Stygofauna Survey – Exmouth Cape Aquifer: Scoping Document Describing Work Required to Determine Ecological Water Requirements for the Exmouth Cape Aquifer

Prepared for
Department of Water

by Bennelongia Pty Ltd

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Report 2008/09

Stygofauna Survey – Exmouth Cape Aquifer: Scoping Document Describing Work Required to Determine Ecological Water Requirements for the Exmouth Cape Aquifer

Bennelongia Pty Ltd
64 Jersey Street
Jolimont WA 6913
www.bennelongia.com.au
ACN 124 110 167

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Executive Summary

Water resources on the Exmouth peninsula are very limited and future expansion of the Exmouth townsite will place considerable pressure on potable water supplies. The Exmouth aquifer, which underlies Cape Range and the adjacent coastal plains and extends from North-West Cape south to Yardie Creek, is the likely source of all future supplies. Significant abstraction already occurs around the Exmouth townsite, where the aquifer is locally over-allocated, which has the potential to impact adversely on conservation values.

The purpose of this document is to summarize what is known about the ecological (or conservation) values of the Exmouth aquifer and the steps necessary to protect them. These steps include identifying ecological management objectives, determining what additional studies are required to identify Environmental Water Requirements (EWRs), and outlining the major issues in designing a monitoring program to identify whether future EWRs are effectively protecting the ecological values on which they are based. EWRs represent the amount of water needed to maintain ecological values in their undisturbed state.

The most significant conservation values of the Exmouth aquifer relate to stygofauna. These are animals, mostly invertebrates, restricted to groundwater habitats. Western Australia is a global hotspot for the occurrence of stygofauna and 43 stygofaunal species, belonging to 12 major taxonomic groups, occur on the Exmouth peninsula. Nine of the 10 species occurring on the Exmouth peninsula and listed for protection under the *Wildlife Conservation Act* 1950 are found west of Cape Range. In contrast, the only listed species in the Water Corporation's Exmouth borefield for town water supply is the fish *Milyeringa veritas*, which occurs both sides of the range. Although based on inadequate survey, current information suggests nearly all species on the eastern side of the Cape Range are widespread and there are no sites on the eastern coastal plain of very high conservation significance.

Existing monitoring suggests that historical levels of pumping at the Water Corporation borefield have not adversely affected stygofauna, despite salinity having risen at times, but the level of information does not support firm conclusions.

There is currently insufficient information to develop ecological management objectives except at the broad level of committing to maintenance of groundwater conservation values and recognizing that stygofauna constitute the primary set of values. The studies necessary to identify EWRs will enable management objectives to be refined within Groundwater Sub-Areas. A broad framework for the development of EWRs on the eastern and western side of Cape Range is proposed.

The easiest method of calculating the EWR of an aquifer is as a fixed proportion of annual recharge. Based on current knowledge of stygofauna communities and their values, such an approach is likely to be satisfactory for the eastern Groundwater Sub-Areas (North, Town, Central, South) after additional investigations to confirm that current understanding of the conservation significance and distribution of the various groundwater communities is correct.

Most of the West Sub-Area is eventually expected to be World Heritage listed, with conservation being the focus of groundwater management. Studies into the effect of groundwater abstraction on local conservation values should be undertaken at all sites of existing and future abstraction.

Monitoring to determine whether EWRs are adequately protecting conservation values will be difficult because stygofauna present significant challenges for monitoring. The Exmouth peninsula is not a situation in which adaptive management, in the sense of reacting to monitoring feedback, will be easy and a precautionary approach to setting EWRs is required.

Monitoring of stygofauna themselves will require considerable sampling effort, although the pattern of sampling will depend on the availability of bores. Guidelines recommended by the Environmental Protection Authority for the sampling of stygofauna should be followed.

Contents

1.0 Introduction

The pressure on water supplies within the Exmouth Cape or peninsula (Fig. 1.1) was recognized more than 40 years ago when the Exmouth Groundwater Area was proclaimed in 1965, as part of Pilbara Groundwater Area, to provide a mechanism for regulating water allocations. In 1990, the Exmouth Groundwater Area (Fig. 1.2) was excised and transferred (as a Sub-Area) into the Gascoyne Groundwater Area.

Water resources on the Exmouth peninsula are very limited and the predicted continuing expansion of the Exmouth townsite will place considerable pressure on potable water supplies. In the early 1990s, private bores within the Exmouth townsite began to experience elevated salinities as a result of being pumped at a rate that was depleting fresh water and causing a local upwelling of saline water around bores. The salinities in many bores was sufficient to make water unsuitable for irrigation and a groundwater allocation plan was prepared for the Exmouth Groundwater Area in 1999 (WRC, 1999).

The objectives of the allocation plan were

- to recognize and protect the environmental values of groundwater [in the Sub-Area], thereby protecting the attendant beneficial (human) uses of groundwater for present and future generations

- to harvest water at sustainable level; to conserve and protect the long-term security of the groundwater resources in the region; and to ensure that the use of the resource benefits as many people as possible
- to ensure that, where possible, a reasonable quantity of water is available to existing enterprises dependent upon a continued supply of good quality groundwater
- to promote the allocation of the available water resource on a basis which provides the most beneficial use to the community
- to encourage efficiency in water use through improvements to methods of agriculture and irrigation and encourage development consistent with the regional planning and landuse objectives.

The above objectives of the 1999 groundwater allocation plan are generic in nature and did not highlight particular environmental concerns for the Exmouth aquifer, which most obviously include the occurrence of a significant community of stygofauna (Knott, 1993; Humphreys, 2001a). Stygofauna are animals that inhabit groundwater. Various terminology has been applied to describe the relationship between stygofaunal species and groundwater. The most common scheme is that stygoxenes are surface species that are facultative users of groundwater, stygophiles are species with most or some - usually larval - life stages completed in groundwater, and stygobionts are obligate users of groundwater throughout the life cycle. In this document, however, all species using groundwater will be referred to as stygofauna. The significance of the stygofauna occurring in the Exmouth peninsula will be discussed in more detail elsewhere but the peninsula (usually referred to as Cape Range in scientific publications), the Pilbara and the Yilgarn are either rich in stygofauna by international standards or support very significant communities (Humphreys ,2001a; Cooper et al., 2007; Eberhard et al., 2008).

Despite the generic nature of the objectives in the 1999 plan, it recognized that the Exmouth aquifer should be managed according to the principles of sound ecologically sustainable development and biodiversity protection, as outlined in a series of State and National agreements. The emergence of the National Water Initiative, which Western Australia signed on 6 April 2006, has led to a wider need for water allocation plans in Western Australia and, because the need for the environment to receive water must be explicitly included in these plans, has increased focus on Environmental Water Requirements (EWRs). The EWR of a system is defined by WRC (2000) as "the water regime needed to maintain ecological values of water dependent ecosystems at a low level of risk". Information on four topics is needed to determine the EWR of a groundwater system (modified from SKM, 2001). These are

- the key ecological attributes of the system that depend on groundwater
- the quantity and quality of groundwater required by the key ecological attributes
- the groundwater regime (temporal and spatial occurrence of groundwater) that provides the available water to the key ecological attributes in an appropriate way
- the impact of change in groundwater quantity, quality and regime on key ecological attributes and the ecological processes that support them.

The purpose of this document is to summarize what is currently known about the ecological values of groundwater in the Exmouth aquifer, identify ecological management objectives, determine what additional studies are required to identify EWRs for the aquifer, and outline the major components necessary for a monitoring program to identify whether the EWRs set are effectively protecting the ecological values on which they are based.

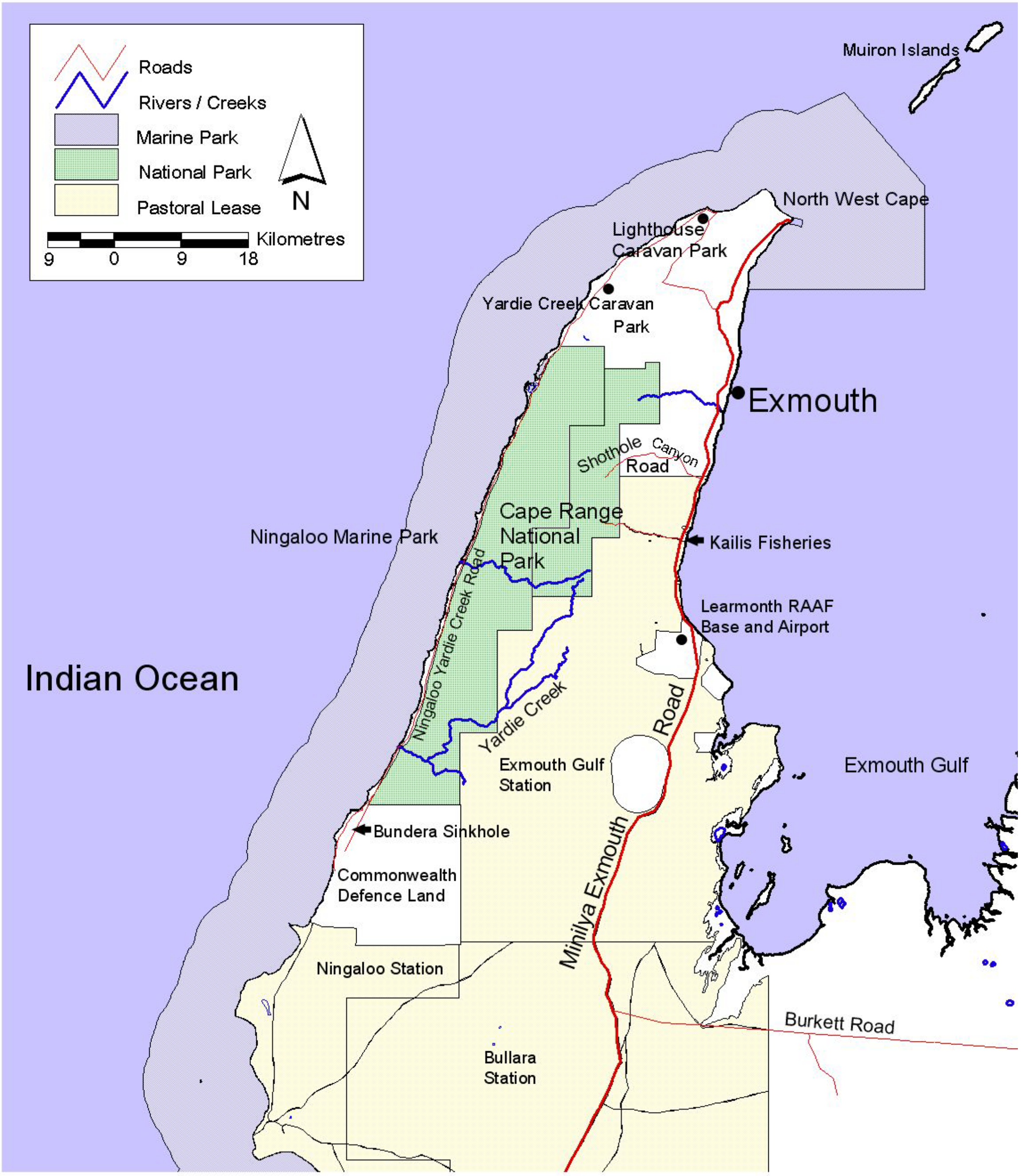


Fig. 1.1. Exmouth Cape or peninsula

Cape Range, Exmouth townsite and places of significance mentioned in text are shown

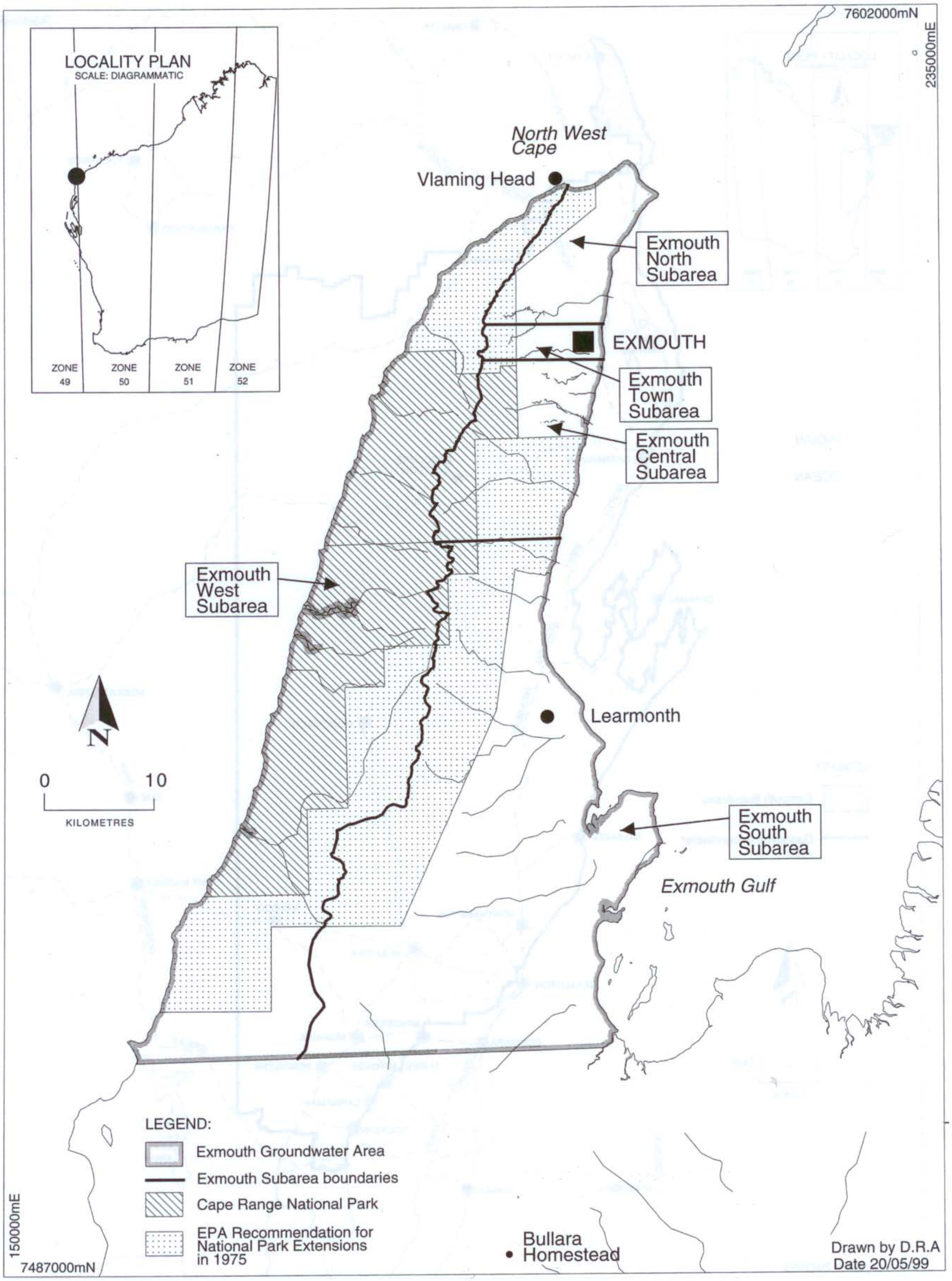


Fig. 1.2. Exmouth Groundwater Area
Groundwater sub-areas (from WRC, 1999) are shown

2.0 Exmouth peninsula setting

The Exmouth peninsula, containing Cape Range, is the westernmost part of Australia and has two significant marine features associated with it. Ningaloo Reef lies within a Marine Park on the western side of the peninsula and Exmouth Gulf forms a large, shallow embayment with important values as nursery habitat for fish on the eastern side.

Cape Range itself is a low limestone ridge (rising to 300 m ASL) that forms the spine of the peninsula. On either side of the Range (and geologically part of it) is coastal plain. The drainage system on the northern two-thirds of the Range is deeply incised. The southern third is partly buried under an extensive Pleistocene sand sheet (red-brown silty sand with seif dunes) and has less incised drainage. The sand sheet, as well as sandstone, occurs locally in northern parts of the Range.

The overall form of the Range is the result of intermittent uplift and changes in sea-level. A series of uplifts, caused by an underlying geological fault, have slowly raised the Range out of the sea since the Late Miocene/Pliocene (ca 10 Ma BP) (Allen, 1993). The history of these uplifts is visible in the terrace structure on the western side of the peninsula. Groundwater levels, and associated cave formation within the Range, have largely been controlled by sea level. During the last intergacial in the late Pleistocene (125 Ka BP) the ocean was 5-8 m higher than today. During the six subsequent climatic oscillations, sea level tended downwards until it was 130 m lower than today during the last glacial maximum (18 Ka BP). Since then sea level has steadily increased to the current height.

The terrace structures on the western side of Cape Range have considerable geological interest. The most recently formed terrace, Tantabiddi – formed during the last interglacial - makes up the current coastal plain on the western side of the peninsula. Except at the northern end where there is an extensive Tantabiddi terrace, the coastal plain of the eastern side of the peninsula consists of alluvial and coastal units, with strongly developed alluvial fans associated with drainage lines coming off the Range (Wyrwoll et al., 1993). The fans contain some calcrete.

In terms of groundwater study, the limestone systems of Cape Range and its coastal plain are important (Fig. 2.1). Three layers of limestone can be distinguished, although they intergrade. They are (from top to bottom)

- Trealla, which is 0-20 m thick near Exmouth, is transmissive and contains most of the accessible sinkholes and caves, i.e. large karst features
- Tulki, which is ca. 80 m thick, is transmissive and also has well developed karstic features, although lower sections are silty and less consolidated
- Mandu, which lacks karst and contains layers of marl-like calcareous sediment that act as barriers to water flow (or at least zones of low transmissivity).

More than 300 caves are known to occur within these limestone systems, with the most extensive caves occurring on the southern plateau of Cape Range. Wanderers Delight is the largest known cave system. Most caves within the Range itself are vertical solution pipes extending to a maximum depth of 90 m, any galleries are small and inaccessible, and the caves are dry. The caves on the coastal plain are partially or completely filled with water.

The very extensive karstification that created the caves probably commenced when the Range emerged from the ocean and a groundwater system became established within the permeable Trealla and Tulki Limestone. The relatively impermeable Mandu Limestone prevented caves extending deeper and caused galleries to form as dissolution moved laterally. During the late Pleistocene, when sea levels were very low, cave systems extended laterally towards the coast and offshore. More recently, as conditions became wetter and approached current climate, most of the cave systems in the upper parts of the Range were destroyed by headward erosion through the Trealla and Tulki Limestone to establish the present incised drainage system. Caves persisted only under the plateau remnants of the Range (mostly in the south) and within the coastal plain and offshore. Subsequently, a cave system has also developed in some coarse alluvium of the coastal plain (either relating to collapsed older systems or as a new system developed by the changed hydrological conditions) (Allen, 1993).

3.0 Groundwater

The Exmouth aquifer occupies the northern part of Exmouth peninsula, underlying Cape Range and the adjacent coastal plains and extending south to Yardie Creek. The aquifer is fresh (salinity < 1000 mg L^{-1}) under the central part of the Range and sits ca. 10 m above sea level. Groundwater extends to a depth much greater than 100 m below sea level (Fig. 2.1). Under the adjacent coastal plains, the depth of the freshwater aquifer is reduced and it is underlain by seawater in a Ghyben-Herzberg relationship (i.e. ratio of depth of freshwater above and below sea level is 1:40). Salinity of the 'freshwater lens' increases slightly close to the coast.

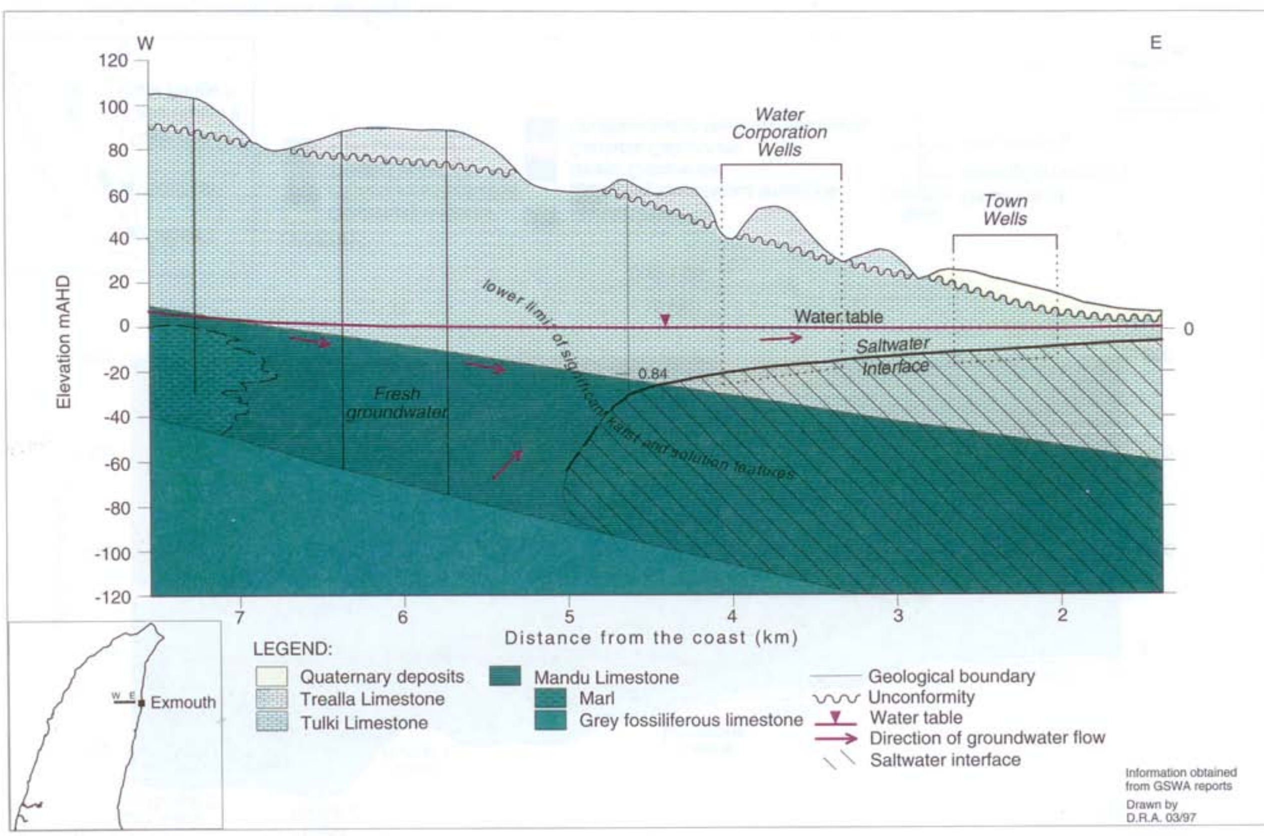


Fig. 2.1. Transect (west-east) across Exmouth peninsula

Taken near Exmouth township showing the geology and groundwater position (from WRC, 1999).

The stratigraphy of the regional aquifer is relatively well understood. It consists of a non-homogeneous karstic system with hydraulic continuity between elements, which are principally Mandu Limestone under the Range (with significant flow only in joints and minor permeable interbeds), Tulki Limestone on the flanks of the Range, and Pliocene-Recent sediments and/or Tulki Limestone on the coastal plain (Allen,1993). Groundwater flows both eastwards and westwards from under the Range. Flow is probably more rapid on coastal plain than within the range because of higher permeability in the cavernous Tulki Limestone/coastal plain sediments.

Recharge of the aquifer occurs mainly through direct infiltration after heavy rain. Considering the karstic nature of the aquifer on the coastal plain, most discharge may be through discrete sub-sea springs rather than diffuse oceanic discharge. Other known discharge points are the pools in Yardie Creek, which are maintained by discharge, and the permanent spring at the Tulki/Mandu Limestone boundary in the creek within Shothole Canyon. Through-flow in the aquifer on the eastern side of the Range is about 170 ML/km coast/year and may be as high as 300 ML/km coast/year in wet years.

Prior to development of the Water Corporation's borefield to supply water to Exmouth (Fig. 3.1), groundwater salinity was 400-600 mg L^{-1} TDS close to the Range on the eastern coastal plain. It increased towards the coast and the northern part of the Cape. Salinity increased with development of the borefield and, between 1982 and 1999, 60 % of bores within the borefield periodically produced water >1000 mg L^{-1} TDS although water has been fresher subsequently (e.g. KBR, 2005). South of the borefield, groundwater salinity is 500-700 mg L^{-1}.

Within the Exmouth townsite, where the freshwater lens is very thin, salinity has always been higher than in the borefield. Nevertheless, there are many small bores for domestic water supply and a substantial decline in water quality was experienced in the late 1980s. Thirty-three per cent of bores had salinities >2500 mg L^{-1} in 1988, 55 % in 1991, 63 % in 1992 and 81 % in 1993. While recognizing that abstraction from a thin aquifer is difficult, these salinity increases were triggered by poor design and/or over-abstraction in domestic bores. A subsequent education campaign has succeeded in reducing abstraction and lowering salinities. Current allocations for groundwater abstraction are summarized in Table 3.1.

Some caves within the Range lie above the regional watertable and occasionally contain pools as a result of the transient occurrence of local perched aquifers after rain. These small perched aquifers have little relevance to water supply schemes or the occurrence of stygofauna within the Exmouth peninsula.

Table 3.1. Estimates of groundwater availability and allocations in the Exmouth Groundwater Area

Allocation information for 1999 from WRC (1999) and 2008 from A. Maskew (pers. comm.)

Sub-Area	Estimated water available ML pa	Allocation 1999 %	Allocation 2008 %
West	Limited	?	42
North	200	129	118
Town	300	103	89
Central	1000	88	86
South	4700	3[1]	5
Total	6200	-	-

[1] A temporary allocation for upgrade of the Airport is excluded

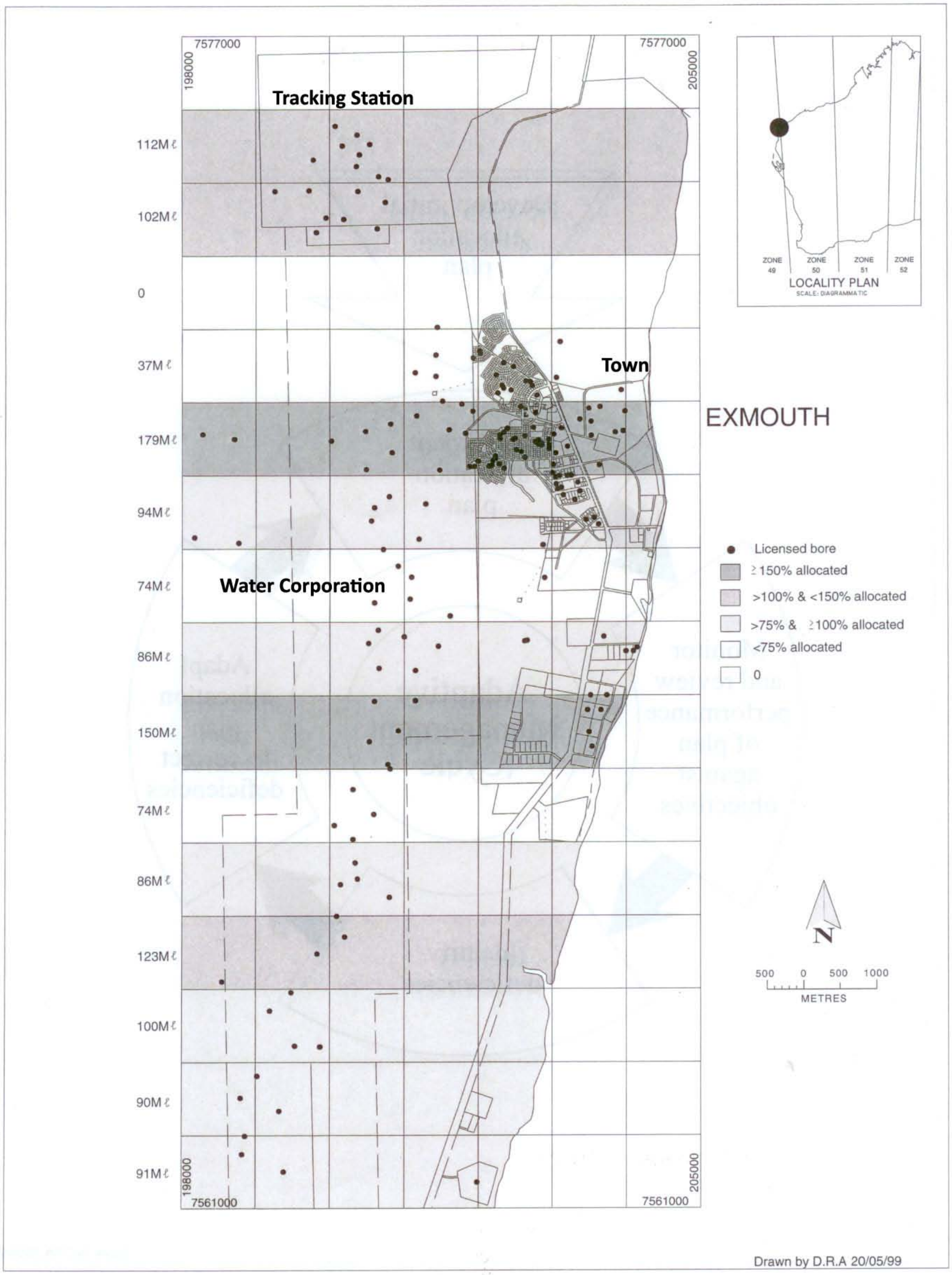


Fig. 3.1. Location of borefields on the eastern Exmouth peninsula

Major borefields are Tracking Station or Harold E. Holt base, Water Corporation and Town. Estimates of local water allocation as percentage of sustainable use are shown by shading (from WRC, 1999)

4.0 Key ecological attributes

Karsts on the Exmouth peninsula contain a rich community of subterranean fauna. The groundwater allocation plan (WRC, 1999) stated that Cape Range contains the richest and most diverse subterranean fauna community in Australia, and possibly the world, with 26 species of stygofauna and 41 species of troglofauna (air-breathing obligate subterranean animals) and other cave-inhabiting animals. More recent work has increased the number of known stygofauna species, which are the focus of this document, to 43 species belonging to 12 major taxonomic groups (Table 4.1). The habitat of the troglofauna in caves has existed on the crest of the Range in relatively unaltered form since the Range emerged from the sea in Late Miocene/early Pliocene. By contrast, the habitat of stygofauna in groundwater on the coastal plain has undergone substantial changes over the same time period in response to sea level changes and the continuing rise of the Range.

Planning for conservation and protection of Exmouth peninsula subterranean communities is based on the view that the ecosystem has international significance. It should be recognized, however, that despite the known number of subterranean species on the peninsula having increased over time, current information indicates the Range is not much richer in stygofauna than all other areas of Western Australia, as originally thought. Conversely, it has become increasingly clear that Western Australia as a whole has global importance for stygofauna. For example, about 500-550 stygofaunal species are estimated to occur in the Pilbara alone (Eberhard et al., 2007), whereas only 35 obligate stygofauna species are known from the United Kingdom (www.bcra.org.uk/biology/obligate.html) and about 600 across the United States (Culver & Sket, 2000).

While the comparative richness of the subterranean fauna on Exmouth peninsula may have been slightly over-stated in the past, because it was the first area studied intensively in Western Australia, the community retains outstanding biogeographic significance with a uniqueness that has been confirmed by the wider survey. This is reflected by the listing of 17 species (trogofauna as well as stygofauna) from the area under conservation legislation and the informal protection of 2 communities, with the consequent need to ensure their conservation in land and water planning (Table 4.2).

One of the 2 listed communities is troglofaunal rather than stygofaunal. There has been insufficient survey to assess the global importance of Western Australia for troglofauna, or to place the peninsula in a Western Australian context, although troglofauna are known to be abundant on Barrow Island and in the Pilbara (e.g. Biota, 2006a; Subterranean Ecology, 2007) and to occur in the Yilgarn (Biota, 2007; Bennelongia, unpubl. data). Like stygofauna, they have considerable conservation and scientific importance. However, the documented troglofaunal communities occur mostly within caves in the Range rather than on the coastal plain. Groundwater management will have little impact on these communities (even on the coastal plain, it will have much greater effects on stygofauna) so that troglofauna are not considered in this report.

4.1 Stygofauna species

The distribution of stygofauna on Cape Range is illustrated in maps within Appendix 1. The species with greatest conservation significance are the polychaete *Prionospio thalanji*, ostracod *Danielopolina kornickeri*, copepods *Speleophria bunderae*, *Stygiocyclopia australis* and *Bunderia misophaga*, amphipod *Liagoceradocus branchiali*, decapod *Stygiocaris lancifer,* remipede *Lasionectes exleyi* and the fish *Ophisternon candidum* and *Milyeringa veritas* (see Table 4.2). Conservation significance reflects a variety of factors including known distribution, perceived threats, taxonomic interest or uniqueness, and confidence in the available information. Thus, the blind gudgeon *M. veritas* (occurring from south of Yardie Creek to Exmouth and on Barrow Island) is considered to have higher conservation value than some apparently more restricted but poorly studied invertebrates (Appendix 1). All listed species are members of the Bundera: Cape Range Remipede Threatened Ecological Community.

Management of water abstraction in the Water Corporation borefield has been a focus of biological work but the only species that appears to be restricted to the vicinity of the borefield is the syncarid '*Australobathynella' sp. 7 'brooksi'* ms (collected by the Museum). The amphipod *Nedsia douglasi*, which is found in the borefield, occurs on the west coast as well (Barnard & Williams, 1995). There are references to the occurrence of other amphipods in Water Corporation monitoring reports but no information about what species may be involved. The isopod *Haptolana pholeta* and *Milyeringa veritas* both occur on Barrow Island (Bruce and Humphreys, 1993; Humphreys, 2001b). The thermosbaenacid *Halosbaena tulki* is widespread on the peninsula, on Barrow Island and in coastal parts of the Pilbara. Likewise, all copepods found in the borefield are relatively widespread species. Inference from Museum

Table 4.1. Stygofauna species collected from Exmouth peninsula

Species	Source[1]	Species	Source
Fish[2]		*Halicyclops spinifer*	1
Milyeringa veritas	1	*Metacyclops mortoni*	1
Ophisternon candidum	2,3	*Microcyclops varicans*	1
Oligochaete		*Nitokra fragilis*	1
Dero furcata	1	*Nitokra humphreysi*	1
Aktedrilus n. sp. 2 (WA18)	1	*Nitokra lacustris*	1
Pectinodrilus n. sp. 1 (WA19)	1	*Amphiascoides subdebilis*	1
Polychaete		*Onychocamptus bengalensis*	1
Prionospio thalanji	1	*Phyllopodopsyllus wellsi*	1
Sphaerosyllis centroamericana	1	**Syncarida**	1
Typosyllus (Ehlersia) cf. *broomensis*	1	'*Australobathynella*' sp. 7 '*brooksi*'	1,6
Crustacean		**Amphipoda**	
Remipede		*Elasmopus* ? *yunde*	1
Lasionectes exleyi	1	*Liagoceradocus branchialis*	1
Thermosbaenacid		Melitidae gen. nov.	1
Halosbaena tulki		*Nedsia douglasi*	1,7
Ostracoda		*Norcapensis mandibulis*	1
Candonopsis tenuis	1	*Psammogammarus/Victoriopisa* sp.	1
Phlyctenophora mesembria	1	**Isopoda**	
Danielopolina kornickeri	1	*Haptolana pholeta*	1,2
Copepoda		Philosciidae genus? sp. A	1
Bunderia misophaga	4	Philosciidae genus? sp. B	1
Stygocyclopia australis	1	**Decapoda**	
'*Styioridgewayia westaustraliensis*' ms	5	*Stygiocaris lancifera*	1,3
Speleophria bunderae	1	*Stygiocaris stylifera*	1,3,8
Apocyclops dengizicus	1	**Snail**	
Diacyclops humphreysi	1	*Iravadia* sp.	1
Halicyclops longifurcatus		*Melanoides* ? *tuberculata*	

[1] Source: 1 Western Australian Museum collection (source W.F. Humphreys); 2 Knott (1993); 3 Humphreys (2001b); 4 Tang et al. (2008); 5 Jaume & Humphreys (2001); 6 Goater (2007) as *Hexabathynella*; 7 Barnard & Williams (1995); 8 Holthuis (1960)

[2] the introduced fish *Poecilia reticulata* has been recorded on the eastern coastal plain

Table 4.2. Listed species and communities on Exmouth peninsula

Species listed as threatened under the *Wildlife Conservation Act* 1950 and communities signed off for informal listing by the Minister for Environment. Note that the Commonwealth *Environmental Protection and Biodiversity Conservation Act* 1999 provides formal protection for communities but the Exmouth communities are not listed

Species	Common name	Habit
Fish		
Ophisternon candidum	Blind Cave Eel	Stygofauna
Milyeringa veritas	Blind Gudgeon	Stygofauna
Polychaete		
Prionospia thalanji	(segmented worm)	Stygofauna
Millipede		
Stygiochiropus peculiarus	(millipede)	Troglofauna
Stygiochiropus sympatricus	(millipede)	Troglofauna
Arachnids		
Bamazomus subsolanus	Eastern Cape Range Bamazomus	Troglofauna
Bamazomus vespertinus	Western Cape Range Bamazomus	Troglofauna
Draculoides brooksi	Northern Cape Range Draculoides	Troglofauna
Draculoides julianneae	Western Cape Range Draculoides	Troglofauna
Hyella sp.	Camerons Cave pseudoscorpion	Troglofauna
Crustaceans		
Lasionectes exleyi	Cape Range Lasionectes (remipede)	Stygofauna
Liagoceradocus branchialis	Cape Range Liagoceradocus (amphipod)	Stygofauna
Danielopolina kornickeri	(ostracod)	Stygofauna
Bunderia misophaga	(copepod)	
Speleophria bunderae	(copepod)	Stygofauna
Stygiocyclopia australis	(copepod)	Stygofauna
Stygiocaris lancifera	Lance-beaked Cave Shrimp	Stygofauna

Community	Description
39. Camerons	Cameron's cave troglobitic community
41. Bundera	Cape Range remipede community

records is that the only ostracod in the borefield is *Phlyctenophora mesembria*, although confirmatory identifications are required (Table 4.1, Appendix 1K). The copepod '*Stygoridgewayia westaustraliensis*' ms (Tang et al., 2008) was apparently identified from the borefield only in samples from 2006 but is widespread and occurs across the Pilbara. The other known copepod species in the borefield (*Diacyclops humphreysi, Halicyclops spinifer, Apocyclops dengizicus, Nitocra lacustris*) also have distributions extending well beyond the Exmouth peninsula. It is possible other copepods also occur. Polychaetes and nematodes have been collected from the borefield but identifications are not available.

4.2 Stygofauna communities

The Bundera: Cape Range Remipede Threatened Ecological Community occurs at Bundera Sinkhole, south of Yardie Creek (see Appendix 1B). This is an anchialine environment, where fresh water overlays seawater in karst. It is well studied because it has a surface opening that allows access to divers. Similar environments must occur elsewhere on the west coast of the peninsula and a key management issue is locating these areas of anchialine karst.

Bundera Sinkhole has outstanding conservation value because it contains a specialised community of animals known elsewhere only from isolated parts of the Canary Islands and the Caribbean (see Humphreys, 2001b). It supports the only occurrence of remipede crustaceans outside the North Atlantic: this group of animals was discovered only 30 years ago and has substantial scientific value. The Sinkhole extends down about 30 m through a freshwater lens and into seawater with some animals (like the remipede) restricted to seawater, some occurring only in upper freshwater parts of the system and other animals (like the gudgeon *Milyeringa veritas*), found throughout the system. The principal management measures required for its protection are likely to be

- maintenance of an undisturbed water regime
- prevention of physical disturbance and mixing of the water column.

The stygofauna community occurring in the Exmouth borefield is not particularly rich and, unlike the anchialine community, does not contain species of great scientific interest. In terms of its composition, the community is widespread and similar to that found on the coastal plain of the Pilbara (Halse et al., in prep). In some cases the species occurring in the borefield are those of the Pilbara community [e.g. *Halosbaena tulki*, various copepods including '*Stygioridewayii westraliensis*' ms (Tang at al., 2008), *Diacyclops humphreysi* and *Halicyclops* spp.] or are very closely related (e.g. *Nedsia*, *Haptolana*). Thus, the need for protection is less than for the anchialine community. Nevertheless, the borefield community warrants protection in its own right, as well as because it is part of the more significant stygofaunal community of the peninsula as a whole.

4.3 Genetic investigations

Adams & Humphreys (1993) put forward a hypothesis, based on genetic study of the gudgeon *Milyeringa* and shrimps *Stygiocaris* spp., that there is limited gene flow between the eastern and western coastal plains. In the case of the gudgeon, there is an apparent barrier between populations on the west coast around Vlamingh Head. In the case of the shrimps, populations of *Stygiocaris stylifera* from Milyering Well and south of Exmouth show relatively little difference, suggesting they do not perceive the barrier at Vlamingh Head. However, the occurrence of *Stygiocaris lancifera* on the west coast and absence from the eastern coastal plain suggests either a barrier or habitat difference.

Of the other stygofaunal groups with larger numbers of records, cyclopoid copepods, ostracods and syncarids do not appear to recognize differences either side of the peninsula (see Appendix 1). Most harpacticoid copepods appear to be restricted to the west coast, perhaps reflecting more saline water, but *Nitocra lacustris* occurs both sides of the peninsula. The syncarid *Halosbaena tulki*, which has widespread occurrence is a species that would be suited to genetic studies.

4.4 Threats

Water abstraction is usually the principal threat to stygofauna species and communities because it results in direct loss of habitat. Water abstraction occurs in 4 groups of bores on the Exmouth peninsula according to 1999 allocation data (Fig. 3.1)

- Water Corporation borefield, which provides water to Exmouth townsite and associated development and accounts for most of the abstraction. Annual abstraction is about 1029 ML and provides about 75 % of water taken from the aquifer.
- The Harold E. Holt borefield, which provides water to facilities at the former tracking station. Annual abstraction is about 258 ML.
- The townsite borefield, consisting of small 'private' bores within the townsite. Annual abstraction is about 133 ML.

- Private bores elsewhere on both the eastern and western coastal plains. In some cases, use is substantial (e.g. Kailis prawn processing plant 130 ML, Lighthouse Caravan Park 20 ML plus use of water from Harold E. Holt borefield, Learmonth Airport 17 ML). Other nodes include Yardie Creek Caravan Park (15 ML), Milyering Visitor Centre, and Yardie Creek campsite, where current annual abstraction is not well documented but is likely to be about 13 ML and increasing.

The ecologically sustainable levels of abstraction in different parts of the aquifer are unknown, although hydrological studies have provided estimates of the available groundwater and abstraction is currently managed according to the 1999 allocations (WRC, 1999). There has been reduction in abstraction since 1999, so that committed and requested use at June 2008 exceeded the sustainable yield only in Exmouth North, although Exmouth Town and Central remain close to fully committed (Table 3.1).

Monitoring at the Water Corporation borefield has provided some information about the threat of current allocations in the Town and Central Sub-Areas (see Section 5.0). Although results cannot be used directly in determining EWRs, they suggest that over-allocation of small parts of the aquifer does not necessarily have major impacts on conservation values in the medium term. The impacts of allocations elsewhere cannot be evaluated with the data available because there is neither hydrological impact nor biological information for these sites.

Other commonly cited threats to stygofaunal communities are increased nutrients, changes to carbon inputs and pollution (in the sense of pesticides, petroleum products, heavy metals etc) (Hancock et al., 2005; Hose, 2005). Little is known about these threats but, in most cases, they are likely to have incremental impacts on populations as they level of pollution increases. The same is usually true of water abstraction, where populations are likely to decline more-or-less in relation to the proportion of habitat loss as a result of abstraction. The focus on impacts of water abstraction in the assessment process are largely related to species with small ranges and the very substantial aquifer de-watering that often occurs when open cut mining extends below the watertable (EPA, 2007).

5.0 Existing biological monitoring

When a licence to extend the Exmouth borefield was granted in 1997, the Minister of the Environment imposed a series of environmental conditions on the Water Corporation that were, in fact, proponent commitments. The commitments relevant to stygofauna are

- (1) The proponent will finalize a detailed stygofauna and aquifer monitoring program
    - The proponent will
    - (2) submit data on stygofauna species composition and numbers
    - (3) implement actions to protect stygofauna populations and habitat to the requirements of the EPA on the advice of DEC [trigger for management response was changed in 2000 from loss of a species in one-third of monitoring bores to apparent reduction in stygofauna densities and/or stygofaunal diversity within production field when compared with DSO bores) (Brown & Root, 2001)]
- If monitoring reveals that salinity of production or monitoring wells is increasing, the proponent will
    - (4) immediately reduce the rate of pumping from the bore(s)
    - (5) reduce the total production from the group of bores in the area
    - (6) if the above measures do not improve salinity levels, cease groundwater production from the bores involved.

Table 5.1. Species composition information from the Water Corporation monitoring
Results of program presented for 1999-2006 (1999 represents the 1998-99 year)

Species	Group	Occurrence
Unknown	Nematoda	Sometimes occurs (KBR, 2005)
Unknown	Polychaeta	2000, 2001, mentioned in KBR (2005)
Halosbaena tulki	Thermosbaenacea	All years
Unknown	Ostracoda	2004, 2005
Diacyclops humphreysi	Copepoda	All years (species identity usually inferred)
'Stygoridgewayia westaustraliensis'	Copepoda	2006
Hexabathynella sp	Syncarida	2006, assumed = '*Australobathynella*' sp. 7 '*brooksi*'
Nedsia douglasi	Amphipoda	All years, dominant amphipod
Unknown	Amphipoda	Implied that other species occur (KBR, 2005)
Haptolana pholeta	Isopoda	All years (species identity usually inferred)
Stygiocaris stylifera	Decapoda	All years
Milyeringa veritas	Fish	2001, 2002, 2003

Subsequently, the Water Corporation has sampled a series of bores for salinity and stygofauna. Stygofauna are sampled at 14-17 bores within the 'zone of influence' of the production bores and 4-5 reference bores farther away (all to the south) (Figs 5.1 & 5.2). These bores are referred to as monitoring (MON) and designated stygofauna observation (DSO) bores, respectively. Salinity monitoring also occurs at western transect (WST) and salt-water interface (SWIM) bores and, occasionally, stygofauna monitoring has occurred in some WST bores.

The frequency of sampling has been reduced during the program and currently occurs in July, December and April of each 12-month reporting period. Samples are collected with a haul net and the volume sampled differs between DSO and MON bores. There are a number of grounds on which the validity of stygofaunal data produced by the monitoring program may be questioned (see Goater, 2007 and earlier reports) but a picture emerges that there has been no catastrophic change in the stygofauna community since 1999 as a result of managed abstraction (Fig. 5.3).

Any further interpretation of the monitoring data is prevented by the lack of pre-abstraction data, the imbalance between numbers of MON and DSO bores, the fact that abundances are consistently an order of magnitude higher in the MON than DSO bores, and the lack of consistent species level identification (Table 5.1). Results really represent Order level abundance and, in this respect, do not meet the proponent's environmental conditions. The current corrections to sampling results according to the different volumes of water sampled from each bore are also problematic: if animals occur only in the upper part of the profile, they will be sampled equally well in all bores. The monitoring program is aimed at species occurring in the water column and it is possible that some interstitial species remain to be detected. For example, bathynellid crustaceans were recorded for the first time in 8th year of monitoring (although they had been collected in earlier, non-monitoring sampling) and there has been very sporadic detection of polychaetes and ostracods. Goater's (2007) claim that efficiency of collecting

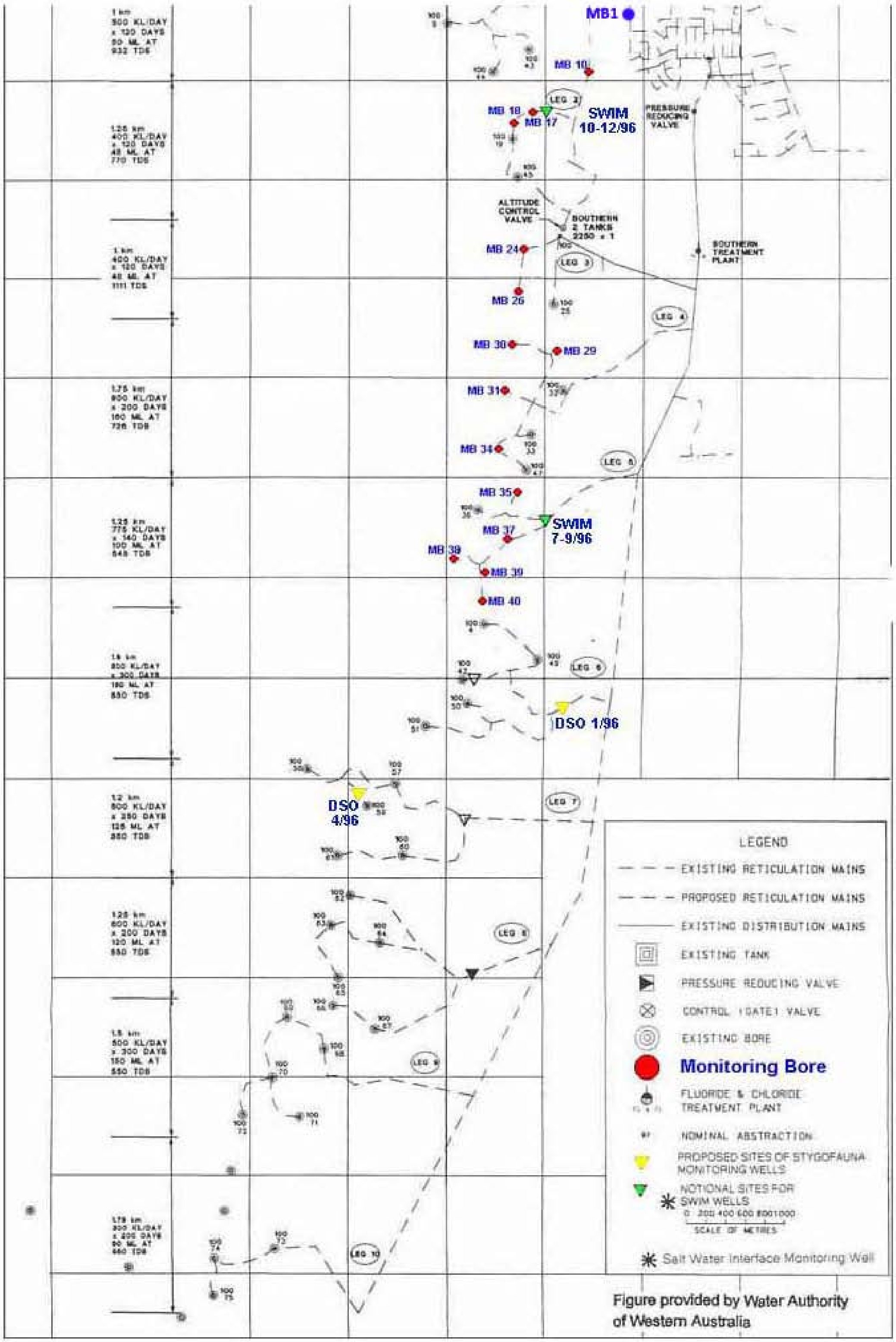


Fig. 5.1. MON bores and the northern 2 DSO bores where stygofauna monitored in 2006

15 of the 17 MON bores are shown. Those marked in red are the 14 MON bores sampled prior to 2006 (see KBR, 2005), MB1 (blue) and 2 bores to the north were added in 2006 (based on map in KBR, 2005)

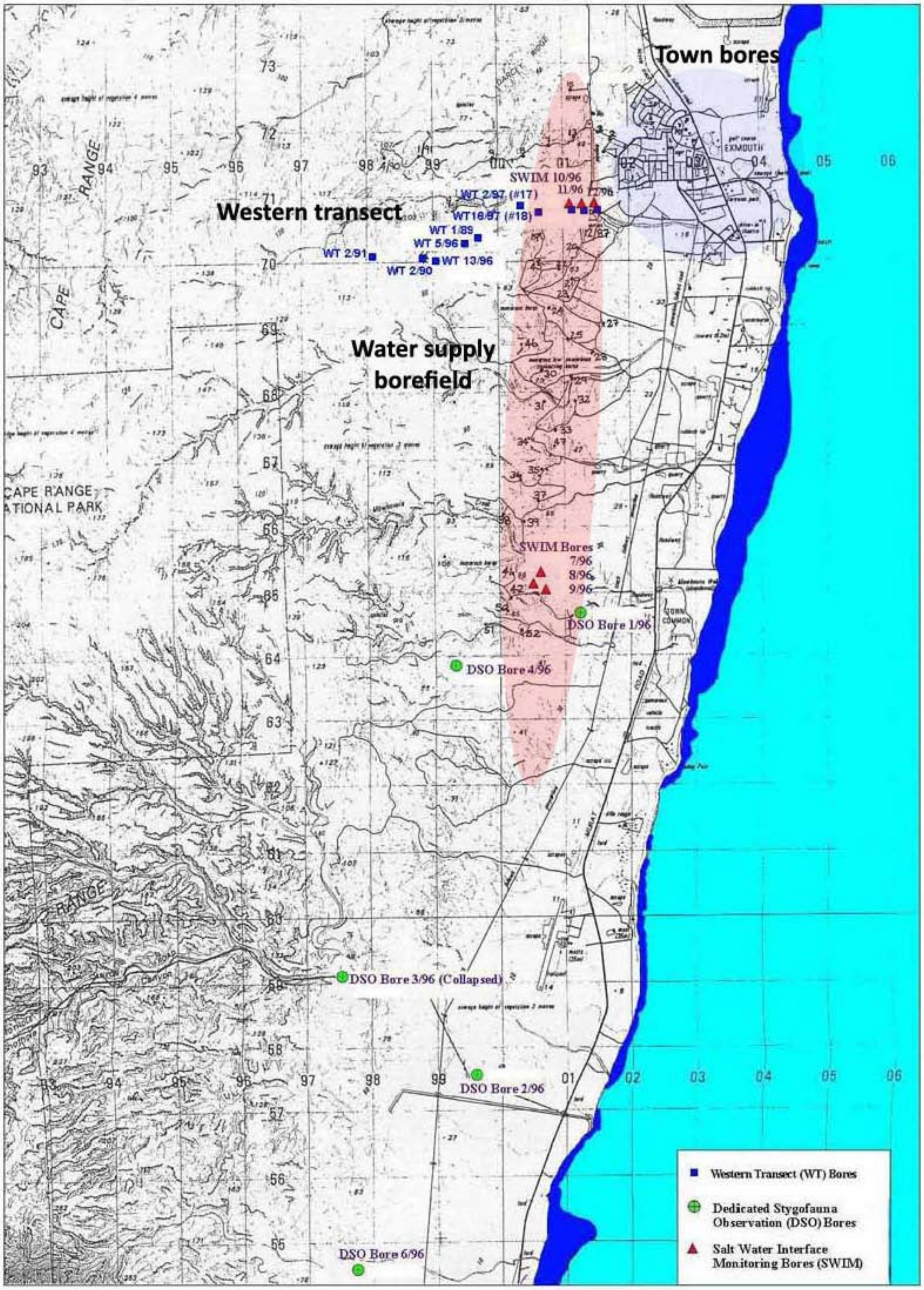
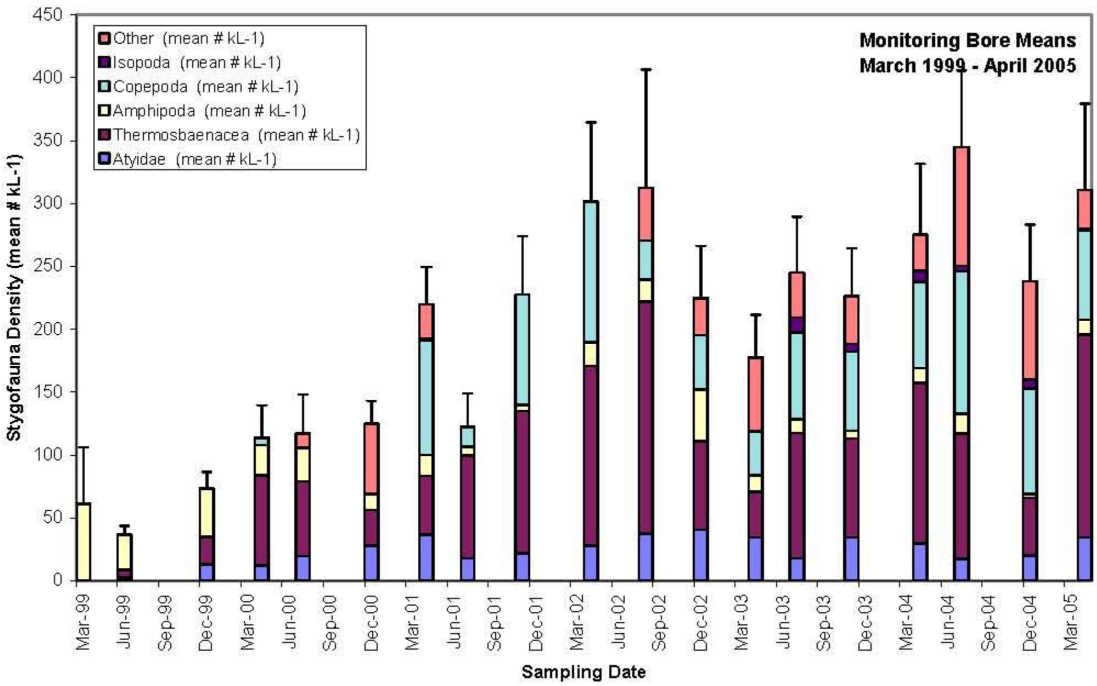


Fig. 5.2. Location of the DSO bores

DOS bores shown in green, production bores in Water Corporation borefield shown in blue. DSO 3/96 is no longer used (from KBR, 2005)

a)



b)

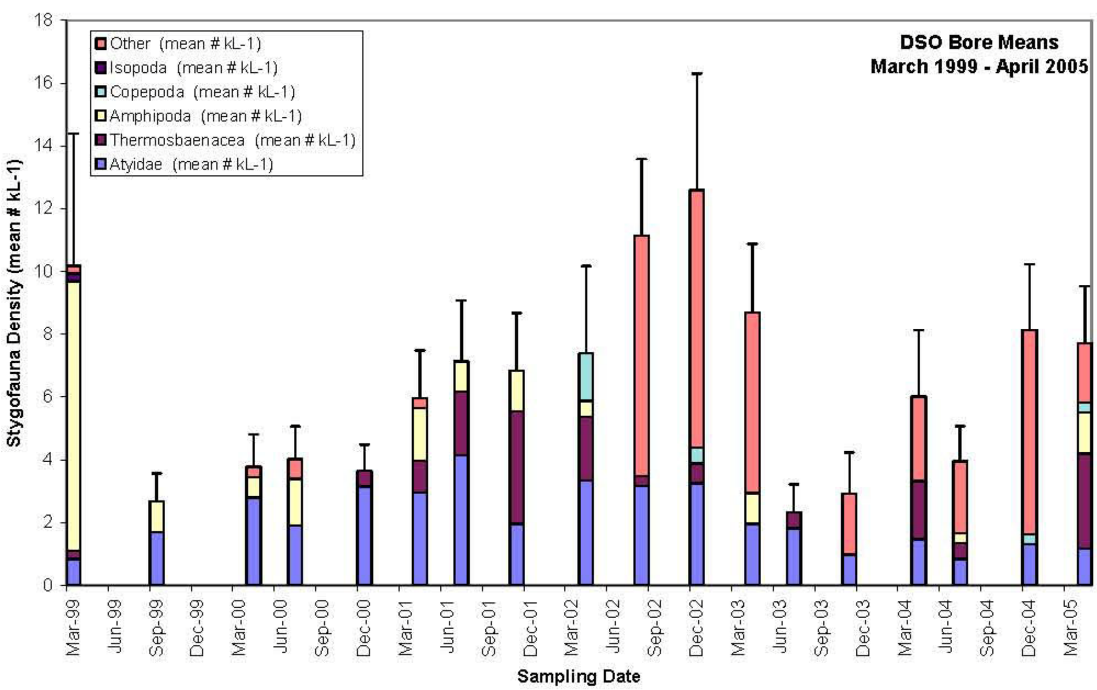


Fig. 5.3. Composition of stygofauna from 1999-2005 in Exmouth borefield

Composition indicated by results bore sampling at the Water Corporation borefield. (a) within borefield (MON bores) and (b) in reference bores to the south (DSO bores) (from KBR, 2005) interstitial species has increased over time owing to unrecorded changes in protocols does not appear to be supported by the data.

While this report has not examined the monitoring program in detail, the current effort probably represents over-sampling. Perusing the data suggests that a single round of effective sampling of the existing bores is probably sufficient to characterize community composition and abundance each year (see section 7.2). However, greater effort to collect all species present in the bores is required (although this will cause inconsistency with previous data) and it must be recognized that there is an obligation to report on species composition and abundance rather than higher taxonomic level abundance.

6.0 Environmental water requirements

There is currently a three-tier approach within Department of Water to setting EWRs, based on the amount of environmental pressure. Where consumptive uses are low, a fixed percentage of the annual flow of a river (or recharge of an aquifer) is reserved for the EWR. In this situation the EWR will translate directly into a planning allocation known as the environmental water provision (EWP). Where consumptive uses are higher, holistic methodologies may be used to calculate an EWR based on generic information and general ecological principles (e.g. SKM, 2007). When consumptive use threatens the viability of the designated EWR/EWP, or in situations where ecological values are thought likely to be threatened by water abstraction, detailed ecological studies may be undertaken to define the EWR (e.g. Braimbridge & Malseed, 2007). The EWP, representing water actually allocated to the environment, will sometimes be less than this EWR because of trade-offs between ecological, social and economic values in the final water allocation process.

Most EWR methodology has been derived for surface water, particularly rivers, and can only be transferred to groundwater allocations at a generic level (Schofield et al., 2003). One of the challenges in setting EWRs is that the process is most efficiently achieved if a top-down approach can be used (e.g. a hydrology based approach where a proportion of recharge is allocated to the EWR). However, the ecological need for water varies between different biological elements at a site, as well as spatially within the aquifer for the one element because of hydrogeological factors. Thus, in theory an EWR is more likely to reflect biological requirements accurately when based on a bottom-up approach with detailed ecological studies (SKM, 2001). Bottom-up studies are expensive and, in practice, can miss key ecological processes in systems where values and threats are not clearly delineated, giving rise to false EWRs. For this reason, bench-marking has been widely advocated in Australia as a practical method of deriving EWRs, especially in large systems. This top-down approach examines a range of aquifers where abstraction (or other use) is occurring to identify the threshold at which marked deterioration in conservation values begins. An EWR is then determined for the aquifer under study (Arthington & Bunn, 2002; Arthington et al., 2006).

6.1 Groundwater Sub-Areas

The easiest method of calculating the EWR of an aquifer is as a fixed proportion of annual recharge. The proportion of recharge reserved for the EWR can be varied according to Groundwater Sub-Areas relatively easily to reflect their environmental values and what is known about water volumes needed to sustain those values, including information about threshold responses to threats. Based on current knowledge of stygofauna communities and their values, such an approach should be satisfactory for the eastern Groundwater Sub-Areas (North, Town, Central, South) but it is unlikely to be suitable in the West Sub-Area (Fig. 1.2).

6.1.1 Eastern Sub-Areas

Existing biological data suggest that restricted, high value stygofaunal communities do not occur in the eastern Sub-Areas. The stygofaunal community on the eastern side of the peninsula appears to be widespread, although this view is based more on inference and opinion than survey results, which must be regarded as incomplete. The community around Exmouth and to the south has already been exposed to considerable water abstraction within the Water Corporation borefield without apparent adverse effect. It should be recognized in this regard that the current allocation regime was designed to prevent further water abstraction and improve management of existing abstraction activity to reduce water salinity (WRC, 1999). The ecological management objective for these Sub-Areas should be to prevent any local loss of stygofauna species from the aquifer. This is, however, a difficult operational objective (see section 7.0) and further investigation and analysis is required to convert it to a quantifiable trigger to induce management response. The change of trigger for monitoring of the Water Corporation borefield in 2000 reflected the difficulty of defining operational triggers.

Studies examining ecological processes and the environmental tolerances of stygofauna to determine whether the stygofauna community can persist with a lower EWR than represented by the current groundwater allocation are not recommended. In the case of the borefields supplying water to Exmouth, where abstraction is the only recognized threat, such studies would be complex, unlikely to produce clear-cut results, and difficult to apply to management of the aquifer where a large number of environmental factors interact. Furthermore salinity, the likely focus of such work because of its impacts on faunal occurrence and its ease of study, is unlikely to be a relevant environmental factor until it reaches a level in excess of drinking water standards (by which stage abstraction would have ceased). Borefield operating procedures will prevent risk to conservation values from increasing salinity.

An alternative approach to determine the appropriate EWR is to confirm that the current understanding of the conservation significance of the various groundwater communities is correct, map the distribution of these communities on the peninsula, and characterize insofar as possible the habitat in which they occur in terms of hydrogeology and physico-chemistry. The EWR could then be determined for each Sub-Area using hydrological data, with the objective of minimizing the change that will occur in habitat characteristics throughout most of the community range. This somewhat blind and precautionary approach is based on the assumption that maintaining existing habitat conditions, as best they can be measured, will protect the species present. The purpose of management to maintain existing values of a suite of hydrogeological and physico-chemical parameters is simply to maintain groundwater habitat. It is assumed that doing this will result in species protection. No causal relationship between the parameters measured and stygofauna occurrence is assumed.

Further identification of material from the existing Water Corporation monitoring program, combined with surveys to identify all species forming the stygofaunal communities of the eastern peninsula, would provide the required confirmation (suggested by current results) that the operation of the Water Corporation borefield has not exceeded the threshold of abstraction that will result in substantial detrimental change to stygofauna (small and subtle changes are never likely to be reliably detected by field monitoring).

A program of investigation to determine the EWR is outlined in Section 6.2. It should be noted that the groundwater requirements of areas such as the permanent spring at the Tulki/Mandu Limestone boundary in the creek within Shothole Canyon will need to be addressed separately. Its position within Cape Range upstream of water extraction means that protection should be easy to achieve.

6.1.2 West Sub-Area

The Bundera: Cape Range Remipede Threatened Ecological Community, which lies on the coast, is currently known from a single occurrence and its importance means that the EWR of its groundwater catchment, which lies in the southern part of the West Groundwater Sub-Area should be all available groundwater in a natural regime. Geological and biological investigations to locate any further occurrences of the community are a priority and such areas would also require an EWR that matched all naturally available groundwater. The pools at Yardie Creek are also likely to require all available groundwater.

The conservation value of the stygofaunal community in other parts of the western coastal plain is perhaps higher than for the east, with species such as *Stygiocaris lancifera* and *Ophisternon candidum* apparently restricted to the west. More importantly, the western coastal plain from Cape Range National Park southwards is expected to be nominated for World Heritage listing (CALM, 2007), which means that conservation should be the focus of groundwater management (this is already the case in the National Park). It should be recognized, although not addressed in this stygofauna-focussed report and a technically challenging issue to study, that groundwater discharge along the coast opposite Ningaloo Reef may have an ecological role in maintaining that ecosystem. Thus, the EWR for most of the Western Groundwater Sub-Area should be the entire groundwater resource , reflecting an ecological management objective for the Sub-Areas of no reduction in biodiversity in the aquifer.

There is, however, a need for continuation of existing water abstraction and for some growth in this abstraction to cater for tourism. A blanket EWR across the Sub-Area that allocates all water to the environment is impractical and will not fit well with the process of trading off social and economic values to develop an EWP nor accommodate existing annual allocations such as that of the Lighthouse Caravan Park (20 ML). Probably the most effective way of developing an EWR for the West Groundwater Sub-Area that will contribute to development of an EWP is to identify the existing potential consumptive users of groundwater and undertake studies into the potential constraints on, and effect of, their groundwater abstraction on local conservation values within the context of an ecological management objective of no biodiversity loss. A program of investigation is outlined in Section 6.2.

6.2 Studies required for EWRs

This report does not propose ERWs or advocate detailed methodology for EWR calculations. The most appropriate parameters to use in calculations, and the best approach to determining EWRs, should emerge from further study. Some of the investigations proposed should have occurred before installation of the bores currently abstracting water from the aquifer.

The following studies and/or information should provide sufficient information to determine EWRs for the Exmouth Groundwater Area.

1) Habitat survey of the coastal plains to locate karstic areas close to the coast that may potentially support anchialine systems. If such areas can be identified, a subset should be drilled and studied to determine whether they are anchialine and whether they support significant stygofaunal communities. Video camera investigation, as well as net haul sampling, should be employed
    - The hypothesis on which the EWR strategy in this report is based is that anchialine karstic areas are likely to be found on the western coastal plain but not the eastern coastal plain
2) Stygofaunal survey of all parts of the coastal plains to identify all stygofauna species occurring on the peninsula and provide information on the range, conservation status and habitat associations of each species

- The survey would provide a context for assessing the significance of the communities around areas of high water abstraction and would identify any sites with important communities and high conservation value species such that creation of a management zone is required where specific licensing rules and policies would apply to ensure no unacceptable impact occurs
- The survey would also provide general guidance about the environmental conditions the species currently occupy. These could be used to assist setting management targets in areas of water abstraction, where it is intended to maintain current physico-chemical conditions. Note, however, that identification of site-specific trigger values for physico-chemical parameters is unlikely to be a useful tool in protecting stygofauna communities
- Currently about 50 bores have been surveyed on the coastal plains of the peninsula but the EPA (2007) guidelines should be considered when designing the survey and at least 50 bores should sampled on the eastern coastal plain and 50 on the western plain, distributed along the full length of each plain and representing a range of prospective geologies. The guidelines require 40 samples from impact areas the size of mining operations. Impacts from water abstraction are much less than de-watering but the area of interest is an order of magnitude greater

3) Re-analysis of the monitoring data from the Water Corporation borefield to confirm that the picture of no decline in troglofauna is correct
   - The pattern of occurrence of low abundance species needs to be better elucidated
   - While current knowledge suggests that all stygofauna on the coastal plain will be tolerant of the changes in salinity likely to result from abstraction, the assumption should be confirmed by analyzing abundance of species in relation to salinity in each bore/sampling date
4) Re-evaluation of current estimates of annual recharge and sustainable extraction in the different Sub-Areas to provide the basis for setting EWRs on hydrological grounds where the stygofaunal community does not have particularly high conservation value. The purpose of these calculations is to break up each Sub-Area into units where the sustainable yield may differ
   - Information from the re-analysis of Exmouth monitoring data, and any other available studies, should be used in a bench-marking process when setting sustainable extraction.

It is anticipated that the above studies will provide sufficient information to set EWRs in the eastern Sub-Areas.

5) Based on the habitat survey, additional anchialine areas and other habitats supporting stygofauna communities with high conservation on the western coastal plain can be identified for protection from water abstraction (and inappropriate nearby surface development)
   - These areas should be mapped and their groundwater catchments identified
6) Areas of likely future water demand on the western coastal plain should be identified in conjunction with tourism, and other land-use, planning. Given that the area is intended for World Heritage listing, detailed assessment of the impacts of current and planned abstraction should be undertaken to determine the stygofaunal values of the sites and whether impacts are acceptable. These studies should be undertaken using EPA (2007) guidelines and then EWRs set to restrict abstraction to a level that does not cause unacceptable impact (any loss of biodiversity)
   - Site-specific hydrological investigation and modeling will be required to determine the size of EWR required to prevent unacceptable impact (this is effectively a conventional environmental impact assessment)

7.0 Monitoring and managing ecological values

The cost of monitoring programs can be substantial and an important aspect of monitoring design is the trade-off between conservation and other government programs. Within the conservation budget, there must be further trade-offs between money spent monitoring the stygofaunal community and managing potential threats (although, without monitoring, management proceeds only on general principles and may represent misplaced or wasted effort). Thus, monitoring should be done with the simplest indicators that reliably provide the required information.

Successful monitoring requires an appropriate conceptual framework in which the elements to be monitored, and the reasons for using them, are clearly identified (Vos et al., 2000). The most straightforward approach to monitoring the adequacy of EWRs/EWPs in protecting groundwater conservation values is to assume that abstraction is the principal threat to the values. In this case, any departure from pre-abstraction conservation values is presumed to mean that the EWR/EWP is inadequate. If significant departure is detected, but it is considered unlikely that abstraction is the cause, then other possible impacts on values are examined.

On the Exmouth peninsula, the outstanding groundwater values are stygofaunal and, therefore, the element(s) to be monitored must reflect what is happening to stygofauna conservation values. One of the difficulties in monitoring stygofauna is that they usually occur in very low numbers, so that for most species absence of animals from samples cannot be equated with their disappearance from the habitat (see Eberhard et al., 2008) and accurate measurement of changes in abundance requires prohibitive sampling effort (EPA, 2007). This has led to suggestions that monitoring would be more effectively achieved by measuring physico-chemical parameters (Biota, 2006b; Goater, 2007). Such approaches are risky, however, when the environmental tolerances and responses of the stygofauna species present are unknown.

Defining environmental responses well enough to enable chemical monitoring to be used to infer what is happening to the stygofaunal community usually requires even greater sampling effort than detecting changes in abundance. One solution is to use data from other sources, such as ANZECC guidelines, to identify thresholds that are likely to affect stygofauna but it must be recognized that error rates with this approach will be high (e.g. Hose, 2005). Another potential solution is community-based monitoring where multivariate analyses synthesize the information available from all species present to identify different community types of varying species composition. In speciose communities, this approach is tolerant of a high degree of sampling error and many missing species (e.g. Halse et al., 2002) but the Exmouth stygofaunal communities appear to contain too few species for such an approach to be viable.

From the above discussion, it should be clear that it will be very difficult to find appropriate elements to monitor groundwater conservation values and the Exmouth peninsula is not a situation in which adaptive management, in the sense of reacting to monitoring feedback, will be easy (see Holling, 1978). Consequently, EWRs/EWPs should be set in a precautionary way based on an understanding of groundwater conservation values and hydrology provided by widespread survey and modelling.

7.1 Sites and frequency of monitoring

Despite the expense and logistical difficulties associated with monitoring, it is difficult to justify its complete absence in areas of high conservation value because stewardship requires periodic reassurance that values are being maintained in areas where anthropogenic activity may in some way affect groundwater. This is likely to mean some form of direct monitoring of stygofauna. It is suggested, however, the monitoring need not be frequent and an interval of 5-10 years might be appropriate in areas where there is no active use of groundwater or obvious threat.

Decisions about whether to monitor particular sites should be made according to the significance of the biological community (based on results of the widespread survey) and the likely scale of maximum possible impact of abstraction or other anthropogenic activity. Given the long history of monitoring in the Water Corporation borefield and the scale of abstraction, stygofauna should be monitored at this site. Any anchialine sites near abstraction should also be monitored, although care will be required to minimize disturbance caused by monitoring (see Humphreys, 1999).

7.2 Elements to be monitored and sampling effort

The objective of monitoring should be to show that stygofauna conservation values are being maintained. It is often argued that rare species have greater conservation value than frequently encountered species (e.g. Angermeier & Winston, 1997) and, on this basis, it is important that the occurrence of rare species is accurately determined. Thus, species occurrence is probably the most satisfactory element to monitor.

Stygofauna sampling methods in bores are moderately well documented. Net sampling is widely used and has been shown to be efficient and to yield animals that are readily identifiable, although under some circumstances pumping large volumes of water will yield better results (Allford et al, 2008; Eberhard et al., 2008; Hancock & Boulton, 2008). Monitoring should employ the sampling methods of the Pilbara Biological Survey as recommended by EPA (2007). Depth to water, salinity, pH, dissolved oxygen levels and nutrients should be measured at all bores where stygofauna monitoring occurs to provide data to help interpret any changes in fauna. In addition, there may be a need to measure particular contaminants when establishing reasons for a decline in stygofauna occurrence. At the start of monitoring, and periodically thereafter, salinity and dissolved oxygen should be measured at 1 m intervals to establish a groundwater profile for each bore.

There is no definitive prescription of when to monitor and how many bores to sample at a site but there is evidence from both Schmidt (2005) and Eberhard et al. (2008) that ≥ 12 samples are required within the impact area of a homogeneous site (such as a small borefield of uniform geology) to collect nearly all species present. This could be achieved by sampling 12 bores once or a smaller number repeatedly during the year if the site is small and a large number of bores will not be available. Medium-sized borefields are unlikely to be geologically uniform and a larger number of samples is likely to be required from there. It is suggested that acceptable reliable monitoring data on species occurrence there (where the emphasis is on trends through time rather than the results of any particular year) may be achieved by sampling 18 bores once (November), 9 bores twice (November, July) or 6 bores 3 times during the year (July, November, April). Multiple sampling events minimizes the number of bores required and allows for some temporal variability in yield, which sometimes occurs with stygofauna (see Eberhard et al., 2008). Only at large borefields, such as that of the Water Corporation, is there likely to be an excess of potentially suitable bores for sampling.

Monitoring may be restricted to a longitudinal comparison of sampling results from impact areas, looking for changes in species occurrence over time. However, this before and after approach can be difficult to interpret if climate or other factors are changing and there are substantial benefits in also sampling control bores outside the zone of impact (Underwood, 1991), even when monitoring begins after abstraction. It is useful to have more than 1 set of control bores associated with monitoring abstraction (see Underwood, 1993) but the within-site replication and sampling costs associated with stygofauna are likely to preclude this. It is essential, however, that sampling effort within the single set of control bores at least matches that in the impact zone (i.e. 6 bores sampled 3 times).

The sampling effort proposed here is modest compared with either the level of sampling the Environmental Protection Authority requires for environmental assessment of developments or with the level of sampling required to detect changes in abundance of rare species (Biota, 2006b; Fig 3.3 in EPA, 2007). It should be regarded as the minimal acceptable level of effort in any area selected for monitoring.

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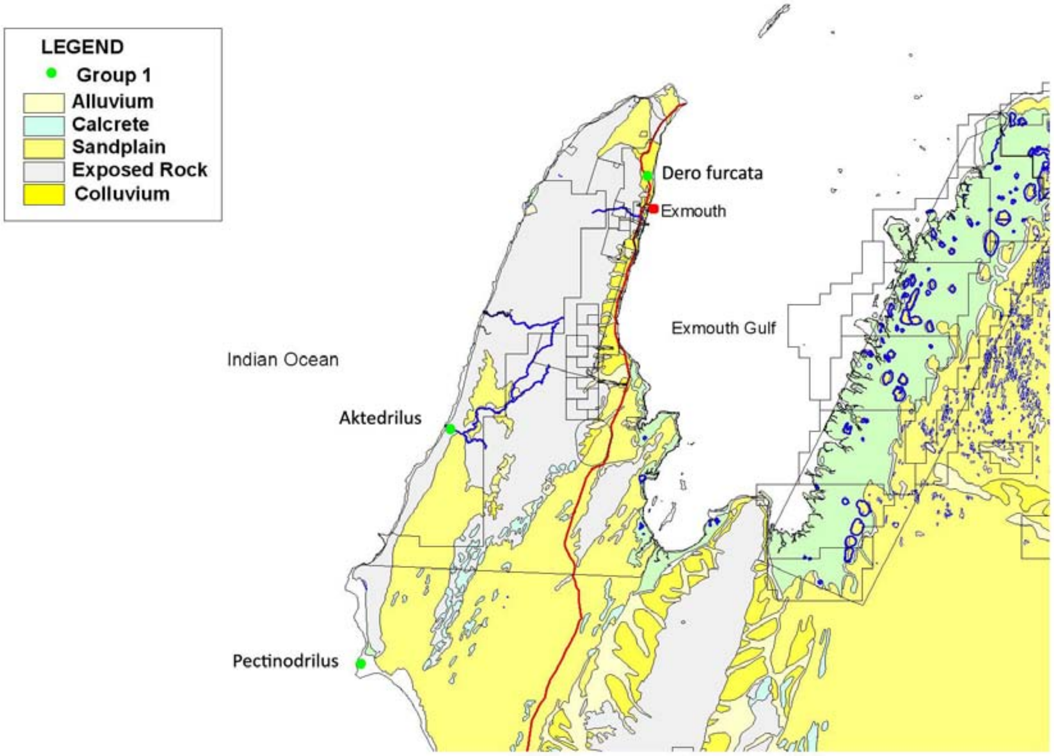
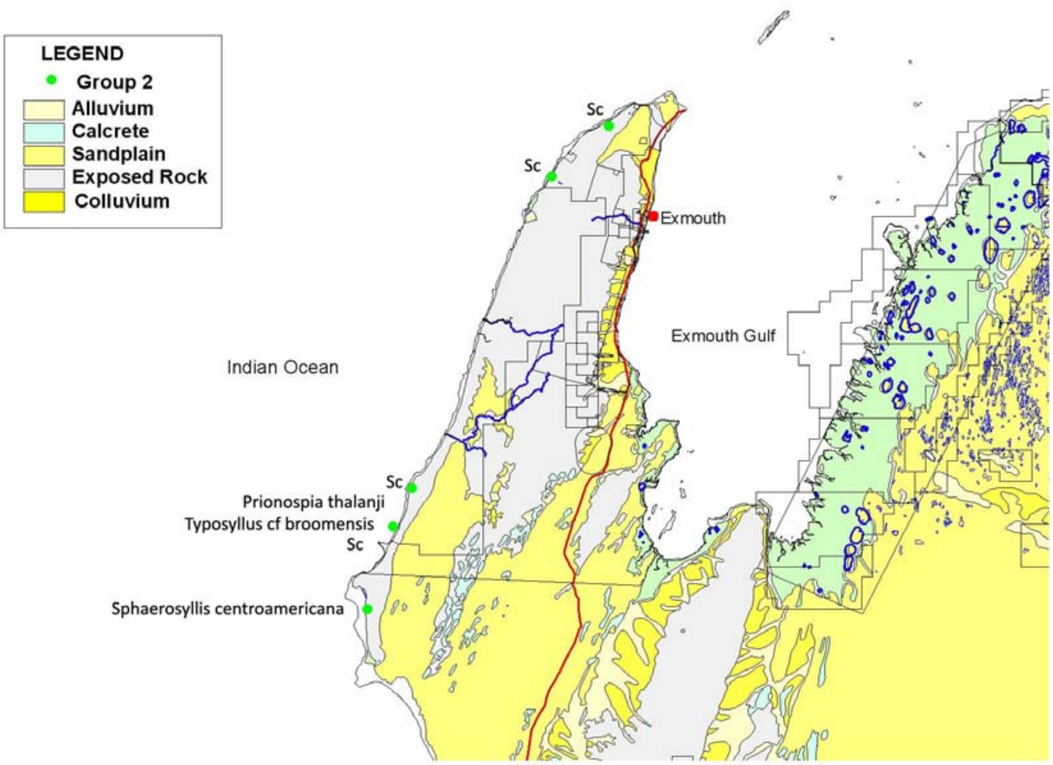
Appendix 1. Distribution of groups of stygofauna on Cape Range based on Western Australian Museum records

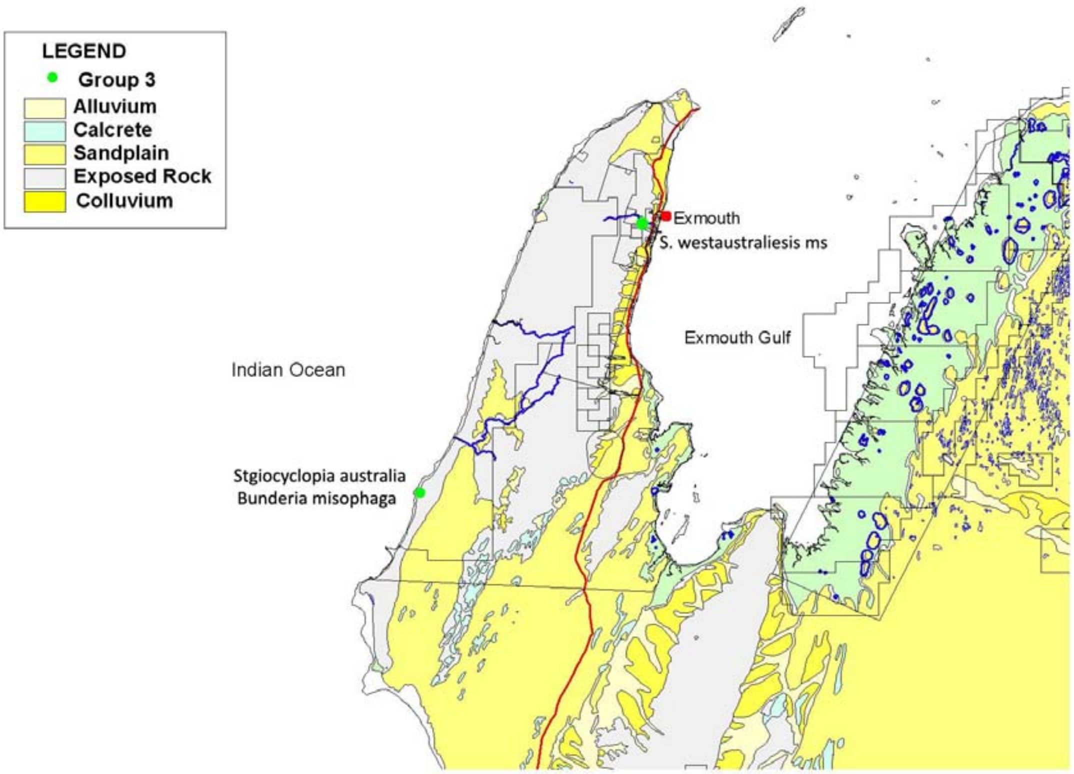
A Oligochaete



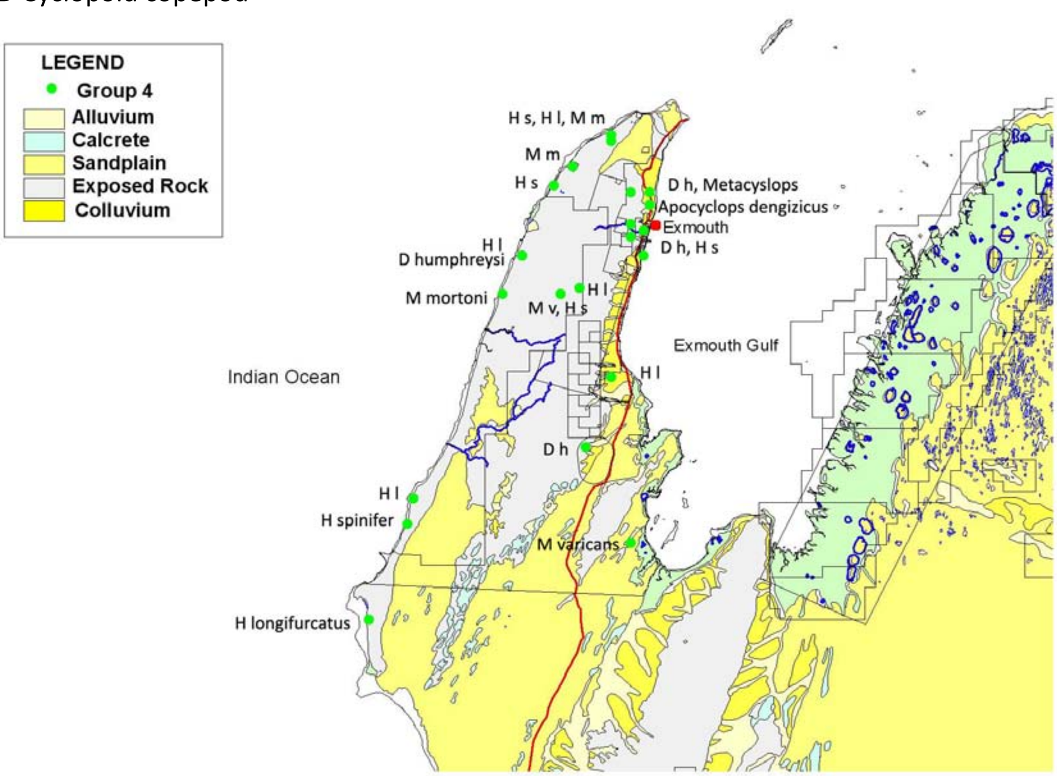
B Polychaete (*Prionospia thalanji* listed)



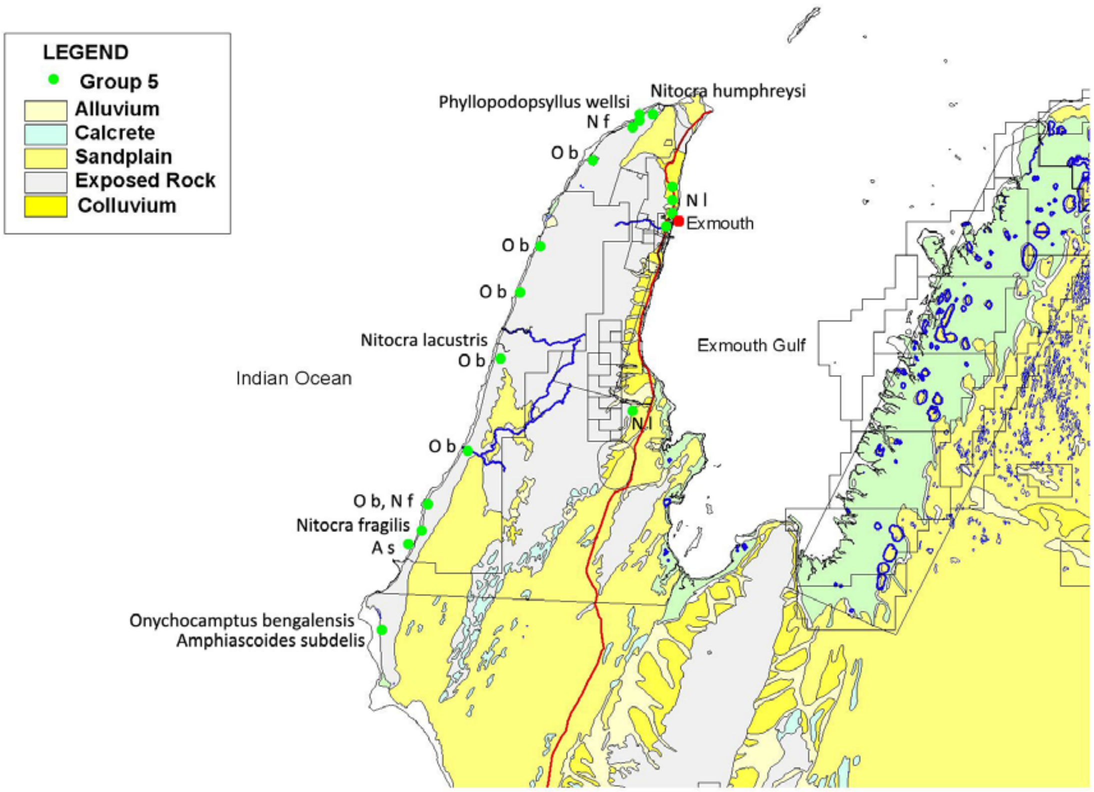
C Calanoid copepod (*Bunderia misophaga*, *Stygiocyclpia australis* listed)



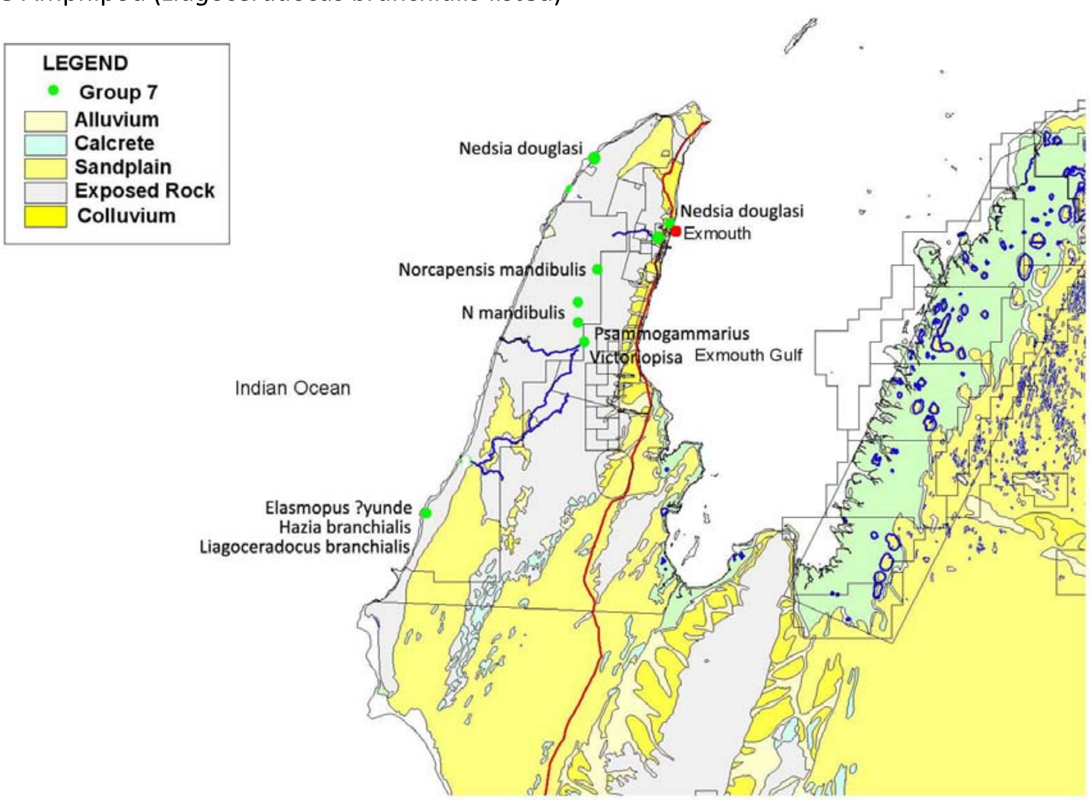
D Cyclopoid copepod



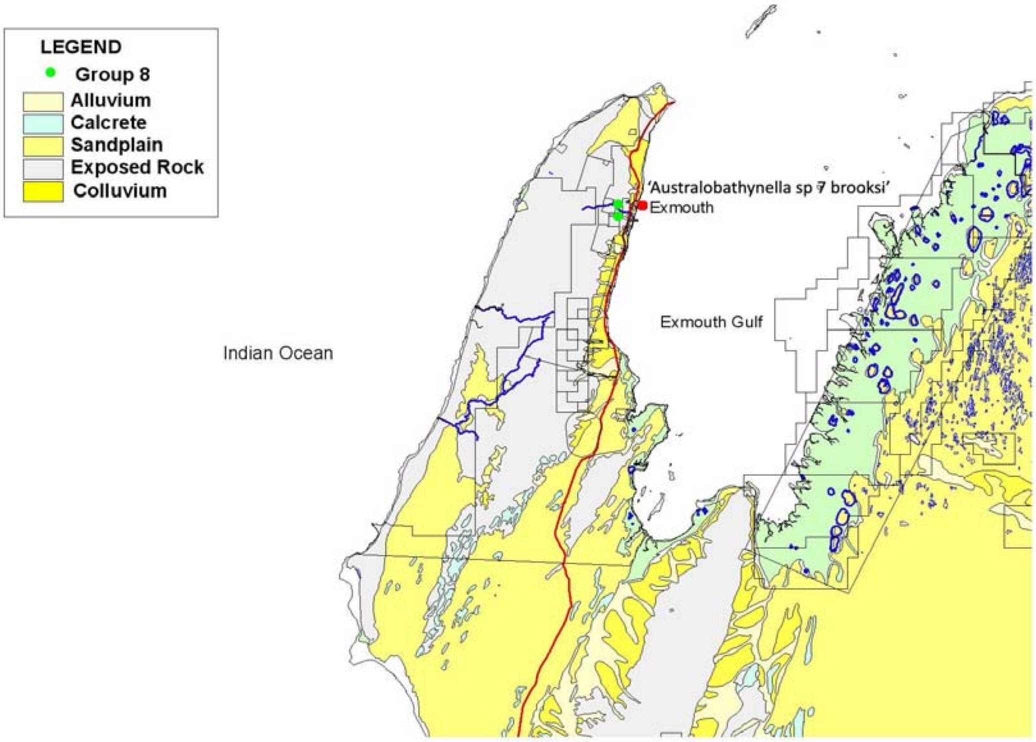
E Harpacticoid copepod



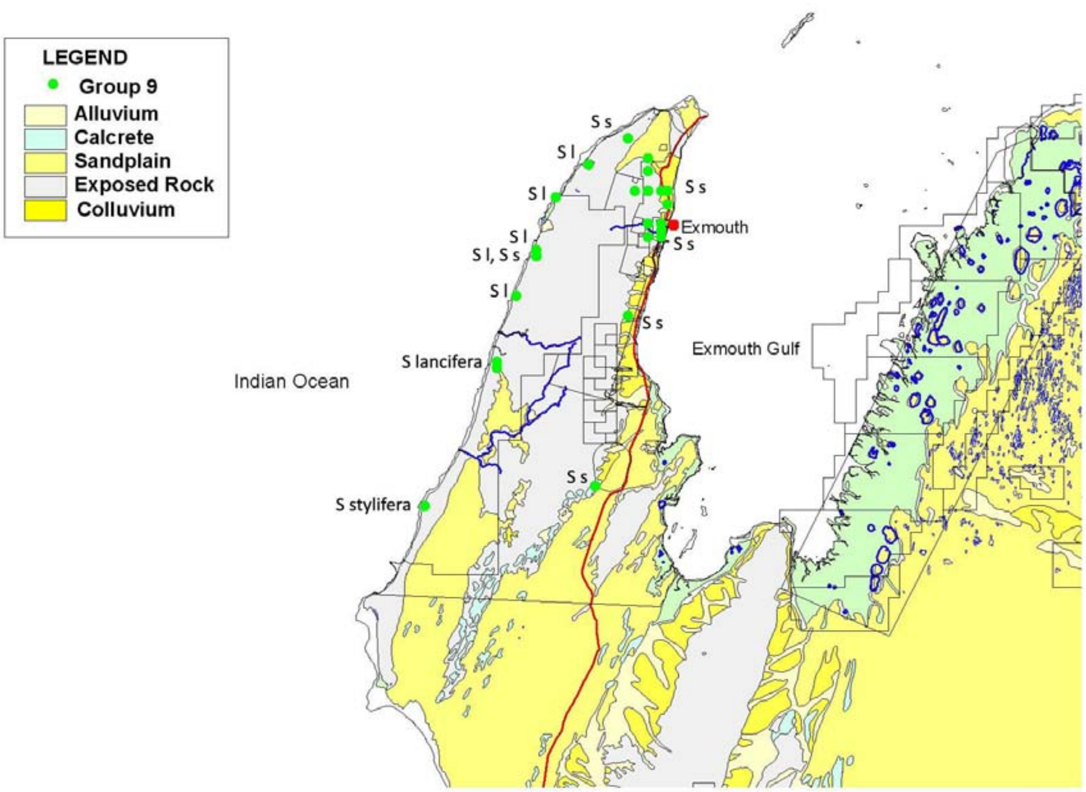
G Amphipod (*Liagoceradocus branchialis* listed)



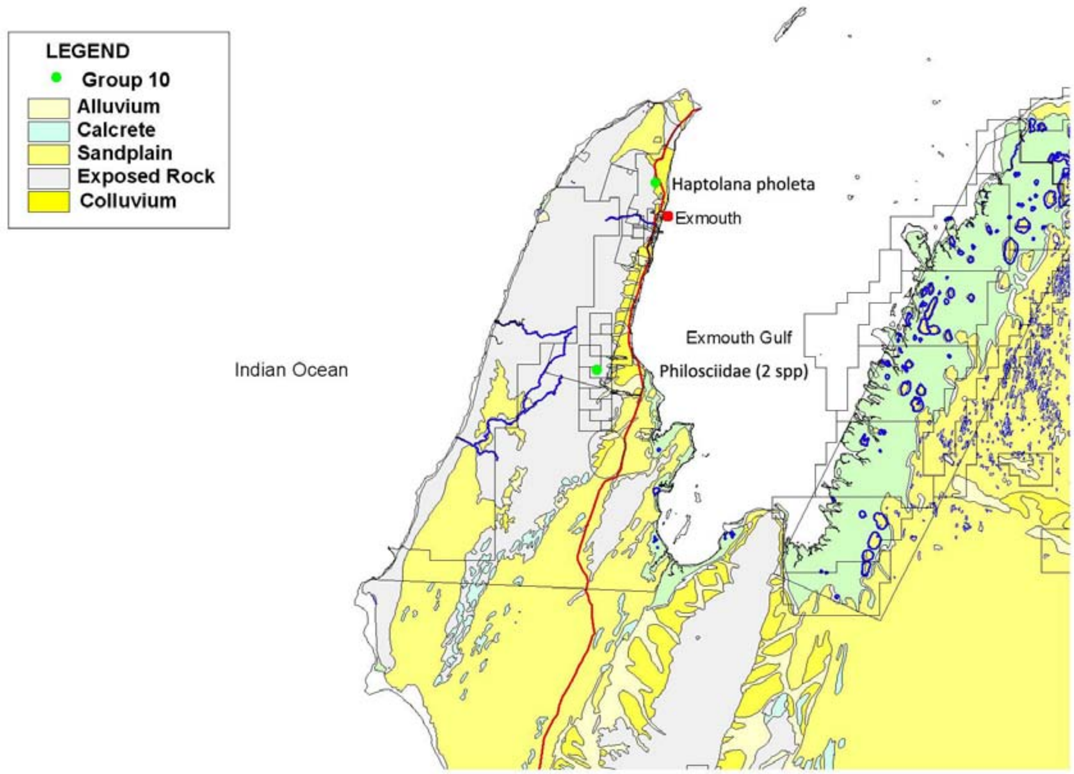
H Bathynellid



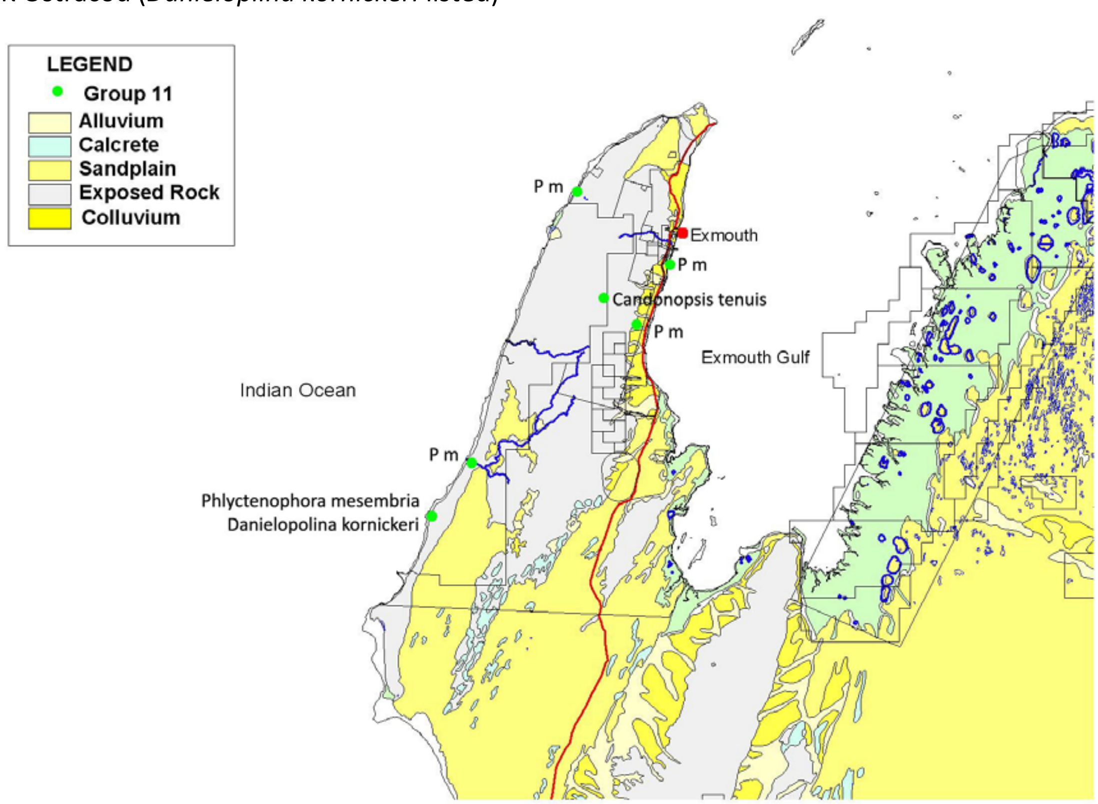
I Decapod (*Stygiocaris* shrimps, *Stygiocaris lancifera* listed)



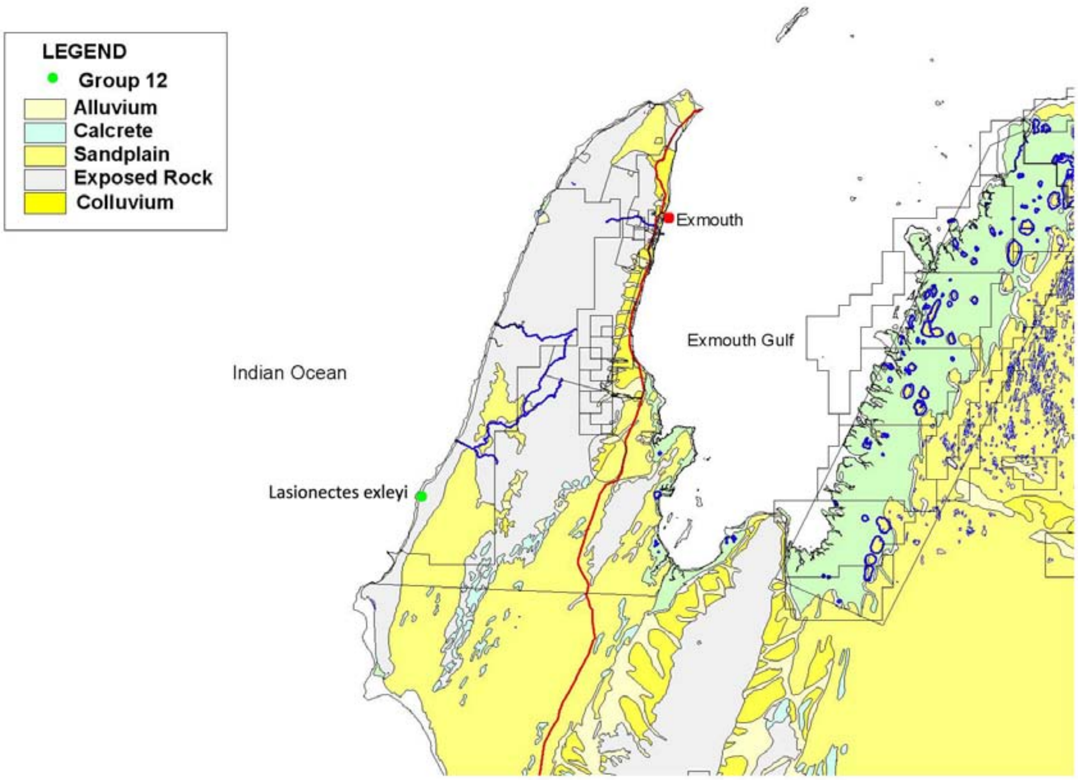
J Isopod



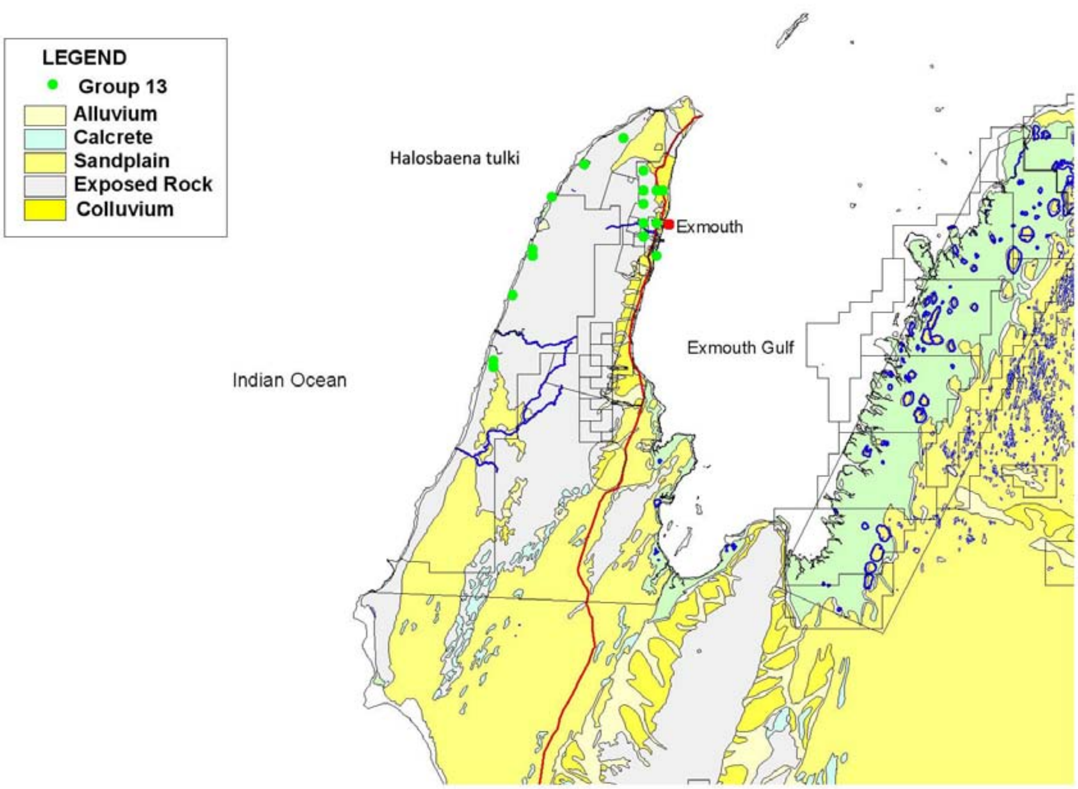
K Ostracod (*Danieloplina kornickeri* listed)



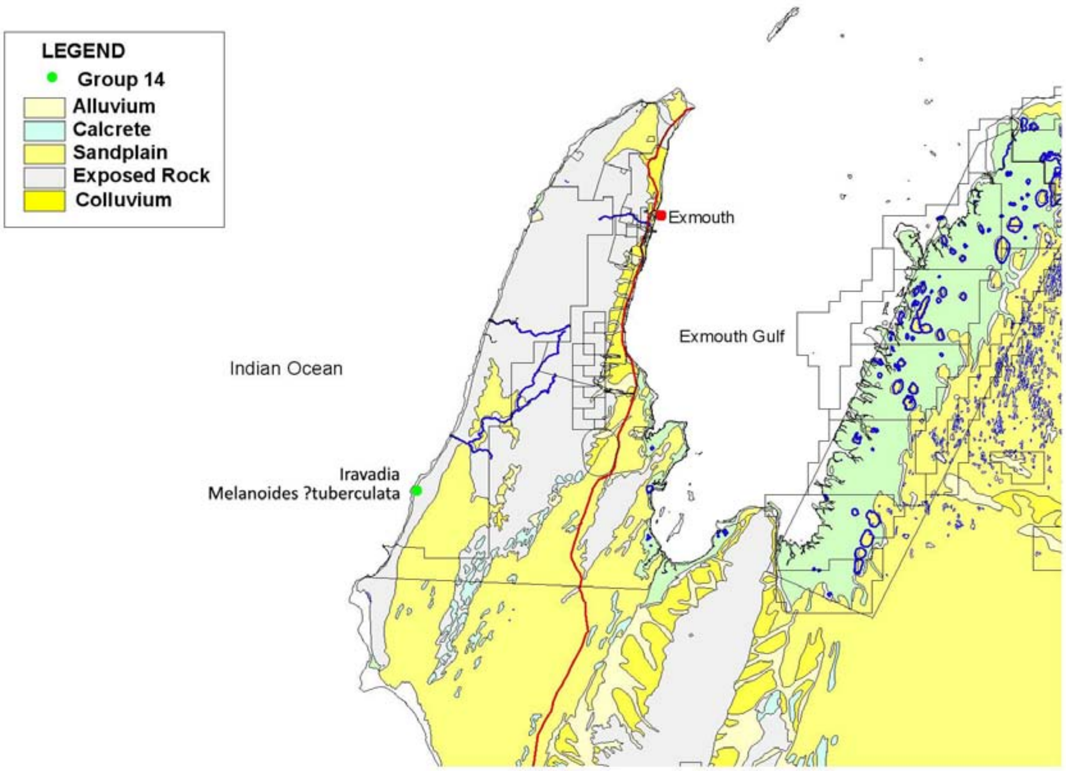
L Remipede (*Lasionectes exleyi* listed)



M Thermosbaenacid



N Snail



O Fish (*Milyeringa veritas*, *Ophisternon candidum* listed)