KARST MANAGEMENT CONSIDERATIONS FOR THE CAPE RANGE KARST PROVINCE WESTERN AUSTRALIA

Elery Hamilton-Smith, Kevin Kiernan and Andy Spate

A report prepared for the Western Australian Department of Environmental Protection

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EXECUTIVE SUMMARY

This report consists of three main parts. It was prepared after a brief visit and considerable review of the scientific literature and a large number of environmental assessment and planning documents. Following an introduction we analyse the significance of the resource in detail. We also discuss some basic concepts of the dynamics of karstic terrain and some of the physical constraints attendant on use of the natural and cultural heritage of the site.

As is obviously foreshadowed in the literature, our review reinforces the argument that the Cape Range peninsula and its associated fringing reefs is a highly important site with a range of unique values. We would not usually use the term 'unique' at all and do not do so lightly. We note that the archaeological, geomorphic and subterranean faunal attributes and setting of the peninsula amongst the fringing coral reefs is increasingly receiving both national and international recognition as a site of considerable importance. We suggest that consideration should to be given to its further recognition through the nomination of Cape Range peninsula as a site of World Heritage significance. The area is one of particular interest and importance for scientific research which is really only in its infancy in this area.

The second major part reviews in more detail the special conditions affecting the dynamics of karstic terrain including those of the 'island-type' aquifer regime which pertains on the peninsula. We express our concerns about the narrowness of perceptions of the complexities and routes of water through karst areas. Many of the values of the site are threatened or could be perturbed by lack of appreciation by planners and developers of the special hydrologic, ground stability and ecological conditions operating above and below the water table.

We go on in this part to examine a range of specific land management issues shown to us during our visit. We discuss these issues in light of karst system dynamics and make clear a number of concerns about existing and proposed developments.

Thirdly, we build on the demonstration of significance, on the discussion of karst dynamics and on the management implications of development. Here we make some 35 specific technical or policy recommendations to assist in the ongoing development and management of this special and sensitive site.

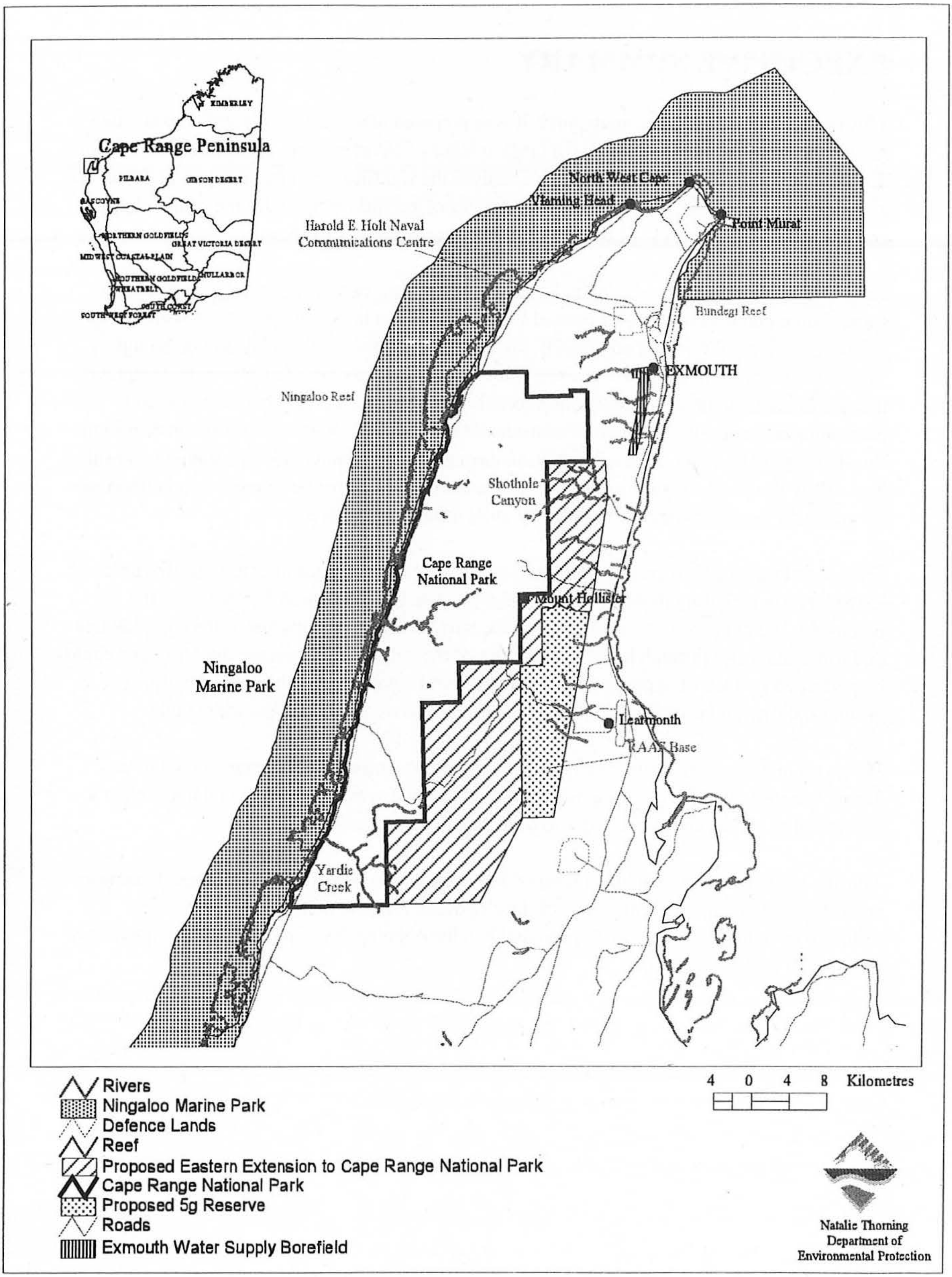

Figure 1. Cape Range Peninsula, Western Australia.

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1. INTRODUCTION

This report has been prepared in response to an open-ended brief of the Western Australian Department of Environmental Protection. The brief reads as follows:

> The team will be required to apply their professional expertise in the management of karst environments and policy development, to investigate and report to the EPA on:
>
> - the significance of the Exmouth /Cape Range region:
> - key karst management issues as they pertain to this region generally and specifically in relation to current and anticipated development proposals; and
> - contribute to the development and review of an environmental policy to guide existing and proposed development on the environmental management and protection of the karst environments of the Exmouth /Cape Range region.

Four days were spent by the authors (see Appendix 1) at Cape Range in the company of a number of officers of Western Australian Government agencies and with an experienced local speleologist, Mr Darren Brooks. Some of the proposed development sites were visited as were a number of existing infrastructure operations. Discussions were held with many of the proponents or operators of these sites.

Whilst the time spent in the field clearly cannot do justice to the important, fascinating and diverse natural and cultural environments of the Cape Range peninsula we hope that we offer an external perspective to the values and problems extant in this highly significant area. Hopefully, this perspective will provide a framework for the management of existing infrastructure and for future development in this internationally significant karst province.

The term 'karst' is used to describe landscapes that are commonly characterised by closed depressions, subterranean drainage and caves. Karst landscapes are formed principally by the *solution* of the rock, most commonly limestone and its close relatives' (Gillieson 1996 ; for further details of the complexity of the concept, see Self & Mullan 1996). The term refers to a total geomorphic province, not just to the characteristic features. So, in the case of Cape Range, it refers to the peninsula as a whole and we argue that it must be seen as including the associated reefs and the waters of the aquifer. Yuan (1988) and Eberhard (1994) further emphasise the complex and integrative nature of karst by referring to a karst system as 'incorporating component landforms as well as life, energy, water, gases, soils and bedrock.' We further discuss the concept of karst and its local application in 3.1 below.

Other technical terms are dealt with in the glossary, included as Appendix 2.

We have used the terms 'peninsula', 'region' and 'sub-region' somewhat interchangeably throughout the document. The context for the former is for a geographic region consisting of the Cape Range peninsula, **including the fringing reefs**, as a groundwater province bounded to the south by an unconfined aquifer of relatively high salinity (Hocking et al. 1987). 'Region' usually refers to a similar physical geographic area. The term 'sub-region' is used in the context of regional planning and policy issues and approximates the geographically defined area.

This report consists of three main sections:

- a discussion of the significance of the site (Section 3).

- an outline of some key concepts in karst land management and discussion on some specific management issues encountered during our visit (Section 4).

- Section 5 sets out a series of 35 technical and policy recommendations.

We have indicated (in 'boxes') three areas where there should be caution in our understanding of the resources or where the use of the resource requires special consideration.

As well as visiting Cape Range we have reviewed a large number of documents and memoranda, published and unpublished. Many are cited in the references or listed in the text. A number of Consultative Environmental Reviews, Public Environmental Reviews and similar documents have also been consulted but are not necessarily cited directly.

2. ACKNOWLEDGMENTS

We are grateful to Gary Whisson, Department of Environmental Protection, for his organisation of the field inspection and to the many people who contributed to our understanding of the area at that time, a number of whom are listed below. The field work was followed by an afternoon debrief and discussion with many of these people, together with other officers of Western Australian government agencies. We are grateful to them all for their inputs, understanding and suggestions. Obviously we cannot be completely au fait with the Western Australian administrative structures and thus beg forgiveness if we have misrepresented any agency's names, affiliations and, perhaps, viewpoints.

We are indebted to the following for their inputs to our review:

- Gary Whisson - Department of Environmental Protection
- Juliet Cole - Department of Environmental Protection
- Mike Martin - Water Corporation
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- Department of Transport quarry and marina supervisors
- Councillors and workforce of the Exmouth Shire Council
- Commander and environmental staff of the RAN Communications Centre
- Officers of various WA government departments who attended the Friday debrief.

Finally, we acknowledge the assistance of various government officers and others who provided valuable and thoughtful comments upon an earlier draft of this report.

3. SIGNIFICANCE OF THE RESOURCE

3.1 WHAT IS KARST?

Karst landscapes are primarily the product of selective chemical dissolution of limestone or some other relatively soluble bedrock by natural waters. Karst comes about because of a complex interplay between geologic, pedologic, climatic, topographic, hydrologic, biologic and temporal factors. The features exhibited by any particular karst are the product of precisely how that interplay is balanced. Success in managing karst depends upon recognition of the need for it to be managed as a total integrated and dynamic system. The cornerstone of successful karst management is a recognition of, and successful response to, the need to maintain the natural regime and quality of the fluids that flow through it - both liquids and gases (Kiernan 1988).

The surface environment in a karst area is often characterised by enclosed depressions of various kinds (sinkholes), streams that disappear underground, springs and dry abandoned valleys. There may also be a variety of residual forms that range in scale from large hills and ridges to small scale solution sculpture on rock surfaces that is known collectively as karren. Evolution of many of the surface landforms results from the fact that a comprehensive suite of landforms is also evolving underground. Caves and underground streamways are perhaps the most widely recognised attributes of karst. These under-ground landforms are also developed at a variety of scales and provide a wide variety of resources for the organisms that dwell in karst, humankind among them. But directions of underground drainage through the caves are often at variance with what is suggested by surface contours. The reality is that much that happens in karst can be counter-intuitive - our experience gained elsewhere can lead us to believe quite the opposite of what is really the case.

The tempting differentiation of karst environments into surface and subsurface components is really an arbitrary and erroneous exercise that seriously blurs reality. More to the point, it is a hazardous misconception. The reality is that there are not really two separate realms, but one unified system, and a highly interactive one. There is no separate world beneath our feet.

In a karst area the interface between the geosphere and the atmosphere simply dips out of sight below the general lie of the land, much as it does when we gaze across a barren plain and fail to notice that it is riven by a narrow and deep canyon that is brimful with water, life, beauty and opportunity.

The underground parts of a karst landscape are such a place, though the windows that allow us a glimpse into them may be tiny, and the contours of the real surface-subsurface interface are often upside down and almost impossibly complicated to draw on a map. Beyond constrictions through which we may not pass, lie caverns sufficient to hold cathedrals, and countless thousands of kilometres of tiny subways where the lives of creatures that have never known the sun, unfold.

Living on the external ground surface in such a place is a little like living on the threadbare thatched roof of a house that is occupied by someone else. Not only are we confronted by the difficulty that rain does not gather on our ground surface but instead passes straight through, but so too do many other resources we may seek, soil among them. Our waste products and the pollutants we create similarly slip through the thatch with consummate ease. A misjudged step and we may ourselves fall through. The occupants below, however, are well adapted to their environment. Having followed the resources to where they gather, they are buffered from the extremes experienced on the ground surface, but they are also reliant upon maintenance of the stable conditions in which they have evolved. Changes in the rates at which matter and energy is transferred underground, and in the nature and composition of what is transferred, can have serious implications for them. What we do while seeking to dwell upon their roof may have even more impact upon them than it does upon us.

In more humid karst water tracing experiments using coloured dyes or other agents are commonly used in order to allow catchments to be delineated and management planned accordingly. But in arid karst, such as Cape Range, this is much more difficult and sometimes impractical. Water flows through karst much as it flows through the pores of a sponge, its rate and direction governed largely by how high the water level has risen in the sponge. Insight into groundwater movements at Cape Range has been derived primarily from artificial boreholes, and to a lesser extent from natural wells on the coastal plains. The information they offer is far from comprehensive. It is akin to what might be obtained by inserting a drinking straw into a sponge, or scaled up to the Cape Range case, a couple of hundred drinking straws - but into a sponge that extends over the area of many city blocks.

Karst areas, deserts and low-lying coasts are perhaps the most sensitive of all geomorphic environments, that is, they have a low capacity to cope with disturbance, and are difficult, if not impossible, to restore once degraded (Yuan 1988). Cape Range peninsula combines all three of these geomorphic environments. The extreme sensitivity of the Cape Range karst is compounded by the fact that this would be a desert even were it not the case that such rain as it does receive rapidly disappears into that part of the karst that is inaccessible to us. All elements of this karst environment are closely interrelated. The Cape Range karst is no less interactive than any other.

The karst environmental system comprises the rock masses; the soils; the surface, soil and cave atmospheres; waters on the surface, in the soil, in various contexts in caves, and marine waters; the surface and subsurface fauna and flora; and energy. The most conspicuous parts of the karst complex at Cape Range peninsula are the result of denudation of the limestone masses in the Cape Range. But there are also constructional karst features involving the build-up of new carbonate masses that range in scale from minor tufas on hillsides to the large Ningaloo and Bundegi coral reef complexes. These reefs are as much a part of the Cape Range peninsula karst complex as the older reefs that form the Cape Range itself. Like the red desert dunes that attest to even greater aridity than now during much of the time the karst has been evolving, the Ningaloo Reef is being built up above the groundwater flow systems that evolved during times of lower sea level when the aquifer developed in response to a much steeper hydraulic gradient than is presently the case. Destabilisation of the dunes may have implications for the karst features. So may construction of limestone jetties to allow exploitation of the resources offered by the denudational karst have implications for the constructional karst if there is interference with patterns of longshore drift that cause unnatural accretion of sands and silts on parts of the living reef.

The karst of the Cape Range peninsula is a resource of immense value. It is also a resource of great complexity. And while many aspects of that complexity are as yet very poorly understood it is already very clear that it is also a place of great sensitivity. Management must take an holistic perspective if the immense value of this place is to be safeguarded. That applies whether the goal be the protection of its intrinsic values; the safeguarding of natural environmental processes including its role as habitat for an extraordinary underground fauna; or securing the instrumental values it presents for humankind, including the economic opportunities it offers.

3.2 KARST AREA ANALYSIS

3.2.1 Analysis framework

Karst areas contain a potentially wide range of phenomena. In broad terms these may conveniently be grouped or recognised by analysis at a variety of levels (Kiernan 1995a and the descriptions in Section 3.3 follow this framework):

3.2.1.1 Karst systems

The evolution of any karst, and the phenomena that evolve within it, are the product of an interaction between a range of environmental controls, such as rock type, climate, palaeoclimate, tectonic setting, topographic setting etc., and interactions between essentially karstic and other non-karstic geomorphic processes.

3.2.1.2 Landforms and landform assemblages

The diversity that exists among karst landforms comprises a wide range of features such as closed depressions, surface solution sculpture, caves etc. In effect, there are different types of karst landforms and landform assemblages just as there are different species and communities of plants and animals. As with biological species, there are some landform types that are common and some that are rare; some that are robust and some that are fragile.

3.2.1.3 Landform contents

Landforms such as caves and sinkholes have the potential to contain phenomena that are also of consequence to the management of a karst area. For example, sediments that are important to the interpretation of landscape evolution and the environmental history of an area or wider region may survive protected in relict cave passages long after erosion has removed their counterparts from the surface. Karst landforms may contain important values both above and below ground, and these may include both non-living and living resources such as plant or animal species, archaeological remains etc.

3.2.1.4 Human use and aesthetics

Whereas the systems, landforms and contents levels relate to objectively described physical phenomena, this level also integrates human values. Human use values of a karst area may derive from the uses to which karst resources are put either in the past, at present, or potentially in the future. For example, karst can be important for shelter, economic reasons (e.g. limestone, tourism, water supply), scientific research, educational, spiritual, recreational or aesthetic reasons.

These four levels of analysis provide a useful framework within which to examine the nature of the Cape Range karst, but to arrive at useful management it is necessary to go beyond simply objective description and consider how phenomena are valued. Significance assessment can be a complicated process, due to the differing value systems of different people and communities and changes to these through time. There are three broad groups of reasons why the conservation of karst phenomena may be warranted.

3.2.1.4.1 Intrinsic values

For some people the protection of natural phenomena such as karst landforms may need no greater justification than that they have value in their own right, irrespective of any use humans may seek to make of them. Living creatures or physical features are seen as having importance for their own sake, or perhaps as a part of God's creation, and for that reason alone to warrant respect, care and stewardship.

3.2.1.4.2 Natural process values

The diversity of geological materials, landform diversity, soil diversity and natural processes underpins biodiversity in karst areas. This perspective attaches value to phenomena for the role they play in allowing natural systems to continue to function, or for the habitat they provide for valued species, such as the subterranean fauna of Cape Range peninsula.

3.2.1.4.3 Instrumental values

This perspective values karst phenomena only for the use that humans can make of them, and, hence, it is essentially an economic perspective. Hence, karst may be valued because it is an important source of water, minerals, recreational opportunity, scientific information, aesthetic appreciation etc.

3.2.2 Scales of significance

Karst areas or phenomena may be judged as being significant at several scales:

- local
- regional
- state
- national
- international.

Significance may be identified through a consideration of any or all of the four basic levels of analysis, or from any or all of the three value perspectives.

3.2.3 Conservation strategies

The question then arises as to the strategies that might be employed in order to safeguard geodiversity and conservation values. Here there are a range of possible approaches but they can be grouped into three broad categories:

3.2.3.1 General stewardship

This approach is founded on the view that within the constraints of meeting the need for resources, important natural phenomena are worthy of protection wherever possible if there is no genuine need for them to be damaged; in the karst context, caves and other features warrant protection whenever possible, and not merely those examples that have been included in formal protected areas. Hence responsible environmental management is perceived to represent a normal duty of care.

3.2.3.2 Protection of representative samples

This approach seeks to ensure that examples of each different type of phenomena are protected in some manner. Attempts to conserve biodiversity are an example of this strategy, but while a similar approach is readily adapted to the conservation of different types of karst landform and conservation of representative examples of different soil types, it may be less easily adapted to the conservation of some bedrock geological phenomena. For this approach to be viable it is necessary to employ typologies that allow phenomena to be differentiated and compared (e.g., Kiernan 1995a, 1997)

3.2.3.3 Key site/outstanding example approach

In the past, conservation initiatives have often been focused solely on places that have been considered outstanding in some manner, often a cave considered by someone to be outstandingly beautiful or because a site such as a particular geological exposure was at some time considered a key one in understanding some aspects of the Earth's history.

Each of these perspectives has its place in the protection of karst areas, but approaches that focus solely on key sites or outstanding features can be hazardous because tastes differ between individuals, fashions change, the knowledge base changes, and new techniques of scientific inquiry evolve that require different sorts of sites and materials for their successful application. A focus on a specific feature such as an individual cave can also lead to a failure to recognise that many caves cannot be protected in isolation from their dripwater or streamwater catchments.

On the other hand, a representative approach, while overcoming many of these disadvantages, runs the risk of not incorporating some key sites. But a failure to secure representative samples runs the risk of allowing even common phenomena ultimately to become rare.

Economic and political reality, however, means that not all aspects of the natural diversity that exists in karst environments are ever likely to be included in formally designated protected areas, much less is an adequate set of replicates likely to be so designated. For these reasons, a more general stewardship approach that includes a variety of strategies for off-reserve management, is needed to complete an adequately comprehensive approach to the conservation of nature conservation values in karst areas.

3.2.4 Status and tenure

All the considerations outlined in the preceding sections need to be taken into account in developing strategy for the conservation and management of the Cape Range karst. Elements of each are already evident in the variety of strategies already adopted.

The status of Cape Range peninsula as a special site has been recognised for many years. Initially, and at the initiative of the Shire of Exmouth, a 'C' class reserve was created over part of the Range in 1964, and this area was extended in 1968. In 1974, the status of the reserve was upgraded to 'A' class, and it was formally named 'Cape Range National Park'. At the same time, the Conservation Through Reserves Committee made various recommendations for extensions of the protected area but only some of these were adopted. Various proposals for extension remain extant, and we have made further recommendations below in Section 5.

In 1987, amended State legislation made possible declaration of the Ningaloo Marine Park; and area of Commonwealth waters were gazetted as part of the park in the same year - a coastal strip was also reserved to be managed as part of the total Ningaloo Marine Park. This recognises, perhaps indirectly the coupling of aquatic and terrestrial ecosystems. As a marine park, management is based in various pieces of legislation, but is managed by the State, through the Department of Conservation and Land Management, as a single unit.

Carter (1987) states that:

> *Cape Range is one of the great geological set-pieces of the State...*(p108)

Main (1993) says:

> *...it ranks more and more as a world class subterranean fauna.* (p 243)

and later:

> *...the area ranks as unique and scientifically as world class.* (p246)

The views of the tens of thousands of visitors to the two parks and to the other natural and cultural features seem to be positive as they have 'voted with their feet'!

Parts or all of the area have been nominated on no less than three occasions for inscription on the Register of the National Estate (Australian Heritage Commission, pers. comm.). Two of these, Cape Range Geological site and Cape Range National Park and surrounds, are listed on the register.

We suggest below that the area is of World Heritage quality and that listing should be pursued as a matter of pride for all Western Australians. The criteria for identification of a natural area as being of World Heritage status are :

- 'be outstanding examples representing the major stages of the earth's evolutionary history,
- be outstanding examples representing significant on-going geological processes, biological evolution and man's interaction with the natural environment,
- contain superlative natural phenomena, formations or features, and
- contain the most important and significant natural habitat where threatened species of animals or plants of outstanding universal value . . . still survive.'

It is not the role of this report to fully detail the extent to which Cape Range meets these criteria, but we believe that the data presented here demonstrates very clearly that all four could be well substantiated. Further, the required criteria of integrity can also be satisfied, at least at this time, but the threats indicated in this report and by the Karst Waters Institute (1997) cannot be ignored.

In spite of the demonstrated significance of the region, we discuss below the extent to which not all is necessarily well. Given the need to manage karst terrain in a holistic manner, the pattern of antecedent development of military facilities, municipal facilities, pastoral properties, limestone mines, borrow pits and conservation reserves has produced a mosaic of tenures and uses which is not compatible with best practice management of karst. We recognise, of course, that the wheel cannot be turned back and thus the community faces a considerable challenge in arriving at more adequate protective management.

The problems of the region have recently been highlighted at the international level by the prestigious Karst Waters Institute which has listed Cape Range amongst the 'top ten' endangered karst ecosystems of the world (Karst Waters Institute, 1997). Their criteria for listing include both the significance of the ecosystem and its long-run vulnerability as well as any immediate threats.

Firstly, and fundamentally, it must be recognised that the lines drawn on maps and enshrined in legislation do not reflect the dynamics of the terrain. As examples we have repeatedly drawn attention in this report to the various quarries, extant or proposed, upstream of reserves set aside for the conservation and supply of groundwater and to the need to consider the terrestrial Cape Range as part of the Ningaloo and Bundegi Reef complexes (and *vice versa*).

We believe that significant natural resources are not provided with the protection they should properly receive and thus have made recommendations in Section 5 below to redress this balance.

3.3 ASSESSING THE SIGNIFICANCE OF THE CAPE RANGE KARST

It is hardly possible to detail the conservation values of the Cape Range karst based on the narrow range of investigations undertaken and reported upon to date and an additional four day field inspection by the writers. While some most valuable attributes have been recorded in the literature the coverage is far from comprehensive. However, sufficient is known to enable assessment of the area in very general terms.

3.3.1 The Systems Level: What is special about the general karst environment at Cape Range?

Diversity in karst arises from the mix of environmental controls in a given area, and these in turn vary in time and space. Hence, a consideration of the nature of those controlling environmental systems can at least help with a first approximation of its likely significance in broad terms. Where a particular system mix recurs there can be a reasonable expectation of karst style recurring in more than one place. Conversely, where a system mix does not occur in more than one place, the karst style is unlikely to recur. Hence, notwithstanding the lack of detailed information on particular karst landform types present at Cape Range peninsula, and other attributes of the area, some estimation of significance is possible from a systems level perspective.

3.3.1.1 Lithological systems

The karst features of Cape Range peninsula are formed in a variety of carbonate rocks that range in age from Palaeocene (65-54 million years BP) to Holocene (15,000 years to present). The karst of the older formations largely originates from solution and other erosional processes, while that of the younger formations is largely constructional, involving reef formation, aeolianite consolidation and tufa precipitation.

The erosional karst phenomena have formed mainly in middle Miocene (24-5 million years BP) carbonates of the Cape Range Group. These comprise the Mandu Limestone (foraminiferal calcarenite, calcirudite and calcisiltite), a low energy shallow marine limestone; the Tulki Limestone (foraminiferal calcarenite, packstone, grainstone), also a low energy shallow marine sediment; and the Trealla Limestone (calcirudite, calcisiltite, coralgal limestone, packstone, grainstone) deposited in a high energy shallow marine environment (Allen 1993).

Other minor carbonates occur in other formations within the Cape Range Group including the Vlaming Sandstone, and the Pleistocene (1.8 million years BP) Exmouth Sandstone which includes the Muiron and Milyering members that occur on emergent terraces on the west coast. More recent carbonates of Pleistocene to Holocene age include the Bundera Calcarenite, a formation that consists of both aeolian and marine facies (calcarenite and calcirudite). Within this, the Jurabi, Mowbowra Conglomerate and Tantabiddi members are all carbonates that exhibit degradational karstic features on one scale or another. Current carbonate deposition is occurring in the Ningaloo Reef complex (Allen 1993).

The most conspicuous karst has formed in the Tulki Limestone. The Tulki is significantly more permeable than the Mandu Limestone, with the recrystallised upper part of the Tulki being the most highly karstified part of it. The Mandu Limestone beneath the Tulki appears to be relatively impermeable, while the Trealla Limestone which overlies the Tulki is relatively pure and susceptible to karstification. The Trealla Limestone and the most karstic part of the Tulki Limestone together give a stratigraphic thickness of about 100 m at most. Karst and calcrete development in the Mowbowra Conglomerate varies in intensity (Wyrwoll et al. 1993).

What is significant about the lithological systems at Cape Range as far as karst geoheritage is concerned? Relatively few Australian karsts are formed in limestones of comparable age to the Cape Range Group. Most of the karsts in the eastern states have formed in much older, crystalline limestones of Palaeozoic (570-290 million years BP) age. The only other significant karsts formed in Miocene limestones apart from Cape Range are the Nullarbor karst and some karsts in the Murray Valley of South Australia - there are a few very much more minor examples only, such as those in the Wynyard and Redpa areas in Tasmania. Oligocene (37-24 million years BP) limestones also host karsts in SE South Australia and the Glenelg River, Victoria.

3.3.1.2 Structural systems

Rock structure exerts a major control on karst morphology because structural features such as bedding planes and joints provide planes of weakness that guide the penetration and flow of underground waters. The Cape Range area is tectonically complex. Cape Range is essentially an asymmetric anticlinal upwarp the eastern flank of which is steeper than that to the west. This anticline has resulted from an inversion of fault movement from normal to reverse along the Learmonth Fault that has controlled Cainozoic sedimentation. Uplift of the anticline has been occurring intermittently since the Late Cretaceous (Allen 1993).

While karsts formed in highly deformed limestones in orogenic belts are common in other parts of the world, Cape Range is the only orogenic Tertiary limestone karst in Australia.

3.3.1.3 Climatic and geomorphic systems

Climate is an important factor in the evolution of karsts because available moisture and temperature govern rates of weathering and erosion both directly and also less directly through their impact on vegetation and soils that in turn play a major role in acidifying groundwater. Thus landforms reflect the climatic influences over extremely long periods of time and the two must be considered together.

The contemporary climatic/geomorphic context is that of a semi-arid karst lying in the tropics and subject to both cyclonic and lesser frontal precipitation. The dominant sets of geomorphic processes responsible for karst evolution at Cape Range are of fluvial and coastal type. The fluvial processes are mainly denudational. The coastal processes are denudational near and somewhat inland of the present coasts (tidal movement is evident in underground waters up to 1.3 km inland of the west coast) and constructional along the Ningaloo Reef complex.

The palaeoclimatic context is also that of a tropical karst, much of its history more arid than at present, although in earliest times probably somewhat more humid than now. During the Glacial Climatic Stages of the late Cainozoic (55 million years to present) sea level was as much as ~130 m lower than at present, hence the hydraulic head in the karst was increased and areas that are currently coastal karst were subject solely to fluvial-type karstification. However, the degree to which karstic penetration of the limestone was facilitated by the potentially more energetic water circulation as a result of the increase in the hydraulic head needs to be evaluated against the increased aridity of glacial times.

Considerable aridity is demonstrated by the presence of fossil desert dunes some of which have been dated to the Last Glacial Maximum (Wyrwoll et al. 1993), that overlie the limestones in places, notably north of Exmouth. High topographic relief, and a potentially high hydraulic head are not enough on their own to ensure cave and karst development, as the very limited karstification that has occurred in various places on the arid northern slopes of the high Himalayas so dramatically demonstrates (Sweeting et al. 1988, Kiernan, 1995b). Correct interpretation of the relationship between the known karst at Cape Range, the coastal terraces, fossil desert dunes and the extensive alluvial fans that flank the Range is critical to interpretation of the evolution of the Cape Range karst and the structure and function of its aquifers.

Particularly along the western side of the Range pronounced emergent terraces occur at up to ~60 m altitude. These represent former shorelines that have been subject to tectonic uplift. While the lowermost of these surfaces appears to be of Last Interglacial age the dating of the higher terraces is uncertain but sediments upon even the lowermost suggest they are no younger than Pliocene (5-1.8 million years BP) (Wyrwoll et al. 1993).

In broad terms the climatic/geomorphic systems that have conditioned the evolution of the Cape Range karst are highly distinctive and unusual and make it a site of at least national significance.

3.3.1.4 Solvent systems

Normal meteoric water is the primary agent of denudation on the Range itself today, and during times of lower sea level was dominant over a wider area. However, the ionic concentration of precipitation in the area undoubtedly reflects the close proximity of the area to the ocean sources of its moisture. The large evaporative loss to be anticipated in this environment is presumably reduced by the torrential nature of cyclonic precipitation events (Jennings 1983). The shallow depth of the water between Barrow Island and the mainland coast (20 m) would allow its exposure with much less sea level lowering than the maximum figures attained during the Glacial Climatic Stages.

Mixed and brackish solvent systems are evident from borewater sampling. Given the history of changes in relative levels of land and sea, there have been vertical and lateral fluctuations of the foci of dissolution by these waters and in the position of those zones subject to mixing corrosion. Anecdotal evidence exists for the presence of undersea springs (Allen 1993) that may be related to earlier lower relative base levels as a result of eustatic changes.

Tidal fluctuations in the groundwater up to 1.3 km inland of the western coastline indicate the western coastal plain is highly karstified. Under some circumstances marine water can be an effective solvent in its own right since it is not necessarily saturated with respect to all forms of carbonate. It may have played a significant role in evolution of the karst, but at the very least has been significant because of mixing corrosion and ionic strength effects (ford and Williams 1989).

3.3.1.5 Denudation systems

The Cape Range karst is not impounded by non-carbonate rocks as is the case with most of the better known karsts of eastern Australia where allogenic surface runoff is delivered onto the margins of the karst from adjacent lithologies. Allogenic denudation systems imply that a concentration of flow is focused at a specific point on the karst margin. The converse is currently the case at Cape Range where karst denudation is accomplished almost entirely by diffuse infiltration of autogenic waters. To at least some degree allogenic denudation may have prevailed at times in the past.

Differences in the style of karst between autogenic denudation systems as at Cape Range and karsts that develop under allogenic denudation systems are compounded by two factors. First, allogenic waters are generally chemically more aggressive than free water flows in autogenic denudation systems. Second, allogenic runoff commonly carries with it rock fragments derived from upstream of the karst and these contribute to mechanical enlargement of cave passages initiated by solution processes (or may sometimes block them). This is not the case in autogenic systems where only less soluble materials from within the limestones themselves, such as diagenetic flints and detrital materials in the case of Cape Range, serve this function.

While Cape Range is by no means rare in being subject to an autogenic rather than allogenic denudation system, when this attribute is coupled with other environmental factors that have conditioned the evolution of the karst the interactions have inevitably had important implications for the way in which it has evolved. For example, while the area is a semi-arid one, such rain as it does receive commonly occurs as torrential cyclonic downpours that allow the capacity of the input points to be exceeded such that concentrated flows are initiated on the surface. This has important implications not only for the nature of the landforms that have evolved but also for land management.

3.3.1.6 Topographic systems

The karst at Cape Range peninsula can be divided into three broad topographic systems. The crest of the Range gives the impression of having been rather planed off leaving a flat topped remnant characterised by areas of internal drainage and having essentially the character of a plateau karst. The slopes of the Range are typical hill-flank karst (Kiernan 1995a) that bear evidence of more energetic runoff. They have been incised by channels of various kinds and sizes. The potential exists in such settings for runoff to be deflected laterally by the steeply sloping ground surface, at least for a short distance.

Flanking the Cape Range is typical plains karst (Kiernan 1995a) where the very low gradient surface morphology is the product of both karst denudation and sediment accumulation. Here, the gradient of the water table is less steep than elsewhere. However, the initial hydraulic gradient is vertical from the surface to the water table allowing sediment or pollutants to rapidly reach the groundwater, and also raising the possibility of ground surface instability that may pose engineering difficulties in that part of the karst presently most attractive to developmental activity.

Finally, there are extensive areas of coastal karst where both denudational and constructional processes are in operation. In some respects Cape Range is almost an island karst, set on the edge of the Australian continental shield. Indeed, it has actually been said to have been an island during significant early stages of its evolution, at which time a groundwater lens formed beneath it that served as a focus for early karstification. Kendrick (Humphreys, pers. comm.) feels that the evidence is against the Range ever having been an island and it is not necessary to invoke island status for a freshwater lens to form. Irrespective of this debate, the Cape Range groundwater system is effectively an island type given the surrounding seawater and the unconfined, saline aquifer to the south (Hocking et al. 1987)

Climate change has caused sea level decline that at times left the karst standing much higher above sea level than is presently the case. Conversely, the sea has been much higher relative to the land during much of the areas earlier evolution, before the Range had risen to its present height. The sea was a few metres higher than present during the Last Interglacial Stage.

Earlier in the process of uplift little of the Range would have stood above the sea. Emergence of the Cape Range has involved a progressive downslope migration of the area that was subject to predominantly fluvial-type processes, of the zone of coastal carbonate deposition, and of the focus of marine erosion. The emergent shorelines so prominent along the west coast stand as testimony to these changes in the topographic systems within this karst.

This is a very varied range of contemporary topographic systems for an Australian karst. The older topographic systems are equally as interesting.

The coastal setting is one of the most important attributes of the Cape Range karst, and the nature of the particular characteristics of this coastal environment in particular warrant some further comment. The Cape Range peninsula is the only Australian terrestrial karst locality bordered by currently forming coral reefs. It exhibits a variety of geomorphological features and assemblages not evident elsewhere in Australia.

But the Cape Range karst should perhaps be considered in a wider context than simply Australia. In broad terms the character of any coastline depends upon its position relative to the margin of the major tectonic plates of the Earth and the relationship of the margins on which they occur to sites of crustal spreading or plate collision (Inman and Nordstrom 1971). Cape Range lies on the margin of one of only two plate margins of Afro-trailing edge type, a situation characterised by low sediment inputs and low waves, amongst other attributes. As such, the only location that is potentially comparable in geomorphological terms occurs on the western coastline of Africa. However, we have been unable to locate any references to significant karst along the broadly comparable stretch of the African coastline.

But even if coastal karst is ultimately revealed along the relevant sector of the west African coastline, the West Australian coast at Cape Range peninsula exhibits some striking differences in general terms (Davies 1972). It is subject to tropical cyclones, to which the west African coast is not. Cape Range peninsula is subject to stronger winds (a significantly higher percentage of Beaufort force 8); possibly greater potential evaporation; probably less mechanical erosion (as expressed by solid discharge per annum from rivers); and more intense chemical weathering (as expressed in kaolinite in ocean floor clays: 40-60% versus 10-40%). Wave heights are probably lower at Cape Range peninsula than on the west African coast (where sea level is also lower above an arbitrary datum: 1.2 m versus 1.6-1.8 m), but whereas the African coast is a west coast swell environment, this influence is mixed with cyclonic influences at Cape Range peninsula. In broad terms the coast at Cape Range peninsula is much richer in coral species than comparable African latitudes, it lies in the modern beach rock zone which the west African coast does not, and constructional forms have a more seaward orientation. **There may be no comparable karst setting elsewhere in the world.**

3.3.1.7 Exposure style systems

The pattern of limestone exposure also conditions the manner in which a karst evolves. The anticlinal axis that defines the Cape Range plunges gently northwards. The Miocene carbonate formations within the Cape Range Group are overlain by the largely non-karstic Vlaming Sandstone and Pilgramunna Formation. Given the broad structure, remnants of these younger rocks crop out predominantly towards the northern end of the Cape and as a narrow strip close to the western coast where the sandstone caprock has not been completely stripped and the coastal plain karst is essentially interstratal in type. Windows to the underlying Mandu Limestone exist along the eastern flank of the Range where deep valleys such as Shot Hole Canyon have been incised.

As a caprock recedes the potential for allogenic denudation systems to operate on the karst margin is replaced by autogenic denudation. Streams that drain from the retreating edge of a caprock may enter a pre-existing network of cavities or encounter unkarstified limestone, depending upon local structure (Ford and Williams 1989). Essentially, if stripping is in the down-dip direction and this is also the direction of the hydraulic gradient, as it is in the Cape Range, then pre-existing caves are more likely to exist beneath the retreating contact. Given this, the oldest, best developed and most highly integrated karst should lie towards the southern end of Cape Range, because stripping down the length of the plunging anticlinal axis should not have exposed significant terrestrially pre-karstified limestone (although caves formed by mixing corrosion during earlier phases of uplift might exist at depth).

The largest known caves are, in fact, located towards the south, but this is also the area in which dissection is most likely to have progressed to the stage of cave destruction. Such a control is consistent with the pattern of cave elaboration suggested by Allen (1993). This scenario carries with it the probability that the locus of intact integrated karst, and the groundwater resources that it contains, should progressively be shifted northwards by natural processes to a point between the retreating contact and the dissected karst towards the south.

The upshot of all this is that Cape Range peninsula provides an opportunity for various stages in the karstification process to be identified, and this is of significant research value for karst geomorphologists.

3.3.1.8 System integrity

While much of the Cape Range peninsula karst appears undeveloped, significant human intervention has occurred in the area. This has included the drilling of numerous boreholes for groundwater; abstraction of karst groundwater and the advent of increasing problems with salinity; changes to surface landforms as a result of road construction, quarrying and other activities. Groundwater quality may or may not have been affected as yet by waste disposal and runoff from areas disturbed by human activities. These issues, together with possible impacts of recreational caving and scientific research are addressed at greater length elsewhere in this report and are merely flagged here. Despite them, substantial areas of the karst remain intact.

3.3.1.9 Time

Important attributes of any karst environment are likely to be related simply to the passage of millennia and the time over which it has been able to evolve. The limestone at Cape Range peninsula is younger than most of the limestones that host Australia's most important karsts, many of which are older than 400 million years. These older karsts have in some cases been subject to multiple phases of exposure, karstification and reburial. Hence, the interpretation of extant karst phenomena is complicated by the inheritance of fossil features and the role they have played in conditioning the outcomes of new phases of karst evolution, and by the different environmental conditions that have prevailed during different phases. Extremely long time periods have been available for various processes to leave their mark.

This is not the case at Cape Range. Allen (1993) has suggested that the Cape Range did not emerge above sea level until the Pliocene. He further suggested that initial karstification of the Trealla and Tulki limestones extended downwards for ~100 m until the relatively impermeable Mandu Limestone was encountered, and then spread laterally as the Range continued to emerge, a trend emphasised by Pleistocene sea level lowering.

While there is some evidence of palaeokarst phenomena in the form of fossil sediments in protocave conduits, the youthfulness of the limestone precludes palaeokarst of any great antiquity. In stark contrast to most other Australian karsts then, Cape Range is a young karst that may have seen little humidity other than at the very earliest stages in its evolution.

Caution 1

This analysis of the Cape Range karst in terms of the environmental determinants that have conditioned karst evolution allows a first approximation of its importance. However, it is critical to stress that this serves as a surrogate measure only for assessment purposes. It is not a sufficiently robust data set upon which to found management.

Detailed inventory work is utterly fundamental for sound management. But from a systems level perspective it is clear that the Cape Range karst is a quite extraordinary place, quite irrespective of the values that are dependent upon the karst, such as its troglobitic fauna.

3.3.2 What is special about the landforms and landform assemblages?

As previously indicated, no comprehensive inventory of the landforms of the Cape Range is available, notwithstanding the fact that broad morphological types may have been delineated during the course of land systems mapping. More specifically, data concerning the nature and distribution of karst landforms in the area is poorly known. In part this reflects the priorities of researchers and their motivations and reward systems. However, the situation perhaps highlights the validity of the lament by Forsyth (1996) that 'many scientists denigrate the conservation value of inventory work'. Despite this being first and foremost a karst environment, the geomorphology has been neglected in environmental inventory procedures and has not even been included in environmental impact assessments for major development proposals.

Nevertheless, some very useful contributions have been provided by Wyrwoll et al. (1993) and various papers cited therein. Cavers have also well recorded those particular karst landforms that are of interest to them, in the relatively small part of the area they have investigated to date. The resulting data, while uneven in their coverage and detail, enable some advance from the very broad-brush significance assessment that is possible from a systems level perspective alone.

The study of arid and semi-arid karst has been rather neglected by karst geomorphologists. Virtually no geomorphic environment is the result solely of one process, and just as glacial and periglacial processes interact with conventional karst processes in some mountain karst environments, so do desert processes interact with dissolution effects in the karsts that form in dry areas (Jennings 1983).

3.3.2.1 Terrestrial karst landforms

3.3.2.1.1 Negative landforms (depressions)

A variety of sinkholes of various kinds occurs in the Cape Range but detailed information is not yet available. Most appear to be simple solution dolines, but some collapse sinkholes are known. Cover collapse sinkholes occur in some areas which demonstrates potential for engineering difficulties in some parts of the karst, as at Dozer Cave. The entrance to C18 lies in an alluvial streamsink doline. The full range of closed depression types present at Cape Range cannot presently be reviewed, nor can their patterns of fabric and scale yet be properly described.

Some larger sinkholes are indicted on topographic maps of the area but closed depressions are far more abundant than the maps indicate. The most extensive sinkholes have formed on the planed-off upper part of the Range. A shallow uvala occurs in the vicinity of Anomaly Cave and forms the catchment of waters that drain through other minor caves into what is in effect a master cave of very special type.

Many shallow solution sinkholes form the catchment for water that vanishes underground into vertical solution pipes. Some of these sinkholes are moderately extensive but generally not very deep. Intense phreatic preparation of the limestone is evident in bedrock surfaces exposed at the lowest points of some sinkholes.

Karst surface channels are of either intermittent, ephemeral or dry type. Losing type channels are widespread on the lower slopes and across the coastal plains. In some cases the main channel dies out across the lower part of the alluvial fans that flank the Range (Wyrwoll et al. 1993), presumably due to water loss into the karst. No karst channels of gaining type are known to the writers but some may become evident under extremely wet conditions.

In summary, very little has been documented regarding the various karst depressions, but what little is known suggests that the assemblage is an interestingly varied one, the evolution of which has been closely interwoven with the history of climate change.

3.3.2.1.2 Positive landforms

In the absence of water, limestone commonly forms a resistant rather than recessive rock (Jennings 1983), and indeed it does so in the semi-arid environment of the Cape Range. The strong influence of structure upon the evolution of this karst may be enhanced by this environmental setting, since structural influences are not overwhelmed by vigorous non-karstic processes of weathering and erosion to the degree that they are in karsts in some other higher energy environments.

In broad terms, tectonic structures dominate the morphology of the Cape Range. The Range represents the crest of an anticlinal structure. In part this crest has been planed-off such that a small karst plateau exists. Dip slopes occur to either side of the Range, being pronounced, for instance, on the eastern slopes near the Charles Knife Road.

The recrystallised upper part of the Tulki Limestone gives the impression of owing its character more to subaerial exposure than to subsurface diagenesis. Where fluvial channels or karstic depressions have incised this upper Tulki, steep escarpments have resulted. Where this incision has extended into the deeper, less consolidated lower part of the Tulki the slopes are less steep and are commonly mantled by rubble that ranges in calibre from sands to large blocks. In large measure this rubble is derived from rockshelters of various kinds.

Undercutting of the more competent upper slopes has commonly led to the detachment of blocks and boulders, which reach prodigious dimensions on the slopes beneath the escarpment in the middle reaches of Shot Hole Canyon. Where hills capped by the more consolidated part of the Tulki have been isolated totally from neighbouring slopes, small mesas have resulted. Some large free faces exhibit alternating elongate horizontal projections and notches that are formed respectively in more and less consolidated rock. In some cases the projections have the form of remnant aprons and convey a strong impression of owing this to their having been indurated surfaces. This general situation probably has implications for understanding the nature of the recrystallisation in the upper part of the Tulki Limestone.

At a still smaller scale, karren is locally well developed but its character has not been examined in detail. Karren species that develop on bare rock are the most conspicuous, but some partly covered and covered rock karren occurs locally. White (1989) suggests that there are only 'some' surface solution features confined to the well cemented surfaces of the Tulki Limestone, and reports them as being less extensive than in the Kimberley. However, this is to be anticipated given the considerable differences in the types of limestone involved. However, she does not report upon the actual karren species present at either locality, and nor has it been possible during the very brief field exercise upon which this report is based. However, some investigation of these attributes of the karst, their degree of development and their implications, is warranted. There has also been significant solutional exposure of fossils and diagenetic flints in the limestone, as evident for instance, in the area of the proposed Whitecrest development.

3.3.2.1.3 Springs

Perhaps the most widespread springs of the Cape Range are free-draining contact exsurgences on some escarpments. These springs have an episodic regime and a very small discharge. The waters are soon lost again into the slopes. While the nature of the contacts that cause drainage to reach the surface is uncertain, relatively resistant limestone beds appear to be responsible for their emergence.

Most of the springs are exsurgences, that is, they are not fed by sinking streams. The general paucity of large coastal springs around the foot of the Range and on the coastal plains suggests that the aquifer discharges directly into the sea. The incursion of marine waters beneath the coastal plains, which in some cases shows tidal fluctuations, indicates the presence of well developed solution channels into which fresh water can discharge directly as dammed coastal springs. Indeed, some cave entrances on the coastal plains may have developed as overflow springs in response to sea level rise since the Last Glacial Stage. Anecdotal reports suggest the existence of submarine springs in some locations, which would be consistent with the geologic history of the area. The limited runoff from the Cape Range plays a major role in allowing the Ningaloo Reef to approach closely to shore; karst springs may account for gaps in the reef.

3.3.2.1.4 Biokarstic phenomena

Tufa accumulations occur on some escarpments. One might presume that in the semi-arid climate of Cape Range evaporation is likely to have played a greater role in their formation than is commonly the case in more humid karsts. However, caution is suggested by the work of Barnes (1965) who found that even in the very arid environment of California's White Mountains degassing of CO_2 still accounted for in excess of 90% of travertine precipitation.

The largest biokarstic feature is the Ningaloo Reef. This reef extends for 260 km along the coast, from south of Bundegi Reef just inside the mouth of Exmouth Gulf, then out around Point Murat and North West Cape before extending down the western coastline to Armherst Point. In places it lies within 50 m of the present coast.

3.3.2.1.5 Caves

The caves of the area vary in terms of many of the criteria that permit caves to be differentiated from one another. Such criteria include their internal character (plan, cross-section, relation to water table/s, predominant development and size) and in terms of the external controls upon their evolution (geological, topographic setting and relationship, fluvial role, geomorphic /hydrologic role) (Davey 1984, Kiernan 1995). Local cavers have recorded over 580 caves (D. Brooks pers. comm.) and White (1989) has provided some general comments on the character of some of them. For present purposes they may be differentiated into six broad categories.

It cannot be stressed too strongly, however, that the distribution of known caves reflects where cavers have looked (ie. close to the easiest access routes) and is an artefact of this search pattern that almost certainly bears no relationship to the true extent of cave development in the area.

Rock shelters.

These are common in the recrystallised upper part of the Tulki Limestone. Their floors are generally mantled by sandy breakdown material and sometimes rise steeply from the dripline to an inner apex near ceiling height, many examples being evident in Shot Hole Canyon. Their most probable origin is through salt weathering or wetting and drying processes, not by wind erosion although wind will have a role in the transport of material freed by other processes.

Short horizontal caves

In some cases rock shelter type entrances give access into short horizontal caves which inside may broaden into low-roofed and flat-floored chambers. These appear to be due to seepage water having been directed horizontally towards the hill margin by structures in the limestone. They occur at various levels, sometimes in relatively close proximity to one another, and are difficult to interpret as reflecting former water-table levels.

In the vicinity of the proposed Whitecrest site, access into one horizontal cave was gained through a narrow vertical cleft among blocky limestone masses. This gave access to a cave that extended laterally in two directions, both parallel to the hill margin. Active seepage water flows at the time of the visit were discharging over flowstone and from stalactites. The appearance was of a cave having been formed by solution either along an unloading joint or perhaps at an interface between more and less case-hardened limestone.

Larger horizontal caves

Some more extensive horizontal caves are also known, varying in length, volume and complexity. The entrances are sometimes vertical solution pipes that intersect with the horizontal development. The longest cave in the area, Wanderer's Delight (C163) is a low horizontal, joint controlled passage with stream deposits on its floor (White 1989) that has been explored for 6.5 km. Shot Hole Tunnel (C64) is reported by White to be of similar character, and the formation of both at former water table levels is suggested. On the other hand, Anomaly (C96) is much more spacious, consisting of a broad horizontal passage. Wanderers Delight appears to form something of a master cave for drainage that collects from a very large enclosed depression via smaller caves. Any suggestion that horizontal cave passages reflect a former water table that should correlate with the emerged coastal terraces on the western side of the Range (White 1989) would appear courageous at this stage, not least because of the limited quantitative data on the various cave levels and in view of their altitude above the confirmed terraces.

Vertical caves

Caves that take the form of solution pipes are common. White (1989) suggests that most terminate at a similar level and suggests a former water table might be responsible for this. Other mechanisms might also account for it, including contact with the less consolidated lower part of the Tulki Limestone or the Mandu Limestone. Some of these caves bear evidence of occasional large discharge into them; others are also spacious but this may be due to age rather than discharge.

Caves of the coastal plains

Small caves occur on some of the coastal plains and appear to be developed primarily in the horizontal plane. They may lead to water, and contain archaeologically significant material and/or important fauna (eg. Camerons Cave). In the case of Dozer Cave, the ceiling is formed from tough conglomerate that has sufficient mechanical strength to span voids formed beneath it in less competent limestone beds.

Protocaves and mesocaverns

In geomorphological terms, a cave is an opening of greater than 5-15 mm diameter or width, that is, a void of sufficient dimensions to allow turbulent rather than laminar flow of water (Ford and Williams 1989). Very small solution tubes allow the movement of groundwater and the unique cave fauna of the Cape Range peninsula karst through the limestone masses.

It warrants emphasis that caves which may be considered very small by human standards are critically important habitat for the cave fauna. What we see of the fauna is just the tip of the iceberg, creatures displaced from their optimal environment by the exigencies of the weather. The importance of protocaves and mesocaverns is discussed at greater length in Section 4.1.2 below; their existence is merely flagged here.

3.3.2.2 Alluvial fans

One very conspicuous attribute of this karst is the presence of extensive alluvial fans, especially on the eastern side of the Range. The sediments of which these consist have become prominent by the midslope area and dominate the landscape in some areas towards the east coast. They are discussed in a little more detail later in this report. Quite clearly the fans are the product of torrential discharge, yet there seems little evidence of flow sufficient to mobilise significantly the downstream gravels during storm events at present.

A variety of channel mesoforms are described by Wyrwoll et al. (1993). The fans and channels are of particular importance both in their own right, as landforms that have developed in a very unusual environmental setting, and for the insight they offer into the evolution of this landscape more generally. In particular, they have important implications for understanding the evolution of the karst and for understanding the structure and function of the karst aquifer, and they are almost certain to be intimately related to the aquifer.

3.3.2.3 Coastal terraces

Warped marine terraces occur in the area and are an extremely important attribute in their own right. They rise to ~60 m altitude. They are best developed along the western side of the Range and represent a series of emergent reef complexes (Wyrwoll et al. 1993). These terraces are the result of that particular mix of processes that occurs on a limestone coast and are just as much karst landforms as are terrestrial caves. They bear comparison with the celebrated Huon Peninsula terraces of New Guinea (Chappell 1974).

Wywroll et al. 1993) have suggested that the major uplift of the Cape Range anticline occurred in the early-middle Pliocene (~7-10 ma BP) and that the Jurabi terrace (+10-15 m MLWS) has not been below the sea since the Pliocene. Early elevation of the Range is supported by speleobiological evidence (Humphreys 1993). Dating of the terraces currently rests upon dating of sediments deposited upon them, discussed later.

These features are superb examples of emergent terraces. Moreover, they have major implications for the understanding of landform evolution throughout the region. In particular, these terraces are likely to prove to be intimately related to the evolution of the karst. Not only do the terraces represent foci of marine erosion, but they also indirectly define former base levels of vadose groundwater circulation (though not karstification, due to mixing corrosion at the fresh water - salt water interface) that have prevailed at earlier stages in evolution of the more inland landscape.

3.3.2.4 Landforms along the present coastline

The beach and dune fringe is narrow. Some blowouts are present and this has implications for land managers. Development of the foreland at North West Cape proper is related to trapping of a sediment train northwards from Cape Murat, and to the shelter from wave action that is provided by Ningaloo Reef (Wyrwoll et al. 1993). Hence, the karst of the area conditions even the development of the current beaches.

3.3.3 Landform contents

3.3.3.1 Water

The area receives a mean annual rainfall of ~260 mm. The only permanent surface watercourse in the area is Yardie Creek. Other than during torrential cyclonic downpours, most rainfall that occurs at Cape Range rapidly disappears underground into the karst. Lighter frontal rains contribute a little to discharge but also doubtless bring in salt. Overland flow is generally extremely brief, although in heavy rains discharge is maintained down some of the principal stream channels as far as the coast, to some extent perched upon clastic sediments along their course.

Groundwater plays a major role in shaping the landscape and is a critically important resource to the biota of the area, cave fauna and humans alike. Its importance to humans is as evident in the location of Aboriginal archaeological sites (Morse 1993) as it is in the location of Exmouth. Exmouth derives its water from a borefield that lies to the west and south of the town, while a separate field has been established for the defence facilities in the area. There are proposals to extend this latter borefield further southwards. The borefields exploit a Ghyben-Herzberg aquifer system which is discussed in detail in Section 4.1.3 below.

The Ghyben-Herzberg principle implies the depth to the salt water interface beneath the land is 40 times the height of the water table at sea level. Hence, 1 m of fresh water drawdown allows 40 m of upward movement of saltwater. Based on assumed chloride concentrations in rainfall, recharge is estimated at ~10% (M. Martin, pers. comm.). Further discussion of the

Ghyben-Herzberg system and management issues related to borefield operation and protection of the groundwater resources are addressed elsewhere in this report.

An interpretative diagram based on borehole results and monitoring and on geological and hydrogeological considerations, supplied by M. Martin, suggests that the water table lies a couple of metres above present sea level near the coast, rising to ~+15 m altitude towards the inland part of the borefield (Figure 2).

The Ghyben-Herzberg principle does not allow precise definition of the fresh-salt interface and there is commonly a brackish zone. At Cape Range the freshwater interface is interpreted as descending gradually to ~20 m depth 4-5 km from the coast, then more steeply as the surface relief increases. A second interface between brackish and salt water probably lies at ~-35 m depth at the coast, descending fairly gradually to~-70 m inland before steepening.

Inland of the borefield fresh water extends to more than -100 m below sea level (Martin, *fide* Allen 1993). The lower limit of karstification is inferred as descending from ~+40 m ASL beneath the Range to >80 m ASL at the eastern margin of the coastal plain. The groundwater lens behaves essentially as occurs beneath an island, the thickest part of it being located beneath the limit of karstification under the Range proper, where flow rates are probably very slow, and the thinner outer section lying beneath highly karstified limestone with relatively rapid flow rates.

3.3.3.2 Atmospheric phenomena

The other critically important fluid that is contained within the cave systems of the area is air. Cave climates vary in accordance with the nature of the cave configuration, but in general terms conditions are far more stable than on the surface. Temperature, for instance, tends broadly to approximate the mean annual temperature at the surface, within a couple of degrees. Humidity of the atmosphere in a cave is probably a significant factor for terrestrial troglobitic fauna. The condition of the cave atmosphere is also a significant factor in speleothem precipitation processes.

Little information is available concerning cave climates and regimes in the Cape Range karst. Clearly many of the caves are very dry for much of the time, although the conditions that exist in mesocaverns (defined in Section 4.1.2 below) are less easy to discern. Humidity must increase dramatically underground during cyclonic storms. Similarly, little is known regarding the gaseous composition of the cave atmospheres, other than that high levels of CO_2 occur in some caves. Local controls and periodicities of this are unknown, nor their significance if any for cave fauna.

A number of management issues arise in connection with cave atmospheres, mostly related to cave use management. However, some relate to wider land use, including the possibility of gas from old oil exploration holes escaping into caves once the casings corrode.

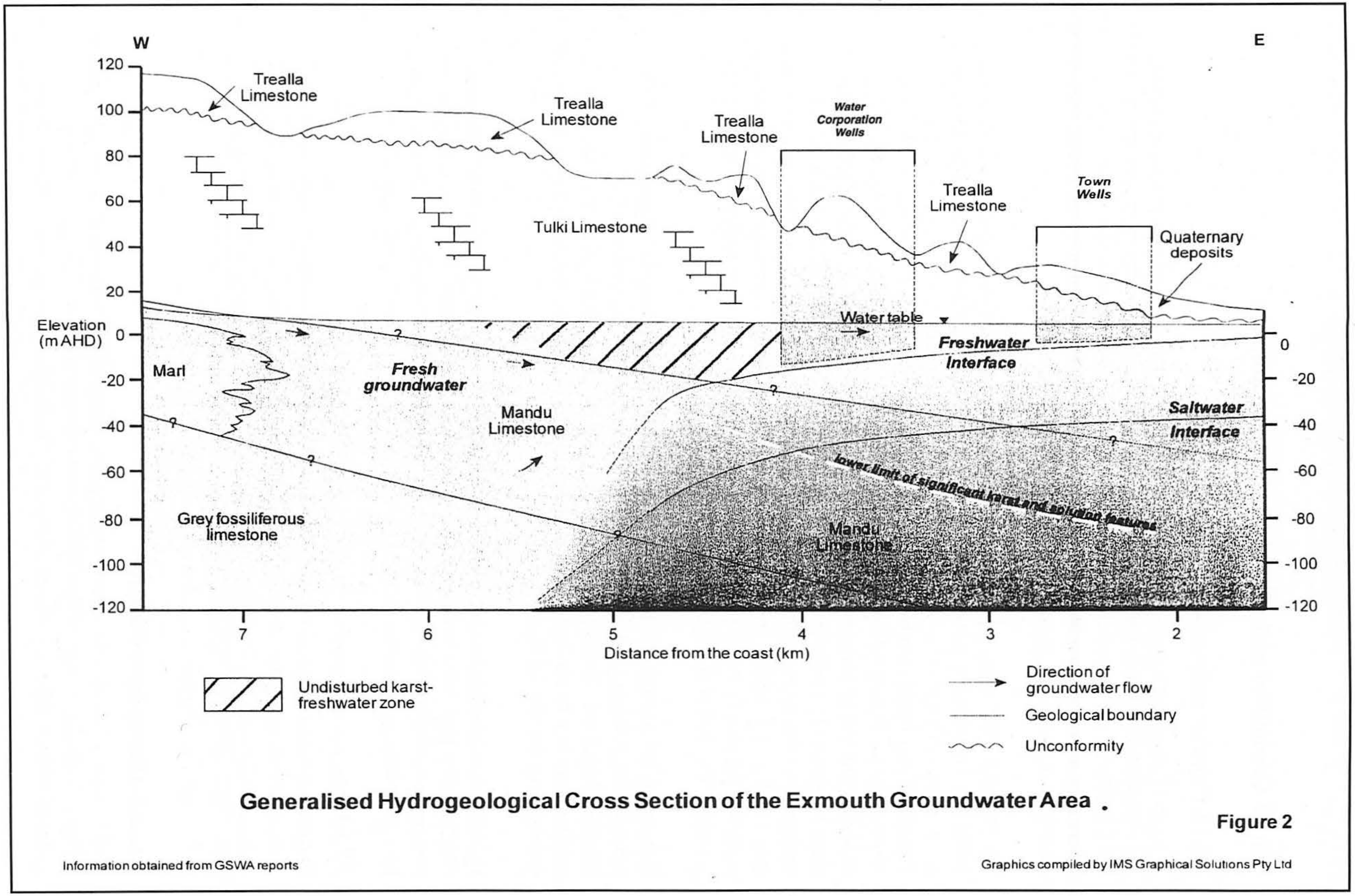

Figure 2. Schematic cross section through the eastern side of Cape Range (figure provided by Water Corporation.

3.3.3.3 Geological and geomorphological resources

3.3.3.3.1 Marine sediments

A series of marine and nearshore morpho-stratigraphic units of Middle(?) to Late Quaternary age are interspersed with and are associated with the alluvial fans (Wyrwoll et al. 1993). They are valuable for the information they contain regarding past environmental conditions and, where they are present in conjunction with other landforms and sediment sequences, they can contribute to understanding the chronology of landscape evolution

The potential significance of the marine sediments is as yet far from fully realised. In broad terms they have already proven important. For example, the sediments that occur upon them allow a minimum age to be established for the coastal terraces. Hence the dating of the Tantabiddi and Jurabi members of the Bundera Calcarenite, and the Milyering and Muiron members of the Exmouth Sandstone, assume considerable significance for dating landscape evolution and coastal emergence. Radiometric dating allows a Last Interglacial (global isotope stage 5e) date to be confidently ascribed to the Tantabiddi Member, and hence a date no younger than that to the surface upon which it rests. Dating of the Jurabi Member rests upon palaeontological evidence and in particular the assumption that *Carcharocles megalodon* was extinct in the area by the late Pliocene. The Jurabi terrace, and those upslope of it, can be no younger (Wyrwoll et al. 1993).

Pleistocene coastal units to the east are dominated by the Mowbowra Conglomerate. This unit contains a nodular soil carbonate profile similar to that developed over the landward/beach unit associated with the Tantabiddi Member (Wyrwoll et al. 1993). The conglomerate is a beach deposit that incorporates both marine fossils and well rounded gravels derived from the alluvial fans.

Holocene coastal sequences include dune ridge and beach sequences and localised tidal flats. The Ningaloo Reef is the source of most of the beach sands and the evolution on the coastline is strongly conditioned by the manner in which the reef controls circulation, which is driven by wave pumping across the reef and by wind and tidal forcing (Wyrwoll et al. 1993).

3.3.3.3.2 Desert sediments

Pleistocene desert dunes occur to the north and south of the Cape Range. They imply more arid conditions in the past than at present. They rest upon deposits of Last Interglacial age and at one site have been dated by thermoluminescence to the late Last Glacial maximum (Wyrwoll et al. 1993). However, the degrees of calcrete development seem to vary and in some cases they suggest some of the dunes might be of greater age.

3.3.3.3.3 Alluvial fan sediments

The fan gravels are derived from the limestones. Steep rubbly slopes cloak the flanks of many valleys. In the upper part of Shot Hole Canyon various stages in their progression from colluvial rubble to alluvial terraces can be seen. In some localities large scale slope failure is evident where the outer edge of a meandering stream channel impinges against a steep slope, undermining it. Downstream these gravels form aprons across the coastal terraces and plains.

The presence of calcrete horizons indicates that discrete time-based stratigraphic units are present in the fans (Wyrwoll et al. 1993). Latisol development in the area (Vine et al. 1988), including iron-rich material in profiles exposed at cave entrances such as C18, suggest wetter periods in the past.

3.3.3.3.4 Cave sediments

Cave sediments include both clastic and chemical deposits. The most prominent clastic sediments are silts and clays derived from breakdown of the limestone. Coarse calibre deposits comparable to the gravels that occur along the major valleys that descend from the Range were not encountered in any of the caves visited although White (1989) has reported well rounded cobbles from a number of caves, including Wanderers Delight, and also stratified mudbanks, some of which have been incised by streams. Rockfall deposits occur in some caves but may have been removed from others by water action (White 1989). However, neither the form of the caves nor the clastic deposits necessarily provide evidence for previously wetter conditions; rather, both may be explicable by the torrential rainfall that characterises the area at present.

Carbonate speleothems occur in a number of caves. Freshly deposited calcite was observed in a small cave at the proposed Whitecrest site, and tufa deposits are widespread in some areas such as Shot Hole Canyon. On the other hand, substantial speleothems occur in some caves, such as Anomaly (C96). Many of these are actively accumulating, even if episodically. There is some evidence of degradation of older flowstone in both Anomaly (C96) and Owls Roost (C4) consistent with the report of (White 1989). A period of previously wetter conditions has been interpreted from the presence of some of these speleothems. However, evidence from Nullarbor caves suggests that massive speleothem deposits can accumulate in semi-arid to arid areas given time, and perhaps more effective, rather than greater absolute, rainfall regimes.

3.3.3.3.5 Subfossil deposits

Significant subfossil deposits have been obtained from a number of caves. These remains have enabled understanding of the composition of the earlier mammal fauna. Other subfossil material has been obtained during excavation of archaeological sites. At least half of the original mammal fauna appears to have become extinct since European settlement of the peninsula (Baynes and Jones 1993). Archaeological sites also provide subfossil evidence of the presence and then decline of an intertidal environment more diverse than that which exists in the area today (Morse 1993).

3.3.3.4 Biological Values

3.3.3.4.1 Marine biota

Some 460 species of fish and 180 species of coral occur on Ningaloo Reef. It is not the purpose of this report to review the significance of this biota, but it is important to recognise its richness and importance, and the potential implications the karst environment has for at least some elements of it. This must include the potential for detrimental affects upon inland karst waters, such as contamination, to be transferred rapidly to marine habitat and breeding areas.

3.3.3.4.2 Surface flora

Very little if any information appears to be available concerning the lower plants of the area. A little more information is available regarding higher plants, but far less than is needed for informed management.

While limestone soils in arid areas are generally species poor, the environmental conditions that prevail on the Cape Range peninsula make it an exception. Keighery and Gibson (1993) record 630 taxa of vascular plants from the peninsula, grouped into seven major communities. The area features a mixing of both tropical and temperate floras at the extremes of their limits, disjunct species, and hosts 12 endemic taxa and six taxa that are largely confined to the peninsula.

Cape Range is far more species rich than Western Australia's other major arid and semi-arid karst, the Nullarbor, which at any rate is a combination of Mediterranean and temperate desertic species. The Kimberley flora is not comparable since it is a tropical flora with desertic influences because of the strong climatic and latitudinal differences its relative remoteness from the coast. While some similarities to the Burrup Peninsula and Barrow Island exist, there are more than twice as many species recorded from Cape Range. This knowledge exists despite the lack of detailed botanical studies of the Cape Range area (Keighery and Gibson 1993).

3.3.3.4.3 Surface fauna

Information is almost or entirely lacking regarding many groups of terrestrial invertebrate fauna. This is due to the limited investigation that has taken place, the lack of appropriate taxonomists or of a systematic base, or inadequate stages in collection (WF Humphreys, pers, comm.).

The non-marine mollusc fauna of Cape Range contains high proportion of endemic species with nine of the 16 recorded species being endemic to the peninsula and seven endemic to the plateau and slopes of the Range itself. Some non-camaenid species that occur here are at the southern limits of their ranges and have only been found in caves despite their not being generally cavernicolous. This situation supports the hypothesis that the disjunct populations are relictual (Slack-Smith 1993).

The Cape Range area hosts a rich vertebrate fauna that includes 30 species of mammals, 84 reptiles, five amphibians and about 200 birds. The distribution of species is closely related to landform units. Most of the ground dwelling mammals are common elsewhere but one species now occurs only in scattered locations in Western Australia (Kendrick 1993). The Cape Range area is important for the conservation of remaining Australian mammal communities, smaller areas such as Barrow Island being important for conservation of individual species but having a restricted fauna that lacks the vast majority of the small animals that occur in the region. Cape Range appears to provide particularly favourable habitat, and this allows the possibility that one species for which no known living population exists, the Central Rock Rat, may survive there (Baynes and Jones 1993).

The bat fauna is poorly known but it includes both southern and northern species. The bird and reptile faunas are also typical of those from elsewhere in semi-arid and arid areas of the state, but two southern species are present. Endemism on the peninsula is low among the bats, possibly because isolation has been relatively recent, but two show specific and sub-specific endemism.

Aeolian units are important reptile habitats. Thirteen reptile species are restricted to the area, but only one of these is dependent upon the rocky slopes of the Cape Range. Only one reptile is truly endemic. Frog species are also widespread.

The diversity of available habitats underpins the richness of the vertebrate fauna (Kendrick 1993).

3.3.3.4.4 Cave fauna

Perhaps the most celebrated attribute of the Cape Range karst at present is its cave fauna. It is the richest and most diverse troglobite community in Australia, and probably in the World. The only community in Australia which even approaches it is that in the Undara Caves of North Queensland. Up to seven troglobites occupy some individual caves (Humphreys 1993). The area contains entire classes, orders, families and genera known elsewhere only in caves on either side of the North Atlantic. The important fauna is very restricted:

> *Elements of the subterranean fauna are known to occur on the Cape range peninsula north of a line between Point Cloates and the Bay of Rest, on Barrow Island throughout the area that samples have been taken, and on Varanus Island.*
>
> *On the Cape Range peninsula 25% of the overall distribution of the subterranean fauna lies within the Cape Range National Park. The presently known terrestrial and aquatic fauna found in Cape Range proper will be well represented within Cape Range National Park when the proposed extensions into part of the Temporary Reserve for Limestone (TR5980H) are complete. However, there will be significant elements in the northern end of the Range that are not included in conservation reserves.*
>
> *Both the aquatic and terrestrial fauna of the coastal plains and foothills of Cape Range are distinct from that of the Cape Range proper. They are poorly represented within reserves and major components are unknown in any reserve. Only five of the 10 species (four of nine genera) of stygofauna are known to occur within Cape Range National Park. Of the terrestrial fauna, only one of the nine species is known to occur within Cape Range National Park* (WF Humphreys, pers. comm.).

Subterranean faunal research on Cape Range has been executed with very limited resources; its volume does not correspond to the hundreds of person-years of research carried out in some of the other karst regions of the world. This latter has included the development of full scale and high-tech underground laboratories with research being continued over many decades. The very fact that so much has already been discovered at Cape Range with such limited resources is in itself some indication of the importance of the site.

- The faunal community at Cape Range - a relatively small karst area by world standards - probably has both a higher number and higher proportion of troglobitic forms than any other karst region in the world. It would seem that nowhere else is comparable. This alone makes it a research site of the highest importance.

- The fauna is also remarkably diverse, containing a wider cross-section of the animal kingdom than any other equivalent subterranean fauna.

- It includes a number of classes, orders, families and genera which are only known elsewhere from a few caves on islands of the Atlantic Ocean - this is a remarkably disjunct distribution and suggests that this fauna comprises one of the most ancient faunal communities anywhere in the world. In fact, when the first remipedes were discovered in the Bahamas only a few years ago, their discovery was seen as one of the greatest zoological discoveries for a very long time. They have survived from long before the first dinosaurs walked the earth!

The groundwaters of Cape Range peninsula contain an ancient Tethyan sea community. The aquatic fauna includes 11 species, comprised of two fish, two shrimps, a thermosbaenacean, an ostracod, a cirolanid isopod, at least two melitid isopods, and a recently described member of the class Remipedia (*Lasionectes exleyi* Yager and Humphreys 1996). It includes three genera and one class unknown elsewhere in the southern hemisphere. Part of the fauna occurs on Barrow Island, but the two fish, the remipede, one shrimp and the ostracod occur only on the peninsula (Knott 1993, Humphreys 1994, Yager and Humphreys 1996).

Much of this aquatic fauna occurs only in the anchialine zone, that is where sea water and fresh water meet and diffuse into each other. Thus, changes in the relative levels of seawater and the fresh groundwater may well pose a threat to the fauna. The first major study on the ecology of an anchialine system (Pohlman et al., 1997) indicates that this is indeed complex, and fauna may also be threatened by changes in soil cover, in the associated algae and by any changes in the nitrifying bacteria present within the zone. Much more research will be necessary before the necessary conditions for survival of the Cape Range fauna can be clearly defined, but it is clear that until such knowledge is available, the approach to management should be a conservative one.

Cape Range is already known to contain one of the most diverse cave faunas in the world. For example, while 243 caves have been sampled from 8 karst provinces in the lowland tropics of Central America, in countries where the research effort has been 100 times greater than in the Cape Range group (including Barrow Island), Cape Range has revealed 67 troglobitic species compared to 46 in Central America. Comparable systems in South East Asia have yielded 30 terrestrial species, compared to 34 in Central America (plus 12 aquatic species and 41 at Cape Range (plus > 24 aquatic species. Central America has revealed 12 aquatic troglobites, less than half the total known from Cape Range, despite the dearth of investigation in the latter area (WF Humphreys, pers. comm.).

The distribution of the stygofauna through the rock mass is unknown. The porosity of the unconsolidated lower part of the Tulki limestone is around 20% but the degree of interconnectedness of the voids is not known. While the stygofauna is likely to be confined to caves in the recrystallised upper part of the Tulki, elements of it might extend through more of the rock mass in the unconsolidated material.

In contrast to the Tethyan affinities of the coastal stygofauna, the terrestrial fauna of Cape Range has affinities with moist closed forest litter faunas associated with tropical and temperate Australia and more distant areas, including those with Gondwanan distributions (Harvey et al. 1993). The terrestrial fauna includes a number of undescribed taxa. Harvey et al. (1993) record 64 species of arachnids and myriapods collected from caves or their entrances.

Adams and Humphreys (1993) suggest there are eastern and western components of the fauna, based on patterns of diversity displayed by shrimps and gudgeons. They suggest gene flow has been restricted or absent in most troglobites even in caves located relatively close to one another, but this is not the case for the one non-troglobitic group they studied. Gorges cut through the Tulki Limestone into the underlying non-cavernous Mandu Limestone seem to play a role in isolation of the provinces (Humphreys 1993). Fragmentation and re-unification of populations related to Glacial-Interglacial cycles is suggested by sympatric congeners both in the Range and on the coastal plain.

Although only very limited investigation has been focussed on the area, it has already proven to contain a richness well in excess of that which has been revealed by many decades of detailed investigation elsewhere.

3.3.3.5 Archaeological resources

The Cape Range area contains a wide range of archaeological sites, ranging from isolated artefacts to artefact scatters, quarry sites, major stratified deposits and a full spectrum of art sites including pre-figurative art.

Cape Range peninsula is the point at which the Australian continent most nearly approaches the edge of the continental shelf (Morse 1993; although the same claim is made for the coast off Narooma, New South Wales). For this reason, it provides a unique opportunity to obtain information regarding the coastal economies of Pleistocene people. Evidence of this aspect of the human settlement of Australia has elsewhere generally been drowned with the postglacial transgression of the sea over the broad coastal areas that formed the coastal zone during the Last Glacial Climatic Stage. The Cape Range was never more than 10-12 km from the coastline (Morse 1993).

Mandu Mandu rockshelter is the oldest reliably dated archaeological site in northern Western Australia. Combined with evidence from two other occupied rock shelters there is a record of human utilisation of the Cape Range area for over 30,000 years. That record indicates that coastal resources played a major role in the subsistence strategies adopted by the people who lived in the area. Use of the rockshelter sites on the terraces at the foot of the Range intensified once the coastline had moved to within ~1 km distance during the middle-late Holocene (Morse 1993).

Evidence of Aboriginal entry to the upland areas, including artefacts, rock art, and bailer shells near cave water sources demonstrate use of these areas, and deserve further study.

3.3.4 Human use and aesthetics

A wide range of resources that are potentially available for human use exist in the Cape Range karst. Management of their use demands careful prior inventory and informed, conservative regimes. This section of the report very briefly describes some aspects of human use of the area.

3.3.4.1 Art

As previously indicated, this karst area contains artworks created by the Aboriginal people who previously lived there. This is an important resource that should not be underrated.

3.3.4.2 Human occupation

The natural phenomena that occur at Cape Range peninsula are obviously by no means the only important considerations in its management. The present human occupants of the area were preceded by at least 30 millennia of human colonisation by Aboriginal Australians. That these original settlers are no longer present in the area means that the legacy they have left is one of the few remaining links with the Jinigudira culture. More recent human and ongoing human use is based in large measure upon karstic resources. These resources include those karst phenomena that attract people, such as Ningaloo Reef, and those karst phenomena that enable their survival, such as the groundwater. Respect for the natural processes that sustain these resources is essential for future sustainable human use of the area.

3.3.4.3 Recreational use

A wide range of recreational opportunities exist in this karst area and are likely to be the basis of much of its economic future. These uses include formally organised commercial tourism ventures focused on the reef or the caves, or fishing for species that inhabit the coastal karst habitat. Less organised tourist use of these and other attributes of the area is no less significant. The area offers a wide range of activities that vary from hard physical challenges such as caving, to more sedate and relaxed sightseeing, diving, photography and other forms of nature-based creative art.

3.3.4.4 Education

The Cape Range peninsula is a stunning outdoor classroom, the potential of which is limited only by its distance from major population centres. Notwithstanding this, its enormous possibilities for instruction in a wide range of disciplines must be highlighted. In few places are such an enormous range of environments, spread over such extraordinary time scales, so accessible. The potential of the area in this regard should not be dismissed.

3.3.4.5 Scientific research

This peninsula karst, lying as it does so close to the edge of the continental shelf, and containing as it does such a wide range of resources, offers huge potential as a scientific resource. The extraordinary results that have been gained after only extremely limited study of its cave fauna, for instance, highlight its possibilities. These span a wide range, including various aspects of the earth sciences (within each of geology, geomorphology and pedology), a wide range of biological sciences, hydrogeology, micro-climatology, archaeology and many, many others. Aspects of this potential will be evident from earlier in this report, but a few areas perhaps warrant emphasis if only because progress that demonstrates how real the potential is has already been made.

For instance, the area provides excellent opportunities for studies of karst processes in a very special environment. These include investigations into rates of cave formation, speleothem formation rates in this semi-arid environment, and the rate and timing of changes in the relative levels of land and sea. Dating of a stalagmite from C126 indicates a growth rate an order of magnitude lower than those typically recorded from humid areas (Humphreys 1993:180). A maximum age of 170 ka BP was obtained for the speleothem, which implies the cave in which it occurs must be older. Such initial steps will necessarily be slow and cautious. But they will also be very rewarding.

The emergent nature of the coastline means that a suite of denudational and constructional karst phenomena exist that are of potentially of considerable value in understanding the morphology of coastal karsts and coral reefs more generally, including the relative importance of primary depositional form versus antecedent karst in determining the morphology of coral reef systems (Hopley 1982).

Such coastal terraces offer the prospect of important data concerning the timing of a whole suite of geomorphic events, either in relative terms or through the establishment of numerical ages on the basis of various dating techniques. An example of the sorts of use that can be made of them comes from New Zealand, where the upper part of one cave at Paturau is graded to a major marine terrace, while marine sediments contained within the cave indicate that at least part of it existed prior to terrace formation. A second cave extends beneath the terrace. Uranium-series dating of speleothems from both caves has allowed major insights into landscape evolution (Williams 1982).

The largely unstudied terraces of Northwest Cape are a resource of enormous geomorphological importance that offer the prospect of dating cave development, valley incision and relief evolution, terrace formation, and the age and rates of coastal uplift.

Much work also remains to be done with respect to the alluvial fans, coastal sediments and fossil desert landforms. They will in time tell us much about the nature of this three-dimensional environment in which people seek to live and sustainably earn a living, an environment of which most is hidden underfoot.

Very important biological research has already been completed in the area, although much more basic data acquisition remains to be completed. Important work will flow from this in turn. For instance, Adams and Humphreys (1993) have utilised allozyme electrophoresis to provide a robust systematic framework independent of morphology for all six faunal groups recognised. The technique has allowed them to elucidate species delineation, reconstruct evolutionary relationships, estimate times of divergence and assess intraspecific diversity. Their results confirm the existence of multiple species within the millipedes and shrimps; indicate additional discrete lineages within single morphospecies of millipedes and amphipods; and allow the postulation of a designated sequence of evolutionary events within each group of troglobites. It has also facilitated recognition of three geographically based genetic provinces within both the millipedes and the amphipods, and of substantial population substructuring within most troglobitic species.

It is difficult for many people to see invertebrates as being important. This is the problem with the Cape Range fauna. It is clear that the community can identify with 'showy' invertebrates such as the Eltham Copper Butterfly and the 'lower' vertebrates such as the Western Swamp Tortoise - given enough stimulation - at lower limits for their perception of values of animals. Given that some of the Cape Range species predate the dinosaurs and all warm and cuddly mammals by tens, if not hundreds, of millions of years we can only argue that we need to set aside prejudices about invertebrates as being insignificant, unimportant or uninteresting. This is a fauna of the highest importance which deserves our respect even just for the intrinsic fact of its existence. But it is also a resource of the highest potential value. We are only at the beginning of recognising the extent to which molecular biologists can help to unravel the history of all life on Earth; and so we cannot afford to neglect protection of the Cape Range fauna.

There will be much to be gained by integrating various strands of scientific effort. For example, genetic distance between cave populations has allowed Humphreys (1993) to suggest a possible chronology for development of the area. He suggests late Miocene-early Pliocene uplift of the Range may have been contemporaneous with speciation in *Stygiocaris* species at ~5 ma BP. He believes the terrestrial fauna may have speciated later (~3 Ma BP) and separated into genetic provinces by ~2 Ma BP which he deduces to be the time when rainforest was lost from the valleys. He suggests that the amphipods might imply that perched water tables in the Range were isolated in the early Pleistocene (~1 Ma BP) and that species populations were isolated between caves and on the coastal plain in the mid-late Pleistocene.

Many strands of scientific research will have implications far beyond North West cape. For instance, some geomorphological work will have regional implications, touching upon such areas as past climates and global circulation patterns during both Glacial and Interglacial climatic stages (Wyrwoll 1993).

3.3.4.6 Special uses

3.3.4.6.1 Religious and ceremonial uses

Although few descendants of the original inhabitants of Cape Range peninsula remain, there is evidence of their religious and ceremonial customs in the area. It may well be the case that there are very few with direct connections left, and it may equally be that as a consequence Aboriginal elders from other parts of Australia themselves have no attachment to the sites on Cape Range. Nevertheless, such places are still sites that deserve to be treated with respect and to do so will not be without its rewards (Kiernan, 1995b).

3.3.4.6.2 Defence

The establishment of the RAN communications facility at North West Cape, of the RAAF base at Learmonth, of a bombing range adjacent to Cape Range, and of various other facilities, have all involved adaptations to the karst environment, most conspicuously through the establishment and management of borefields.

3.3.4.6.3 Other cultural uses

The availability of sufficient water supplies is frequently a major concern where settlement occurs in a karst area, either because of the limitations imposed by water scarcity, or through settlement being focussed at karst springs. Karst can of itself give rise to virtual desert conditions even where precipitation is abundant, parts of China, for instance, offering numerous examples, as do parts of coastal Yucatan. The cultural heritage of both these areas includes features that reveal creative and ingenious solutions to the problems of existing in the area (Kiernan 1991, Back 1992).

Such physical remains are of heritage significance in themselves. The same is true of the Cape Range peninsula, whether that legacy be a physical one in the form of bailer shells left in caves by Aborigines, relicts of borefield investigation, development and management by more recent settlers, or simply a legacy of association and place. Other significant aspects of the cultural heritage of the area lie in its association with past activities of the Australian Defence Forces.

3.3.4.6.4 Economic uses

It is beyond the scope of this report to canvass the economic resources of the Cape Range area but they are quite clearly fundamental and many exist because the area is karstic. Some are largely self evident, while some are yet to be realised. Economic issues are as evident in the siting and composition of Aboriginal archaeological sites as they are in current debate about future developments on the peninsula.

The siting of the Defence facilities and of the town of Exmouth was in large measure a response to the setting of the area, strategic location and the economic importance of the karst groundwater. Advent of the bases clearly had major economic importance for associated and later developments in the region. The area has been utilised for pastoral purposes, while the karst environment of the area, including the reef, is a major factor in the developing tourist industry that is emerging as an important part of its economic base. Large reserves of limestone exist at Cape Range and Rough Range at the head of Exmouth Gulf, and the petroleum industry, which is itself not without its karst connections, is likely to figure in the economic future of the Cape Range peninsula.

While the resources offered by this karst therefore play a major role in facilitating and encouraging human use of this environment, they also pose the principle difficulties and limitations. This report has been commissioned in response to a recognition of the need to ensure that future use of the area is established upon a soundly based technical understanding of the nature of the environment, its limits as much as its opportunities, and upon a firm commitment to the sorts of management principles that such an arid karst area demands.

4. KEY KARST MANAGEMENT ISSUES

The various proposed developments and existing infrastructure in the Cape Range karst province have considerable potential to impact on the dynamic karst system with possible consequences for use of these lands. Some of the impacts may have considerable impacts on the users of this area. Overuse, or contamination, of the freshwater aquifer are obvious issues but land stability and modifications to the highly significant, unique animal communities inhabiting the fresh, brackish and saline waters of the Cape are other potential problems. Developments on the west coast may well present a multitude of problems - not the least aesthetic issues. The new developments at the Lighthouse Caravan Park are an obvious example.

In this part of our report we revisit some basic concepts of karst environments and management and then go on to discuss some of the existing and proposed developments on the peninsula.

4.1. SOME BASIC CONCEPTS

Although the term 'karst' has now entered the lexicon of much of the Australian land utilisation and management community there is still a marked lack of understanding of what karst is, how it forms, its dynamic nature and why its management needs are so specific. Kiernan (1988) presents an excellent summary of the issues facing the users and managers of karstic terrains.

To some extent the basic functioning of karst systems has been discussed above. Before turning to land use questions in detail it is necessary to expand upon, or reiterate, some of the physical and process concepts that relate to karst management.

4.1.1 How is karst produced?

Jennings (1985) defines karst as 'terrain with distinctive landforms and drainage arising from greater rock solubility in natural waters than elsewhere'. This simple definition, stated to be such by Jennings, hides a number of complexities the first of which is the source of the rock solubility. For evaporite rocks such as halite or gypsum the solubility arises from simple dissociation of salts in aqueous solution. This is also the case for carbonate rocks such as limestone. Pure water is able to dissolve limestone in only very limited quantities.

However, the solubility of limestone is much enhanced if the waters contained dissolved carbon dioxide. The gas is a minor component of the atmosphere (~0.036%) but is found in much higher levels in the soil as a result of root and animal respiration and as a result of the decay of organic matter. The partial pressure of carbon dioxide in the soil can reach 5% or more but is more commonly in the region of ~0.5% in the Australian, especially arid, situation. Figure 3 shows the 'cascade' of carbon dioxide through the atmosphere, soil and rock system - the **whole** is the karst system.

Water moving through the atmosphere and soil picks up carbon dioxide and thus becomes more aggressive and dissolves more limestone as it descends through the soil/rock system. Studies in temperate climates suggests that around two thirds or more of the total limestone solution takes place at the soil rock interface, within a few metres of the interface or in very small spaces in the limestone mass (see discussion below on cave sizes). It would seem likely that a similar situation pertains in arid environments but with the proviso that karstification will be highly episodic event following rainfall intense enough to provide for water movement through the soil profile and into the rock mass.

The process of carbonate deposition to produce stalactites and similar forms is the reverse of the solution process in that carbon dioxide is given off on reaching areas with a lower partial pressure of carbon dioxide than in the soil. This can occur in caves or at the surface.

Decaying vegetable matter washed into caves during extreme rainfall events may markedly raise carbon dioxide levels thereby rejuvenating the aggressiveness of water at depth in cave systems and elevating CO_2 in cave atmospheres.

Although solution can take place in pure waters it is much enhanced by elevated carbon dioxide levels such as are found in soils and thus:

> *Karst topography is the outcome of a complex interplay between climatic, topographic, hydrologic, [soil], biologic and temporal factors* (Kiernan 1988).

Hence management of karst must take into consideration:

- climate
- the topographic setting (including geological issues such as structure and lithology)
- soil characteristics
- vegetation characteristics
- the time available for karstification and past climatic settings.

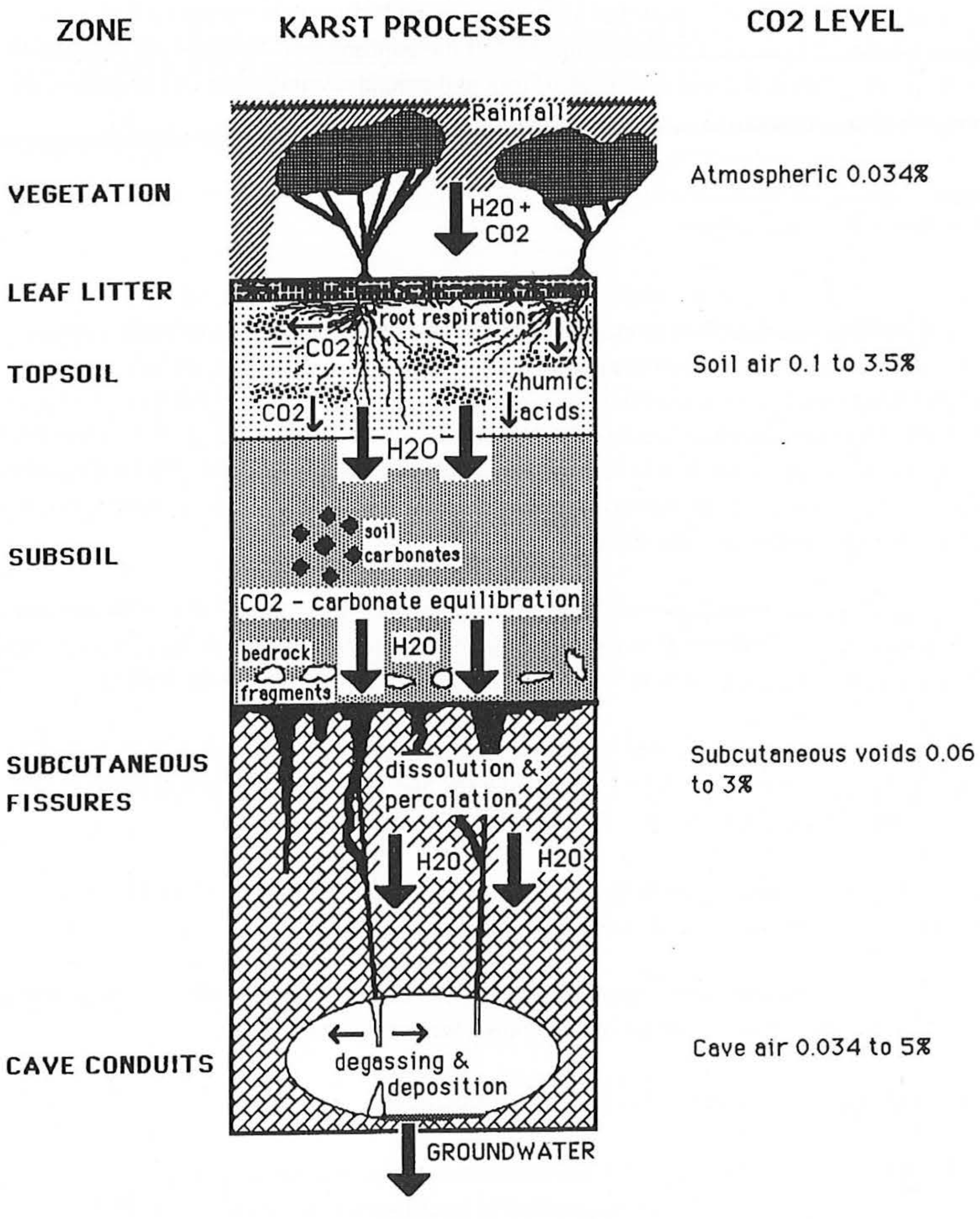

Figure 3. The carbon dioxide cascade (after Gillieson, 1996).

Maintenance of the carbon dioxide cascade and thus of karst processes is thus a process of maintenance of hydrologic relationships and of the conservative management of vegetation and soils.

The factor that sets karst terrain apart from other geomorphic systems is the extraordinary degree of interconnectedness, and inter-relationships of the surface, soil and subsurface environments. The community recognises that dune, estuarine and reefal geomorphic systems are sensitive to disturbance but does not usually recognise that karst and groundwater systems have equal or greater sensitivities. The fact that the most complete karst development is found in rocks of greater purity often produces conflict with those wishing to extract that most vital of commodities for our modern society - calcium carbonate.

The quality of any karst environment is most importantly dependent upon the integrity of the catchment and aquifer and hence the quantity and quality of hydrologic recharge. In the case of Cape Range, the importance of this is highlighted by the stygofauna - but even without the stygofauna, best practice would demand maintaining aquifer levels and quality. Thus proper management of the aquifer will ensure the long-run health of the faunal system ; at the same time, the faunal system probably provides a natural indicator of water quality.

4.1.2 What is a cave?

The opening stanza of Samuel Taylor Coleridge's unforgettable poem, Kubla Khan, runs as follows:

In Xanadu did Kubla Khan
A stately pleasure dome decree:
Where Alph, the sacred river, ran
Through caverns measureless to man
Down to a sunless sea.

It is generally felt that 'measureless' means so big that they cannot be evaluated. However, in the case of the Cape Range karst aquifer, as in many other similar situations across the world, 'measureless' might well, and very properly, refer to very small spaces that cannot be measured by man - because we can't enter them! However, the openings are there and water and air can flow through them delivering health on one hand and the potential for catastrophe on the other.

4.1.2.1 Porosity and permeability

The characteristics that allow water to move through the rock mass are known as porosity and permeability. Porosity is the measure of the pore spaces in the rock. However, unless the pores are connected water cannot flow through the rock. For example, the volcanic rock pumice, has an extremely high porosity being so full of gas bubbles as to be literally a solid foam. The pores in pumice are not interconnected and thus it will float on water. Permeability is effectively a measure of interconnectedness of the pores. Thus pumice has a low permeability in spite of the very high porosity.

Generally speaking, limestone, especially the pre-Pliocene limestones, has a low *primary* porosity. That is, there are only small pores in intercrystalline or interparticle spaces - permeability due to this primary porosity is also low. The mechanics of flow through such homogeneous media are governed by Darcy's Law. However, many crystalline limestones have a high or very high *secondary* porosity due to the presence of fractures, bedding planes and, most importantly, to the solutional enlargement of the flow paths provided by the fractures and other partings. Darcy's Law does not necessarily apply in such conditions. Permeability is expressed by a measure termed *hydraulic conductivity* that reflects the properties of both the fluid and the medium - in this case water and the limestone (Ford and Williams 1989). Karst limestone has greater permeability than other rocks due to the large size of the secondary pores - caves and other tubes.

Some workers, notably JF Quinlan, consider that porosity can be assigned to three classes:

- primary intergrannular porosity in which flow follows Darcy's Law
- secondary porosity arising from fractures and other partings within the rock mass
- tertiary porosity arising from the development of karstic conduits.

In these latter two cases the conventional assumptions of hydrogeology (which are based on Darcy's Law) break down. The rates at which water will flow through the rock mass rise by many orders of magnitude as one moves from primary to tertiary porosity.

Conventional groundwater hydrology is based on the assumption that the aquifers are generally considered to be simple porous media with laminar flow in which Darcy's Law operates. However, even in well-sorted sands and gravels water behaviour will often depart from the theoretical. The presence of large, open conduits in which laminar flow is replaced by critical (= turbulent) flow regimes as in karstified rocks produces great changes in the dynamics of flow systems.

The lower limit for the development of critical flow is around 6 mm diameter (Ford and Ewers 1978). Below this size solution and mass transport of solutes is slow. Once critical flow is developed both solution and mass transport can become very rapid dependant on the rate at which water moves through the system.

Quinlan et al. (1992) provide a comprehensive discussion of the hazards of assuming too much, based on standard hydrogeologic methods, about flow regimes through limestone aquifers and the potential for groundwater pollution.

Unfortunately we do not have any estimates of the hydraulic conductivity of the Cape Range limestones above the watertable. The presence of many anastomosing tubes ranging up from several millimetres to ten or more centimetres in diameter is clearly seen in the Trealla Limestone exposed in the Department of Transport quarry and in the 'zone of intense phreatic preparation' intersected by the caves on the crest of the Range. Apparently intervals of these tubes can be seen in some of the cores obtained as part of investigations for quarrying proposals. Many of the tubes in the Trealla Limestone are at least partially clay filled; some were open. However, without field evidence or experimentation we do not have any information on the degree of interconnectedness of the tubes nor of the rate of water movement through the rock mass.

The Water Corporation (1996) point out that the hydraulic gradient, and hence hydraulic head in the ground water, is very low and the mean flow velocity is also very slow (~60 m per year). However, in a quarry or pollutant spill situation we are dealing with essentially vertical gradients down to the watertable. Depending on the situation and the amount of water or other fluid involved, with relatively high hydraulic heads, downward velocities might well be orders of magnitude greater. Estimates of these velocities can be achieved using down-bore hydraulic conductivity tests above the watertable (Castany 1984).

Clearly, if the tubes are narrow and torturous and sediment filled in part, frictional effects on fluid movement may be very high and drilling water or air may not be completely lost (see also the quotation in Section 4.2.3 below). The impression may be given that the limestone is not cavernous. Wyatt (quoted in D Lewis 1996a) says in part in discussing the drilling results from the proposed Whitecrest quarry site:

> *...Most holes encountered primarily hard rock limestone with but with occasional zones of broken and fractured ground. Generally, these zones were less than 0,5 m in extent and most, especially those in excess of 1 m length, filled with red sandy clays. Very few open cavities of any size were identified.*
>
> *It is important to note that no percussion holes experienced* ***total*** *air loss... Whilst* [blanked out in our copy] *water loss was experienced in diamond drill holes between 4-20 m drill depth, with water sometimes issuing from adjacent near surface hill slopes by way of bedding and joint planes, it was not necessary to cement any hole to allow drilling to continue. This indicates that no major openings or cavities were present. In some instances, partial water return was regained which confirms that the broken ground was not extensive.* [emphasis ours; what happened in those instances where water return was not regained?]

There seems to be an assumption in the above quote and more generally in the Cape Range scene that flows in karstic situations are either instantaneous (that is, by intersecting open caves a metre or more in size) or that flow does not occur at all.

Benson and La Fontaine (1984) have calculated the probabilities of cavity detection by drilling in an area of one acre. With a 90% probability of detecting a cavity of the size shown below they estimate the number of holes required as:

- *cavity size of 23 m diameter: Requires ~10 holes [one every ~400 square metres]*
- *cavity size of 7 m diameter: Requires ~100 holes [one every ~40 square metres]*
- *cavity size of 2.3 m diameter: Requires ~1000 holes [one every ~4 square metres]*

...assuming uniform grid spacing. If drilling locations are randomly selected, the number of borings increases significantly. (p 205)

They go on to say:

> *Direct cavity hits by drilling are unusual for most subsurface investigations because the number of borings must be limited in order to be cost effective and the probability of hitting a cavity is low.*
>
> *....it should be clear that most subsurface investigations do not begin to approach 100% accuracy. In fact many investigations are probably < 10 to 20% accurate. Yet many professionals and their clients continue to think of subsurface investigations in terms of high accuracy.* (p205)

From the evidence in the Department of Transport quarry we can clearly see that we are not dealing with one cavity of one or two metres diameter per acre but with a multiplicity of tubes of centimetre scale. Subsequent to our visit, quarrying activities did reveal the presence of a large cavity, reinforcing the fact that low drilling densities are inadequate to assess the presence or otherwise of caves.

We believe that many of the questions that are being asked about what impact various developments, especially quarrying, might have on groundwater might have far more substantive answers if determinations of hydraulic conductivity above the watertable were available. The answers will not necessarily be definitive but may allow the community to more adequately assess the possible impacts of developments. We recommend that such measurements be made as part of the development of the southern borefield and as part of the requirements for the investigations of quarry sites. Castany (1984) provides some discussion of the techniques. Quinlan et al. (1992) provide some cautionary advice on the whole issue of measurement of water flows through karstic terrain.

4.1.2.2 Dimensions of Cave Systems

Whilst clearly related to water movement through rock masses, the spaces through which subterranean fauna move have their own nomenclature as pointed out by Howarth (1983). It is worthwhile to quote him at length:

> *In both soluble and volcanic rocks, therefore, a complex of inter-connected voids of varying sizes anastomoses throughout the rock in a great labyrinthine system. Within this system there is a continuum of various sized voids from the microscopic to the largest caverns. The existence of these voids, their size, depth, and extent, depends on the geological history of the area. From a biological perspective, this continuum can be divided into three size classes: microcavernous (< 0.1 cm), mesocavernous (0.1-20 cm) and macrocavernous (> 20 cm).* (page 370)

Howarth goes on to point out that we know little of what goes on in microcavernous habitats once we are below the soil layer (most soil pore sizes are within the microcavernous range). The spaces that form the principal habitat of most troglobites and similar subterranean fauna are greater than about 1 cm width (mesocavernous) and thus fluids, including nutrients and pollutants, may move easily through such systems. To quote Howarth again:

> *The macrocavernous habitat is the deep cave zone of traditional biospeleological research. The voids are generally large enough for man to enter, or at least sample, and range in size from 20 or 30 cm in width to the largest cave passages, sometimes over 100 m in diameter. They interconnect* [freely] *and are continuous with the mesocavernous voids and, as far as troglobites are concerned, only differ from mesocaverns in that portions of the larger passages are more likely to be too dry or otherwise do not provide their unique environmental requirements. A number of vertebrate species also use voids in this size range* (*op cit*, pages 370-71).

Thus, human beings concerned with cave biology, and indeed other aspects of cave science, have placed their emphasis on caves into which they can walk or perhaps crawl. Much of the terrestrial cave fauna is essentially a mesocavernous fauna, adapted to live in these tiny cavities with their high humidity and high carbon dioxide atmosphere; their occurrence in large caves must be seen essentially as an accident of their mobility; they sometimes tumble into, or enter in their search for food, spaces big enough for humans to find them (Howarth, pers. comm.). It is important to recognise that many of the most important sites at Cape Range at which cave fauna has been recorded are very small and unspectacular (e.g. C111, C215, C218, C225; Humphreys 1991, pp 31-35).

This discussion of cave sizes indicates that definitions such as that proposed by Whitecrest as:

> *...an open cavity within the limestone formation being mined exceeding 2.0 m diameter horizontally or 1.0 m vertically and giving reasonable indications of extending to the water table* (J Lewis 1996b)

may very considerably underestimate the extent of caves, the extent to which they may provide a faunal environment and the complexity of water movements through non-Darcian media.

4.1.3 Hydrogeologic setting and systems

The geologic and hydrologic setting of the Cape Range peninsula is discussed in Allen (1993) and a generalised cross-section (after Water Corporation 1996) is given in Figure 2 above. In summary, the peninsula has an anticlinal spine of Middle Miocene limestones and associated sedimentary rocks. The lower slopes surrounding the uplands are frequently mantled in alluvial and colluvial materials. Fringing the spine and lower slopes are a variety of Pleistocene to Holocene materials including carbonate based conglomerates, calcarenites and siliceous dunes and sand plains.

The uplands are dissected by deeply entrenched canyons floored with cobbles, gravels and finer materials. These canyon floors probably act as very efficient recharge areas following episodic heavy rains. There are some areas of internal drainage on the crest of the anticline that will also act as rapid routes for water to enter the aquifer. As is common on islands and peninsulas made up of permeable rocks the groundwater system consists of a lens of fresh water floating on more saline waters beneath. Given the importance of these so-called Ghyben-Herzberg systems at Cape Range it is worthwhile considering their dynamics further. The following is summarised and simplified from Ford and Williams (1989):

Near the coast the watertable declines toward sea level. Water quality analyses from samples taken at various depths from bores just inland show that fresh water overlies the salt water, that penetrates the aquifer at depth. The depth below sea level at which the fresh water/salt water interface occurs is related to the elevation of the watertable above sea level and to the density of the fresh and of the salt waters respectively.

If the density of the fresh water is 1.0 and that of the salt water is 1.025, then under hydrostatic equilibrium the depth to the salt water interface is forty times the height of the water table above sea level. This is the Ghyben-Herzberg Principle. A [very] *practical consequence of this is that the pumping of a bore in a coastal aquifer causes the watertable to be drawn down by 1 m, then salt water will intrude upwards beneath the well by 40 m. Excessive pumping can therefore risk contamination by saline water.*

The Ghyben-Herzberg principle simplifies the relationship usually found in nature, because the two fluids are treated as immiscible and groundwater conditions are normally dynamic rather than static.

The situation on the eastern limb of the Ghyben-Herzberg system operating at Cape Range is shown in Figure 2 and is considerably more complex as there are effectively three miscible fluids - freshwater overlying brackish overlying the seawater wedge. Because recharge rates are so low, given the limited magnitude and infrequency of sufficient rain water to infiltrate the aquifer, and presumably because of a high degree of secondary porosity within the limestones the hydraulic gradient is only of the order of 20 cm per kilometre and the freshwater lens is relatively thin within the first 3 or 4 kilometres from the eastern coastline (Water Corporation 1996). The drawdown cones produced by pumping must be managed very carefully to avoid the invasion of more saline waters from beneath.

The situation on the western coastline is far less clear but it appears that the groundwater system may be even more fragile in that area. The Ghyben-Herzberg system appears to be asymmetric with the freshwater lens perhaps being thinner and hence more fragile. The landward incursion of tides as shown by the rise and fall of water in the cave systems on the western plain may well be more pronounced than on the eastern side. This perhaps points to a greater degree of karstification in the western plain. The greater exposure to an active coast may well be playing a role here. If there is more karstification and thus a greater direct connection of the freshwater aquifer to the coastline in the west this again reinforces the need to consider the Ningaloo Marine Park in the context of the dynamics of the terrestrial system (and *vice versa*).

The dynamics of the watertable rise and fall given tidal effects, the long return periods between effective rains and the changes consequent on changing sea levels in recent geologic time may well have very significantly enhanced karstification and the development of conduit systems near the present water table. Owing to the peculiarities of the chemical systems operating here the mixing of salt and fresh waters may result in the increased aggression of groundwater - even if the two source waters are already saturated or supersaturated with respect to carbonate. It is suggested that the caves in (and below?) the Mowbowra Conglomerate, as well as others on the east coast, may show a high degree of interconnection between the sea. These caves and the various wells and caves on the western coastal plain may well arise from such mixing effects. The mixing would be rejuvenated by sea level change.

It should be emphasised that the nature of the Ghyben-Herzberg aquifer system operating here reinforces the integrated nature of the hydrological and ecological systems operating on Cape Range peninsula itself, in Exmouth Gulf and in the Ningaloo and Bundegi Reefs and environs. There must be fresh and brackish submarine springs and it is more than probable that at least some of the openings evident in the fringing reefs to the west are maintained by flows with less than seawater salinities.

4.1.4 Engineering considerations

Karst terrains can often present a particular suite of engineering problems to the unwary (Kiernan 1988). Some issues, leakage and stability questions for water storage dams for example, need not concern us here. Some potential problems at Cape Range include ground stability problems of various types. White (1988) defines three types of stability problems of relevance to this region:

> *Processes of soil piping, and bedrock collapse and stoping, produce cover collapse sinks, cover subsidence sinks, and bedrock subsidence sinks as part of the natural evolution of the karst landscape. These processes can be greatly influenced by human activities, however, and in turn are among the most important land use hazards in karst terrain.* (page 362)

The difference between collapse and subsidence is largely one of speed - collapse implies virtually instantaneous catastrophic failure. Where drainage is concentrated, as along roads, in borrow pits or in runoff from buildings and other sealed areas, water movement through the soil and into caves beneath can lead subsidence and sometimes collapse as the fines a removed from the soil. Collapse may well be exacerbated when the hydraulic support provided by water is removed by over-abstraction from the aquifer.

The collapse through the Mowbowra Conglomerate of a cave known as Dozer Cave occurred some years ago and was probably as a result of direct physical loading once the extra 'cushioning' provided by the soil layer had been excavated.

Prediction of sub-surface cavities by a wide variety of geophysical methods has been attempted around the world (see, for example, Kiernan 1988). Usually good results are only obtained when the sub-surface conditions are very simple and any cavities are at shallow depths. Drilling on close centres is the safest method but can still lead to cavities being missed as has been pointed out in Section 4.1.2 above.

As development proceeds in the Cape Range area more engineering encounters can be expected. As there is little topographic relief, the distance to the water table is small and groundwater abstraction should not be lowering the water table significantly, these happenings should be of limited impact. Individual happenings, however, could have quite momentous outcomes - consider the situation of a house sited above Dozer Cave. Concentration of runoff flows or leakages from sewage pipes or ponds should be avoided if at all possible. Lined water-holding ponds are a particular risk:

> *Lagoon failure through catastrophic sinkhole collapse can be quite dramatic. In one case a sewage lagoon at West Plains, Missouri, had an impoundment area of 19.8 hectares and a water depth of about 1 m. A collapse occurred at a time when the lagoon contained about 1.68 x 10^5 m^3 of effluent. All of the water drained out within 52 hours [this is an average flow rate of about 900 litres per second]. The collapse created a vortex of such magnitude that the manager of the facility was unwilling to get close to it with a boat* (White 1988, page 369).

4.1.5 Sedimentary regimes

Changes in erosion and deposition patterns can have far reaching effects in karstic terrains. The high degree of integration between surface and subsurface means sediments can rapidly be transmitted to the aquifer perhaps reducing its porosity and permeability and hence reducing its value for water supply and as a habitat for the stygofauna. Turbid loads transmitted to the reef systems *via* subterranean channels could also have undesirable effects.

As has been mentioned above concentration of water flows can lead to dramatic effects if fines are carried into cavities. Unless raw soil surfaces in borrow pits and similar surfaces are rapidly stabilised and potential runoff waters are dissipated the potential for karst-related problems remains.

4.1.6 Resource conservation issues

The fundamental tenet of karst management is to protect the whole karst hydrogeologic system. In the case of an 'island' like Cape Range this requires the integrated management of the Range, the surrounding coastal lowlands and of the fringing seas (and reef systems). Clearly a more pragmatic approach is required than just blanket creation of a national park or similar reserve over the area. There are too many resource uses operating on the site at this time - some of which are potentially conflicting uses - for such an approach.

However, we believe that extension of the Cape Range National Park to the eastern coast via a 5(g) or 'better' reserve is in the interests of the resource for both its intrinsic and extrinsic values. We also strongly support proposals to extend the Park to the north of the existing boundaries to provide statutory protection in this area which has a distinct species assemblage. We understand that there is a community-based proposal to establish a 'Desert Museum' in the area to the north of the Park but we have no firm details. We fully support any suggestion that the area should be better protected, managed and interpreted. Indeed, the area has a tremendous amount to offer both the casual visitor and those in search of ecotourism experiences. However, we believe that this is best done in a national park or similar tenure.

There are many instances where infrastructure and operations conflict with the undoubted aesthetic values of the peninsula both within and without the National Park. Clearly the many communications towers are going to remain for the foreseeable future however issues such as the multiplicity of vehicular tracks and the daily burning of landfill can be addressed.

4.2 SPECIFIC LAND MANAGEMENT ISSUES

4.2.1 Groundwater use

Maintenance of the four elements of the aquifer under Cape Range is clearly critical to the subterranean fauna, karst processes and to the continued existence of human settlement in this area (unless other sources of water can be considered). The four elements of the Ghyben-Herzberg system operating here are:

- the vadose (free-draining) waters above the water table
- the freshwater lens floating on, and grading into,
- the brackish water that in turn rests upon
- the seawater wedge beneath.

The characteristics of the Cape Range system are an extremely low hydraulic gradient, significant tidal influences in the aquifer (at least on the west coast), very limited recharge and the resultant thinness of the freshwater lens. The low gradient is probably at least partly a measure of the degree of karst development in the vicinity of the water table. In addition, the low rainfall will not allow the development of higher gradients or thicker lenses.

The groundwaters are currently exploited in a number of ways by a variety of operators. There are considerable dangers in water abstraction from Ghyben-Herzberg systems. These are recognised by the Water Corporation in both theoretical and operational aspects. From a karst perspective the main dangers are to the distinctive faunas found in the differing parts of the system if one or more of the elements is removed or the whole homogenised. The time scale at which physical karst processes operate, together with the fact that they have evolved at Cape Range through a number of cycles of sea-level rise and fall and possibly climatic change, means that human-time scale changes are not necessarily catastrophic for the physical system. However, homogenisation of the system may well have catastrophic impacts on the unique stygofauna.

Caution 2

We believe that there should be a more conjunctive operation of the use of the aquifer by the Water Corporation, the Department of Defence and private water miners It also must be recognised at all levels of government, local, State and Federal, that water supply from the groundwater is constrained by recharge rates and is thus a limited resource which must be used only within the determined sustainable yield level That is, extraction and natural flow rates must not exceed recharge over the long run. There is a recognisable and definable limit to development unless water can be supplied from other sources

4.2.1.1 Water and Rivers Commission

The Water and Rivers Commission is the agency responsible for the management of the State's water resources, including groundwater. The Commission's role is to ensure that water is allocated for community and environmental needs, balancing an efficient and sustainable supply for public and private purposes, with the maintenance of environmental values

Currently, all bores in the Exmouth area, including those managed by the Water Corporation are licensed by the Commission. The licences give an allocation volume, but not all bores are metered. This includes the Department of Defence bores; their licence includes conditions requiring monitoring of quantity and quality. The Water Corporation is the utility operator of the public water supply.

4.2.1.2 Water Corporation

Given that the Water Corporation is operating the borefield with an understanding of the system and in such a fashion as to optimise water supply whilst preserving the balances between the fresh, brackish and seawater elements and between recharge, loss and abstraction, there seems little to be concerned about. The extension of the borefield to the south, given that the conservative operational approach is followed, should present few problems to the karst and its inhabitants. The Corporation's support of ongoing research.into the aquifer behaviour and into the stygofauna is to be applauded.

4.2.1.3 Defence Establishments

The Department of Defence operates a number of water supply bores at the various facilities. Given, that in the north at least, the thickness of the freshwater lens appears to be significantly less than in the Water Corporation borefield as would be expected from topographic and other considerations the dangers of over-exploitation are much higher here. As a result of the aquifer characteristics water quality is lower here than in the south and there is apparently some evidence that water quality has been impaired by over abstraction.

The recent connection of the Lighthouse Caravan Park to the Navy water system may be one example where the augmentation of water supply may lead to unplanned or uncoordinated extension of development. Whilst there may be more co-ordination between the Water Corporation and the Department of Defence than was apparent during our brief visit, it is our view that the Water and Rivers Commission should further review this issue.

4.2.1.4 Urban Use

It is understood that there are a number of licensed private bores within the Exmouth township and on the various semi-rural blocks. Although these bores are licensed there is a possibility that overuse may well increase the landward extent of the saltwater wedge near the water table or fragment the fresh or brackish water lenses. Indeed, amongst the reasons advanced by the Water Corporation (1996) for scaling down of the northern end of the existing borefield are concerns for the interaction between the private bores and the government operation.

The possibility exists that the green oasis produced in the township by watering with effluent from the sewage treatment plant is exacerbating water demand for domestic garden purposes, including the planting of species ill-adapted to the semi-arid climate of this area should be considered. A campaign to make the public aware of the fragility of the ground-water system seems to be warranted.

It must be recognised that the constrained water supply is the major limit on development on the peninsula and that even if the supply problem was to be solved, disposal of effluent and waste without adverse impacts upon water quality remains a second major constraint.

4.2.1.5 Quarries

Ekmekci (1993) points out that:

> *The karst groundwater system can be altered by limestone quarrying in greater magnitude and extent than by any other activity of man. This change may be concentrated within a small area compared to the whole limestone outcrop, but its negative effects on the quality and quantity of the groundwater potential can extend further.* (p6)

The possible impacts of limestone quarrying on the groundwater system are discussed below. It is not known if groundwater is extracted or is proposed to be used in the existing Department of Transport quarry, the Whitecrest Enterprises proposal or in the Southern Limestone tenements.

4.2.1.6 Other

Groundwaters are used from a number of both natural and man-made wells on the coastal plain. Some of these, especially on the western side of the peninsula may be very important from a faunal viewpoint and *ad hoc* use for such purposes as road watering should be carefully considered. Indeed, the dynamics of groundwater system on the west coast is much less understood than on the east and the landward expression of tidal change is far more marked in this region. Hydraulic gradients seem lower and correspondingly the chance of seawater invasion is higher.

Hirschberg's (1991) report on the Perth Basin provides a methodology for an inventory of potential groundwater contamination sources which could be used on the peninsula. It is suggested that such an inventory is needed very rapidly to assist planners and residents to understand the sensitivity of the groundwater system. To this end it is suggested that a public education campaign is needed to raise the importance of this issue in the community.

4.2.2 Defence lands

The Department of Defence operates a variety of military installations in the region. These are chiefly based around the RAAF's Learmonth Base and the RAN's Harold E Holt Communications Centre. There are many other facilities, active and inactive in the area, notably the RAAF bombing range in the south. We briefly inspected parts of the naval borefields and were briefed on some environmental issues by navy staff. We believe that there is a need for fully co-operative land management approaches between the State and Federal agencies and applaud those steps already taken for better management of the groundwater resource, for example.

Issues which were apparent during our visit included:

- dead and dying trees around the RAN headquarters. This problem may arise from a decline in groundwater quality or local rise or fall in the watertable or from other causes such as fungal root pathogens. However, not all is well...

- the perpetuation of the 'oasis syndrome' where much water is being applied in a climate and environment where such an activity is perhaps inappropriate.

- concerns that the Department of Defence may see augmentation by desalinisation as a viable approach to water problems. Our concerns are twofold. Firstly, high-tech approaches merely hide the fact that there are very real physical limits on land use in this region and, secondly, the ultimate fate of salt or highly saline waters discharged from desalination plants.

- ongoing degradation of coastal dunes in the Port Murat area is a matter for concern in itself as well as an Aboriginal cultural resource matter.

- the area is rich in military history. There should be a formal program of site documentation and the development of conservation plans in line with the guidelines laid down by the Burra Charter. Many of these sites could become important tourist attractions in their own right if properly interpreted.

- although we have done no more than think about the issues, water shedding and channelling at the Learmonth Base may be of concern. Nutrient inputs to groundwater arising from nitrogen and phosphorus compounds used on the RAAF bombing range may also need assessment. Nitrates resulting from explosives use are transmitted into the groundwater in short-lived but strong pulses, and so would best be detected by specific monitoring almost immediately shortly after an event, and not necessarily by standard monitoring practice. These inputs are unlikely to be quantitatively significant even at peak times but it must be remembered that the demobilisation of nitrates in groundwater is extremely slow and hence levels may be cumulative. There has been research on this issue in New South Wales by the Australian Defence Force Academy. This has indicated, for phosphorus at least, that runoff from ranges may include phosphorus levels at a similar order of magnitude to that supplied by a small sewerage plant or from a farm area (Colton 1987). In this case at least the phosphorus on the range was rapidly converted to insoluble forms and thus not all the phosphorus contributed to the nutrient loads within the stream.

4.2.3 Limestone quarries

The location of large reserves of high to very high grade limestone close to the sea clearly make Cape Range an attractive site for limestone extraction. A number of active or proposed quarries are operating in the area and it is expected that further proposals will emerge from time to time. The Department of Minerals and Energy show 12 'live' or 'pending' proposals between Exmouth and Learmonth on their recent map entitled 'Cape Range - High grade limestone resource, proposed 5(g) reserve and proposed extensions to National Park'.

Kojan et al. (1995) have investigated the very considerable limestone resources of the region. they state:

> *The less environmentally sensitive areas south of Mt Hollister contains approximately 2500 Mt of this resource; this is well in excess of the estimated future requirements of the iron and steel industry.* (p1)

Accepting this, and assuming the conclusion about the environmental sensitivity proves correct, it seems unfortunate that there is incremental quarry development in the sensitive areas to the north. The distance from a deep water port is understood but it may be environmentally (and economically?) more responsible to introduce appropriate infrastructural facilities to support extraction from this site.

Given that the desirable high grade resources are also those which generally show the highest degree of karstification it is not surprising that limestone extraction proposals can generate considerable angst in the community. Quarrying operations have often been shown to have considerable impacts on karst systems and processes. These impacts range from complete destruction to gross groundwater pollution. However, if properly sited, well managed and comprehensively rehabilitated, limestone extraction should lead to minimal problems provided issues such as aquifer dynamics and karst processes are considered.

It should be emphasised, however, that quarry rehabilitation is not just an exercise in restoring landscape aesthetics. Full consideration must also be given to questions of restoring, in so far as is possible the normal conditions of groundwater recharge (and discharge).

The Department of Minerals and Energy (1988, 1994) has guidelines for the environmental management and ultimate decommissioning of quarries and mines in the arid zone and elsewhere. The Department has not directly addressed the karst-related questions that arise from quarrying proposals in limestone terrain and above karstic aquifers.

We must also emphasise that karst environments do not recognise humanly defined lines across terrain. There is little point in gazetting national parks, 5(g) reserves or water reserves if the karst environment and underlying aquifers are going to be subject to disturbances from whatever source outside the legally defined area.

4.2.3.1 Department of Transport quarry

This quarry was developed and operated to provide relatively large volumes of limestone boulders for the construction of a marina on the east coast. The quarry is sited in the northern part of the proposed southern extension to the government borefield. A number of concerns arose from our inspection of this site. Leaving aside the question of the wrecked Haulpak truck which seems to have been somewhat of a local environmental icon, there seems to be differing environmental management expectations and procedures to those operating on privately run proposals.

The wisdom of siting a quarry, any quarry, within or up-gradient of a reserve for water production seems unusual, to say the least. The lack of sanitary facilities and containment of vehicle refuelling and servicing areas on such a site is of further concern. We recognise the commitment by the Department of Transport that these activities should be carried out near the Marina site, and this is may have been addressed since our visit.

The enormous proportion of waste materials to product appears both economically inefficient and potentially environmentally dangerous in addition to the question of visual impact. Blaming the contractor for his interpretation of the ground conditions is scarce justification for what appears to be an under-resourced drilling program.

In contradistinction to D Lewis (1996c), we believe that there is ample evidence in this quarry to suggest that potential rapid flow routes to the aquifer exist. The evidence of karstification at scales of several millimetres to ten centimetres and more is clear. Whilst many of the anastomosing tubes are blocked by fine sandy clays, others are open. We will admit that any routes to the aquifer may well be tortuous and flows consequently slow. The Water Corporation (1996) points out that average flow rate in the karstified parts of the aquifer below the watertable is as low as 60 m per year. These low rates point to the potentially very lengthy residence times of any pollutants which reach the groundwater.

However, these flow rates are calculated for the essentially horizontal flows in the aquifer. Hydraulic heads and steep gradients are more than possible in a quarrying situation and flow rates may be much higher. The lack of runoff from Cape Range except under the most extreme rainfall events is additional evidence for vertical infiltration toward the water table.

Caution 3

*Until clearly proved otherwise by down-bore hydraulic conductivity tests we suggest that the potential for aquifer pollution from quarrying and other ground-disturbing activities **does** exist in this karst province.*

The discussion by Quinlan et al. (1992) is especially relevant to the discussion of flow rates and paths through karstic, even partially karstic, terrain.

The excess of clays produced in the Department of Transport operation may well mitigate against water movement toward the aquifer in that vehicular movements on the site may well have compacted the fines into any open fissures. However, the question of movement of fines is not restricted to the quarry site *sensu stricto.* Clays and other fines are being transported on truck tyres and bodies from the quarry to the marina site. The repetitive working of the tyres on the haul route will also be generating fine materials. The question of fines at the marina will be discussed below.

As an example of potential impacts from haul roads, there is a least one important cave in this area (Camerons Cave, C452) which reaches down to the water table and contains significant stygofaunal elements. This cave is the site of important monitoring of conditions within the karst aquifer designed to elucidate more of the dynamics of the karst groundwater system particularly its coupling to the sea via tidal flows (Humphreys pers. comm.) The man-sized, physical entrance to this cave is within 50-100 m of the haul road and is located to one side of a minor drainage line. There are undoubtedly more direct routes into this cave. Very considerable disturbance and sediment movement was occurring with each truck pass. In most civil engineering situations one would expect to see, at the very least, a hay-bale or geotextile dam to reduce sediment flows from the drainage line crossing.

In light of the Department of Mines (1988) and Department of Minerals and Energy (1994) guidelines for mining and quarrying, the questions of decommissioning and rehabilitation do not seem to be addressed on this site. The Water Corporation (1996) identified streambeds as being important aquifer recharge areas and the mullock heap encroaching on Stoney Creek may well inhibit recharge through the deposition of fines into the current coarse bedload of the creek.

4.2.3.2 Whitecrest Enterprises Pty Ltd quarry proposal

As indicated on-site and in the debrief we have a number of concerns about this proposed operation. The proposal is located up-gradient, both topographic and hydrologic, from the proposed southern extension to the Exmouth borefield and from the gazetted water reserve in the headwaters of Stoney Creek. It is proposed that the haul road will follow the bed of Stoney Creek. The proposal will see the removal of a ridge line down to creek level between the two major tributaries of the creek. This level is approximately 50 m ASL; the water table level is estimated to be only a few meters ASL at this distance from the coast.

Although it has been claimed that the area is not cavernous, the presence of caves and subterranean fauna on the site was demonstrated without difficulty. Several small and easily entered caves were discovered during our brief visit ; they contained active speleothems and troglobitic fauna. Approaches to defining what is, and what is not, a cave have been addressed in Section 3.1 above. We also noted evidence of extensive Aboriginal activity on the site.

Although the situation in the Cape Range karst aquifer may be simpler than in many of the situations encountered by Quinlan and his colleagues (1992) it is probably worth labouring the point to quote them again:

> *Monitoring wells in karst terrains generally do not work as such for the same reason one does not win a state lottery with every ticket: The odds do not favour success. The odds for a monitoring well being successful are explained in terms of scale, however, not economics - although in both situations, one cannot afford to continue drilling (or playing) until success is attained. The extremely heterogeneous organisation of groundwater flow in caves and dissolutionally enlarged fractures of a karst aquifer, and organisation that is commonly dendritic or trellised and similar to that of a surface river* [although perhaps not in the Cape Range situation?], *is not adequately sensed by the number and size of the wells drilled - except by improbably good luck. These facts compromise the presumed relevance and effectiveness of a conventional monitoring system based solely on wells. The wells yield water and data, but the samples are unlikely to sense drainage from the facility in question. Accordingly, the samples from such wells are most likely irrelevant. Certainly the cost of their analysis does not justify the gamble on their relevance.*
>
> *...The consequences of installing an ineffective monitoring well, missing pollutants that are going off-site and the possibility that an on-site or off-site drinking water supply may be adversely affected, are serious. It is typically argued that such monitoring results indicate a 'clean well' (i.e., no contamination or, that if no cavities are intercepted or there was no loss of drilling fluid, there is no karst. Such interpretations are based on insufficient sampling and are usually specious!* (p 562)

As mentioned above the karst aquifer at Cape Range probably behaves with a more Darcian-type flow regime than in many karst situations, but it is also clear that there are rapid flow paths through the limestone both above and below the watertable. However, the climatic regime and karstic conditions pertaining at Cape Range mitigate against standard tracer tests being useful in simplifying the problems confronting the community.

We do not believe that unequivocal statements can be made at this time about whether or not the proposed operation will have impacts on the aquifer. The data on the potential for water movements through the karst are clearly inadequate. The precautionary principle en-shrined in the concept of ecologically sustainable development would suggest that this proposal should be evaluated very carefully by the responsible agencies.

We again emphasise the artificial nature of the lines defining water and other reserves.

Again we have concerns about the siting of the haul route in a creek bed but recognise both economic and aesthetic considerations enhance the attractiveness of this ecologically less than optimal route. We note that that a conveyor and off-shore loading facility are ultimately proposed as this quarry develops. The question of road haulage along the coastal highway to Cape Murat is outside of our brief but we do raise the question of mixing industrial traffic with the tourist community.

We share the concerns of Humphreys and others (as outlined in Halpern et al. 1996) as to the possibility of potential problems with lime production if it is inadvertently introduced to the groundwater system. However, because of the physicochemical processes involved it is a less likely contaminant than hydrocarbons or other liquids.

Without having visited the proposed Point Murat stockpile site it is difficult to say much about that site. However, a large stockpile of white limestone will be very visible from many points along the road between Exmouth and the old Vlaming Head lighthouse. It might also add an unwanted sense of scale to the naval communication towers?

In summary we are deeply concerned that the site is clearly located on cavernous lands with an inevitable incidence of troglobitic fauna and clear evidence of Aboriginal occupation; the quarrying itself will impact adversely on both these resources and almost certainly (but to an unknown degree) upon the underlying aquifer; the quarry will be upstream from both the water reserve and borefield; the access road will have a major impact along Stoney Creek; the environmental impact assessments to the date of our visit are demonstrably inadequate; and the arrangements for removing, transporting and shipping the limestone still await final definition and assessment.

4.2.3.3 Southern limestone tenements

We know nothing about the southern limestone tenements beyond the issues discussed in Kojan et al. (1995). It is stated therein that the area is less environmentally sensitive than the areas to the north. However, the basis for this statement is unknown and we believe that formal archaeological, geomorphological and biological studies should be funded in this area to act as a basis for their future exploitation (or otherwise).

4.2.4 Coastal developments

As emphasised above, we believe the ground water, coastal plains and the fringing reefs must all be considered as components of the total karst system. For a variety of self-evident reasons the coastal plains and the immediately surrounding beaches, seas and fringing reefs are the site for many of the human-induced pressures evident on the peninsula. We have a number of concerns - especially in light of the need for the area to remain visually attractive, to maintain the very features that visitors come to the area to experience and, of course, to protect the natural and cultural attributes of the area for their own intrinsic values.

4.2.4.1 Marina and canal development

Whilst there may have been very strong community support for the marina and there may be significant economic benefit arising from its construction and use there may well be downsides. There is considerable world wide evidence regarding the environmental disbenefits of marinas and canal developments. The proximity and sensitivity of the Bundegi Reef is apparent. The lack of understanding of sediment transport regimes in Exmouth Gulf, means that attention should also be payed to the potential for risk to the Ningaloo Reef. Calculations based on examination of the nautical charts appears to indicate a clockwise circulation in the Gulf - albeit at very low rates. Sediment does appear to have moved up the coast from the marina site toward the Bundegi Reef. Comments by the proponents that sediment is not moving along the coast are negated by their own design which suggests the natural development through time of pocket beaches at the junction of the existing natural beaches and the rock revetments.

Construction of the proposed Whitecrest Enterprises limestone loading facility or any similar structures required by the development of the southern limestone tenements will need to be carefully considered from the point of view of coastal processes.

We have severe reservations about the canal development proposal. We have not calculated gross or net movements of the tidal prism. This should be done rigorously. However, excavation into the rocks of the coastal plain can only exacerbate the extension of the seawater wedge into the freshwater aquifer if the Ghyben-Herzberg system is perturbed. D Lewis (1996c) claims that there is no evidence in the marina of freshwater incursion from the coastal plain into the marina nor can evidence of springs be seen at low tide along the beaches. Forth (1972) has estimated that the throughflow of the aquifer was about 460 m^3 per day per kilometre length of the Range. This water cannot simply disappear.

Possible contamination of the groundwater or sea by effluents from vessels in the marina do not appear to have been considered in any depth.

4.2.4.2 Subdivision proposals

Proposals for semi-urban (semi-rural?) subdivisions south of Exmouth appear to have a number of drawbacks. At least some of these proposals are directly on demonstrated karstic terrains containing large cavities as can be seen in the Dozer Cave collapse. Humphreys (pers. comm.) considers the area to have great importance for the stygofauna.

Engineering problems can be expected to be encountered with increasing frequency in these environments. Problems with absorption trenches from septic or similar systems have been alluded to below as have the downside of extensive trenching to provide deep sewage across wide areas. Increased water abstraction from private bores may lead to disturbance of the groundwater systems; the Water Corporation has moved from the northern part of its borefield at least partly from concerns arising from interactions with private bores. A hotch-potch of developments and businesses leading into Exmouth may also be a consideration.

4.2.4.3 Dune management

There are a number of instances where both coastal and desert dunes are eroding as a result of vehicular or other disturbance of the existing vegetative cover. Again this is a problem extending across a variety of tenures and there seems to be *ad hoc* access taking place. Once the cover is breached, erosion is virtually inevitable and costly to repair - especially on exposed coasts. Planning for the region should take account of the sensitivity of the dune systems; access should be carefully planned and the situation regularly monitored so that problems can be repaired before they become major issues

4.2.4.4 West coast developments

We understand that there are a very large number of development proposals for the west coast of the peninsula but we have no concrete details. We regard the west coast within the national park and north to Vlaming Head and North West Cape as an area which should see little or no infrastructural development to protect its scenic qualities and natural attributes. The Ningaloo Reef is a prized asset which will come under increasing pressure from both on- and off-shore activities. Many of the problems which have confronted the Great Barrier Reef Marine Park Authority such as damage from anchoring, antifouling paints, rubbish and other wastes can be expected to occur here. Ningaloo and Bundegi Reefs are far closer to the shoreline, and thus human activities, than the Great Barrier Reef.

4.2.5 Municipal operations

The Exmouth Shire Council is in a difficult situation in that it must provide a full range of municipal functions at a very great distance from suppliers and with a very restricted rates base. The problem is further compounded by the seasonal pressures of tourism, by the large areas of Defence and protected lands and by the environmental setting. However, the Council is responsible for the management of lands with very significant natural and cultural heritage values.

Municipal rubbish landfill

The burning-off of tips appears to be a great Australian tradition and some reasons for the practice are relatively obvious. These include reduction in volume and the oxidation of putrescible waste - if enough dry fuel is available to fully support combustion. However, there are substantial downsides to landfill burning.

The first, and most obvious at this site is the reduction in visual amenity produced by continual, oily (as a result of incomplete combustion) smoke. The second is the release into the atmosphere and, potentially, into the groundwater of various chemical compounds (including such things as dioxins) that arise from the incomplete combustion. These may be more toxic than the original materials. We believe that firing of municipal tips in Western Australia is not permitted and accordingly, this practice should cease.

It is clear that the tractor available at the landfill is too small to cope adequately with landfill management generally including such matters as compaction and the covering of wastes with soil. Presumably the Department of Defence bases are using the municipal landfill site and they may be able to make heavier machinery available on a *quid pro quo* basis to enable better landfill management.

We understand that the licensing of landfill sites was introduced in October 1996. General guidelines for landfills and a code of practice for country landfills both exist and that specific guidelines for the Exmouth site will be developed shortly. These would address the issues of burning, day to day compaction and covering of putrescible wastes and, importantly, establish protocols for the monitoring of groundwater conditions around the site. Guidelines for the dumping of vehicles should be introduced which specify the removal of fuel, lubricating and hydraulic fluids.

Clearly, considering the distances involved, recycling will be considered an expensive option. But, the tiny resort of Lord Howe Island, more than 700 miles from Sydney and with a population of under 300 permanent residents and up to 1200 tourists has been forced to adopt stringent recycling procedures as there is no land available for landfill. The success of recycling here could be taken as a model; the issue should not be beyond the resources of Western Australia. White goods, vehicles and bottles are items which might usefully be returned to Perth. Can the large quantities of fish heads and offal be incorporated in fish meals if these are being produced in the local fisheries plants? There is considerable scope for 'thinking globally, acting locally' here.

Other municipal functions

Unfortunately the supervisor of the Water Corporation sewage treatment works was not available at the time of our visit and although we were able to inspect the plant we were not able to gather information on the operational details. We gather that the plant is operating successfully.

We recommend extension of the deep sewerage system to the remainder of the Exmouth township. The question of sewering the rural subdivisions is problematic. On one hand there is the need to protect the groundwater and this is best done through the provision of a professionally operated, centralised system. However, the environmental impacts consequent on trenching across many kilometres of karstic terrain must also be taken into consideration.

4.2.6 Regional issues

There are a number of issues which arose during our visit which have region-wide contexts but which are relatively non-specific.

4.2.6.1 Regional aesthetics

We have referred to the visual impacts of smoke and dust from the landfill and drilling operations and the potential of unappealing limestone stockpiles. However, there are very many other visual scars on the landscape. Clearly the multitude of communication towers must be lived with (although it is interesting how non-intrusive they are unless one is very close to the installations). There are many other man-made intrusions on the various viewscapes. These include inappropriately sited and perhaps not needed vehicular tracks, borrow pits in the desert dunes, various breaches of coastal dune systems and the siting of new developments such as that appearing on the hilltop adjacent to the Lighthouse Caravan Park.

Many of the developments and infrastructure on the coastal plains are camouflaged or dwarfed by the 'strong horizontal component' of this part of the landscape. However, the situation is radically different when one looks down on the plains from the Range itself. The road along the west coast with the various offshoots to the minor camping areas within the national park provide a fine example of sore thumbs. It is possible to construct facilities which 'disappear' into the setting as the park visitor centre and nearby staff accommodation demonstrate.

The apparent inevitability of further hydrocarbon exploration and possible exploitation will increase water demands, contamination possibilities and visual impacts as well as introducing a whole range of potential engineering problems. Again this points to the need for comprehensive regional planning which may well need to be proscriptive as well as prescriptive.

We believe strongly that the sensitive and unique environment of the Cape Range peninsula is not an appropriate location for any large-scale onshore developments based on the North West Shelf hydrocarbon prospects.

4.2.6.2 Cave use management

Webb (1995) has produced a masterly summary of the cave management problems at Cape Range from the use perspective. He identifies a variety of questions including:

- current visitor regimes
- visitor safety including liability issues
- cave conservation including a review of damage already evident
- access and tenure problems
- the need for permanent anchors and similar devices.

Webb provides a series of recommendations for the management of cave use with which we mainly concur. We are bitterly aware, from many sites in New South Wales, Victoria and south west Western Australia, as examples, of the difficulties in reining in unfettered cave use once use patterns become entrenched and suggest that Webb's recommendations be implemented by the relevant authorities as a matter of priority.

4.2.6.3 Scientific research and environmental assessment

We have emphasised the need for further research in many disciplines throughout this report. However, science itself can have environmental impact and there is a need to consider these.

Many of the projects or issues we inspected or have read about have been the subject of various forms of environmental assessment and review. These studies have been of variable quality. There are several matters that merit the attention of those charged with the supervision of the environmental assessment process. Firstly, in an arid, karstic area where the landscape and its contents are more than usually driven by geomorphic processes there has been a real paucity of professional geomorphic input to environmental assessment. Secondly, there appears to be a piecemeal approach toward resource, urban and tourism development. The virtual superimposition of marina development, rural subdivision and transport routes are but one example.

5. TOWARDS POLICY AND MANAGEMENT

5.1 THE POLICY CONTEXT

In discussing how land management policies might best respond to the issues and problems posed by the Cape Range Karst, it must be recognised that :

- although there are well-developed bodies of policies and practices relating to karst management, including the recently published IUCN guidelines (Watson et al., 1997), these cannot provide a recipe which might be applied unthinkingly to Cape Range; rather they must be adapted to fit the quite remarkable and probably unique configuration of the area (see Section 3 above).
- as so often happens, and despite the considerable body of research already carried out at Cape Range (Humphreys 1993, 1994), there is a great deal not known, for instance, in respect to the dynamics of the watertable, the microclimatology of the caves or even the local distribution of anchialine fauna; this means that any planning policies should be conservative in nature, simply because the environmental impacts of mistakes will be difficult or perhaps impossible to correct.
- there are major issues confronting the Cape Range peninsula. We have emphasised that there are real and definable limits to development mainly arising from the limited water resources and from the capacity of the environment to absorb more development. Sea level rise consequent on global warming and possible changes in storm patterns and magnitude arising from climatic change are real issues as are associated implications for groundwater regimes.

There is, of course, a body of existing planning policy already in place and a great number of land management decisions which have already been made. In so far as we have been able to grasp the current policies and practices, we will position our recommendations within this context, both supporting many existing decisions and proposing changes in others.

In particular, we have recognised and considered the directions determined or proposed by:

- Legislative Council Select Committee report on Cape Range National Park and Ningaloo Marine Park (Dec 1995)
- Gascoyne Coast Regional Strategy (Mar 1996)
- Cape Range National Park Management Plan (1987-1997)
- Ningaloo Marine Park Management Plan (1989-1999)
- North-west Cape Tourism Development Study. Report by Jones, Lang Wootton for the Department of Resources Development (1993)

5.2 SIGNIFICANCE AND BASIC APPROACH

We start with the most basic of all policy considerations, namely, the significance of the Cape Range sub-region. It is a matter of real concern that despite all available evidence and the current protected status of much of the area, the importance of the area is still being questioned by many individuals and organisations. Our own field investigation, limited as it was, only served to convince us that, if anything, the significance of the area has been under-estimated. It would be of **world significance** even if there was no subterranean fauna; given the existence of the fauna, it can only be rated **as one of the more significant natural heritage areas of the world**.

Its unique character and quality should be a matter of pride for all Western Australians; not a matter of debate.

Recommendation 1

The State Government should recognise and accept fully that the Cape Range sub-region is one of the state's most significant natural resources and must be afforded maximum protection.

Recommendation 2

Given the demonstrated international significance of the area, the necessary processes should be set in motion to fully evaluate the extent to which the area meets the formal criteria for World Heritage status and then proceed to nomination of suitable boundaries as an appropriate response to the already established significance of the area.

Recommendation 3

There should be a formal program of cultural heritage documentation and development of conservation plans in line with the guidelines laid down in the Burra charter.

There is also a decision to be made (see Select Committee Recommendation 24) as to whether the Shire of Exmouth boundaries should be extended to include Coral Bay, currently within the Shire of Carnarvon. This would provide for more integrated management of the sub-region; but it may be that this integration can be adequately carried through by the Gascoyne Development Commission?

The Legislative Council Select Committee has already recognised (Recommendation 1) the consequent need for limitations on development. We essentially repeat their recommendation:

Recommendation 4

Any further housing or accommodation facilities in the Cape Range sub-region must be consistent with conservation management strategies for both the terrestrial and marine environment, so that any construction activities do not impact adversely upon significant environmental features nor the ambience of the surrounding topography.

Recommendation 5

Visual impacts of developments must be considered as part of the development approval process.

If these are adopted, then there must be not only a number of policies directed towards the limitation of impacts, but also policies which effectively limit both physical development and population growth. We turn to these below.

Because of the many and varied land uses, past and present, there is a need to better document potential pollution sources and the geomorphic capability of the region. A geomorphic evaluation and mapping program similar to that which produced the Yanchep 1:50,000 Environmental Geology sheet would provide a valuable framework for the planning of the future of the peninsula. This would provide a base for an inventory of potential groundwater contamination sources such as has been produced by Hirschberg (1991) for the Perth Basin.

Recommendation 6

A project to map and evaluate both the geomorphic capability and potential pollution sources should be initiated without delay.

5.3 INTEGRITY OF THE KARST

5.3.1 The waters of the system

The central problem, as already outlined above, is to maintain the integrity of the karst as a dynamic system. Most centrally, this must be approached through management of the total water resource and regime, although any activity that has a destructive impact upon the rock and soils of the area must also be extremely carefully managed.

The management of water resources is not just a matter of limiting extraction to a sustainable level, but also maintaining the health of the aquifer, particularly water quality and the relationship between fresh groundwater and seawater. Maintenance of recharge has both quantitative and qualitative aspects.

In order to achieve this, there must be co-ordination between the management of the main Exmouth borefield, the RAN and RAAF borefields as well as those of pastoral, commercial and private enterprises. The responsible authorities are well aware of the need for this, and have been making progress in negotiations to bring this about.

We understand that some bores, particularly in the RAN borefields, have already suffered from excessive extraction and a moratorium on pumping from any such bores should be declared until the water quality is restored.

We also recognise that the excellent work being done by the Water Corporation on monitoring the aquifer must be maintained and extended. A better knowledge of aquifer behaviour is essential to sound management.

Recommendation 7

Water extraction must be maintained at a sustainable level congruent with both providing a high quality supply of freshwater and maintaining the spectrum within the anchialine zone.

Recommendation 8

The Water and Rivers Commisssion should ensure co-ordinated management of all groundwater extraction in the area, including that by the Department of Defence.

Recommendation 9

If ground waters are to be extracted for quarrying operations, the operation of any bores should be under the direct control of the Water and Rivers Commission.

Recommendation 10

Investigations of site conditions for quarries or other major ground disturbance developments on the peninsula should include investigations of water flow dynamics above the watertable. Such investigations should include hydraulic conductivity deteminations.

The very constrained sustainable water supply represents the greatest limitation upon development. More effective use policies (see below) can make a significant contribution to easing this problem, but the bottom line is that there will probably never be a water supply adequate to maintain a large increase in either resident or visitor population. Even desalination is not currently a viable option because of cost, the ultimate problem of salt disposal and other issues. Moreover, increases in local population that desalination might make possible would be likely to greatly escalate other environmental problems in the area. In fact, this means that any increase in the resident population will ultimately come to represent a major constraint on the expansion of tourism and expansion of either, or perhaps even both, must be limited.

Recommendation 11

Serious consideration should be given to limiting either the expansion of residential population, any increase in tourism numbers, or both.

Recommendation 12

A program of detailed planning and zoning for the management of the west coast, including the fringing reefs, should be undertaken as soon as possible.

The 'oasis' syndrome, which characterises many human settlements in tropical regions, results in an excessive and unnecessary demand upon water resources. Residents and tourism operators should be encouraged to use desert species (desirably local species) in all gardens; to use low-consumption plumbing fittings and water-use behaviour at all times. Council should take a lead role in such behaviour.

As a relatively minor aspect of this, we were shocked to find that resorts paid less attention (that is, none whatsoever) to excessive water consumption than is now usual in Melbourne or Sydney hotels.

Recommendation 13

Public education and other strategies should be established to achieve reduced use of water throughout the sub-region.

5.3.2 Issues of pollution

Even if the water problem were solved by some means not known to us today, this would not in itself enable further population expansion due in part to the related problems of increased waste disposal and pollution control. More to the point, much more attention must be paid to this issue at the present time.

To both protect water quality and ensure the survival of the remarkable fauna of the area, prevention of contamination is essential. Humphreys (1994) has discussed the various sources of pollution in some detail, and we do not see any need to repeat this very thorough review. However, there are various recommendations which must be made, and all of these deal essentially with the impacts of human population and activity.

Waste disposal and other practices, including the use of artificial fertilisers, must be reviewed to minimise contamination. The karst areas principle that 'What goes down must come up' must be made widely known and recognised as the basis for the prevention of pollution. In particular, cognisance must be taken of the extent to which entry of untreated human wastes into the aquifer represents both a damaging environmental impact and a major public health hazard.

Recommendation 14

Pollution of the aquifer must be minimised, even when it may occur on only a localised basis.

Recommendation 15

Detailed environmental investigations of the southern limestone tenements should be appropriately funded and commenced as soon as possible.

Recommendation 16

The Departments of Minerals and Energy and Environmental Protection and the Water and Rivers Commission should develop and enforce specific guidelines for the environmental management and decommissioning of borrowpits, quarries and open cut mines in karstic terrains.

This in turn must include policies directed to specific sources of pollution.

Recommendation 17

Any significant existing or new human settlement, even on the coast, should be required to install sewerage or other appropriate waste disposal systems which will prevent water pollution from human wastes.

Any constructional activity, whether roads, dwellings and other buildings, car parks, etc. serve to divert water from some areas and concentrate run-off in others. This has significant impact upon the distribution and quality of recharge to the aquifer. Although most important in relation to bituminised roads or other sealed areas, even compaction and the consequent drainage from gravel roads or other compacted soils leads to concentration of run-off into defined channels. These channels should be fitted with traps to minimise entry of pollutants and where possible, run-off should be diverted into soakage areas to reduce concentration of drainage. This is particularly important in close proximity to constructional activity.

Recommendation 18

Any paving of roads or other areas or construction of buildings should be carried out in a way which recognises the impact of such areas upon entry of stormwater to the aquifer and minimises both channelling and pollution effects.

Recommendation 19

Any extractive industry (particularly quarrying) must prevent any spillage of hydrocarbons and must utilise traps on any run-off sites to restrict the entry of silt or other pollutants, including liquids, to the aquifer.

Recommendation 20

Public education and other strategies should be established to achieve a reduction in household pollution, including minimising spillage or un-necessary use of hydrocarbons and other inappropriate chemicals, particularly insecticides and artificial fertilisers.

Recommendation 21

An aggressive waste reduction campaign should be initiated together with a recycling program.

Finally, we again emphasise that maintaining the integrity of the karst, especially through proper management of the aquifer, is not just important in terms of the well-being of the troglobitic fauna; it is fundamental to sound planning for human settlement and tourism. We will turn below to further issues in karst integrity while dealing with some specific areas of human activity within the sub-region.

5.4 CONSTRUCTIONAL AND INDUSTRIAL ACTIVITY

Quarrying, other industrial development and further developmental construction are currently planned to occur within the sub-region. Although the very occurrence of these activities may be totally undesirable from an environmental protection perspective, it appears to be inevitable, and so should be carried out in a way which minimises undesirable impacts. We note the emphasis on this issue in the Gascoyne Coast Regional Strategy and reinforce their caution.

We are obviously aware of the requirement for environmental impact studies of major projects. However, the quality of these is often questionable. For example, we have noted above the very scant regard paid to geomorphic issues and geoconservation generally. So, unless there is adequate review of such studies, they become a mere token to environmental protection and this is not acceptable in an area of such international significance as Cape Range. We recognise this is problematic for both the Exmouth Shire Council and the Environment Protection Authority, but ways must be found to ensure that development proposals are subjected to adequate review before granting approval.

Recommendation 22

In planning and evaluating proposed developmental activities in the area, professional expertise in karst geomorphology should be involved as early as possible. Geoheritage and geoconservation considerations should be properly taken into account as an integral part of any evaluation.

Recommendation 23

Resources must be provided for adequate review and assessment of any environmental impact studies of developmental projects.

We are concerned to see that the eastern coastal plain has been assessed as being of only moderate environmental sensitivity (Gascoyne Coast Regional Strategy, 1996:52-53). This is a demonstrable oversimplification.

This coastal plain is a major area of water mixing; the relatively fresh groundwater merges here with the seawater, and a spectrum of varying degrees of salinity results which is fundamental to the survival of the troglobitic fauna and the overall integrity of the total karst system. Even local pollution might have dramatic and disastrous impacts.

However, the stability of the land is also in question, and this has already been noted by the Gascoyne Coast Regional Strategy. The existence of Dozer Cave is likely to be the tip of an invisible iceberg. Continuing exploitation of the coastal plain will gradually but inexorably increase the likelihood of further such collapses. Experience in other karstic settings, e.g. Florida, Kentucky and South Africa, has already demonstrated the potential losses in both collapse of valuable constructions and human life. Every effort should be made to limit and confine developmental activity on this land; to carry out appropriate land capability assessment before approving developments and to ensure minimal impact design.

Recommendation 24

The sensitivity of the coastal plain must be reassessed, given that it is a key zone within the groundwater system and will be subject to structural instability, but at the same time, will be subject to continuing pressures from development.

Although consideration of the Ningaloo Marine Park was not specifically written into our brief, and we have not had the opportunity to examine it in any depth, the concept of the total sub-region as an integrated system means we cannot avoid dealing with at least the shore-based impacts upon it. We note and agree very strongly with the very heavy emphasis of the Select Committee on the protection of the Reef. In particular, it is located very close to the shore-line and so any shore-based threats are likely to be much more significant than in the case of the Great Barrier Reef (where great attention is paid to the possible impacts of coastal developments). Again, in addition to any consideration of the intrinsic values of the reef system, this has fundamental implications for the sustainability of the tourism industry.

Simple observation suggests that the construction of the Exmouth marina may be leading to silt deposition on the Bundegi reef; it is inexcusable that this possibility has apparently not been considered in advance, and monitoring established to assess possible impacts upon the health of the reef.

We note that the EPA has already recognised the existing nutrient management problem emanating from the Coral Bay townsite and potentially impacting upon the Ningaloo reef and will be attending to its resolution as a matter of urgency.

We also question, from the world experience of impacts resulting from marina construction, whether any further such projects should be allowed within a distance which would risk impact upon any part of the Ningaloo Marine Park.

Recommendation 25

The impact of any shore-based activity upon the continuing health of the Ningaloo and Bundegi Reef systems must be carefully considered and protective action taken where necessary.

5.5 ISSUES RELATING TO PROTECTED AREA MANAGEMENT

We note that much of the peninsula already has protected area status. Given the value and significance of the sub-region, this is entirely appropriate. The Select Committee recommended extension of the Cape Range National Park to the east and south, and argued that CALM should manage a coastal strip along the west Coast adjoining the Ningaloo Marine Park. The Gascoyne Coast Regional Strategy also supports these extensions. Given the nature of karst, we do not believe that management of a coastal strip would be of significant value without managing the hinterland also; thus we would argue simply for maximum extension of the National Park.

We strongly support the proposed extensions of the existing protected areas, particularly east of Cape Range National Park. However, we would argue additionally that an extension to the north is necessary, given that this has a distinct species assemblage. We understand the feelings behind the 'Desert Museum' proposal and strongly support better management and interpretation of the areas north of the existing Park. However, we feel that national park or similar tenure is the better approach. The southern extensions are obviously desirable - but of lower priority.

Recommendation 26

Where the opportunity exists, the present Cape Range National Park should be extended, at the earliest possible date, to both the north and east of current boundaries and southwest coast as recommended by the Select Committee.

A number of surface activities may well prove to be quite in keeping with protection of some natural values. Thus, a properly planned and managed residential area may well be developed under some form of arrangement, perhaps comparable to that which prevails at Molloy Island (but with constraints matching the very different protection requirements at Cape Range). The Exmouth Shire Council and the Gascoyne Development Commission might play a key role in furthering discussions and negotiations between landholders and CALM in this matter.

Recommendation 27

Should it not be practicable to extend the National Park to the East Coast, or indeed to make other desirable extensions, then every effort should be made to negotiate a heritage agreement or other co-operative arrangement for protection of such areas.

The bottom line in any protected area management is the extent of resources available to the managing agency. We note and particularly support Recommendations 16-17 of the Select Committee. We also support their commendation of the co-operative program established by CALM in relation to whale shark viewing.

5.6 TOURISM DEVELOPMENT

It is clear that the demand for tourism access to the sub-region is increasing at a rapid rate, and that both consideration of environmental impacts and the current tourism infrastructure fail to match the demand. We note that the majority of visitors (84%) are holidaying in the region, and that over half (55% of all visitors) either camp or stay in a caravan park. This makes special demands of the infrastructure and has its own specific impacts upon the environment.

The North West Cape Tourism Development Study (Jones, Lang and Wootton, 1993) is a valuable analysis of the commercial pragmatics of tourism in the sub-region. However, it does not genuinely recognise and respond to the unique character of Cape Range. We believe the problems presented by tourism for protection of the karst can only be resolved by re-considering the nature of tourism on the Cape Range peninsula. It demands a very special kind of vision and imagination to maximise the relationship of the tourism industry to the sub-region.

We envisage the establishment of a Cape Range and Ningaloo Special Environmental Region (under whatever title). This would operate as a specialised tourist destination, with an emphasis on quality of experience rather than simple maximisation of visitor numbers. The unique character of the environment would be highlighted to all visitors, both in pre-publicity, in appropriate gateway signs and in local information and services.

Every effort would be made to ensure top quality experience for all visitors. This should provide a spectrum of infrastructure from (ultimately) five-star accommodation and service through to simple camping. But accommodation capacity should be limited to the present level of overall environmental impact or only slightly more. Under this scenario any expansion would only be permitted if it could be demonstrated that this would not lead to exceeding the sustainable level of water supply or the capacity for waste disposal and pollution control. Provided that environmentally sound development planning is carried out, many additional visitors would thus be accommodated off site, either at Coral Bay, Maud's Landing or a further accommodation complex on an appropriate inland site, and visit the peninsula on a daily basis. High quality nature-based tourism operators would be encouraged, and access to interesting sites would be enhanced.

Similarly, and without any on-site examination, we are very aware of the problematic nature of the currently underdeveloped infrastructure in the Coral Bay area and obviously, this must be dealt with.

At the same time, strict limits on informal camping would be observed. Activities which could equally well be carried out elsewhere would not be encouraged on the peninsula. Visitors would be encouraged to observe environmentally responsible behaviour and to share in protection of identified values.

Our recommendations here and in relation to protected area management assume this kind of framework. We also emphasise that this approach is not without precedent. Much Great Barrier Reef tourism occurs under similar controls; the well-known and rapidly growing Undara Resort and some others in North Queensland also do so. Local tour operators should be encouraged to establish linkages with the Savannah Guide Project of North Queensland and share in their quality development program.

We believe our arguments in this are congruent with the Gascoyne Coast Regional Strategy.

Recommendation 28

A process should be set in motion, probably under the leadership of the Gascoyne Development Commission, to examine the potential for creation of a Cape Range and Ningaloo Special Environmental Region for purposes of tourism development and management (as outlined above) and if possible, co-operative arrangements should be put in place to implement this approach.

Recommendation 29

Tourism accommodation capacity should only be increased when it can be demonstrated that this would not lead to exceeding the sustainable level of water supply or the capacity for waste disposal and pollution control.

Recommendation 30

All existing tourist resort developments should be encouraged to reduce the environmental impact of their operation and to upgrade the quality of accommodation and visitor services offered.

A quite specific group of recreational visitors to the karst are those who visit the caves. A series of proposals in this regard have been formulated by Webb (1995) and we see no need to comment further, but do draw attention to the importance of managing this growing activity so as to minimise any undesirable impacts and maximise its educational potential.

Recommendation 31

Guidelines for the use of caves by all classes of visitors on public lands must be produced and the use of caves effectively managed.

5.7 ISSUES RELATING TO ABORIGINAL HERITAGE

Regrettably, the Jinigudira culture has all but disappeared. In our view, this does not lessen but rather strengthens the case for proper stewardship of the remaining evidence of their lifestyle.

It appears to have been assumed, even by Morse (1993), that Aboriginal occupation of the peninsula, other than along the Western shoreline, was sparse and occasional. This is perhaps due, at least in part, to the traditional archaeological dependence on stratified sites. We believe this cannot be assumed. The presence of bailer shell fragments in caves on the Range, the ready availability of good quality chert (at least some of which has been quarried) on the top of the Range, ready availability of comfortable camp sites, and the existence of a full spectrum of art forms in caves and shelters on the Range all point to considerable habitation. The use of bailer shells indicate that, like the early Aboriginal people throughout Australia, at least the earlier Aboriginal settlers were able and willing to enter caves in order to exploit water or other resources in this way.

We recognise that archaeological expertise is a scarce commodity when assessed alongside of the number of potential sites demanding investigation. Thus, first priority must be given to sites or potential sites which are threatened by any changes. Given this :

Recommendation 32

Any future investigation of a site for Environment Impact Analysis must assume the likelihood of Aboriginal occupation, and hence give thorough attention to the search for

and assessment of potential Aboriginal sites, and any such investigation should include the caves as well as the surface.

The Aboriginal Heritage Act of 1972 demands that any sites must be reported to the Registrar and that anyone who without authorisation 'destroys, damages, conceals or in any way alters any Aboriginal site' is guilty of an offence under the Act. It also provides for the declaration of protected areas under the act.

Recommendation 33

A continuing inventory of all identified aboriginal sites should be developed ; these should be reported to the Registrar, and where appropriate, the Registrar should be asked to consider the declaration of protected areas.

5.8 CONTINUING KNOWLEDGE DEVELOPMENT

Knowledge of the Cape Range karst is growing rapidly. The Western Australian Museum has taken the lead in this, and in doing so has developed excellent co-operative arrangements with a number of institutions and departments. It is clear that there are so many avenues for further research that this growth in understanding will continue long into the foreseeable future. The question must be raised as to whether it is time to further develop this program through the establishment of a Co-operative Centre for Cape Range Studies. The lead in this should probably remain with the Museum for the time being, but a structure established which includes the universities and other research groups in an integrated program. One test of such a proposal is clearly the extent to which it might serve to attract further resources for research within the sub-region (See the Select Committee Recommendation 13, where this responsibility is located only with CALM).

Recommendation 34

The feasibility and possible administrative arrangements for a Co-operative Centre for Cape Range Studies should be investigated, and if appropriate, such a centre should be established.

Many of our recommendations above imply or specifically refer to the need for monitoring. Environmental and social monitoring probably demands an integrated program, even though much of the actual work must remain with those agencies (e.g., the Water Corporation) who have the appropriate expertise and other resources. The only fully integrated program of this kind currently operating in Australia is that at Jenolan Caves in New South Wales, based in the Visitor Impact Management (VIM) model of Graefe et al. (1990). Further such programs are currently being developed by the Australian Alps Liaison Committee and the New South Wales National Parks and Wildlife Service. We note that a program of this kind has already been proposed by both the Select Committee (Recommendations 12a, b) and the Gascoyne Coast Regional Strategy.

Recommendation 35

The establishment of an overall program of environmental and social monitoring should be further examined to ensure that monitoring is comprehensive, integrated and relevant to management requirements.

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APPENDIX 1.

BRIEF RESUMES OF THE AUTHORS

All three authors have been foundation members and officers of the Australasian Cave and Karst Management Association Inc. This Association has provided an important professional development network for karst management in Australasia and South-east Asia. All three were members of the small group invited to develop and write a guidelines publication on Cave and Karst Management for the International Union for the Conservation of Nature. Similarly, all three have experienced working on the development or assessment of nominations for World Heritage Status.

Professor Elery Hamilton-Smith

Member, IUCN World Commission on Protected Areas; Chairman, IUCN Working Group on Cave and Karst Protection; Member IUCN Committee on Collaborative Management; Member, Melbourne Parks and Waterways Advisory Council (1992-1995); Chairperson, Planning Committee, Centennial Park and Moore Park Trust, Sydney; Chairman, Social and Environmental Monitoring Committee, Jenolan Caves Trust.

Extensive experience in all aspects of Speleology; Member or Honorary Member of speleological organisations throughout the world; Leader of speleological and biological expeditions to many parts of Australia and the Pacific region; has studied cave management and tourism throughout the world.

Offices held include President, Australian Speleological Federation; Honorary Associate in Zoology, South Australian Museum; Editor, Australian Bat Research News for CSIRO Division of Wildlife Research; Foundation member of Council, International Union of Speleology; Convenor, Australasian Commission on Cave Tourism and Management; Member, Editorial Board, International Journal of Speleology; Executive Officer, Australasian Cave Management Association; Thomas Ramsay Scholar, Museum of Victoria.

Has been involved in preparation of management planning or other resources management projects in various karst regions, including Mt. Etna (Qld) Jenolan, Wellington (NSW); Naracoorte, Tantanoola, South-Eastern Region (SA); Nullarbor Plain, Yallingup (WA); Katherine (Northern Territory); Waitomo, Paparoa National Park (NZ), Batu Caves (Malaysia). Provided training programs in cave and karst management in all Australian States and in Thailand.

Has published several hundred research papers, books and reports in aspects of speleology or karst management. Most recently served as lead author, Guidelines for Cave and Karst Protection, for International Union for Conservation of Nature.

Dr Kevin Kiernan

Professional geomorphologist with many years experience in karst and karst management. Author of over 100 papers and articles; many of these are on aspects of karst science (geomorphology, hydrology, landscape evolution, archaeology).

First hand experience of caves and karst management issues from most Australian states, New Zealand, Nepal, China and Thailand. Earlier experience as a national park planner for the Tasmanian World Heritage Area and in a variety of other capacities and roles.

Previously a member of the International Geographical Union's Working Group on Man's Impact on Karst; recipient of the Australian Speleological Federation Inc's Edie Smith Award and national finalist in BHP's Bicentennial Pursuit of Excellence Awards.

Currently an Associate Member of the International Association of Hydrologist's Karst Commission; Corresponding Member of the International Union of Speleology Commission on Physical, Chemical and Hydrological Research in Karst and a Fellow of the Australasian Cave and Karst Management Association Inc.

Has worked in forestry industry for the last eight years, primarily on karst and related geomorphological issues, and currently as Senior Geomorphologist with the Forest Practices Board, Tasmania, and is an Honorary Research Associate of the University of Tasmania

Andy Spate

Has thirty five years of experience in many aspects of karst science and management. Author of over 100 papers, articles, environmental impact statements, plans of management and consultant reports dealing with karst matters, natural resource assessment and environmental management matters generally.

Appointed to the New South Wales National Parks and Wildlife Service in 1981 as the first professional karst manager in Australasia. For the decade prior to this he was with the CSIRO Division of Land Use Research undertaking research into various aspects of groundwater hydrology, soil/water relationships and into land renovation practices including mine site rehabilitation. During this period he was Environmental Adviser to the Department of Defence.

Previously Vice-President and President of the Australasian Cave and Karst Management Association Inc; currently Executive Officer. Fellow both of this association and of the Australasian Speleological Federation Inc. Has conducted training courses for cave guides, rangers and other karst management professionals in all states of Australia. He has also participated in management planning activities and heritage assessments in all Australian states.

Member, Social and Environmental Monitoring Committee, Jenolan Caves Trust; Member, Jenolan Caves Scientific Advisory Committee; Member, Wee Jasper Caves Trust; Member, Wellington Caves Advisory Committee; former Member, Lord Howe Island Board.

APPENDIX 2.

GLOSSARY

aeolianite : Limestone which results from consolidation of wind-blown calcareous sand
allogenic: Generated elsewhere and transported to the current location.
anastomosing: Branching, braided, interlacing, intercommunicating thereby producing a three-dimensional netlike or braided appearance. Hence **anastomoses.**
anchialine: Relating to that groundwater zone in coastal regions where mixing occurs between fresh and salt water.
anticline: A fold in rock which is convex upward.
autogenic: Generated at the current location.
calcarenite: A limestone composed of coral or shell sand or of sand derived from the erosion of older limestones.
calcirudite: A limestone made up of the broken or worn fragments of coral or shells with the interstices filled with calcite, sand or mud and with a calcareous cement.
calcsiltite: A limestone composed of calcareous sediments of silt size.
Darcy's Law: A derived formula for the flow of fluids which assumes that flow is laminar, hence **Darcian flow** is flow through homogeneous media.
detritus : Material produced by the disintegration and weathering of rocks that has been moved from its site of origin, hence **detrital**
diagenesis: Process involving physical and chemical changes in sediments after deposition that converts it into rock. Hence **diagenetic.**
doline : A closed depression, due to either collapse as a result of sub-surface solution, or solution from above.
eustatic: Pertaining to simultaneous, world-wide changes in sea level.
exsurgence: A spring fed entirely by percolation water and not by sinking streams.
facies: Part of a rock body as differentiated from other parts by appearance or composition - often as a result of changing depositional environments.
foraminifera: unicellular animals mostly of microscopic size that secrete skeletons made up of calcium carbonate.
foraminiferal calcarenite: A calcarenite made up largely of the skeletons of **foraminifera.**
grainstone : Rock made up of grains cemented to each other (cf. **packstone)**
interstratal: Between two beds or strata of rock
ionic strength effects : enhancement of the ability of water to dissolve calcium carbonate in the presence of large concentrations of other salts such as sodium chloride (e.g., in seawater)
karren: a term used to describe a range of small-scale limestone dissolution features on exposed surfaces; the nomenclature and classification of karren is complex.
macrocaverns : Voids in karst greater than 20 cm. in size
master cave: A low-level major streamway cave draining a large area which contains other smaller caves or sinking streams which contribute to its flow.
meteoric water: Water derived from the atmosphere.
mesocaverns : Voids in karst between 0.1 and 20 cm in size, often anastomosing
microcaverns : Voids in karst less than 0.1 cm in size

mixing corrosion: The solutional ability of water is enhanced when two bodies of water each saturated with respect to calcium carbonate but which had reached saturation under differing partial pressures of carbon dioxide. The resultant mixture is always under-saturated. This might occur when vertically moving percolation waters reach the watertable.
orogen: Belt of deformed rocks, hence **orogenic.**
packstone : Rock made up of grains cemented by fine material in the interstices (cf. **grainstone**)
palaeokarst : Former caves or former karst surfaces filled with sedimentary or other deposits and now exhumed by contemporary karst processes.
phreatic : Developed by solution below the water table.
protocave : The early stage of cave development, too small to be entered by man.
solution pipe : a generally circular tube extending downwards from the surface and resulting from solution of limestone.
speleothem : General term for all cave mineral deposits, including stalactites, flowstone, etc.
streamsink doline : A **doline** which provides for a surface stream to enter below ground.
stygofauna : Fauna living in groundwater.
travertine : Hard deposits of limestone deposited from flowing water, normally used for deposits outside of caves.
troglobitic : Fauna living permanently underground and generally beyond the daylight zone of a cave.
troglofauna : A general term for all cave fauna.
tufa : Soft porous form of travertine; plants or algae often play a role in deposition and hence contribute to the porous character of the deposit.
uvala : A closed depression with multiple dolines.
vadose : Referring to cave development which occurs above the water-table, usually due to erosion by running water.