Jewel Cave Karst System, Western Australia: Environmental Hydrogeology and Groundwater Ecology

by Stefan Eberhard

Report prepared for the
Augusta Margaret River Tourism Association Inc.
Western Australia.

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Cover:
Aerial photograph of portion of the Leeuwin - Naturaliste Ridge between Cape Leeuwin (bottom) and Deepdene (top). The limestone ridge is the continuous vegetated band between the Indian Ocean (left) and cleared lands to the north and east where the township of Augusta and the Blackwood River estuary are visible. Jewel Cave is located on the inland margin, north-east sector of the ridge. Digital aerial photograph by Department of Land Administration, The State of Western Australia.

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Acknowledgements

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Summary

When Jewel Cave was developed for tourism in 1959 it contained a spectacular lake. The walls and ceiling of the lake chamber were profusely decorated with speleothems and the reflection of these formations in the lake waters formed a stunning display. The lake and its reflections became a major attraction on the cave tour, however by 1988 the groundwater table had dropped by more than one metre, the lake and its famous reflections had all but disappeared.

The watertable has continued to decline and in 2002 was at the lowest level recorded since 1958. Two other nearby caves, Easter Cave and Labyrinth Cave, have experienced a similar watertable decline.

During 1993, a lake in Easter Cave was found to contain species of aquatic subterranean fauna (stygofauna) associated with submerged tree roots. Because of the watertable decline, this aquatic root mat community, together with root mat communities in three other caves on the Leeuwin-Naturaliste Ridge, were listed as critically endangered under the *Environmental Protection and Biodiversity Conservation Act (1999)*. The reasons for the watertable decline remained uncertain, although lower rainfall, groundwater pumping and increased groundwater usage by tree plantations were speculated causes.

In 1999 the Augusta-Margaret River Tourism Association, through CaveWorks, initiated a three year research project to investigate:

(a) Cause of the watertable decline in the Jewel Cave karst system, and;

(b) Distribution and ecological / conservation requirements of stygofauna, including root mat communities.

This research report provides the hydrogeological and ecological framework for dealing with current environmental management issues associated with groundwater and dependent ecosystems within the Jewel Cave karst system. The study findings have broad relevance and significant implications for research, monitoring and management of other cave systems on the Leeuwin-Naturaliste Ridge, and elsewhere in Western Australia.

This study has contributed, in part, toward realizing the original vision and aims of CaveWorks (*Caves World of Research Karst Science*) - that of contributing to better understanding and protection of caves and karst in the Leeuwin-Naturaliste region.

Southwest Australia is a region notable for a prolonged and significant decrease (21 %) in winter rainfall over the period since 1968. Rainfall patterns in the study area have not followed the regional trend however - Cape Leeuwin recorded a decline in winter rainfall of only 1 % over the same period. Groundwater pumping and tree plantations have not contributed to the watertable decline because these processes do not occur within the karst catchment.

Groundwater recharge to the karst aquifer does not occur during every winter season, and is dependent on rainfall intensity and antecedent conditions. Mean groundwater recharge rates decreased 29 % after 1979-80, corresponding with a significant change in fire regime within the karst catchment - fire frequency decreased from an average 4.3 fires per decade to less than 0.5 fires per decade. The virtual absence of fire during the previous 25 years has allowed a dense growth of understorey vegetation and accumulation of ground litter, which through interception and evapotranspiration of rainfall, is hypothesised to be a major contributing factor to the watertable decline.

A prescribed wildfire hazard reduction burn of the Cliff Spackman Reserve (including the Jewel Cave precinct) will be undertaken by CALM in Spring 2003. The effects of fire treatment on groundwater recharge will be investigated with Before-After-Control-Impact (BACI) monitoring of rainfall, leaf area index, ground fuel load, soil moisture, infiltration rates and watertable response.

The conservation status and ecological requirements of root mat communities are reassessed. The known distribution range of the Easter Cave root mat community, recorded previously from one small pool, has been extended to > 2 km^2 area, throughout Jewel, Easter and Labyrinth Caves.

Species in the threatened ecological community either do not have an obligate dependence on tree roots for survival, and/or, occur widely in other groundwater and surface habitats. This has important implications for conservation management.

The Easter Cave root mat community may not presently meet the criteria for classification as critically endangered, because it has survived lower water levels in the past. All stygofauna remains vulnerable to watertable lowering, however the threshold at which watertable lowering becomes critical to the survival of stygofauna remains to be determined.

Strategies for the conservation of subterranean biodiversity within the Jewel Cave karst system will be most effective if:

(a) They encompass all stygofauna communities, and not solely root mat communities;

(b) They are integrated with karst system processes, especially hydrogeologic and geomorphic processes;

(c) They are applied at an appropriate spatial and temporal scale, viz. karst catchment / karst geo-ecosystem.

The principal management issue relating to stygofauna concerns the need for revision of the Interim Recovery Plan (IRP) prepared by the Department of Conservation and Land Management (CALM). Threatening processes, recovery actions, fauna monitoring methods, and future research directions in the IRP need to be reviewed and reset.

In view of the wider distribution of stygofauna and root mat communities on the Leeuwin-Naturaliste Ridge, combined with increasing pressure from regional developments and associated threatening processes, a regional-scale survey and mapping of all karst catchments, karst drainage systems, and stygofauna needs to be undertaken. The survey needs to be initiated as a matter of high priority, by the government departments responsible for water resources (Water and Rivers Commission) and wildlife (CALM).

The Jewel Cave aquifer is very sensitive to contamination. A localized area of contamination occurs in the vicinity of the Organ Pipes in Jewel Cave, where groundwaters show concentrations of both chemical and biological species that are significantly higher than background levels. Elevated levels of metals, nitrate, bacteria and protozoa, are linked to a number of potential sources located both inside and outside the cave.

Key recommendations

1. Support prescribed wildfire hazard reduction burns in the Jewel Cave precinct and Cliff Spackman Reserve.

2. Monitor and evaluate the effects of fire treatment on groundwater recharge, including BACI monitoring of rainfall, leaf area index, ground fuel load, soil moisture, infiltration rates and watertable response.

3. Revise the Interim Recovery Plan for aquatic root mat communities in caves (CALM in process).

4. WA government (eg. Water & Rivers Commission, CALM) to instigate a regional-scale survey and mapping of all karst catchments, karst drainage systems, and stygofauna on the Leeuwin-Naturaliste Ridge .

4. To characterise and control the contamination in Jewel Cave, AMRTA to undertake:

(a) Further testing of water quality and investigation of different contaminant sources, including inter alia, a potential link between the septic system and cave waters;

(c) Remedial actions as appropriate.

Introduction

Background

When Jewel Cave was entered in 1958, the explorers encountered chest deep water and used a boat to explore some sections (Figure 28, p. 58). The walls and ceiling of the lake chamber were profusely decorated and the reflection of these formations in the lake waters formed a stunning display. The cave was developed and opened for tourism in 1959, with the lake and its reflections being a major attraction on the tour. Jewel Cave receives 45,000 visitors annually and it remains an important tourism attraction in the Margaret River region.

For a time water was pumped from the lake in Jewel Cave to augment the existing rainwater tank supply for the toilets, but by 1982 concerns were being expressed about the declining lake level. Pumping from the lake was discontinued around this time, but the water level continued to decline until by 1988 the lake and its famous reflections had all but disappeared. The watertable had dropped by an unprecedented 1.1 m in eight years. Since then the watertable has remained at a low level, and at time of writing (2002) is continuing to decline below the lowest levels ever recorded since 1958. Two other nearby caves, Easter Cave and Labyrinth Cave, have experienced a similar watertable decline. Until this study and report however, the causes of the watertable decline remained uncertain.

Jewel Cave and a significant portion of Easter Cave underlay Sussex Location 4174, being a portion of Class A Reserve 8438 (Cliff Spackman Reserve) within the Leeuwin-Naturaliste National Park. In 1961, Location 4174 (the Jewel Cave precinct) was vested in the Augusta-Margaret River Tourism Association (AMRTA) for the continued purposes of, *"Protection and Preservation of Caves and Flora, and for Health and Pleasure Resort"*.

Through CaveWorks, the AMRTA is responsible for the protection and preservation of Jewel, Easter, Moondyne, Skull and other caves within the Jewel Cave precinct. About two thirds of Easter Cave extends beyond the precinct boundary but still within the Cliff Spackman Reserve, however the AMRTA is responsible for managing access to the entire cave through the single accessible entrance situated within the Jewel Cave precinct.

During 1993, a lake in Easter Cave was found to contain species of aquatic fauna associated with submerged tree roots. This *aquatic root mat community*, together with root mat communities in three other caves on the Leeuwin-Naturaliste Ridge, and other caves at Yanchep near Perth, were identified as being *'on the brink of extinction'* due to falling watertable levels in both regions (Jasinska 1997). These communities were subsequently listed as critically endangered under the commonwealth *Environmental Protection and Biodiversity Conservation Act (1999)*.

The Department of Conservation and Land Management (CALM) in Western Australia prepared separate Interim Recovery Plans (IRP) for both the Leeuwin-Naturaliste Ridge and Yanchep cave communities. The IRP for the Leeuwin-Naturaliste Ridge outlined recovery actions required to ameliorate several threatening processes that were perceived to be affecting the survival of four identified root mat communities, including the community in Easter Cave (English and Blyth 2000). Lower rainfall, groundwater pumping and tree plantations were identified as processes contributing to the watertable decline. The IRP recommended, *inter alia*, that research be conducted into the hydrology of the caves, as well as the water quality requirements of the root mat communities.

In 1999 the AMRTA, through CaveWorks, initiated a three year research project to investigate the cause of the watertable decline in Jewel Cave, and the effects of this on the endangered fauna community in Easter Cave. The results of this research are presented in this report which contributes, in part, toward realizing the original vision and aims of CaveWorks - that of contributing to better understanding and protection of caves and karst throughout the Leeuwin-Naturaliste region.

Purpose and scope

Because groundwater is of vital importance to the natural integrity of the Jewel Cave karst system, this research aims to provide an understanding of the hydrogeological basis for management and protection of the groundwater resources and associated groundwater dependent ecosystem.

The primary research aims were to:

(a) Investigate the causes of the watertable decline in Jewel and Easter Caves;

(b) Investigate the distribution and ecological / conservation requirements of stygofauna, including the endangered root mat community in Easter Cave.

The research provides the hydrogeological and ecological framework for dealing with current environmental management issues associated with groundwater and subterranean fauna within the Jewel Cave karst system. The framework will form the basis for future research, management and development projects. It also has broad relevance and implications for research, monitoring and management of other cave systems on the Leeuwin-Naturaliste Ridge, and elsewhere in Western Australia. Specific recommendations are given for management of water quantity and water quality, and subterranean biodiversity. This report does not cover environmental management issues not directly associated with groundwater.

Location

Leeuwin-Naturaliste region

The Leeuwin-Naturaliste geographic region is a distinctive anvil-shaped promontory at the southwestern tip of southwest Western Australia (Figure 1). It is bounded by Geographe Bay to the north, the Indian Ocean to the west, and the Southern Ocean to the south. The Leeuwin-Naturaliste Ridge is a narrow strip of coastal limestone ridge extending approximately 90 km between Cape Leeuwin in the south and Cape Naturaliste in the north.

Study area

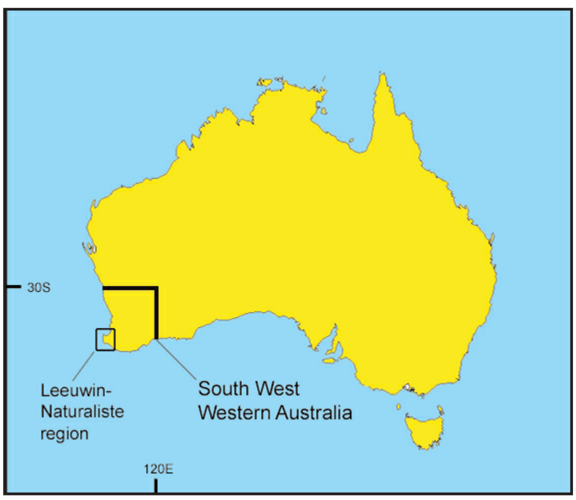


Figure 1. *Location of southwest Australia and Leeuwin-Naturaliste regions.*

Jewel Cave is located in the *Augusta karst area* which comprises the section of coastal limestone ridge situated between Cape Leeuwin and Turner Brook (Figure 4, p. 6). The section of ridge is up to 3.5 km wide and 14 km in length, with a surface area of about 40 km² and reaching an elevation of 210 m above sea level.

Regional and local setting

Climate

The climate is a Mediterranean type with hot dry summers and mild wet winters. Most rainfall occurs between April and October. The average annual rainfall ranges from 838 mm at Cape Naturaliste to 1192 mm at Margaret River, with inland sites (Margaret River and Forest Grove) experiencing up to 21 % more winter (June-July-August) rainfall than coastal sites.

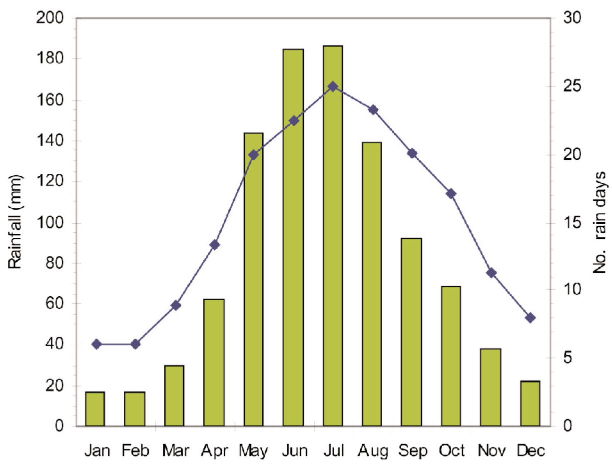


Figure 2*. Long term average monthly rainfall and number of rain days at Cape Leeuwin (1897 - 2000).*
Data from Bureau of Meteorology.

The nearest currently operating meteorological station to Jewel Cave is at Cape Leeuwin, located 11 km to the south, for which rainfall records have been collected since 1897. The long term (1897 -2000) average annual rainfall at Cape Leeuwin is 998 mm. Long term average monthly rainfall, and number of rain days, for Cape Leeuwin are shown in Figure 2.

Geology

A simplified regional geology is shown in Figure 3. The Leeuwin Complex consists of strongly metamorphosed igneous rocks (granitic and anorthositic gneisses) (Myers 1994). The Leeuwin Complex and the basement beneath the Perth Basin to the east form part of the Pinjarra Orogen, accreted to the western margin of the Yilgarn Craton during the Proterozoic. The Perth Basin contains Mesozoic sediments deposited within a rift system developed on the older orogen. The Yilgarn Craton consists mainly of Archaean (> 2500 Ma) granitoid rock (Hassan 1998), whilst the Leeuwin Complex consists of younger (ca. 540 - 780 Ma) rocks of Proterozoic age. The Dunsborough Fault forms a structural boundary between the eastern margin of the Leeuwin Complex and the Perth Basin which contains the Vasse Shelf and Bunbury Trough (Lasky 1993).

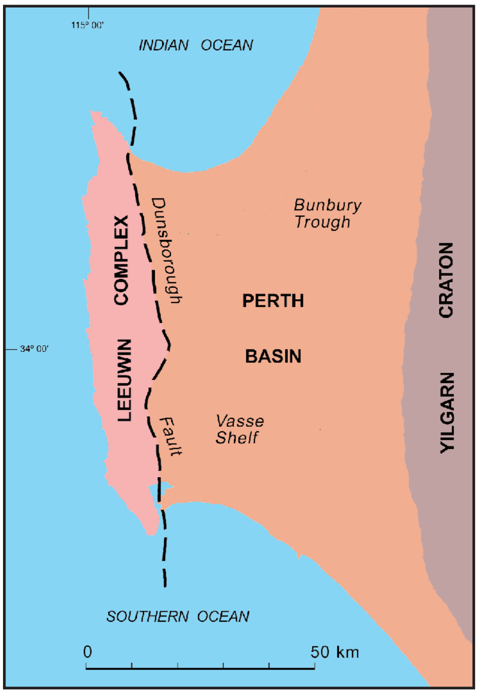


Figure 3. *Selected tectonic elements of the southern Perth Basin. Adapted from Lasky (1993).*

Most of the Leeuwin Complex and Perth Basin rocks are overlain by a veneer of Cainozoic regolith composed of residual and transported materials, including colluvial (mass-wasting), fluvial, aeolian, coastal and marine materials (Hall and Marnham 2002; Hassan op. cit.). A laterite duricrust covers much of the area. A succession of shorelines and associated dune deposits ranging from Pliocene to Holocene in age extends along the coastal margins (Figure 4). These units include the 'Tamala Limestone' which contain the cave systems.

Geomorphology

The Leeuwin-Naturaliste region has been divided into five geomorphic / physiographic sub-regions (Tille and Lantzke 1990) (Figure 4). The *Blackwood Plateau* is a gently undulating, dissected plateau formed on the laterized sedimentary rocks of the Perth Basin. The *Margaret River Plateau* is a gently undulating, dissected plateau formed on the laterized surface of the Leeuwin Complex. The *Leeuwin-Naturaliste Coast* corresponds to the narrow strip of Plio-Pleistocene and Holocene dune sediments which forms the prominent landscape feature known as the Leeuwin-Naturaliste Ridge. The *Swan Coastal Plain* is a flat to gently undulating plain formed on Quaternary marine, alluvial and aeolian sediments, whilst the *Scott Coastal Plain* is an analogous structure located in the south (Baxter 1977; Tille and Lantzke op. cit.).

The coastal plains abut the Blackwood and Margaret River Plateaus, at the *Whicher Scarp* in the north and the *Barlee Scarp* in the south. The scarps are located between about 20 to 40 m above present sea level, and are interpreted to be marine erosion features (Baxter op. cit.). The sequences of Quaternary shoreline and dune deposits extends from the oldest, most inland deposits at the base of the scarps, with successively younger deposits further shorewards. In order these are the Yoganup Formation, Bassendean Sand, Spearwood Dune System and the Quindalup Dune System. The Spearwood System incorporates dune limestones ('Tamala Limestone') of presumed Pleistocene age which contains the caves, whilst the Quindalup System is composed of younger (Holocene) sand dunes and beach deposits (Hall and Marnham 2002).

Vegetation

The Augusta karst area is situated within the Warren Botanical Subdistrict (Karri Forest Subregion), and includes tall forests of karri on deep loams, with forests of jarrah-marri on leached sands (Beard 1990).

The vegetation directly overlying the cave systems is tall (20-40m) open karri (*Eucalyptus diversicolor*) forest developed on well drained reddish brown loam sands of the Spearwood System. The karri forest understorey in this area is dominated by peppermint (*Agonis flexuosa*). West of the Spearwood-karri forest association, calcareous sands of the Quindalup System support coastal scrub heath and heath dominated by *A. flexuosa*, *Banksia grandis*, *E. angulosa, Acacia* spp. Leached sandy soils at the foot of the limestone ridge alongside Caves Road support jarrah-marri forest (*E. marginata-E. calophylla*). East of Caves Road, most native vegetation has been cleared to pasture.

Land use

Europeans settled Augusta in 1830 and although most of the Augusta dune ridge remains uncleared, the area has a long history of agricultural development. Grazing of dairy cattle was the main basis of agriculture, although forestry was also an important early industry. On the eastern side of the ridge, the growth of viticulture, horticulture and other economic enterprises is changing the nature of land use, which together with tourism developments and Rural Residential subdivisions, has increased the potential for land use conflicts (*Leeuwin-Naturaliste Ridge Statement of Planning Policy Report 1998*).

Methods

Brief descriptions of the methods are included, where appropriate, in relevant sections of the report, embedded in tables and table footnotes, and in the appendices. Detailed descriptions of methods will be provided in the thesis and published papers following this work.

Definitions and abbreviations

In this report the abbreviation 'JELSS' is used to refer collectively to both the Jewel-Easter Subsystem and the Labyrinth Subsystem. In some instances, this description is simplified to Jewel Cave Karst System, or 'JCKS', although this term implicitly includes both Easter Cave and Labyrinth Cave. The Jewel-Easter Subsystem is distinguished from the Labyrinth Subsystem where necessary in the text.

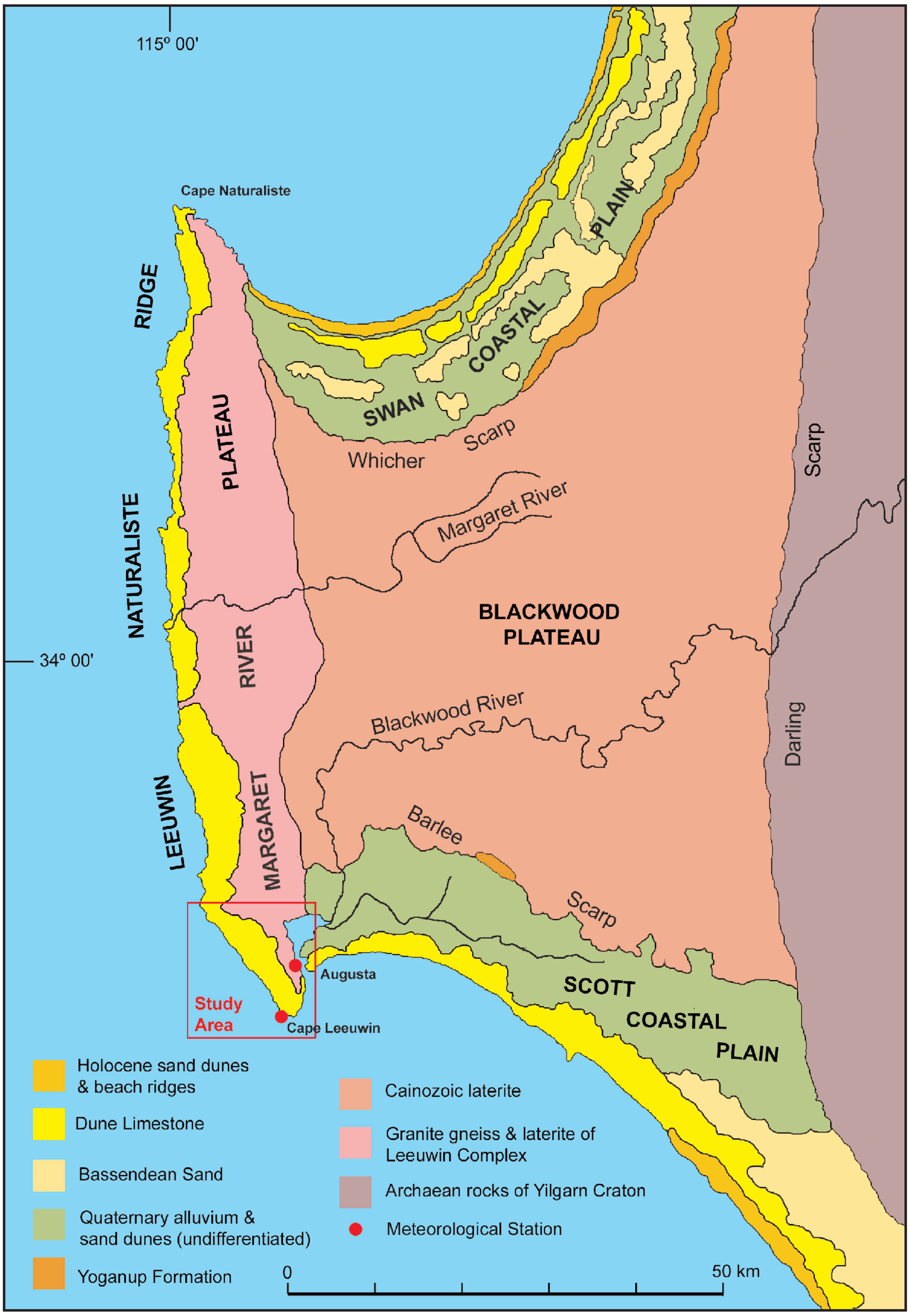


Figure 4. *Study area showing selected topographic, geomorphic and geologic features of the Leeuwin-Naturaliste region. Adapted from Baxter (1977), Hassan (1998), Tille and Lantzke (1990).*

Catchments and Karst Sub-Systems

Catchment areas and karst subsystems

The Augusta karst area is subdivided into three major water catchment areas based on the major surface watercourses that drain them - Turner Brook, West Bay Creek and Estuarine-Coastal - the last is an amalgam of streams that drain directly into the estuary of the Blackwood River, the Southern or Indian Oceans.

Within each catchment area, a number of *karst subsystems* are identified, based on the geographic clustering of karst features or interpreted groundwater catchment boundaries. The karst subsystems, catchment areas, and identified karst features within each are listed in Table 1, with locations shown in Figure 5.

The greatest concentration of caves with entrances presently open to the surface occurs on the inland flank margin of the dune ridge between Turner Brook and Greenhill Road. Located within this area are the Jewel-Easter, Labyrinth, Creswell Road, and Deepdene subsystems. Potentially significant cave and karst development also occurs on the inland flank margin of the ridge between Greenhill Road and Turners Spring - the Greenhill Road, Hillview Road, and Turners Spring subsystems.

The absence of cave openings which breach the surface should not be construed to indicate an absence of karst, or major subsurface cavities, since cave entrances may be blocked by collapse, or obscured by sands. An example of this is the Lost Leeuwin Cave explored in

Table 1. *Surface catchment areas and karst subsystems in the Augusta karst area.*

Surface catchment area	*Karst subsystem*	*Identified karst features*
Turner Brook	Deepdene	Deepdene Cave, Deepdene Spring, caves in Deepdene Gorge, AU17
	Creswell Road	AU-2, 3, 28
	Labyrinth	Labyrinth Cave, AU-4, 5, 6, 7
West Bay Creek	Jewel-Easter	Jewel, Easter, Moondyne Caves, AU-8, 9, 10, 12, 20, 21, 29, 30
	Greenhill Road	doline at AGD3266/62036, ?Lost Leeuwin Cave
Estuarine-Coastal	Hillview Road	Solution pipes, springs at base of ridge
	Turners Spring	Turners Spring
	Leeuwin Spring	Leeuwin Spring
	Quarry Bay	Springs and tufa
	Other undefined subsystems	Eg. Numerous small springs between Skippy Rock and Barrack Point

1958 when a small opening in the ground was descended on ladders to a stream passage and a waterfall, with unexplored passage continuing beyond. The explorers, Lloyd Robinson and Cliff Spackman, later returned but could not relocate the entrance which is believed to have been obscured by sand or collapse (*The Western Caver December 1969,* Vol. 9(6): 121).

Cave development on the seaward (western) flank of the Augusta dune is very limited, as it is elsewhere along the Leeuwin-Naturaliste Ridge, and this may be partly due to burial of features beneath younger dune limestones and unconsolidated sands (Bastian 1964, Jennings 1968). Nonetheless drainage is entirely subsurface and significant karst features exist, for example, the Leeuwin Spring and Quarry Bay tufa deposits.

Jewel - Easter and Labyrinth Subsystems

The Jewel-Easter and Labyrinth subsystems (JELSS) are confined within a narrow belt generally less than 500 m wide and extending for a little over 2 km in a NW-SE direction, parallel to the long axis of the dune ridge (Figure 6). The majority of cave entrances are situated between 50 and 65 m AHD, but two caves (AU- 9, 10) are situated at 90 m AHD. Cave development on either side of this narrow band is limited by the eastern boundary of the limestone, whilst towards the west the older limestone containing the caves is mantled by younger unconsolidated sands above 90 m AHD.

The JELSS occupies a land surface area of some 2 km^2 with most cave passage development (> 8 km) occurring in Jewel (2 km), Easter (> 4 km), Labyrinth (> 2 km), and Moondyne (< 400 m) Caves (Appendices 1 - 5). With the exception of Moondyne, these caves are primarily developed within a narrow vertical watertable zone of 5 m thickness, ranging from 22.5 to 27.5 m AHD.

In year 2002 the watertable stood at 23.4 m ASL, which is close to floor level in the cave passages.

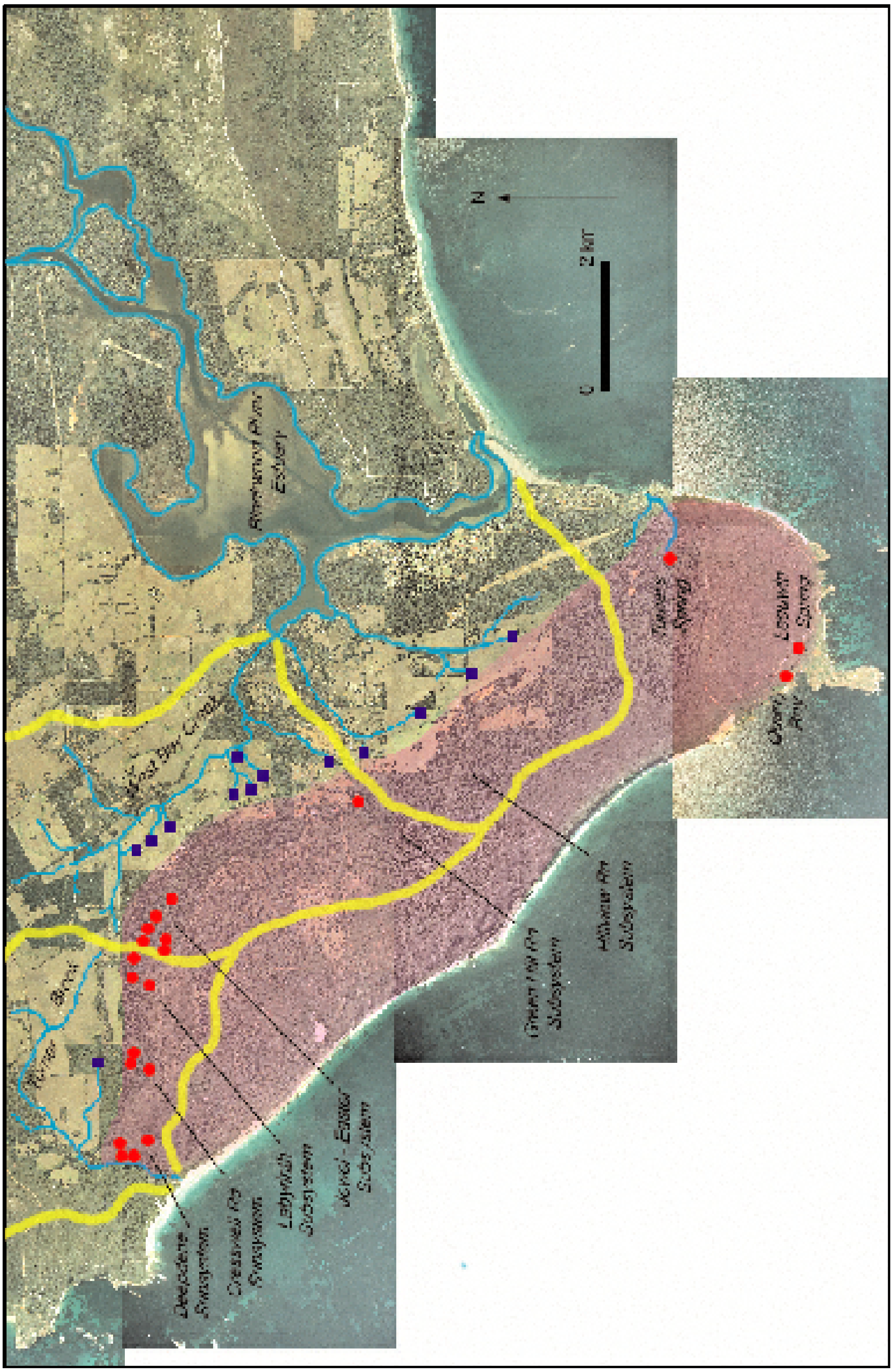


Figure 5. *Augusta karst area (pink) showing surface drainage (light blue) and surface catchment divides (yellow), karst features (red dots) and karst subsystems, plus adjacent sites of groundwater discharge (dark blue squares).*

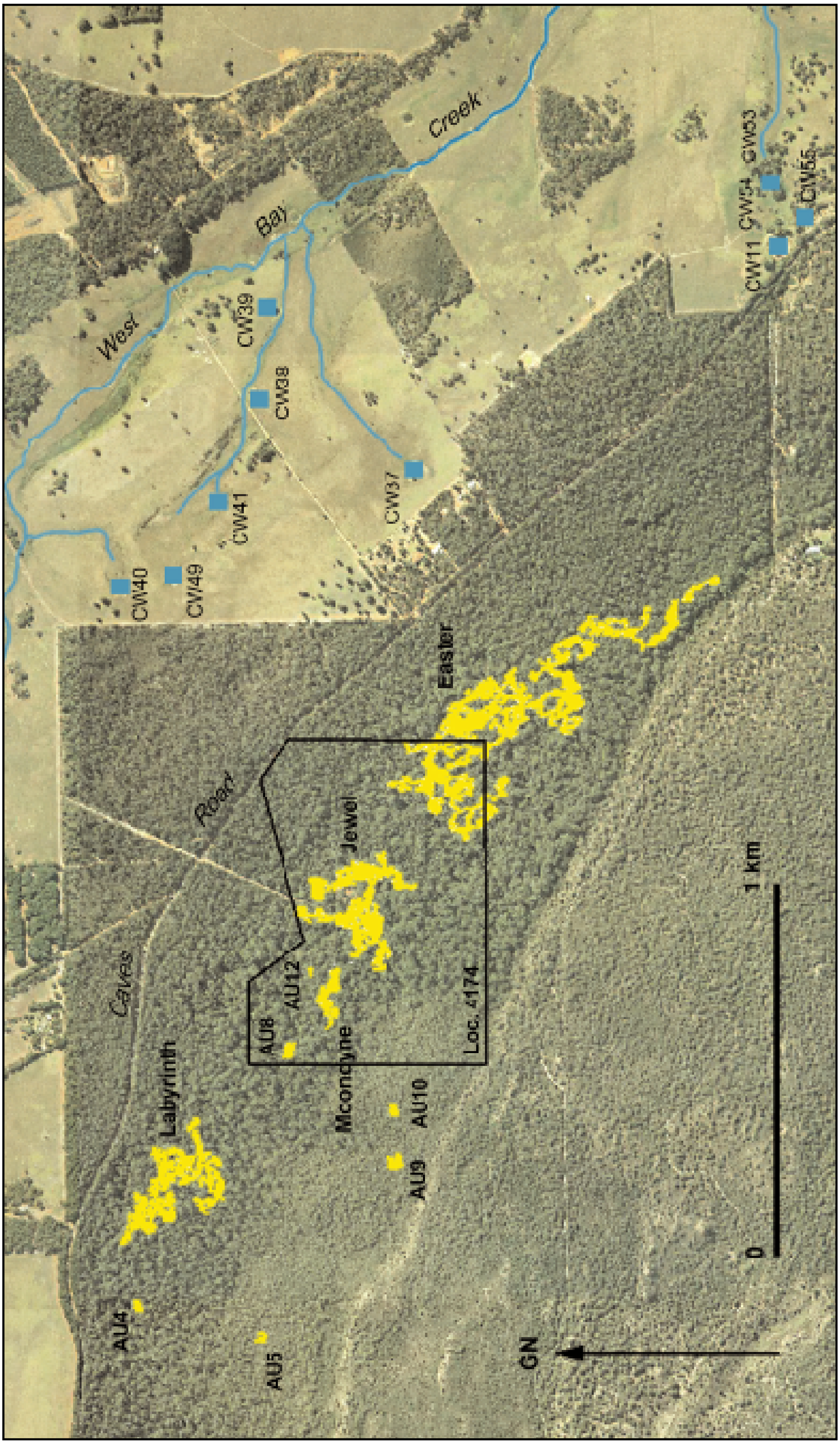


Figure 6. *Surveyed caves (yellow) within the Jewel-Easter & Labyrinth Subsystems. Surface water courses, springs and seepage dams, (including site reference number) are shown in blue. Dune margin is aligned approximately along Caves Road. Boundary of Jewel Cave precinct (Location 4174) shown within the Cliff Spackman Reserve (Leeuwin-Naturaliste National Park).*

Stratigraphy and Age of the Limestone

Introduction

The age of the Augusta dune limestone, and of the caves developed within the limestone, is poorly constrained. Constraining the ages for the onset of both karstification and speleogenesis is important for determining the rates of karst system processes, including ecosystem processes, and to provide a time scale for the evolutionary development of the karst fauna.

In terrestrial limestone such as aeolian calcarenite, the process of eogenetic diagenesis and syngenetic karst development - where karstification may be initiated more or less simultaneously with consolidation of the dune sands - has been invoked to explain the development of large cave systems within the comparatively young (Pleistocene) dune limestones of Western Australia (Bain 1967, Bastian 1964; Ford & Williams 1989, Grimes 1997, 2002; Jennings 1968). If syngenetic karstification is assumed, as is generally the case for soft calcareous dune limestones throughout Western and Southern Australia, then the age of the cave systems may be close to that of the host sediments. This is relevant to constraining the timing of colonisation by groundwater fauna.

The aim of this investigation then, was to better constrain both the age of the limestone, and the age of the cave systems. The age of the limestone and caves were investigated by field stratigraphic mapping and thermoluminescence dating of the basal limestone unit, and chrono-stratigraphic correlation with other sedimentary units and palaeo-shorelines.

Stratigraphy

The 'Tamala Limestone' is a bioclastic calcarenite deposited in coastal dune and nearshore environments. The calcarenite unconformably overlies hard and impermeable Late Proterozoic granulite-gneiss of the Leeuwin Complex (Myers 1994). The basement rocks are visible in the lower passages within Jewel Cave and the *Gneiss Extension* within Easter Cave. The basement surface is irregular with isolated outcrops appearing as *in situ* boulder or ridge-like structures projecting above the floor level of passages. The basement is not visibly exposed in Labyrinth Cave, nor elsewhere in the JELSS, although presumably it lies not far beneath the floors of the lower level cave passages. The floors of cave passages are generally composed of in situ limestone bedrock, or are buried in sediment or collapsed blocks.

Drilling in the floor of the *Lake Chamber* in Jewel Cave revealed clayey sediments to depths of up to 2.6 m, interspersed with layers of coarse crystalline calcite interpreted to be old pool deposits. A deeply weathered granite surface was contacted at a depth 1.5 m below floor level in the vicinity of the *Organ Pipes* (T. Brown pers. comm., 2001).

The JCKS is developed within a consolidated limestone dune that consists of a number of distinct stratigraphic units that are exposed in section within passages and chambers that truncate the strata. The lowest level of cave passages throughout the JCKS lie between 22.5 and 27.5 m AHD, whilst the surface of the dune containing the cave entrances lies generally between 50 to 65 m AHD. The basal limestone unit in Jewel Cave is a marine deposit. The marine unit occurs in lower level passages in the vicinity of the *Y Junction* in Easter Cave, although other parts of this cave are also excavated in aeolian units. The marine facies consists of fine-laminated calcarenite displaying small-scale cross-bedding features of subtidal origin, and bands of dark-coloured heavy minerals. Bedding dips are shallow ($< 15^{o}$). In the *Flat Roof One* and *Volcanoes* passages in Jewel Cave the dip direction is SW, whilst at the *Y Junction* in Easter Cave it is SE.

The upper margin of the basal limestone unit is typically capped by a *palaeosol* (fossil soil) unit, or units, that generally lie between 25 and about 30 m AHD. The palaeosols are coloured dark red, yellow or grey and are generally less than 0.5 m thick although a grey palaeosol between the *Y Junction* and *Epstein* in Easter Cave is more than 3 m thick. The palaeosols contain calcified plant roots (*rhizomorphs, rhizoliths*, or *rhizo-concretions*), and casts of shells of the common terrestrial mollusc *Bothriembryon* sp. These lower palaeosols are sometimes capped by a layer of flowstone calcite some 200 - 400 mm thickness, the calcite layer often remaining in the ceiling of passages after collapse and removal of the less resistant palaeosols.

The contact between the limestone and overlying palaeosols is sometimes a karstified surface displaying rounded subsoil solution features (*rundkarren*) and solution pipes, as exposed, for example, in Moondyne Cave. Solution pipes filled with palaeosol penetrate into the underlying limestone unit.

Successive episodes of calcareous sediment deposition followed by subaerial weathering and soil formation are evident throughout the profile as a stacked series of limestone-soil 'couplets' (*sensu* Hearty and Kaufman 2000). The basal limestone-soil couplet is overlain by at least two, and possibly more, limestone-soil couplets representing later episodes of aeolian deposition and dune stabilisation. In the SE sections of Easter Cave the aeolian units strike roughly NW-SE and dip between 30-35^{o} NE. The fossil soils within the aeolian units are grey-coloured bands generally less than 500 mm thick. The bands are well lithified and commonly contain angular dark-coloured clasts, described as pedocalcic breccias by Yonge (1997). The absence of stratification in these bands identifies them as *protosols* (*sensu* Vacher & Hearty 1989).

Vertical sections of the aeolian strata and palaeosols are exposed by upward stoping of the roof of the underlying watertable cave systems, with collapsed material accumulating in the prior chambers. The section exposed in the entrance chamber of Jewel Cave includes aeolian units about 10 m and 21 m thick respectively. A caprock containing well developed solution pipes is developed in the top 9 m of the upper aeolian unit - the thickness of caprock and well developed rundkarren features is suggestive of prolonged exposure to subaerial weathering of the upper most aeolian unit. The present karst surface overlying the JCKS is obscured by deep yellow-brown siliceous sands (Tille and Lantzke 1990).

Lying uphill to the west of Jewel Cave between about 70 and 90 m AHD there is a younger but well consolidated dune identified by Bain (1967). The surface of this dune unit has been stripped of covering sediments to reveal a strongly karstified surface exhibiting rounded subsoil weathering features including rundkarren and perforating tubes. Since removal of the soil cover the rock has been exposed to direct aerial wetting resulting in rain pitted surfaces and sharply etched solution flutes (*rillenkarren*) (Jennings 1985). The entrances of several caves (Old Kudardup, AU10 and possibly Bat Cave) are developed within this younger dune, whilst Jewel, Easter, Moondyne and Labyrinth Caves are developed within the older dune.

The aeolian limestone-soil couplets vary considerably in their elevation, thicknesses, and disposition throughout the JCKS, this reflecting the fluctuating conditions of a dune-swale sedimentary environment. This has complicated stratigraphic correlation of units between different sections, including an upper margin for the basal marine unit in Jewel Cave which remains to be identified. A generalized schematic interpretation of the limestone stratigraphy is shown in Table 2.

Age

The age of the limestone in the Augusta karst area is poorly defined. The limestone is assigned geomorphologically to the Spearwood Dune System, and geologically as the 'Tamala Limestone' (Abeysinghe 1998; Playford et. al 1976). Previously it was known as 'Coastal Limestone' (Lowry 1967). The interpreted age of this 'formation' ranges from Middle to Late Pleistocene, but Murray-Wallace and Kimber (1989, citing Wyroll & King 1984) emphasise that the 'Tamala Limestone' is strongly diachronous and caution should be exercised in its correlation between different localities. 'Tamala Limestone' is described variously as Late Pleistocene (10 - 125 ka) (Abeysinghe 1998; Marnham et al. 2000) to Middle Pleistocene (125 - 750 ka) in age (Kendrick et al. 1991; Murray-Wallace & Kimber 1989). The next oldest date for the 'Tamala Limestone' comes from a sample taken at Kings Park, Perth that yielded a TL age of > 422 ka, implying that onset of the deposition of the 'Tamala Limestone' occurred in the Middle Pleistocene or earlier (Price et al. 2001).

Based on residual soil mineralogy and geomorphic context, Bastian (1996) substantiated the multi-aged, or polychronous, origins and subdivided the Spearwood Dune System into several dune subsystems. The dune subsystems run parallel to each other and the present coastline, and increase in age from the present shoreline eastwards (Bastian 1964). Based on the number of ridges identified on the Swan Coastal Plain, and assuming that their close proximity probably means that some ridges are buried, Bastian (1996) suggested the possibility that the 'Tamala Limestone' spans a substantial portion of the Pleistocene. This does not preclude the possibility that a range of ages comparable to that proposed for the Pleistocene beach ridges of southeast South Australia (Idnurum & Cook 1980) is represented.

Huntley et al. (1994) used TL dating techniques and palaeomagnetism to bracket the ages of the stranded dune sequences in southeast Australia over the last 800 ka. These dune sequences have been preserved because this flat region has been progressively uplifted during the Quaternary. The dune sequences on the flat-lying Swan Coastal Plan also form a well-defined prograding sequence decreasing in age towards the present coastline. On the Leeuwin-Naturaliste Ridge however, the dunes are vertically stacked on top of eachother, with older dunes buried by younger dunes, and these sequences eroded during later high-stands of the sea.

The oldest dated sediment from a cave formed in 'Tamala Limestone' is a uranium-series date of a flowstone speleothem in Moondyne Cave - 627.4 ka - whilst the ages of six other speleothem samples from this site and Jewel Cave ranged upwards from 197.4 to 466.6 ka (Marianelli 2000; Marianelli et al. in press). These uranium-series ages establish a minimum age for speleothem development at 627,000 years (Middle Pleistocene) - hence the deposition of the limestone must predate this, presumably by a considerable amount. Systematic differences in the uranium chemistry of speleothem calcite specimens from the Augusta caves (Jewel and Moondyne), compared with other caves in the Leeuwin-Naturaliste Ridge (Golgotha, Tight Entrance, Quininup and Yallingup), may reflect significant age differences between the Augusta dune ridge and other dune ridges in the Leeuwin-Naturaliste region, the Augusta dune ridge being significantly older (Marianelli 2000). Marianelli's data indicates that, at least in the Leeuwin-Naturaliste region of the Perth Basin, dune sequences older than Middle Pleistocene are likely present.

Thermoluminescence dating

Undertaken as part of this study, thermoluminescence (TL) dating of a sample of limestone from the basal marine unit in Jewel Cave yielded an age > 781 +/-57 ka. The TL age corresponds to Marine Isotope Stage 21 or older, which is consistent with Marianelli (2000) data which suggests limestone may be older than Middle Pleistocene. Following the Quaternary time scale of Williams et al. (1998), the TL age for the JCKS limestone falls within the late Lower Pleistocene (750 - 1,800 ka). The TL age determination is close to the *Bruhnes-Matuyama* magnetic reversal at about 780 ka. Palaeomagnetic studies may therefore help in further constraining the age of the limestone. Tabulation and further discussion of the TL results appears in Appendix 17.

Correlation with palaeo shorelines

The elevation of the JCKS marine unit and palaeo shoreline, at about 23 to 28 m AHD, cannot be readily correlated with known high sea level stands or other marine limestone units in the region. This makes chrono-stratigraphic correlation difficult. All other known high sea level stands associated with the 'Tamala Limestone'fall below 10 m ASL and are generally inferred to be Last Interglacial (MIS 5e) or younger in age (Fairbridge & Teichert 1952). Documented palaeo shorelines and associated sedimentary deposits of > 20 m AHD relate to high sea stands of presumed Late Pliocene to Early Pleistocene age (Baxter 1977, Kendrick et al. 1991). These include the Yoganup and Ascot Formations, and the Bassendean Sand. The Ascot and Yoganup Formations are thought to be lateral equivalents (Baxter and Hamilton 1981 *cited* Davidson 1995). Chrono-stratigraphic correlation of the 'Tamala Limestone'carbonate sediments with these predominantly siliclastic units is not generally supported on lithostratigraphic or biostratigraphic evidence (Kendrick et al. 1991), however, the Ascot Formation includes subordinate carbonate units, so carbonate sedimentary environments were present at times during the Late Pliocene to Early Pleistocene.

Playford and Leech (1977) and Semenuik & Searle (1986) attributed variability of Holocene sea level history along the south western coast to the effect of significant local tectonism. The position of the JCKS limestone indicates at least 20 to 30 m of uplift since deposition. This interpretation has been applied to other sediments from the Perth Basin that points to some 20 to 30 m of uplift since the Pliocene, including ca. 20 m of uplift for a Middle Pleistocene marine unit located 11 km southwest of Busselton (Kendrick et al. 1991).

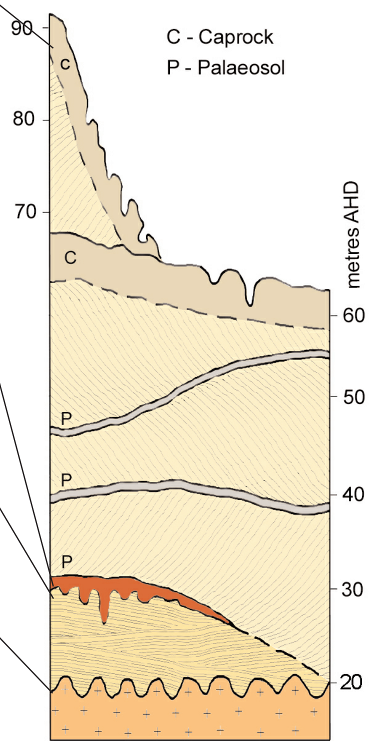
Two kilometres to the east of Jewel Cave, the northern edge of the Scott Coastal Plain meets the base of the Barlee Scarp, which is interpreted to be a marine scarp extending from Augusta to Cape D'Entrecasteaux (Figure 4, p. 6). The Donnelly Shoreline at the base of the Barlee Scarp, lies between 20 and 35 m above sea level, and appears equivalent to the Yoganup Shoreline on the Swan Coastal Plain (Baxter 1977). Age correlation of the Yoganup-Ascot Formation is not well constrained, but the formation comprises a sequence of depositional events that indicate a Late Pliocene to Early Pleistocene age (Kendrick et al. 1991). The Yoganup Formation is a shoreline deposit consisting of beach and dune sediments exposed along the base of the Whicher and Darling Scarps between 25 and 50 m above present sea level (Baxter op. cit.). This altitude range closely corresponds with the elevation of the JCKS 23-28 m shoreline, to which it is tentatively correlated.

Conclusions

The Augusta dune limestone is multi-aged and consists of a basal marine unit and palaeosols overlain by punctuated sequences of aeolian limestone-soil couplets.

Thermoluminescence dating and altitudinal correlation with palaeo shorelines suggest an early Pleistocene or Late Pliocene age for the basal marine unit of the Augusta dune limestone.

Table 2. *Simplified interpretation of the lithostratigraphy of the Augusta dune limestone in the vicinity of Jewel Cave.*



Time period	*Geologic 'units'*	*Stratigraphy*	*Description*	[1] *Determined ages*	*Notes*
Early Pleistocene	Spearwood Dune System Aeolian limestone-soil couplets		Deposition of aeolian units with protosol development – two or more limestone-soil couplets. A thick layer of caprock is developed from the present surface. A younger lithified dune partly overlies an older lithified dune sequence.	Older than watertable caves	Caves truncate limestone-soil couplets Collapsed material in caves is consolidated
Early Pleistocene or Late Pliocene	Lower palaeosols and palaeokarst		Subaerial exposure and early syngenetic karstification – soil & solution pipe development	Similar age to marine unit, but younger	After emergence of marine unit
	Marine limestone unit		Deposition of marine limestone unit on granitic-gneiss basement	> 780 ka (+/- 57 ka)	TL age of marine limestone unit (Eberhard & Price in prep.)
Proterozoic	Granitic gneiss basement		Granitic-gneiss basement of the Leeuwin Complex	550 - 570 ma 1,130 – 1,160 ma 540 - 760 ma	U-Pb zircon date (Wilde & Murphy 1990) Sm-Nd model ages (McCulloch 1987) U-Pb date (Nelson 1996 cited Hassan 1998)

[1] ka - 10^3 years; ma - 10^6 years

[2] See section on palaeohydrology and sediments for more details

Speleogenesis

Speleogenesis in the Augusta dune ridge is confined to older limestones belonging to the Spearwood Dune System that are exposed on the lower slopes of the inland flank of the dune ridge. The younger, less consolidated limestones of the Quindalup Dune System contain solution pipes, caprock and rhizomorphs, but no enterable caves, although some development of conduit drainage is evident near spring exsurgences. The Quindalup dunes are mostly deposited on the seaward flank of the ridge and partly mantle the underlying Spearwood dunes. Some cave systems developed in the Spearwood dunes may therefore lie obscured beneath this mantle.

Most cave development is concentrated within the northern sector of the Augusta dune ridge. This includes the Deepdene, Creswell Road and Labyrinth karst subsystems within the Turner Brook catchment, and, the Jewel-Easter karst subsystem within the West Bay Creek catchment (Figure 5). The caves within these four subsystems share morphological characteristics that suggest a genetic relatedness of development associated with fossil watertable levels.

Cave Patterns

Cave patterns are controlled by a hierarchy of hydrogeologic influences: (1) The location and overall trend of a cave depends on the distribution of recharge and discharge points; (2) The passage pattern (branchwork vs. maze) depends on the mode of groundwater recharge and flow; (3) The orientation of individual passages is controlled by geologic structure and geomorphic evolution of the aquifer (Palmer 1991, 2000).

Speleogenesis immediately below the water table is indicated by passage morphologies that are wide in cross section and have flat ceilings (Figure 7). The dominant passage morphologies, at both small and large scales, are spongework which is characteristic of dissolutional erosion within the phreatic zone under hydraulic conditions that typically involve slow or stagnant water movement (Lauritzen and Lundberg 2000). Small diameter scalloping on flat passage ceilings is indicative of relatively rapid water movement which occurs close to the piezometric surface under epiphreatic conditions. The small-sized scalloping is overprinted on larger scalloping and spongework.

Figure 7. *Flat Roof chamber and lake in Jewel Cave 1977. The flat scalloped ceiling marks an upper limit of water table development at 27.4 m AHD. Photo by Peter Bell.*

Confinement of phreatic spongework features to within a 5 m vertical range between 22.5 - 27.5 m AHD, indicates the range in watertable levels experienced during the geomorphic evolution of the watertable caves (Figure 9). Development of cavities above the water table zone is caused by upward stoping collapse of material from above cave passages accompanied with partial removal of the collapsed material by dissolution below the watertable. Cave entrances are formed when solution pipes intersect underlying collapse cavities (eg. Jewel, Easter, Labyrinth Caves), or when upward collapse breaches the surface (eg. Skull Cave).

Owing to the predominance of piezometric components, Jewel (6AU-13), Easter (6AU-14) and Labyrinth (6AU-16) Caves fall into the category of *Ideal Watertable Caves* based on the Four State Model for the development of common cave systems (Ford and Ewers 1978). This model was originally devised for jointed and bedded hard-rock limestones, so the mechanisms may not be entirely applicable to porous soft-rock karst, however for descriptive purposes the term is useful. This category of cave is characterised by a virtual absence of deep phreatic components, in this instance such development being limited by the impermeable basement rocks. These caves have developed under shallow phreatic conditions.

The pattern of passages within the Jewel, Easter and Labyrinth Caves is predominantly that of a *spongework maze* (sensu Palmer 1991) as shown in Figure 8.

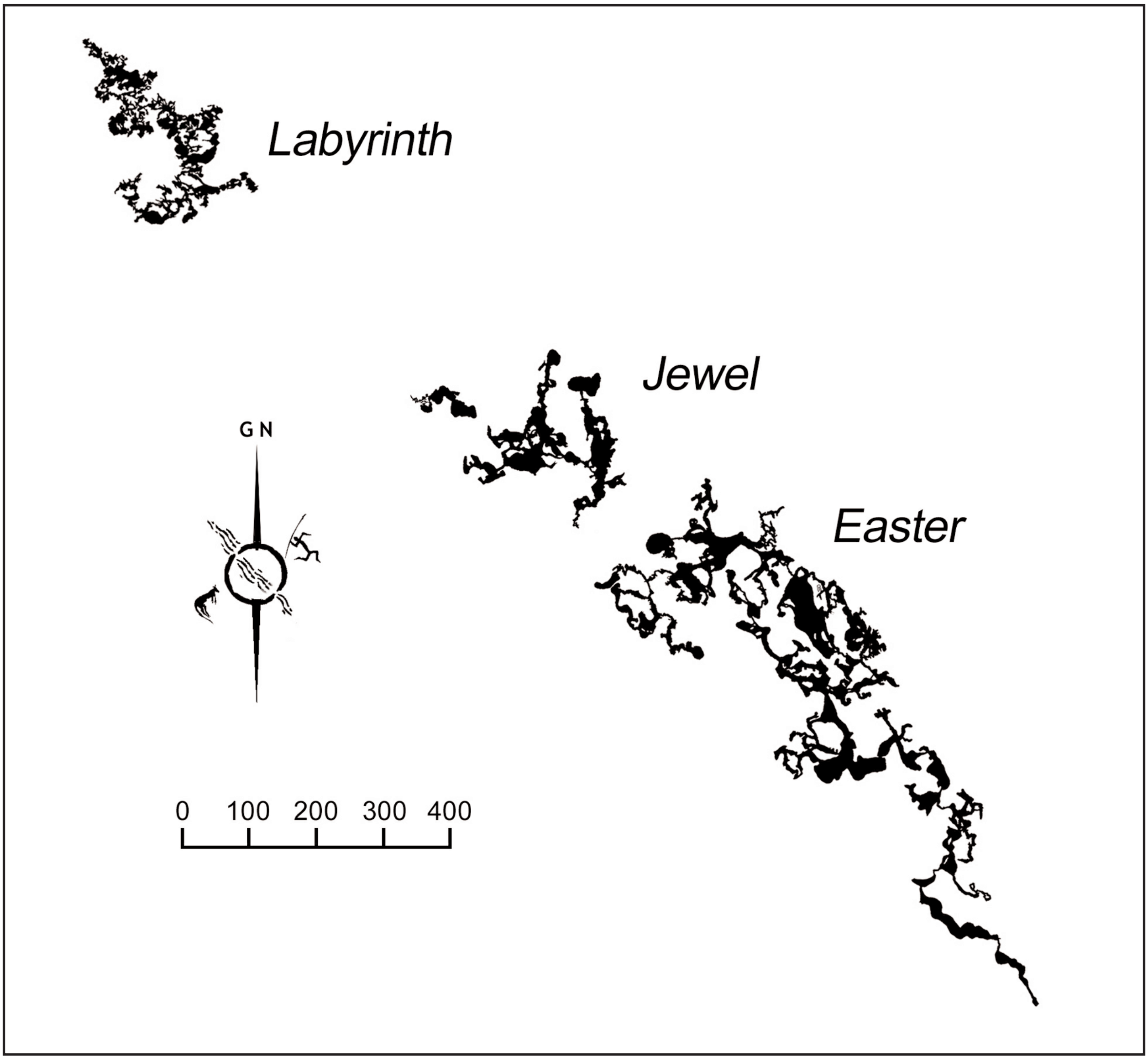


Figure 8. *Plan of Jewel-Easter and Labyrinth Caves showing spongework maze patterns of development. Scale is metres.*

Spongework maze caves are formed by diffuse, vertical autogenic recharge into carbonate rocks of high primary porosity. Spongework maze caves can also be formed by recharge that enters the soluble rock as bank storage along entrenched rivers during floods (Palmer 1991, 2000). Considering the proximity and similar elevation of the caves to adjacent streams and swamps in Turner Brook and West Bay Creek, a lateral component of flood or swamp water recharge might also be invoked in speleogenesis at this locality. This interpretation is supported by the small-diameter scalloping on flat passage ceilings at about 27.5 m AHD, indicating dynamic flow conditions at times during high water levels. in a southeast direction parallel to the dune margin The small-diameter scalloping is superposed on the dominant spongework pattern. At three locations in Jewel -Easter Cave where flow direction could be inferred from the scallop orientation, flow was apparently towards the south, however further measurements are needed to establish if this is the general pattern throughout the system.

Macroscopic horizontal openings, that might either have been inflow or outflow points for streams or springs, are unknown in the watertable maze caves. All these caves are entered by secondarily developed vertical openings on the ridge (Figure 9). The absence of horizontal openings and associated blind valleys or steepheads (*sensu* Jennings 1968, 1985) implies that sinking streams and resurgences, as common elsewhere in the Leeuwin - Naturaliste karst, were not involved in the development of the watertable maze caves, although it is possible that fossil inflow and outflow caves may have collapsed or subsequently been buried beneath sediments.

The pattern of maze development is most pronounced in Labyrinth Cave, so that distinct flow paths through the maze are not readily discernible (Appendix 4). In Jewel and Easter Caves, anastomotic and rudimentary branchwork patterns are superposed on the primary maze

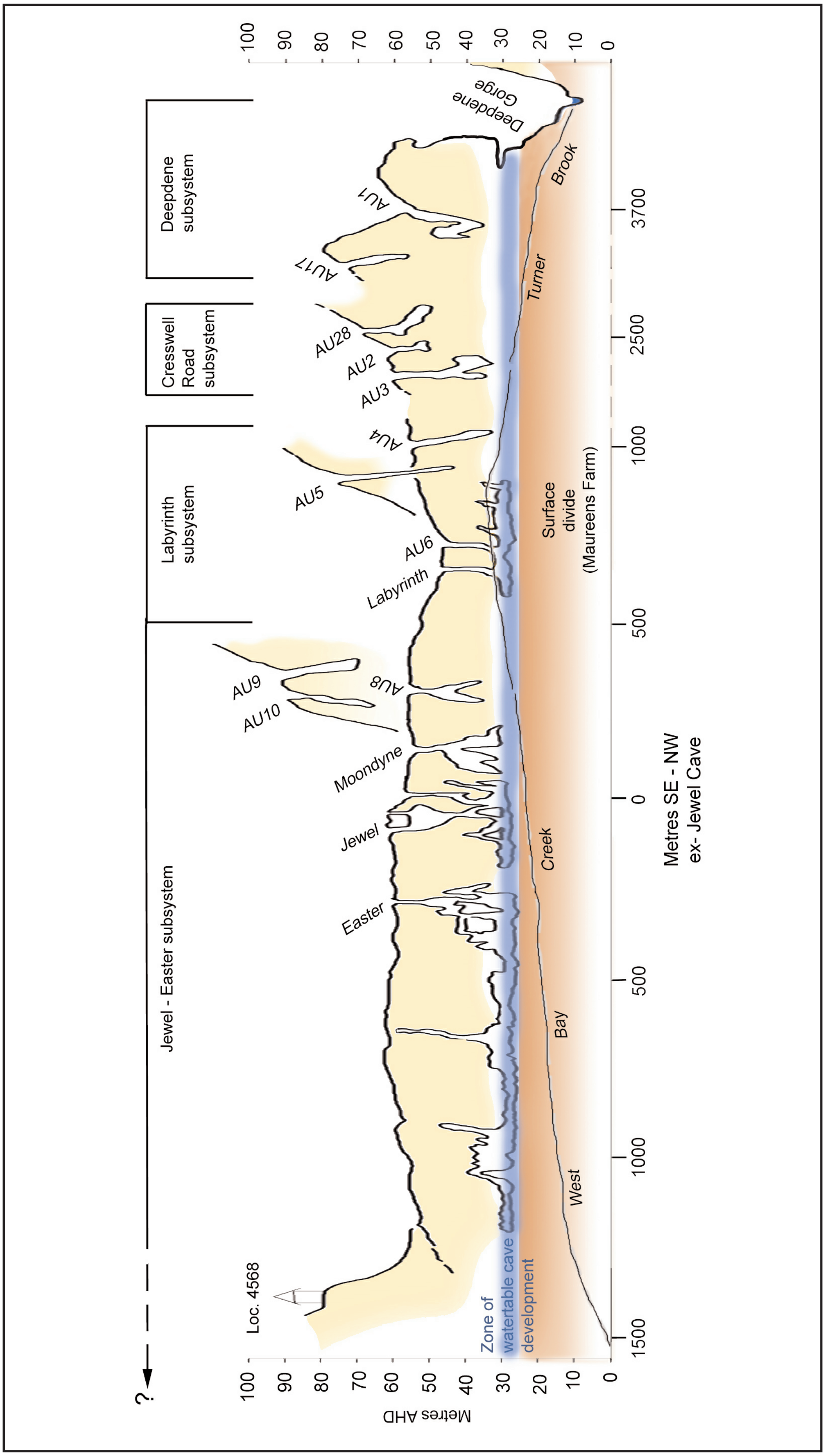


Figure 9. *Cross section SE - NW along the longitudinal axis of the Augusta dune showing vertical relationships between the watertable caves, karst subsystems and adjacent non-karst terrane. Note the zone of intense cave development near the watertable at 22.5 to 27.5 m AHD. All cave development above this level is the result of stoping collapse into pre-existing underlying cavities. Also shown lying alongside the dune, are the channel profiles of West Bay Creek and Turner Brook, and the surface divide between them. Vertical scale exaggerated (x 12).*

pattern (Appendices 1, 2, 3). These secondary patterns may be due to reorganization of diffuse flow, with selective enlargement of major flow paths. In Easter Cave there is a pronounced alignment of passages NW-SE parallel to the edge of the dune (Figures 6, 8).

Jewel Cave is distinct in possessing two wide but very linear passages (*Flat Roof One* and *Flat Roof Two*) that run parallel to each other in a roughly N-S direction. The aberrant linearity and directional trend of the flat roof passages in Jewel Cave may be controlled by the elevated structure of the basement rocks that appear to guide passage patterns in this localized area (Appendix 2).

Passages with a large cross-sectional area may be formed by amalgamation of separate but closely spaced conduits, eventuating from gradual removal of intervening rock masses to produce a single very wide, low-roofed passage with possibly a few remnant pillars of bedrock. Alternatively such passages may represent mixing chambers of the *flank margin cave* type (sensu Mylroie and Carew 2000), where water entering diffusely at the wall interface induces mixing corrosion upon contact with the chamber water. This process produces large irregular chambers which terminate abruptly at the mixing front, although such terminations are not evident in the Augusta caves. Whatever their mechanism of formation, the large passages with weakened support are prone to collapse, whilst ongoing dissolution of collapsed material at the base enables continued upward enlargement producing chambers of large volume such as in Jewel Cave.

Several distinct levels of phreatic development are evident in the Augusta watertable caves. These include an upper, discontinuous level extending to about 30.5 m AHD which relates to an early stage of development. This level is truncated below by the main zone of watertable cave development lying between 23.5 and 27.5 m AHD. This zone contains two obvious levels, an upper level (ca. 26.5 - 27.5 m AHD) and a lower level (ca. 23.5 - 24.5 m AHD), each presumably representing successively younger watertable stillstand episodes.

Geologic Controls

Geologic structure and lithology can exert strong controls on cave development and morphology (Ford & Williams 1989, White 1988). A number of such possible controls are evident in the development of Jewel, Easter and Labyrinth Caves.

Throughout most of the Leeuwin - Naturaliste Ridge, cave development is strongly controlled by the topography of the underlying granite-gneiss basement, in addition to other factors noted by (Bastian 1964), including precipitation regime, age and vertical relief of the limestone, allogenic drainage and variation in its solutional capacity. The basement forms a more or less impervious barrier (aquiclude) to deep penetration of groundwater, the movement of which is thus directed laterally along the limestone-basement contact. The karst aquifers and stream caves are perched on the basement rocks, and this contact is the focus for cave development which is influenced by the topography of the basement surface (Williamson 1980).

Many of the linear stream caves in the Leeuwin - Naturaliste Ridge are developed along palaeo channels incised into the basement prior to emplacement of the dunes, and basement bedrock forms the floor in these caves (Bastian 1964, Jennings 1968). In the Augusta watertable caves however, the control of basement topography is less obvious, with basement rocks visible only in the lower passages within Jewel Cave and the *Gneiss Extension* within Easter Cave. The basement is not visibly exposed in Labyrinth Cave, nor elsewhere in Jewel, Easter and Labyrinth Caves, although presumably it lies not far beneath the floors of lower level cave passages. In the Augusta caves, other structural controls including dune bedding and palaeosols have influenced cave development, as they have elsewhere, however; an oscillating watertable has been the most conspicuous influence on cave geomorphology. The influence of laterally extensive watertables is either less apparent, or absent, in the other cave systems on the Leeuwin - Naturaliste Ridge which are dominated by conduit throughflow.

Where the basement is exposed in the watertable caves, the surface is irregular and expresses some local relief with a vertical range of 8 m within a horizontal distance of 100 m measured in Jewel Cave. The basement crops outs in the cave passages as in situ boulder-tor or foliation ridge structures which strikes roughly N-S following the dominant regional jointing trend. The *Flat Roof* passages in Jewel Cave clearly follows this lineation. In *Flat Roof One* the granite structure dips to the east whilst 100-200 m away in the *Gneiss Extension* in Easter Cave it dips to the west, suggesting that fold axes or a synclinal structure lies in between (Appendices 2, 3). This granite structure might cause a ponding effect on groundwaters or form a partial barrier to groundwater flow between Jewel and Easter Caves, although water level monitoring proved hydraulic connectivity between both caves (see Figure 13).

Where cave passages are developed in aeolian units they tend to be predominantly developed parallel with dune bedding as noted by Bain and Lowry (1965). Strike oriented passages are well developed in the SE sections of Easter Cave, where the dune beds dipping at 30-35^{o} form the NE wall and ceiling of the passage inclined at the same angle.

Palaeosol horizons and caprock influence cave development in dune limestones by forming planes of differing resistance to collapse. Passage ceilings, or former ceilings, sometimes coincide with these horizons, although such horizons play a secondary role to guidance of passage morphology in the phreatic zone. In the vadose zone, palaeosols act as aquitards or aquicludes, and appear to redirect vertical infiltration waters laterally along the horizon until a weakness such as a fracture, solution pipe or other cavity is encountered. The entry point of such deflected infiltration waters is seen in the walls of chambers where horizontal bands of calcite deposition coincide with palaeosol horizons (see Figure 11).

As noted by Jennings (1968), jointing is not well developed in the poorly lithified dune limestone so it cannot influence cave structure and morphology as strongly as it does in more consolidated limestones. There are exceptions in the Augusta karst area however, for example, a vertical joint in the ceiling is aligned with a minor side passage in Jewel Cave (*Flat Roof One* chamber). Additionally, thin steeply inclined fissures filled with dark-coloured calcite are common throughout the Jewel, Easter and Labyrinth Caves. These fissures may be incipient joints developed parallel to the edge of the dune, possibly caused by stresses developed during lithification of the dune sands. These joints influence passage morphology locally, and possibly also passage trends at a larger scale. Local influence on passage morphology occurs because the calcite filling the joints is more strongly cemented than the surrounding limestone and therefore more resistant to dissolution or collapse. At the larger scale, passages in Easter Cave follow a pronounced alignment NW-SE parallel to the dune edge, a trend which might be linked to the jointing pattern, although further investigation is needed to determine if this is the case.

Age

Directly determining the onset (ie. maximum age) of speleogensis is difficult because caves are solution features, however dating of *in situ* cave sediments (eg. speleothems, clastic sediments, bone deposits) can help to indirectly define a *minimum* age for cave development because the dated sediments were deposited into the pre-existing karst cavity (eg. Gillieson 1996, White 1988).

A number of dates from the JELSS have been obtained that indicate a lengthy and diverse sedimentary history. A radiocarbon date based on charcoal from a stratified bone deposit in Skull Cave (6AU-8) yielded a Holocene date of 7,875 +/- 100 years BP (Porter 1979). Radiocarbon ages of charcoal and other organics contained in fluvial sedimentary deposits from Jewel and Easter Caves, dated during this study, ranged between 33,000 - 35,400 +/- 600 years BP (Appendix 21). Burial sediments associated with the megafaunal unit in Moondyne Cave (6AU-11) yielded an optically stimulated luminescence (OSL) age of 131 +/- 14 ka (Roberts et al. 2001).

The next oldest date for cave sediments from Western Australia is >212 ka for uranium-series dating of flowstone in Tight Entrance Cave (6WI-101) (Prideaux et al. 2000). The oldest sediment date - 627.4 ka in Moondyne Cave - establishes a *minimum* age for cave development in the Augusta area (Marianelli 2000; Marianelli et al. in press). However, if the Augusta caves developed syngenetically - where karstification may be initiated more or less simultaneously with consolidation of the dune sands - then the age of the limestone can be used to infer a likely age for cave inception.

Syngenetic karst

Elsewhere in the world, most karst is developed in marine limestone that has consolidated previously, and a long time interval is common between diagenesis of the sedimentary body and its subsequent emergence and exposure to karst weathering processes (Jennings 1968). Syngenetic karst occurs where karst features, including caves, developed at the same time as the calcareous host sand was being cemented into a rock. This process was recognised in the dune limestones of southwestern Australia by Simpson (1906), then later described in detail by Bastian (1964), and subsequently Jennings (1968) who coined the term syngenetic karst. Syngenetic processes are generally implicated in karstification and speleogenesis within the soft calcareous dune limestones of South and Western Australia (Bastian 1964; Ford & Williams 1989; Grimes 2002, 2003; Grimes et al.1999; Hill, 1984; Jennings 1968; White 1994, 2000).

Characteristic features of syngenetic karst are: shallow horizontal cave systems; clustering of caves at the margins of topographic highs or along the coast; palaeosol horizons; vertical solution pipes; extensive breakdown and collapse to form collapse-dominated cave systems; a variety of surface and subsurface breccias and locally large collapse dolines and cenotes; development of a cemented (calcreted) caprock near the surface and limited surface sculpturing (karren) (Grimes op. cit.).

Syngenetic cave forms tend to be low irregular chambers with cavity enlargement by progradational collapse playing an important role in speleogenesis. One syngenetic cave form in southwestern Australia, described as a linear cave by Bastian (1964), consists of a single directed conduit instead of low irregular chambers. Another distinctive syngenetic cave form described from Yanchep is the watertable slot, which is a low broad slot with a horizontal ceiling developed at the watertable. These slots are typically only a few centimeters in height, but may extend laterally for many meters, where groundwater flows between the ceiling and sandy floor of the cave (Bastian 2003). The broad ceilings of both watertable slots and linear caves are prone to collapse resulting in collapsed domes with 'inclined fissures' formed between collapsed and un-collapsed segments.

'Inclined fissure' caves are not fissures formed in bedrock but are the inclined spaces left along the sides of a collapse dome, between the side of the central rubble pile and the solid bedrock of the hanging walls. The collapse domes have an inverted U shape although only part of the dome may be accessible and so cavers use the term 'inclined fissure' for the narrow sloping lower sides of the domes (Grimes 2003). The 'inclined fissure' cave described by Bastian (1964) is not a genetically distinct cave form, but represents a secondary form derived by collapse during genesis of either of the two primary cave forms associated with an underlying watertable, or conduit. Where collapse prevents human access to the cave stream or watertable zone deeper below, and where little of the collapsed material has been removed by subjacent dissolution, then caves are usually of limited size and extent.

At Yanchep in the Perth region, where groundwaters in the shallow unconfined granular aquifer of the Gnangara Mound intersect the base of dune limestones, extensive watertable slot and 'inclined fissure' cave development occurs. In the Leeuwin-Naturaliste region, the primary cave forms are linear or watertable types, with secondary development of inclined fissure forms. The Augusta watertable caves are not linear or 'inclined fissure' type caves, but more closely resemble the watertable slots at Yanchep and the low irregular syngenetic maze cave forms of southeastern Australia.

In the Augusta karst area, the phase of major cave development did not occur until some time after substantial consolidation of both the marine and aeolian units had occurred. The prominent spongework dissolution features and flat, solutionally-eroded passage ceilings with unsupported spans up to 50 m could not have formed otherwise (Jennings 1968). In contrast to the linear stream caves, the development of the watertable caves has not depended to the same extent, on cavity enlargement by upward collapse in the early stages of development.

Geomorphic History

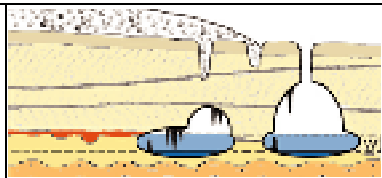
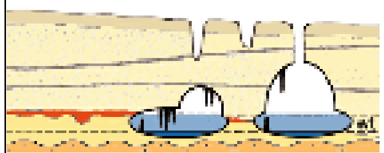
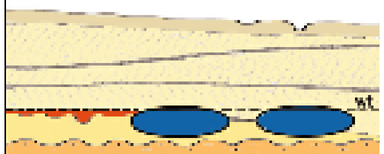
In the Augusta dune limestone, karstification and speleogenesis have been separate and multiphase processes. As described in the previous chapter, following emergence of the basal marine unit, and prior to deposition of overlying aeolian strata, there was a significant phase of subaerial karstification and soil development. This phase was probably a syngenetic one as solution pipes are a distinctive feature of early syngenetic karst (Grimes 1997). This limestone-soil couplet marks an initial phase of karstification which preceded the deposition of overlying aeolian limestone-soil couplets, and a later phase of speleogenetic karstification.

The initial phase, described above, is interpreted as representing a prolonged period of time as suggested by the substantial thickness of concentric calcreted rinds (up to 500 mm) in solution pipes in Easter Cave (cf. Hearty and Kindler 1997). This surface - now a buried palaeokarst - is truncated by the watertable caves, which must therefore be younger in age. Where the surrounding rock has been preferentially removed by solutional development of cave passages, then the insoluble remnants of the palaeosol protrude from the cave ceilings and walls. A good example of this occurs between the *Y Junction* and *Epstein* in Easter Cave.

Late syngenetic speleogenesis is inferred to date from the Early to Middle Pleistocene as indicated by uranium-series speleothem dates to 627 ka (Marianelli 2000, Marianelli et al. in press). Ongoing cyclic speleogenesis associated with oscillating watertables combined with episodes of subaerial and subaquatic spelethem deposition, surface karstification and caprock development is inferred to have occurred from the Middle Pleistocene up to Present. Cave entrances open to the surface had developed by the Late Pleistocene. These acted as pitfall traps for fauna, as indicated by 131 ka OSL age for the megafauna unit in Moondyne Cave (Roberts et al. 2001). During the Holocene (< 10 ka) portions of the Spearwood dunes including caves and karst were buried beneath sands of the Quindalup dunes.

A simplified geomorphic history of the Jewel-Easter and Labyrinth Subsystems, based on interpretation of the stratigraphy and dated sediments, is presented in Table 3.

Table 3. Simplified interpretation of the geomorphology and geochronology of the Augusta dune limestone and karst. Geomorphic units, processes and effects are described from youngest to oldest.

Time period	*Geomorphic 'units' & processes*	*Geomorphic effects & features*	*Description*	[1] *Determined ages*	*Notes*
Holocene	Quindalup Dune System		Partial burial of the Spearwood Dunes and karst	< 10 ka	Quindalup System consists of poorly lithified calcareous sands (eg. Hall & Marnham 2002)
Holocene to Late Pleistocene	Caves open to surface		Upward collapse and solution pipes form cave entrances that act as fauna pitfall traps	131 ka (+/- 14 ka)	OSL age megafaunal unit Moondyne Cave (Roberts et al. 2001)
Holocene to Middle Pleistocene	[2] Fluctuating watertables & speleothem growth		Surface karstification, Fluctuating watertables, flood events, and cyclic episodes of subaerial and subaquatic speleothem deposition	1 ka to < 627 ka (- 89.0 + 265.8 ka)	Uranium-series speleothem dates (Eberhard, Ayliffe & McCulloch this study, Marianelli 2000, Marianelli et al. in press)
Middle to Early Pleistocene	Speleogenesis		Late syngenetic karstification - caves developed by dissolution at the watertable	> 627 ka	Speleothems deposited in pre-exisiting cavities

[1] ka - 10^3 years; ma - 10^6 years

[2] See section on palaeohydrology and sediments for more details

Distribution of watertable caves

The distribution of watertable maze caves appears to be confined to a narrow, continuous band about 5 km in length situated along the northern margin of the Augusta dune ridge (Figures 5, 10 A). The high density of known entrances and mapped cave passage found along the northern margin contrasts with the paucity of enterable caves in other sectors of the ridge where karstified Spearwood limestone remains exposed at the surface. The observed distribution pattern may signify a real absence of watertable caves in other sectors of the ridge, or it may be because they have not been detected. If the latter is true then this is unlikely to be due to a paucity of exploration conducted for caves in other sectors, however it could be that any potential entrances may be blocked by soil.

The occurrence of solution pipes, by themselves, does not necessarily signify underlying cave development because these features develop independently of speleogenesis. Dolines however, of collapse origin, signify the existence of underlying cavities or caves. Beyond the northern margin of the Augusta dune there appears to be a significantly lower density of soil subsidence or collapse dolines. One collapse doline is recorded within the Green Hill Road subsystem, plus a stream cave (Lost Leeuwin Cave, 6AU-18) within the Hillview Road or Turners Spring subsystems. The flowing stream reported in Lost Leeuwin Cave, and the location of the Green Hill Road doline at the base of a well developed drainage gully suggest that cave development within these sectors of the Augusta ridge is of the linear stream type rather than a watertable type.

Mixing corrosion

Water infiltrating directly into porous limestone quickly becomes saturated with carbonate and thus rarely forms caves because it loses its aggressiveness within a few metres of the surface (Palmer 1991). However, when this water reaches the watertable it may become aggressive again upon mixing with phreatic waters of different chemistry. Mixing of fresh or brackish groundwaters with sea water in coastal aquifers may also produce this effect. Thus caves tend to form in the mixing zones between vadose and phreatic waters, and/or the interface between karst waters and intruding marine waters.

Mixing corrosion (*sensu* Bogli 1964) provides one possible mechanism to explain the high intensity of solution that seems to occur near the watertable (White 1988), which has clearly occurred throughout development of the Augusta watertable caves. The effect of mixing corrosion occurs when two different karst waters that are saturated with calcite, and therefore incapable of further dissolution alone, become solutionally aggressive upon mixing (Ford and Williams 1989). If each body of water is saturated with respect to calcite at different partial pressures of carbon dioxide (pCO_2), then by mixing they will produce a new solution which is under-saturated.

The Augusta watertable caves are inferred to have originated and developed by processes of mixing corrosion near the watertable, either solely through mixing between vadose and phreatic fresh waters, but possibly also involving mixing with adjacent swamp waters, or marine/estuarine waters during periods of high sea level.

Speleogenetic mechanisms

A possible explanation for the restricted distribution range of the watertable systems, and their absence elsewhere on the Augusta ridge, might be if the basement topography within this sector of the ridge permitted ponding of groundwater to form a narrow perched aquifer at this level. Where a more steeply inclined and/or channelled basement topography occurs, this would promote more rapid throughflow and development of directed conduit drainage systems. Such a topography is postulated to exist below the surface catchment of the Leeuwin Spring for example, where reduced storage and rapid recharge response is indicated in the hydrograph and chloride mass balance (refer to chapter on water level histories).

Within the northern margin subsystems the pattern of watertable cave development is restricted to a narrow belt less than 500 m wide which parallels the flank margin of the dune ridge. West of the 90 m contour on the eastern flank, no cave entrances are known, although if these exist they would likely be obscured by the Quindalup dunes. One cave (6AU-17) is known on the western flank of the ridge near Deepdene, where a small area of Spearwood limestone has not been covered by the Quindalup dunes. Nonetheless, the > 10 km of mapped cave passages within the JELSS show no extension or trend beneath the crest of the ridge toward the western coastline, as would be expected if drainage had previously, or presently, occurred in this direction.

In this respect the pattern of watertable maze cave development within the Augusta karst presents a striking contrast to cave patterns and karst drainage elsewhere on the Leeuwin - Naturaliste Ridge, where linear stream caves drain transversely through the ridge, from allogenic sink points on the inland margins to springs on the coast, or, diffuse autogenic recharge exsurges along the basement contact either as dispersed seepage or localized at springs.

Bastian (1964) and Jennings (1968) noted that passage dimensions in southwestern stream caves typically decrease with increasing distance downstream from the sink point. Inflow cave passages may initially be quite

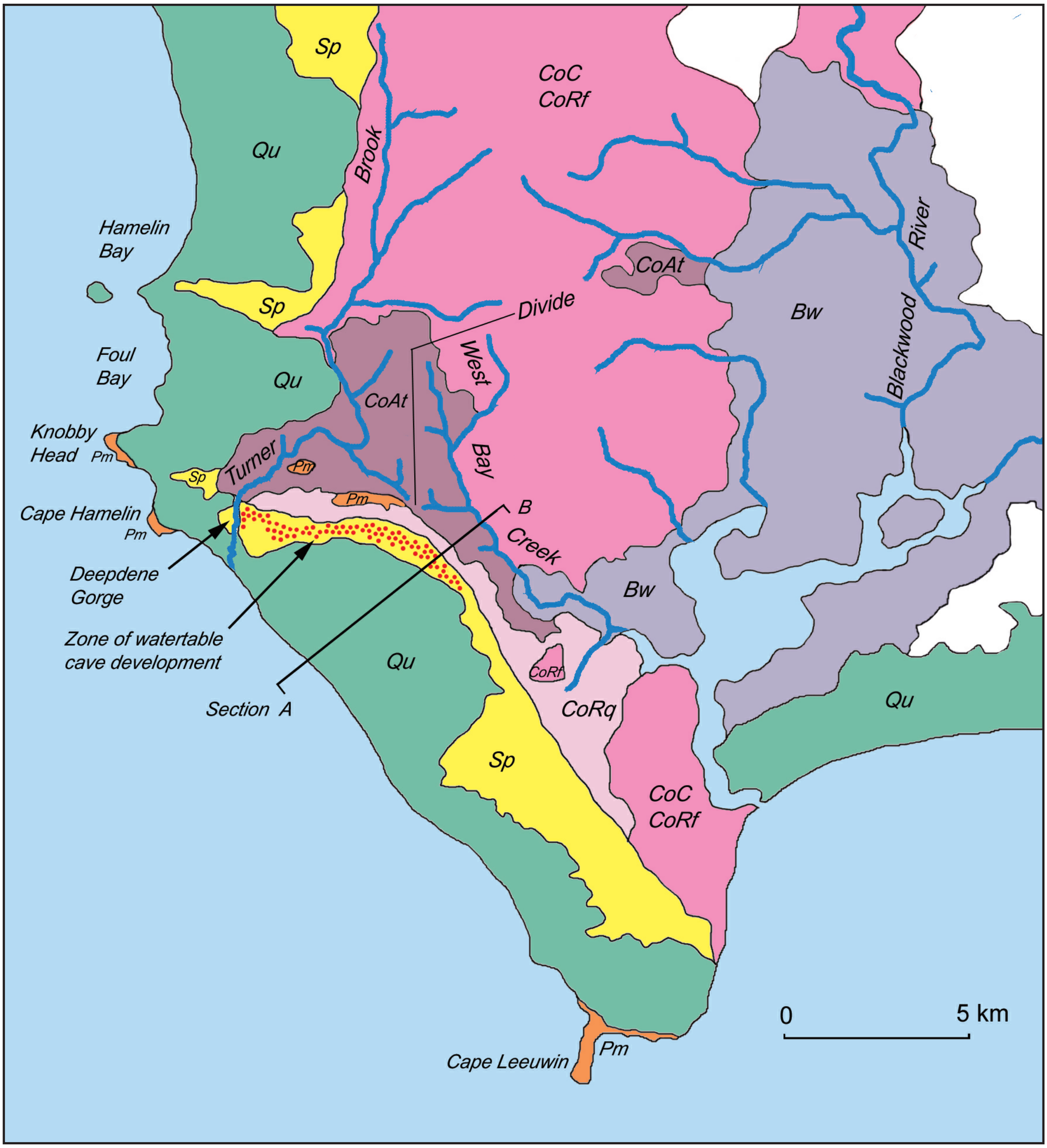


Figure 10, A. *Simplified land systems and drainage in the study area showing distribution of watertable caves and features mentioned in text. Land systems adapted from Hall and Marnham (2002): (Qu) Quindalup System - beach and poorly lithified dunefields (Holocene); (Bw) Blackwood System - estuary and river system; (Sp) Spearwood System - strongly lithified dunes (Pleistocene); (Co) Cowaramup System - low hills underlain by Proterozoic rocks; (CoAt) Alluvial terrace - silty sands and gravels; (CoC) Colluvial, silty gravelly sand over sandy clay on undivided slopes; (CoRq) Residual, leached quartz sand; (CoRf) Residual, ferruginous duricrust overlying mottled soil; (Pm) Leeuwin Complex, granite-gneiss (Proterozoic).*

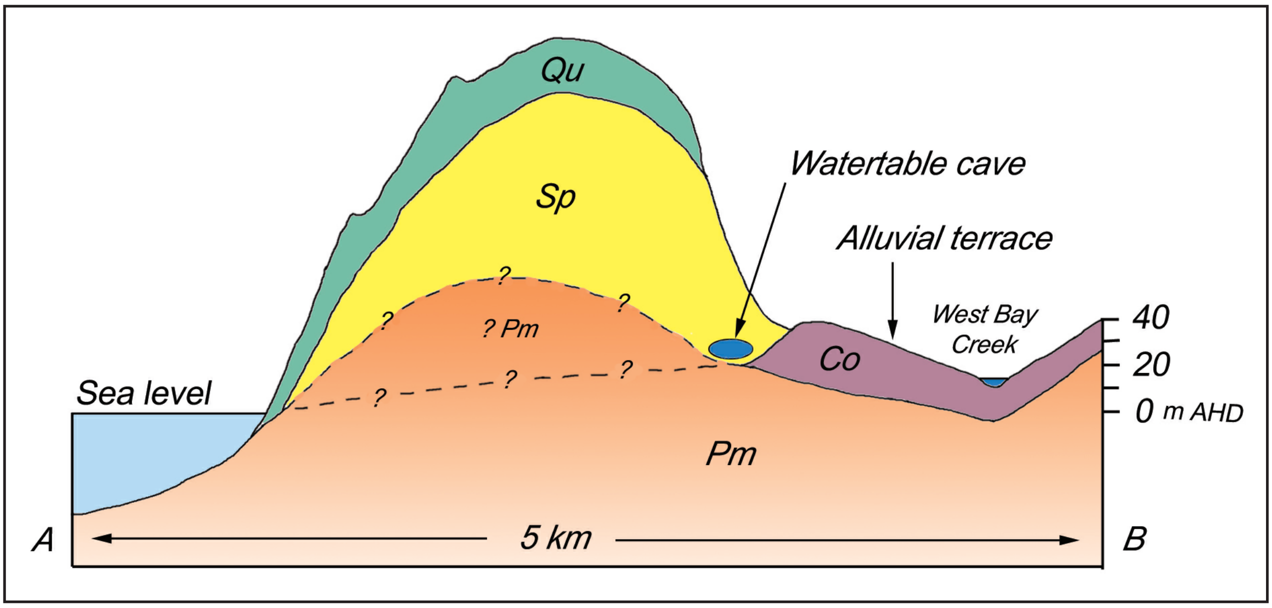


Figure 10, B. Schematic cross section SW-NE of the Augusta dune ridge with a simplified interpretation of the geomorphic structure and relationships. The topography of the granite-gneiss basement beneath the dune is uncertain. Vertical scale exaggerated approximately 20 times. Refer to Figure 10 A for section A-B and land system codes.

large but then gradually constrict in size or disperse into distributaries that are too small for humans to explore. This is interpreted to be due to diminishment in aggressiveness of allogenic waters, as limestone is dissolved and the waters reach saturation with carbonate along the flow path. Dissolutional enlargement of inner passages may thus be restricted to flood events when large volumes of aggressive water are transmitted rapidly along the flow path.

The possibility of this process operating in the Augusta watertable caves needs to be considered if aggressive allogenic waters drained westwards as a broad diffuse sheet rather than a stream. This possibility assumes that the granite basement beneath the dune slopes consistently down towards the western coastline, with no rise in between. If this were the case then the absence of cave development beneath the main body of the dune might be explained by gradual saturation of the westward flowing waters. The topography of the granite basement beneath the dune ridge remains uncertain however, whilst a steeper hydraulic gradient presently exists between the karst aquifer and Turner Brook-West Bay Creek to the east (Figure 10 B).

The clustering of watertable caves along the flank margin of the Augusta dune suggests genetic relatedness of development linked with proximal allogenic water bodies. They resemble flank margin caves (*sensu* Mylroie and Carew 1990) in respect of their position under the flank of the dune ridge, spongework maze patterns, and the absence of primary macroscopic openings to the surface. Flank margin caves are described from carbonate islands and coasts where they are influenced by the chemistry of mixing marine and fresh water, and by the migration of sea level in response to Quaternary glacioeustacy (Mylroie and Vacher 1999, Mylroie and Carew 2000).

On oceanic carbonate islands and carbonate coasts a freshwater lens, which increases in thickness away from the coast, sits on top of underlying marine waters. Cave development occurs both at the top of the freshwater lens that receives and mixes with vadose infiltration water, and at the bottom of the freshwater lens where seawater and freshwater mix. Cave development is enhanced under the flank of the enclosing high ground, towards the thinning distal margin of the freshwater lens where flow and mixing corrosion processes are concentrated.

The coastal setting of the Augusta karst, with its watertable caves developed within the probable range of Quaternary glacioeustacy, combined with their 'flank margin' characteristics indicates the potential for involvement of marine influences in speleogenesis. The tectonic history and range of Quaternary sea level changes experienced in this location remain to be precisely elucidated, but even if earlier sea level highstands were not of sufficient elevation (+20 - 30 m inferred) to permit direct intrusion of marine waters, then highstands of lower elevation might still be involved by controlling regional base levels of inland waters in the near coastal setting.

Sea level highstands documented in southwestern Australia include a Middle Holocene highstand + 2.7 m on Rottnest Island in the Perth region (Playford 1988). In the Australind - Leschenault Inlet area, Semenuik (1983) described a late Holocene sea level of + 3-4 m. Playford and Leech (1977) and Semenuik & Searle (1986) attributed variability of Holocene sea level history along the south western coast to the effect of significant local tectonism, with more pronounced uplift in the southern parts. It is pertinent to note that despite this, the heights of the Last Interglacial deposits throughout much of the Perth Basin fall within the limits set by studies in other relatively stable coasts (Kendrick et al. 1991).

At Foul Bay 7 km west of Jewel Cave, a fossil coral reef at + 2-3 m yielded a uranium-series age of 124.8 +/- 3.2 ka (Eberhard & McCulloch, unpublished data). This deposit matches in age and elevation the Rottnest Limestone (Playford 1988), with these and other coral reef members of the 'Tamala Limestone' ascribed to the Last Interglacial (Marine Isotope Stage (MIS) 5e). One kilometer south of Foul Bay (Figure 10 A), between Cape Hamelin and Knobby Head, a prominent raised bench at + 4.5m is composed of marine limestone, whilst Fairbridge & Teichart (1952) recorded a shelly conglomerate and marine limestone + 3-8 m located 800 m north of Cape Leeuwin. Elsewhere along the Leeuwin-Naturaliste and southern coast, Pleistocene marine shoreline deposits occur between + 3-8 m (eg. Lowry 1967, Fairbridge & Teichart *op. cit.*), whilst in the Perth region, dated sediments infer sea levels up to + 7m or slightly higher during both the Last Interglacial (MIS 5e) and the Penultimate Interglacial (MIS 7) (Murray-Wallace and Kimber 1989).

Based on the topographic positions of Pliocene deposits, Kendrick et al. (1991) infer some 20 to 30 m of uplift in the Perth region of the Perth Basin. In the southern Perth Basin, these authors suggest some 20 m of uplift since the middle Pleistocene as evidenced by the occurrence southwest of Busselton of late and middle Pleistocene marine deposits at + 10 m and + 20 m respectively.

Outcrops in Bermuda, Bahamas and Hawaii reveal strong evidence of a Middle Pleistocene 'super interglacial' indicating global rise of sea level to approximately 20 m during the middle Pleistocene between 300 - 500 ka, and probably corresponding with MIS 11 (Hearty et al. 1999; Hearty 2002).

Independently of the region's isostatic-eustatic history, the local evidence clearly indicates several episodes of relative high sea levels within the time frame of development of the Augusta watertable caves. During these periods the shoreline and marine waters would have been much closer to the karst system, if not directly impinging upon it. However, the nature of the freshwater lens would have been influenced by the impermeable granite basement lying beneath the carbonate rocks, which would restrict inland intrusion of marine waters. The zone of fresh /salt water mixing would thus be confined to a marginal collar in a manner analogous to an oceanic island with a carbonate-cover overlying a non-carbonate core (sensu Mylroie and Carew 2000).

Assuming the present topography and surface drainage has not been greatly modified since emplacement of the dunes, sea level highstands above + 10 m would have brought the shoreline to within 750 m of the Jewel-Easter subsystem. However, marine influences during periods of higher sea level would have been most prevalent at the northern end of the Augusta dune ridge, near the Deepdene subsystem. This assumes that the course of Turner Brook was maintained in earlier periods as now, where it dissects the toe of the ridge inducing locally steep topographic gradients, including a 60 m high cliff forming the eastern side of Deepdene Gorge. Maintenance of this stream course prior to emplacement of the dunes is inferred if the development of Deepdene Gorge was a syngenetic 'gorge of construction' as proposed by Jennings (1980). However, caves exposed in the eastern wall of the gorge exhibit flat ceilings, all developed at the same level, estimated to lie between 23 - 28 m above present sea level. The ceilings have projections which resemble roof pendants, plus other rounded erosion features interpreted to be the result of shallow phreatic solution processes. If this interpretation is correct then a fossil watertable cave system, may be exposed in Deepdene Gorge. This interpretation requires an earlier base level considerably higher (> 20 m) than present. This could be attained by a higher sea level and/or a higher incision level of Turner Brook. An earlier high sea level of unspecified elevation is postulated in Deepdene Gorge by Archer and Baynes (1972) who recorded marine fossils alongside Turner Brook, rounded heads of granite cobbles that resembled coastal cobble beds, and cemented limestone rubble in the roofs of small caves or pockets in the cliffs.

An alternative hypothesis for the development of the lower level caves within Deepdene Gorge, if the watertable origin suggested for them proves correct, is that the caves were formed before the gorge developed. The level of the inferred fossil watertable exposed in Deepdene Gorge lies within the range of the other watertable subsystems, including Jewel, Easter and Labyrinth Caves, to which it might be genetically related. This explanation obviates the problem of attaining a significantly higher base level within the gorge, but presumes a different prior course to the sea by Turner Brook. Local eastward diversion of Turner Brook may have been caused by inland advancement of the Quindalup dune system between Deepdene and Hamelin Bay (Figure 10 A). Immediately beyond this barrier the brook abruptly changes direction to break through to the sea via Deepdene. If Turner Brook previously debouched into the sea further northward, via a course now blocked by the Quindalup dune, the new longer diversion course could account for the lower gradient along this section of the brook.

The steepening at Deepdene might indicate stream capture near this point. This could have been by underground piracy through a pre-existing cave that took the overflow from the dammed brook, or spring sapping / headward erosion working inland from the coast, or both. These events, if related to the Quindalup dune, must be considerably younger than the watertable caves. An older capture of upper West Bay Creek by Turner Brook is also possible, which, if this has occurred, happened prior to the approximately 5 m of incision that left the low divide between them in the area between Maureens Farm and Stockdill Road (Figure 10 A). The scenarios described above remain speculative and further investigation of geomorphic relationships in the area, including Deepdene Gorge, are required to properly address them.

The main control over the vertical distribution of cave passages is the regional history of fluvial dissection, which in turn is determined by the tectonic and climatic history (Palmer 2000). Yonge et al. (1997) postulated cave enlargement by direct penetration of the Augusta dune by allogenic waters of the Blackwood River, or its estuary, to the level of the watertable caves, followed by rapid draining of the caves caused by rejuvenation during the low sea stand of the Last Glacial Maximum. However, the absence within the caves of allogenic sediment deposits of either fluvial or estuarine origin, does not support direct invasion of the karst aquifer by such waters. Moreover, any involvement of allogenic waters is more likely to be associated with Turner Brook and West Bay Creek, both of which run alongside the dune margin containing the watertable caves.

If direct involvement of marine or estuarine waters is inferred as a primary speleogenetic mechanism it remains difficult to account for the apparent absence of flank margin type caves outside the northern sector of the Augusta dune ridge. If flank margin cave processes as described by Mylroie and Carew (2000) were responsible, then spongework maze caves should be found in dune margin settings wherever Spearwood limestone is exposed to the old coast at appropriate elevations. This does not appear to be the situation however, as spongework maze cave development is clustered within a 5 km segment at the northern end of the ridge, despite continuation of the inland margin of the Augusta dune for a further 8 km.

An alternative mechanism for speleogenesis does not depend on marine waters, but instead invokes flank margin processes linked with inland waters. Flank margin type caves also develop along the edge of dune ridges adjacent to swamps that provide a source of aggressive water (Grimes 2003). In the Mount Gambier region of southeastern Australia a slowly rising land surface coupled with sea level variations has deposited a broad sequence of stranded coastal dune ridges and intervening swamps dating back at least 800 ka (Huntley, Hutton and Prescott 1994). Numerous spongework maze caves are developed in the dune margins, and whilst in the initial stages some of these caves may have developed by fresh / saltwater mixing, swamp waters are implicated as the major agent in cave formation as passage levels in the caves are controlled by water levels in adjacent swampy plains that also provides acidic water (Grimes, Mott and White 1999, Grimes 2002).

Similar swamp margin type caves occur in mid to late Pleistocene dunes at Bats Ridges and Codrington in southwestern Victoria. At these locations, watertable cave development is inferred to have occurred during conditions of wetter climate in the past when water levels in nearby swamps were higher than present (Berryman and White 1995; White 1994, 2000).

Swamp margin mechanisms may thus provide the most parsimonious explanation for the distribution and primary origin of the Augusta watertable caves. This is because their distribution range and elevation closely corresponds with adjacent swampy terrain in the catchments of Turner Brook and West Bay Creek. Under the present climate, extensive areas of low lying terrain within these catchments remain waterlogged throughout winter. This extensive swampland consists of silty sands and gravels interpreted to be an alluvial terrace and assigned to the Cowaramup land system (Hall and Marnham 2002). The terrace sediments are mapped as lying at 50 m elevation in the upper reaches of Turner Brook, sloping down to 10 m elevation in the lower reaches of West Bay Creek, where the southern distribution boundary of the terrace sediments coincides with the apparent distribution limit of watertable caves.

It is conceivable that under a wetter climate and/or higher base level during a sea level highstand, discharge from the swampy basins would have been impeded thus raising the local watertable, and presumably facilitating swamp margin speleogenesis within the adjacent dune. In southeast Australia the influence of swamp waters on speleogenesis is often clearly expressed in the form of watertable notches and maze caves excavated in dune flanks at the same level as adjoining swamps. In the Augusta area however, the contact zone between the dune flank and adjacent swamplands is poorly defined and its geomorphic expression is obscured by sediments, thus direct evidence invoking swamp margin processes remains wanting.

In summary, three possible mechanisms to explain the distribution and development of the Augusta watertable caves are discussed. All invoke mixing corrosion as the dominant process, but the degree of involvement of allogenic water bodies, whether inland or marine, remains to be fully clarified. The three mechanisms are:

(1) Basement topography locally causing perched aquifer - speleogenesis by mixing corrosion between vadose and phreatic waters entirely of autogenic origin.

(2) Flank margin - speleogenesis by mixing corrosion at margins of freshwater lens overlying marine waters during higher sea level.

(3) Swamp margin - speleogenesis by mixing corrosion between karst waters and allogenic swamp waters.

It is possible that all of these mechanisms have been involved, to varying degrees, at different times throughout the evolution of the karst system. However, in consideration of the geomorphic evidence, a basement topography locally causing a perched aquifer combined with swamp margin processes, most adequately accounts for the restricted distribution and elevation range of the watertable cave systems. Swamp margin speleogenesis would be facilitated during periods of wetter climate. Marine influences during high sea levels may also be invoked, primarily through control of base levels of inland waters, as opposed to flank margin processes involving direct intrusion of marine waters into the karst system.

The location of the watertable caves permits colonization of the karst aquifer by aquatic species derived from neighbouring surface waters, whether fresh, brackish or saline. The present swamp margin setting provides a suitable route for colonization by freshwater forms within the Blackwood River catchment. Elevated watertables under wetter climate conditions would facilitate dispersal of aquatic fauna from swamp waters into the adjacent karst aquifer. The karst aquifer contains species with inland freshwater origins, as opposed to species with close marine affinities.

Conclusions

The geomorphic history of the Augusta dune limestone has involved multiple phases of karstification and speleogensis. Late syngenetic speleogenesis is inferred to date from the Early to Middle Pleistocene.

The Jewel, Easter and Labyrinth Caves are watertable maze caves. The pattern of watertable maze cave development within the Augusta karst presents a striking contrast to cave patterns elsewhere on the Leeuwin - Naturaliste Ridge, where linear stream caves drain transversely through the ridge. The distribution of watertable maze caves appears to be restricted to the northern part of the Augusta dune ridge.

The Augusta watertable caves are inferred to have originated and developed by processes of mixing corrosion near the watertable; however, the degree of involvement of allogenic water bodies remains to be fully clarified. The development of these caves has been controlled predominantly by fluctuating watertable levels between 22.5 and 27.5 m ASL.

The pattern of passages within the Jewel, Easter and Labyrinth Caves is predominantly that of a spongework maze formed by diffuse recharge into porous rock. Superposed on this primary pattern are anastomotic and rudimentary branchwork patterns, in addition to small-diameter scalloping, which are interpreted to be the result of discharge fluctuations during different stages in the geomorphic history of the karst system.

Geologic control of cave development by the granite - gneiss basement rocks is less evident than elsewhere on the Leeuwin - Naturaliste Ridge. A basement topography locally causing a perched aquifer combined with swamp margin processes, most adequately accounts for the restricted distribution and elevation range of the watertable cave systems. Marine influences during high sea levels may also be invoked, primarily through control of base levels of inland waters, as opposed to flank margin processes involving direct intrusion of marine waters into the karst system.

The Augusta watertable caves have been available for colonisation by fauna since the Middle to Early Pleistocene. The location of the watertable caves permits colonization of the karst aquifer by aquatic species derived from neighbouring inland waters, facilitated by the swamp margin setting and elevated watertables existing during periods of wetter climate.

KARST AQUIFER

Structural properties

The carbonate aquifer is superficial and unconfined, perched on an impermeable aquiclude of granite-gneiss basement rocks. The saturated thickness is estimated to be about 2 m (year 2000), with the level of the watertable showing fluctuations up to 4 m above this in response to varying conditions of recharge experienced over geological time scales. Overlying the saturated zone is an unsaturated zone of 20 - 40 m thickness which includes the soil, subcutaneous and transmission zones.

The soils are deep yellow-brown siliceous sands (Tille and Lantzke 1990). The subcutaneous zone, or *epikarst*, is the upper layer of more intensely weathered bedrock immediately beneath the soil and above the less-weathered transmission zone (Williams 1983, 1985). The subcutaneous zone is exposed on steeper dune slopes where the soil mantle has been stripped to reveal a limestone surface that is highly perforated by subsoil solution features including fissures, small-diameter tubes, and solution pipes. The epikarst has significant water storage capacity and sufficient interconnectivity that enables lateral movements of water (interflow) and drainage along preferential pathways to the subsurface (Friederich and Smart 1981, Smart and Friederich 1986).

The aquifer exhibits triple porosities characteristic of karst terranes. A high primary porosity is a consequence of the low degree of consolidation of the limestone, which permits storage and transmission of water through the intergranular pore spaces of the rock matrix. There is a high degree of secondary and tertiary porosity, through fissures and bedding plane partings (secondary porosity), and dissolution through pores, fissures, bedding planes, and conduits (tertiary porosity). Integrated flow pathways are well developed both in the saturated and unsaturated zones.

Hydraulic conductivity and storativity is spatially variable - the aquifer is non-homogenous and highly anisotropic. Porosity is locally diminished by precipitated carbonate cements in paedocalcic horizons and caprock zones, which behave as perched, leaky aquitards in the unsaturated profile. Palaeosols may redirect and concentrate vadose seepage flows laterally along the top of the horizons. Where these flows intersect a cavern then the discharging waters, which are saturated with calcium carbonate, deposit calcite speleothems. The speleothem feature in Jewel Cave known as the *Cave Coral* appears to originate, at least in part, from a truncated palaeosol horizon in the wall above.

A conceptual model of the karst aquifer, showing structural properties, storages and flow paths appears in Figure 11.

Aquifer boundaries

The boundaries of the karst aquifer(s) are more or less defined by the distribution of carbonate dune sediments and topography of the underlying granite-gneiss basement, however leakage of allogenic waters either into, or from, adjacent granular aquifers is postulated where hydraulic gradients are favourable. Delineation of the aquifer boundaries is complicated by lack of information on the basement topography, and, burial beneath sands, of the eastern edge of the dune limestone which may inter-finger with both the underlying and overlying sediments. The karst catchment therefore cannot be precisely defined, but should be considered as a zone which has a dynamic outer boundary dependent on local details of geology and water regime (Gillieson 1996).

A core catchment area is defined by the inland margin of the karstified dune, and envelopes all land surfaces directly above the known caves and the 'cave belt' inferred to extend, more or less continuously, along the inland margin and slopes of the ridge between Deepdene and Turners Spring. The western boundary of the karst aquifer catchment is represented by a subsurface divide presumed to exist in the basement rocks that lie buried beneath dune sands emplaced on the crest of the Augusta ridge. The location of the subsurface divide may not be coincident with the surface topographic divide, owing to inland progradation of stacked aeolian dunes, although the dune expression probably reflects the basement topography to at least some degree. Accordingly, the peripheral, or buffer catchment area, attempts to encompass such uncertaintities, which includes adjacent aquifers with which hydraulic connectivity or exchange may be periodically activated.

The existence of a common level of watertable cave

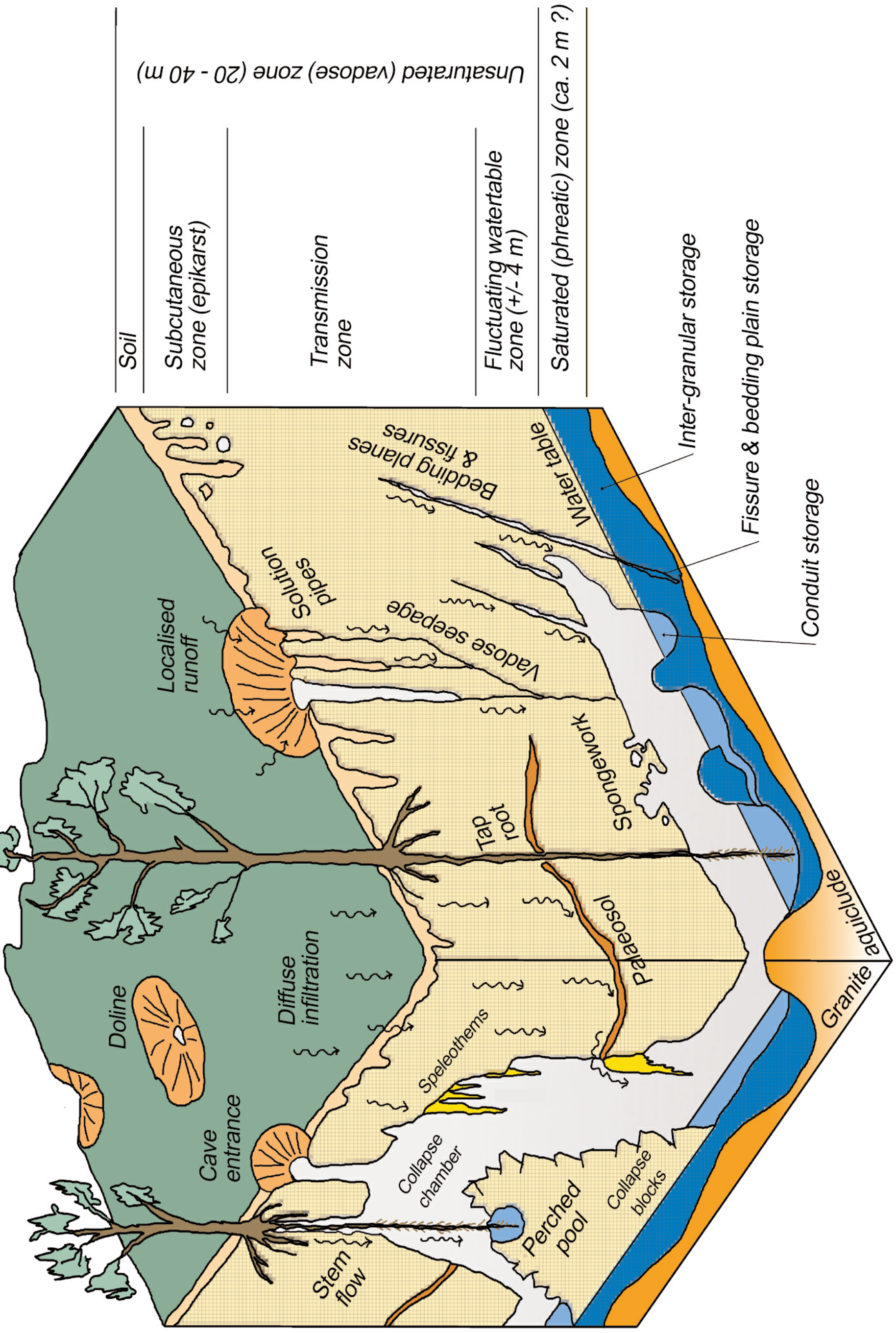


Figure 11. *Conceptual model of the Jewel Cave karst aquifer, showing structural properties, storages and flow paths. Not shown beneath the deep-rooted tree canopy is shallow-rooted understorey vegetation.*

development, that persists between subsystems situated on either side of the Turner Brook - West Bay Creek surface divide, and which likely breaches this divide, suggests a genetic relatedness of development associated with a regional base level controlled by a higher palaeo sea level. Thus there remains the possibility that the boundaries of the karst aquifer, palaeo or otherwise, encompass all the karst subsystems located on the inland margin of the Augusta dune ridge - viz. Deepdene, Cresswell Road, Labyrinth, Jewel-Easter, and by extrapolation, Green Hill Road, Hill View Road and Turners Spring. In addition to management of groundwater resources, this possibility is relevant to the interpretation of stygofauna distribution.

Aquifer relationships

There existed a general watertable level, or levels, in Jewel, Easter and Labyrinth Caves lying between 23.2 - 24.2 m AHD during December 2000. Over the horizontal transect distance of 1,720 m the water surfaces at 9 spatially dispersed sites were measured as lying within a 0.5 m height range of eachother (Table 4). The results of trigonometric heighting and spirit leveling indicate that water surfaces at *The Beach* and *Epstein* in Easter Cave are coplanar, and that both these water surfaces lie within 0.07 m (+/- 0.04 m) of the water surface in Jewel Cave. The leveling precision obtained at other sites was less than this given the resolving accuracy with the barometric method, which is limited by a standard deviation in measurement of 0.2 - 0.6 m. Within this limitation however, the results do not suggest a sloping water table, nor a stepped series of perched pools, in the direction NW - SE along the longitudinal axis of the cave systems. AHD benchmarks and reference points established during this study are listed in Appendix 7.

Aquifer dynamics

Water levels were monitored at 17 spatially dispersed sites within Jewel Cave (3 sites), Easter Cave (12 sites) and Labyrinth Cave (2 sites), over the 3 year period, June 1999 to May 2002 (Appendices 1, 14).

There is a distinct cyclic fluctuation in groundwater levels that is linked to winter rainfall and summer drought. The hydrograph curves were generally congruent between sites monitored within each cave, indicating they were hydraulically connected. The hydraulic conductivity exists through either primary or secondary porosity, developed below the level of tertiary porosity, which is the main level containing cave passages of humanly enterable proportions. At present the main cave passage level is almost completely drained.

The water level monitoring results support hydraulic connectivity between Jewel and Easter Caves at the present time and water level, but not with Labyrinth

Table 4. *Height of the water surfaces in metres above mean sea level (AHD) measured during December 2000 at nine sites in Jewel, Easter and Labyrinth Caves. Horizontal distance along a transect line corresponding to the NW-SE long axis of the cave systems is indicated relative to the Organ Pipes in Jewel Cave.*

Locality	*Site*	*Distance (m) & direction relative to Organ Pipes*	*AHD (m)*	*Method and measurement confidence*
Jewel	Organ Pipes	0	23.69	[1] +/- 0.02 m
Easter	Epstein	325 SE	23.62	[2] +/- 0.04 m
	Beach	430 SE	23.61	[2] +/- 0.04 m
	lake F	590 SE	23.7	[3] SD = 0.5 m
	Lemon	670 SE	23.4	[3] SD = 0.2 m
	lake W	755 SE	23.7	[3] SD = 0.3 m
	Tiffanys	830 SE	23.9	[3] SD = 0.6 m
	lake Z	1020 SE	23.7	[3] SD = 0.5 m
Labyrinth	L20	700 NW	24.0	[4] SD > 0.2 m

[1] Trigonometric heighting, differential barometric leveling

[2] Trigonometric heighting, spirit & water tube leveling

[3] Differential barometric leveling, standard deviation (SD) of measurement

[4] Differential barometric leveling, clinometer and tape

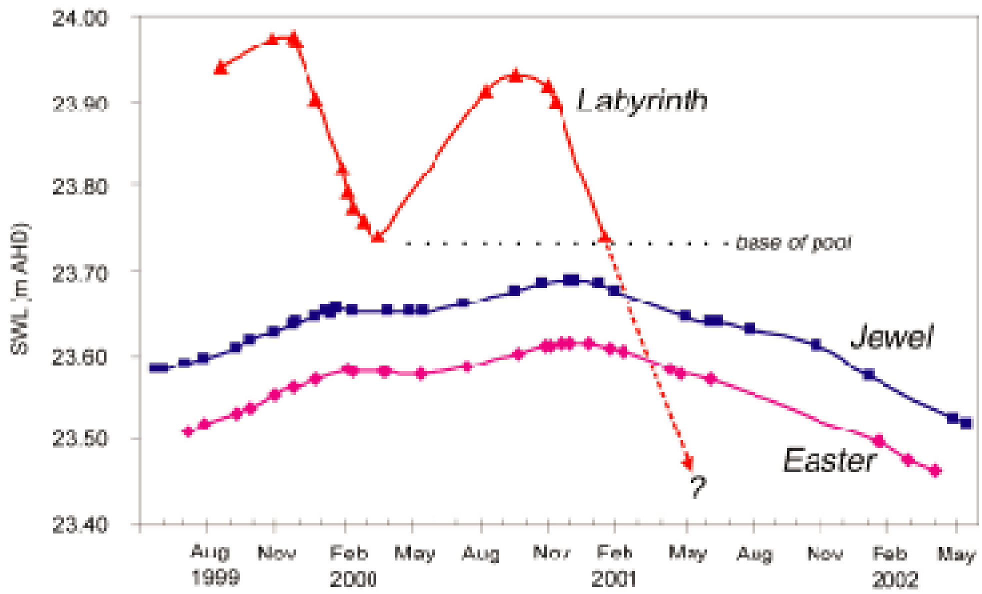


Figure 12. *Relative water level changes in Jewel, Easter, Labyrinth Caves, July 1999 to May 2002.*

Cave (Figure 12). Thus a hydraulic discontinuity appears to exist between these two subsystems at about 23.5 m AHD. However, hydraulic connectivity between all three caves is inferred under conditions of higher watertable, including a similar watertable surface at about 25 m AHD in 1965, and, multiple higher, palaeo water levels and flood strandlines that are well-correlated between sites and caves.

The results contrast, in part, with Lowry (1965) who concluded that no water-filled connection existed between Labyrinth Cave and Jewel Cave, or between the latter cave and Easter Cave, although he did concede that measurement inaccuracies might account for the apparent divergence in his hydrograph curves.

Subsequent proving of a rapid and direct subsurface air connection between Jewel and Easter Caves (Webb 1980) indicated the existence of a palaeo hydrological connection between these two caves, when water levels were up to 4 m higher than present. A minimum horizontal distance of 110 m separates passages in Jewel and Easter Caves. Where the caves approach each other, a ridge of granite-gneiss is encountered that rises to meet the flat ceiling of the watertable passage at about 27.5 m AHD. Passages at this junction diminish to a size that is too constricted for humans to explore, although a narrow gap between the top of the granite ridge and the limestone ceiling continues to allow the free flow of air between the caves. Whilst this basement structure might appear an impermeable barrier, it must be breached or fractured at some point to enable a groundwater connection to exist under the present low watertable elevation (Figure 13).

A horizontal distance of 300 m separates Labyrinth Cave from the next nearest karst feature within the Jewel-Easter subsystem - Skull Cave is a collapse chamber that cannot be humanly explored to the depth of the watertable but has evidently originated from stoping collapse into underlying watertable cavities. A further 420 m separates Skull Cave from visible groundwaters in Jewel Cave. Exploration to date suggests that cave development is limited in the section of dune ridge between the Labyrinth and Jewel-Easter subsystems. This apparent gap in cave development lies opposite the crest of the topographic divide between West Bay Creek and Turner Brook. The divide occurs in basement rocks immediately to the east of the dune system. Thus if there is a westward continuation of this divide, which is partly mantled by sediments, this might form a partial or complete groundwater barrier accounting for the incongruence observed in the hydrographs.

Adjacent non-karst aquifers

Non-karstic granular aquifers lie adjacent the karst aquifer in the catchments of Turner Brook and West Bay Creek. These shallow aquifers occur in podsolized residual quartz sands and silty clay to sandy gravels up to 4 m deep overlying laterite along the western margins of the surface watercourses and the Turner Brook - West Bay Creek surface divide (Hall and Marnham 2002, Tille and Lantzke 1990). These aquifers hold significant

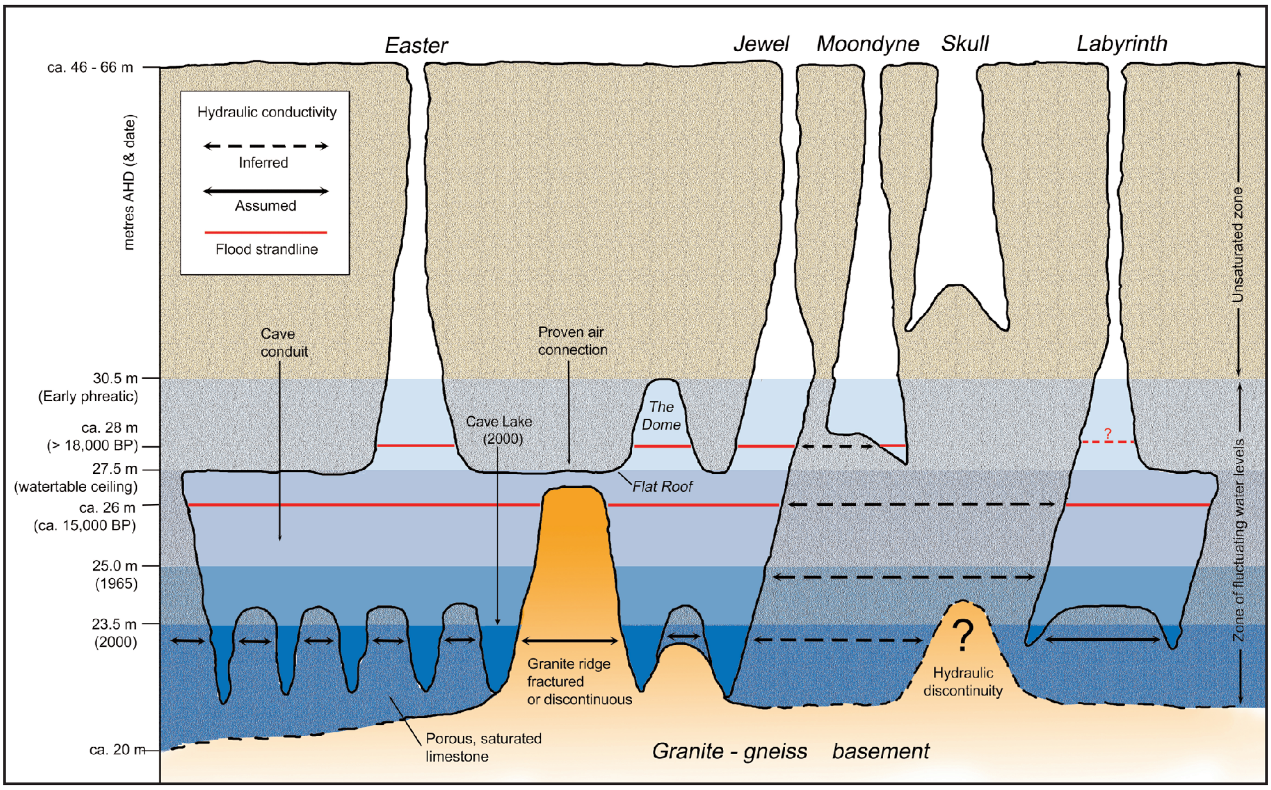


Figure 13. *Schematic model (cross-section NW - SE) of the JELSS showing hydraulic connections and geological barriers (assumed and inferred), under different water level regimes. Hydraulic conductivity is assumed between water bodies within individual caves, and also between Jewel and Easter Caves at the present water level. An hydraulic discontinuity is inferred between the Jewel-Easter subsystem and Labyrinth subsystem when water levels are below about 25 m AHD. The zone of fluctuating water levels is vertically exaggerated relative to the thickness of the unsaturated zone.*

perennial groundwater storage (Slade Ag Tech 1997, 1999).

Some leakage and mixing of groundwaters between the karstic and non-karstic aquifers possibly occurs, although the precise relationship, and location, of the interface between these aquifers remains ill-defined. Irrespective of this, the elevation (25 - 30 m AHD) of the land surface in the area of the Turner Brook - West Bay Creek divide (Location 4371 and vicinity) indicates a hydraulic gradient in the direction towards the karst watertable, so penetration of diffuse lateral interflow from proximal margins is considered a probability (Figure 7, p. 16). Proclivity to capture of proximal allogenic waters is more likely in the Labyrinth and Cresswell Road subsystems where the topography incorporates a swale-like depression paralleling the dune margin.

Further downstream from the surface divide the hydraulic gradient between the karstic and non-karstic aquifers is reversed. In these parts, groundwater discharges to the surface during winter at the junction with the break of slope, where it is concentrated in swampy areas and springs located at elevations generally between 15 - 25 m AHD (Figure 6, p. 10).

In West Bay Creek, some of the groundwater discharge points have been developed into soak dams or wells, where limited pumping is presently undertaken for stock and domestic supply - all except one are down-gradient of the karst watertable. At Location 1497 to the east of Jewel Cave pumping tests on two soak dams that hold water over summer yielded recharge rates of 3.44 and 5.4 m^3/hr (Slade Ag Tech 1999). Water is also pumped from Locations 1397 and 230.

Drawdown in the superficial aquifers of West Bay Creek and Turner Brook might have already occurred by excavation of drains and evapotranspiration from pine plantations. Usage of the shallow groundwater resources will increase in the future as this section of West Bay Creek has been identified as suitable for vines and an irrigation water supply that could be partly drawn from this source (Slade Ag Tech 1997, 1999).

Recharge

Recharge type

Under the present water regime, groundwater recharge to the watertable caves is predominantly *autogenic*, viz. fed by direct rainfall infiltration and localised runoff on the karst surface. There is no *allogenic* recharge from surface streams originating on surrounding non-karst areas, but there may be a component of diffuse recharge derived from adjacent non-karst aquifers, where hydraulic gradients are favourable.

Recharge regularly occurs following winter rainfall, but during periods of little or no recharge, when the rate of discharge exceeds that of vertical infiltration, the watertable lowers. This cycle is repeated seasonally, depending on the amount and intensity of rainfall. In addition to seasonal recharge, occasional extreme precipitation events also contribute flood recharge that may significantly add to aquifer storage.

Rapid flow and slow flow

Major sources of autogenic recharge can be grouped into two sets based on the rapidity of flow - rapid flow and slow flow (Atkinson 1977, Gunn 1986, Smart and Hobbs 1986). The slow flow recharge is dispersed and enters the aquifer diffusely, by infiltration through the soil. Some localised integration of this vadose seepage flow occurs during percolation through the subcutaneous zone and otherwise porous, unsaturated mass of limestone. At low recharge rates, flow is predominantly via these many low capacity routes (Smart and Friederich 1986).

A component of the recharge includes concentrated (point source) inputs via fissures, solution pipes and stem flow via tree roots. Whilst the surface catchment area of concentrated inputs may be small compared to that of dispersed input, the preferential pathway flows developed provide a component of rapid flow recharge to the aquifer that bypasses losses that would otherwise occur in maintaining field-capacity moisture content of the soil, and, evapotranspiration in the shallow root zone. Rapidly transmitted recharge waters may still be solutionally aggressive when they reach the watertable, whereas slow flow seepage waters quickly lose aggressivity as they become saturated with carbonate during their longer transit time through the unsaturated zone (Palmer 1991).

Fissures, solution pipes and cave entrances play a role in delivering episodic recharge to the aquifer. During this study, a rapid flow pulse was observed to enter cave passages through fissures and stalactites at 25 m depth, within 30 - 60 minutes of an intense short duration rainfall event. During August 2002, vadose seepage flow was observed on the Organ Pipes within 4-5 days following a 56 mm - 24 hour rainfall event. Prior to this, the appearance of seepage flow at this location had not been observed since similar episodes in 1996 and 1997 (B. Hall pers. comm., 2002).

During intense precipitation events, localised surface runoff occurs on the sandy water-repellent soils, which then may be channelled down solution pipes and cave entrances. After fires, recharge via point source inflow may assume a relatively greater role as raindrop infiltration may be reduced on water repellant, bare soil surfaces and surface run-off is increased (O'Loughlin et al. 1982).

A sloping basin of about 1 Ha surface area feeds surface runoff down solution pipe entrances into Jewel Cave. Anecdotal reports indicate that during earlier times (1958 - 1980) when the basin was burnt more regularly than present, intense rain storms resulted in substantial surface runoff which drained down the pipes into the cave (L. Robinson & J. McManus pers. comm., 2000). This process still occurs presently, albeit of reduced magnitude owing to the absence of fire over the previous 25 years, which has permitted the development of a dense ground-litter layer that absorbs rainfall and impedes surface runoff. The area of basin catchment where concentrated runoff presently occurs is limited to about 80 m^2 of bare ground surface in the vicinity of the *Natural Entrance* to Jewel Cave.

Rapid flow recharge conduits play an important role in injecting particulate organic matter underground, where it may be utilised as a food source by cave dwelling organisms.

Some form of storage of water in the unsaturated zones of karst aquifers has long been postulated to account for the persistence of percolation inflows to caves during drought (Bottrell and Atkinson 1992). Storage of this type occurs within the JELSS aquifer, as demonstrated by hydrograph analysis. Perennial unsaturated storage enables survival in the vadose zone, of aquatic fauna that includes species with no drought-resistant life stages.

Chloride mass balance

Recharge rates to the JELSS were estimated using the chloride mass balance method (eg. Herczeg et al. 1997) through the water balance equation - viz. at steady state, precipitation to a catchment is balanced by loss terms of evapotranspiration, groundwater recharge and surface runoff (Fetter 1994, Shaw 1999):

$$P = E + R + Q$$

Where P = precipitation amount, E = evapotranspiration, R = recharge to groundwater, Q = discharge to streams plus runoff. Chloride concentrations [Cl] can be substituted in this equation assuming that chloride is neither gained nor lost via weathering, anthropogenic inputs are zero, and no significant Cl is removed via evapotranspiration. Losses through surface runoff are negligible in the JELSS, so the equation can be simplified to:

$$R = \frac{P[Cl]_{pptn}}{[Cl]_{gw}}$$

Where $P[Cl]_{pptn}$ = Cl concentration in precipitation, $[Cl]_{gw}$ = Cl concentration in groundwater. A value of 20 mg/L was obtained for [Cl] measured in rainwater samples collected at Margaret River and Lake Cave.

A series of chloride measurements made by Caffyn (1973a) enable comparison when water levels were 1.5 m higher. The results are compared with other groundwater environments (springs and stream caves) exhibiting a range of recharge and flow types in the Leeuwin - Naturaliste Ridge. (Table 5).

Recharge rates for most phreatic lakes in the watertable caves ranged from 24 - 27 mm/year, which is 2.4 - 2.7 % of the mean annual precipitation recorded at Cape Leeuwin. Higher recharge rates were evident in a few lakes that contain less saline waters, and, in vadose percolation waters (range 41 - 115 mm/year). Higher recharge estimates can be expected from vadose percolation waters, and in the few lakes that appear to receive more direct, or a greater proportion of, vadose recharge. Higher rates were not recorded in most other watertable lakes measured, presumably because further concentration of chloride is occurring by evaporation and transpiration through the roots of phreatophytic vegetation.

The recharge estimate based on chloride measurements made in 1964 (26 mm/year) when water levels were 1.5 m higher, is not significantly different to that between 1993 - 2000 (24 mm/year). However, these estimates do not represent annual variations in recharge resulting

Table 5. *Estimated recharge rates based on chloride measurements from different groundwater environments across a range of recharge, flow, and catchment vegetation types on the Leewuin-Naturaliste Ridge.*

Groundwater environment	*Recharge & flow type*	*Sites*	*[1]Year(s)*	*[2]Chloride balance (%)*			*[3]Est. recharge*	*Catchment vegetation*
				Mean	*s.d.*	*n*	*mm/yr*	
Watertable caves	Autogenic Diffuse/ conduit	Vadose percolation waters & 'fresh' lakes	1964-2000	**4.1-11.8** (range)		6	41 - 115	Forest
		Jewel-Easter Caves lakes	1964	**2.6**	0.5	10	26	
			1993-95, 1999-00	**2.4**	0.4	17	24	
		Labyrinth Cave lakes	1964-2000	**2.7**	0.4	2	27	
Linear stream caves	Autogenic + ?allogenic Diffuse/ conduit	Strongs Cave	1993-95	**13.7**	1.4	3	158	Forest
		Lake Cave	1963, 1999-00	**7.8**	0.9	3	90	
Karst springs	Autogenic Diffuse/ conduit	Leeuwin	1999-00	**8.8**	0.5	9	87	Coastal heath
		Quarry Bay	1999-00	**7.1**	0.4	3	71	
		Turners	1999-00	**5.0–11.0** (range)		2	59 - 110	Forest
	Mixed autogenic/ allogenic, Diffuse/ conduit	Bobs Hollow	1963, 1999-00	**6.2**	0.7	4	72	Forest, Coastal heath
		Contos	1999-00	**7.3**	2.3	3	85	
Non-karst spring	Autogenic, Diffuse	West Bay Creek	1999-00	**16.9**	0.9	2	160	Pasture, Forest
Non-karst bore	Autogenic, Diffuse	Reays Bore	1999-00	**16.8**	2.0	2	167	

[1] Chloride values 1963-64 from Caffyn (1964), 1993-95 from Jasinska (1997), 1999-00 this study.

[2] Chloride mass balance (%) = ([Cl] precipitation/[Cl] groundwater) x 100, where [Cl] precipitation = 20 mg/L. Measured values in appendices.

[3] Estimated recharge = chloride mass balance (%) x mean annual preciptation (mm); Cape Leeuwin (998), Forest Grove (1156), Margaret River (1127).

from short-term changes in seasonal rainfall, rather the average recharge over many years (Davidson 1995). The recharge estimates obtained using the chloride balance method show some disparity with recharge estimates obtained from hydrograph analysis (see later). Owing to the uncertainties involved with the chloride balance method, the tabulated values are not a reliable indicator of seasonal recharge amounts, however, they can be used to compare recharge in the Augusta watertable caves relative to other groundwater environments on the Leeuwin - Naturaliste Ridge.

Mean recharge estimates for the watertable caves (47 mm/year) are lower than that for other groundwater environments sampled, including stream caves (124 mm/year), karst springs (81 mm/year), and non-karst groundwater/springs (164 mm/year). By implication of its lower capacity to integrate recharge, the JELSS karst aquifer may be more sensitive to a decline in rainfall, or other recharge limiting processes, compared with other groundwater environments on the Leeuwin - Naturaliste Ridge.

The higher recharge rates measured in other groundwater environments were attributed, variously, to different aquifer type (karstic/conduit cf non-karstic/granular), characteristics of recharge (dispersed autogenic cf concentrated allogenic), flow velocity (rapid cf slow), and catchment vegetation (deep-rooted/phreatophytic cf shallow-rooted/cleared). Low recharge rates to the watertable caves are expected from the interception of highly seasonal rainfall by a dense understorey vegetation and deep ground litter layer, virtually stagnant flow in the saturated zone, with continual depletion of storage by evaporation, capillary action, and transpiration by deep-rooted phreatophytic vegetation. This is compounded by the absence of concentrated allogenic recharge inputs to the watertable caves, in contrast to the linear stream caves fed by sinking streams elsehwere on the Leeuwin - Naturaliste Ridge.

Transmission and storage

The shape of the water level hydrograph is a unique reflection of the response of the aquifer to recharge, the form and rate of recession, in particular, provide significant information on the storage and structural characteristics of the aquifer (Ford & Williams 1989). There are two periods for which good time-series water level data exists, 1973-1981, and 1998-2002. Importantly, the period 1973-1981 spanned a significant recharge episode, and, coincided with the highest watertable levels recorded since 1958, whilst the period 1998-2002 included the lowest winter rainfall in a century coinciding with the lowest watertable levels recorded. Water level fluctuations and correlations with monthly rainfall for these periods are described following.

Period 1973 to 1981

This 8 year period coincided with significant multi-annual fluctuations in water levels, including the most rapid and highest magnitude rise observed in the watertable since 1958 (Figure 14). Effective groundwater recharge occurred after winter rainfall during 3 out of 8 years (viz. 1973-74, 1978), with recession of the water level occurring between these years.

During the 18 month period from July 1973 to January 1975 the water level rose 616 mm, at an average rate of 30 mm/month. The peak in water level lagged 6 - 8 months after the peak in winter rainfall. Annual rainfall totals recorded at Cape Leeuwin for 1973 and 1974 were 124 % and 109 % of the long term average. The winter rainfall components (June-July-August) during these years were respectively 117 % and 95 % of the annual average.

Rainfall during September 1973 was exceptional (181 mm) with nearly twice the September average recorded at Cape Leeuwin. Privately held daily rainfall records from Augusta indicate that two thirds (147 mm) of this September rainfall was delivered on five separate rainfall days of 20 - 40 mm each (M. Sowry unpublished data). The intense September rainfall preceded a rapid rise in the water table observed in Easter Cave in the following month. Access into the *Gondolin* section of Easter Cave was possible up until October 1973, but in early November *The Ducks* (a nearly water-filled passage with minimal air-space) were completely submerged by water rising at the unprecedented rate of 80 mm/month (Caffyn 1973).

July 1974 was also an exceptional month with intense precipitation causing unusual run-off and flooding in southwest Western Australia. Cape Leeuwin recorded 142 % of the long term monthly average, whilst *The Copse* located 5 km southeast of Jewel Cave, recorded 166 % of the average rainfall logged at this site over a 7 year period. Two-thirds of *The Copse* rainfall was delivered on 8 separate rainfall days of >19 mm, including one day (29th July) when 59 mm was recorded. The monthly rainfall amounts recorded at *The Copse* and Augusta, both located on the inland, leeward side of the Leeuwin - Naturaliste Ridge, tend to be greater than those recorded over the same periods at Cape Leeuwin situated on the coastal, windward side.

In contrast to the vigorous recharge response of 1973 and 1974, the following year experienced a relatively small water level response. Winter rainfall at Cape Leeuwin

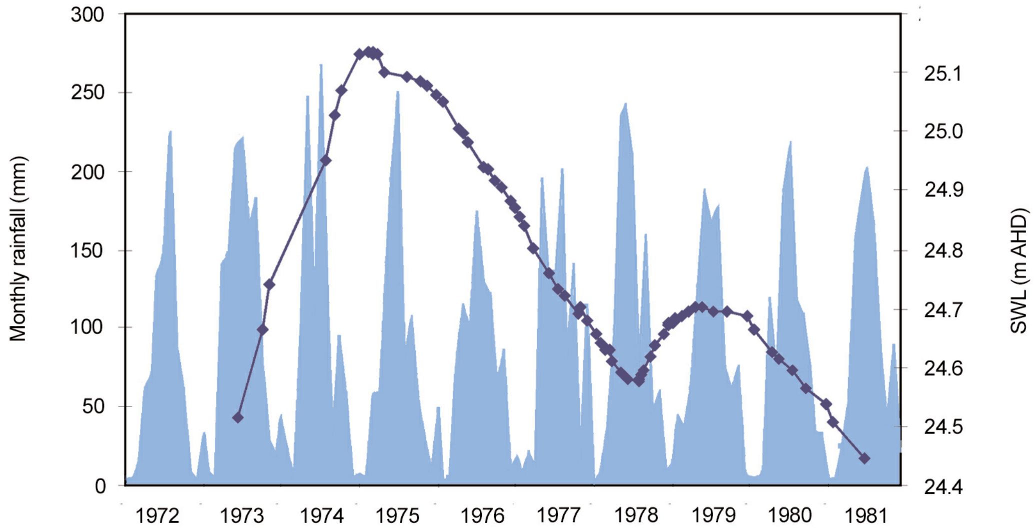


Figure 14. *JELSS water level fluctuations and monthly rainfall 1973 to 1981.*

during 1975 was 102 % of average, and despite July rainfall that was 133 % of average, no actual rise in water levels was detected, although effective recharge did cause muting of the recession curve.

From November 1975 water levels declined steadily at a rate of about 16 mm/month over the subsequent two and a half years until August 1978. No effective recharge occurred during 1976 and 1977. Winter rainfall total for 1976 was 72 % of average. The entire JCKS was burnt by wildfire on 11th April 1977, but this event did not stimulate recharge by winter rains of that year, which were 90 % of average. However, significant recharge occurred the following year when a water level rise of 12 mm occurred in response to May-June-July rainfall that was 117 % of the long term average (514 mm) over the same period. During this period, *The Copse* recorded 8 rain days of > 20 mm, including two days where > 50 mm was recorded. An initial lag time of 3 - 4 months occurred between the start of significant rainfall in May, and the water levels starting to rise in August-September. The peak in water levels lagged 10 months behind the rainfall peak.

No water level rise occurred during 1979 and 1980 although some effective recharge derived from winter rainfall in 1979 may have slowed steepening of the recession limb that continued through 1980 - 81 at a rate of about 13 mm/month. Winter rainfall at Cape Leeuwin during 1979 and 1980 was 104 % and 102 % of average respectively. At *The Copse*, there were 7 rain days of > 20 mm during winter for each of 1979 and 1980, including one exceptional rain day (63 mm) on 13th July 1979.

Period 1998 to 2002

The period 1998 to 2002 spans 5 consecutive years, with water level readings made at about monthly intervals during the latter 3 years (Figure 15). From a low point reached in July 1998, recovery of water levels occurred over 3 consecutive years, but winter rainfall in 2001 was the lowest in a century (59 % of mean) and contributed to a decline in water levels to the lowest historically recorded.

From the low point reached in July 1998, water levels started to rise about one month after heavy rainfall in May 1999. Prior to May negligible rainfall was recorded. The water level continued to rise at a rate of 9 mm/month to a peak which lagged 8 months behind the rainfall peak. From this peak, reached in February 2000, only minimal recession of the hydrograph curve had developed prior to recharge from the next winter precipitation regime having an effect. This recharge pulse was initiated within one month of June rainfall, that nonetheless was only 53 % of average. The water level rose a further 35 mm at a rate of 5 mm/month to a peak which lagged 4 months behind the rainfall peak.

A recharge peak of small amplitude and short duration occurred in response to winter rainfall 2001 that was 59 % of the long term mean - a water level rise of 5 mm was measured in Jewel Cave, with a lag of 1 - 2 months after

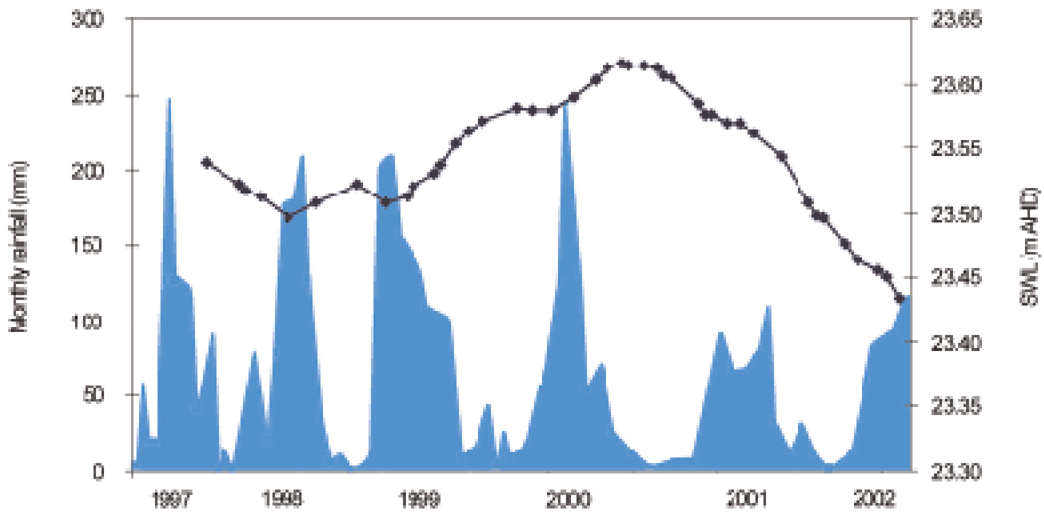


Figure 15. *JCKS water level fluctuations and monthly rainfall 1999 - 2002.*

May rainfall (93 mm Cape Leeuwin), which occurred with negligible antecedent rainfall. Cape Leeuwin recorded 219 mm during June - July - August, only 59 % of average and the lowest proportion for this period recorded to date. Very low rainfall was recorded throughout SW Western Australia during winter 2001, overall the region received only 54 % of its January to August average rainfall, the lowest for a century (Augusta-Margaret River Mail Sept. 5th 2001).

After winter 2001 the rate of water level recession increased from 5 - 7 mm/month, up to 11 - 24 mm/month. As at June 2002, the watertable has declined to the lowest level historically recorded.

Discussion

There exists a distinct annual periodic component in the water level signal that typically shows a recharge response to winter rainfall, followed by water level recession during summer drought. However, effective recharge does not occur in every year, and there is considerable variation in the magnitude, rate, and lag times in the water level response.

The shape of the hydrograph curves indicates considerable storage of water in the unsaturated zone, with slow release of this storage causing flattening and broadening of the curves, and delayed responses. The lagged response times also suggest that recharge via slow flow pathways, as opposed to rapid flow pathways, constituted the major component of recharge over the sampled periods.

Anecdotal evidence indicating significant storage in the unsaturated zone, as well as a decline in this storage over the longer term, is provided by *The Drip*, a perennial source of vadose seepage that discharges from the ceiling near the Organ Pipes in Jewel Cave. The Drip has never ceased flowing since 1958, although the rate of discharge has declined from that described during earlier years as, *'like a slow running tap'* (< 1 L/min.) (J. McManus pers. comm., 2000), to 0.0015 L/min (measured 11th Oct 2000). The decline in vadose seepage at this site mirrors the general decline in recharge observed over the longer term.

The initial delay in water level response of about one month, or longer, after the commencement of autumn - winter rainfall following summer drought, may be due to a number of processes. These include the replenishment of soil moisture and evapotranspiration losses, as well as replenishment of vadose storage and time taken for transmission of vadose seepage to the phreatic zone 30 - 40 m below the surface. If the soil is less permeable than the rock beneath, then it provides a recharge regulator, limiting recharge to the infiltration capacity of the soil (Ford & Williams 1989).

The water level signal displays rising and falling limbs that are mostly linear. The rate of water level decline between separate periods of recession ranged from 5 - 24 mm/month (Mean 13, n = 8). The rate of water level rise between different cycles was more variable and ranged from 5 - 80 mm/month. The high variability in recharge rates reflects the high variability in rainfall amounts, including rainfall events of varying intensity and duration. Within cycles, the rising limb generally tended to be steeper than the recession limb, indicating that recharge generally occurs at a greater rate than discharge, a process that may be accentuated by rapid flow recharge pulses. The base of the recession limb is representative of baseflow recharge/discharge conditions, whilst the low variability in recession rates between cycles suggests a state is reached where the baseflow recharge versus discharge remains more or less constant.

There is a lag time ranging from 4 to 10 months (Mean 7.5, n = 4), between the winter rainfall peak and the corresponding water level peak. This variability in recharge response times was not detected in earlier studies utilising smaller available data sets - Lowry (1965) and Webb (1988) measured a 3 - 4 month lag from commencement of substantial rainfall to initial water level response.

Dispersed autogenic recharge can generate pulses in percolation throughput, with variable lags of minutes to months for pulse through times (i.e. hydraulic response time *cf.* flow-through time), although some of the water displaced may be many months old due to storage in the epikarstic aquifer (Ford & Williams 1989). Antecedent conditions of storage strongly influence the proportion of the rainfall input that runs off or generates a throughput pulse, as well as the lag between the input event and the recharge response. Thus with a range of flow-through and pulse-through rates in the unsaturated and saturated zones, the recharge and output response of a karst aquifer to recharge is complex. As a consequence, hydrograph form and recession characteristics show considerable variety. The responses observed in the JCKS are consistent for basins composed of highly permeable formations such as limestone, particularly limestone formations dominated by autogenic recharge, whereas impermeable rocks yield strongly peaked hydrographs because of little storage and rapid runoff (Ford & Williams 1989).

The prolonged lag associated with the rising limb and peak of the hydrograph means that the recession limb can be ameliorated, or interrupted entirely, by recharge originating from the following winter rains. Two (or more) consecutive winters that contribute substantial recharge may, cumulatively, effect a greater rise in water level than wet winters interspersed by dry winters with water level recessions in-between. This amalgamation of recharge pulses has an apparent synergistic effect on effective recharge, as supported by substantial water level rises in 1973-74 and 1999-2000, both linked with consecutive wet winters. Similarly, the recession limb may continue uninterrupted into following years if there is no effective recharge in-between. This has the effect of introducing a multi-annual cyclic fluctuation on top of the annual cyclic fluctuation in the water level signal.

There is a high level of uncertainty involved with attempting to quantify recharge response based on annual, winter or monthly rainfall totals, although above average monthly rainfalls during mid-late winter are more likely to cause effective recharge, particularly when these occur in successive months. Based on an earlier and smaller data set Appleyard (1989) inferred that water levels in caves increase only if monthly rainfall exceeds about 300 mm, however this study found that water levels rose after less than 100 mm monthly rainfall at Cape Leeuwin during May 2001, which occurred with negligible antecedent rainfall. Similarly, effective recharge also occurred after about 200 mm of rainfall in each of May and June 1999, with negligible antecedent rainfall for 6 months prior.

Effective recharge appears to depend on rainfall events of sufficient intensity to exceed losses by surface detention and evapotranspiration. There is evidence to suggest that high rainfall days, rather than total monthly rainfall, are more useful indicators of potential recharge within the JCKS. Recharge from intense rainfall events will be most effective if the vegetation, soil and epikarst are already saturated from antecedent rainfall. Thus a succession of high rainfall events occurring after soil moisture capacity has been reached, is likely to promote more effective recharge, such as observed during September 1973.

Flow measurements

Fluorescein dye placed in lakes in Jewel and Easter Caves before 1964 showed no signs of movement after several months, suggesting virtually stagnant flow conditions (Lowry and Bain 1965). This observation contrasts with a series of flow measurements undertaken in 1979 when water levels were at a similar height. The 1979 measurements utilised partly-submerged bottles and time-lapse photography (*sensu* Webb 1988) to measure flow velocity and direction. In the *Epstein Lake* in Easter Cave a flow of about 1 m/hour was recorded in an easterly direction (R. Webb, unpublished data), whilst in the *Flat Roof Lake* in Jewel Cave a southwesterly flow direction of unspecified velocity was recorded (R. Webb, pers. comm., *in* Williamson and Bell 1979). Further investigation of flow conditions is warranted.

Scalloping

It has long been recognised that scallop features are indicators of the direction of flow, whilst the size of scallops is inversely related to the flow velocity of the water that sculptured them (White 1988). In Jewel, Easter and Labyrinth Caves there is well developed scalloping on the higher water table ceiling of passages that are 4 m above present water level. Two populations of scallops are present, of which the smaller (approximately 30 - 40 mm diameter) are indicative of more rapid flow conditions and younger in age, being superimposed upon the larger (> 200 mm). The orientation of the smaller scallops at three separate locations in Jewel Cave, and in the *CEGSA Extension* in Easter Cave, suggests a palaeo flow direction towards the south.

The small diameter scalloping which is confined within a narrow vertical range, suggests a period, or periods, in the water regime, of rapid flow velocities. This contrasts with the dominant flow regime involving slow-moving waters, as indicated by cave patterns, and the wide vertical range of nothephreatic speleogens (spongework). Further measurement of scallop orientation and dimensions is required for proper interpretation of the palaeo flow regimes.

Phreatic storage

The volume of water held in phreatic (saturated zone) storage was estimated for the period prior to the watertable decline (1958-1980), and 20 years later (2001) (Table 6). Between 1980 and 2001 the phreatic storage volume is estimated to have declined by about 33 %. The estimates of storage volume are considered to be conservative as the saturated area likely extends beyond the limits of surveyed cave passages.

The saturated thickness is assumed to average about 2 m depth below the general floor level of cave conduits, and is based on the 1 m water depth measured in the deeper cave lakes (2001), and, coring in Jewel Cave which intersected the granite - gneiss basement at 1.5 to 2.5 m depth below floor level. In the Perth region the estimated specific yield value used of the Tamala Limestone is 0.3 (Davidson 1995). In the JELSS the specific yield, and hence storage volume, is likely to be greater owing to the degree of conduit development.

Table 6. *Estimates of phreatic storage in the Jewel - Easter and Labyrinth subsystems for the periods 1958 - 1980 and 2001.*

Subsystem	[1]*Minimum saturated area (Ha)*	[2]*Estimated storage volume (ML)* [3]		*Storage decline since 1980 (%)*
		Years 1958–1980	*Year 2001*	
Jewel - Easter	42	378	252	33
Labyrinth	10	100	60	33

[1] Defined by the rectangular area enclosing surveyed cave passages of subsystem

[2] Assumed saturated thickness 3 m (1958- 1980); 2 m (2001); assumed specific yield 0.3 (Davidson 1995)

[3] 1 megalitre (ML) = 1 million litres

Discharge

Groundwater discharges from the karst aquifer by three main routes:

1. Gravitational discharge where downward hydraulic gradients occur;

2. Capillary action and evaporation in cave conduits;

3. Evapotranspiration.

The combined rate of discharge by these routes can be estimated from the slope of the recession limb of the hydrograph curve, the base of which represents the point where seasonal recharge is at a minimum. The mean annual discharge rates for the periods 1973-1981 and 1998-2002, were estimated using this method:

1973-1981: 174 mm/year (n = 2)
1998-2002: 156 mm/year (n = 6)

The relative contributions made by each of these discharge processes remains difficult to quantify in the absence of defined outflow points to the JELSS, such as springs where discharge could be monitored. Evaporation and transpiration are likewise difficult to quantify, the rates varying seasonally depending on air temperature and velocities, soil moisture content, and the density of plant canopies (Davidson 1995, Shaw 1999). Discharge by evaporation and capillary action are influenced by cave climate processes, which are in turn dependent upon surface climate variability (Michie 1997). Losses through surface runoff or groundwater abstraction are negligible, but evaporation from foliage (interception) and evaporation from the litter layer or soil surface is significant in the JELSS.

Gravitational discharge

The quantities of groundwater discharged by gravitational routes, remains to be established for the JELSS. The hydraulic gradient supports discharge to the surface, or leakage into adjacent granular aquifers, along the margins of West Bay Creek and Turner Brook. Downward discharge into the underlying basement rocks is likely to be minimal. As proposed by Bain (1967), leakage from the Labyrinth subsystem would likely drain into the catchment of Turner Brook, whilst that from the Jewel-Easter subsystem into West Bay Creek. Whilst there is substantial winter discharge of groundwater in these areas, this is mainly derived from shallow non-karstic, granular aquifers. This interpretation is based on the rapid and highly seasonal discharge responses, and chemistry of the waters which are not enriched with bicarbonate.

Any exsurgence points for the karst groundwaters are predicted to show a delayed seasonal response to the dispersed autogenic recharge, and, deposition of tufa by bicarbonate-saturated waters, as occurs elsewhere on the Leeuwin -Naturaliste Ridge. However, no outflow caves or likely exsurgence points, either extant or extinct, are known for the JELSS. It is possible that such features may lie buried beneath sediments, and that present gravitational discharge occurs as subsurface underflow, semi-confined within adjacent aquifers.

Evaporation and capillary action in cave conduits

Discharge of water held in phreatic storage occurs by capillary action in addition to evaporation from open water surfaces and from microscopic water films on, and in, porous rocks and sediments (Michie 1997). These

Table 7. *Estimates of pan evaporation in different climatic environment zones within the JELSS.*

Climatic environment zone	*Pan evaporation (mm/year)*			*No. measurements*	*No. sites*
	Mean	*SD*	*Range*		
[1] Deep zone	4.8	6.1	0 – 18.0	18	[3] 4
[2] Transition zone	45.0	52.0	0 – 120.0	4	[4] 2
Combined	12.1	25.8	0 – 120.0	22	6

[1] Annual temperature range < 1 °C

[2] Influenced by inflow of cool dry air in winter

[3] Jewel Cave – Flat Roof 1; Moondyne Cave – Tower of Babel; Easter Cave – Y Junction, Epstein lake in blind alcove

[4] Jewel Cave - Flat Roof 2; Easter Cave – base of entrance chamber

processes result in saturation of the cave atmosphere with water vapour - in the deep cave zone the temperature remains near 17 (+/- 1) ^{o}C year-round, and the relative humidity is between 95 - 100 %. Circulation of the cave atmosphere is driven by changes in surface barometric pressure, which alternately causes movement of air masses into, and out of, the caves and porous rock mass by the process of barometric pumping. When the surface barometric pressure falls then the caves 'exhale' near-saturated air, thus water is lost from the karst system. Conversely, water is gained during inhalation cycles.

Evaporation also occurs when surface air masses which are cooler, denser and drier than the cave atmosphere are drawn underground by gravity or pressure change. Evaporation by this process occurs mostly during autumn - winter, and is most evident in the transition zone closer to cave entrances where surface climatic influences are greater.

Evaporation rates in deep zone and transition zone climatic environments within the JELSS were estimated by the pan evaporation method (Table 7). Seasonal differences were recorded at the transition zone sites, with greater evaporation rates during autumn and winter, than during spring - summer. Evaporation in the deep zone showed less variation between seasons, and the rates were lower, or below detection limits.

The mean annual evaporation rate within deep zone climatic environments was estimated to be 4.8 mm/year, whilst the combined deep - transition zones rate was 12.1 mm/year. The lesser rate is likely to be most representative at the scale of the karst aquifer, where deep zone climatic conditions predominate. This figure represents only 3 % of the mean annual total discharge estimated from the hydrograph recession curve.

It is concluded that evaporative water loss from open water surfaces in cave conduits represents a relatively small component of total discharge from the karst system.

Evapotranspiration

In common with other similar climate-vegetation associations, evapotranspiration constitutes the major component of discharge from a catchment, in most of southwest Western Australia annual evapotranspiration from forest is limited by lack of water (Borg et al. 1987). The evapotranspiration component within the JELSS includes sub-components of:

1. Interception and evaporation of rainfall from foliage;

2. Evaporation from the ground litter layer or soil surface;

3. Transpiration by shallow-rooted vegetation in the soil and subcutaneous zones;

4. Transpiration by deep-rooted vegetation in the phreatic zone.

Shallow-rooted understorey vegetation, dominated by peppermint trees, transpires water stored in the soil and subcutaneous zones, whilst karri and marri eucalypts have tap roots that penetrate the entire aquifer profile to depths up to 40 m below the surface. Water stored in the saturated zone is continually depleted through transpiration by this deep-rooted phreatophytic vegetation, thus making it difficult to discriminate component contributions in the water budget.

Water budget

The water budget may be evaluated through the hydrologic equation

Inflow = Outflow +/- Changes in Storage

Hydrologic input to the karst aquifer is primarily via autogenic precipitation. Inputs via allogenic surface water and groundwater inflow are negligible. The hydrologic outputs from the karst catchment include evapotranspiration, subsurface capillary action and evaporation, and gravitational discharge. The latter two components are relatively minor, whilst evapotranspiration constitutes the major component of output. Outputs via surface runoff and groundwater abstraction are negligible or non-existent. In the absence of these outputs, the water budget for the karst aquifer can be evaluated by substituting in the hydrologic equation:

$$P = ET + R$$

where P = precipitation and R = recharge to groundwater (eg. Fetter 1994, Shaw 1999). The evapotranspiration component can be estimated by rearranging the equation to:

$$ET = P - R$$

Within the saturated zone,

$$R = Q_{gw} +/- \ast S$$

Where Q_{gw} = groundwater discharge, and $\ast S$ = change in groundwater storage (eg. Fetter 1994, Shaw 1999).

Recharge and discharge rates were estimated from the slopes of the rising and falling limbs, respectively, of seasonal hydrograph curves over the selected time periods 1973 - 1981 and 1998-2001 (Table 8).

The hydrograph analysis indicates the mean groundwater recharge rate 1998 - 2001 was 3.5 times less than 1973 - 1981, or expressed as percentage of rainfall, 10 % (1998 - 2001) as opposed to 28 % (1973 - 1981). The water budget for the earlier period indicated a net gain in groundwater storage, whilst that for the later period indicated a deficit.

The estimated discharge and evapotranspiration components respectively, were similar between periods (< 10 % difference). The similar discharge rates, despite a drop in storage head of about 1 m between the earlier and latter periods, is attributed to the regulation of outputs via slow gravitational leakage into adjacent granular aquifers, and, evapotranspiration by the deep-rooted phreatophtyic vegetation.

Recharge rates are influenced mainly by rainfall intensity and distribution, soil condition, geology, depth to the watertable and landuse (Davidson 1995). Recharge rates, expressed as a percentage of rainfall, generally range from 10 - 25 % in coastal limestone aquifers in the Perth region, however the vegetation is less dense than in the Cape Leeuwin region. In areas of dense vegetation (native bushland and pine plantations) most of the rainfall is intercepted above ground level and evaporates (Sharma and Pionke 1984 *in* Davidson 1995). That which reaches the soil surface may infiltrate into the shallow root zone and be transpired by the understorey vegetation. Under these conditions there may be negligible recharge to the aquifer.

Table 8. *Water budget from the JELSS over the time periods 1973 to 1981 and 1998 to 2001.*

mm/year	*Period*		*Comments*
	1973 - 1981	*1998 - 2001*	
[1] Mean annual rainfall (P) (mm)	1065	826	Mean annual rainfall for the period 1998 - 2001 is 77 % of that for the period 1973 - 1981
[2] Mean recharge rate (R) (mm/year)	294	84	Mean recharge rate for the period 1998 - 2001 is 29 % lower than 1973 - 1981
R as % of P	28 %	10 %	c.f. 10 – 25 % coastal limestone aquifers in the Perth region (Davidson 1995)
[3] Estimated evapotranspiration (ET)	945	898	Estimated evapotranspiration for the period 1998 -2001 is 10% lower than 1973 - 1981
[2] Mean discharge rate (Q)	174	156	Discharge rates for the period 1998 -2001 is 10 % lower than 1973 - 1981
[4]Net gain/loss in storage (S)	+120	-72	Recharge > discharge 1973 – 1981 Discharge > recharge 1998 - 2001

[1] Cape Leeuwin

[2] Estimated from slope of rising limb of seasonal hydrograph curves (n = 2 for each period)

[3] ET = P – R

[4] R = – Q +/- * S

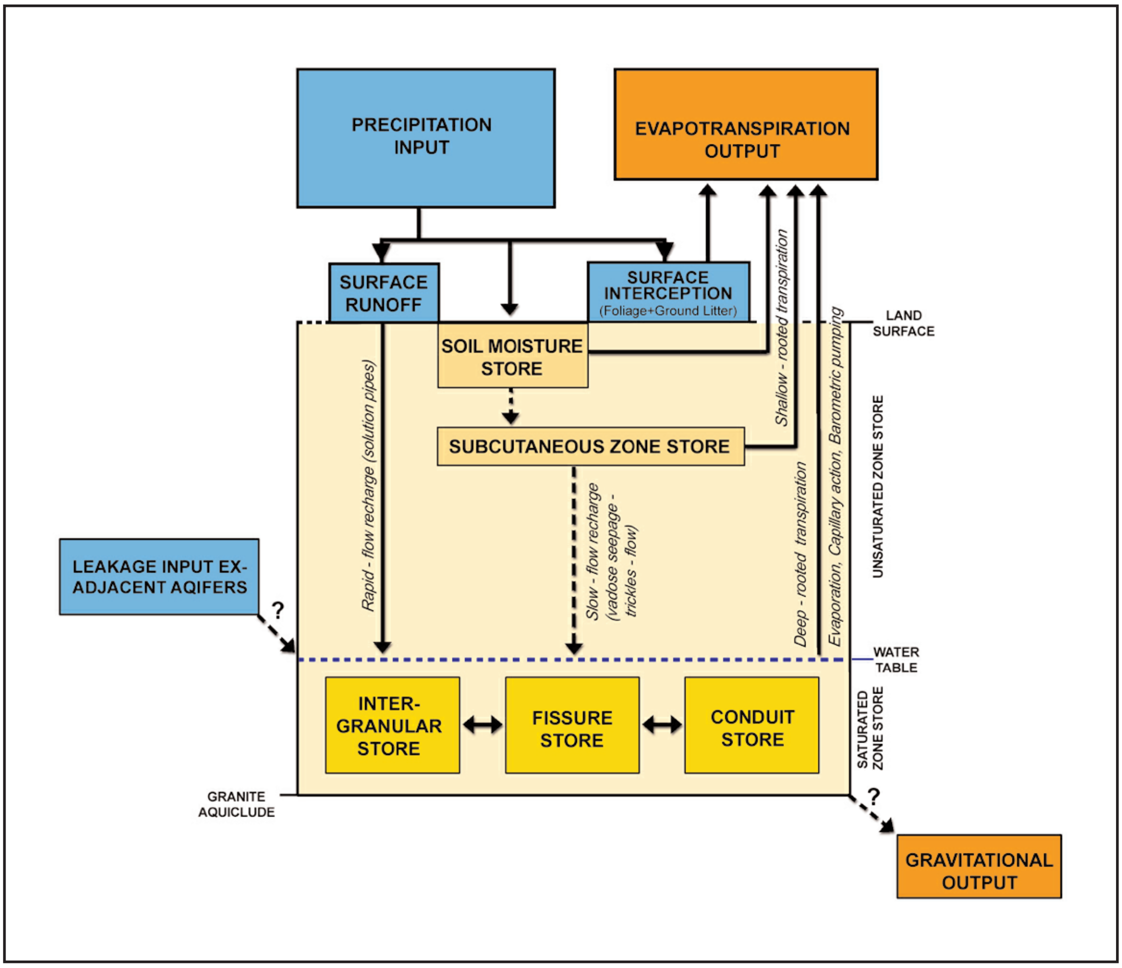
Flow system model

A flow system model for the JELSS karst aquifer is presented in Figure 16. The model shows inputs (blue) and outputs (orange) to the karst system (yellow) incorporating stores, linkages and transfer mechanisms.

Distinctive features of the JELSS karst flow system include:

1. No allogenic surface water inputs (viz. sinking streams);
2. No output via surface runoff;
3. Rapid-flow and slow-flow recharge components;
4. Significant storage in the unsaturated zone (subcutaneous store);
5. Delayed responses in transmission of rainfall input through unsaturated zone (20 - 40 m thick) to saturated zone store;
6. Triple porosity storages in the saturated zone (inter-granular, fissure, conduit);
7. Discharge from the saturated zone store via deep-rooted phreatophytic vegetation, evaporation, capillary action and barometric pumping;
8. No deep circulation or loss, presumed due to underlying granite-gneiss aquiclude.

Figure 16. *Flow system model for the JELSS karst aquifer. Adapted and modified from Ford and Williams (1989), White (1988), Smith, Atkinson and Drew (1976).*



Conclusions

Aquifer characteristics

The karst aquifer is unconfined, anisotropic and non-homogenous, with a high degree of primary (matrix), secondary (fissures and partings) and tertiary (conduit) porosity .

There exists a common level of watertable cave development between about 22 to 28 m AHD, extending in a belt between Deepdene and Jewel-Easter Caves. The belt of cave development may also extend along the inland margin of the dune to Turners Spring.

Groundwater discharges from the karst aquifer by three probable routes:

i) Gravitational discharge where downward hydraulic gradients occur;

ii) Capillary action and evaporation;

iii) Evapotranspiration.

The relationship between the karstic and adjacent, non-karstic aquifers includes hydraulic gradients that permit groundwater flow both into, and out of, the karst system. Gravitational discharge outlets remain unidentified, but the hydraulic gradient favours discharge from the Jewel-Easter subsystem into West Bay Creek, and that from the Labyrinth subsystem into Turner Brook.

Changes in hydrological connectivity between caves are inferred under different water level regimes. Hydraulic connectivity is inferred between the Labyrinth and Jewel-Easter subsystems when the height of the watertable surface is higher than about 25 m AHD, whilst a discontinuity or groundwater divide is inferred below this level.

Recharge to the karst aquifer is predominantly autogenic and dispersed. Recharge is delivered by seasonal rainfall and occasional extreme precipitation events causing surface runoff and flooding in caves.

Transmission of recharge includes rapid flow and slow flow components that are related to concentrated and diffuse flow paths developed in the unsaturated zone. There is considerable storage of water in the unsaturated zone, with slow release of this storage causing delayed responses. Recharge via slow flow pathways, as opposed to rapid flow pathways, constituted the major component of recharge over the sampled periods.

Chloride mass balance suggests that recharge rates to the Augusta watertable caves are lower than recharge rates to other karstic and non-karstic groundwater environments on the Leeuwin - Naturaliste Ridge. By implication of its lower capacity to integrate recharge, the JELSS karst aquifer may be more sensitive to a decline in rainfall, or other recharge limiting processes.

A flow system model developed for the JELSS incorporates several distinctive characteristics:

i) No allogenic surface water inputs (viz. sinking streams);

ii) No output via surface runoff;

iii) Triple porosity storages in the saturated zone (matrix, fissure, conduit);

iv) Discharge from the saturated zone store via deep-rooted phreatophytic vegetation, evaporation, capillary action and barometric pumping;

v) No deep circulation or loss, presumed due to underlying granite-gneiss aquiclude.

Aquifer dynamics

There exists a distinct annual periodic component in the water level signal that typically shows a recharge response to winter rainfall, followed by water level recession during summer drought. Effective recharge does not occur in every year, and there is considerable variation in the magnitude, rate, and lag times in the water level response.

Effective recharge appears to depend on rainfall events of sufficient intensity to exceed losses by surface interception and evapotranspiration. Recharge from intense rainfall events will be most effective if the vegetation, soil and epikarst are already saturated from antecedent rainfall.

There is a high level of uncertainty involved with attempting to quantify recharge response based on annual, winter or monthly rainfall totals, although above average monthly rainfalls (and high rainfall days) during mid-late winter are more likely to cause effective recharge, particularly when these occur in successive months.

Evapotranspiration is the major component of discharge in the water budget.

Between 1980 and 2001 the volume of water held inphreatic (saturated zone) storage is estimated to have declined by about 33 %.

The mean groundwater recharge over the period 1973 - 1981 was estimated to be 28 % of the rainfall received, whilst for the period 1998 - 2001 it was 10 %.

Stygofauna

The vadose (unsaturated) zone is a habitat for stygofauna due to the perennial storage held there.

The dispersal and mixing of stygofauna populations may be influenced by changes in hydrological connectivity between caves, which are inferred under different water level regimes.

Mixing between populations would be enhanced under elevated watertable conditions, when separate pools which remain hydraulically connected only through primary and secondary porosity, became reconnected through flooding of higher level tertiary conduits. Under low watertable conditions, the dispersal and mixing of stygofauna populations within the JELSS aquifer may be retarded owing to the reduced permeability, and potential barriers developed in basement rocks, which occur below the level of the main conduits.

Water Quality

Characterization and interpretation of the physical, chemical and bacteriological properties of groundwater has been the basis for many studies of karst, and groundwater quality generally, whilst protection of water quality in karst lands is a significant environmental, and potentially human health, issue (Ford & Williams 1989, Gillieson 1996, Drew & Hotzl 1999). Karst aquifers are difficult to characterise because of their inherent heterogeneity resulting from their triple porosity, variability along flow paths and differing recharge sources. Much karst water variability results from mixing among these sources, and from rock-water interaction (Mayer 1999). Spatial and temporal variability in water properties however, may be used to interpret aquifer characteristics, including conditions of recharge, storage and flow, which in turn are useful in determining the vulnerability of aquifers to contamination (Quinlan et al. 1992). All of these properties are relevant to understanding and management of groundwater quality and dependent ecosystems.

This study aimed to characterise and interpret water physicochemistry, geochemistry and microbiology within the Augusta karst area and adjacent non-karst water bodies. Sampling locations and results are in Appendices 1, 8 to13.

Physicochemistry

The results of repeated field measurements made during 1999-2000, of water physico-chemistry (temperature, pH, salinity/conductivity, dissolved oxygen) are summarised below, and in Appendix 9.

Temperature

During the study period, the mean temperature of groundwater measured in the Jewel-Easter subsystem was 17.4°C (sd 0.2, n = 66), whilst that in Labyrinth subsystem was 15.1°C (sd 0.1, n = 3). There is little spatial or temporal variation in groundwater temperature within the Jewel-Easter subsystem. The disparity in groundwater temperature between Labyrinth Cave and Jewel-Easter Caves, is consistent with Jennings (1968) who recorded similar disparity in water temperature between these caves in 1963 (Labyrinth - 15.5, Jewel - 16.5, Easter - 17.0°C).

pH

The pH values of the groundwater in Jewel, Easter and Labyrinth Caves are close to neutral, or very slightly alkaline. During this study pH values ranged from 6.83 to 7.65 (n > 60). The pH values are similar to earlier values ranging from 7.2 to 8.1 recorded from Jewel, Easter and Labyrinth Caves in 1963 (Jennings 1968); from Easter Cave in 1972 - 7.4 to 7.8 (Caffyn 1972), and between 1993 and 1995 - 6.9 to 7.2 (Jasinska 1997). All pH values were close to the range of 7.0 to 8.0 recorded from groundwater in other calcareous sediments of the 'Tamala Limestone' and Ascot Formation near Perth (Davidson 1995).

Salinity

The calculated salinity of the groundwater in Jewel, Easter and Labyrinth Caves ranged from about 600 to 2300 mg/L total dissolved solids (TDS) (Figure 17). Little seasonal variation was measured within sites. Nearly three-quarters of sites (n = 17) measured ranged between 1500 to 2000 mg/L TDS, a concentration that classifies the water as brackish and non-potable (Davidson 1995).

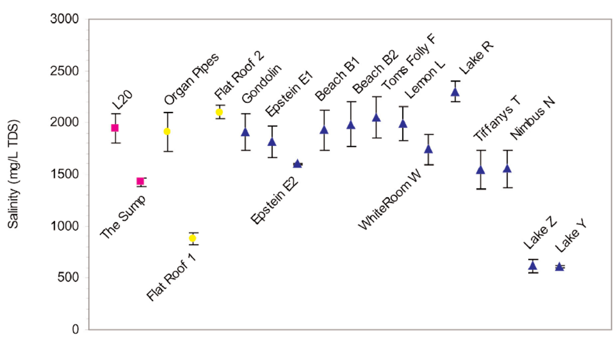


Figure 17. *Seasonal variation in salinity (mg/L TDS) measured at monthly intervals in watertable pools in Labyrinth (squares), Jewel (circles) and Easter (triangles) Caves during 1999-2000. Sites are arranged in linear order from NW to SE along the longitudinal axis of the cave system (see Appendix 1). Error bars are one standard deviation. Data in Appendix 9.*

No large-scale longitudinal gradients in salinity across sites were identified that might infer an overall flow direction along the 1,700 m NW-SE axis of the cave system. As salinity generally increases in the direction of groundwater flow (Davidson 1995), the results imply that groundwater flow along this axis is retarded or non-existent under the present water regime.

Localised, vertical gradients in salinity were detected at 4 sites where the water column profile was measured. In Easter Cave (*Gondolin, Lemon, White Room*) salinity increased between 2 and 8 % at a depth of 500 mm below the watertable surface, whilst in Jewel Cave (*Flat Roof 1*) the salinity increased by more than 30 % between 500 to 1000 mm depth. The vertical salinity gradient within these sites, and the overall lower surface salinities recorded at Flat Roof 1 and other sites (*Lake Z* and *Lake Y*), might be explained by added vadose input with limited mixing occurring between lower salinity infiltration waters and more saline phreatic waters. The measured salinity of vadose infiltration waters at one site in Labyrinth Cave was 942 mg/L TDS.

Dissolved oxygen

Measurements of dissolved oxygen (DO) indicate the cave pools are generally well-oxygenated, except in the vicinity of submerged tree roots. Measurements in *Tiffanys Lake* showed a declining gradient in DO concentration from 82 % saturation at the water surface to 32 % at a depth of 200 mm, to 2 % at a depth of 300 mm within the matrix of the root mat. These levels do not appear to adversely restrict the distribution of stygofauna, which are abundant within the root mat at this site. Measurements at *Lake Nimbus*, a connected water body within 50 m of Tiffanys where root mats are absent, showed only a slight decline in DO from 89 % to 85 % saturation at a depth of 500 mm below the surface. A steeply declining DO gradient (45 % surface to 6% at 300 mm depth) was measured in a bore sunk into clayey sediments in the *Organ Pipes* chamber, Jewel Cave.

Geochemistry

Major ions

The dominant ion in both karst and non-karst waters in the Augusta area is sodium (Na). The predominance of this cation, and the chloride anion, is attributed to proximity of the coast. Two water types are distinguished, based on the second dominant cation being either calcium (Ca) or magnesium (Mg) (Figure 18). Mg dominated waters occur in non-karstic groundwaters and surface waters in the upper reaches of West Bay Creek. Ca dominated waters occur in the karst aquifers and karst springs, and parts of the adjacent granular aquifer in the lower reaches of West Bay Creek. The karst groundwaters generally have greater overall ionic concentrations, and the proportions of Ca and bicarbonate (HCO_3) are higher (Figure 19).

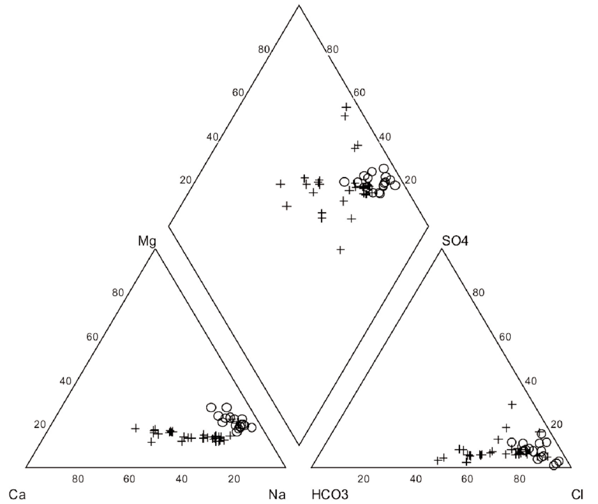


Figure 18. *Trilinear diagram showing percentage composition of ionic species in water samples from the Augusta karst and West Bay Creek. Upper West Bay Creek (Mg dominated) sites (circles) are distinguished from Ca dominated sites (crosses) in lower West Bay Creek and the karst aquifer. Data in Appendix 10.*

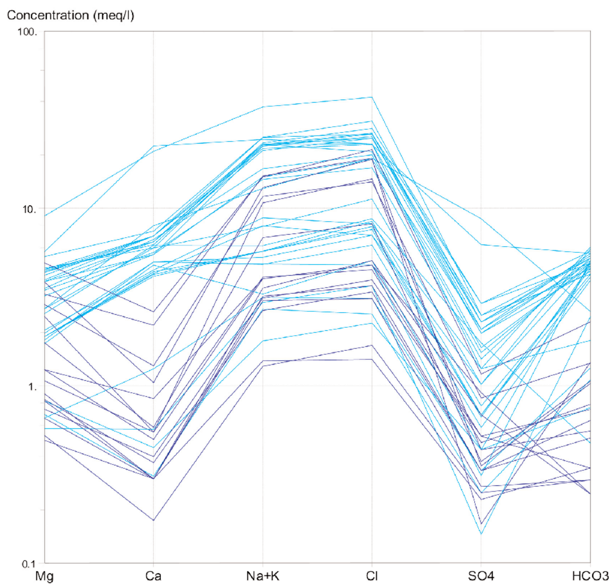


Figure 19. *Schoeller diagram showing major ion chemistry of water samples from the Augusta karst and West Bay Creek. Ca dominated waters (light) are distinguished from Mg dominated waters (dark). Data in Appendices 10, 11.*

There is considerable variation in the hydrochemical facies of Ca dominated waters in the Augusta area. This is attributed to heterogeneity in recharge, storage and transmission characteristics between different karst subsystems, and, mixing of karst waters with waters in adjacent granular aquifers in West Bay Creek. Groundwater discharging at the base of the ridge in the vicinity of the Old Marron Farm (sample sites CW53 and 54) and Reays Bore (sample site CW42), has been in contact with carbonate rocks, which is consistent with interpretation of the dune-basement topography suggesting that subsurface drainage from the ridge might discharge in this area. Other springs and seepage dams fed from the superficial aquifer in the upper reaches of West Bay Creek do not show a carbonate signature (Figure 6, p. 10; sample sites CW37, 38, 39, 40, 41, 49).

Calcite saturation index and Ca/Mg ratio

The calcite saturation index ($SI_{calcite}$) is a useful means of describing quantitatively the deviation of carbonate waters from equilibrium with respect to solid calcite (calcium carbonate) (White 1988). It is defined as

$$SI_{cal} = \log (K_{iap} / K_{eq})$$

where K_{iap} is the ion activity product of Ca^{2+} and CO_3^{2-} and K_{eq} is a coefficient termed the thermodynamic equilibrium (or solubility product) constant (Ford and Williams (1989).

The value of SI_{cal} indicates whether the solution is understaurated (negative SI_{cal}), supersaturated (postive SI_{cal}), or at equilibrium ($SI_{cal} = 0$) with respect to calcite. Supersaturated waters will be capable of depositing calcium carbonate, as speleothems or tufa for example, whilst undersaturated waters will be chemically aggressive and capable of further dissolution of carbonates.

The atomic ratio of calcium to magnesium provides information on the type of rock that a water sample has contacted (White 1988). The parameter is derived from the measured concentrations

$$Ca/Mg = [Ca^{2+}]/[Mg^{2+}]$$

Mg dominated waters are derived through contact with ultrabasic rocks containing ferromagnesium minerals, whilst Ca dominated rocks are derived from limestones. Ca/Mg = 1 for waters in contact with dolomite $CaMg(CO3)_2$.

The 'Tamala Limestone' is composed of quartz sand and 10 to 90 % calcium carbonate sand, with accessory amounts of feldspar, sponge spicules, and heavy minerals (mostly ilmenite) (Abeysinghe 1998). The carbonate fraction was reported in Lowry (1967) as approximately 5 % magnesium carbonate and 95 % calcium carbonate. In the Cape Naturaliste - Cape Leeuwin region, limesand belonging to the Quindalup Dune System sampled at the Boranup Sand Patch and

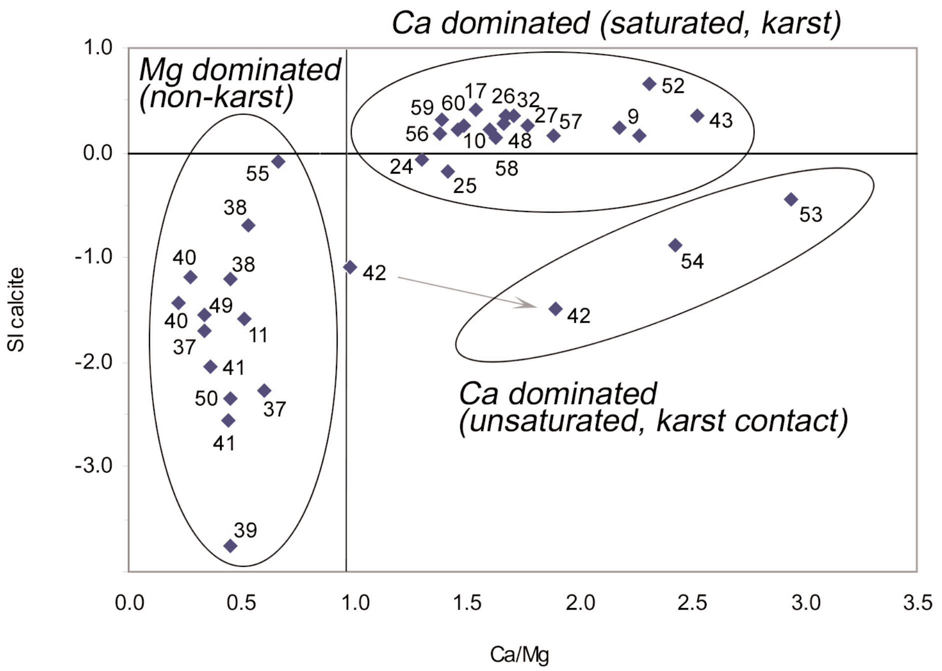


__Figure 20.__ Ca/Mg ratios vs. SI calcite for water samples collected in the JELSS and West Bay Creek. Three distinct water types are represented: (1) Mg dominated; (2) Ca dominated, calcite saturated; and, (3) Ca dominated, calcite undersaturated. Values in Appendix 12.

Quininup Brook contained an average of 77-79 % $CaCO_3$, 6 % $MgCO_3$, and 13 % insolubles, whilst limestone caprock from Margaret River contained an average of 90 % $CaCO_3$, 2 % $MgCO_3$, 6 % SiO_2, and 0.5 % FE_2O_3 plus Al_2O_3 (Abeysinghe 1998).

When the observed Ca/Mg ratios are plotted against $SI_{calcite}$ for water samples collected in the JELSS and West Bay Creek, three distinct water types are indicated: (1) Mg dominated; (2) Ca dominated, calcite saturated; and, (3) Ca dominated, calcite undersaturated (Figure 20).

The Mg dominated waters are derived through contact with ultrabasic rocks of the granite-gneiss basement which contain the ferromagnesium minerals pyroxene, amphibole and biotite (Myers 1994). Ca dominated waters are derived through contact with carbonate sediments of the Spearwood or Quindalup Dune Systems. The calcite saturated group includes vadose and phreatic groundwaters sampled in the JELSS, whilst the undersaturated group is represented by groundwaters discharging from a granular, non-karstic aquifer alongside the lower reaches of West Bay Creek. The bicarbonate load carried by these waters suggests contact with karst rocks, whilst their state of under-saturation may be due to mixing with other, non-carbonate waters.

Discussion

Virtually all groundwater sampled within the JELSS was saturated with respect to calcite. Thus dissolutional cave enlargement is not an active or dominant hydrochemical process occurring in the phreatic zone at the present time. Instead, the process of calcite precipitation predominates, as evidenced in the form of calcite rafts actively developing on the surfaces of most lakes throughout the JELSS.

The general hydrochemical environment below the watertable has ranged from aggressive, undersaturated conditions to non-aggressive, saturated conditions on multiple occasions in the past. These alternate phases of precipitation or dissolution persisted for sufficient periods of time to allow precipitation of thick deposits of subaquatic calcite speleothems (calcite rafts and dog-tooth spar crystals), and respectively in turn, dissolution of calcite. The contrasting hydrochemical environments have strongly shaped the expression of internal cave geomorphology, and added complexity to interpretation of the evolutionary history and development of the karst system. These different hydrochemical regimes are integrated into the mixing corrosion model for cave development (Figure 10, p. 19).

Three samples collected from Jewel, Easter and Labyrinth Caves in July 1963, when water levels were about 1 m higher than present, were saturated with carbonate. From this Jennings (1968) concluded that dissolution could not have been going on at the time, even though these samples were taken in the middle of a wet winter when waters might have been at their least saturated and most aggressive level. Analysis of water samples collected from Easter Cave during April 1972 also showed high levels of dissolved carbonate (Caffyn 1972).

The chemical analyses and observations suggest that aggressive groundwater conditions have not generally persisted in the JELSS during the previous 40 years, and, the conditions required for this probably predate the present hydrochemical regime by some considerable time as indicated by the deep accumulations of calcite raft deposits, and thick growths of dog-tooth spar, which have not been subject to secondary subaqueous weathering. Uranium-series dating of subaquatic spar deposits indicate calcite precipitation environments existed below the watertable at 1.1 ka, and, from 4.35 to 2.16 ka (Appendices 18,19). The absence of any weathering to the surfaces of these spar deposits, which are located 1 to 2 m above the present watertable, suggests that aggressive groundwater conditions have not occurred in the phreatic zone during the previous 4, 350 years at least. On this basis, the watertable caves are interpreted to be a fossil, or relict system, with little or no dissolutional speleogenesis occurring since about the mid Holocene.

Aquifer type and sensitivity

Variation in specific conductivity (SC) or salinity is one of the more useful and readily measurable physicochemical parameters that may be used to interpret aquifer characteristics, including conditions of recharge, storage and flow. These properties in turn are useful in determining the vulnerability of aquifers to contamination (Quinlan et al. 1992). The coefficients of variation in specific conductivity (CV = standard deviation SC x 100 / mean), with interpreted aquifer characteristics and sensitivities are given in Table 9.

The conductivity CV values support the interpretation that the karst aquifer tends toward a combination of diffuse and conduit flow characteristics. This is consistent with the geology and geomorphology, being that of a limestone with high primary (intergranular) porosity, but also with a well developed tertiary (viz. conduit) porosity. The JELSS aquifer is characterised by dispersed recharge, and perennially saturated storage conditions. Utilising Quinlan et al. (1992) scheme for the classification of carbonate aquifer sensitivity, the JELSS is very sensitive to disturbance. (Figure 21).

Table 9. *Coefficients of variation (CV) in specific conductivity (SC) for phreatic groundwaters in the JELSS. Interpretation of aquifer flow type and aquifer sensitivity are based on Quinlan et al (1992). Site data in Appendix 9.*

Sample period	*No. sites*	*No. samples*	*Mean SC (mS/m @ 25°C)*	*Std. Dev. SC (mS/m)*	*Mean CV [1] (%)*	*Aquifer flow type [2]*	*Aquifer sensitivity [3]*
Dec 1999 to Nov 2000	18	93	314	93	7.0	Diffuse / Conduit	Very sensitive

[1] CV = standard deviation SC x 100 / mean – calculated from individual site means in Appendix **

[2] Flow type: 'diffuse' (CV < 5 %), 'diffuse/conduit' (5 – 10 %), 'conduit' (> 10 %)

[3] Aquifer sensitivity: 'moderately sensitive ' (CV < 5 %), 'very sensitive' (5 – 10 %), 'hypersensitive' (> 10 %)

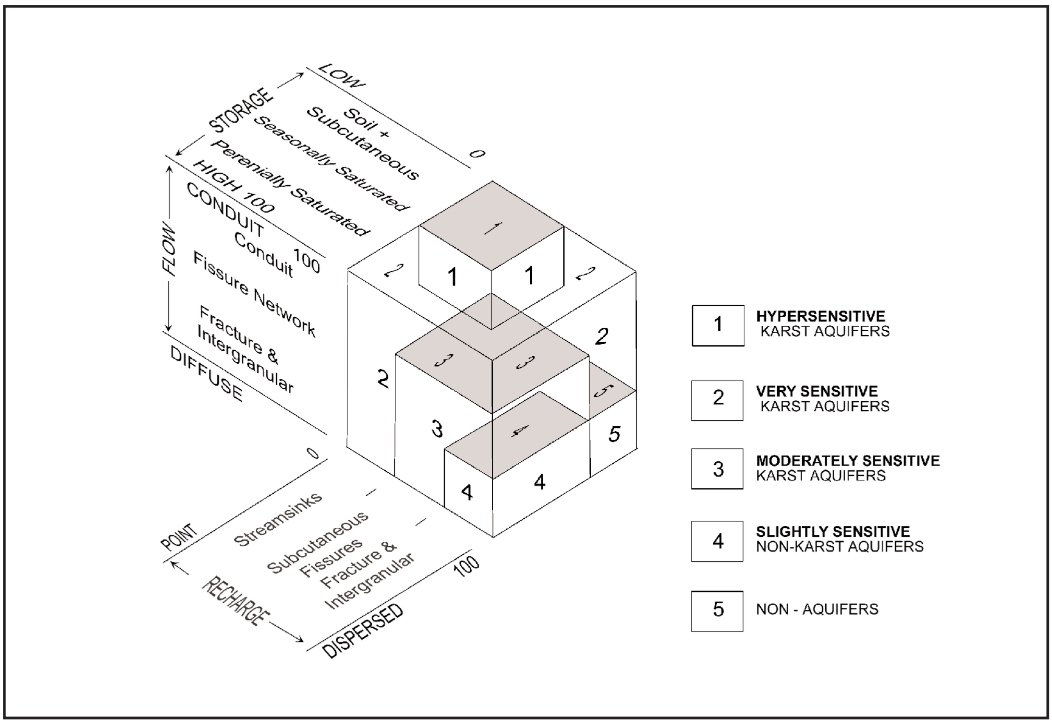


Figure 21. *Conceptual scheme of sensitivity of karst aquifers to disturbance, for storage, recharge and flow types. Boundaries between fields are approximate. The Jewel-Easter-Labyrinth aquifer is characterised by dispersed recharge, perennially saturated storage, and a mixture of diffuse and conduit flows. It classifies as type 2 - very sensitive to disturbance. Adopted from Smart and Hobbs (1986), Quinlan et al. (1992), Gillieson (1996).*

Contamination in Jewel Cave

Groundwater in the vicinity of the *Organ Pipes* in Jewel Cave show concentrations of both chemical and biological species that are indicative of contamination, and which exceed the Australian Drinking Water Guidelines (2000). Elevated levels of metals, nitrate, bacteria and protozoa, are linked to a number of potential sources located both inside and outside the cave (Table 10). Concentrations of potassium, chloride, sulphate, and phosphorous are higher than background levels.

Metals

During 1994, the metals copper and zinc were detected in the groundwater at the *Organ Pipes*, but not at other sites sampled in Jewel Cave (*Flat Roof One*), Easter Cave (*Epstein, Nimbus*) and Labyrinth Cave. The source of copper could be from electrical wiring or coins tossed into the Organ Pipes lake, whilst the zinc could be derived from galvanised infrastructure. These metals are potentially toxic to aquatic life (Boulton and Brock 1999).

Table 10. *Summary of testing on chemical and biological 'species' at 'contaminated' site (Organ Pipes) in Jewel Cave, compared with 'natural' background levels recorded at other sites in Jewel, Easter and Labyrinth Caves. Additional data is in Appendices 10, 13.*

		'Contaminated' site levels		*'Natural' background levels*	*Comments*
		Organ Pipes dripwater	*Organ Pipes lake*		
Chemical 'species'	Nitrate (mg/L) [1]	370 – 425	12	< 1	Levels exceed Australian drinking water quality guidelines
			7.4 [2]	< 0.28	Elevated levels detected by 1994
	Ammonium [3]	Not detected			NH_4 may have been nitrified
	Phosphorous (total mg/L) [1, 4]	< 0.1	0.35	< 0.1	Elevated P level in lake
	Caffeine [4]	Not detected			Potential indicator of septic contamination
	Boron (mg/L) [4]	0.05			Trace levels only, Potential indicator of septic contamination
	Copper (mg/L) [2]		0.06 – 0.13	0	Possible source coins and electrical wiring
	Zinc (mg/L) [2]		0.26	0	Possible source galvanic infra-structure
Biological 'species'	Heterotrophic bacteria [5] (CFU per ml) [6]		700 - 1600	16 - 32	Higher than background levels
	General coliforms (CFU per 100 ml) [7]	0	440	60	Levels exceed Australian drinking and bathing water quality guidelines
	Faecal bacteria (including *E. coli, Streptococcus, Salmonella*) [7]	Low or absent	Low or absent	Low or absent	Survival time in groundwater may be limited
	Protozoa (ciliated)	Very abundant	Abundant	Not detected	Higher than background levels; Probably feed on bacteria
	Meiofauna	Present		Present	Includes Copepoda and Oligochaeta

[1] Australian Government Analytical Laboratories, sampled Oct 1999 – May 2000
[2] Pallin Test Kit, P. Bell, 1994
[3] Merck Aquaquant test kit, 2002
[4] Chemistry Centre (WA), 2002
[5] State Health Laboratory, 1992
[6] Colony Forming Units (CFU) per ml; Coliscan Easygel test kit, 2000
[7] Colony Forming Units (CFU) per 100 ml; tests in 1992, 2000, 2002

Nitrate

The recorded levels of nitrate (370-425 mg/L) are about 400 times natural background levels, and about 40 times the Australian Drinking Water Guidelines (Appendix 10). Beneath native bushland, rural and forested areas in the Perth region, the nitrate concentration is generally less than 1 mg/L (Davidson 1995). In the coastal limestone belt with abundant nitrogen-fixing *Acacia* vegetation, nitrate concentrations may be slightly higher (1 - 7 mg/L). Septic sewage and intense fertilization may generate nitrate concentrations up to 60 mg/L, whilst concentrations greater than this may be associated with industrial and liquid waste (Davidson 1995).

The occurrence of nitrate in vadose infiltration waters, which enter the cave above the pathway alongside the Organ Pipes, identifies the probable source of contamination to be outside the cave. The zone of contamination is localised to the vicinity of the Organ Pipes, although additional nitrate infiltration points were detected in the *Beehive* and beginning of the passage to the *Volcanoes*. Elevated nitrate concentrations were not detected in other lakes in Jewel Cave, including the Pendulite Lake less than 30 m distant, which suggests that groundwater flow, or dispersal of the nitrate, is restricted or absent in this direction at least.

The septic system, which is located directly above the cave but separated through 35 m thickness of porous limestone, is strongly implicated as the potential source of nitrate contamination, although the extreme levels recorded in the cave suggest that a process of nitrate concentration is occurring within the infiltration zone. Tests of the infiltration waters for other chemical and biological indicators of septic contamination (boron, caffeine, faecal pathogens) were inconclusive (Table 10).

Microorganisms

The results from limited testing do not indicate serious contamination of the groundwater by faecal pathogens, however the abundances of non-faecal microorganisms in the lake chamber, which is visited by about 45,000 people per year, are substantially higher than background levels (Appendix 13). The impact of this microbial loading on the groundwater ecosystem and stygofauna communities remains to be fully elucidated, however, Protozoa were very abundant at this site, and and meiofauna are still present in the infiltration waters.

Sampling undertaken during 1992 did not detect any coliform bacteria, faecal *Streptococcus* or *Salmonella*, however a raised level of heterotrophic bacteria was measured in the *Organ Pipes* lake. Sampling in Jewel Cave during 2000 detected coliform bacteria at the *Organ Pipes* and *Pendulite* lakes, but not elsewhere in the cave. General coliform densities were greatest at the *Organ Pipes*, but the specific faecal coliform, *Escherichia coli*, was not detected. The *Organ Pipes* and Pendulite lakes also contained substantially greater numbers of other colony forming microorganisms.

High abundances of heterotrophic bacteria were measured both in infiltration waters contaminated by nitrate, as well as infiltration waters not contaminated by nitrate. The nitrate contaminated infiltration waters contained very high abundances of ciliate protozoans, whilst these organisms were not detected in non-contaminated waters. These animals probably feed on bacteria (Boulton and Brock 1999). Both the contaminated and non-contaminated infiltration waters contain meiofaunal communities that include species of copepod crustacean and oligochaete worms.

Conclusions water quality

Physicochemistry

There is little spatial or temporal variation in groundwater temperature within the Jewel-Easter subsystem (mean 17.4 ^{o}C), which differs from the Labyrinth subsystem temperature (15.1 ^{o}C). The pH values of the groundwater in Jewel, Easter and Labyrinth Caves are close to neutral, or very slightly alkaline, and generally within the range (7.0 - 8.0) recorded from groundwater in the 'Tamala Limestone' near Perth. The calculated salinity of the groundwater in Jewel, Easter and Labyrinth Caves ranges from about 600 to 2300 mg/L total dissolved solids (TDS), but there was little seasonal variation measured within sites. No gradients in salinity indicative of groundwater flow directions were detected. The cave lakes are generally well-oxygenated, except in the vicinity of submerged root mats where DO concentrations of 2 % did not appear to limit the distribution of stygofauna.

Geochemistry

Three distinct water types are represented in the JELSS and adjacent waters in the West Bay Creek catchment: (1) Mg dominated; (2) Ca dominated, calcite saturated; and, (3) Ca dominated, calcite undersaturated.

Mg dominated waters derived through contact with ultrabasic rocks of the granite-gneiss basement occur in non-karstic groundwaters and surface waters in the upper reaches of West Bay Creek. Ca dominated waters derived through contact with carbonate sediments of the Spearwood or Quindalup Dune Systems occur in the karst aquifer and karst springs, and parts of the adjacent granular aquifer in the lower reaches of West Bay Creek The carbonate load carried by non-karstic groundwaters in the lower reaches of West Bay Creek suggests some mixing with, and discharge of, karst groundwater in this area.

Virtually all groundwater sampled within the JELSS was saturated with respect to calcite. Under the present climate conditions, the dominant hydrogeochemical process in the phreatic zone tends toward precipitation rather than dissolution of calcite. Dissolutional speleogenesis has not operated during the previous 4,350 years at least, although the hydrochemical environment below the watertable has alternated from aggressive, undersaturated conditions to non-aggressive, saturated conditions on multiple occasions before this time. The watertable caves are interpreted to be a fossil, or relict system, with little or no dissolutional speleogenesis occurring since about the mid Holocene.

Aquifer type and sensitivity

The JELSS aquifer tends toward a combination of diffuse and conduit flow characteristics, and, is classified as very sensitive to disturbance.

Contamination

Groundwater in the vicinity of the Organ Pipes in Jewel Cave show concentrations of both chemical and biological species that are indicative of contamination. Elevated levels of metals, nitrate, bacteria and protozoa, are linked to a number of potential sources located both inside and outside the cave.

Palaeo water regimes

A complex, multiphasic history of changing *water regimes* is evident within the Augusta watertable caves. The primary components of water regime are timing, frequency, duration, extent and depth, and variability. These scale-dependent variables are related to each other in space and time whilst the combination of timing, frequency and duration is analogous to flow history (Boulton and Brock 1999). In the JCKS this history has involved significant adjustments to local watertables, interspersed by prolonged still-stand episodes, in addition to major flood events of short-duration. At various times in the past, water levels have been as much as 1 m lower, and 4 m or more higher than present.

Major water level fluctuations are recorded in erosional and depositional features that are well-preserved in the low energy cave environment. In addition to recording the height of past watertable stillstands and flood events, some of these features provide information on the hydro-chemical nature of groundwaters and flow environments at the time of their formation or deposition. Together, these records are a valuable source of information on past water regimes in the karst catchment, including *inter alia*, conditions of recharge, storage, flow, water balance and fire-flood events.

The reconstruction of palaeo water regimes thus facilitates evaluation, within a broader spatial and temporal context, of the present watertable decline and implications of this for dependent stygofauna. In this study, palaeo water regimes were reconstructed by stratigraphic mapping, leveling, and dating of various types of water level markers. A complex stratigraphic succession of palaeo water level indicators occurs, which includes several distinctive marker horizons and strata that are ubiquitous and can be traced between different sites.

Figure 22. *Erosional horizons indicating former watertable levels in Flat Roof chamber, Jewel Cave. Chamber ceiling marks zone of spongework solution features associated with early speleogenesis. After this phase of development the watertable lowered and subaerial stalactites and flowstone formed. Subsequently the lower part of the flowstone feature was dissolved by aggressive, groundwaters - the upper limit indicated by the truncated surface (finger pointing). After the watertable dropped again, subaerial stalactites grew from the truncated surface.*

Water regime indicators

Palaeo water regime indicators include erosional horizons (speleogens) and deposited strata (speleothems, clastic sediments, bone deposits). Erosional horizons include flat-lying, piezometric-controlled ceiling development, or other surfaces secondarily truncated by a rising watertable (Figure 22). Depositional horizons include fluvial sediments, bone deposits, and subaquatic speleothems. In addition to recording the elevation of past water levels, some indicators infer past conditions of recharge, storage, flow, water balance and fire events for example.

The hydro-chemical nature of past groundwaters has ranged from dissolutional aggressive waters undersaturated with respect to calcite, to non-aggressive waters that are near-saturated or supersaturated with respect to calcite. Supersaturated groundwaters have precipitated subaquatic calcite in the form of dogtooth spar and coralloid crystal growths, as well as calcite rafts, whilst aggressive waters have resulted in secondary dissolution of calcite speleothems and speleogens. Superposed cycles of emersion and submersion in groundwaters that are variably saturated or dissolutionally aggressive, are preserved on the surfaces of speleothems that were formed originally in either a subaerial (eg. stalagmites, stalactites), or subaquatic (raft cones, volcanoes) environment (Figures 23, 25).

Figure 23. *Subaerial and subaquatic deposits in the Gondolin, Easter Cave. Subaerial stalactites were formed (specimen dated 304 ka) before a high watertable phase deposited a black stain (ca. 8,930 - 9,799 BP.) which was subsequently partly covered by a red clay. Later, groundwaters superstaurated with calcite deposited crystals of dogtooth spar which grew on top of the stalactites between 2.16 - 4.35 ka. Photo by Sid Roatch ca. 1972.*

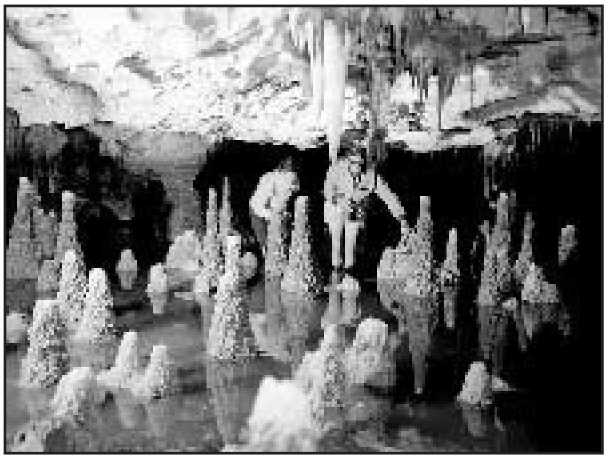


Figure 25. *Raft cones are subaquatic speleothems built up through sinking of calcite rafts below dripwater points. After the watertable receeded below the apex of the cones, dripwaters continued to excavate a 'crater' in the apex of the cones. The Volcanoes, Jewel Cave 1958, photo by Barry Hall, WA Newspapers Ltd.*

Figure 24. *Flood strandline in The Dome, Jewel Cave. The strandline is a brown band about 400 mm thick situated at a level just above the head of the standing figure. The deposit is rich in organics and charcoal with a radiocarbon age of 25,900 BP.*

Recharge waters of low energy have deposited fine caliber red clays, whilst fast flow, high energy flood recharge waters have transported from the surface, coarse caliber sediments and organic material rich in charcoal. These materials have been deposited underground in fluvio-clastic sedimentary sequences and organic strandline deposits. Good examples of these water regime indicators occur in The Dome, Jewel Cave (Figure 24, Appendix 20).

Other water borne materials have left behind distinctive brown stains and black veneers (Figure 29, p. 58). Compositional analysis (Energy Dispersive Spectroscopy, X Ray Diffraction, Scanning Electron Microscopy) of the stains indicated the presence of aluminium silicates (smectite and halloysite), manganese and the rare earth elements, lanthanum and neodymium. These elements could be derived from weathering of the granitic-gneiss basement rocks. The black and brown colouration of these stains may be due to manganese and iron oxides respectively (eg. Boulton and Brock 1999), and/or organic compounds (eg. Caldwell et al. 1982).

The different types, subcategories and characteristics of palaeo water level indicators are summarized in Table 11.

Stratigraphic relationships

A complex stratigraphic succession of palaeo water level indicators occurs, which includes several distinctive horizons and strata that are ubiquitous and which can be traced between different sites throughout the JCKS. The vertical range and the highstand elevation point, of water level horizons was accurately leveled and correlated between sites where possible. Stratigraphic relationships and relative ages were determined by the principle of superposition. Radiocarbon and uranium-series dating of sediments constrained the ages of water regime phases and flood events (Appendices 18 to 21). Determined ages were cross-checked for consistency with the interpreted stratigraphy, and, by dating replicate samples from the same indicator horizon in different locations.

A preliminary chrono-stratigraphic sequence of palaeo water regime indicators in the Augusta watertable caves is presented in Figure 26.

Table 11. *Types, subcategories and characteristics of palaeo water regime indicators in the Augusta watertable caves.*

	Water regime indicators - types, subcategories & description			Interpretation	Notes
Erosional features	Primary speleogenetic forms		Phreatic / nothephreatic features	Early speleogenetic phase, aggressive groundwaters	Early Pleistocene
Erosional features	High watertable phases		Truncated primary forms, intermediate level notches, truncated subaerial speleothems	Subsequent speleogenetic watertable phases, aggressive groundwaters	Early- Mid Pleistocene
Erosional features	Scallops		Two populations - Small diameter superposed upon large diameter	Younger, small diameter scallops indicate directional rapid flow conditions	Older large scalloping indicate slow flow conditions
Depositional features	Fluvio-clastic deposits High & low energy types	Organic (flood) strandlines	Flood strandlines rich in charcoal & organics	High energy, rapid-flow recharge event after fire	[1] Multiple fire-flood events, 14C ages range 15,100 – 35,507 BP
Depositional features		The Dome sediments	Stratified fluvio-clastic sequences rich in charcoal & organics	High energy, rapid-flow recharge events after fire	[2] Six fire-flood events, [1] 14C ages 33 – 35,400 BP
Depositional features		Clays	Red clay fluvial deposits	Low energy depositional environment	
Depositional features	Water-borne stains	Black or brown stains	Stain or veneer with distinct upper horizons	Water borne deposits - colour derived from weathering products of granite-gneiss rocks and/or organics	Contain: [3] Manganese [4] Aluminium silicates – smectite & hallyosite [3,4] Rare earths - lanthanum & neodymium [1] Organics 14C ages 3,372 – 9,799 BP
Depositional features	Speleothems	Subaqueous	Subaqueous spar, coralloid & raft deposits	Groundwaters supersaturated with calcite, watertable still-stand episodes	Eg. [1] Gondolin spar 2.16 – 4.35 ka; Tunnel spar 1.1 ka; grey coralloid band, The Volcanoes raft cones
Depositional features		Subaerial	Stalagmites, stalactites, flowstone	Lower watertable for duration of subaerial growth	Eg. Lake Nimbus stalagmite 11.3 – 13.15 ka

[1] Refer appendices for details of radiocarbon and Uranium-series age determinations.

[2] Refer appendix for stratigraphy of sediments in The Dome, Jewel Cave.

[3] Energy Dispersive Spectroscopy & Scanning Electron Microscopy by CSIRO Particle Analysis Service, Perth.

[4] X Ray Diffraction analysis by Pauline Treble, Australian National University

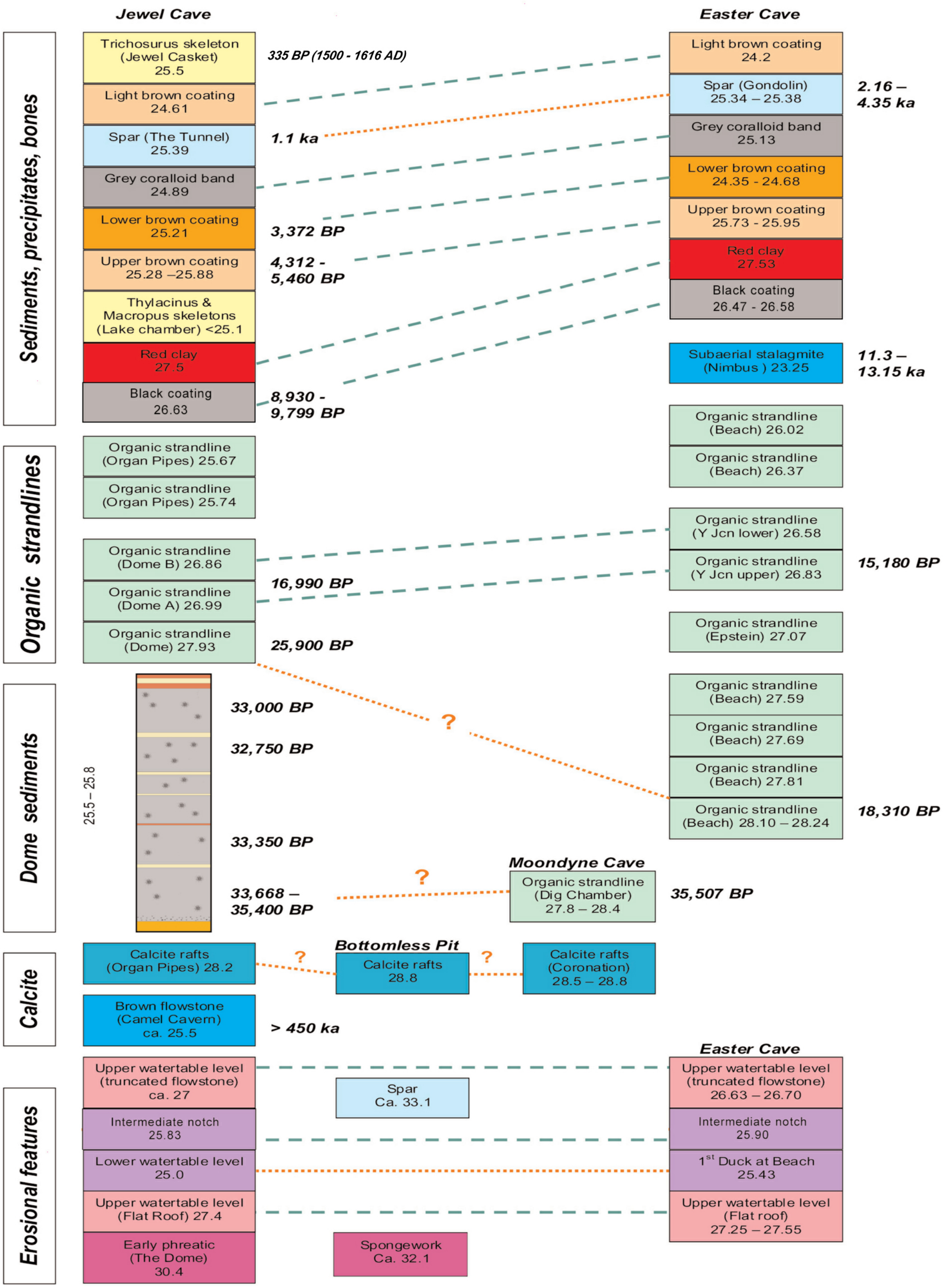


Figure 26. *Preliminary chrono-stratigraphic sequence of palaeo water regime indicators in Jewel, Easter, Moondyne Caves, and Bottomless Pit. The types and subcategories of strata and horizons are distinguished. Individual strata are identified by a descriptive name, location and elevation (metres AHD) of the highstand level. The age ranges of dated strata are shown. Proven stratigraphic correlations between caves are indicated by green dashed line, inferred correlations by orange dotted line, and speculative correlations with a question mark (?). Descriptions of dated strata in Appendices 18 to 21.*

Hydrograph reconstruction and water regime history

A reconstructed water regime history for the Augusta watertable caves is presented in Figure 27. The elevation of watertable highstand and lowstand phases, and flood events is indicated in relation to the present (2002) watertable level. The reconstruction represents a partial history only, as some phases and events may not have been preserved or detected. The hydrograph record is biased towards the preservation of water level peaks more than troughs, as younger highstand events tend to obscure older lowstand events. Thus the history and elevation of lowstand events remains poorly defined, although significantly, water levels have been up to one metre lower than present as indicated by submerged speleothems of subaerial origin. A submerged stalagmite in Lake Nimbus grew in subaerial conditions between 11.3 - 13.15 ka.

A significant feature of the hydrograph record are the multiple strandlines and sediment sequences rich in charcoal and organics which are the result of fire-flood recharge events. Fire has clearly been a recurrent process in the karst catchment up to at least 35,400 BP, and it has had a major impact on recharge and water regimes in the karst system. Periods of the early - mid Holocene were characterized by high watertable phases resulting in deposition of distinctive black and brown stains, whilst the late Holocene was characterized by hydrochemical conditions which favoured precipitation of subaqueous speleothems in groundwaters supersaturated with calcite.

Conclusions

1. The water regime history of the Augusta watertable caves has involved since the Early Pleistocene, major variability in water levels (storage), recharge, flow, and hydrochemical environments, in addition to variability in timing and duration of phases and events.

2. Fire has been a recurrent process in the karst catchment up to at least 35,400 BP, and it has had a major impact on types of recharge and water regimes in the karst system.

3. Water levels were lower than present near the end of the Pleistocene (11.3 - 13.15 ka).

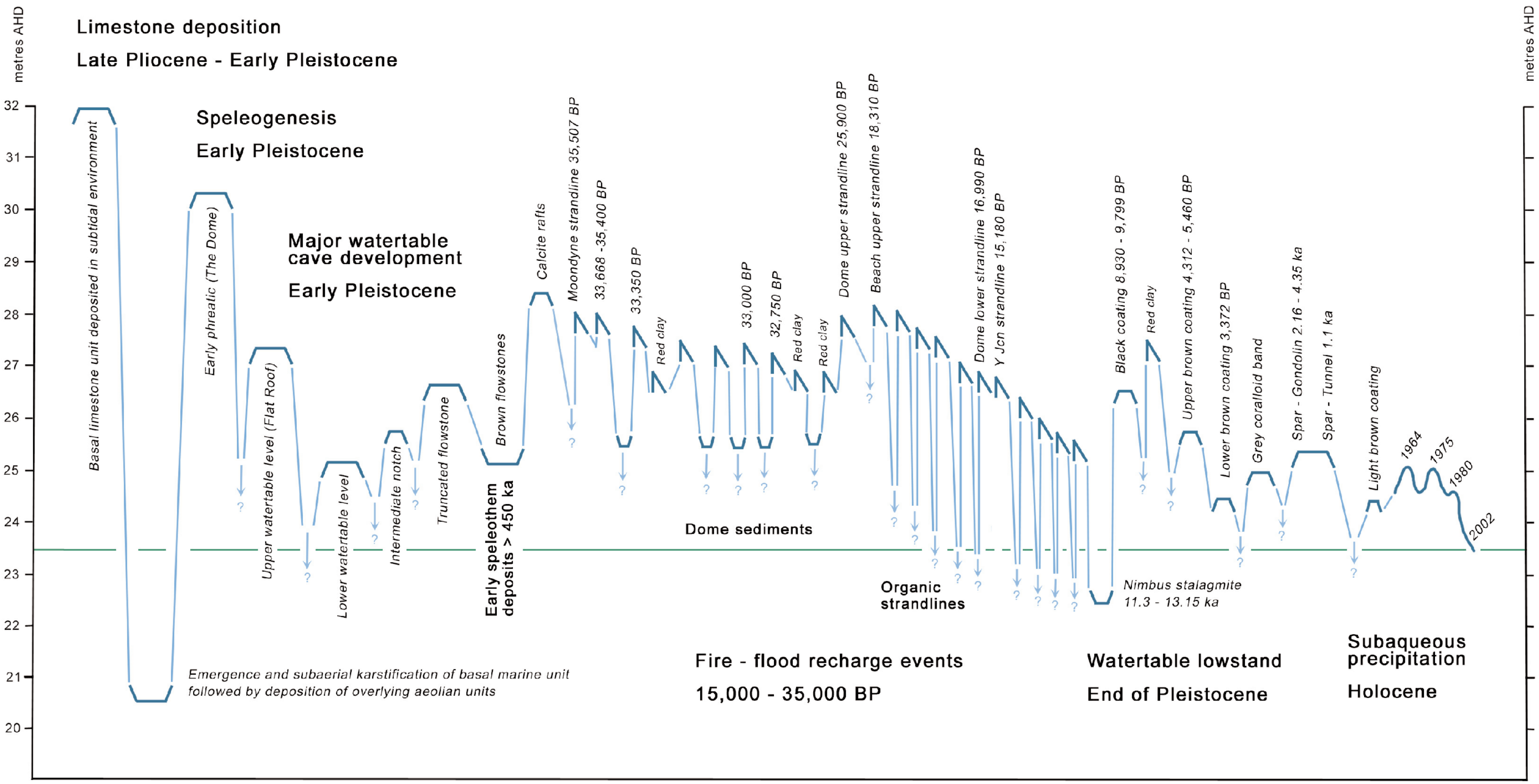


***Figure 27.**. Palaeo hydrograph reconstruction and partial water regime history for the Jewel Cave karst system. Elevation (metres AHD) of watertable highstand and lowstand phases (broad peaks and troughs), and fire-flood recharge events (steep peaks) shown in relation to present (2002) standing water level (green line at 23.5 m AHD). The time scale is relative from oldest to youngest (left to right). Names of indicator strata and horizons are the same as in Figure 26. The elevations of water level lowstand phases are generally poorly preserved.*

Fire History

Pre - European

Whilst lightning strike can be a significant contributor to fire regimes in southwest Western Australia (Ward & Sneeuwjagt 2000), anthropogenic fire regimes have been imposed on the southwest landscape for at least 48,000 years, as evidenced by early human occupation dates from Devils Lair (Turney et al. 2001). Fire was used frequently by the Nyungar people who occupied south-western Australia before the arrival of Europeans. Traditional knowledge suggests that the Leeuwin-Naturaliste region was well populated and that 'fire stick farming' was regularly practised to encourage growth of grasses and attract game (Cresswell 1989; Macpherson 2000). Reconstructed fire histories from balga stems, and early European accounts indicate fire frequencies of about three fires per decade in southwest jarrah forests (Ward & Sneeuwjagt 2000).

The abundance of charcoal in stratified cave sediments indicates the recurrence of fire within the JELSS catchment over a long time period. Charcoal from two strata in Skull Cave yielded ^{14}C ages of 2,900 and 7,875 years BP respectively (Porter 1979). During this study, radiocarbon dates of charcoal from sediments deposited in Jewel Cave yielded a series of ^{14}C ages ranging from 35,400 to 8,930 years BP.

Post - European

The settlement of Augusta was established in 1830 and the timber industry commenced in 1875 (Cresswell 1989). The early European settlers adopted the regular burning practises of the Nyungar to encourage new grass for their stock (Ward & Sneeuwjagt 2000). Photographs of the Karridale region at this time show an open understorey beneath tall karri forests (*Millars' Karri & Jarrah Company Ltd, 1902*). The early timber industry closed down circa 1900-1910. A large influx of new settlers and clearance of forest to establish farms and cattle grazing occurred in the region under the Group Settlement Scheme between 1921 and 1930 (Creswell 1989). Whilst forest clearance in the JELSS has mostly avoided the rocky, sandy slopes of the limestone ridge directly overlying the mapped cave passages, the adjacent land has been mostly cleared up to the base of the ridge.

The fire history prior to 1958 is poorly documented but anecdotal stories indicate the Leeuwin Naturalistse ridge was regularly burnt for cattle grazing purposes up until the mid-late 1970's. The growth of understorey vegetation was limited as a result, such that it was possible to - *'ride a horse through the forest between Deepdene and Moondyne'* (Bill O'Halloran of Deepdene Farm, personal communication to Lex Bastian, 1958).

1958 - 2001

After Jewel Cave was developed for tourism in 1958, sections of the surrounding cave reserve (Location 4174) were subject to regular controlled hazard reduction burns (J. McManus, R. Spackman, pers. comm., 2001). This practise continued until the area was incorporated into the Leeuwin - Naturaliste National Park around 1980. Since then, the land overlying theJELSS has been burnt only once in the previous 25 years.

Fire frequency within the JELSS catchment has changed from an average 4.3 fires per decade over the period 1958 to 1977, to less than 0.5 fires per decade between the period 1978 - 2002.

The fire history 1958 to 2001 was reconstructed from CALM microfiche records, dated photographs, caving trip reports, and discussions with local residents (Appendix 16). Between 1958 and 2001, at least three major wildfires (1958, 1961 and 1977) burnt over the JELSS, although the widespread devastating effects of the 1961 Karridale Fires were mitigated at Jewel Cave due to prior hazard reduction burns within the cave reserve (R. Spackman, pers. comm., 2001). A portion of land overlying the JELSS southeast of Easter Cave was burnt in 1967, and again in 1979. A prescribed burn of the Cliff Spackman Reserve (Location 8438) in Spring 1987 is recorded on CALM microfiche, but the extent of this burn remains uncertain and it may not have impinged on the Jewel Cave precinct.

The changed fire frequency is reflected in the vegetation with the development of a dense understorey of predominantly peppermint (3 - 6 m height) and accumulation of ground litter and trash (fuel load > 8 tonnes/Ha). This situation carries a high risk of destructive wildfire, with associated risks to human life and property, including within the Jewel Cave precinct.

Conclusions

Fire has been a pervasive, recurrent process in the karst catchment over the last 35,400 years at least. High fire frequency was probably maintained through Aboriginal burning practises.

The karst catchment has also been subject to frequent fire through European burning practises over nearly 150 years between 1830 to 1977.

Within the last 50 years the fire regime within the karst catchment has changed dramatically from a *high frequency* (mean 4.3 fires / decade 1958 - 1977) to a *low frequency* (mean < 0.5 fires / decade 1978 - 2002).

The changed fire frequency is reflected in the vegetation with the development of a dense understorey and accumulation of ground litter.

The present situation (2002) carries a high risk of destructive wildfire, with associated risks to human life and property, including within the Jewel Cave precinct.

Water Level Histories (post 1958)

Jewel Cave

A report in the *South Western News* (March 1958) describes the exploration more than forty years previously (viz. before 1918) of a mysterious hole in the ground adjacent to the Coronation (Moondyne) Cave. Caves custodian Tim Connelly was lowered on a long rope, and armed with packets of candles he explored a cavern containing many magnificent formations and signs of underground water. The vertical entrance, proximity to Moondyne Cave, and the description relating - *'that when leaning over the hole one's hat would blow off'* - leave little doubt that this was the so-called Wind Hole, known to the early settlers in Augusta since at least 1908, if not earlier (Bastian 1958). Caves were reported in the Augusta area by at least 1848 (*The Inquirer, 29th November 1848*).

When the Wind Hole was re-explored and re-named Jewel Cave in 1958, the explorers encountered chest deep water and used a boat to explore some sections (Figure 28). The walls and ceiling of the lake chamber were profusely decorated with speleothems and the reflection of these formations in the lake waters formed a stunning display. The cave was developed and opened for tourism in 1959, with the lake and its reflections being a major attraction on the tour.

Cliff Spackman, the first head guide at Jewel Cave, recorded the lake level at intervals and reported a seasonal fluctuation that was about 6 months out of phase with the rainfall. During 1959, the first year the cave was opened for public inspection, the water level reportedly dropped 9 inches (228 mm), but after this the annual rise slightly exceeded the recession such that by 1964-1965 the boardwalks around the lake were flooded to a depth of about one inch (25.4 mm) (Lowry 1965). This peak in water levels, the highest recorded to date at 25.0 m AHD, simultaneously corresponded with a peak of the same elevation in Labyrinth Cave.

Subsequent water level fluctuations went largely unrecorded, although photographs show elevated lake levels persisting until 1980 when the major watertable decline commenced. The level continued to decline more than a metre over the next decade, until by 1993 the lake and its famous reflections had all but disappeared (Figure 29).

Figure 28. *Jewel Cave March 1958 showing water level at about 24.6 m AHD. Lloyd Robinson (left) and Cliff Spackman. Photo Courtesy WA Newspapers Ltd.*

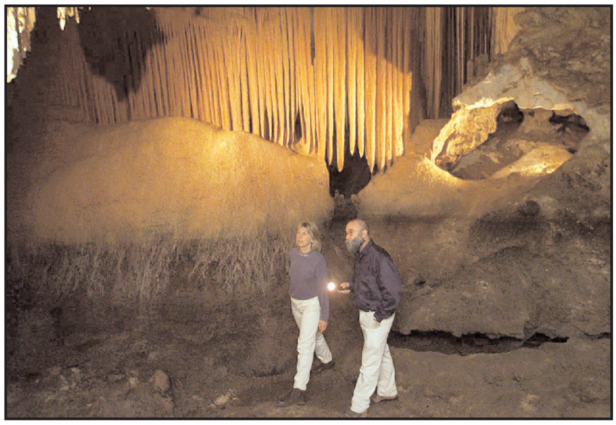


Figure 29. *Jewel Cave January 1999 showing water level decline of 1.1 m since 1958. The prominent brown stain marks a palaeo water level. Photo Courtesy WA Newspapers Ltd.*

Moondyne Cave

In 1910 Ludwig Glauert of the Western Australian Museum collected the skeleton of a thylacine found lying in a pool at the bottom of Moondyne Cave (Hatcher 1995). Moondyne Cave contained a pool of > 6 m^2 area when it was visited by Lloyd Robinson in Februray 1958 (letter to CaveWorks, 22nd October 2000). In this letter Lloyd mentions that the old residents of Augusta in 1958 (Longbottom, Ellis, McClusky, Eats) claimed the pool was always present in Moondyne since the cave's discovery. Lloyd also reported that by 1960 the pool had shrunk to approximately 1 m^2 area, and in 1972 the pool was absent.

The pool was present again in 1976 to 1978 when it had a surface area of about 4 m^2 and estimated depth of 400 mm, but it receded during 1979 and by 1980 it had disappeared altogether (Peter Bell, pers. comm. 2000).

During this study the base of the pool was levelled at 25.9 m AHD, a level that is 0.7 m above the highest recorded water level in Jewel Cave since 1958. This clearly establishes the Moondyne pool as a perched water body in the vadose zone, that is not connected to the local groundwater table. Nonetheless, fluctuations in the pool level would likely reflect general recharge conditions in the karst aquifer. This notion is supported by the anecdotal reports of the pools decline circa 1972 and 1979, which coincide with significant declines in the local groundwater level.

Moondyne Cave contains evidence of higher groundwater levels and flood strandlines that coincide with similar palaeo levels in Jewel, Easter and Labyrinth Caves.

Easter Cave

When explorers first dug through into the main passages of Easter Cave in 1958 they encountered water that in places was waist deep (Lloyd Robinson pers. comm.). Further exploration of the cave over the ensuing 20 years was affected by water level fluctuations that either closed off, or alternately opened, access into low roofed passages. For example, the *Gondolin* section was first entered in October 1972, but within 12 months the entry passage had become completely submerged and access was not regained until 1977. Earlier monitoring had indicated concordant water level fluctuations between proximal lakes at *Epstein* and *The Beach* (Caffyn 1973b, Webb 1988, S. Roatch, unpublished data). Later measurements made at six different pools within Easter Cave (*Gondolin, Epstein, Beach, Tiffanys, Nimbus,* and beyond the *Suspended Table*) showed a concordant water level rise over a 4 month period (Wood 1993).

Labyrinth Cave

The first explorers who entered Labyrinth Cave in 1959 waded through water 1-2 feet (305-610 mm) deep in the *South West Passage* (Robinson 1975). By January 1965 the water level had risen higher than at any time since the cave was explored, to a point about 4 inches (101 mm) above the top of the ruler embedded in the pool at the *Lunch Room* (Lowry 1965). Leveled at 25.0 m AHD during this study, this standing water level, and the six year period of rising water level preceding it, corresponds with water level changes in Jewel Cave at the same time.

The persistent decline in water levels recorded in Jewel and Easter caves from circa 1980 onwards also occurred in Labyrinth Cave, as described in reports made by cavers in *The Western Caver* (TWC). By February 1980 the pool at the Lunch Room and the South West Passage were reported as being dry (TWC 20(1): 18). In Februray 1981, the only water encountered in the *North West Passage* was at *The Sewer* (TWC 21(1): 10), whilst in May the same year the South West Passage was reported as *"almost dry"* (TWC 21(2-4): 56). By October 1982 water had disappeared from *The Ripper* (TWC 23(1-2): 13). In March 1984 the *North East Passage* and *Bastian Network* were reported as dry (TWC 24(1): 26).

Leeuwin Spring

Flow from the Leeuwin Spring was used to drive a waterwheel that pumped water to the Cape Leeuwin lighthouse from circa 1895. A weir and pumping station were later installed at the spring outlet that is still used to supply the lighthouse and supplement the supply to South Augusta and Flinders Bay. The Water Authority monitored discharge from the spring between February 1979 to October 1981.

During the monitoring period a mean maximum instantaneous flow of 3.6 ML/day (41.5 L/s) was recorded, but this had declined at a rate of about 6 % per year during this time (Appleyard 1989). The decline in spring discharge corresponds with the water table decline in the JCKS. Appleyard attributed the decline not only to changes in annual rainfall, which had not varied much, but to changes in rainfall intensity.

Later flow measurements suggested a continuing decline in spring discharge. A flow measurement done in June 1998 (S & T Consultancy 1998) recorded 1.3 ML/day, a more than twofold reduction in 17 years. Snapshot measurements done during this study in May 1999 and October 2000 recorded 1.2 and 1.5 ML/day.

The catchment area to the Leeuwin Spring comprises coastal heathland of approximately 1 km^2. The spring hydrograph (Eberhard unpubl. data) and chloride balance (Table 5, p. 30) indicate that infiltration throughput is more rapid and epikarstic storage is reduced compared with the JELSS. Interpretation of the geomorphology supports the notion of a relatively thin thickness of limestone resting on an impervious granite basement that closely underlies and mimics, more or less, the present surface topographic expression. The hydrogeological evidence does not support the existence of a hydraulic connection between the Leeuwin Spring and the JCKS, as sometimes earlier postulated (eg. S &T Consultancy 1998).

Deepdene Spring

Deepdene Spring is located on the terrace of Turner Brook in Deepdene Gorge where a massive tufa mound

20 - 30 m in diameter and 6 m high is developed (Figure 5, p. 9). In recent years the spring has ceased to flow, but reports indicate the spring had perennial flow throughout the 1960's - 1970's (P. Bell, pers. comm., 2002). Jennings (1968) reported on the physico-chemistry of the spring which indicated the waters were under-saturated with respect to calcite when sampled in July 1963.

Reconstructed watertable history 1958 - 2002

The reconstructed chronology of watertable levels in the Jewel-Easter subsystem, from 1958 to 2002, is shown in Figure 30. Over this 43 year period the water table fluctuated over a vertical range of 1.6 m but with an overall decline of 1.1 m. For much of the period from 1958 to 1979 the water levels remained elevated above 24.5 m AHD but in 1980 the levels started to decline at a rate of about 100 mm per year. By 2002 the levels had declined 1.1 m to the lowest recorded level at 23.5 m AHD.

The water table signature shows cyclic fluctuations of different frequency ranging from seasonal-annual, to multi annual-decadel. Two major peaks of high water levels occurred in 1963-65 and 1975 with the rise-to-fall period for each spanning about 5 and 10 years respectively. Three other smaller but distinct peaks occurred in 1979, 1984 and 1993, each with wavelength durations from 2 to 5 years. A fourth peak was registered in 2000.

Correlation with rainfall

For the period 1961 to 2001, there was a strong statistical correlation ($r = 0.95$) between monthly rainfall (cumulative deviation from mean) at Cape Leeuwin, and groundwater level in the JELSS karst system (Appendix 15). The best correlation is obtained when a 4 month lag is fitted to the groundwater response time (C. Yesertener, unpublished data, 2002).

The long term (1901-2001) mean monthly rainfall recorded at Cape Leeuwin was 83 mm. Within this 100 year time span a cycle of alternate wet and dry periods was identified by plotting the cumulative deviation from mean (CDFM) monthly rainfall (Figure 31). Five wet and dry periods, each ranging from 14 to 32 years duration, were identified (C. Yesertener, unpublished data). The period 1934 to 1961 corresponded with a general rainfall trend toward increasing dryness. From 1961 to 1993 the rainfall pattern inverted toward a trend of generally increasing wetness. This wet period lasted for 32 years. From 1993 to 2001 the rainfall trend has been towards increasing dryness. In the period 1968 to 1998 Cape Leeuwin experienced a 1 % decline in winter (June-July-August) rainfall whilst the southwest region overall experiemced a 21 % decline (Figure 32).

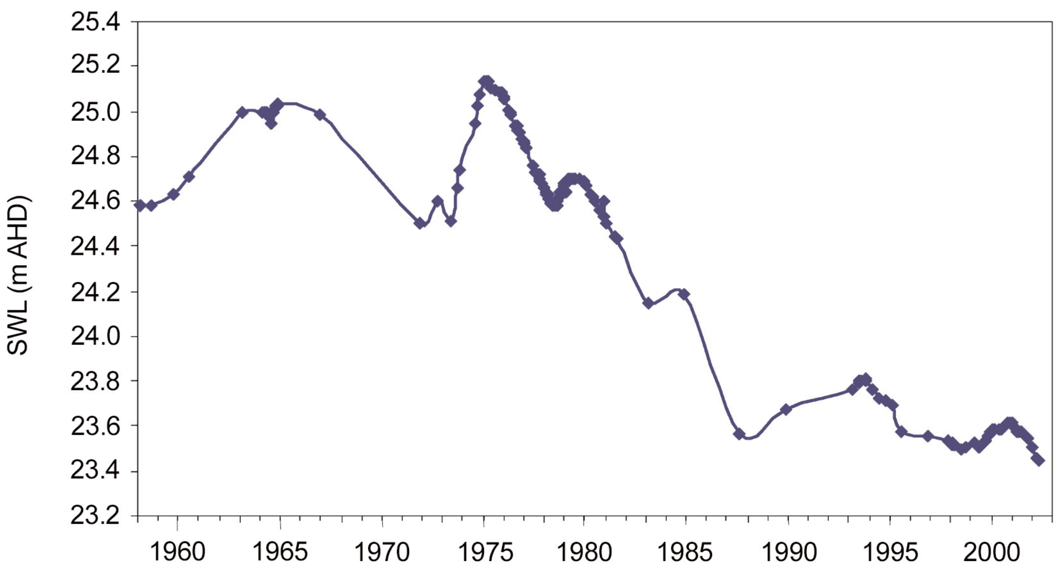


Figure 30. *JCKS reconstructed chronology of watertable levels from 1958 to 2002. Standing water level (SWL) shown as metres above Australian Height Datum (AHD). The interpolated line between data points on the hydrograph curve is speculative only - some major peaks and troughs in water levels may have occurred which have not been recorded.*

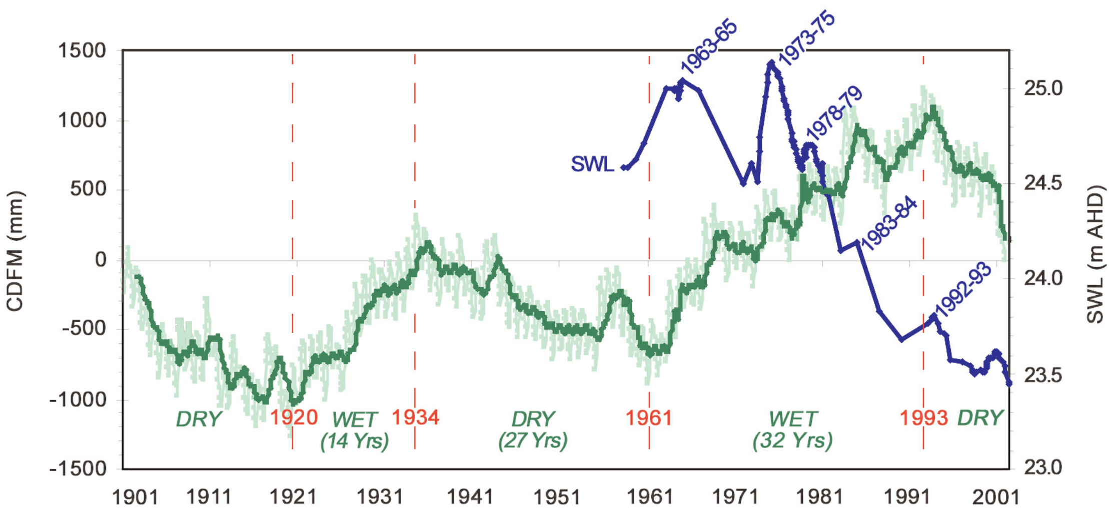


Figure 31. *Cape Leeuwin cumulative deviation from mean (CDFM) monthly rainfall 1901 to 2001 and Jewel-Easter watertable levels from 1958. Rainfall data from Bureau of Meteorology.*

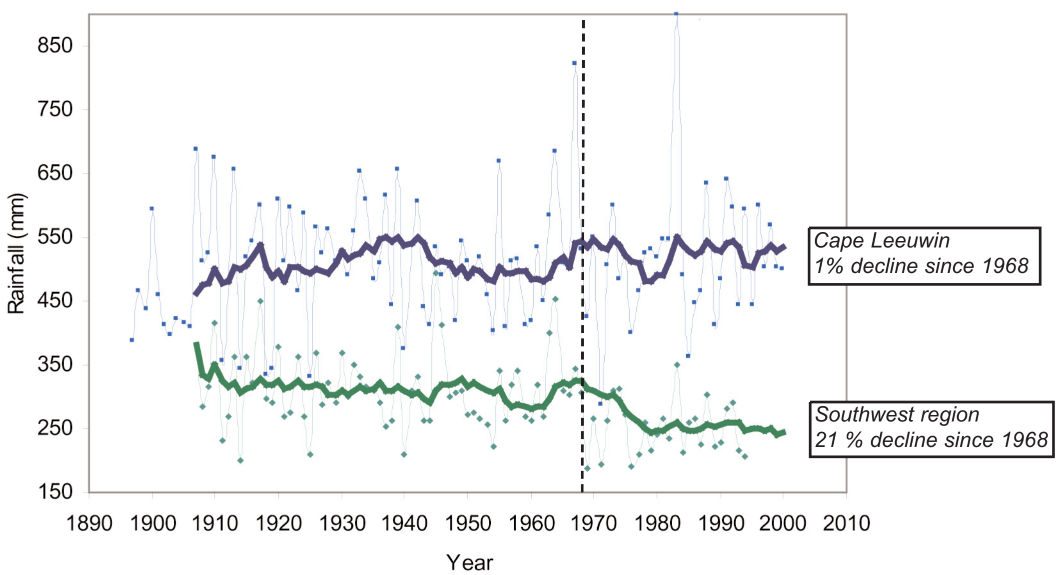


Figure 32. *Comparison of winter (June-July-August) rainfall totals at Cape Leeuwin (1897-2000) with regional southwest Australia (1907-1994). Trendline is 11 year moving average. The dashed line marks the year 1968, after which time winter rainfall in the southwest region declined 21% below the long term average, whilst Cape Leeuwin experienced only a 1 % decline over the same period. Data from Bureau of Meteorology and Smith et al. (2000).*

The rainfall trendline shows peaks that are reflected in the water level signature. Major rainfall-water level peaks were identified for 1963-65, 1973-75, 1978-79, 1983-84, 1992-93, and 1997-2000. Importantly, the persistent 25 year decline in the watertable from 1978-79 onwards, is not reflected in the overall rainfall pattern. Figure 31 shows that discharge from the karst catchment has effectively increased during the period from 1978-79 to 2001. The increased discharge could be caused by greater evapotranspiration and interception of rainfall by vegetation.

Correspondence with fire frequency and vegetation structure

Despite the rainfall trend, mean groundwater recharge rates have decreased by about 30 % after 1979-80. The change in recharge rates corresponded with a significant change in fire regime around the same time - fire frequency within the catchment changed from an average 4.3 fires per decade over the period 1958 to 1977, to less than 0.5 fires per decade between the period 1978 - 2002 (Figure 33).

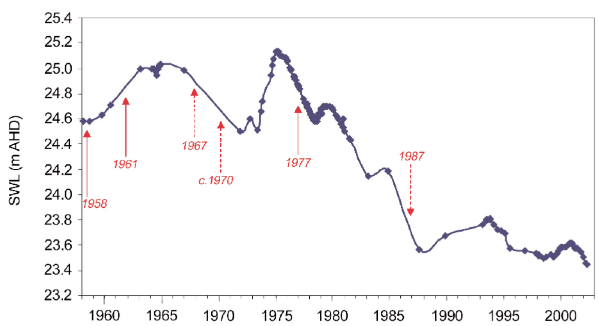


***Figure 33.** JCKS water level changes and recorded fire events (major wildfires - solid arrows; controlled burns - dashed arrows). Refer Appendix 16 for more details.*

The virtual absence of fire during the previous 25 years has allowed a dense growth of understorey vegetation dominated by peppermint *(Agonis flexuosa)*, and accumulation of ground litter to develop. Prior to 1979, the growth of understorey vegetation and accumulation of litter on the forest floor was inhibited by frequent burning practices. Through interception of rainfall recharge, it is hypothesised that understorey vegetation and ground litter have been a major contributing factor to the watertable decline in the JELSS.

From 1830 onwards, European settlers practiced frequent burning of the Leeuwin-Naturaliste Ridge, which maintained the forest structure with an open understorey and promoted conditions suitable for stock grazing. Thus the vegetation community within the JELSS catchment was probably held, for about 150 years, in a state of dis-equilibrium in relation to the climatic-leaf area index (cf. Borg, Stoneman and Ward 1987, and studies cited in Ellis et al. 1999, in press). This state was reflected in the elevated watertable levels encountered when the caves were explored in 1958.

Aboriginal burning practices would also have contributed to maintaining elevated watertables during 50, 000 years of occupation in the region. Dating of cave sediments indicates that elevated watertable conditions have mostly persisted in the JELSS from around 4,350 years ago until recently, and several other significant high watertable periods have occurred since the start of the Holocene 10, 000 years ago. A strong causal link exists between major episodes of flood recharge , and fires in the JELSS catchment, since at least 35, 400 years BP.

Discussion

Southwest Australia is a region notable for a prolonged and significant decrease (21 %) in winter rainfall over the period since 1968 (Smith et al. 2000). Synoptic patterns over SWA have changed during the last 40 years, resulting in a marked reduction in the number of rain days when precipitation is generated by westerly airflow, caused by a significant increase in anticyclone activity (Bates, Charles and Campbell 2001). Whilst winter rainfall in the study area has declined by only 1 % over the same period, changes in the intensity and duration of rainfall events may have contributed to the reduction in effective recharge. If predictions of a drying climate in the southwest prove correct (eg. Sadler et al. 1987), then recharge rates to the karst aquifer may decline even further.

Long climate model simulations indicate that: (1) the low precipitation sequence in SWA is uncommon but not extreme; (2) annual rainfall totals over SWA can exhibit variability on decadel, multi-decadel, and millennial time scales due to internal processes; (3) there is limited predictability for this region during winter; (4) the enhanced greenhouse effect may have made only a minor contribution to the observed reduction in SWA winter rainfall (Bates, Charles and Campbell 2001; Smith, Hunt, Watterson and Elliot 2001).

In water limited environments, vegetation will grow to maturity in a way that is related to climate wetness (Ellis, Hatton and Nuberg 1999, in press). Water use by vegetation is related to leaf area, and general relationships between leaf area index of vegetation communities and rainfall, or some other water balance index, have been demonstrated (eg. Borg et al. op. cit., Ellis et al. 1999).

Evapotranspiration increases with vegetation cover. Ellis et al. (in press) describes a relationship between a climate wetness index (Precipitation/ Evapotranspiration) and the potential long-term average leaf area index (LAI) of native vegetation in southern Australia (latitudes 30^0 - 40^0 S). It follows that native forest/woodland systems in water-limited environments, if they remain undisturbed, will tend towards a climatically-driven equilibrium leaf area.

The implication is that when leaf area is at its maximum then the groundwater recharge rate will be at a minimum. This is supported by measurements of recharge to native vegetation in southern Australia of less than 1 % of rainfall, whilst replacement with European-style agricultural systems leads to increases in recharge of one or two orders of magnitude (Walker, Blom and Kennett-Smith 1992, Kennett-Smith, Thorne and Walker 1993). Logging may also effect an increase in groundwater recharge, as measured in the southern forests of Western Australia by Martin (1986).

Moisture relationships in native woodland and *Pinus pinaster* plantations have been studied on the northern Swan Coastal Plain at Yanchep near Perth. (Butcher 1977, 1979, Butcher and Havel 1976). Yanchep shares geomorphic and hydrologic similarities with the Augusta site, both being karstified systems developed within the Spearwood Dune System, and, characterized by the virtual absence of surface runoff. Yanchep receives less rainfall than Cape Leeuwin (< 780 cf. 998 mm/year), and the height and density of native vegetation is correspondingly lower, being an open woodland dominated by tuart *(Eucalyptus gomphocephala)* and banksia *(Banksia attenuata)*.

Butcher (1977) determined that moisture availability is a strong determinant of growth potential, and this in turn, is governed by the depth and moisture-holding capacity of the soil, which limits the magnitude of moisture storage during the winter. During the spring and summer growing season, the rate of exhaustion of stored water is controlled by the density of the vegetation. Open native woodland and low-density pine stands showed similar wetting and drying phases of the annual soil moisture cycle. By comparison, in the densely stocked pine stands, the wetting is slightly delayed and soil drying is greatly accelerated. Manipulation of the stand density by thinning increased *throughfall* and recharge of the soil moisture system by as much as 15 %.

The inverse relationship between vegetation density and throughfall, has a major bearing on the recharge of the soil moisture reservoir, and potentially through this, deep drainage to the karst watertable. At Yanchep, canopy interception of annual rainfall ranged from 10 % in low density pine plantation to 26 % in high density plantation, whilst that for native woodland was somewhere intermediate (Butcher 1977). On moderate rainfall days (> 6 mm) in dense karri forests, the canopy may intercept up to 2.7 mm of the rainfall (Burrows 1987). Rainfall is also intercepted by the organic litter layer on the forest floor. Eucalypt litter can absorb 8-12 mm of rain per tonne of litter (McArthur 1964).

Fire can induce a significant change in the hydrology of a forested catchment (Batini et al. 1980; McArthur 1964; O'Loughlin, Cheney and Burns 1982). Generally there is an increase in water yield (stream runoff) for a short period (1-5 years) as a consequence of reduced transpiration and interception. The magnitude of the change in catchment condition is related to fire intensity, with severe wildfires having a greater impact than mild, prescribed burns. Immediately following the January 1961 Dwellingup wildfires in Western Australia, the North Dandalup River catchment composed of jarrah *(E. marginata)* forest showed an increased water yield of 72 %, but this had returned to pre-fire levels in the following year.

Fire can also have an effect through altering the infiltration properties of soils by inducing a temporary hydrophobic condition at the surface thus increasing surface runoff (O'Loughlin et al. 1982). If the first rainfall event after a fire is a high-intensity storm, this can lead to soil stripping and mobilization of sediment in surface runoff. As raindrop infiltration may be reduced on bare soil surfaces and surface run-off is increased, rapid-flow recharge via point source inflows such as solution pipes may contribute relatively greater input. In the Augusta caves, flood strandlines and fluvial sediment deposits enriched with charcoal indicate that major recharge episodes have occurred soon after fires on several occasions. The coarse caliber of these sediments, together with charcoal fragments up to 20 mm in size, indicates mobilization and transport by a high energy flow system rather than diffuse infiltration. Enhanced recharge via rapid-flow routes down solution pipes, fed by localised surface run-off occurring after fires, is a major process occurring within the JELSS.

Conclusions

A significant decline in groundwater levels and spring discharge rates is evident throughout the Augusta karst area between 1979 to 2002.

For the period 1961 to 2001, there was a strong statistical correlation (r = 0.95) between monthly rainfall (cumulative deviation from mean) at Cape Leeuwin, and groundwater level in the JELSS karst system . The best correlation is obtained when a 4 month lag is fitted to the groundwater response time.

The major watertable recession 1979 - 2002 does not coincide with the rainfall trendline, which has been toward increasing wetness from 1961 to 1993. Discharge from the karst catchment has effectively increased during the period from 1979 to 2001. The increased discharge has most likely been caused by greater evapotranspiration and interception of rainfall by vegetation. There is no groundwater abstraction or tree plantations within the karst catchment.

From 1993 to 2002 the rainfall trend has been towards increasing dryness, a factor which will exacerbate the watertable decline under the present forest vegetation structure.

It is hypothesized that the absence of fire within the JELSS catchment during the previous 15 (possibly 25) years is a causative factor contributing to the decline in the watertable since 1979. Before 1979 the frequent burning regime (4.3 fires per decade) restricted ground litter accumulation and promoted surface runoff and rapid-flow recharge. Additionally, it maintained the leaf area of the JELSS forest community below the climatically-driven equilibrium, as evidenced by the reduced understorey growth. Under these conditions, evapotranspiration and interception losses were reduced, thus promoting greater groundwater recharge.

Groundwater recharge may be promoted, as predicted through the fire-vegetation-recharge relationship, by manipulating the forest vegetation structure to reduce the density of understorey vegetation and ground litter. This could be achieved by controlled burning of the forest within the karst catchment.

Groundwater Ecology (Stygofauna)

Background

Tree roots which grow into cave waters constitute an important source of nutrition and shelter for aquatic invertebrates. This substantial and reliable food source has enabled the development of diverse and abundant faunas in the groundwater streams of a number of caves in southwestern Australia (Jasinska et al. 1996; Jasinska and Knott 2000). *Aquatic root mat communities* occur in caves throughout Australia.

Nine species were reported from an aquatic root mat community in a watertable pool (Tiffanys Lake) in Easter Cave (Jasinska 1997). The assemblage of species in Tiffanys Lake was, so far as known until this study, described only from this single locality of less than 10 m^2 area. Jasinska (op. cit.) reported that the Easter Cave community, together with several other root mat communities in caves on the Leeuwin-Naturaliste Ridge, and at Yanchep near Perth, were on the brink of extinction due to falling watertable levels in both regions.

Based on their restricted distributions and apparent vulnerability to known threatening processes, these communities were subsequently listed as *critically endangered* under the commonwealth *Environmental Protection and Biodiversity Conservation Act (1999)*. The Department of Conservation and Land Management (CALM) in Western Australia prepared separate *Interim Recovery Plans* (IRP) for both the Leeuwin-Naturaliste Ridge and Yanchep cave communities. The IRP for the Leeuwin-Naturaliste Ridge outlined recovery actions required to ameliorate several threatening processes perceived to be affecting the survival of four identified root mat communities, including the community in Easter Cave (English and Blyth 2000).

A primary aim of this study was to investigate the biology and ecology of stygofauna in the JELSS, with particular reference to conservation of the endangered root mat community in Easter Cave.

The fauna

The subterranean aquatic fauna (*stygofauna*) of the JELSS comprises crustaceans (Amphipoda, Ostracoda, Copepoda), worms (Oligochaeta, Nematoda), Protozoa and bacteria. At least twelve taxa (excluding Protozoa and bacteria) are recorded from a range of aquatic subterranean habitats, including habitats where submerged tree roots are not present. At time of writing, additional material is still being identified, whilst further sampling is likely reveal a richer diversity of subterranean species than hitherto recorded.

The stygofauna includes species whose distribution range appears restricted to the JELSS and the Augusta karst area, whilst other species are distributed in surface and/or groundwaters at other localities on the Leeuwin-Naturaliste Ridge, or more widely. A provisional list of taxa, their recorded habitats, and distribution, appears in Table 12.

Classification of the stygofauna

The stygofauna includes species which exhibit varying degrees of ecological and evolutionary dependence on subterranean environments. *Stygobites* obligatorily spend their entire lives within caves and other groundwater habitats. They are distinguished by the possession of clear morphological characteristics (*troglomorphies*) that may be linked to the absence of light, including reduction, and sometimes complete loss, of eyes and body pigment, and, enhancement of sensory structures, including lengthening of appendages (Gibert, Stanford, Dole-Olivier and Ward 1994). *Stygophiles* are facultative subterranean species which are found living permanently in groundwaters, but they also do this in suitable surface habitats. *Accidentals* are species that wander, fall, or are swept into caves where they may survive for varying lengths of time, but further generations are not established within the cave.

At least three taxa in the JELSS are stygobitic - *Diacyclops humphreysi* n. ssp., *Uroctena* n. sp., Candoninae: n. gen. et sp. A fourth stygobitic species, *Parapseudoleptomesochra* n. sp. (Copepoda: Harpacticoida: Ameiridae) was collected at a spring discharging from non-karstic sediments adjacent to the JELSS.

Aquatic fauna may also be classified according to body size, as: (1) *macrofauna* (> 1000 µm); (2) *meiofauna* (50 - 1000 µm); (3) *microfauna* (< 50 µm) (eg. Giere 1993). The macrofauna component in the JELSS is represented

Table 12. *Provisional list of taxa recorded from the JELSS with recorded presence (+) or absence of taxon in relation to habitat (root mat cf. non-root mat) and distribution range (JELSS cf. other areas). Note that a recorded absence does not necessarily signify a real absence. The first four taxa listed are stygobites whilst the remainder are stygophiles or accidentals. Macrofauna are indicated by an asterisk (*) and all others are meiofauna.*

Group	*Taxon*	*Habitats*		*Distribution*		*Notes*
		Root	*Non-root*	*JELSS*	*Other areas*	
Amphipoda	*Uroctena* n. sp.*	+	+	+		1
Ostracoda	Candonidae n. gen. et sp.*	+	+	+		3
Copepoda	*Diacyclops humphreysi* n. ssp.	+	+?	+		4
"	*Parastenocaris* sp.	+	+?	+	?	6
"	*Mesocyclops brooksi*	+	+	+	+	
"	*Nitokra lacustris pacifica*		+	+	+	8
"	*Thermocyclops* sp.		+	+		5
"	*Paracyclops sp.*	+		+		6
Amphipoda	*Perthia acutitelson**	+		+	+	2
Oligochaeta	Enchytraeidae sp.	+	+	+	+	7
"	Phreodrilidae sp.	+		+	+	7
"	Megadrile sp. indet*	+		+	?	
Nematoda	sp. indet.	+		+	+	

NOTES

1. Previously Paramelitidae n. gen et sp. in Jasinska (1997)
2. Previously *Perthia* n. sp. in Jasinska (1997); subsumed into *Perthia acutitelson*
3. Previously *Candona* n. sp. in Jasinska (1997); Karanovic, I. (submitted)
4. Previously ?*Acanthocyclops* sp. in Jasinska (1997)
5. Accidental
6. Recorded Jasinska (1997); genus contains stygophilic or stygoxenic spp.

7 Same form in Lake Cave, Leeuwin-Naturaliste Ridge

8. Occurs widely in marine, freshwater, surface and subterranean biotopes

by the amphipods and ostracods, the meiofauna component by the copepods, oligochaetes and nematodes, and the microfauna component by protozoa and bacteria. The structure and organization of groundwater ecosystems is strongly controlled by hydrogeologic and geomorphic processes, and thus the dispersal and distribution of fauna will be constrained, amongst other things, by their body size and the porosity characteristics of the habitat (see papers in Gibert, Danielopol and Standford 1994). The migration and distribution of macrofauna within the JELSS is thus constrained to fissures and conduits within the phreatic zone, whilst the meiofauna and microfauna may also colonise interstitial phreatic habitats, in addition to minor seepages, flows and pools within the vadose zone.

Systematics

The taxonomy and nomenclature of the fauna is revised after further taxonomic treatment subsequent to the work of Jasinska (1997).

The paramelitid amphipod previously ascribed to a new genus is assigned to *Uroctena* Nicholls (Figure 34). At least one new stygobitic species of *Uroctena* is represented by specimens collected in Jewel, Easter and Labyrinth Caves (J. Bradbury, Appendix 23). The undescribed species completely lacks eyes and pigment, suggesting that it has been isolated underground for some time. It is distributed in watertable pools throughout the JELSS, including pools with tree roots and pools without tree roots. Minor differences occur between specimens from the three caves, but only one morphospecies is present, thus supporting the notion of hydraulic connectedness (at times), between the Jewel-Easter and Labyrinth subsystems. Three other described species of *Uroctena* are recorded from springs and brooks near Perth, and a fourth species at Katanning in southwest Western Australia (Williams and Barnard 1988). One of the species collected near Perth, *Uroctena westralis*, is also a subterranean form possessing degenerate eyes and pigment (Williams 1986).

Figure 34. Uroctena *n. sp. Undescribed species of stygobite amphipod. Modifications to subterranean life include absence of eyes and pigment, slender body (length about 5 mm) and elongation of appendages. Endemic to the Jewel Cave karst system, but not restricted to root mat habitats.*

Figure 35. Perthia acutitelson. *A species of stygophile amphipod, not highly modified for subterranean life - note presence of eyes, pigment, and robust body (length about 10 mm). Occurs in root mat habitats in the Jewel Cave karst system. The same species is also widely distributed in stream caves, springs and surface waters throughout the region.*

The perthiid amphipod genus *Perthia* is represented in Jewel and Easter Caves by a single species, *Perthia acutitelson* Straskraba (Figure 35). Jasinska (1997) earlier suggested that two species of *Perthia* were present in Easter Cave, based on differences in eye pigmentation and body size in specimens collected from Tiffanys Lake. However, examination of these and other characters in specimens from Tiffanys Lake, and other localities in Easter and Jewel Caves, did not show any consistent differences which would indicate a specific difference between the two groups (J. Bradbury, Appendix 22). *Perthia acutitelson* is a stygophilic species distributed in freshwaters of southwest Western Australia (Williams and Barnard 1988). The species is also recorded from stream caves and springs on the Leeuwin-Naturaliste Ridge, including Strongs and Calgardup Caves (Jasinska 1997); Mammoth, Ruddocks, Connelleys, Arumvale Caves; Turners, Cape Leeuwin, and Bobs Hollow Springs (S. Eberhard, unpublished data).

In Easter and Jewel Caves, the distribution of *P. acutitelson* appears restricted to watertable pools containing root mats. This observation is consistent with its ecological status, being that of a weakly cave-adapted stygophile. *P. acutitelson* appears unable to survive in the otherwise food-poor sectors of the karst aquifer where root mats are absent.

A stygobitic candonid ostracod is recorded from the JELSS. The ostracod belongs to a new genus and species (Karanovic, I. submitted), earlier assigned to *Candona* by Jasinska (1997). Ostracods were collected from watertable pools in Jewel and Easter Caves, including pools where root mats were present, or absent. A congeneric species is also known from riverine sediments in the Upper Brockman River near Perth (Karanovic, op. cit.).

At least five species of cyclopoid, and one species of harpacticoid copepod, are recorded from the JELSS. Copepods were collected from both root mat and non-root mat habitats in the phreatic zone, in addition to seepage flows and small pools in the vadose zone. A new cyclopoid subspecies, tentatively assigned to *Acanthocyclops* by Jasinska (1997), is reassigned to *Diacyclops* Kiefer, 1927. The new subspecies from JELSS is closely related to *Diacyclops humphreysi*, recorded from karst groundwaters at Cape Range in northwest Western Australia (Pesce and De Laurentiis 1996). Both the JELSS and Cape Range subspecies are stygobitic. *Diacyclops humphreysi* n. ssp. was collected from root mat habitats in the JELSS, and considering it's stygobitic facies, is likely to be found in non-root mat habitats as well.

The ameirid harpacticoid, *Nitokra lacustris pacifica* Yeatman 1983, plus unidentified cyclopoids (copepodids and naupliuses) were collected from vadose seepage flows discharging from stalactites. *Nitokra lacustris pacifica* is a versatile species that occurs in a wide range of surface and subterranean biotopes. The species is also recorded from groundwaters in the Murchison region, Western Australia (Karanovic, T. 2002 in press).

Mesocyclops brooksi Pesce, De Laurentiis & Humphreys 1996 is also recorded from the Pilbara and Yilgarn regions of Western Australia (Pesce et al. 1996; De Laurentiis et al. 1999; Karanovic, in press). In these regions it has mostly been collected from pastoral wells, and a few narrow bores usually close to pastoral wells (W. Humphreys, pers. comm.).

The stygobitic taxa - viz. *Diacyclops humphreysi* n. ssp., *Uroctena* n. sp., Candoninae: n. gen. et sp. - have not so far been collected outside of the JELSS karst aquifer. From sampling in springs and other caves on the Leeuwin-Naturaliste Ridge it seems reasonable to conclude that their distribution within caves and karst at least, does not extend beyond the Augusta area. Nonetheless, these species or closely related forms, might be found in other fresh groundwater environments neighbouring the Leeuwin-Naturaliste Ridge, such as the Blackwood River catchment and the Scott Coastal Plain.

Sampling of a nearby karst spring (Turners Spring) and adjacent non-karst groundwaters in West Bay Creek (sample sites CW54, CW42) revealed different assemblages of copepods, amphipods and ostracods. None of the taxa recorded from these two springs and one bore were subterranean, with the exception of a new species of ameirid harpacticoid of the genus *Parapseudoleptomesochra*. This stygobite was collected at a small spring discharging from non-karstic sediments alongside the dune ridge in West Bay Creek (site CW54, Figure 6, p. 10). The high bicarbonate load carried by the spring waters indicates some contact with limestone rocks, and possibly a hydraulic connection to a karst drainage system. *Parapseudoleptomesochra* is also recorded from groundwater in the Murchison region, Western Australia (Karanovic, T., op. cit.).

Distribution and Habitat

A diversity of subterranean aquatic habitats, defined at a range of spatial and temporal scales, are colonised by stygofauna (Gibert et al. 1994):

1. The regional/continental drainage or megascale
($> 10^5$ m^3; $> 10^4$ years);

2. The aquifer or macroscale
(10^2 - 10^5 m^3; 10^2 -10^4 years);

3. The habitat (aquifer sector) or mesoscale
(10^0 - 10^2 m^3; 10^0 - 10^2 years);

4. The microhabitat or microscale
(10^{-2} - 10^0 m^3; 10^{-1} - 10^0 years).

Figure 36 depicts the habitat domains within the JELSS karst aquifer and the adjacent non-karstic, granular aquifer in West Bay Creek. These domains are a nested series of spatial configurations, each integrating all the patterns and processes ongoing at lower levels within the hierarchy and each linked by the next larger scale (Gibert op. cit.). The karst aquifer exhibits greater heterogeneity and complexity in habitat structure, and flow regime, compared with the non-karstic aquifer. This is reflected by the greater diversity of groundwater species within the karst.

The distribution of stygofauna is not restricted to watertable pools containing tree roots. Tree roots provide a concentrated but highly localized food source that supports a high biomass and diversity of fauna (Jasinska 1997, Jasinska, Knott and McComb 1996, Jasinska and Knott 2000). This contrasts with sectors of the aquifer where tree roots are absent, and food resources are more limited and dispersed. Stygobitic fauna is present throughout these non-root mat sectors, but it is dispersed in very low abundance where it is difficult to detect by conventional sampling methods.

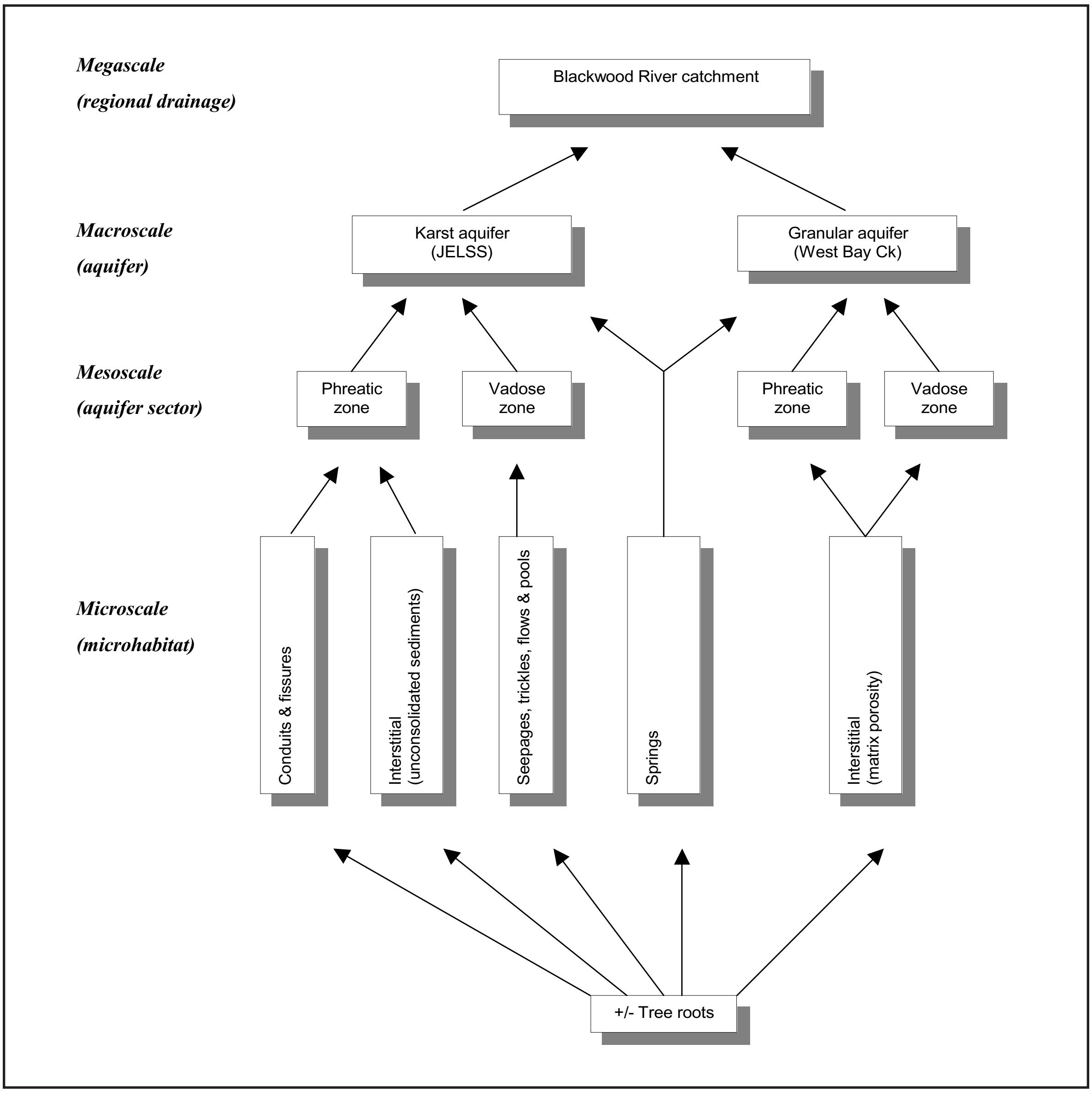


Figure 36. *Habitat domains within the JELSS karst aquifer and the adjacent non-karstic, granular aquifer in West Bay Creek.*

Stygofauna communities

Four distinct faunal communities were identified in the JELSS, as well as karst and non-karst springs in the Augusta area. Each community has a characteristic assemblage of taxa, and can be distinguished on the basis of mesoscale habitat characteristics, and, faunal size-class limitations. The two major mesohabitats within the karst aquifer (phreatic zone and vadose zone) may be subdivided further, based on the presence or absence of tree root microhabitat. A preliminary classification scheme is presented in Table 13.

The known distribution range of the Easter Cave root mat community has been extended from 1 pool (Tiffanys Lake, Figure 37) of < 10 m^2 area to multiple localities throughout Jewel, Easter and Labyrinth Caves.

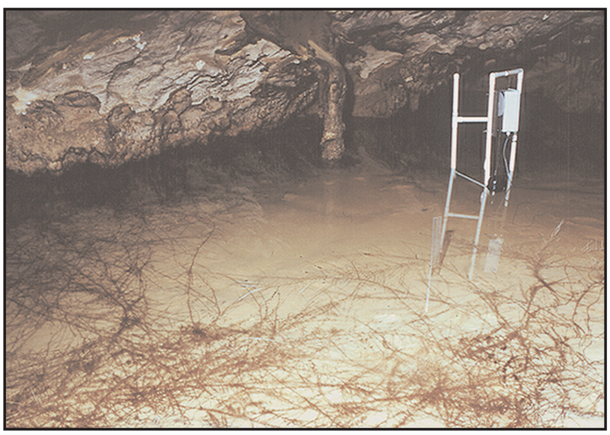


Figure 37. *Tiffanys Lake, Easter Cave 1999, showing submerged tree roots and water level recording instrument (height about 500 mm).*

Table 13. *Faunal communities identified within the JELSS, karst and non-karst springs in the Augusta area, including physical (habitat) and biotic characteristics.*

Community		*Mesoscale habitat (+ microhabitat) characteristics*	*Fauna size classes*	*Biotic assemblage characteristics*
Type	*Description*			
1	Phreatic conduit, Non-tree root	Phreatic zone (non-interstitial)	Macro- + meiofauna	**Stygobites only:** *Uroctena* n. sp. *D. humphreysi* n. ssp. Candoninae: n. gen. et sp.
1a	Phreatic conduit, Tree root	Phreatic zone (+ tree roots) (non-interstitial)	Macro- + meiofauna	**Stygophiles**: *P. acutitelson, M. brooksi* Oligochaeta, Nematoda **+ Stygobites** (as above)
2	Vadose zone, Non-tree root	Vadose flows & pools	Meiofauna	*Nitokra lacustris pacifica,* Oligochaeta
2a	Vadose zone, Tree root	Vadose flows & pools (+ tree roots)	Meiofauna	*M. brooksi* , Copepoda, Oligochaeta
3	Karst spring	Karst aquifer, concentrated, conduit flow (conduit + interstitial)	Macro- + meiofauna	*Perthia acutitelson* Mollusca Ostracoda, Copepoda
4	Non-karst spring	Granular aquifer, dispersed, matrix flow; (interstitial)	Meiofauna	Copepoda

This distribution range covers > 2 km^2 area. The distribution, across this range, of amphipod morphotypes which are conspecific, supports the notion of panmictic populations, which is consistent with interpretation of the system hydrology.

Mixing between populations would be enhanced under elevated watertable conditions, when separate pools which remain hydraulically connected only through primary and secondary porosity, became reconnected through flooding of higher level tertiary conduits. Under low watertable conditions, the dispersal and mixing of stygofauna populations within the JELSS aquifer may be retarded owing to the reduced permeability, and potential barriers developed in basement rocks, which occur below the level of the main conduits.

Colonisation, origins and affinities

Most of the stygofauna is derived ultimately from freshwater stocks which originated on the Yilgarn Craton, although the copepod genera *Nitokra* and *Parapseudoleptomesochra* may be derived from marine stocks. The freshwater ancestors of the cave populations colonized the karst from neighbouring inland waters within the Blackwood River catchment. The Blackwood River rises on the Yilgarn Craton then traverses the Perth Basin towards the Leeuwin Block where it debouches into the Southern Ocean at Augusta. Consequently, forms related to the colonizers of the JELSS might be found in neighbouring fresh groundwater environments within the Blackwood River catchment, and the Scott Coastal Plain. The Scott Coastal Plain contains extensive superficial groundwater environments suitable for stygofauna, including limestones of the Spearwood Dune System, as well as sandy aquifers and springs. The existence of stygofauna in this area has already been established.

Totgammarus eximius, an eyeless, presumably subterranean, paramelitid amphipod was collected from a temporary roadside pool in sands alongside the Scott River Road (Bradbury and Williams 1995).

The cave system could also potentially be colonised by marine or estuarine species derived from nearby coastal-estuarine environments. Colonisation could occur actively by interstitial routes, or stranding during sea level transgression-regression cycles (Coineau and Boutin 1992; Rouch and Danielopol 1987). Pleistocene transgressive phases involving high sea level stands of greater than 20 m, if these have occurred, would have impinged on the JELSS, and might have caused extinction of earlier freshwater colonisers.

The stygofauna in the JELSS is composed of two distinct assemblages, which based on their degree of troglomorphy, indicates at least two separate cave colonization episodes separated from each other by a significant time span. The earlier colonization episode(s) is/are indicated by the stygobites *Uroctena* n. sp., *Diacyclops humphreysi* n. ssp., and Candoninae: n. gen. et sp. A more recent colonization episode(s) is evidenced by the stygophile *Perthia acutitelson*, and other non-stygobitic forms.

Relationships are evident between the JELSS subterranean fauna and other groundwater (and surface) faunas in Western Australia. Within the Perth Basin and Yilgarn Craton these include the amphipod genus *Uroctena,* the candonid ostracod (Karanovic, I., submitted) and the copepod *Mesocyclops brooksi* (Karanovic, in press). *Mesocyclops brooksi* and *Diacyclops humphreysii* (separate subspecies) also occur in the Pilbara (Pesce and De Laurentiis 1996; Pesce et al. 1996; De Laurentiis et al. 1999).

Habitat - fauna distribution and dispersal model

A conceptual model for the dispersal and distribution of macrofauna and meiofauna within microscale, mesoscale and macroscale habitats of the karst aquifer is presented in Figure 38. The *habitat-fauna distribution and dispersal model* was developed from the observed distributions of stygofauna, faunal size-classes and dispersal limitations, and, integrated with hydrologic flow, storages and linkage characteristics of the karst aquifer. The model is intended as a framework around which to plan, test and develop conservation strategies for stygofauna in the JELSS.

Stygofauna is potentially distributed throughout the Augusta karst area, wherever there is permanent groundwater within the karstified, cavernous Spearwood Dune System. The Spearwood Dunes are buried on the seaward flank and crest of the Augusta ridge, by younger less-karstified, non-cavernous dunes of the Quindalup System, although stygofauna communities might still be expected to occur at depth below this cover. Based on surface exposures of the Spearwood System, and where this coincides with the distribution of karri eucalypt forest, the potential distribution range of stygofauna associated with tree root microhabitats (community types 1a and 2a) is predicted to occupy > 10 km^2 area (Figure 39).

Discussion - threats and conservation

Earlier perceptions of the processes contributing to the watertable decline in Easter Cave, and other caves on the Leeuwin-Naturaliste Ridge, need to be revised.

The watertable decline was earlier attributed to lower rainfall combined with anthropogenic impacts - groundwater abstraction and tree plantations (Jasinska 1997, English and Blyth 2000, Storey and Knott 2002). However, rainfall in the study area has not generally been lower, and there is no groundwater abstraction or tree plantations within the Easter Cave catchment. Groundwater abstraction and tree plantations cannot be construed as causal to the watertable decline in the JELSS.

Similarly, there is no groundwater abstraction occurring within the catchments of the three other listed root mat communities on the Leeuwin-Naturaliste Ridge - Strongs, Calgardup, and Kudjal Yolgah Caves. A pine plantation in the upstream catchment of Strongs Cave would have intercepted a component of the recharge to this karst system, prior to it being felled circa 1998.

Water levels in the JELSS have been lower in the past however, as indicated by the occurrence of subaerially formed speleothems, submerged *in situ* up to 1 m depth below the present watertable. Uranium-series dating of a submerged stalagmite in *Lake Nimbus* suggest that it grew between 11.3 and 13.15 ka ago, when the watertable was 0.5 m or lower than present (Appendix 18). If the stygofauna had colonized the aquifer before this time, which is considered probable for the cave-modified forms at least, then the aquatic fauna has survived watertable levels lower than present. On this basis it is suggested that the root mat fauna may not presently meet the criteria for classification as *critically endangered*, as earlier suggested by Jasinska (1997), and English and Blyth (2000).

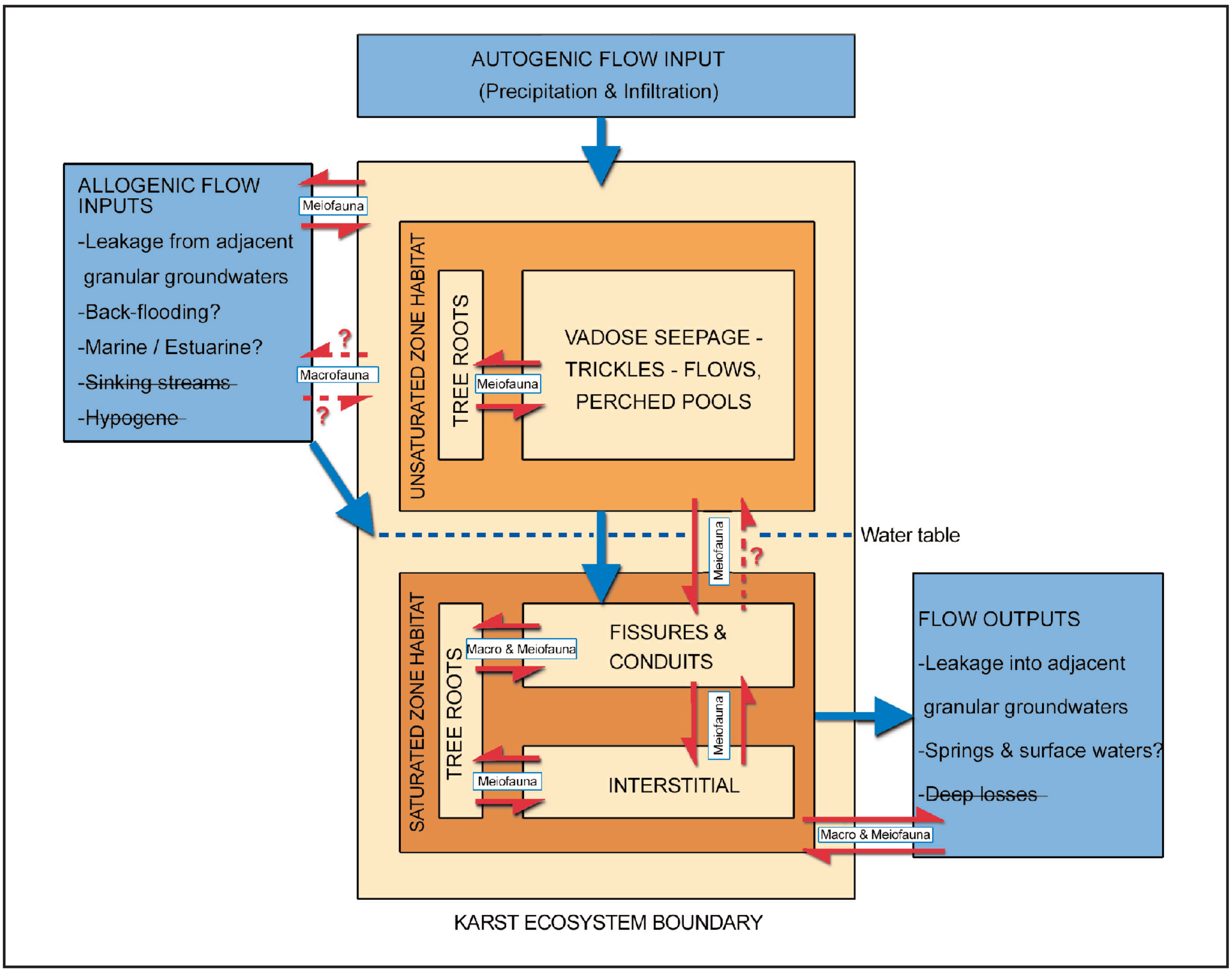


Figure 38. *Conceptual model for the dispersal (red arrows) and distribution of macrofauna and meiofauna between microscale (light tan), mesoscale (dark tan) and macroscale (light tan), habitats within the JELSS karst aquifer. Hydrologic inputs, outputs and flow linkages (blue arrows), storages (light and dark tan) adapted from Figure 16, p. 39.*

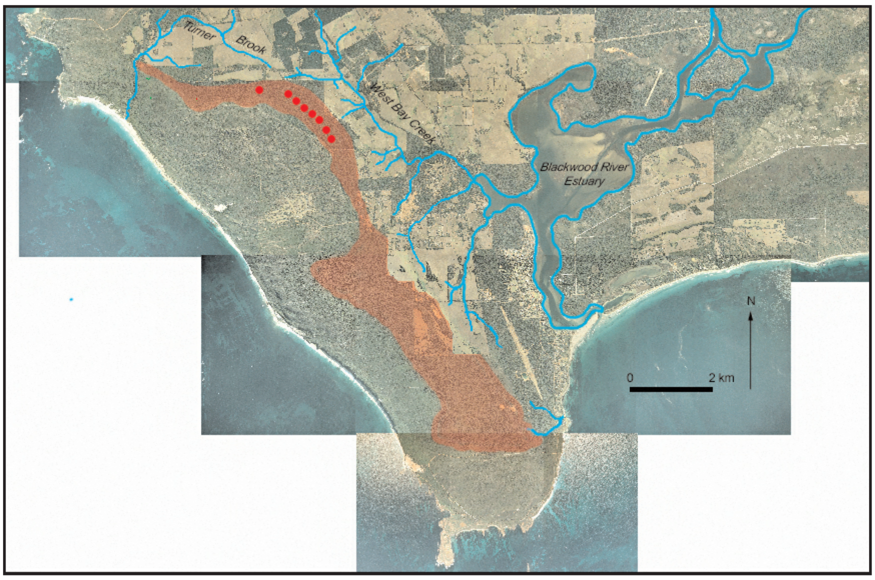


Figure 39. *Mapped (red dots) and potential (shaded red) distribution range of stygofauna associated with tree root microhabitats in the Augusta karst area. The potential distribution range is inferred based on surface exposures of the Spearwood Dune System, where this coincides with the distribution of karri eucalypt forest.*

All stygofauna communties in the phreatic zone remain affected by watertable lowering, and vulnerable to a complete loss or reduction in phreatic storage volume. The area of aquatic root mat habitat has decreased as watertable pools in caves have shrunk in size leaving root mats stranded on mud banks. However, the threshold at which watertable lowering becomes critical to the survival of the phreatic communities remains to be determined.

Threatening processes acting through the hydrologic system, such as watertable lowering and contamination, will impinge on stygofauna communities within root mat habitats as well as stygofauna communities within non-root mat habitats. The potential impact of these threatening processes therefore needs to be considered in relation to all stygofauna communities within the karst catchment / karst geo-ecosystem. This is important more so because the biotic assemblages within root mat and non-root mat habitats overlap with eachother.

If a root mat community is locally threatened or destroyed, then sectors of the aquifer where root mats are absent provide a refuge for species which have a non-obligate association with tree roots. This includes the stygobitic species *Uroctena* n. sp., Candoninae: n. gen. et sp., and *Diacyclops humphreysi* n. ssp. Preservation of trees with roots in caves is not critical to the survival of these species. The other, non-stygobitic, species recorded from the Easter Cave root mat community have distribution ranges which extend beyond Easter Cave and the Augusta karst area. Thus preservation of trees with roots in Easter Cave is not critical to the survival of these species either. However, preservation of trees is required for maintenance of the sympatric assemblage of species comprising the Easter Cave root mat community, which is restricted in distribution to the JELSS.

Because the distribution of stygofauna within the JELSS is determined by hydrogeologic boundaries defined at the macro (aquifer) scale, and processes which operate on geo-evolutionary time scales, conservation requirements of the fauna need to be integrated at the more expansive levels of karst catchment and karst geo-ecosystem.

Strategies for the conservation of subterranean biodiversity within the JELSS will be most effective if:

1. They encompass all stygofauna communities, and not solely root mat communities;

2. Are integrated with karst system processes, especially hydrogeologic and geomorphic processes;

3. Are applied at an appropriate spatial and temporal scale, viz. karst catchment / karst geo-ecosystem (Boulton, Humphreys and Eberhard 2001, Eberhard 1999; 2000; 2001; Hamilton-Smith and Eberhard 2000).

The distribution range of the Easter Cave root mat community has been extended by six orders of magnitude. Knowledge on the occurrence, distribution and biology of root mat communities and stygofauna outside the Augusta karst area on the Leeuwin-Naturaliste Ridge has been extended by this study. A diverse assemblage of species inhabiting root mats coexists with a population of gilgie (*Cherax crassimanus*) introduced into Lake Cave around 1990. A previously unrecorded root mat community was found in Budjur Mar Cave. The diversity of species recorded from Strongs Cave and Kudjal Yolgah Cave has been increased from that known previously. Stygofauna has been identified in Crystal Cave and Green Cave for the first time.

The occurrence and distribution of root mat communities and stygofauna on the Leeuwin-Naturaliste Ridge is predicted to be substantially greater than so far described.

Conclusions

Stygofauna is distributed throughout the JELSS karst aquifer, including the phreatic and vadose zones, and, habitats where tree roots are absent.

Four distinct faunal communities were identified in the JELSS, as well as karst and non-karst springs in the Augusta area.

There is overlap in species assemblages between *root mat* and *non-root mat* communities in the phreatic zone.

The stygobitic species have a non-obligate dependence on tree roots, whilst the non-stygobitic taxa have a distribution range which extends beyond the JELSS.

The known distribution range of the Easter Cave root mat community has been extended to an area > 2 km^2, throughout Jewel, Easter and Labyrinth Caves.

The stygofauna is composed of two distinct assemblages, which based on their degree of troglomorphy, indicates at least two separate cave colonization episodes separated from each other by a significant time span.

Groundwater abstraction and tree plantations have not contributed to the watertable decline in the JELSS.

The Easter Cave root mat community may not presently meet the criteria for classification as critically endangered, because it has survived lower water levels in the past.

All stygofauna communties in the phreatic zone remain affected by watertable lowering, and vulnerable to a complete loss or reduction in phreatic storage volume. However, the threshold at which watertable lowering becomes critical to the survival of the phreatic communities remains to be determined.

The habitat-fauna distribution and dispersal model provides a framework around which to plan, test and develop conservation strategies for stygofauna in the JELSS.

Strategies for the conservation of subterranean biodiversity within the JELSS will be most effective if:

1. They encompass all stygofauna communities, and not solely root mat communities;

2. They are integrated with karst system processes, especially hydrogeologic and geomorphic processes;

3. They are applied at an appropriate spatial and temporal scale, viz. karst catchment / karst geo-ecosystem.

Management Issues

At the present time, watertable decline is seemingly the most pressing environmental issue confronting management of the Jewel Cave Karst System, however there exist a number of other hydrological and biological management issues which, although not so obvious, are nonetheless important for conservation of natural heritage and biodiversity values. These issues include water quality and contamination in Jewel Cave, and stygofauna, as discussed below.

Water quantity

Water quantity is the major hydrological issue affecting the entire karst aquifer. The watertable in Jewel, Easter and Labyrinth Caves is, at the time of writing (2002), at the lowest level recorded since 1958. The watertable in Labyrinth Cave has dropped below the main level of cave passages and groundwater is no longer visible anywhere in the cave. The lake in Jewel Cave, once a famous attraction for visitors with its beautiful reflections, has all but disappeared. Once extensive interconnected lakes in Easter Cave have shrunk to small, isolated residual pools. The deepest lakes remaining contain about one metre depth of standing water.

Changed fire regime

There is strong circumstantial evidence that reduced fire frequency in the catchment over the previous 25 years has contributed to the watertable decline by allowing growth of a dense understorey vegetation and accumulation of ground litter resulting in increased interception and evapotranspiration of potential groundwater recharge. If the predicted lower rainfall trend continues, then inhibition of groundwater recharge will be further exacerbated under a low frequency fire regime. Irrespective of future rainfall patterns, groundwater recharge may be promoted by prescribed burning of understorey vegetation and ground litter within the catchment.

Abstraction from karst aquifer

For a time water was pumped from the lake in Jewel Cave to augment the existing rainwater tank supply for the toilets, and possibly to avoid the cost of carting additional water during the summer months, as had apparently been done previously. The year the pumping started is undetermined, but by 1982 16-20,000 gallons (73-91 kilolitres) were being pumped annually and concerns were being expressed about the declining lake level (Ron Spackman, letters to AMRTB 8th Feb and 29th Oct 1982). With an estimated minimum surface area of 42 Ha for the Jewel-Easter aquifer, this rate of abstraction represented less than 0.2 mm of the mean annual recharge (294 mm/year) for the period 1973-1981. The pumping therefore, would not have made a measurable impact on the water level.

In an attempt to counter the decline in lake level, one of the rain water tanks (capacity 88 kL) was drained into the lake which rose approximately 1.5 inches (38mm) as a result but declined to its pre-existent level after two days (Lloyd Robinson, pers. comm., 2001). The rapid return to the pre-existent water level demonstrates the high transmissivity of the aquifer. Around 1982-83 pumping from the lake was discontinued and an additional tank installed to augment the rainwater supply.

Diminishment of water inputs

Diminishment of water inputs, both by concentrated and dispersed routes, has occurred with the development of Jewel Cave for tourism. Blockage of solution pipe entrances has reduced flood recharge inputs, and in association with this process, input of particulate organic material which constitutes a food resource for cave dwelling organisms. The siting of buildings and clay-sealed carpark surfaces directly overlying the cave has locally restricted dispersed recharge, with associated potential diminishment of speleothem growth in underlying cave passages.

The size of the doline surrounding one of the upper entrances to Jewel Cave has been reduced in size from the original - *'cone shaped depression measuring some 12 m (approx.) in diameter with a depth of 6-7 m'* (Tony Tapper in letter to Dr John Williams, 30th December 1992) - to a depression about 5 m in diameter with a depth of 4 m. This modification, and the concrete collar installed in the entrance circa 1981, may be affecting infiltration via this point. Another solution pipe nearby, which in it's natural condition was partially sand-filled, was known to channel significant surface runoff into the entrance chamber and *Playfords Cut* stairway, which interfered with the cave tours. After one such flood recharge event circa 1959, the pipe was plugged with gravel fill, thus preventing further episodic recharge via this route (L. Robinson pers. comm., 2000).

The tourist entrance to Jewel Cave was originally a group of sediment-filled solution pipes that were enlarged by blasting then later re-sealed with an air-lock door. A roof erected above this entrance collects and diverts rainfall. These modifications have reduced local infiltration at these points. Similarly, inflow via the Deeondeup entrance, originally a rubble-filled, but otherwise open, solution pipe, has likely been reduced after it was plugged with concrete circa 1958.

Owing to the small area of the karst catchment affected by cave tourism modifications, the extent to which water inputs have been diminished is insignificant at the scale of the karst aquifer, but may be locally significant in terms of restriction of organic matter inputs and speleothem growth within Jewel Cave.

Drawdown in adjacent aquifers

Draw-down in the superficial aquifers of West Bay Creek and Turner Brook might already have been caused by the excavation of drains and evapotranspiration from pine plantations. However, these effects are considered unlikely to have influenced the water table decline in the karst aquifer due to the small amount of draw-down possible (estimated < 2 m depth of drain excavation), even assuming that the granular and karst aquifers are fully hydraulically connected, an interpretation which is not supported by water chemistry analysis. Nonetheless, further investigation of the relationship between the karst and superficial aquifers in West Bay Creek and Turner Brook may be warranted in view of proposals for future more intensive utilisation of groundwater resources for vine irrigation (eg. Kolatz-Smith and Partners 1997).

Management options

Management options for restoring water levels include both artificial and/or ecological methods. Water levels could be restored by injection of artificial recharge, although the physico-chemistry of artificial recharge waters would need to be carefully controlled to prevent adverse impacts to karst system processes. Artificial recharge waters would also need to be filtered to prevent the introduction of foreign organisms into the karst ecosystem. Artificial recharge waters might potentially be sourced from adjacent catchments in West Bay Creek and Turner Brook. This would require the collection (in dams) of winter surface runoff and pumping of this into the karst aquifer.

An alternative ecological approach involves the manipulation of natural recharge conditions through prescribed burning within the catchment. Prescribed burning conveys additional benefits in terms of reducing the hazard posed to life and property by destructive wildfires, the risk of which remains high under the present low frequency fire regime. Accordingly, it is recommended that prescribed burning of the Jewel Cave precinct and Cliff Spackman Reserve be supported, and the effects of fire treatment on groundwater recharge be investigated.

The fire-vegetation-recharge relationship predicts that recharge effects will be optimized if burning is timed to cause maximum areal coverage, maximum consumption of ground litter, and maximum reduction in leaf area. Accordingly, moderate to higher intensity burn conditions could be timed to maximise areal coverage, as well as consumption of ground litter and leaf area of understorey vegetation. Reduction in the leaf area of the eucalypt overstorey would also enhance the recharge effect. The fire prescription would of course consider possible deleterious effects of a higher intensity burn on overstorey trees, fauna, soils, and aesthetic values, in which case a lower fire intensity would be prescribed.

The effects of fire treatment should be measurable with changes expected in the forest leaf area index, fuel load (ground litter depth and weight, trash), understorey cover, and soil moisture. Changes in groundwater recharge rates associated with fire treatment should be measurable in vadose infiltration rates and the watertable response. So that changes can be properly evaluated, a Before-After-Control-Impact (BACI) monitoring design is recommended. Pre-burn monitoring of water levels and water quality undertaken over the previous 3 years will provide an adequate baseline on which to assess the effects of fire treatment. Post-burn monitoring of water levels will need to be undertaken, and may need to span several years depending on winter rainfall patterns in years succeeding the burn treatment.

The results of experimental fire treatment have important implications for future management of groundwater quantity and biodiversity, both in the Jewel Cave karst system, and other groundwater systems in Western Australia, particularly if predictions of a drying climate in the southwest prove correct (eg. Sadler et al. 1987).

Recommendations

1. Support prescribed wildfire hazard reduction burns in the Jewel Cave precinct and Cliff Spackman Reserve.

2. Monitor and evaluate the effects of fire treatment on groundwater recharge, including BACI monitoring of rainfall, leaf area index, ground fuel load, soil moisture, infiltration rates and watertable response.

Water quality

The JCKS aquifer is very sensitive to contamination. A localized area of contamination has been identified in the vicinity of the Organ Pipes in Jewel Cave, where groundwaters show concentrations of both chemical and biological species that are significantly higher than background levels. Elevated levels of metals, nitrate, bacteria and protozoa, are linked to a number of potential sources located both inside and outside the cave.

The recorded levels of nitrate (370-425 mg/L) are about 400 times natural background levels. The septic system, which is located directly above the cave, is implicated as the potential source of nitrate contamination, although further testing is required to determine this. The results from limited testing do not indicate serious contamination of the groundwater by faecal pathogens, however the abundances of non-faecal microorganisms in the lake chamber, which is visited by about 45,000 people per year, are substantially higher than background levels. The impact of this microbial loading on the groundwater ecosystem and stygofauna communities remains incompletely investigated.

Recommendations

To characterise and control the contamination in Jewel Cave, AMRTA to undertake:

(1) Further testing of water quality and investigation of different contaminant sources, including inter alia, a potential link between the septic system and cave waters;

(2) Remedial actions as appropriate.

Stygofauna

The principal management issue relating to stygofauna concerns the need for revision of the *Interim Recovery Plan* (IRP) prepared by the Department of Conservation and Land Management (CALM) in relation to aquatic root mat communities which are listed as critically endangered under the *Environmental Protection and Biodiversity Conservation Act (1999)*. Specifically, the IRP threatening processes, recovery actions, fauna monitoring methods, and future research directions need to be revised and reset. More generally, a systemic, integrative approach to the conservation of subterranean biodiversity throughout the Leeuwin-Naturaliste region is recommended.

Earlier perceptions of the vulnerability, conservation status, and threatening processes affecting the 'critically endangered' root mat community in Easter Cave are revised as a result of this study. Groundwater abstraction and tree plantations are not threatening processes contributing to the watertable decline in the JCKS. Preservation of trees is not critical to the survival of species in the Easter Cave root mat community.

Whilst the Easter Cave root mat community may not at present meet the criteria for classification as critically endangered, all stygofauna in the JCKS remains vulnerable to watertable decline. The critical threshold at which watertable decline threatens survival of the groundwater communities remains to be determined. If the decreasing rainfall trend for southwest Australia continues, as some long-term climate forecasts have predicted, then the groundwater dependent ecosystem in the JCKS will be subject to further stress. Further research needs to be done to better define the critical thresholds for watertable decline.

Knowledge on the occurrence, distribution and biology of root mat communities and stygofauna elsewhere on the Leeuwin-Naturaliste Ridge has also been extended by this study. A diverse assemblage of species inhabiting root mats coexists with a population of gilgie (Cherax crassimanus) introduced into Lake Cave around 1990. A previously unrecorded root mat community was found in Budjur Mar Cave. The diversity of species recorded from Strongs Cave and Kudjal Yolgah Cave has been increased. Stygofauna has been identified in Crystal Cave and Green Cave for the first time. Taxonomic descriptions of several new species have been prepared for publication (Karanovic, I submitted; Karanovic, T. in preparation).

The occurrence and distribution of root mat communities and stygofauna on the Leeuwin-Naturaliste Ridge is predicted to be substantially greater than so far described. Mapping of this subterranean biodiversity should be a priority for future work. This needs to be undertaken in tandem with the mapping of all karst catchments and karst drainage systems on the ridge. Hydrogeologic and biologic characterisation of all karst systems on the ridge will enable assessment of biodiversity values and threats within a regional context.

The need for a regional scale survey is supported by:

(a) The wider distribution of root mat communities and stygofauna beyond the four communitites already listed;

(b) Deleterious impacts to stygofauna communities, for example the reported extinction of a root mat community in Northcotte Grotto (Jasinska 1997);

(c) Bacterial contamination of groundwater supplies for human use, for example at Prevelley Park;

(d) Existence of potential threatening processes, including groundwater pumping, and contamination, plus other land uses and developments (especially expansion of Rural Residential subdivisions) which may impact on water quality and subterranean biodiversity values.

Methods for the monitoring of fauna in root mat communities need to be reviewed so that a useful assessment of community health can be made, whilst minimizing destructive sampling of root mat habitat. Sampling conducted in March 2002 by Storey and Knott (2002) for example, detected only 30 % of taxa recorded previously, but the sampling was unable to distinguish if the observed decline in species presence indicated a real change in the community composition, or merely reflected the sampling limitations as noted by the authors. These results raise some important considerations for conservation biologists. Firstly, it is very difficult to detect even substantial changes in population size (or presence / absence) of organisms with low, natural background densities. Secondly, even when background densities are quite high, several independent control locations are needed to give a powerful test of changes in population size (Barmuta 1998; Eberhard 1999, 2001).

Earlier perceived differences between some of the root mat communities, both within and between caves, may be attributed, in part at least, to limited sampling. Sampling undertaken during this study showed that heterogeneity in microhabitat and fauna distributions accounts for some of the observed differences. Thus interpretations of community 'uniqueness' need to be based on adequate sampling, and supported by a proper taxonomic framework.

Taxonomic studies undertaken during this study have improved the conservation status of some species, as well as contributing to a better understanding of the systematic relationships between stygofauna communities. Descriptions of several new species have been prepared for publication (Karanovic, I. submitted; Karanovic, T. submitted). Most of the root mat fauna remains scientifically undescribed, thus description of these taxa should also be encouraged and supported.

Future research and monitoring strategies need to incorporate hydrogeologic and geomorphic characterization of individual karst drainage systems. Monitoring of flow conditions and water physico-chemistry parameters can provide useful information for interpreting conditions of aquifer recharge and storage, although appropriate sampling intervals need to be determined beforehand (Quinlan et al. 1992). These parameters may also be useful in assessing the general health of groundwater ecosystems. Analysis and evaluation of monitoring data needs to be regular and ongoing, and integrateded with adaptive management responses.

Some IRP recovery actions are focused at the micro-habitat scale, including the protection of individual trees with roots in caves. This approach is impractical in some karst systems of the Leeuwin-Naturaliste Ridge however, including the JELSS where there are hundreds of trees with roots penetrating groundwater throughout more than 8 km of cave passages.

Because the distribution of stygofauna is determined by hydrogeologic boundaries defined at the macro (aquifer or subcatchment) scale, and processes which operate on geo-evolutionary time scales, conservation strategies for the fauna need to be developed and integrated at the more expansive levels of karst catchment and karst geo-ecosystem.

Strategies for the conservation of subterranean biodiversity within the Leeuwin-Naturaliste Ridge will be most effective if:

1. They encompass all stygofauna communities, and not solely root mat communities;

2. Are integrated with karst processes, especially karst hydrogeologic and geomorphic processes;

3. Are applied at an appropriate spatial and temporal scale, viz. karst catchment / karst geo-ecosystem (Boulton, Humphreys and Eberhard 2001, Eberhard 1999; 2000; 2001; Hamilton-Smith and Eberhard 2000).

Recommendations

All actions listed below need to be initiated and funded by the WA government departments responsible for water resources (Water and Rivers Commission) and wildlife (CALM).

1. Revise the Interim Recovery Plan for aquatic root mat communities.

2. Undertake analysis and evaluation of water level monitoring in other caves in the region.

3. Revise fauna monitoring strategies for listed root mat communities.

4. Support taxonomic description of species.

5. Map and characterize the hydrogeology of *all* karst catchments and karst drainage systems on the Leeuwin-Naturaliste Ridge, and;.

6. Survey and characterize the stygofauna in *all* karst catchments and karst drainage systems on the Leeuwin-Naturaliste Ridge.

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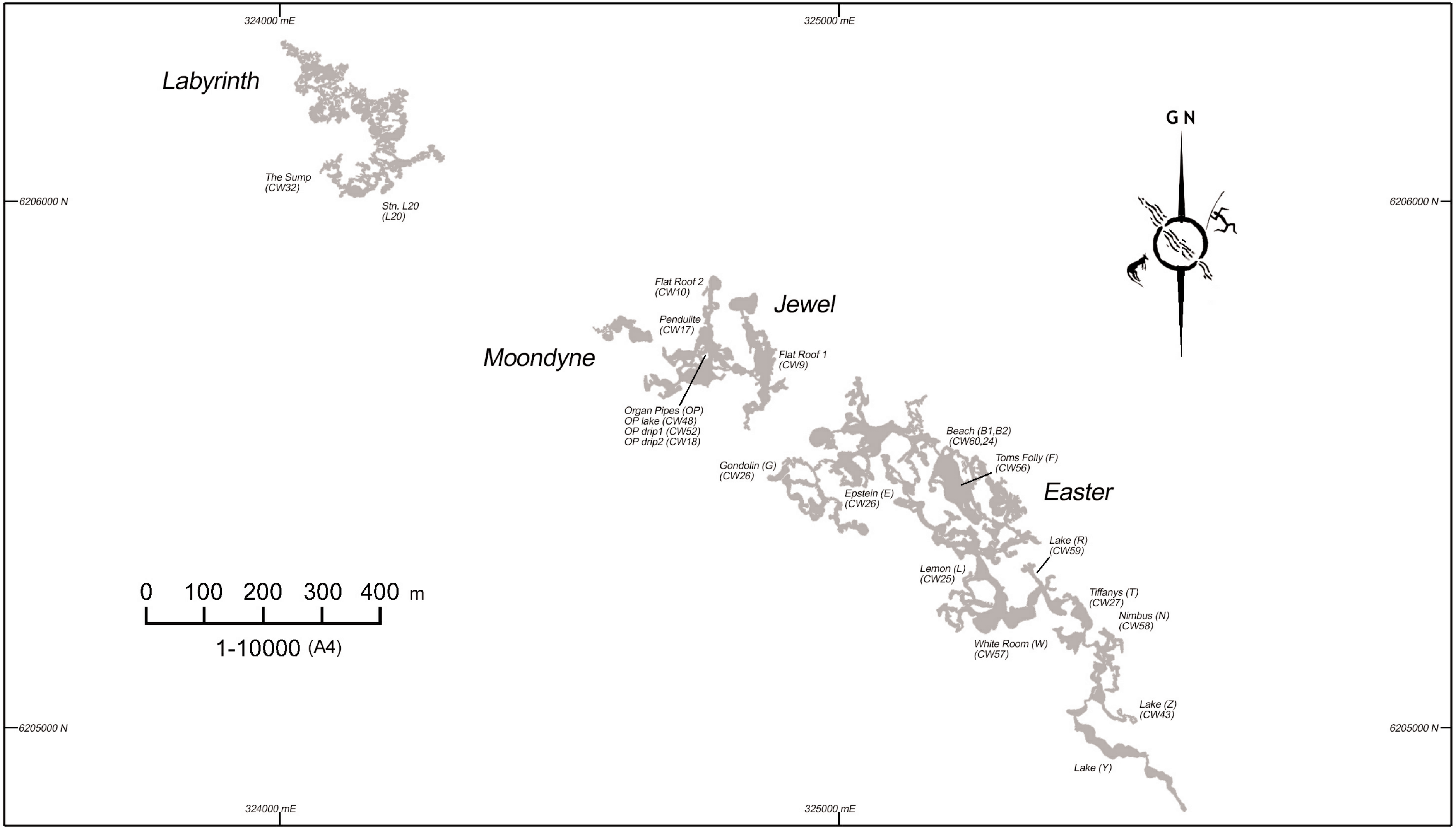
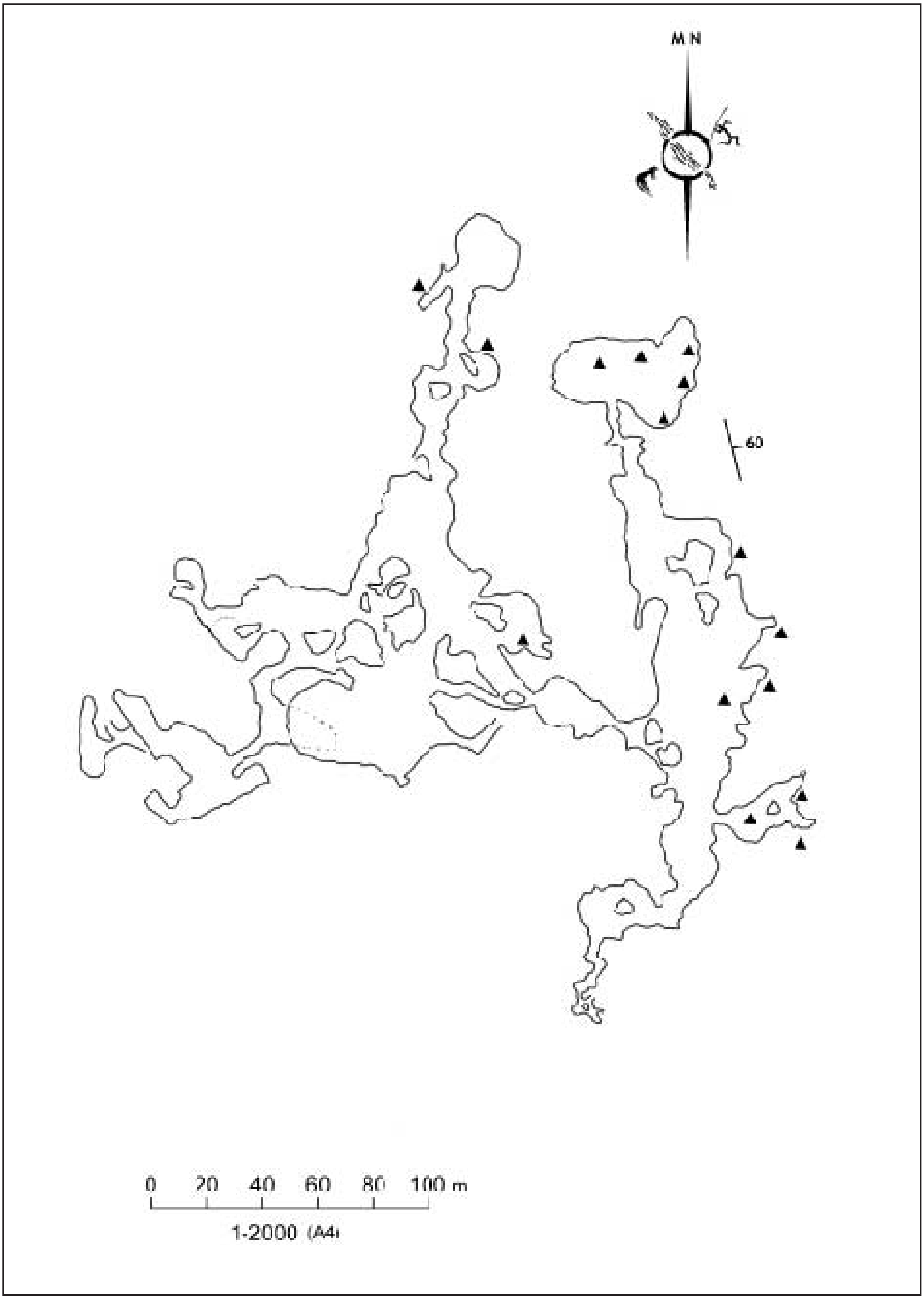
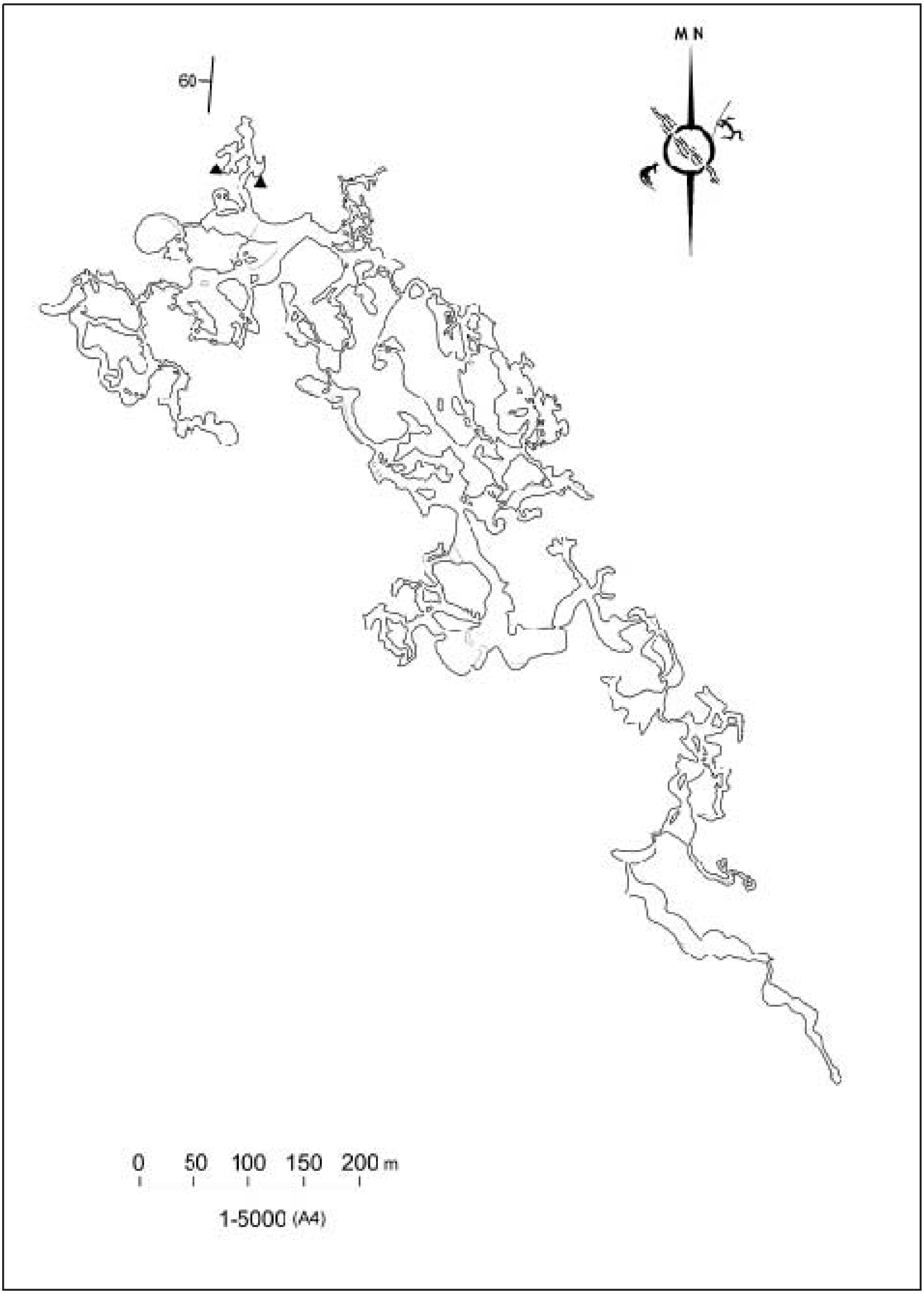
Appendices



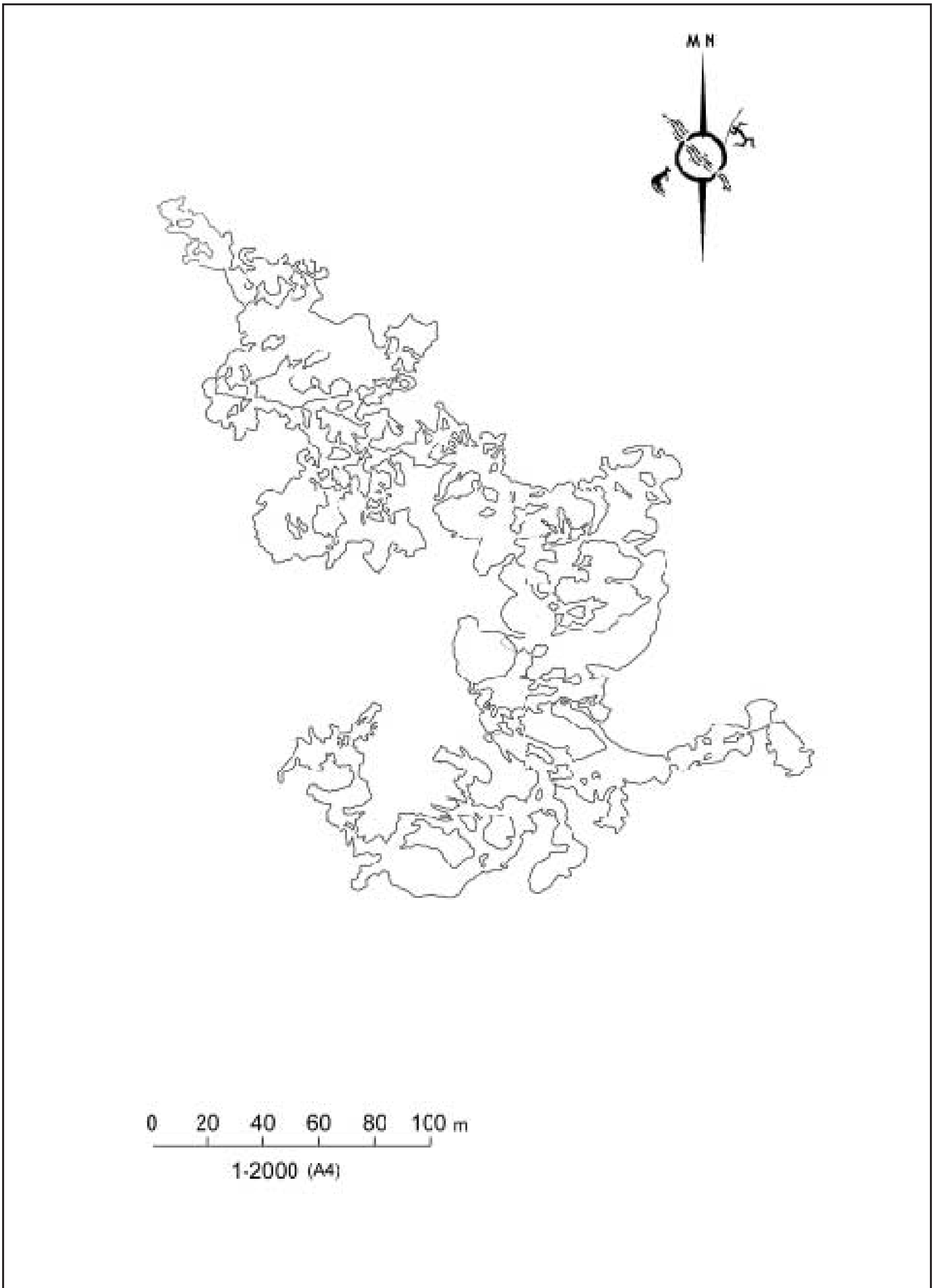
APPENDIX 1. *Plan of Jewel -Easter and Labyrinth Subsystems showing outline of surveyed passages (grey) and locations of water sampling and monitoring sites. Refer Appendix 8 for site details.*



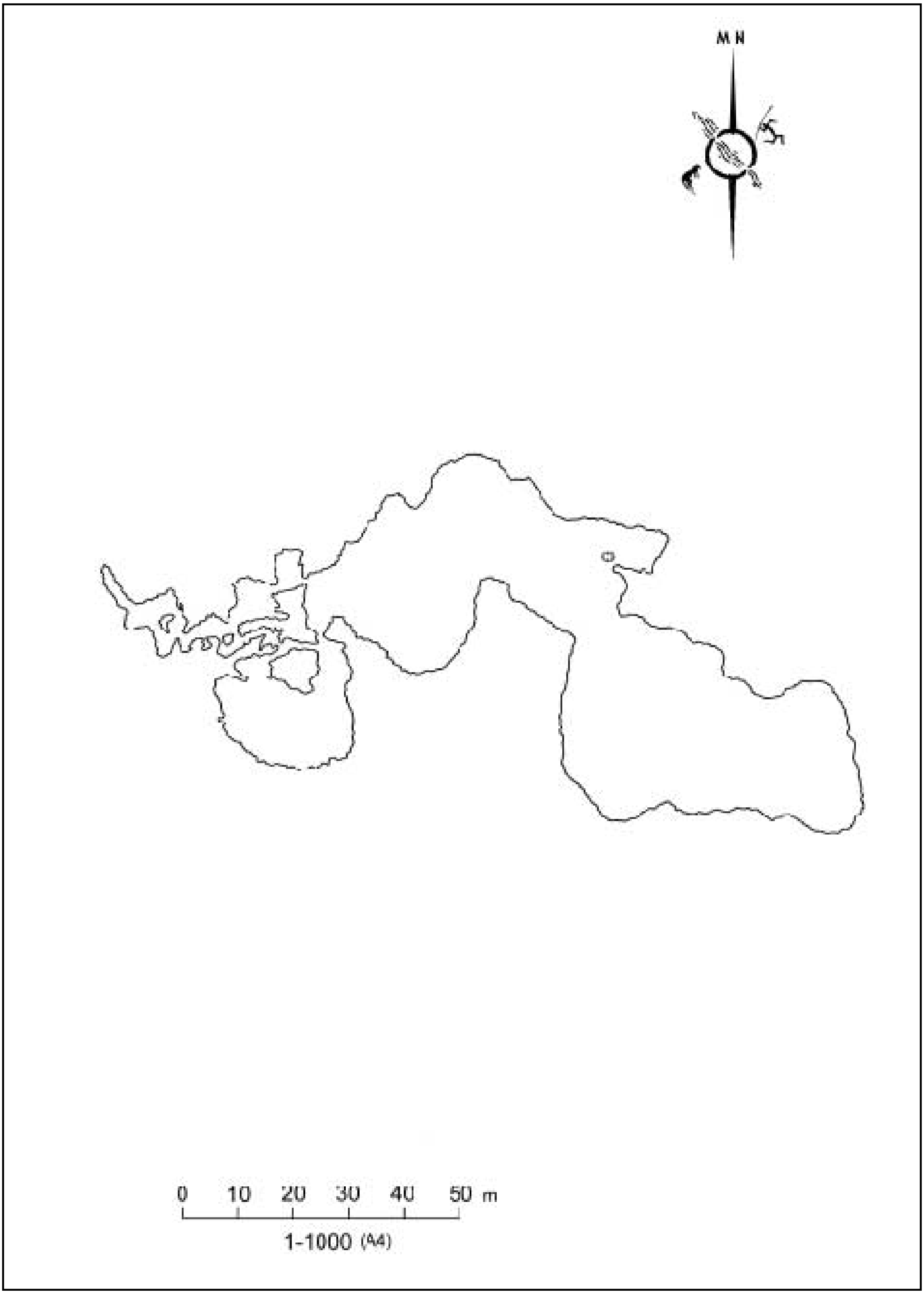
APPENDIX 2. *Plan of Jewel Cave showing locations of granite - gneiss outcrops (triangles), dip and strike of outcrop foliation.*



APPENDIX 3. *Plan of Easter Cave showing location of granite - gneiss outcrops, dip and strike of outcrop foliation.*



APPENDIX 4. *Plan of Labyrinth Cave, Adapted from map drawn by Michael Bradley, 2002*



APPENDIX 5. *Plan of Moondyne Cave. Adapted from map drawn by Rauleigh Webb, 1978.*

APPENDIX 7. *Australian Height Datum (AHD) benchmarks and reference points. TBM = Temporary Bench Mark, SD = Standard deviation of measurement, SWL= Standing water level, CW# = CaveWorks site reference number (refer Appendix 8).*

Locality	*Site name*	*m AHD*	*Site description*	*Survey & precision*
Easter Cave	doline	63.088	TBM Spike & peg near large tree	Cape Surveys 3rd order spirit level
	entrance	60.107	TBM No. AU14 screw & plate in rock at entrance	Cape Surveys 3rd order spirit level
	gate	59.826	TBM screw in entrance gate	Cape Surveys 3rd order spirit level
	pitch base	50.592	TBM peg at base of entrance pitch	Cape Surveys 3rd order spirit level
	entrance crawl peg	29.687	TBM peg at start of entrance crawl	Cape Surveys trig heighting +/- 0.020 metres
	entrance crawl tag	30.254	TBM screw & plate at start of entrance crawl	CaveWorks +/- 0.002m
	Y junction	26.119	TBM screw & plate in floor near flowstone corner	CaveWorks spirit & water tube level SD 0.006m
	Stn 10 at Y Junction	25.247	TBM tag in floor at Y Junction	CaveWorks spirit & water tube level SD 0.006m
	Epstein SWL datum	24.966	TBM No. 066 screw & plate Epstein Lake	CaveWorks spirit & water tube level SD 0.006m
	Epstein E2 Ruler 0cm	23.437	0cm mark on E2 ruler	CaveWorks +/- 0.002m
	Epstein E2 SWL 21-Dec-00	23.615	17.8cm E2 SWL , 21-Dec-00	CaveWorks +/- 0.002m
	Epstein Leaning Stake 0cm	25.097	0cm/0" mark on leaning stake	CaveWorks spirit & water tube level SD 0.007m
	Epstein Roach Ruler 0cm	24.146	0cm/0" mark on Roach stake	CaveWorks spirit & water tube level SD 0.007m
	Epstein P. Wood Ruler 0cm	23.763	0cm mark on P. Wood ruler	CaveWorks spirit & water tube level SD 0.007m
	Epstein E1 Ruler 0cm	23.473	0cm mark E1R2 ruler	CaveWorks spirit & water tube level SD 0.007m
	Gondolin Ruler 0cm	23.454	0cm mark on Gondolin ruler	CaveWorks +/- 0.002m
	Beach Barometer Stn	26.822	TBM No. CW BARO screw & plate above The Beach Lake	CaveWorks spirit & water tube level SD 0.006m
	Beach CW060 datum	24.595	TBM No. 060 screw & plate at The Beach La ke	CaveWorks water tube +/- 0.002m
	Beach Roach Ruler 0cm	24.017	0mm (0") mark Roach ruler	CaveWorks water tube +/- 0.002m
	Beach WASG Ruler 0Ft	23.496	0 foot mark red WASG ruler (not in original location)	CaveWorks water tube +/- 0.002m
	Beach B1 Ruler 0cm	23.392	0cm mark B1R2 ruler	CaveWorks +/- 0.002m
	Beach B1 SWL 21-Dec-00	23.613	B1R2 SWL 22.1, 21-Dec-00,	CaveWorks +/- 0.001m
Augusta	SSM Augusta 49	37.072	Standard Survey Mark - Calkarri Drive	DOLA third order spirit level

APPENDIX 7. *Continued*

Locality	*Site name*	*m AHD*	*Site description*	*Survey & precision*
Caves Rd	Raey's Bore	17.005	Bore t.o.c., Lot 3, Location 230, Caves Rd	Cape Surveys 3rd order spirit level
	Power pole TBM 2	22.060	Peg at base power pole No. B912, NW Reay's Dam	Cape Surveys 3rd order spirit level
	Power pole TBM 3	23.974	Peg at base power pole No. 1299,1 4,15 (1103), Marron Dams	Cape Surveys 3rd order spirit level
	Caves Rd TBM 4	41.811	Spring head nail in center Caves Rd, opposite Lot 23	Cape Surveys 3rd order spirit level
	Telstra Pit TBM 5	41.364	Ramset nail in collar of Telstra Pit, Lot 23, loc. 1497	Cape Surveys 3rd order spirit level
Jewel Cave Surface	Stn 9000 Jewel Cave Rd	42.469	Bridge spike near edge of Hotmix (Jewel Cave Rd)	Cape Surveys 3rd order spirit level
	Stn 9001 Jewel Cave Rd	45.673	Bridge spike near edge of Hotmix (Jewel Cave Rd)	Cape Surveys 3rd order spirit level
	Stn 9002 Jewel Cave Rd	56.365	Spring head nail in Hotmix (Jewel Cave Rd)	Cape Surveys 3rd order spirit level
	Natural entrance	65.941	TBM No. 9029 peg at natural entrance	Cape Surveys 3rd order spirit level
	Tourist entrance	63.953	TBM screw No. 9016 / JWC0 on top of wall	Cape Surveys 3rd order spirit level
	Water tank	64.465	TBM 2001 screw on rock behind water tank	Cape Surveys 3rd order spirit level
	Seat at tourist entrance	64.050	TBM is outside stud nearest to cafe	Cape Surveys 3rd order spirit level
	Table in guides hut	64.485	Level is table top in guides hut, used for barometric base	CaveWorks water tube +/- 0.002m
Jewel Cave	Coral Boardwalk	25.240	Stn 9106 = CW survey stn. JEC 11 on walkway	Cape Surveys +/- 0.020 metres
	Organ Pipes Corner	25.030	TBM No. 9100 screw & plate on rock near Organ Pipes	Cape Surveys +/- 0.020 metres
	Dripping Boardwalk	25.130	TBM No. 9103 screw & plate on boardwalk	Cape Surveys +/- 0.020 metres
	Organ Pipes Ruler top	24.010	Top of ruler support tube	Cape Surveys +/- 0.020 metres
	Organ Pipes Ruler 0cm	23.592	0cm mark 0.418m below top ruler support tube	CaveWorks water tube +/- 0.002m
	Organ Pipes Platform	25.330	Stn 9101 tack on wooden deck	Cape Surveys +/- 0.020 metres
	Lake Chamber	26.620	TBM No. 9100 screw & plate on rock Lake Chamber	Cape Surveys +/- 0.020 metres
	Organ Pipes SWL 28-Dec-00	23.689	OP ruler 5.5cm, 28-Dec-00	CaveWorks water tube +/- 0.002m
Moondyne Cave	Gate	54.804	Top of trap door gate	Cape Surveys 3rd order spirit level
	Moondyne sign	55.975	Galvanised tack on top of "moondyne Cave" sign	Cape Surveys 3rd order spirit level
Labyrinth Cave	Entrance	45.9	Concrete peg at entrance	Barometric survey, SD = 0.23m
	L20 Ruler 0cm	23.9	0cm mark R1 ruler near Bastian survey peg #20	CaveWorks tape & clinometer survey, not closed
	L20 SWL 3-Dec-00	23.9	L20 R1 ruler 6.1cm, 3-Dec-00	CaveWorks tape & clinometer survey, not closed

APPENDIX 8. *Details of water sampling sites including description, location, field measurements, dates sampled and cross reference numbers. Sites listed in order by CaveWorks sites reference number.*

[1] WRC No	[2] CW No	Site name	Grid ref. (AGD 1966) East	Grid ref. (AGD 1966) North	Depth [3] (mbgl)	Description	Date sampled	Field Temp	Field pH	Field [4] SC (µS/cm)
	5	Leeuwin Spring	3289	61956	0	Karst spring, Augusta water supply	25-Oct-99			
200001637							29-May-00	17.7	7.26	1127
	6	Quary Bay 1 (South)	3285	61957	0	Karst spring - tufa 'shower'	25-Oct-99			
200001638							29-May-00	14.4	8.13	1059
	7	Turners Spring	3303	61974	0	Karst spring	25-Oct-99			
200001636							29-May-00	17.8	6.8	9'9
	0	Jewel Cave - Flat Roof 1	3247	62056	35	Groundwater in cave	25-Oct-99			
200001675							27-Apr-00	17.4	7.16	1468
	10	Jewel Cave - Flat Roof 2	3247	62056	35	Groundwater in cave	25-Oct-99			
200001674							27-Apr-00	17.2	7.24	3280
	11	Old marron farm cam 1 (North)	3203	62047	0	Fed by sub-surficial seepage	25-Oct-99			
200001691							31-May-00	13.7	8.16	532
	12	Augusta surface stream	3288	62038	0	Possibly some groundwater discharge	25-Oct-99			
	13	Augusta surface stream	3293.5	62030	0	Possibly some groundwater discharge	25-Oct-99			
	14	Augusta surface stream	3295	62028	0	Brown coloured water	25-Oct-99			
	15	West Bay Creek	3285	62045	0	Possibly some groundwater discharge	25-Oct-99			
	17	Jewel Cave - Pendulite Chamber	3247	62056	35	Groundwater in cave	25-Oct-99			
	18	Jewel Cave - Organ pipes drip No. 2	3247	62056	35	Seepage water in cave	25-Oct-99			
	24	Easter Cave - Lake B2 (near Beach)	3249	62056	30	Groundwater in cave	27-Oct-99			
	25	Easter Cave - Lake L (Lemon)	3252	62055	30	Groundwater in cave	27-Oct-99			
	26	Easter Cave - Lake G (Gondolin)	3248	62056	30	Groundwater in cave	27-Oct-99			
	27	Easter Cave - Lake T (Tiffanys)	3255	62053	20	Groundwater in cave	27-Oct-99			
	31	Seawater	3154	62277	0	Seawater at Conto's Beach	11-Jan-99			
	32	Labyrinth Cave	3243	62062	30	Groundwater in cave - The Sump	22-Dec-99			
	35	Rainwater	3221	62420	0	Margaret River - rainwater tank	4-Jan-00	26.0	7.03	86.7

APPENDIX 8. *Continued*

[1] WRC No.	[2] CW No.	Site name	Grid ref. (AGD 1966) East	North	Depth [3] (mbgl)	Description	Date sampled	Field Temp	pH	[4] SC (µS/cm)
	39	Seepage dam Lot 23	3262	62058	1	Pump test Dam No 2 by Slade Ag Tech	20-Jan-00	26.1	5.60	425
	40	Seepage dam (North) Lot 21	3256	62064	1	Pump test Dam No 1 by Slade Ag Tech	20-Jan-00	25.7	8.61	1415
200001682							24-May-00	14.1	7.71	1770
	41	Seepage dam Lot 22	3258	62061	0	Perennial groundwater seepage	20-Jan-00	25.5	7.73	453
200001683							24-May-00	13.8	7.40	385
	42	Raey's Bore	3267	62041	1	Uncapped bore beside well and windmill	20-Jan-00	21.3	6.86	514
200001681							24-May-00	17.9	7.13	641
	43	Easter Cave - Lake Z	3255	62052	20	Groundwater in cave	19-Jan-00	18.9	7.02	1164
200001673	48	Jewel Cave - Organ pipes lake	3247	62056	35	Groundwater in cave	27-Apr-00	17.6	7.36	2980
200001679	49	Seepage dam (South) Lot 21	3256	62063	1	Groundwater seepage outflow	24-May-00	14.3	7.35	841
200001680	50	Raey's seepage dam	3266	62044	0	Groundwater seepage outflow	24-May-00	14.6	7.29	369
200001689	51	Quarry Bay 2 (North)	3285	61957.5	0	Karst spring - N end of Quarry Bay	29-May-00	15.2	7.59	1113
200001690	52	Jewel Cave - Organ Pipes drip No. 1	3247	62056	35	Stalactite drip water	29-May-00	17.5	7.19	6540
200001694	53	Old marron farm - seepage outflow	3266	62047	0	Groundwater seepage outflow	31-May-00	12.9	7.41	1994
200001693	54	Old marron farm - windmill spring	3265	62047	0	Groundwater seepage outflow	31-May-00	11.8	7.5	1000
200001692	55	Old marron farm dam 2 (South)	3264	62046	0	Fed by sub-surficial seepage	31-May-00	12.9	8.13	1858
200001695	56	Easter Cave - Lake F (near Toms Folly)	3250	62055.5	30	Groundwater in cave	6-Jun-00	17.4	7.39	3090
200001696	57	Easter Cave - Lake W (near White Room)	3253	62054	30	Groundwater in cave	6-Jun-00	17.5	7.09	2610
200001697	58	Easter Cave – Lake N (Nimbus)	3255	62052.5	30	Groundwater in cave	6-Jun-00	17.5	7.02	2240
200001698	59	Easter Cave - Lake R (R survey)	3254	62053.5	30	Groundwater in cave	6-Jun-00	17.6	7.19	3510
200001699	60	Easter Cave - Lake B1 (The Beach)	3249	62056	30	Groundwater in cave	6-Jun-00	17.1	7.24	2920
200008302	63	Rainwater	3181	62272	0	Rainwater from tank at Lake Cave	26-Sep-00	17.3	5.82	76.8

[1] Water & Rivers Commission sample reference number

[2] CaveWorks site reference number

[3] Metres below ground level (mbgl)

[4] Specific conductivity at field temperature

Appendix 9. *JCKS, variation in physico-chemical parameters measured in cave water bodies between December 1999 and January 2001.*

Locality	*Site name (CW ref. No.)*	*Sampling period (Month/Year)*	*n*	*Temp. Range (°C)*	*pH range*	*[1] SC mS/m @ 25 °C*		*[2] CV %*	*[3] Flow type*	*[4] Salinity TDS mg/L*		*[5] DO % sat.*
						Mean	*s.d.*			*Mean*	*s.d.*	
Labyrinth	SW Passage drip pool	Jan-00	1		7.33	184				942		
	Stn. L20 (CW67)	Dec-99 to Nov-00	6	15.0 - 15.6	7.17 - 7.64	364	24	7	D/C	1943	144	100
		Dec-99 to Jan-00	2		7.22 - 7.26	276	7	2	D	1424	39	
Jewel	Organ Pipes lake (CW48)	Mar-00 to Oct-00	5	17.0 - 17.6	7.36 - 7.65	358	32	9	D/C	1908	190	95
	Flat Roof 1 (CW9)	Nov-99 to Oct-00	7	17.4 - 17.5	7.16 - 7.48	171	12	7	D/C	876	61	87
	Flat Roof 1 (50-100 cm)[6]	Dec-99 to Mar-00	2	17.4	7.14	229	7	3	D	1173	33	77
	Flat Roof 2 (CW10)	Dec-99 to Oct-00	8	17.2 - 17.4	7.12 - 7.60	392	10	3	D	2103	60	67
	Organ Pipes drip 1 (CW 52)	May-00	1		7.19	773				4348		69
Easter	Gondolin (CW26)	Dec-99 to Jun-00	5	17.2 - 17.3	7.01 - 7.42	359	30	8	D/C	1910	177	
	Epstein E1	Dec-99 to Jun-00	4	17.0 - 17.1	6.85 - 7.30	342	26	8	D/C	1813	152	
	Epstein E2 (CW66)	Apr-00 to Oct-00	4	16.7 - 17.1	7.11 - 7.30	306	1	0.4	D	1600	7	
	Beach B1 (CW60)	Dec-99 to Jun-00	4	17.1 - 17.4	6.98 - 7.24	362	33	9	D/C	1931	192	
	Beach B2 (CW24)	Dec-99 to Jun-00	4	17.1 - 17.3	6.95 - 7.28	371	37	10	C	1983	217	
	Toms Folly F (CW56)	Dec-99 to Jun-00	5	17.4 - 17.7	7.01 - 7.44	382	34	9	D/C	2048	198	
	Lemon L (CW25)	Dec-99 to Jun-00	6	17.5 - 17.6	6.98 - 7.18	373	29	8	D/C	1994	168	94
	White Room W (CW57)	Dec-99 to Jun-00	6	17.5 - 17.6	7.05 - 7.28	331	25	8	D/C	1745	146	
	Lake R (CW59)	Dec-99 to Jun-00	2	17.6 - 17.7	7.05 - 7.19	425	17	4	D	2301	98	
	Tiffanys T (CW27)	Dec-99 to Oct-00	9	17.4 - 17.6	7.01 - 7.29	297	33	11	C	1546	192	2 - 82
	Nimbus N (CW58)	Dec-99 to Jun-00	9	17.4 - 17.5	6.83 - 7.09	299	31	11	C	1558	182	83 - 89
	Lake Z (CW43)	Jan-00 to Jan-01	5	17.4	7.00 - 7.09	119	13	11	C	616	68	
	Lake Y	Aug-00 to Jan-01	2		7.12	118	2	2	D	606	12	
	Mouse Hole	5 Feb-02	1		7.09	330				2310		

[1] Specific conductivity (SC) @ 25 oC
[2] Conductivity coefficient of variance (CV) = standard deviation (s.d.) x 100 / mean
[3] Flow type from Quinlan et al. (1992); Diffuse (D) – CV < 5 %; Diffuse/Conduit (D/C) – CV 5-10 %; Conduit (C) – CV > 10%
[4] Salinity calculated from SC as Total Dissolved Solids (TDS)
[5] Dissolved oxygen (DO) % saturation
[6] Measured 50 - 100 cm depth below water surface; all other sites measured at 1 cm depth

Appendix 10. *Chemical analyses of groundwater in JELSS caves. Analyses by Australian Government Analytical Laboratories (refer to methods).*

Locality	Site	Date	[1] pH	[2] SC mS/m	mg/L													
					[3] TDS	[4] TH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	Fe	NO_3	Total N	Total P
Labyrinth	The Sump (CW32)	22-Nov-99	7.6	256	1650	430	110	39	340	10	<1	300	670	100	<0.1	0.3	0.35	0.023
Easter	Beach B1 (CW60)	6-Jun-00	7.4	346	2150	540	130	53	480	12	<1	320	880	110	<0.1	<0.2	0.057	0.007
	Beach B2 (CW24)	27-Oct-99	7.4	355	2200	530	120	56	520	14	<1	260	880	120	<0.1	<0.2	0.12	0.014
	Gondolin (CW20)	27-Oct-99	7.5	330	2046	520	130	47	620	10	<1	310	820	95	<0.1	0.8	0.85	0.007
	Lemon L (CW25)	27-Oct-99	7.1	348	2158	470	110	47	510	9	<1	270	900	95	<0.1	0.3	0.49	0.008
	Toms Folly F (CW58)	6-Jun-00	7.4	364	2260	540	125	55	510	12	<1	280	930	110	<0.1	<0.2	0.24	0.021
	White Room W (CW57)	6-Jun-00	7.3	300	1860	510	134	43	380	8	<1	300	710	74	<0.1	<0.2	0.19	0.026
	Lake R (CW59)	6-Jun-00	7.4	415	2570	640	149	65	570	13	<1	330	1100	110	<0.1	<0.2	0.046	0.007
	Tiffanys T (CW27)	27-Oct-99	7.4	275	1705	550	140	48	520	10	<1	290	740	79	<0.1	0.2	0.17	0.005
	Nimbus N (CW50)	6-Jun-00	7.3	260	1610	460	113	42	330	8	<1	320	600	68	<0.1	<0.2	0.26	0.012
	Lake Z (CW43)	19-Jan-00	7.5	118	730	350	100	24	110	3	<1	310	170	15	<0.1	0.0	0.09	0.008
Jewel	Flat Roof 1 (CW9)	25-Oct-99	7.4	156	970	310	83	23	180	6	<1	300	250	49	<0.1	<0.2	0.14	0.005
	Flat Roof 1 (CW9)	27-Apr-00	7.4	170	1050	330	90	25	200	6	<1	370	290	60	<0.1	<0.2	0.2	0.017
	Flat Roof 2 (CW10)	25-Oct-99	7.4	381	2360	550	130	54	530	12	<1	300	1000	140	<0.1	0.2	0.22	<0.005
	Flat Roof 2 (CW10)	27-Apr-00	7.3	370	2290	570	140	53	570	11	<1	350	930	140	<0.1	0.6	0.6	0.038
	Pendulite lake (CW17)	25-Oct-99	7.5	373	2310	580	140	55	520	11	<1	340	940	100	<0.1	0.8	0.82	<0.005
	Organ Pipes lake (CW48)	27-Apr-00	7.4	380	2360	560	140	51	490	17	<1	340	810	300	<0.1	12	12	0.35
	Organ Pipes drip 2 (CW18)	25-Oct-99	7.5	600	3720	1400	450	69	480	140	<1	110	820	60	<0.1	425	440	0.015
	Organ Pipes drip 1 (CW 52)	29-May-00	7.4	718	4450	1500	420	110	600	98	<1	320	1500	120	<0.1	370	370	<0.005
Leeuwin	Rainwater	26-Sep-00	6.1	9	56	<5	<1	<1	<10	<1	<1	2	20	<5	<0.1	<0.2	0.16	0.024
	Seawater	1-Nov-96	8.4	5660	34300	6700	390	1400	11000	370	<1	110	21000	2800	<0.1	<0.2	0.12	0.017
Reference [5] GDWQA			6.5-8.5		1000	500			300				400	400	0.3	10		

[1] pH measured in laboratory within 3 days of sample collection
[2] Specific conductivity (SC) @ 25 °C
[3] Total Dissolved Solids (TDS) calculated
[4] Total Hardness (TH) as $CaCO_3$
[5] Guidelines for drinking water quality in Australia, 1987 (GDWQA)

Appendix 11. *Chemical analyses of non-cave water bodies in Augusta area . Refer Appendix 10 for explanation of terms.*

Type	Location	Site name (CW ref. no)	Date	pH	EC mS/m @ 25 °C	TDS	Td	Ca	Mg	Na	K	CO3	HCO3	Cl	SO4	Fe	NO3	TN	TP
						mg/L													
Karst springs	Coastal/Estuarine	Leeuwin Spring (CW5)	25-Oct-99	7.3	134	830	340	100	22	110	2	<1	240	220	28	<0.1	0.9	1.1	0.013
			29-May-00	7.4	133	820	340	100	22	120	3.4	<1	280	250	33	<0.1	1	0.98	0.008
		Quarry Bay South (CW6)	25-Oct-99	7.6	140	870	310	85	23	130	3	<1	290	270	32	<0.1	<0.2	0.21	0.011
			29-May-00	7.2	134	830	300	83	23	130	3	<1	250	280	33	<0.1	0.6	0.71	<0.005
		Quarry Bay North (CW51)	29-May-00	7.0	138	860	310	88	23	130	3.4	<1	260	300	37	<0.1	0.6	0.60	<0.005
		Turners Spring (CW7)	25-Oct-99	7.2	187	1160	440	120	33	180	3	<1	360	400	49	0.1	<0.2	0.37	0.008
			29-May-00	7.3	108	670	320	96	21	75	1.2	<1	300	180	21	<0.1	0.5	0.51	0.012
non-karst groundwater & surface streams	Old marron farm	Dam 1 (North) (CW11)	25-Oct-99	6.2	39	240	64	9	10	40	2	<1	46	80	21	<0.1	<0.2	0.353	<0.005
			31-May-00	7.3	71	440	81	11	13	90	7	<1	48	160	23	<0.1	<0.2	0.52	0.02
		Dam 2 (South) (CW55)	31-May-00	6.1	245	1520	270	44	40	340	17	<1	83	680	8	0.3	<0.2	1.3	0.066
		Seepage outflow (CW53)	31-May-00	7	300	1860	540	160	33	290	12	<1	160	680	420	0.2	1.2	4.1	0.52
		Old windmill spring (CW54)	31-May-00	7.3	168	1040	440	124	31	140	3	<1	20	310	84	<0.1	0.3	30	2.6
			20-Jan-00	5.7	57	350	93	25	8	70	4	<1	77	110	16	<0.1	0.3	1.6	0.054
	Raey's	Raey's Bore (CW42)	24-May-00	7.2	75	460	57	11.4	7	66	3.2	<1	150	130	7	0.7	<0.2	1.5	0.071
		Seepage dam (CW50)	24-May-00	6.6	49	300	50	6.2	8.4	50	21	<1	66	90	12	0.2	<0.2	10	1.1
	West Bay Creek	Seepage dam Lot 22 (CW41)	20-Jan-00	7.1	52	320	56	6	10	70	6	<1	31	130	16	0.2	<0.2	1.8	0.11
			24-May-00	6.7	50	310	60	7.4	10.2	57	7	<1	38	120	16	0.6	0.3	3.1	0.048
		Seep dam (North)Lot 21(CW40)	20-Jan-00	7.5	160	992	150	11	30	240	12	<1	34	520	21	1.8	<0.2	5.6	0.17
			24-May-00	7.4	230	1400	250	20.9	46.9	290	19.6	<1	63	870	17	<0.1	<0.2	5.7	0.2
		Seep dam (South)Lot 21(CW49)	24-May-00	7.2	110	680	120	11.7	21.3	160	12.5	<1	65	290	18	<0.1	<0.2	5.5	0.22
		Seepage dam Lot 23 (CW37)	20-Jan-00	7	23	143	40	6	6	30	3	<1	21	50	11	0.2	<0.2	0.00	0.030
			24-May-00	7.2	110	680	120	11.7	21.3	150	12.5	<1	65	290	18	<0.1	<0.2	5.5	0.22
		Seepage dam Lot 23 (CW38)	20-Jan-00	7	184	1140	210	26	35	260	14	<1	82	500	41	2.5	<0.2	7.6	0.45
			24-May-00	7.2	275	1700	380	52.4	60	330	28.1	<1	140	760	56	0.5	<0.2	6.8	0.41
		Seepage dam Lot 23 (CW39)	20-Jan-00	5.6	48	298	43	6	8	60	16	<1	18	110	13	1	<0.2	12	5.9
		West Bay Creek (CW15)	25-Oct-99	7.2	74	460	100	17	15	90	4	<1	45	170	25	0.3	<0.2	0.47	0.029
	West Bay	surface stream (CW13)	25-Oct-99	6.6	72	450	87	10	15	90	4	<1	15	170	44	<0.1	0.3	0.48	0.006
		surface stream (CW14)	25-Oct-99	6.9	54	340	57	8	9	70	3	<1	21	140	25	0.3	<0.2	0.54	0.022
		surface stream (CW12)	25-Oct-99	5.8	50	370	60	6	11	60	3	<1	15	180	33	0.1	<0.2	0.14	0.006

APPENDIX 12. *Saturation index (SI) for calcite and molar Ca/Mg ratios for water samples collected in the JELSS and West Bay Creek. Analysis used PCWATEQ software.*

Site No	Site name	Date	[1] SI calcite	[2] molar Ca/Mg
60	Easter Cave - Lake B1	6-Jun-00	0.254	1.488
24	Easter Cave - Lake B2	27-Oct-99	-0.071	1.300
26	Easter Cave - Lake G	27-Oct-99	0.345	1.678
25	Easter Cave - Lake L	27-Oct-99	-0.178	1.420
56	Easter Cave - Lake F	6-Jun-00	0.182	1.379
57	Easter Cave - Lake W	6-Jun-00	0.171	1.890
59	Easter Cave - Lake R	6-Jun-00	0.308	1.391
27	Easter Cave - Lake T	27-Oct-99	0.258	1.769
58	Easter Cave - Lake N	6-Jun-00	0.141	1.632
43	Easter Cave - Lake Z	19-Jan-00	0.355	2.527
9	Jewel Cave - Flat Roof 1	25-Oct-99	0.157	2.268
9	Jewel Cave - Flat Roof 1	27-Apr-00	0.249	2.184
10	Jewel Cave - Flat Roof 2	25-Oct-99	0.213	1.460
10	Jewel Cave - Flat Roof 2	27-Apr-00	0.219	1.602
17	Jewel Cave - Pendulite Ch	25-Oct-99	0.404	1.544
48	Organ Pipes lake	27-Apr-00	0.277	1.665
52	Organ Pipes drip No. 1	29-May-00	0.658	2.316
32	Labyrinth Cave	22-Nov-99	0.354	1.711
53	Old marron farm - seepage outflow	31-May-00	-0.443	2.941
54	Old marron farm - windmill spring	31-May-00	-0.881	2.426
11	Old marron farm Dam 1 (North)	31-May-00	-1.577	0.513
55	Old marron farm Dam 2 (South)	31-May-00	-0.083	0.667
42	Raey's Bore	20-Jan-00	-1.493	1.896
42	Raey's Bore	24-May-00	-1.094	0.988
50	Raey's Seepage dam	24-May-00	-2.337	0.448
41	Seepage dam Lot 22	20-Jan-00	-2.036	0.364
41	Seepage dam Lot 22	24-May-00	-2.558	0.440
37	Seepage dam Lot 23	20-Jan-00	-2.270	0.607
37	Seepage dam Lot 23	24-May-00	-1.707	0.333
40	Seepage dam (North) Lot 21	20-Jan-00	-1.439	0.222
40	Seepage dam (North) Lot 2 1	24-May-00	-1.187	0.270
49	Seepage dam (South) Lot 21	24-May-00	-1.549	0.333
38	Seepage dam Lot 23-Jan	20-Jan-00	-1.205	0.451
38	Seepage dam Lot 23-May	24-May-00	-0.695	0.530
39	Seepage dam Lot 23	20-Jan-00	-3.759	0.455

[1] Saturation Index (SI) calcite = log (K_{IAP} / K_{eq}), where K_{IAP} is the ion activity product of Ca^{2+} and CO_3^{2-} and K_{eq} is the thermodynamic equilibrium constant for calcite.

[2] molar Ca/Mg = $[Ca^{2+}] / [Mg^{2+}]$

Appendix 13.. *Results of bacteriological assays from Jewel Cave and Moondyne Cave.*

Sample date	*Testing authority and test type*	*Organ Pipes lake*	*Organ Pipes dripwater*	*Pendulite lake*	*Flat Roof 1*	*Flat Roof 2*	*Moondyne dripwater*	*Septic tank*
4-Oct-92	**State Health Laboratory**							
	HPC * - 32^{0}C/2 days	700		1	16			
	HPC * - 22^{0}C/2 days	1600		2	32			
	Total coliforms **	0		0	0			
	Thermo-tolerant coliforms **	0		0	0			
	Faecal *Streptococcus* **	0		0	0			
	Salmonella	-ve		-ve	-ve			
11-Oct-00	**CaveWorks - Coliscan Easygel test kit**							
	Escherichia coli **	0	0	0	0	0		>5000
	General coliforms **	440	0	0	0	60		0
	Other CFU **	<800	0	0	35	250		0
30-May-02	**WA Pathology Centre**							
	Thermo-tolerant coliforms **	Est. < 2	Est. < 2		Est. < 2		Est. < 2	
	Escherichia coli **	Est. < 2	Est. < 2		Est. < 2		Est. < 2	
	Enterococci ***	< 1	< 1		< 1		< 1	
	HPC* - 35^{0}C	Est. 10	640		47		Est. > 10,000	
	HPC* - 21^{0}C	75	Est. > 10,000		37		Est. > 10	

* Heterotrophic plate count (HPC) measured in Colony Forming Units (CFU) per ml.
** Colony Forming Units (CFU) per100 ml.
*** Most Probable Number (MPN) per 100 ml.

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***Appendix 14.** Water level monitoring 1999 to 2002*

Jewel Cave

The three lakes in Jewel Cave display water level responses which are more or less congruent with each other, although there are some minor differences evident between *Flat Roof Two* (FR2) and the other two lakes, *Flat Roof One* (FR1) and the *Organ Pipes* (OP) (see figure top next page). These latter two lakes appear closely synchronised with respect to the timing and amplitude of water level fluctuations, but lake FR2 displays a more rapid recharge response with higher amplitude rise and recession components.

All three sites show a similar cyclic fluctuation in response to winter rainfall and summer drought throughout the sampling period. However, water levels at lake FR2 attain a peak some 2 to 6 weeks before the other two lakes, and the recession trough some 4 to 5 weeks earlier. The recession rate during summer 2001 was similar at all lakes - about 0.011 m/month. The mean rate of water level rise varied between sites and years. During 1999 lake FR2 rose at 0.014 m/month whilst FR1 rose at 0.010 m/month. During 2000, both lakes rose at 0.007 m/month.

Initial recharge response occurred at lake FR1 within about one month of the first significant rainfall in May 1999. During 1999 the water level peak lagged about 7 months behind the rainfall peak at all sites. The recession following was muted by rainfall in April 2000 (53 mm monthly total recorded Cape Leeuwin). During 2000 the water level peak lagged 5 to 6 months behind the winter rainfall peak. A recharge peak of small amplitude and short duration occurred in response to winter rainfall 2001 that was well below average - a water level rise of 0.005 m occurred at lakes FR1 and FR2 with a lag of 1-2 months behind May rainfall of 93 mm recorded at Cape Leeuwin. Negligible antecedent rainfall was recorded before May, and lake FR2 peaked 2 weeks ahead of lake OP.

Easter Cave

There is a high degree of concordance in timing, rate and amplitude of water level fluctuations for all sites monitored in Easter Cave (see bottom top next page). The results strongly imply underlying hydrological connectivity along the 800 m linear distance of cave system separating the sites.

Earlier monitoring had indicated congruence in water level fluctuations between two proximal lakes (Epstein and Beach) within Easter Cave (Lowry 1965, Webb 1988). As the water level declined, once previously expansive and interconnected lakes became isolated, residual pools. Later measurements made at six spatially dispersed pools within Easter Cave showed a congruent water level rise over a 4 month period (Wood 1993).

Labyrinth Cave

There is a distinct cyclic fluctuation in the water level response that is linked to winter rainfall and summer drought (Figure 12, p. 27). The amplitude of water level fluctuations exceeded 0.019 m to 0.023 m. The lag between rainfall peaks in June-July and water level peaks varied from about 6 months during 1999 to about 3 months during 2000. The mean rate of water level recession during summer-autumn 2000 was 0.057 m/month. During summer-autumn of both years the water level dropped below the base of the pools at the monitoring sites.

Compared with the other two caves, the more rapid recharge response and recession rate at Labyrinth Cave suggests reduced vadose storage, and more rapid infiltration throughput and output. A possible contributor to this effect might involve the reduced thickness of limestone overlying Labyrinth Cave (less than 22 m), compared with 30-40 m generally at the other sites.

Discussion

The hydrograph curves for Jewel and Easter Cave are congruent in both timing and amplitude of water level response whilst Labyrinth Cave is clearly different (see figure next page). Water level fluctuations in Labyrinth Cave are of greater amplitude, and the rate of rise and recession is faster. Additionally, the timing of water level peaks is non-synchronous with Jewel and Easter Cave, occurring in Labyrinth Cave about two months earlier. The results support the possibility of hydrological connectivity between Jewel and Easter Cave, but not with Labyrinth Cave.

Appendix 14. *Continued.*

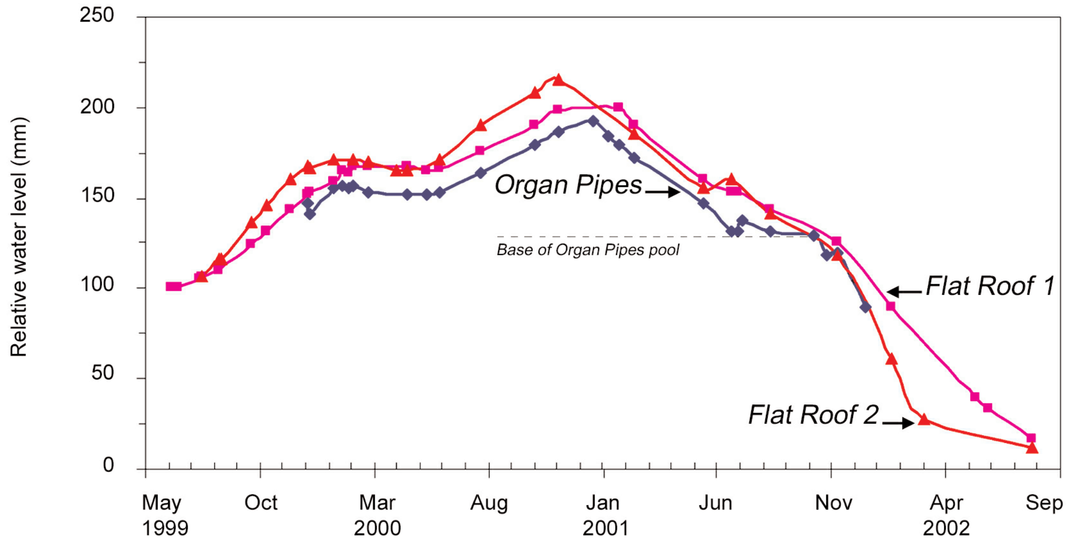


Figure. *Jewel Cave relative water level changes June 1999 - May 2002. Datums arbitrary.*

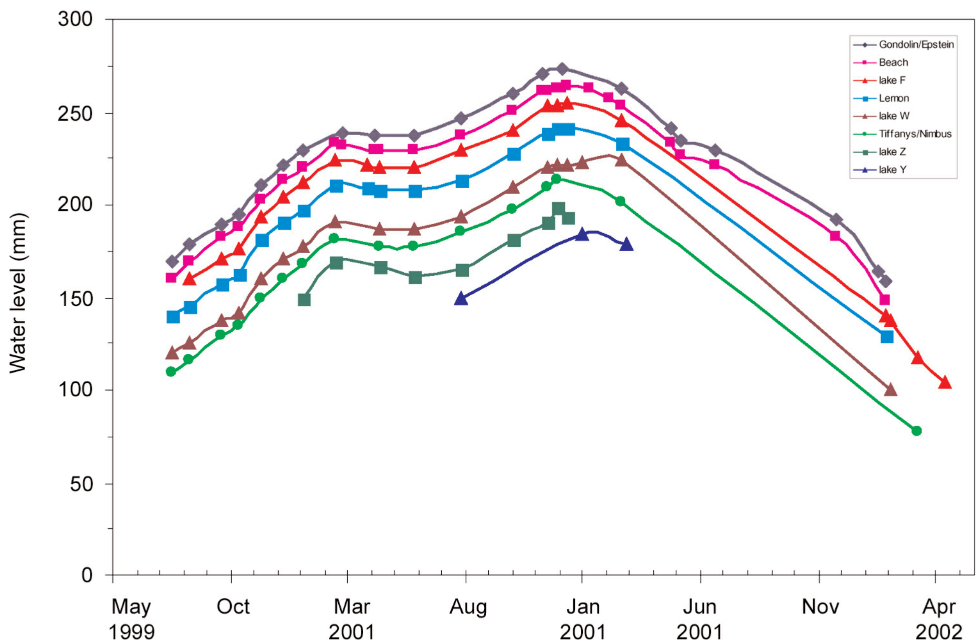
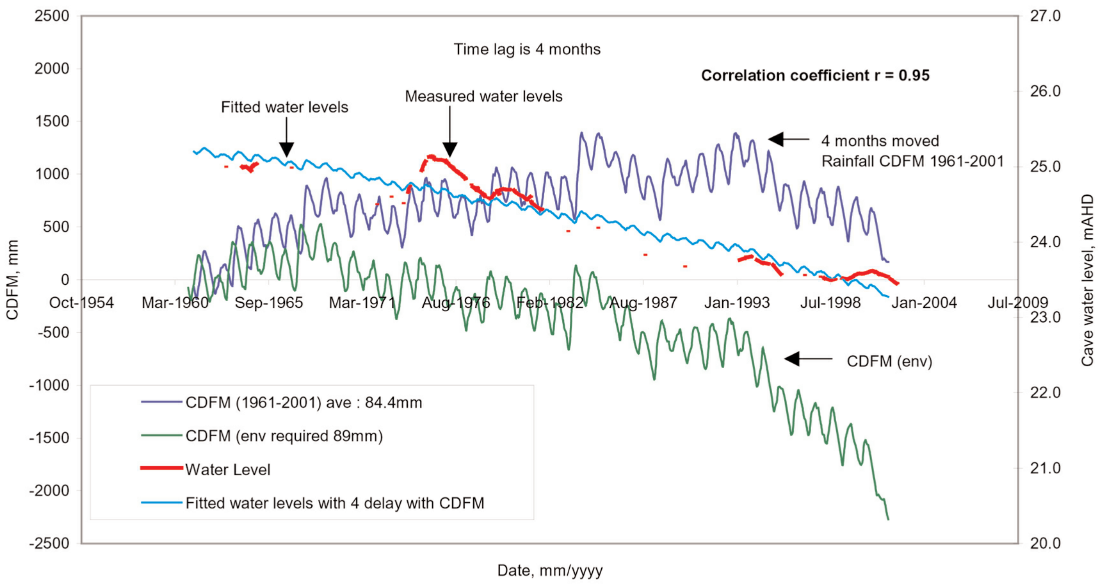


Figure. *Easter Cave relative water level changes August 1999 - June 2001. Datums arbitrary.*

APPENDIX 15. *Correlation (r = 0.95) of cumulative deviation from mean monthly rainfall (CDFM) at Cape Leeuwin versus groundwater level in the JELSS karst system, over the period 1961 to 2001. The best fit in the correlation is obtained with a 4 month lag in the groundwater response to rainfall. Analysis was done by Dr Cahit Yesertener, Water and Rivers Commission, Perth.*



Regression Statistics	
Multiple R	0.952
R Square	0.907
Adjusted R Square	0.905
Standard Error	0.182
Observations	111

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	35.377	17.688	530.772	1.355E-56
Residual	108	3.599	0.033		
Total	110	38.976			

	Coefficients	*Std Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	25.199	0.060	415.385	7.617E-175	25.079	25.319
Acc. res. rain (mm)	0.00023	7.473E-05	3.193	0.0018	9.050E-05	0.00038
Time (month)	-0.0040	0.00012	-32.435	1.692E-57	-0.0043	-0.00383

Appendix 16. *Fire history within the Jewel Cave (Location 4174) and Cliff Spackman (Location 8438) Reserves, 1958 to 2001, including information sources and notes on possible effects to the Jewel-Easter and Labyrinth Subsystems (JELSS).*

Date	*Description*	*Notes*	*Source*
Pre 1958 to circa 1976	Regular burning of Leeuwin ridge by graziers	JELSS affected	A. Lawrence, J. McManus pers. comm., 2001
1958 to late 1960's ?	Small scale controlled burns on Locn. 4174	Jewel Cave affected.	R. Spackman pers. comm., 2001
13th Mar. 1958	Jewel Cave burnt out	Jewel Cave & JELSS affected.	L. Robinson pers. comm. 2001
3rd Mar. 1961	Karridale Fire	JELSS not severely affected due to prior hazard reduction burns	CALM microfiche, R. Spackman pers. comm., 2001
Spring 1967	Fire burnt to within 300 yards southeast Easter Cave entrance	Lower southeast section JELSS (Easter Cave) affected.	The Western Caver 8(1): 10
ca. 1970	Fire Locn. 4174	JELSS affected	1973 photograph (S. Roatch) Easter Cave - estimated 3 years post fire
11th Apr. 1977	Cliff Spackman Reserve burnt out by wildfire	JELSS affected.	Numerous photographs and records
22nd Nov. 1977	Controlled burn & wildfire on Locn. 234	JELSS not affected, Cresswell Rd karst possibly affected.	CALM microfiche
4th Nov. 1979	Wildfire in southeast part Cliff Spackman Reserve, to southeast corner Locn. 4174	Lower southeast section JELSS (Easter Cave) affected.	CALM microfiche
Spring 1985	Wildfire Locn. 1497	JELSS not affected.	CALM microfiche
Spring 1986	Wildfire in west part Cliff Spackman Reserve near Deepdene Cave	JELSS not affected.	CALM microfiche
Spring 1987	Prescribed burn Cliff Spackman Reserve	Jewel Cave location not burnt, part JELSS affected ?	CALM microfiche

NOTES

CALM Microfiche records for the area south of Hamelin Bay Rd are non-existent prior to the mid 1970's.

A number of fires have occurred within a 2 km radius of Jewel Cave which have not directly impinged upon the karst.

Appendix 17. *Jewel Cave calcarenite - Thermoluminescence (TL) data. Specific activity measured by calibrated thick source alpha counting over a 42 mm scintillation screen, assuming secular equilibrium for U and Th decay chains. Uncertainty levels 1 sd. Uncertainty levels 1 sd. TL dating was undertaken by David M. Price, Research Fellow , School of Geosciences - University of Wollongong.*

Specimen No.	Reference	Plateau Region (°C)	Analysis Temp. (°C)	K Content (% by AES)	Rb Content (ppm assumed)	Moisture Content (% by weight)	Specific Activity (Bq/kg U+Th)	Cosmic Contribution (µGy/yr assumed)	Annual Radiation Dose (µGy/yr)	TL Age (ka)
W2967	Jewel Cave Calcarenite	300-500	375	0.110+/-0.005	50+/-25	9.1+/-3	5.8+/-0.2	15+/-5	237+/-8	>781+/-57

The final depositional age >781+/-57 ka is in fact very close, if not at, the point of TL saturation (David Price pers. comm.2000). At this point there is no, or very little, increase in TL with added irradiation. It therefore becomes difficult to accurately fit the mean natural TL value to the regenerated TL growth curve in order to accurately determine the sample palaeodose level. The age indicated is also extremely vulnerable to any change in the radiation flux level as this is extremely low (237 µgrays/year). Any small change in any one of the contributors to this may therefore have a considerable affect upon the age value determined. Hence accurate knowledge of the cosmic radiation level at depth becomes an important consideration.

The elevation of the sample site was estimated to be 25 m (+/- 1 m) above Australian Height Datum (AHD), whilst the present land surface directly above the site is at 56 m (+/- 1 m) AHD. Allowing for 1 m air cavity between the cave passage ceiling and the sample site, the depth of deposit above the sample was about 30 m. There may also exist other unkown karst cavities within the limestone. Clearly the depth of deposit has not remained constant during the entire post-depositional period, as evidenced by the overlying strata of aeolian deposits separated by paleosol horizons - the marine deposit is capped by a palaeosol then overlain by an aeolian deposit with another palaeosol below the upper aeolian deposit with caprock and surface soil. Thus the depth of deposit has been built up gradually with the time spans for each episode remaining unknown, whilst deflation of the overlying strata may have subsequently reduced the depth of deposit. Accordingly, the TL age estimation was based on a half depth of 15 m as far as the average cosmic contribution since deposition is concerned.

APPENDIX 18. *Results for Uranium series dating of subaquatic dog tooth spar growth overlying subaerially formed stalactite in the Gondolin, and submerged stalagmite from Lake Nimbus. All data corrected for detrital contributions using (230/230) det. = 0.29 ±0.04 and (234/232) det. = 0.0004.±0.0041 estimated from measurements made in Devil's Lair, Tight Entrance, Mammoth Cave, Kudjal Yolgah. Analysis by Dr Linda Ayliffe (Department of Geology & Geophysics, University of Utah).*

Sample	*U (ppm)*	$(230/238)_{act}$	±	$d^{234}U_{(t)}$	±	$d^{234}U_{(initial)}$	±	$(230/232)_{act}$	±	***Age (ka)***	± *(Ab)*
Gondolin spar (inner layer)	0.08	0.0548	0.0004	364.90	6.21	369.53	6.29	12.69	0.09	**4.45**	0.04
Inner layer (corrected)		0.0536	0.0007	364.90	17.19	369.42	17.40			**4.35**	0.08
Gondolin spar (outer layer)	0.09	0.0310	0.0003	479.58	6.59	482.72	6.63	4.86	0.05	**2.30**	0.02
Outer layer (corrected)		0.0292	0.0006	479.58	26.21	482.53	26.37			**2.16**	0.06
Gondolin Stalactite	0.11	0.8837	0.0032	-44.65	2.31	-105.67	6.03	195.13	1.24	**303.97**	8.91
Nimbus stalagmite (top)	0.04	0.1363	0.0013	145.47	5.60	151.25	5.83	7.13	0.07	**13.74**	0.17
Top (corrected)		0.1307	0.0023	145.47	19.27	150.99	20.00			**13.15**	0.35
Nimbus stalagmite (base)	0.10	0.1149	0.0007	148.84	5.28	153.74	5.45	26.82	0.16	**11.43**	0.12
Base (corrected)		0.1136	0.0012	148.84	13.14	153.68	13.56			**11.30**	0.20

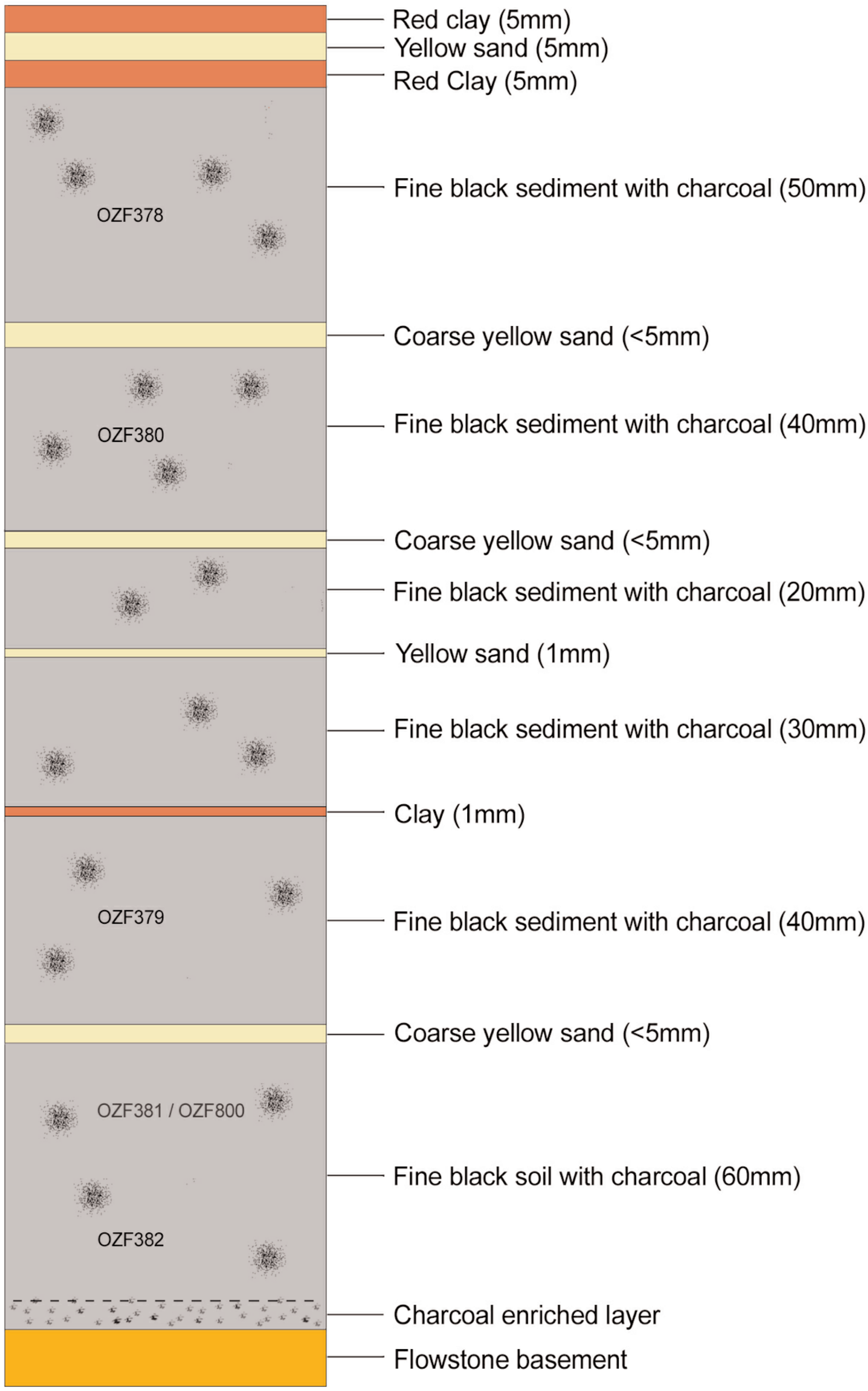
Appendix 19. *Results for uranium series dating of speleothems in Jewel Cave. Analysis by Dr Malcom McCulloch (Research School of Earth Sciences, Australian National University).*

Sample	*DATE*	*Sample wt*	*Delta 234U*	*±Delta 234U*	*U ppm*	*232Th ppb*	*230Th ppt*	*Activity 230Th/232Th*	***Age (y)***	*±Age (y)*	*Initial Delta 234U*	*±Initial Delta 234U*
Dome stalactite (inner)	28-Nov-01	3.72	47.21	2.73	0.0648	0.943	0.722	142	**114,880**	8,150	65.4	3.9
Dome stalactite (outer)	28-Nov-01	4.45	160.98	7.88	0.0902	0.218	0.208	159	**14,165**	1,314	167.6	8.1
Tunnel spar	28-Nov-01	3.94	229.00	1.79	0.0716	2.01	0.0148	1.361	**1,066**	159	229.7	1.7

NOTES

All samples were processed initially using the specific ion exchange resin TRU spec to collect Th and U together, followed by a micro-column anion exchange resin (AG-1) separation of U and Th. U separated fractions ran more or less as well as expected on the TRITON mass spectrometer, but the Th runs were disappointing, suggesting a poor Th yield.
235Yield is data where SEM 235U is used to calibrate SEM yield, SEM is used for 234U and FAR for 233U, 235U and 238U in all other calculations.

Appendix 20. *Stratigraphy of sediments in The Dome, Jewel Cave. OZF numbers refer to ANSTO radiocarbon dated samples.*



Appendix 21. *Radiocarbon age determinations of strata in Jewel, Easter and Moondyne Caves. Analysis by Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights, Sydney. Analysis used ABOX method. Strata are grouped according to types described in text. Includes highstand elevation (metres AHD) of dated palaeo water level stratum / horizon, and CaveWorks (CW) and ANSTO sample reference number.*

Strata group	*Stratum name*	*Description*	*Interpretation*	*Elevation (m AHD)*	[1]*CW No.*	[2]*ANSTO No.*	*Conventional ^{14}C Age* (*yrs BP*)	*+/- 1sd error*	*Notes*
Brown / black coating	*Tricosurus vulpecula* skeleton	Articulated skeleton in Jewel Casket	Overlies brown coatings	Ca. 24.5	RC4	OZF 377	**335**	**40**	*Calibrated age range 1500 - 1616 AD*
	Jewel youngest brown coating	Brown subaqueous deposit, younger than other brown coatings	Palaeo water level, subaqueous precipitation of brown material including organics	< 24.6	RC24	OZF 806	**5,989**	**45**	Carbon date unreliable, overlies other brown coatings, and spar unit with U-Th age of 1.1 ka.
	Jewel lower brown coating	Brown subaqueous deposit, younger than upper brown coating	Palaeo water level, subaqueous precipitation of brown material including organics	25.15 – 25.21	RC22	OZF 803	**3,372**	**79**	Same unit as OZF389, date OK
					RC18	OZF 389	**15,600**	**120**	Same unit as OZF803, date unreliable

Appendix 21. *Continued.*

Brown / black coating	Jewel upper brown coating	Brown subaqueous deposit, older than lower brown coating	Palaeo water level, subaqueous precipitation of brown material including organics	25.88 +/-	RC23	OZF 802U1	**2,064**	**50**	Repeat of OZF387, ABOX method + extraction of humics with NaOH, date unreliable
					RC23	OZF 802U2	**4,312**	**55**	Repeat of OZF387, ABOX method, date OK
					RC16	OZF 387	**5,460**	**140**	Date OK
	Macropus fuliginous skeleton	Articulated skeletons near Lake Chamber	Underlies brown coatings, overlies red clay and black coating	< 25.1	RC4	OZF 377	No collagen extracted, no date obtained		
	Thylacinus cynocephalus skeleton			25.1	RC17	OZF 388			
	Black coating	Black, powdery subaqueous deposit	Palaeo water level, subaqueous precipitation of black material including organics	26.47 – 26.63	RC19	OZF 390	**8,930**	**160**	cf. OZF804, date OK
					RC21	OZF 804	**9,799**	**73**	Repeat of OZF390, date OK

Appendix 21. *Continued.*

Flood strandlines	Jewel lower strandline (A-upper)	Humic flood deposit, thin band	fire-flood event	26.99	RC3	OZF 384	**16,990**	**100**	Upper of twin thin bands ca. 140 mm apart at The Dome (combined sample date); height and age range near lower strandline in Easter
	Jewel lower strandlines (B-lower)	Humic flood deposit, thin band	fire-flood event	26.86	RC3	OZF 384	**16,990**	**100**	Lower of twin thin bands ca. 140 mm apart at The Dome (combined sample date); height and age range near lower strandline in Easter
	Jewel upper strandline	Calcite overlying humic flood deposit	Subaerial speleothem growth	27.78 – 27.93	USD01 (outer)		[3]**14.165 ka**	**1.314 ka**	Uranium-series age (Eberhard, McCulloch, this study)
	Jewel upper strandline	Humic flood deposit, 150 mm thick band	fire-flood event		RC2b	OZF 383	**25,900**	**300**	Prominent humic deposit at The Dome; height range near upper strandline in Easter and Moondyne, but ages do not correlate
	Jewel upper strandline	Calcite underlying humic flood deposit	Subaerial speleothem growth		USD01 (inner)		[3]**114.880 ka**	**8.150 ka**	Uranium-series age (Eberhard, McCulloch, this study)
	Easter lower strandline (A-upper)	Humic flood deposit, thin band	fire-flood event	26.83	RC15	OZF 386	**15,180**	**120**	Upper of twin thin bands 260 mm apart at Y Junction; height and age range near lower strandline in Jewel
	Easter lower strandline (B-lower)	Humic flood deposit, thin band	fire-flood event	26.58					Lower of twin thin bands 260 mm apart at Y Junction; height and age range near lower strandline in Jewel

Appendix 21. *Continued.*

	Easter upper strandline	Humic flood deposits, scattered charcoal	fire-flood event	27.59 – 28.24	RC12	OZF 385	**18,310**	**80**	Deposits sampled over 650 mm vertical range; height range near upper strandline in Jewel and Moondyne, but ages do not correlate
	Moondyne upper strandline	Humic flood deposit, thick band	fire-flood event	27.8 – 28.4	RC11	OZF 805	**35,507**	**423**	Prominent humic deposit > 1000 mm thick at The Dig; height range near upper strandline in Easter and Jewel, but ages do not correlate
Dome sediments	Red clay - upper unit	Clay unit 5mm thick	3rd low energy fluvial deposition event	Ca. 25.55 – 25.78					
	Yellow sand layer 4	Coarse yellow sand 5mm thick	Internal fallout from cave ceiling						
	Red clay	Clay unit 5mm thick	2nd low energy fluvial deposition event						
	Black sediment unit 6	Black sediment unit 50mm thick with charcoal	6th fire-flood event		RC6	OZF 378	**33,000**	**300**	Date OK
	Yellow sand unit 4	Coarse yellow sand 5mm thick	Internal fallout from cave ceiling						
	Black sediment unit 5	Black sediment unit 40mm thick with charcoal	5th fire-flood event		RC7	OZF 380	**32,750**	**300**	Date OK
	Yellow sand unit 3	Coarse yellow sand 5mm thick	Internal fallout from cave ceiling						
	Black sediment unit 4	Black sediment unit 20mm thick with charcoal	4th fire-flood event						
	Yellow sand unit 2	Coarse yellow sand 1mm thick	Internal fallout from cave ceiling						

Appendix 21. *Continued.*

	Black sediment unit 3	Black sediment unit 30mm thick with charcoal	3rd fire-flood event						
	Red clay unit 1	Red clay unit 1mm thick	1st low energy fluvial deposition event						
	Black sediment unit 2	Black sediment unit 40mm thick with charcoal	2nd fire-flood event		RC8	OZF379	**33,350**	**400**	Date OK
	Yellow sand unit 1	Coarse yellow sand 5mm thick	Internal fallout from cave ceiling						
	Black sediment unit 1	Black sediment unit 60mm thick with charcoal (lower layers sampled)	1st fire-flood event		RC1a rpt	OZF 800	**33,668**	**477**	Date OK, Repeat of OZF381
					RC1a	OZF 381	**40,700**	**600**	Date unreliable
					RC1b	OZF 382	**35,400**	**400**	Date OK
	Flowstone base	Dome sediments overlie this unit	Subaerial calcite deposit						Age not known

Notes:

[1] Caveworks (CW) sample number

[2] Australian Nuclear Science and Technology Organisation (ANSTO) Lucas Heights laboratory sample number

[3] Uranium-series age 10^3 years (ka) BP (Eberhard & McCulloch, this study)

Appendix 22.
Perthiidae from Jewel-Easter-Labyrinth Caves examined by Dr John Bradbury (amphipod taxonomist), Adelaide, May 2002.

A - Perthiidae: nominally *Perthia acutitelson*

Specimens from Leeuwin/Naturaliste region include species of *Perthia* among the following Caveworks samples: CW 00; 015, 021, 175, 101, 103, 006, 085, 094, 099, 001, 002, 097, 091, 092, 095, 149, 077, 089, 088, 096, 150, 100, 115, 104, 076, 108, 052, 084, 176, 037, 050.

Collections of *Perthia* were examined first to determine whether specimens with heavily pigmented eyes are actually *P. acutitelson*, and second to determine whether there were significant differences between those and specimens displaying weak eye pigmentation.

The description of *Perthia acutitelson* (Williams and Barnard 1988) is of females only, whilst the majority of specimens in these samples are male. Initial examination therefore involved dissection of a mature female from Jewel Cave, and comparison with the described type of P. acutitelson.

1. Mature female, specimen CW00100, from Jewel Cave, site Flat Roof 2, with distinct, heavy eye pigmentation was dissected for the comparison with characters of the Type:

Non ovigerous female, length 14mm. well developed oostegites. Fully dissected and temporarily mounted under cover slips in glycerol (4 slides). This specimen was remarkably like paratype 's' described by Williams and Barnard (1988), even to the numbers of setae present on many articles.

Differences observed:
L. Mandible: palp article 3 setae = A2B0C0D(27+)E4 vs A3B0C0DmanyE4; (Molar - broken - not seen to bear 3 penicillate hooked brushy basal setae as in the paratype). R. Mandible: setae of palp article 3 A1B0C0D39E4 vs A2B0C0DmanyE4. Second maxilla: outer plate, outer margin with 3 large setae - vs 5. Maxilliped: palp dactyl body inner edge with 8 spinules - vs 7; inner plate inner edge with 3 thick spines on the left side - vs 2, and 3 thinner spines apically on both sides - vs 2; 1 apicomedial strong seta only - vs 1 apicomedial small spine, 2 medial plumose setae, 2 ventrofacial setal spines; the L. outer plate (R damaged) bearing 3 long, naked apical setae, 1 mid medial and 1 mediodistal strong setae, 2 basal to mid medial setae and 1 subdistal long seta - vs 4 apicolateral setal spines, 8 long sharp medial spines plus 1 thin slightly submarginal seta. First Gnathopod: coxal plate with 1 anteroventral seta and 3 postventral setae - vs 3 setae apically. Second gnathopod: coxal plate with 5 postventral setae - vs 4. Pereopods: coxa 3 with 5 postventral and 1 anteroventral setae - vs 4 total; coxa 4 with 6 posterior setules - vs 10. Epimera: E 1-3 ventral spine formula 2-9-7 - vs 2-6-1. Pleopods: retinacula accessories 3-2-1 vs 2-2-2. Third Uropod: outer ramus proximal article with 4 transverse lateral spine rows - vs 6. Telson: cleft 60% - vs 80%; lobe apices with L 2 long and 2 shorter spines, R 4 long and 3 shorter spines in transverse rows - vs 3 each, and lobes with 3 dorsal sets of spines L 1-1-1, R 1-1-2 - vs 2 sets of 2 and 3 spines each.

All other characters were as in the paratype 's': these differences are not indicative of a species other than paratype *P .acutitelson*. The only difference of any significance is the 60% cleft of the telson rather than 80% as in the type, which is insufficient to distinguish separate species status.

2. Seven male specimens were examined for differences:
CW00001 - male, 11mm; fully dissected, temporarily mounted under cover slips in glycerol (4 slides). Dense eye pigment.
CW00006 - male 10mm; partially dissected, temporarily mounted under cover slips in glycerol (4 slides). Dense eye pigment.
CW00085 - male 11mm; partially dissected, temporarily mounted under cover slips in glycerol (4 slides). Dense eye pigment.
CW00077 - male, 8mm; fully dissected, temporarily mounted under cover slips in glycerol (4 slides). Reduced eye pigment.
CW00088 - male 12mm; partially dissected, temporarily mounted under cover slips in glycerol (4 slides). Reduced eye pigment.
CW00089 - male 13mm; partially dissected, temporarily mounted under cover slips in glycerol (4 slides). Reduced eye pigment.
CW00096 - male 11mm; partially dissected, temporarily mounted under cover slips in glycerol (4 slides). Reduced eye pigment.

Comparisons between the male specimens are shown in the table following.

The characters examined do not show any consistent differences which would indicate a specific difference between the two groups; rather, there is significant overlap of character ranges in the majority of cases, and remarkable similarity between the two.

Appendix 22. *Continued.*
Perthia sp. characters examined by Dr John Bradbury (amphipod taxonomist), Adelaide, May 2002.

CHARACTER	CW00001	CW00006	CW00085	CW00077	CW00088	CW00089	CW00096
	fully dissected	partly dissected	partly dissected	fully dissected	partly dissected	partly dissected	partly dissected
Male - size	11mm	10mm	11mm	8mm	12mm	13mm	11mm
Eye pigment	strong	strong	strong	diffuse	diffuse	diffuse	diffuse
A2 calceoli arts	1-7 of 13	1-7 of 12	1-5 of 11	2-6 of 11	2-7 of 12	2-7 of 11	1-7 of 12
L Mandible Palp art3 setae	A1D27E5			A1D23E5			
L Mandible palp art2 setae	8			7			
L Mandible acc. blades	3 + 3			3 + 3			
R Mandible Palp art3 setae	A1D24+3E4			A1D24E4			
R Mandible palp art2 setae	8			7			
R Mandible acc. blades	2 + 3			2 + 2			
Second Maxilla OP lat seta	2 + 1 + 11			2 + 1 + 9			
Maxilliped Palp art3 setae	13 facial			11 facial			
Maxilliped Palp Dactyl	7 setules			9 setules			
Maxilliped OP setae	4 - 2 - 3			4 - 2 - 2			
Gnathopod 1 Carpus lobe	anterior setae 2 - 1 - 2			anterior setae 1 - 2 - 2			
Gnathopod 1 Carpus lobe	apical/subapical setae 8			apical/subapical setae 5			
Gnathopod 1 Propodus arms	2-3-4-5 (med.lat.acc.band)	2-3-4-5	2-3-3-(4)	2-3-4-5	2-4-3-5	2-3-2-4	2-4-3-4
Gnathopod 2 Propodus arms	2-3-6-5 (med.lat.acc.band)	2-4-6-4	2-4-6-4	2-3-6-4	2-5-4-4	2-4-6-4	2-3-5-4
Coxa 1 setae	1-1-4	1-0-3	1-0-3	1-1-3	1-0-3	1-0-3	1-0-3
Coxa 2 setae	(4)	1-0-4	1-0-4	(4)	1-0-3	1-0-4	1-0-4
Coxa 3 setae	1-0-7	1-0-3	1-0-2	1-0-6	1-0-3	1-0-3	1-0-3
Coxa 4 setae	1-0-7	1-0-4	1-0-4	1-0-6	1-0-7	1-0-0	1-0-8
Pereopod 3 dactyl spinules	4	3	3	3	4	4	4
Pereopod 4 dactyl spinules	4	4	3	3	4	3	3
Pereopod 5 dactyl spinules	6	5	4	4	5	6	5
Pereopod 6 dactyl spinules	8	8	6	6	7	9	8
Pereopod 7 dactyl spinules	8	7	6	6	8	7	7
Epimera ventral setae	2 - 8 - 4			2 - 7 - 4			
Pleonite 4 setae	4 + 2			5 + 2			
Pleopod 1	2+1 retinac & access	3+1	2+2	2+1	2+2		2+1
Pleopod 2	2+2 retinac & access	3+1	2+2	2+1	(2)+1		2+2
Pleopod 3	2+1 retinac & access	2+1	2+1	2+1	2+1		2+1
Pleopod articles of rami	23,20 - 22,18 - 20,17	20,23 - 14,21 - 14,18	18,22 - 17,21 - 15,18	21,17 - 20,16 - 17,15	23,24 - 20,24 - 18,21		21,24 - 19,23 - 17,20
Uropod 1 ped vs inn. ramus	1.3x	1.5x	1.4x	1.5x	1.5x	1.3x	1.4x
Uropod 1 ped. setae	4+1 : 5+1 lat apic med apic	4+1 : 3+1	4+1 : 3+1	8+2 : 2+2	5+1 : 5+1	6+1 : 4+-	5+1 : 4+1
Uropod 1 outer ramus setae	5-4-(4) lat med apic	6-0-(4)	4-4-(4)	4-4-5	5-1-(4)	5-7-5	5-4-5
Uropod 1 inner ramus setae	3-5-5 lat med apic	3-10-4	2-4-4	2-4-5	2-5-(4)	3-10-5	1-5-5
Uropod 2 ped vs	1.0x	1.3x	1.2x	1.2x	1.2x	1.3x	1.0x

Appendix 22. *Continued.*

Uropod 2 ped vs inn.ramus	1.0x	1.3x	1.2x	1.2x	1.2x	1.3x	1.0x
Uropod 2 ped. setae	2+1 : 3+1 lat apic med apic	2+1 : 4+1	2+1 : 1+1	2+1 : 3+1	2+1 : 2+1	3+1 : 3+1	2+1 : 3+1
Uropod 2 outer ramus setae	3-3-5 lat med apic	3-4-5	3-0-4	3-2-(4)	3-2-(4)	4-6-5	3-2-5
Uropod 2 inner ramus setae	3-4-5 lat med apic	5-3-5	2-3-4	2-3-5	3-4-5	3-6-5	2-4-5
Uropod 3 ped vs out.ramus	0.6x	0.6x	0.7x	0.7x	0.6x	0.6x	-
Uropod 3 ped. setae	2+2 : 2+1 lat apic med apic	1+4 : 1+1	2+4 : 2+1	2+4 : 2+1	2+4 : 2+1	0+2 : (2)+4	(2)+6 : (2)+1
Uropod 3 outer ramus set. art. 1	4 lateral setal bands	4	4	4	4	4	4
Uropod 3 outer ramus set. art. 1	4 apicolateral setae	4	3	3	3	2	3
Uropod 3 outer ramus set. art. 1	10 plumose med setae	10	9	8	11	8	9
Uropod 3 outer ramus set. art. 1	adjacent plumose 8-10 accessory distal robust setae	7-10	8-9	7-8	8-11	6-8	6-9
Uropod 3 outer ramus set. art. 1	2 apicomedial setae	3	3	3	4	2	3
Uropod 3 outer ramus set. art. 2	3 apical weak setae	2	2	3	2	3	2
Uropod 3 inner ramus setae	12 plumose med.setae	13	8	8	13	0	1
Uropod 3 inner ramus setae	adjacent plumose 12 accessory distal robust setae	nil	nil	nil	12-13	at M0.8, 0.9	at M0.9
Uropod 3 inner ramus	8 plumose lat.setae	7	5	4	6	12	11
Uropod 3 inner ramus	2 strong apical setae	2	2	2	2	1	2
Uropod 3 inner ramus	3 plumo. apical setae	3	2	1	2	3	2
Telson cleft %	70	70	70	75	70	70	75
Telson apical setae; L & R	3+2 : 3+2 lge + small	3+2 : 4+1	3+2 : 2+2	4+1 : 3+1	4+1 : 3+3	4+0 : 4+0	3+2 : 3+3
Telson dorsal setae; L & R	0-1-1 : 0-1-1	0-1-1 : 1-1-1	1-1-1 : 0-1-1	0-2-1 : 1-2-1	1-1-1 : 1-1-1	0-1-1 : 1-1-1	0-1-2 : 0-1-2

Appendix 23.
Uroctena sp. from Jewel-Easter-Labyrinth Caves examined by Dr John Bradbury (amphipod taxonomist), Adelaide, May 2002.

B. *Uroctena* sp.

Caveworks specimens CW 00; 090, 005, 093, 098, 010, 151,CW 00; 083, 082, 079, 116, CW 00 078 included species of the genus Uroctena. At least one new species is represented: differences were observed between the specimens, leading to the question of exactly how many new species are represented. Male specimens from the three caves; Easter, Jewel, and Labyrinth are compared.

Comparisons between the male specimens are shown in the table following.

Minor differences only occur between specimens from the three sites - one species only is present.

CHARACTER	CW00005	CW00116	CW00078
Male - size	4mm	5mm	3.5mm
Antenna 1 - aesthetascs	present	present	present
Antenna 1 accessory flagellum numbers of articles	4	5	4
Antenna 1 - peduncle: ratio of article lengths	53:42:23	53:46:21	53:42:21
Antenna 2 flagellum articles	9	13	9
Antenna 2 - peduncle: ratio of article lengths	20:21:11	20:52:50	20:51:47
Antenna 2 calceoli	absent	absent	absent
L. Mandible palp article 2 setae	1 mid medial, 3 sub-apic. oblique	1 mid medial, 4 sub-apic. oblique	0 mid medial, 2 sub-apic. oblique
L. Mandible palp article 3 setae	B1D14E3	B1D11E3	
L. Mandible incisor-lacinia teeth	5-4	5-4	5-4
L. Mandible rakers-interakers	4-3	3-4	4-3
R. Mandible palp article 2 setae	1 mid medial, 3 sub-apic. oblique	1 mid medial, 3 sub-apic. oblique	0 mid medial, 2 sub-apic. oblique
R. Mandible palp article 3 setae	B1D14E3	B1D10E3	B1D9E3
R. Mandible incisor-lacinia teeth	5-bifid	4-bifid	4-bifid
R. Mandible rakers-interakers	2-2	2-2	2-2
R. Mandible pappose seta	present, long	present, long	present, long
First Maxilla IP	linear-slightly triangular	ovato-triangular	ovato-triangular
First Maxilla OP serrate setae	10	10	10
First Maxilla L.palp no. of articles	2	2	2
First Maxilla L.palp2nd art. setae	7 long, naked	7 long, naked	8 long, naked
First Maxilla R.palp2nd art. setae	4 +1 +1 fused tooth setae+distlateral+distofacial	5+1+1	4+1+1
Second Maxilla	2+1 medial/oblique and distolateral setae	2+1	0+1
Maxilliped IP setae	1+3+7 subdist robust+apic robust+apic plumose	1+3+5	1+3+7

Appendix 23. *Continued.*

Gnathopod 1 coxa form	sub rect+apic.round+not tapered	sub rect+apic.round+not tapered	sub rect+apic.round+sl. tapered
Gnathopod 1 coxal setae	2-0-6 ant.vent-mid vent-post.vent.	1-5-0	1-0-3
Gnathopod 1 carpus post. setae	3 trans. bands	3 trans. bands	3 trans. bands
Gnathopod 1 propodus post. setae	3-3-2-1-2 (med.-lat.-band-recumb-nail base)	2-3-3-1-2	2-2-3-1-3
Gnathopd 2 size vs G1	larger	larger	larger
Gnathopod 2 carpus post. setae	4 trans. bands	4 trans. bands	3 trans. bands
Gnathopod 2 propodus	3-2-5-1-2 (med.-lat.-band-recumb-nail base)	3-2-6-1-2	3-2-5-1-2
P3 coxal setae	1-4-0 ant.vent-mid vent-post.vent	1-4-1	0-5-0
P3 dactyl setules	3	3	2
P4 dactyl setules	3	3	2
P5 dactyl setules	3	3	2
P6 dactyl setules	6	6	4
P7 dactyl setules	7	6	5
Pleopod 1	2-0 retinac & access	2-0	2-0
Pleopod 2	2-0 retinac & access	2-0	2-0
Pleopod 3	2-0 retinac & access	3-0	2-0
Pleopod articles of rami	7,8-7,8-5,6	9,7-8,7-7,6	6,5-6,5-5,5
Uropod 1 peduncle setae	3-1-3-2 med-apic.med.-lat-apic.lat.	0-2-4-2	1-2-2-3
Uropod 1 inner ramus setae	2-3-5 lat-med-apic	2-3-5	1-2-5
Uropod 1 outer ramus setae	2-1-5 lat-med-apic	2-2-5	1-1-4
Uropod 2 peduncle setae	1-1 enlarged-1-2 med-apic.med.-lat-apic.lat.	0-1 enlarged-2-0	1-1 enlarged-0-1
Uropod 2 inner ramus setae	1-4-5 lat-med-apic	2-1-4	0-3-5
Uropod 2 outer ramus setae	1-2-5 lat-med-apic	1-5-5	0-1-5
Uropod 3 peduncle setae total	11	15	9
Uropod 3 inner ramus length vs outer first	0.4	0.8	0.4
Telson cleft	75%	80%	75%