps behind beach ridge plains, with narrow mangrove fringes in sheltered estuaries. The coastal dune systems generate local aquifer systems which discharge into the swamps, estuaries and lakes. Some of these features and their associated ecosystems are described in the South-Eastern Uplands section above.

The dominant terrestrial vegetation type associated with these coastal systems is swamp scrubs *of Melaleuca ericifolia, M. squarrosa* and *Leptospermum lanigerum*, with local swamp forests of *Casuarina cunninghamiana* along river courses. There are additional components of sedge swamps, heath and scrub swamps. On more brackish sites*, M. quinquenervia* can dominate.

Intertidal flats support mangrove communities, although of lower species diversity than mangrove systems farther North. These plants are adapted to an extremely hostile environment involving waterlogging and high salinity (Love 1981; Ball 1988). The local patterning of mangrove and associated salt marsh flora has been ascribed to a number of abiotic factors including physiography, tidal inundation, salinity, drainage, aeration and climate (Clarke and Hannon 1969, Lear and Turner 1977); no explicit interaction or dependency on groundwater was identified.

In more Southerly (temperate) Australian climes, mangrove swamps tend to be replaced by samphire swamps and salt marshes dominated by salt-tolerant grasses such as *Sporobolus virginicus* or other halophytes such as *Salicornia quinqueflora*. In places where they co-occur, the salt marshes tend to be inland of a fringe of mangroves. Zonation of coastal vegetation is summarised by Love (1981).

A particular feature of these ecosystems is the predominance of acid sulphate soils under naturally water-logged conditions, typically in the backswamp behind (dune) levees and under the levee toes and levees themselves. Coastal soils with acid sulphate potential are common and widespread in New South Wales (Naylor *et al.* 1995). The formation of the pyrite responsible for this potential acidity occurs in two main environments. The first and most common is saline and brackish lowland including tidal flats, salt marshes and mangrove swamps (Pons and van Breeman 1982). The second is the bottom sediments of saline and brackish estuaries, rivers, lakes and creeks (Naylor *et al.* 1995). These soils do not realise this acidity until drained; thus, the role of groundwater discharge at these sites in maintaining waterlogged conditions is pivotal. Shallow drainage of swamps, deep excavation or drainage of levee toes and levees, and bottom dredging of rivers run the risk of acidification. On oxidation, the resulting mobilisation of toxic compounds from the soil (Al, Fe, Mn, Ar) have the potential to affect not only the local ecosystems but off-site aquatic fauna as well (Sammut *et al.* 1994). Flushing after rains in areas of drained acid sulphate soils can lead to massive fish kills in estuaries and habitat degradation (Callinan 1993, Phuc Tuong 1993), with economic impacts to commercial estuarine fisheries of one million dollars per annum in discarded fishes affected by Epizootic Ulcerative Syndome alone (Callinan 1993).

North of Brisbane

North of Brisbane to the tip of Cape Yorke exist coastal wetlands which include permanent lakes and swamps in dune hollows as described in the North-Eastern Uplands section (eg. Fraser Island, Cape Flattery) which are dependent on local groundwater discharge. Mangrove/salt marsh systems as described above extend the length of this coastline, although the mangroves themselves are much more extensive and diverse with all 29 recorded species of Australian mangroves present North of Daintree (Love 1981).

The Coastlands of the Gulf of Carpentaria

The supratidal flats of this region are extensive and penetrate up to 30 km inland, and are covered by flood waters in the wet season and by high tides and storm surges (Paijmans *et al*. 1985). There is no evidence that groundwater discharge plays an important role here. In the dry season, these flats only support sparse, halophytic vegetation such as the samphires *Tecticornia australasica* and *Anthrocnemum* spp.. Narrow intratidal flats along the mouths of rivers support a diverse array of mangrove species (Wells 1979).

Northern Territory Coast

This coastline, extending from Southern Arnhem Land across to Wyndham, has coastal wetlands which include intertidal flats with mangroves backed by bare or sparsely vegetated supratidal flats that grade inland into extensive freshwater or brackish swamps (Paijmans *et al*. 1985). The coastline on parts of Groote Eylandt and the Gove area have dune barriers with tidal lagoons, lakes and swamps behind them. The sparseness of vegetation on the supratidal flats increases toward the Victoria River estuary due to the drier climate. As discussed above in the North Australian and Kimberley Plateaux section, fresh groundwater discharge from local aquifers on the floodplains of these rivers maintains dry season billabongs (Chin *et al*. 1992)

Kimberley Coast

Coastal wetlands in this region are confined to the extensive supratidal flats where rivers deposit sediment (Paijmans *et al*. 1985).

North-West Coast of Western Australia

This coastline, extending Southward from Cape Leveque to Kalbarri, consists mainly of supratidal flats which are either bare or carry sparse, salt-tolerant plants. Exceptions include North-West Cape and the Zuytdorp cliffs. There are intratidal flats with mangroves, and where salinity is very high (eg. Shark Bay), algal mats form. Dependency on groundwater in these systems is unlikely. The role of groundwater in the development of the stromatolites in this region is discussed above in the Coastal Lowlands section.

West Coast of Western Australia

This coastline extends from Kalbarri South to Point D'Entrecasteaux. The region has few coastal wetlands in the North but in the South there are extensive permanent swamps and lakes in linear hollows between eolinite dune ridges; the sea occupies one of these hollows to form Leschenault Inlet while others are windows on the water table (Paijmans *et al*. 1985) as discussed in the South-West of Western Australia section. Stromatolite formations as discussed in the Coastal Lowlands section and referred to in the North-West Coast of Western Australia section also occur South of Perth.

South Coast of Western Australia

This coastline extends Eastward from Point D'Entrecasteaux to Cape Pasley (Esperance). The region has a series of inlets rarely open to the sea behind eolianite and sand dune barriers. Behind these barriers are swamps and lakes (seasonal and permanent in the West and intermittent in the East). Although here is no literature available on the groundwater dependency of these systems, it is likely that they have similar relationships to groundwater as similar coastal systems to the North.

Coastal Bight

This coastline is dominated by steep cliffs which preclude the development of coast wetlands, but there are narrow inter-barrier flats and dry lake beds on the Lower coast of the Roe Plain (Paijmans *et al*. 1985). Mangroves can be found in sheltered sites and seasonal lakes between dunes on the North-Eastern end of the Bight. The role of groundwater in these systems is unknown.

The South Australian Gulfs

This coast is characterised by muddy or sandy intertidal and supratidal flats and some mangroves in sheltered positions such as the heads of Spencer Gulf and the Gulf of St. Vincent as well as Port Pirie, Port Adelaide, Franklin Harbour and Ceduna. Jennings and Bird (1967) ascribed the presence of mangroves in these places to a reduced refracted ocean swell, higher tidal range, less wind and fewer barriers than more Southerly estuaries (ie. they did not identify any role of groundwater). There are coastal lagoons and swamps behind dune barriers in more Southerly, exposed positions. There is no evidence of groundwater interactions maintaining these systems.

The South-East of South Australia

The extensive wetlands occupying the succession of coastal dunes and eolinite barriers (eg. the Coorong) are described in the South-Eastern Uplands section. Those wetlands (lagoons) of this type nearest the coast are tidal and permanent, with impermanence decreasing with distance from the coast. In these more Southerly localities, salt marshes of *Arthrocnemum arbusculum, A. halocnemoides* and the salt bush *Atriplex paludosa* dominate (Wood 1937). Lake Alexandrina is now a permanent, freshwater lake as a result of the series of barrages across the Murray Mouth which converted it from a brackish lagoon.

Victorian Coasts

The Western coast of Victoria has coastal wetlands comprised of small lakes, swamps and lagoons behind sand barriers in exposed portions of the coast and are for the most part permanently inundated. In Gippsland, coastal wetlands consist of a series of brackish lakes and lagoons behind a barrier of sand dunes and beach ridges; channels cut through these barriers have increased the salinity of the lagoons and affected vegetation (Paijmans *et al*. (1985). Groundwater discharge to many of the shallow coastal lakes in the region (especially Lake Wellington) and is very important in maintaining the fresh to brackish wetland ecology. Mangroves (*Avicennia marina*) extend to Corner Inlet, but beyond there to the West their location is spotty (Shallow Inlet, Anderson's Inlet, Port Phillip Bay and Barwon Heads) (Love 1981).

O'Rourke *et al*. (1995) discussed the ecological impacts of groundwater discharges to catchment streams and Port Phillip Bay, particularly with respect to the transport of pollutants. It was common practice to dispose of industrial wastes in the Western suburbs of Melbourne prior to the 1970s via injection into local aquifers (Riha 1975). However, there is little data on the relationship between local water quality and the local biota, and less on ecological health (Land Conservation Council 1989, Colman *et al*. 1992).

It is equally difficult to separate out the impact of groundwater from that of surface water (O'Rourke *et al.* 1995). The direct input of groundwater to Port Phillip Bay is 5.5 x 10^4 Ml yr^{-1}, or 2% of the total flux into the bay (Otto 1992), but this doesn't include the base flow component of streams (perhaps another 20%). Certainly the vast proportion of nutrients enters via surface flow; the 35 tonnes per annum of nutrients which enter via the groundwater from the Werribee Treatment Complex is less than 1% of that which enters the bay via outlet drains (Collett *et al.* 1993). As far as O'Rourke *et al.* (1995) were aware, no work has been done on specific ecological impacts of groundwater discharge into Port Phillip Bay; they tentatively suggest that the inference is that increasing concentrations of groundwater solutes (especially contaminants) is having ecological impacts. Other related studies on groundwater aspects of Port Phillip Bay include Anderson (1988), Hall (1992), Leonard (1992), Hydrotechnology (1993), and Shugg (1993).

Tasmanian Coasts

Tasmanian coastal systems include some tidal lagoons, small permanent lakes and swamps behind restricted sand barriers along the East coast and in a small area North of Macquarie Inlet on the West coast (Paijmans *et al.* 1985). Flinders Island has numerous lagoons and lakes behind and between sand dunes. No mangroves occur in Tasmania, probably because of frost (Love 1981). The salt marshes in the vicinity of Launceston and Hobart are characterised by *Salicornia quinqueflora, Distichlis distichophylla* and *Arthrocnemum arbusculum*. The relatively high base flow in Tasmanian rivers may be important in the maintenance of saline gradients in estuaries, but there is no available literature on this phenomenon.

Review by Vegetation Type

The above regional survey and assessment of Australian ecosystems potentially dependent on groundwater is reorganised herein according to the basic ecosystem classification. Although system descriptions and citations are not repeated in full detail, this section may be used for accessing relevant information by ecosystem type. Since mound spring ecosystems are exclusive to the Central Lowlands and South Australian Ranges, this information can be found entirely in the section above and is not repeated here.

Terrestrial Vegetation

Australia has a variety of forests and woodlands which apparently have access to sources of (ground) water in addition to seasonal rainfall. In some cases, this groundwater source may result from local recharge during a pronounced wet season, as is likely the case in tropical upland sclerophyll woodlands and paperbark swamp forests. Other systems of this type include the jarrah forest and the *Banksia* woodlands of Western Australia. In other cases, such as sclerophyll woodlands on the Eyre Peninsula and on the floodplain of the Murray River (and possibly on the Lander–Barkly Plains), these systems access (discharge) groundwater from local or regional aquifer systems but may lack the seasonal or permanent waterlogging characteristic of wetlands. The only known inland stand of mangroves, which occurs in North-Western Australia, may also have a groundwater dependence of this latter type.

It is useful to note that of the Southern (Victorian and Tasmanian) rainforests, their distributions seem to be limited to sites which receive a minimum of 50 mm of rainfall in the driest month (Busby and Brown 1994). This suggests that these systems have no dependency on groundwater through the dry season.

Forestry plantation is being actively extended into lower rainfall areas across Southern Australia. This is motivated in part by an intentional desire to minimise groundwater recharge (or even enhance discharge), while at other times such interactions with the groundwater were not considered by planners. While these plantations are not natural, their productivity can be dependent to some extent on groundwater. This has been demonstrated for eucalypt plantations near Bannister, W.A. (Greenwood *et al* 1985) and near Boho, Victoria (C. Clifton, pers. comm.). It is also suspected for radiata pine plantations in South-Eastern South Australia.

Wetlands

Wetlands comprise the most extensive and diverse set of Australian ecosystems with potential dependencies on groundwater. Here we include a survey of not only Australia's freshwater wetland types (after Briggs 1981), but coastal saltwater systems as well.

Mesophyll Palm Vine-Forests

These wetland forests occur in numerous small patches across the Northern Territory, and in more extensive stands in Northern Queensland. In the former case, the patches are almost certainly dependent on a dry season source of water originating from the near surface aquifer system; this is being investigated at present by the Northern Territory University and CSIRO Land and Water. The more extensive stands on the Cape York Peninsula have an undetermined dependence on groundwater.

Paperbark Swamp Forests and Woodlands

Paperbark swamp forests consisting primarily of *Melaleuca* spp. Occur on coastal floodplains of Northern Australia, in the coastal sand-dune country of Queensland, South-Western Australia and New South Wales, and on certain river floodplains in the latter state. They are usually characterised by seasonal inundation by up to a metre of water and may be dry at other times (Briggs 1981). Chin *et al* (1992) concluded that groundwater was important in maintaining the fresh billabong sites supporting swamp paperbarks. Groundwater is likely to play a major role in all of these systems; the dependence of the Northern floodplain swamp paperbark forests is currently under investigation by the Northern Territory University and CSIRO Land and Water.

Paperbark woodlands consisting of *M. parviflora, M. raphiophyla, M presissiana* and *Eucalyptus rudis* are associated with the damplands and sumplands (coastal dune swales) of South-Western Australia. These systems are almost certainly dependent on groundwater, but to an unknown degree. Similar assemblages of trees occur along the lower reaches of the Blackwood, Warren, Margaret and Kalgan Rivers in the same region; it is again likely that base flow in those rivers supports this vegetation during the dry season. These latter systems also occur around the fringes of inland salt lakes in Western Australia and can include *M. thyoides*. In the Pilbara, the presence of *M. argentia* signifies the continuous availability of water , and during the dry season this condition is maintained by shallow groundwater (Masini 1988a).

Swamp Sclerophyll Forests and Woodlands

These forests are characterised by tree species such as *Eucalyptus robusta, Tristania suaveolens*, *Casuarina glauca* and *C. cunninghamiana* (coastal Queensland and Northern New South Wales*); E. botryoides, E. robusta, Melaleuca* spp. and *C. glauca* in Southern coastal New South Wales; *E. botryoides* in Eastern Victoria; *E. ovata* in South-Eastern South Australia; *E. viminalis* and *E. leucoxylon* in the Mount Lofty Ranges and Kangaroo Island; and *E. rudis* and *Melaleauca* spp. in South-Western Australia. In all of these systems, groundwater use is likely.

Inland swamp sclerophyll forests of *E. camaldulensis* are distributed through much of Eastern and Northern Australia. The degree of dependency on groundwater may vary with the availability and reliability of other sources of water such as periodic riverine flooding. The *E. camaldulensis, E. largiflorens* and *E. microtheca* woodland communities on the Murray and Darling River floodplain have a complex but established dependency on groundwater. It is very likely that a major portion of the annual water balance in such systems along the Cooper, Warburtin, Kallakoopah and Strezlecki Creeks, and permanent floodplain lakes such as Lake Waljeers, in the Central Lowlands of Australia is derived from local groundwater. Less clear is the dependency of the woodland shoreline systems (*E. terticornis, E. tesselaris, E. microtheca* and *E. alba*) surrounding lakes (eg. Lake Pelican and Lake Louisa) in the North-Eastern uplands.

Swamp woodlands communities of *E. camaldulensis* form on the solution hollows associated with fresh, local aquifer systems on the Eyre and Yorke Peninsulas. Swamp sclerophyll woodlands of *E. camaldulensis and E. coolibah* fringe river pools in the Pilbara, and these are certainly dependent to a high degree on groundwater.

Swamp Scrubs and Heaths

Swamp scrubs normally occur on sandy or peaty soils in coastal areas (Briggs 1981). Vegetation of this kind occur along the permanent lakes of coastal dunes and beachridge plains of the South-Eastern uplands, and are maintained by outflow seepage from regional and local aquifer systems operating in deep sands. These systems include off-shore islands in South-Eastern Queensland (*M. nodosa* and *Leptospermum flavescens*) and North-Eastern New South Wales (*M. ericifolia, M. squarrosa* and *L. lanigerum*).

Swamp scrub also occurs on the sumpland and dampland features of South-Western Australia, and consist of *Hypocalymna angustifolium, L. elipticum, Banksia littoralis, Kunzea vestita* and *Regelia ciliata*. Farrington *et al*. (1990) found substantial use of groundwater in these systems over the dry season. Swamp scrubs of *Melaleuca* and *Leptospermum* species with *Restio teraphyllus* occur on the swampy surrounds of Tasmanian lakes such as Lake Edgar and along flowing rivers in this state. In the Coorong and Upper South-East region of South Australia, swamp scrub of *M. halmaturorum and L. pubescens* depend in part on the depth and salinity of groundwaters (Mensforth and Walker 1996).

Swamp heaths occur in both coastal and highland systems on peaty or sandy, acid, waterlogged soils (Briggs 1981), with standing water present at least some of the year. Coastal assemblages in South-Eastern Queensland and North-Eastern New South Wales include *Banksia serratifoila, B. robur, L. lanigerum*, and *Xanthorrhoea* spp.; these heaths are maintained by the same groundwater systems described above under swamp forests and woodlands in the region. Swamp heaths can also be found in Southern coastal Australia.

In Australia's highlands, swamp heaths occur in association with local groundwater discharge and surface (snowmelt) runoff. Swamp heaths with components of Baeckia, Banksia, Epacris, Kunzea and Leptospermum species are found on local groundwater seepages on the Hawkesbury Sandstone country of New South Wales. Swamp heaths are also associated with discharge into local gullies and hollows in the Mount Lofty Ranges and Kangaroo Island, and consist of *Rubus* and *Leptospermum* species. Swamp heaths of *Lepidospermum longitudinale* and *Chorizandra cymbaria* occur in the shallow water of Tasmanian lakes and on the waterlogged, acid soils of the tablelands (*Richea, Epacris* and *Callistemon* spp.); the role of groundwater in maintaining these systems is unknown.

Swamp Shrublands

Lignum (*Muehlenbeckia cunninghamii*) shrublands occur on periodically-inundated, heavy-textured grey and brown soils in the Southern and Central regions of the Northern Territory, in Northern South Australia and Western Queensland, and along the Murray and Darling Rivers and their tributaries (Briggs 1981). In Southern areas, it is often associated with *E. largiflorens* woodlands. The dependence of these systems on groundwater is unknown; in the case of the lignum swamplands along permanent water features in the Central Lowlands, the maintenance of these systems may be linked to the local recharge–discharge systems of floodplains (G. Gates, pers. comm.).

Shrublands of *Chenopodium auricomum, C. nitrariaceum, Atriplex nummularia, Maireana* spp., *Bassia* spp.0 and *Rhagodia* spp. occupy periodically-flooded, heavy-textured soils in Northern and Central South Australia, Western Queensland, Southern and Central portions of the Northern territory and Western New South Wales (Briggs 1981). They occur around the margins of inland salt lakes. Their dependence on groundwater is unknown.

Communities of samphire (*Arthrocnemum* spp.) shrublands colonise the edges and beds of periodically-inundated inland salt lakes and groundwater discharge areas across much of Australia. The ecological role which groundwater plays in samphire shrublands is has not been determined.

Sedgelands

Eleocharis sedgelands are common in coastal Australia. *E. sphacelata* is characteristic of permanent and semi-permanent waterlogging in floodplain country in Northern Australia, on coastal dune swales in South-Eastern Queensland and Northern New South Wales, along the Victorian and South-Eastern South Australian coasts, on the South-Eastern coast of Tasmania, in the lagoons of the Murray River and its tributaries, and on the tablelands of New South Wales and Southern Queensland (Briggs 1981). This huge array of diverse sites makes generalisations regarding groundwater dependence difficult. It is very likely that given the permanent surface wetness required by this species, in many of the above climates one must infer that a dry season supply of (ground) water is present.

By contrast, sedgelands of *E. dulcis* require seasonal inundation only, and are found on tropical coastal plains. It may well be that this sedgeland has a lower dependence on groundwater than those with *E. sphacelata.* Even less likely to have such a dependence are the inland sedgelands *of E. acuta* and *E. pallens*, which are found on regularly flooded, heavy soils in South-Western Queensland, Western New South Wales and in ephemerally-flooded depressions of the Murray River.

Baumea sedgelands occur in the permanent and semi-permanent wetlands in coastal dunes swales in South-Eastern Queensland and Northern New South Wales, and along the Victorian coast. As for other vegetation types in these dune systems, groundwater is likely to play a large role. Inland freshwater swamps of the Mount Lofty ranges support *Baumea* sedgelands; these almost certainly involve groundwater in their maintenance. In the Coorong and South-East regions of South Australia, *Baumea* sedgelands occur where flooding is deeper and more permanent. The same is the case for *Baumea (B. articulata, B. juncea, Gahnia trifida, Leptospermum gladiatum*) sedgelands associated with the coastal plains wetlands and lake margins of South-Western Australia. Lakes of the Huon Plains in South-West Tasmania have *Baumea* sedgelands in water over 0.5 m deep. This need for permanent or almost permanent surface wetness suggests potential dependence on groundwater.

Button-grass (Gymnoschoenus spaerocephalus) sedgelands are a feature of waterlogged, periodically flooded, peaty, infertile soils throughout Tasmania, in particular on the valley floors in the South-West and West (Briggs 1981). Where the watertable is permanently at the surface, in low-lying depressions, button-grass may be replaced by *Leptocarpus tenax, Xyris operculata, Lepidosperma longitudinale, L. filiforme*, and *Restio tetraphyllus*; these depressions may be kept wet through groundwater intersecting the topographic surface. Associations of vegetation including button-grass occupy similar sites on the tablelands of New South Wales.

Carex sedgelands, dominated by *C. gaudichaudiniana*, occupy permanently waterlogged, periodically flooded sites on the tablelands of New South Wales, Victoria and Tasmania. The degree to which these sites are maintained in a permanently wet state by groundwater is the key issue in determining their dependence. In the Snowy Mountains, this may be due to local, shallow groundwater systems' discharge. Carex sedgelands also occur in lagoons of the Murray River and in the Mount Lofty Ranges; no information on their dependency on groundwater is available but is likely in the latter case. Sedgelands (with *Cyperus gymnocaulus*) associated with permanent water features in the Central Lowlands are almost certainly dependent on the local aquifer systems which maintain these waterbodies.

Swamp Grasslands

Wet grasslands are most extensive in Northern Australia and are characterised by the presence of *Pseudoraphis spinescens, Panicum laudosum, Paspalum paspaloides, Leersia hexandra, Echinochloa* spp. and the sedge genera *Cyperus, Eleocharis, Fimbristylis, Fuirena* and *Scirpus*; this assemblage occurs mainly on seasonally flooded, heavy soils; there is no evidence of groundwater dependence. To the South in Queensland and Northern New South Wales, wet grasslands consist of *Paspalum paspaloides*, *Amphibromus neesii, Juncus spp., Carex appressa, Ecinochloa crus-galli* and *Panicum obseptum*. Similar systems occur in Southern New South Wales and coastal Victorian floodplains

Two types of *Phragmites* grasslands occur in Australia. *P. karka* grasslands are tropical and are interspersed among floating herblands and Eleocharis sedgelands on the coastal plain of the Northern Territory and in swamps on river floodplains and between coastal dunes in Queensland (Briggs 1981). Thus, the extended wet conditions which these systems favour may involve groundwater supply during the dry season.

Phragmites australis grasslands are temperate features, with major occurrences in Eastern Queensland South of Rockhampton, coastal and inland New South Wales (eg. the Macquarie Marshes) and Victoria (eg. the Gippsland Lakes), the mouth of the Murray River, and the estuaries of the Derwent and Huon Rivers in Tasmania. Coastal distributions seem to be limited to sandy soils, and to inland sites with soils inundated for part of the year by up to one metre of water. In the case of the Macquarie Marshes, they are associated with the more permanent water features and thus may rely on groundwater flow. The same may be said for where they occur in the Mount Lofty Ranges.

Typha grasslands are widespread throughout coastal and Southern inland Australia (Briggs 1981). They are not soil-specific and exist under a wide variety of water regimes ranging from permanent inundation by up to 1.5 m to seasonally dry. Where they occur in gullies and hollows in the Mount Lofty ranges, it may indicate groundwater discharge. They are commonly present in groundwater lakes on the Swan Coastal Plain and on the fringes of river pools in the Pilbara; in both of these cases groundwater is clearly playing a (undefined) role.

Tussock grasslands occur on waterlogged, acid soils in the highland regions of South-Eastern Australia. Wet tussock grasslands are associated with subalpine and alpine sites in the Snowy Mountains of New South Wales and consists primarily of *Poa caespitosa, Themeda australis, Festuca muelleri, Juncus* spp. and *Carex tereticaulis*. It is not known if groundwater plays a role in this waterlogging. Sod tussock grasslands inhabit more acidic sites in the Southern tablelands and the Barrington Tops of New South Wales, and in the subalpine and alpine areas of Victoria, the Australian Capital Territory, and is characterised by *Poa caespitosa, Themeda australis*, *Danthonia nudiflora* and *Calorophus lateriflorus*. Again, at these elevations, if groundwater is involved it must be local, shallow systems which maintain waterlogging through the dry season.

Canegrass (*Eragrostis australasica*) grasslands are common in low-lying, flood-prone land in South-Western Queensland, North-Eastern South Australia, Western New South Wales and North-Western Victoria on a variety of soil types (Briggs 1981). Fairly regular flooding seems to be required, at least relative to other wetland types in the region. Thus, one might infer that groundwater plays a limited role in general, although in specific instances like along the verges of permanent water features in the Central Lowlands (Goyder Lagoon, Coongie Lakes) this may not be the case.

Swamp Herblands

Floating and floating-leaved herblands occur in permanent waters in most coastal rivers, in swales between dunes, and in lakes across Australia. Typical Northern assemblages include *Nelumbo nucifera, Nymphaea capensis, N. gigantea, Nymphoides indica, Ottelia ovalifolia, Azolla spp., Ludwigia spp., Marsilea spp., Pseudoraphis spp.* and *Eichhornia crassipes* (Briggs 1981). These may be found in the river channels and pools in the tropical coastal plain. On the floodplains of the Northern Territory and the Kimberly, such assemblages may be fringed by *Melaleuca argentia* swamp paperbark forests.

In coastal floodplain and dune systems in New South Wales, species include *N. gigantea, Potamageton tricarinatus, Ottelia ovalifolia, Nymphoides indica, Lemna spp., Azolla filiculoides* and *Eichhornia crassipes.* In similar landscapes in Victoria, species include *Potamageton tricarinatus, Azolla pinnata, Azolla filiculoides, Ottelia ovalifolia, Lemna trisulca,* and *Lemna minor.* In the South-West of Australia, *Najus marina, Myriophyllum propinqua*, *Lemna minor, Azolla filiculoides, Spirodela oligorrhiza, Potamageton tricarinatus, P. pectinatus, Nitella congesta, Chara baueri,* and *Ottelia ovalifolia* dominate. In all of the hydrologic systems associated with these features, groundwater is very likely to play a major role; in some cases the waterbodies supporting these herb communities in coastal systems are clearly windows on the groundwater, as on the Swan Coastal Plain.

Inland floating and floating-leaved communities are associated with the Murray–Darling river system and include *Azolla filiculoides, A. pinnata, Potamageton tricarinatus, Spirodela oligorrhiza* and *Lemna minor.* While the water level maintaining such communities usually remains between one and two metres in depth, it may dry out completely for periods. Coongie Lakes supports floating herblands of *Ludwigia peploides, Azola fillicoides or Lemna disperma,* while Goyder Lagoon supports a system dominated by *Polygonum* sp.; these herblands may be entirely dependent on groundwater. The same holds for the floating herblands of *Marsilea* sp. in the river pools of the Pilbara.

Most of the above floating or floating-leaved systems are fringed by submerged and emergent herblands in shallower waters. In Northern Australia, species *include Triglochin procera, Caldesia oligococca, Limnophila indica, Ludwigia adscendens, Ceratophyllum demersum, Monochoria cyanea, Utricularia* spp., *Myriophyllum* spp., *Eriocaulon* spp., *Vallinsneria spiralis*, *Chara* spp. and filimentous algae (Briggs 1981). Species associated with such communities in coastal New South Wales and Victoria include *Ludwigia peploides, Najus marina, V. spiralis, T. procera, Myriophyllum propinquum, Utricularia* spp., *Potamogeton crispus, P. ochreatus*, *Nitela* spp. and filamentous algae. In South-Western Australia, communities include *Halosarcia halocnemoides, Sarcocornia quiquefolia, Wilsonia humilis*, *T. procera, L. preissii, Najus marina, Ruppia maritima, P. pectinatus, P. ochreatus, Nitela spp., Chara baueri, Villarsia albiflora, Polygonum serrulatum* and filamentous algae occur in coastal sand dune swamps (sumplands) and on the fringes of lakes. Equivalent emergent and submerged herblands exists in coastal and highland Tasmania, in the extreme South-East of South Australia, and on the tablelands of South-Eastern Australia (see above geographic sections).

Coastal Mangroves

These systems, which occur to varying degrees around the Australian coast, but with a predominance North of the Tropic of Capricorn. To the South, they tend to be limited to estuaries and inlets (Adam 1994). While most mangrove communities can be characterised as having, at least periodically, high soil salinities, Adam (1994) noted there are sites which are reliably brackish due to freshwater inputs. This author suggested that groundwater flows may be involved, although this aspect of their hydrology has not been studied in Australia. Sternberg and Swart (1987) reported evidence that mangrove systems in Florida obtained much of their water from deeper fresh groundwater, physiologically isolating them from the fluctuating soil salinity. G. Gates (pers. comm.) suggested that groundwater is generally a minor component to the overall hydrologic regime in these systems.

River Base Flow Systems

River base flow is, strictly speaking, a hydrological concept and not a class of ecosystems. However, we may identify and collate those ecosystems (vegetation types) that are likely to show a strong dependency on groundwater-derived base flow, as well as identify those Australian river systems in which this dependency is likely.

From the above review it is clear that Australia's major Northern coastal rivers, from the Fitzroy River in the West across the Top End and down to the Tropic of Capricorn in Queensland, have dry season base flow which supports the country's largest assemblages of wetland and in-stream ecosystems. These include streamside forests and woodlands as well as floating and emergent herbfields and in-stream biota. These rivers maintain a relatively high base flow through a long dry season, which is presumably vital to the maintenance and health of the ecosystems which it supports. It should be noted that smaller creeks in this region may have no dry season flow at all, and do not support these types of communities.

No less essential (perhaps more so) to ecosystem maintenance is the base flows in the rivers of the Pilbara, which maintain river pools associated with paperbark woodlands, scrub and aquatic systems which almost certainly would not persist in its absence (Masini, 1988a).

The coastal rivers of South-Eastern Australia also generally maintain base flow the year around, and support streamside forests, scrub, sedgelands and grasslands, as well as in-stream biota including floating and emergent herbfields. In these systems (some of which are regulated), it is more difficult to assess the fraction of base flow which originates from groundwater. This is largely the case for the rivers of South-Western Australia as well, although these coastal rivers face a greater problem in the increasing component of base flow which is saline groundwater discharge.

It is worth noting that at least one of Australia's key fauna has a strong dependency on the maintenance of river pools, if not flow, in the coastal rivers of South-Eastern Australia including Kangaroo Island: the platypus. This species, with the highest international scientific and public profile, is completely dependent on the continuous availability of river pools throughout the year. In much of its current habitat, groundwater is likely to play a role in this. In particular, this role may be great in the drier sites which the species occupies (eg. Rocky River on Kangaroo Island). It is apparently not a requirement for platypus to have flowing waters (J. Walmsley, pers. comm.), but if changes in groundwater availability induced a cessation of ponding in these systems at any time, then this may to lead to local extinction. It is important to note that pools have dried up on occasion on Kangaroo Island, but the platypus persisted by some as yet unknown strategy.

The role of base flow in ecosystem health in Australia's inland river systems is far from clear, particularly with respect to base flow of groundwater origin. This is partly due to the extreme variability of flow, and also due to the degree to which these rivers are now regulated. From the ecological literature, the focus has been on flood frequency as opposed to maintenance of low flows. It may well be that this is the hydrological phenomenon which indeed determines the distribution and persistence of ecosystems, with groundwater-derived base flow of small or even negative impact. In this regard we must separate out groundwater discharge into the floodplains of non-flowing inland rivers from situations in which groundwater is helping to maintain flow. An example of the former would be where the sclerophyll woodlands and forests of the Central Lowlands and the Murray Lowlands which (apparently) depend on the diffuse discharge of groundwater on floodplains; we do not in this report consider these as base flow systems.

Aquifer and Cave Systems

There is effectively no literature on groundwater aquifer ecosystems in Australia, apart from faunal surveys of a few cave systems (eg. Jasinka and Knott 1991) and one study of cave flow regimes (Nicoll 1977). Thus, we present here a non-regionalised treatment about what is known generally about these systems and their potential significance in Australia.

In a paper presented this year to the Groundwater and Land-Use Planning Conference in Perth by Gibert (1996), that author argued that aquifers form the most extended array of freshwater ecosystems in the world, and claimed a "complete revolution in groundwater ecological research" in the past two decades.

Groundwater ecology's roots are found in development of biospeleology in the late 1800s, and the development of phreatobiology in the 1950s. Groundwater ecology in its full complexity considers both the ecology of the karst groundwaters (biospeleology *sensu lato*) and that of the porous media of unconsolidated rocks (phreatobiology *sensu lato*), and the interaction zones between surface and groundwater environments (ecotone concept of Naiman and Decamps 1990; surface water/ groundwater ecotone of Gibert *et al.* 1990). It also considers the influence of groundwater on aquifer microbiology and geochemistry, recently reviewed by Chapelle (1993), and deep subsurface microbiology (Frederickson and Hicks 1987 and in a special issue of Geomicrobiology 1989). Basically, hypogean life exists in a continuum through different types of karstic, porous and fissured aquifers. Gibert (1996) claimed that life there is as diversified as in the superficial milieu.

One prominent aspect of these systems is that little or no autotrophy occurs in groundwater; carbon and energy are cycled by heterotrophy on fine organic matter. Other aspects of aquifer ecosystems are discussed in Husman (1975), Mathews *et al.* (1977), Dickson *et al.* (1979), Bosnak and Morgan (1981), Iliffe (1984), Sinton (1984), Brinkhurst (1992), Resh and Jackson (1992), Culver *et al.* (1992), Lafont *et al* (1992), Ward *et al.* (1992), Danielopol *et al.* (1992), Gibert (1992), Notenboom and Van Gestel (1992), Notenboom *et al.* (1992), Plenet (1993), Plenet and Gibert (1994), Gibert *et al.* (1994a, 1994b), and Malard *et al.* (1994a, 1996). Cave fauna references (non-Australian) can be found in Vandel (1964), Mohr and Poulson (1966), Ginet and Decu (1977), Culver (1982), and Camacho (1992). Phreatobiological references can be found in Motas (1958), Motas *et al.* (1957), Danielopol (1982), and Botosaneau (1986).

Until the 1980s, the vulnerability and quality of groundwater were exclusively assessed on the basis of hydrogeological, hydrological, and hydrochemical criteria. Recently, some regulatory agencies(US EPA, IHP Project, French Water Agency) have suggested that information on groundwater invertebrates might be used to manage groundwater resources and in particular to monitor the effect of pollution . Standard methods do not yet exist, but there has been considerable progress in groundwater ecotoxicology and groundwater pollution ecology (Plenet *et al.* 1992, Notenbloom *et al.* 1994, Hervant *et al.* 1995).

Gibert (1996) identified the following gaps in our understanding of aquifer ecosystems:

- impact of physical perturbation on functioning of groundwater ecosystems
- ecological recovery following remediation
- impact of chemical perturbations on biodegradation processes
- change on groundwater invertebrate communities and on organism viability
- the impact of land use practices on the structure and function of groundwater ecosystems

APPENDIX B—

Techniques Used in Production of Ecosystem Dependence Maps

Three maps have been produced to identify ecosystems of Australia and their relative dependence on groundwater.

They are:

Map 1—Vegetation of Australia and its relative dependence on groundwater

Map 2—Wetland ecosystem of Australia and their relative dependence on groundwater

Map 3—Rivers of Australia, Aquifer types and Rainfall: Sensitivity to changes in groundwater levels

All maps have been produced using the ArcInfo and ArcView Geographic Information Systems. These maps have been produced at a scale of 1:5,000,000 (AO size) for the original report, and 1:15,000,000 (A3 size) for report copies.

Map 1

The basemap for the vegetation map is the Auslig 'Present (1988) Vegetation of Australia' dataset. The attributes Tallest Stratum dominant species, growth form and feature were used in this map. Each vegetation type has been classified according to its dependence on groundwater, ranging from certain to no apparent dependency. The classification system also accounts for the confidence of the assessment, classifying each as a certain or likely dependence. Banksias, Graminoids and *Melaleucas* are the broad vegetation types identified as entirely or to proportionally dependent on groundwater. Numerous exceptions of complete to proportional dependencies on groundwater exist throughout the remaining vegetation types and are listed on the map. Nonetheless there are many features which are too small to describe as part of an Australia wide review and which cannot be depicted on a 1:15,000,000 scale map.

Map 2

The basemap for the wetland map has been produced from the 'Wetland Areas of Australia' maps produced by CSIRO (1979). These maps were produced at a scale of 2,500,000 and identify wetland many thousands of individual sites were wetlands occur. To produce a wetland map of Australia at a scale of 1:5,000,000, these maps have been interpreted to create a polygon base map showing the predominant wetland ecosystem.

Within each of the broad groupings there are many exceptions and the map is intended as a generalised identification of areas showing the predominant wetland type. Mound Springs have also been mapped, based on those identified by Morton, Doherty and Barker (1996). Physiographic regions (Jennings and Mabbutt, 1977) are also identified on the wetlands map and have been used in this map as they correspond to the classification system as defined in the report.

Each predominant wetland ecosystem has been classified according to its dependence on groundwater, ranging from certain to no apparent dependency.

Mound Spring are identified as certainly dependent on groundwater. Waterholes and permanent swamps and lakes are classified as highly dependent on groundwater. Exceptions to the remaining wetland types are listed on the map and have been classified as having a certain to proportional dependence on groundwater.

Map 3

The following basemaps have been used in the production of the Rivers, Aquifer Types and Rainfall: Sensitivity to changes in groundwater levels map:

- NRIC (1987) Hydrogeology of Australia
- Australian Bureau of Statistics (1991). CDATA
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Drainage lines, median annual rainfall and physiographic regions are plotted against the hydrogeology (Aquifer Type).

Map 3 is different from Maps 1 and 2, in that it does not show ecosystem dependence on groundwater directly, but rather provides a basis for interpretation. In interpreting this map in terms of ecosystem dependence on groundwater, rainfall is the primary consideration, followed by the geology (Aquifer Type). Where the median annual rainfall is high, water volumes in rivers are expected to have a relatively high baseflow component. Where these areas coincide with porous aquifer systems there is expected to be a direct relationship between groundwater levels and baseflow volume. In these circumstance, ecosystems associated with rivers are expected to have a high dependence on groundwater baseflow to rivers.

The aquifer types are identified as fractured, porous or undifferentiated. In porous aquifer systems, baseflow is interpreted to be generally sensitive to changes in groundwater levels, and in fractured rock aquifer systems generally less sensitive. It is also interpreted that there is a general reduction in baseflow with decreasing medium annual rainfall.