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Adapting to climate change: A risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels

Supporting Document 5: The impacts of declining groundwater levels on stygofauna communities in the Leeuwin Naturaliste Ridge Cave systems, Western Australia

Stacey Chilcott

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Authors

Stacey Chilcott
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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

Declaration

This thesis is the result of my own research and contains no material which has been accepted for the award of any other degree or diploma in any university, and to my best knowledge contains no material published or written material by any other person except where due reference has been made in the text.

Cover image: © Lake Cave, Margaret River region, Western Australia. Lindsay Hatcher, Augusta Margaret River Tourism Association

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Acknowledgements

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ABSTRACT

Groundwater Dependent Ecosystems (GDE's) are intrinsically connected to rainfall and groundwater for survival. Many ecosystems are becoming increasingly threatened due to the accelerating pressures of climate change and disturbances to connecting ecosystems. This thesis examined the structural changes of the Threatened Ecological Communities (TEC's) living within the GDE of Leeuwin Naturaliste Ridge (LNR) and Yanchep, Western Australia, as well as water quality of each of these cave systems. Multidimensional scaling, Simper analysis and BIOENV techniques were used to characterize and compare water quality, quantity and community structure. It was found that each cave contained a distinct faunal community contribution and that three caves of LNR were distinct in their ionic compositions. Factors that may have contributed to the biological and physical differentiation of these caves include the extensive evolutionary and hydrogeological development of each cave. Threats to cave systems were also identified, including climate change induced rainfall decline and anthropogenic stressors. Finally, management strategies for future conservation were suggested. Overall, reduced groundwater levels induced by rainfall decline seemed to have an important effect on cave TEC.

1. INTRODUCTION

1.1 Background

Groundwater systems around the world are the basis for life for an immense variety of subterranean organisms (Danielopol et al., 2003) many of which under the impact of groundwater decline as a result of climate change and anthropogenic stressors (Boulton et al., 2008, Eberhard 2004, Jasinska 1997). The majority of freshwater bodies are found in groundwaters (Barber et al., 1996) and are known to contain an undescribed diversity of globally significant, specialized, relictual, rare and endemic species (Clements et al., 2006, Eberhard 2004, Gibert et al., 2009, Griebler et al., 2010, Humphreys 1995), supporting some of the most biologically diverse communities on Earth (Hedin and Thomas 2010). As research advances and knowledge is gained of these systems, it is becoming apparent that subterranean habitats are often mismanaged as threats to subterranean ecosystems are revealed (Danielopol et al., 2003, Hinsby et al., 2008, Tilman 1996).

Aquatic subterranean ecology is a vastly understudied field with only few thorough investigations into the complex habitats and life histories of subterranean fauna. As a result, conservation is not considered and land management planning is often ill managed. Research into the consequences of land use and climate change is becoming increasingly important as the rate and magnitude of the climate change and anthropogenic effects become accelerated (Fig. 1) (Weins et al., 2009).

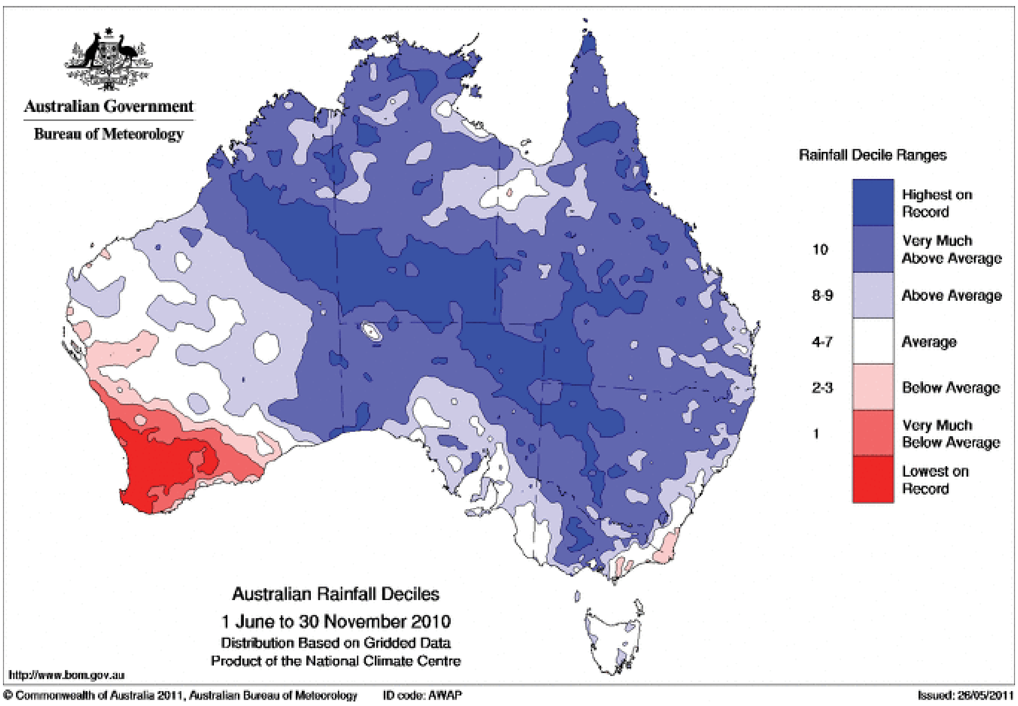

Figure 1: Southwest Western Australia's rainfall is the lowest recorded in history (Bureau of Meteorology, 2010).

1.1.1 *The cave environment*

Groundwater forms from upgradient recharge from rainfall (Schmidt and Hahn 2012) and can be found in many different forms in caves, supporting various ecosystems, each with distinct characteristics. Surface water found in permeable rock in a cave is called the "water-table". Interstitial waters occur between the sediment particles in the substratum and larger bodies of water occur in the cave as lakes, pools or streams (Bayly and Williams 1975). Caves can experience different levels of groundwater at different times, with some completely flooded with hydrologic connections between cave passages and subsystems (Fig.2) while others contain hardly any water at all and formed separate groundwater ecosystems over time. Taproots of groundwater dependent trees (phreatophytic vegetation) can penetrate the cave from surface forests above and provide distinct habitats that are known to represent a main food source for species (Howarth 1993, Jasinska et al., 1996). These ecosystems require the presence of groundwater for survival and are known to house aquatic subterranean ecosystems (stygofauna) with specialized evolutionary adaptations to subterranean life.

There are several terms that describe specialized types of stygofauna, each with varying level of dependence on groundwater and subterranean life. *Stygobites* are groundwater inhabitants that are entirely dependent on groundwater and are highly specialized to subterranean environments. *Stygophiles* are found in groundwater environments, but lack the adaptations to subterranean life that stygobites possess. As a result, many stygophilic species are also found in surface (epigean) environments. *Stygoxenes* are species that are rarely found in groundwater habitats and are usually

Figure 2: Hydrologically connected habitat, Riviera Maya, Mexico (Photo, Luis Leal).

there by accident. Consequently, they also lack any adaptation to subterranean life (Humphreys 1995). Despite the presence of tree roots, not all species rely on phreatophytic vegetation to survive. Some species have been found to fulfill their biological requirements from dissolved organic matter within the water column (Eberhard 2011, Eberhard 2002). These different kinds of specialists make up highly complex ecosystem structures in aquatic subterranean ecosystems. As a result, any changes to groundwater level that could be caused by rainfall decline or anthropogenic land use changes (urban developments, agriculture and tree plantations) can interrupt the hydrologic regime of aquatic subterranean ecosystems, intrinsically threatening the existence of entire aquatic subterranean ecosystems (Fig.3) (Eberhard 2002).

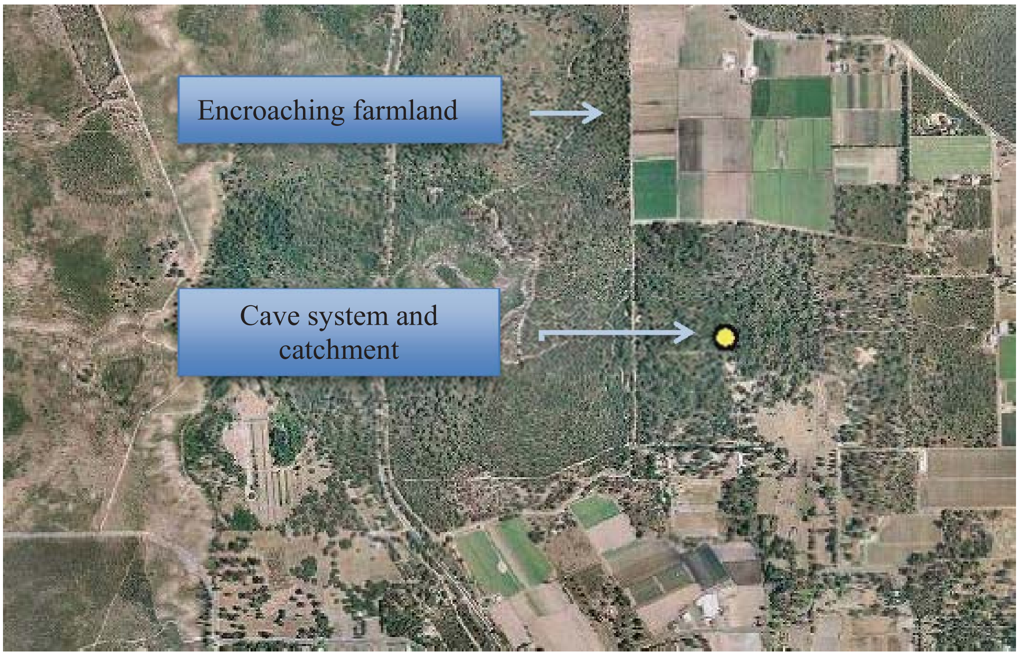

Figure 3: Aerial image of Yanchep cave systems. The small yellow circle symbolises the cave on Lot 51, with encroaching farmland to the north and southwest. Farmland can potentially cause deleterious effects on GDE's due to nutrient loading on the catchment, that runs into the aquifer (Knott et al., 2008) ***Aerial photographs reproduced by permission of Western Australian Land Information Authority, C/L28 –2013.***

1.1.2 Caves of Southwest Western Australia

Southwest Western Australia is known as a hotspot for stygofauna in groundwater dependent ecosystems (Barron et al., 2012), but these are severely imperiled by the projected effects of climate change, such as diminishing rainfall, and/or land use mismanagement (Eberhard 2002, Eberhard 2004, Jasinska 1997). Since 1975, a climate change induced rainfall decline in southwest Western Australia has limited the available groundwater supply (Danielopol et al., 2003, Skurray et al., 2011) to cave catchments. The situation in Leeuwin Naturaliste Ridge is so dire that after research efforts into the cave stygofauna began in 1993, several stygofauna communities became listed under the *Environmental Protection and Biodiversity Act (1999)* as Threatened Ecological Communities (TEC's) (Eberhard 2002).

All caves within Leeuwin Naturaliste Ridge and Yanchep National Park have contained or contain taproots of groundwater dependent vegetation (phreatophytic vegetation)

(Barron et al., 2012, Eberhard 2011, Eberhard 2005). The Karri (*Eucalyptus diversicolor*), Marri (*Corymbia calophylla*) forests and the peppermint trees (*Agonis flexuosa*) of the Leeuwin Naturalist Ridge provides a habitat for the majority of species living in the cave groundwater environments. The karri and peppermint species are known to produce root mats that once filled stream channels "from bank to bank" (Jasinska 1997). Migration and dispersal of species in Jewel Easter cave is mainly restricted to fissures and cracks for any macrofauna because of the size of their body, however smaller microfauna are able to live in tighter habitats such as "minor seepages, flows, and pools within water above the water table (vadoze zone) (Eberhard 2002). These physical characteristics of cave habitats strongly control the organization of each ecosystem (Eberhard 2002).

This thesis examines the impact of groundwater decline on stygofauna in the cave systems of Leeuwin Naturaliste Ridge, southwest Western Australia, that has occurred a result of climate change and anthropogenic stressors (Eberhard 2004) and will also analyse changes to groundwater physicochemistry and fauna of Yanchep caves to compare to those in Leeuwin Naturaliste Ridge. Many species in these caves are relic to Gondwana and endemic to particular caves (English et al., 2000). For example, *Uroctena n. sp* is only found in subsystems of Jewel-Easter cave (Fig.4). Although there are at least 100 caves located within the Leeuwin Naturaliste area, the four caves listed have been chosen as the focus of this thesis because these have been the main focus of past research and data collection.

Figure 4: *Uroctena n. sp*. is endemic to Jewel-Easter caves (Photo by Stefan Eberhard).

1.1.3 Thesis aims

This study will analyse impacts of climate change and other contributing factors on groundwater characteristics and changes to fauna over time in the Leeuwin Naturaliste Ridge karst area. This study will better inform conservation and management of drying GDE's and increase scholarly knowledge of subterranean ecology.

The questions addressed in this research are:

- How has the groundwater depth in the caves of Leeuwin Naturaliste Ridge changed over time?
- Has the groundwater quality in caves of Leeuwin Naturaliste Ridge changed over time?
- Has the faunal composition changed in each cave over time?
- Is there a relationship between changes to the diversity of fauna, water quality and water quantity? Are there species or communities that are tolerant of groundwater decline?
- How do the caves of Leeuwin Naturaliste Ridge compare to other caves in the southwest of Western Australia such as Yanchep caves in terms of changes to the groundwater environment and species diversity?

Addressing management considerations: To enable management of the observed changes, the main contributing factors to groundwater decline and change of community composition will also be identified.

This work also contributes to the risk assessment and decision framework for managing Groundwater Dependent Ecosystems (GDE) with declining groundwater levels, funded by the Department of Climate Change and Energy Efficiency via the National Climate Change Adaptation Research Facility (NCCARF). This thesis will highlight important factors regarding GDE's in cave environments of southwest Western Australia, including valuable information on water depth, water quality, faunal community assemblage and the relationship between these factors.

1.2 Study Sites

1.2.1 Leeuwin Naturaliste Ridge (LNR)

The Leeuwin Naturaliste Ridge is located between 33°31'S and 34°23'S latitude, and 114°59'E and 115°15'E longitude (Jasinska 1997). This karst ridge is located within the Leeuwin Naturaliste geographic region (Eberhard 2002, Jasinska 1997) stretching for approximately 90km between Cape Leeuwin and Cape Naturaliste with the Indian Ocean to the west, Geographe Bay to the north and the Southern Ocean to the south (Eberhard 2002). Jewel Easter karst system is located in the Augusta karst region, 7km kilometers north of Augusta township (Fig.5). It is also located between Cape Leeuwin and Turner Brook with a surface area of approximately 40km^2, 3.5km wide and 14km in length (Eberhard 2002). Jewel Cave and a large proportion of Easter Cave is classified as a Class A Reserve (Cliff Spackman Reserve) inside the Leeuwin-Naturaliste National Park. Augusta Margaret River Tourism Association (AMRTA) has been responsible for management of Jewel, Easter and other caves within the Jewel Cave precinct (located within the Warren Botanical District) (since 1961 (Eberhard 2002).

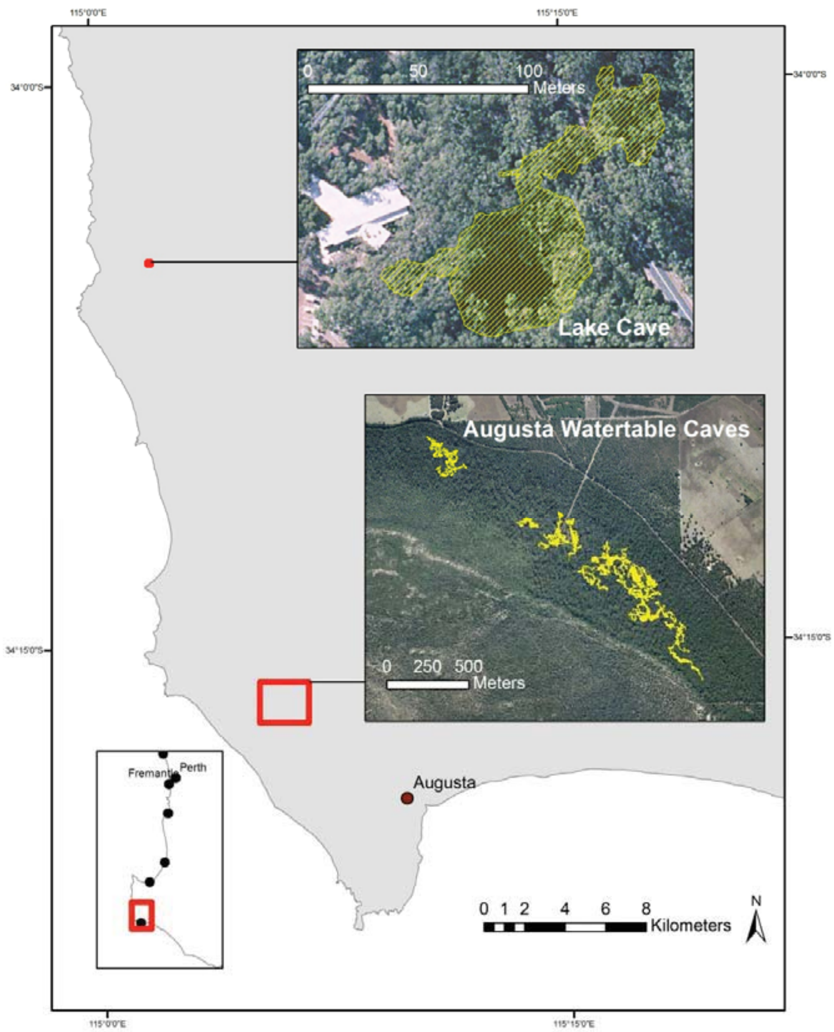

Figure 5: Leeuwin Naturaliste Ridge study sites of Lake Cave and Augusta Water Table Caves including Jewel, Easter and Labyrinth caves. Map of Lake Cave provided courtesy of Augusta Margaret River Tourism Association; Jewel Cave Karst System adapted from Eberhard (2004). Composite map courtesy, Simon Neville, 2012.

1.2.2 Climate

The climate of Leeuwin Naturaliste Ridge is Mediterranean with hot, dry summers and cool, mild winters (Eberhard 2002, Jasinska 1997). Temperature and rainfall data were used from Cape Leeuwin meteorological station as it is the closest station to Jewel Cave, sitting 11km south of the caves (Eberhard 2002). Average rainfall from within 5-year intervals indicated a decline over time from 930mm between 1958-1962 down to 772mm recorded between 2008-2012. Five year average temperatures in Cape Leeuwin showed an increase over time from 19.82° Celcius, between 1958-1962, to 20.5° Celcius, between 2008-2012 (Fig.6).

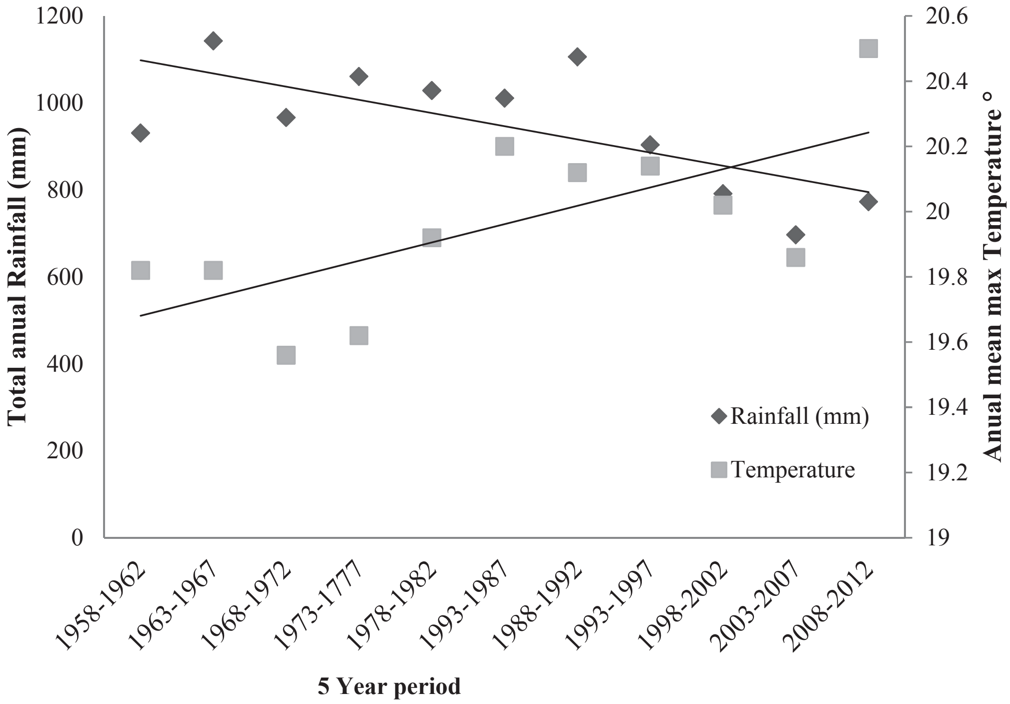

Figure 6: Five-year averages of rainfall at Cape Leeuwin between 1958-2012, plotted with five-year averages of temperature at Cape Leeuwin between 1958-2012 (Data Source, Bureau of Meteorology, 2012).

1.2.3 Geohydrology

The Leeuwin Naturaliste Ridge is an aeolian (windblown) limestone dune created in the Plio-Pleistocene and Holocene (Eberhard 2002). The Spearwood System contains the cave systems within the 'Tamala Limestone', 20km inland from the coast, of presumed mid-Pleistocene age (Jasinksa 1997).

Jewel, Easter and Labyrinth caves are subsystems of one hydrologically connected system of the Augusta Water Table Caves in the Leeuwin Naturaliste Ridge (Eberhard 2002), therefore, any associated groundwater information regarding depth and water quality is relevant to all cave subsystems. The system shall be from hereon referred to as Jewel Easter cave karst system unless otherwise individually stated.

Jewel Cave was first discovered in 1958 and was found with a chest deep lake (Eberhard 2002, Eberhard 2004, Jasinska 1997) and a water table height of approximately 24.3 m AHD (Australian Height Datum) (Eberhard 2004). By 1982, there was a general concern that the water level within the cave was gradually declining due to groundwater extraction from within the lake for the use of toilets above the cave. Despite the cessation of groundwater pumping shortly after this discovery, by 1987, the water level within the cave had dropped by more than a metre (Eberhard 2002). Anecdotal evidence suggests that Easter and Labyrinth caves also exhibited declining groundwater levels throughout this period (Eberhard 2002). From then on, contributing factors to the rapid groundwater decline were thought to come from changes to the catchment including reduced rainfall, groundwater extraction and tree plantations (Eberhard 2004) (Fig.9). At present, the groundwater level in Jewel cave has dropped to the lowest level since it was first recorded in 1958 (Eberhard 2004) (Figures 7-13). Jewel cave karst system is likely to be completely dry within 1-2 years, which will likely result in stygofauna extinctions (Department of Environment and Conservation 2008, Eberhard 2011, Skurray et al., 2011).

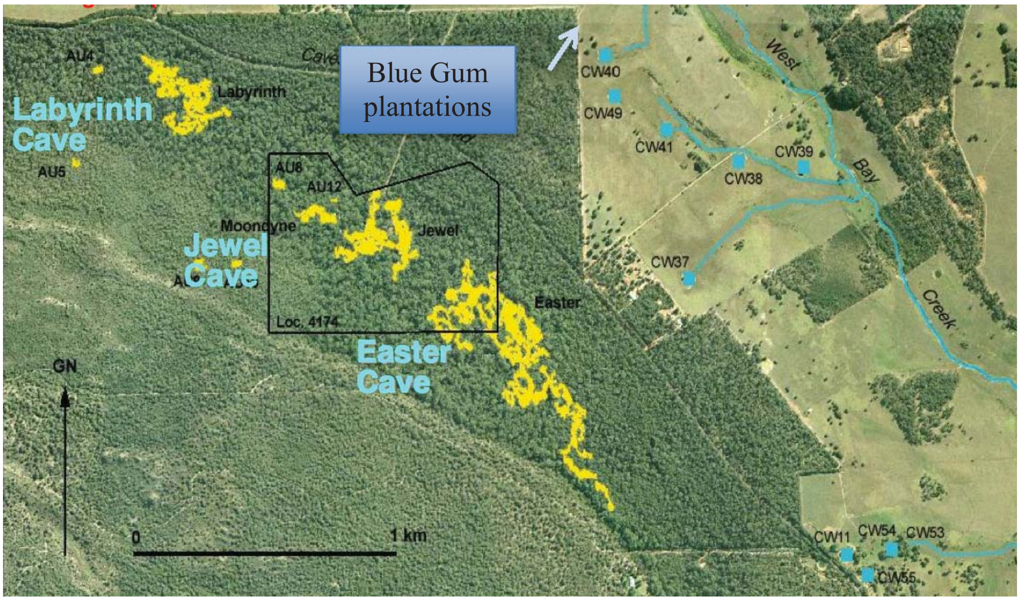

Figure 7: Leeuwin Naturaliste Ridge, the location of Jewel, Easter and Labyrinth subsystems of the Augusta Water Table Caves. ***Aerial photographs reproduced by permission of Western Australian Land Information Authority, C/L28 –2013.***

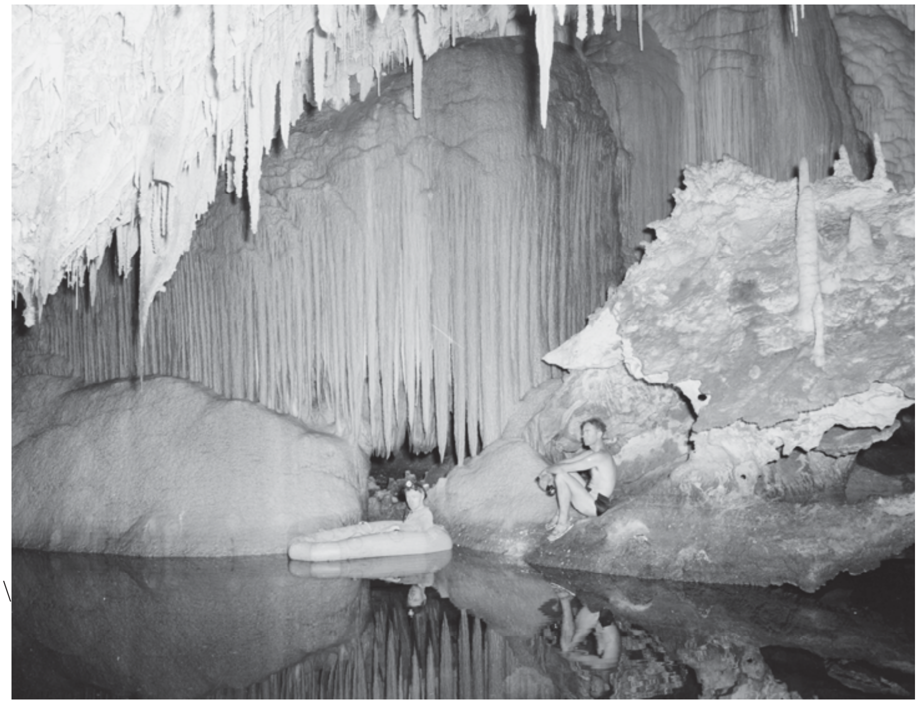

Figure 8: The Organ Pipes, Jewel Cave, 1958. Shows 'chest deep water' soon after the cave was first discovered (Photo Courtesy: *The Western Australian*).

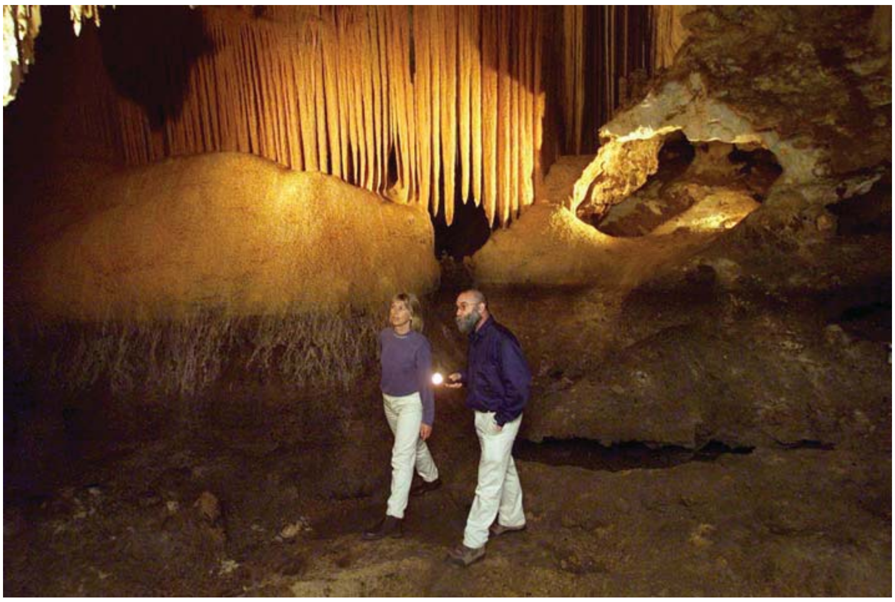

Figure 9: The Organ Pipes, Jewel Cave, 1998. Groundwater is no longer visible (Photo courtesy: *The Western Australian*).

Figure 10: Peter Bell in Easter Cave, indicating the 'hip depth' water level that was present in 1975.

Figure 11: Stefan Eberhard with Giulia Perina in Easter Cave indicating the depth of water in 1999.

Figure 12: "Tiptoe through the raftmites". Note the level of groundwater surrounding the raftmites, Bill Dodds and Beverley Clarke. Photo: Barry Hall, 1960 (Image courtesy: *The West Australian*).

Figure 13: Standing in the same location as Figure 12, groundwater completely absent from this photograph. Photo: Stefan Eberhard, July 2012.

1.2.4 Yanchep karst area

Yanchep National Park is located between 31°30'S to 31°35'S and 115°39'E to 115°43'E (Jasinska 1997) 20km east and inland from the Indian Ocean. Further information on each cave within Yanchep is not included as the main caves focused on in this thesis are in Leeuwin Naturaliste Ridge. Refer to (Jasinska 1997) for more information on each Yanchep cave.

1.2.5 Climate

The Climate in Yanchep is Mediterranean and is characterized by hot summer droughts (Dec-Feb) and cool winters where rains are abundant (June-Aug) (Jasinska 1997). Rainfall collected from the closest meteorological stations with the most comprehensive datasets of Gingin and Moondah Brook, located 20-25km northeast of Yanchep National Park. Gingin rainfall data carries through until 2002, where Moondah Brook rainfall data takes over. Both datasets were used to create a long-standing rainfall dataset as all other stations lacked continuity within their records. Figure 14 indicates that a drop in rainfall over time with data from Gingin averaging 810mm between 1964-1967 to an average of 540mm recorded between 2008-2012 at Moondah Brooke. Temperature data was obtained from Pearce as this site was also the closest with the most comprehensive datasets. Figure 14 indicates a warming average trend over time in 5 year intervals from 25.1° Celcius recorded between 1964-1967 increasing to an average of 25.85° Celcius in 2008-2012.

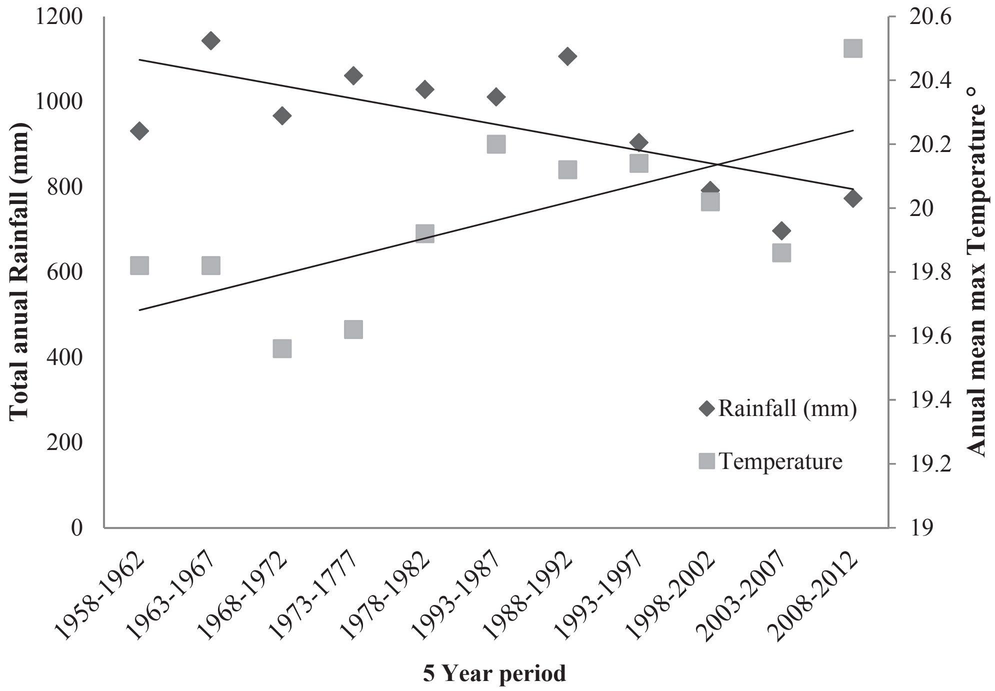

Figure 14: Five-year averages of rainfall in Gingin between 1958-2002 and in Moondah Brook between 2002-2012, plotted with five-year averages of temperature at Pearce between 1964-2012 (Data source, Bureau of Meteorology, 2012).

1.2.6 Geohydrology

Below Yanchep is an extensively unconfined aquifer known as the Gnangara Mound. The reservoir flows through an abundance of caves between the Tamala limestone and Bassendean Sands (Jasinska 1997). In 1997, when Edyta Jasinska undertook her PhD thesis on caves in Yanchep National Park and LNR, there was between 2-20cm depth of groundwater covering Cabaret Cave (Jasinska 1997), approximately 1-2cm depth of water in Carpark and between 5-10cm in Gilgie Cave. Twilight cave was on average 2-5cm deep and Boomerang (which was then titled “unnamed cave”), was at a mean of 2-5cm depth (Jasinska 1997). At present, Gilgie, Twilight, Spillway and Fridge Grotto are either unsafe or are not receiving any inflow of water and are completely dry (Knott et al., 2008).

Caves in the Yanchep National Park karst area, including Cabaret, Carpark, Gilgie, Boomerang, Twilight, Water and Orpheus Caves, as well as a cave located in close proximity to Yanchep National Park (referred to as Lot 51) are located 50km north of Perth and also display changes to groundwater level over time (Eberhard 2004) in correlation with the caves in Leeuwin Naturaliste Ridge. Data collected from these caves are used to display comparative changes in water quality and faunal composition.

2. METHODS

There are three main components of this project: 1) collation and integration of groundwater quality, and faunal assemblage data from previous surveys (Table 1) undertaken in LNR and Yanchep caves (Table 2); 2) Collection of groundwater quantity, quality and faunal assemblage data from three caves within the LNR (Jewel, Easter and Lake cave; 2012 field surveys); 3) Analysis of the previous and new survey data (Part I and 2) to identify changes in water quality chemistry (groundwater quality) over time in relation to groundwater decline, and compare such trends with changes in stygofauna composition in both LNR and Yanchep caves.

Table 1: Synopsis of data used in desktop analysis from caves across LNR and Yanchep. All data was collected between the years 1993-2012.

Threatened GDE name	Data sources
Jewel-Easter and Caves aquatic root mat community	Jasinska, E. J. 1997. Faunae of aquatic root mats in caves of south-western Australia: origins and ecology. University of Western Australia.
	Eberhard, S. M. 2004. Ecology and hydrology of a threatened groundwater-dependent ecosystem: the Jewel Cave karst system in Western Australia. Murdoch University.
Lake Cave Stygofauna Community	Jasinska, E. J. 1997. Faunae of aquatic root mats in caves of southwestern Australia: origins and ecology. University of Western Australia.
	Eberhard, S. M. 2004. Ecology and hydrology of a threatened groundwater-dependent ecosystem: the Jewel Cave karst system in Western Australia. Murdoch University.
	Subterranean Ecology Pty Ltd & Augusta Margaret River Tourism Association (2011) Lake Cave Eco-Hydrology Recovery Project - Progress Report No. 1. Report to Government of Western Australia Natural Resource Management Grant Scheme (No. 09075), April 2012. 29 pp. & appendices.
	Subterranean Ecology Pty Ltd & Augusta Margaret River Tourism Association (2011) Lake Cave Eco-Hydrology Recovery Project - Progress Report No. 2. Report to Government of Western Australia Natural Resource Management Grant Scheme (No. 09075), April 2012. 29 pp. & appendices.
	Subterranean Ecology Pty Ltd & Augusta Margaret River Tourism Association (2011) Lake Cave Eco-Hydrology Recovery Project - Progress Report No. 3. Report to Government of Western Australia Natural Resource Management Grant Scheme (No. 09075), April 2012. 29 pp. & appendices.

Threatened GDE name	Data sources
Yanchep Caves Stygofauna Communities	Knott, B., Storey, A.W. & Tang, D. 2008. Yanchep Cave streams and East Gnangara (Lexia) – Egerton Spring & Edgecombe Spring: Invertebrate Monitoring. Unpublished report prepared for the Department of Water by School of Animal Biology, the University of Western Australia.
	Jasinska, E. J. 1997. Faunae of aquatic root mats in caves of south-western Australia: origins and ecology. University of Western Australia

Table 2: Cave systems and subsystems located in LNR and Yanchep National Park.

Location	System	Subsystem
Yanchep National Park	Boomerang Cave	
	Cabaret Cave	
	Carpark Cave	
	Gilgie Cave	
	Lot 51 Cave	
	Mire Bowl Cave	
	Orpheus Cave	
	Spillway Cave	
	Twilight Cave	
	Groundwater Cave	
Leeuwin Naturaliste Ridge	Lake cave	
	Augusta Water Table Caves	Jewel Cave
	Augusta Water Table Caves	Easter Cave
	Augusta Water Table Caves	Labyrinth Cave

2.1 Collation and integration of past groundwater quality and faunal assemblages data from the LNR and the Yanchep caves

2.1.1 Water Quality data

Physicochemical data available for the LNR and the Yanchep caves include pH, temperature, dissolved oxygen, conductivity, major ions and nutrients (Table 3). Data originated from various theses, published and unpublished data/reports (For a synopsis of data sources, refer Table 1.) Collection methods and equipment differed between each study (Table 1); similarities and differences between methods are summarised in Table 4. Bores chosen to represent the physico-chemical properties of groundwater in Yanchep caves were not necessarily in close proximity to TEC's within the caves.

Table 3: Groundwater quality variables and their source of data.

		Data Source			
	Parameter	**Yanchep and Easter caves Jasinska (1997)**	**Jewel Cave Eberhard (2004)**	**Yanchep cave, Knott, Storey and Tang (2008)**	**Lake cave, AMRTA & Subterranean Ecology (2012)**
In Situ	pH	✓	✓	✓	✓
	E.C. (µS/cm)	✓	✓	✓	✓
	E.C.(mS/m)		✓		
	DO(%SAT)		✓		
	DO (mg/L)	✓		✓	
	Temp. °	✓	✓	✓	
Laboratory (mg/L)	Na^+	✓	✓	✓	✓
	Ca^{2+}	✓	✓	✓	✓
	Mg^{2+}	✓	✓	✓	✓
	K^+	✓	✓	✓	✓
	SO_4^{2-}	✓	✓	✓	✓
	NO3-	✓	✓	✓	
	P_SR			✓	
	HCO_3^-		✓		✓
	Cl^-		✓		✓
	Total N		✓		✓
	TH		✓		
	Total P		✓		✓
	CO_3^{-2}		✓		
	Sal PPT			✓	
	Sal TDS		✓		

Table 4: Physico-chemical sampling collection methods and equipment used for each data source from 1997-2012 (WTW= Wissenschaftlich-Technische-Werkstätten).

	Physico-chemical Variable	Jasinska (1997)	Eberhard (2004)	Knott, Storey, Tang (2008)	AMRTA & Subterranean Ecology (2012)
Timing	All	Between 1993-1996	Collected from December 1999.	Collected from October 2007	
Equipment Used	Dissolved Oxygen (D.O.)	Nester Model 602 Field Dissolved Oxygen Meter	WTW OXI 320	WTW water quality metres	TPS 90 FLMV multi-parameter water quality instrument.
	pH	LC80A TPS pH meter	WTW pH 320		
	Electrical conductivity	LC81 TPS conductivity meter	WTW LF320		
	Temperature	Mercury thermometer (± 0.05°C precision)	WTW metre		
Preservation Methods	All	Preserved, refrigerated water quality samples with $MnSO_4$ and KI-NaOH mixture	Refrigeration	Refrigeration	Refrigeration

2.1.2 Data gaps

There is substantial environmental physico-chemical data and fauna presence-absence data available for most of the caves leading up to 2007. However, after an assessment of cave safety conducted by the Department of Water (DoW), Twilight cave was unable to be entered because it was deemed unstable. Gilgie cave contained no water in the 2007 survey and was therefore not sampled. These caves are still included in the dataset because they provide physico-chemical data prior to 2007. It also should be noted that water quality/quantity measurements in Easter cave were limited due to unguaranteed access or high CO_2 levels in parts of the cave (Jasinska 1997).

2.1.3 Water Quantity data

Water quantity data for LNR was extracted from (Eberhard 2004) who used dated photographs taken within Jewel Cave by cavers from 1958 until the time of his study, then leveled them to the Australian Height Datum (AHD). Unfortunately, similar data for the Yanchep caves were not available thus not included in the analysis. Jewel Cave water level was sampled from the same location, to the nearest 1±mm and read from measuring staffs that have previously been placed in the groundwater pools. The water level measured in Jewel Cave is linked to the water level in Easter Cave. Anecdotal evidence and visual observations of water level change over time have also been provided by previous CaveWorks manager Peter Bell and current CaveWorks manager Lindsay Hatcher as well as a Stefan Eberhard (Subterranean Ecology). (See Appendix 1 for Jewel Cave sampling location). Lake Cave data was measured near Ruler 1, which remains in the groundwater pool, toward the back of Lake Cave (See Appendix 1 for a plan of Lake Cave sampling locations.)

It should be noted that there were less sampling locations per site over time. For the duration of Eberhard (2004), water levels were obtained from 3 different locations within Jewel Cave, 13 locations in Easter cave and 2 different sites in Labyrinth. By 2012, the amount of sampling locations had reduced to 1 in Jewel Cave, 3 in Easter Cave and Labyrinth Cave was not measured, as the cave is now dry.

2.1.4 Fauna data

Fauna samples were collected in caves of Leeuwin Naturaliste Ridge and Yanchep. Sampling techniques varied within individual cave habitats, between studies and across locations (Refer to Table 5 and 6; See Appendix 2 for a summary of preservatives used).

Table 5: Sampling methods undertaken in each study to collect stygofauna samples in various groundwater habitats. N.s = Not sampled.

Location and dates	**Sampling methods in various groundwater habitats**							
	Root mat	**Interstitial**	**Vadose**	**Lakes**	**Streams**	**Pools**	**Drift fauna**	**Macrofauna**
Easter and Yanchep caves. Live samples collected between1992-1996 (Jasinska 1997).	Samples of two non-adjacent handfuls of root mat. Root mats were kept in a bag with 0.5L of the cave water they were found in. At least double the volume of air than the amount of root mat was collected to reduce anoxia in the sample bags.	N.s.	N.s.	(see root mat)	See root mat	N.s.	N.s.	Collected by hand or with a strainer, or recorded in situ
Jewel and Lake Cave. 1999-2003 (Eberhard 2004).	(see streams/lakes/pools)	Karaman-Chappius method. (Refer to Eberhard (2004).	Collected with a cup or pipette, lifting and sieving water through plankton net. Buckets with mesh netting were also left under stalactites for weeks-months, checked periodically for taxa.	Sweep netting	Sweep netting	Sweep netting	Nets left for weeks to months, then collected for taxa	Collected opportunistically

Location and dates	Sampling methods in various groundwater habitats							
	Root mat	**Interstitial**	**Vadose**	**Lakes**	**Streams**	**Pools**	**Drift fauna**	**Macrofauna**
Yanchep Caves. Live samples collected in 2007 (Knott, Storey and Tang 2008)	Sweep netting gently over root mars	N.s.	N.s.	N.s.	N.s.	Sweep netting	N.s.	N.s.
Lake Cave. Live and preserved samples collected between 1999-2011 (AMRTA & Subterranean ecology 2012).	Fragments of wood were shaken over a bag to collect any stygofauna that may be living on them	Karaman-Chappius method (refer to Eberhard (2004).	Collected with a pipette, lifting and sieving water through plankton net. .	Sweep netting (See Fig.15)	Sweep netting (after agitating sediment)	N.s.	N.s.	N.s.

Table 6: Equipment used to sample and identify stygofauna within LNR and Yanchep cave systems for previous surveys between 1993-2012.

	Equipment used for sampling and identification		
Data source	**Sampling**	**Identification**	
	Nets	Microscope	Light source
Jasinska (1997)	In the laboratory, root mats were sieved through a 1000 µm, 90 µm and 45 µm mesh nets	Dissecting microscope (160x to 400x magnification)	(Not listed)
Eberhard (2004)	250 µm, 100-400 diameter mesh nets. Vadose water collected in cup, pipette or bucket.	Motic (SMZ-143) dissecting microscope (80x magnification)	Fibre optic Microlight 150 light source
Knott, Storey, Tang (2008)	70 µm mesh nets	Dissecting microscope	(Not listed)
Subterranean ecology & AMRTA (2012)	50 µm mesh nets	(Not listed)	(Not listed)

Figure 15: Giulia Perina sampling for fauna in Lemon Lake, Easter Cave, 2012 (Photo, Stefan Eberhard).

2.2 2012 Field survey: Water Quality, Quantity and Fauna sampling in LNR

A separate component of this project involved field surveys in Jewel Easter and Lake cave to collect stygofauna, groundwater quality and depth measurements. Water quality samples were analysed in situ and by Marine And Freshwater Research Lab (MAFRL) at Murdoch University. Fauna identification was undertaken by Giulia Perina at Subterranean Ecology. Several water physico-chemical parameters that had previously been recorded in cave systems were unable to be analysed in the 2012 survey due to budget constraints. However, the major ions that were most common across all previous studies were analysed. For details on water quality sampling methods and equipments used, see tables 7 and 8 and for a plan of sampling locations in Jewel Easter and Lake cave for this survey, see Appendix 1.

2.2.1 Jewel Cave

Jewel Cave was visited July 18, 2012 by Stefan Eberhard, Giulia Perina (Subterranean Ecology), Peter Bell, Lindsay Hatcher (AMRTA) and myself. Water quality and fauna samples were not taken on this field survey due to the lack of available water, restricted access and the potential for the few potential surviving groundwater dwelling populations to be contained within the remaining fragments of available groundwater. However, a small amount of drip/vadoze water found on a small plastic plate within the cave for another experiment was taken and analysed for fauna. Water depth was measured in Flat Roof 1 in Jewel Cave (Fig.16) to the nearest (1±mm) and read from measuring staffs that have previously been placed in the groundwater pools. A tape measure was used in areas where permanent water level equipment has been set in place (Fig.17). See tables 7 and 8 for equipment and methods.

2.2.2 Easter Cave

Easter Cave was visited July 19, 2012 by Stefan Eberhard, Giulia Perina (Subterranean Ecology), Peter Bell, Lindsay Hatcher (AMRTA) and myself. Water depth was measured and water quality and fauna samples were collected at three different sites in Easter Cave including Lemon Lake, White Room and Tiffany’s Lake. See tables 7 and 8 for equipment and methods used

2.2.3 Labyrinth Cave

Labyrinth cave was the only cave not to be sampled out of the Augusta Water Table Caves as the cave is now dry of groundwater.

2.2.4 Lake Cave

Lake cave was visited on March 4, 2012 by Giulia Perina (Subterranean Ecology), Andrew Green (AMRTA) and myself to sample water quality and fauna. Fauna and water quality samples were collected toward the back of the cave near Ruler 1, as was depth measurement. See tables 7 and 8 for equipment and methods.

Figure 16: Using a tape measure and steel ruler to measure groundwater depth in Flat Roof 1, Jewel Cave, July 2012. Photo by Stefan Eberhard.

Figure 17: Stefan Eberhard monitoring water depth in Tiffany's Lake 'C', Easter Cave, July 2012.

Table 7: Equipment used for sampling and identification in 2012 surveys in Jewel, Easter and Lake Cave.

Location, Dates and Sampler	Equipment used for sampling and identification			
	Sampling	Identification		Preservative
	Nets, pipes, plates	Microscope	Light source	
Easter Cave, July 2012, AMRTA & Subterranean Ecology	80mm diameter, 150 µm attached to a stick (about 500mm in length for extra access into the lake).	Dissecting microscope Leica M205C (10x ocular) and Compound Leica DM2500 (10x ocular)	Incorporated in microscopes	100% Ethanol
Jewel Cave, July 2012 AMRTA & Subterranean Ecology	No samples were taken with nets due to lack of water, however, a plate that had collected drips was taken for analysis	Dissecting microscope Leica M205C (10x ocular) and Compound Leica DM2500 (10x ocular)	Incorporated in microscopes	100% Ethanol
Lake Cave, March 2012, AMRTA & Subterranean Ecology	Karaman-Chappius method used 50 µm. For vadoze, a small pipe was used to take water from the "wishing well"	Dissecting microscope Leica M205C (10x ocular) and Compound Leica DM2500 (10x ocular)	Incorporated in microscopes	100% Ethanol

Table 8: Groundwater sampling methods used in Jewel, Easter and Lake cave in 2012. N.s = Not sampled.

Location, dates and sampler	Sampling methods in various groundwater habitats							
	Root mat	**Interstitial**	**Vadose**	**Lakes**	**Streams**	**Pools**	**Drift fauna**	**Macrofauna**
Easter Cave, July 2012, AMRTA & Subterranean Ecology	Sweep netting	N.s	N.s	Sweep netting	Sweep netting	Sweep netting	N.s	N.s
Jewel Cave, July 2012 AMRTA & Subterranean Ecology	N.s	N.s	A small plastic plate which has received water drops	N.s	N.s	N.s	N.s	N.s
Lake Cave, March 2012, AMRTA & Subterranean Ecology	Sweep netting	Karaman-Chappius method (refer to Eberhard (2004).	A small pipe was used to suck water from the "wishing well"	Sweep netting	Sweep netting	Sweep netting	N.s	N.s

2.3 Data Analysis

2012 field survey and existing datasets were used to investigate differences and patterns between cave stygofauna composition (species presence) and environmental physico-chemistry in LNR and Yanchep caves, and groundwater depth in LNR only. LNR data were used to find a trend of water decline in the cave systems over time and relate this to climate and anthropogenic change. No hypotheses were tested here to assess correlation between stygofauna and groundwater decline, but several scenarios and trends will be outlined throughout the discussion.

2.3.1 Data standardization - Dealing with mixed data sources

With such varied sources of data, it is important to consider and account for inconsistencies and potential discrepancies within the datasets. Once the data were collated together, some variables contained more missing data than others. To deal with this, an Expectation-Maximisation Algorithm was run to attain an estimated value of the missing parameters. In the interest of preserving as much data as possible, some values were also grouped together (See Appendix 3 for collapsed data and Appendix 4 for values before they were collapsed). To increase the integrity of the dataset used in the analysis, variables that lacked continuity were omitted from the analysis. Jasinska (1997), Eberhard (2007) and Knott Storey and Tang (2007) each investigated only some of the same physico-chemical parameters, therefore, several parameters were omitted from my analysis and others were selected if they were shared between both studies (See Appendix 5 for an summary of why specific data was removed). Only one unit of measurement per variable was included in the dataset. For example, conversion of Dissolved Oxygen (DO) from percentage to mg/L was not possible, so in this case, mg/L was chosen to represent DO over a percent saturation. Jasinska (1997) measured two pH readings, in situ (*init* = initial) and also in the epigean environment (*final*) after equilibration with the outside atmosphere. Only the initial reading was chosen to represent pH in this dataset because it gives a direct indication of the pH reading within the cave system, where the stygofauna are living.

As the physico-chemistry data contained measurements in pH, mg/L, temperature and micro Siemens, the unit measurements had to be normalized so physico-chemistry values could be scaled appropriately, preserving each value in the dataset with a proportionate uniform measurement. This was done in Primer using the “normalize” function.

Other irregularities in the data came from the different sampling techniques, data collection and identification methods, including taxonomic discrepancy and misidentification of species. Species were not counted if they were dead when collected or if only shells or exoskeletons were present, as the period for how long ago they were alive is indeterminable and should therefore not be included to represent present-absent count for that particular time. Yanchep groundwater depth data was also excluded, as specific water level values were unattainable in the timeframe of this project.

2.3.2 Trends in groundwater quantity

Groundwater levels (m AHD) were graphed of Jewel Easter subsystem using existing data to show changes in water level from 1958 until 2012. Additionally, groundwater levels were mapped by Simon Neville (Ecotones & Associates) using geographic information systems (GIS).
Geographic Information Systems (GIS) cave maps were used to identify changes in water level over time, which can be used to identify contributing factors, such as

climate change and anthropogenic changes, to the groundwater decline. Cave maps were previously sketched manually for Easter, Jewel and Labyrinth caves by Stefan Eberhard, Lindsay Hatcher and Peter Bell, then scanned and imported into GIS (Arcview 10) by Simon Neville (Ecotones and Associates) where they were georectified and scaled. This provided an accurate plan view of each cave, which was converted to a solid Arcview shape file using Arcscan (an extension of Arcview).

Peter Bell (AMRTA) and Stefan Eberhard (Subterranean Ecology) prepared maps of approximate water coverage for three periods (1958-1982, 1995-2004 and 2010-2012) based on their historical records. These maps were georeferenced and the areas of water coverage for each year were digitized.

2.3.3 Groundwater quality

Euclidean distance was used to create a similarity matrix of the physico-chemistry data and plotted via Multi-dimensional Scaling (MDS) from Primer version 6 (Clarke and Gorley 2006) to compare groundwater quality environments of caves in LNR and Yanchep caves. Appendix 3 shows the collapsed (grouped together) Jewel-Easter dataset in which groundwater values between 1993 and 1996 are collapsed and all other subsequent groundwater data between 1999-2012 of caves in Leeuwin Naturaliste Ridge and Yanchep. Appendix 6 shows averages of each physico-chemical parameter for each cave, per year.

2.3.4 Stygofauna

Stygobites are groundwater inhabitants that are entirely dependent on groundwater and are highly specialized to subterranean environments. *Stygophiles* are found in groundwater environments, but lack the adaptations to subterranean life that stygobites possess. As a result, many stygophilic species are also found in surface (epigean) environments. *Stygoxenes* are species that are rarely found in groundwater habitats and are usually

Presence of lowest taxonomic rank from various ecological groups, including stygophiles (species found in groundwater environments that lack adaptations to subterranean life), stygobites (groundwater inhabitants entirely dependent on groundwater and specialized to subterranean life), epigean (species found in subterranean and surface waters) and stygoxenes (species rarely found in groundwater habitats, usually there by accident), were extracted for each cave from LNR and Yanchep systems (Appendix 5) and used to assess the similarly in species composition and richness between the caves. An MDS plot based on a Bray-Curtis distance (Clarke and Gorley 2006) was used to create a resemblance matrix to visually investigate the ecological aggregation of the cave systems based on their species composition and to explore changes in species composition over time. To explore the contribution of each of these species into the observed ecological aggregations a Simper Analysis was performed. This analysis characterized each cave by producing a dissimilarity percentage of individual species contributions and then performed a pair-wise test between the faunal assemblages to calculate the probability of each species being present in each cave system. These changes were further explored via plotting species presence over time for each of these caves.

2.3.5 Relationship between groundwater quality and stygofauna

To investigate any influence of groundwater quality on invertebrate assemblages, two separate matrices with environmental values of physico-chemistry and fauna presence-absence data from Jewel-Easter and all physico-chemical Yanchep data were combined into a Biota and Environmental Matching (BIOENV) matrix using Primer (Version 6).

2.3.6 Relationship between groundwater quantity and stygofauna

Species composition in Jewel-Easter cave was explored in relation to groundwater depth. This cave was the only cave from which groundwater depth data from 1958 was available.

A Bayesian Belief Network (BBN) was used to project persistence of rootmat-dependent and independent species at a groundwater level of 24 m AHD. A BBN is a graphical model that can be used to show the relationship between important variables and changing states of an ecosystem (Kapustka and Landis 2010) It was used to assess how groundwater level states can impact on the persistence of species in the presence or absence of exposed or submerged tree roots. This model provided a conditional probability table showing the likelihood of an event occurring, with a percentage value, in different scenarios or states of groundwater change. This method was chosen as it uses expert knowledge and reasoning to develop values from uncertain or limited information; expertise and knowledge were provided by Dr. Peter Speldewinde (University of Western Australia), Dr. Stefan Eberhard (Subterranean Ecology) and myself. The variables in the cave groundwater BBN were: 1) groundwater, 2) tree root state (“wet” or “dry”), 3) the effect on tree roots dependent species and tree root independent species, and 4) overall cave stygofauna health. The survival of stygofauna in cracks or in the presence or absence of tree root mats in varying levels of groundwater is shown in a percentage value in the table attached to each node. Water quality could not be included as a node because physico-chemistry of the individual groundwater habitats is far too complex for this BBN analysis.

Additionally, a Cumulative Rainfall Departure (CRD) analysis obtained from Steve Appleyard (Department of Environment and Conservation) was used to compare measured groundwater levels between 1975-2012 to simulated groundwater levels at Jewel Easter Cave based on contribution from rainfall . The CRD does not account for other land factors such as changes in vegetation density. Information on Land use changes in LNR over time was obtained from Eberhard (2004) and from personal communication with present cave manager Lindsay Hatcher as well as Gabriel Maygar (AMRTA). This information was used to create an historical timeline to show major events in the history of Jewel-Easter cave, post-1958.

3. RESULTS

3.1 Groundwater Quantity in caves

The groundwater depth in the caves of Leeuwin Naturaliste Ridge has changed over time. As seen in Jewel Cave (Fig.17), a very distinctive decline has occurred between 1958 to the present day (2012), where groundwater has reached its lowest level yet. Three different groundwater decline stages “wet”, “drying”, and “dry”, were identified between 1958-1982, 1995-2004 and 2010-2012 respectively, in Jewel, Easter, Labyrinth and Lake Caves (Fig 18-22).

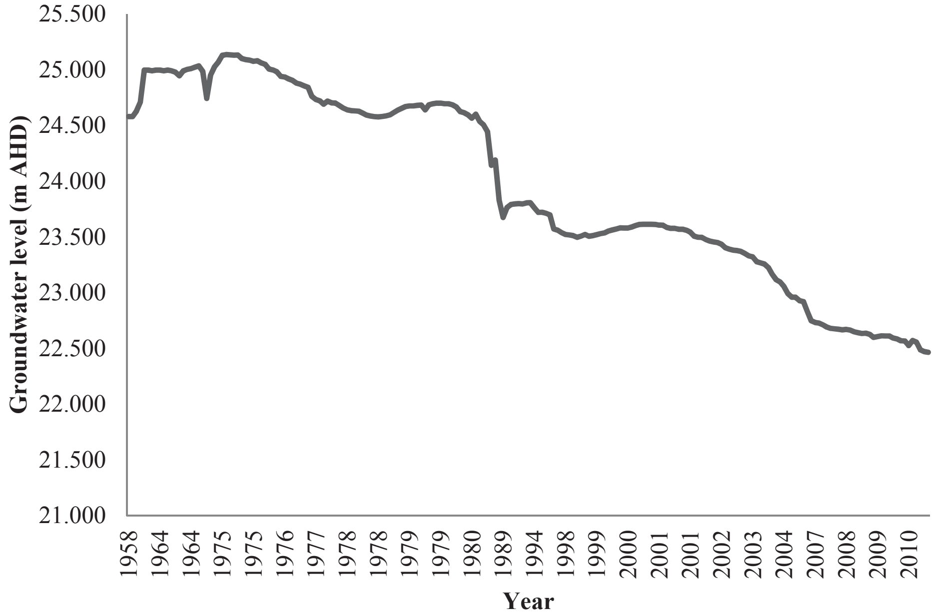

Figure 18: Jewel cave groundwater level, measured between 1958-2012.

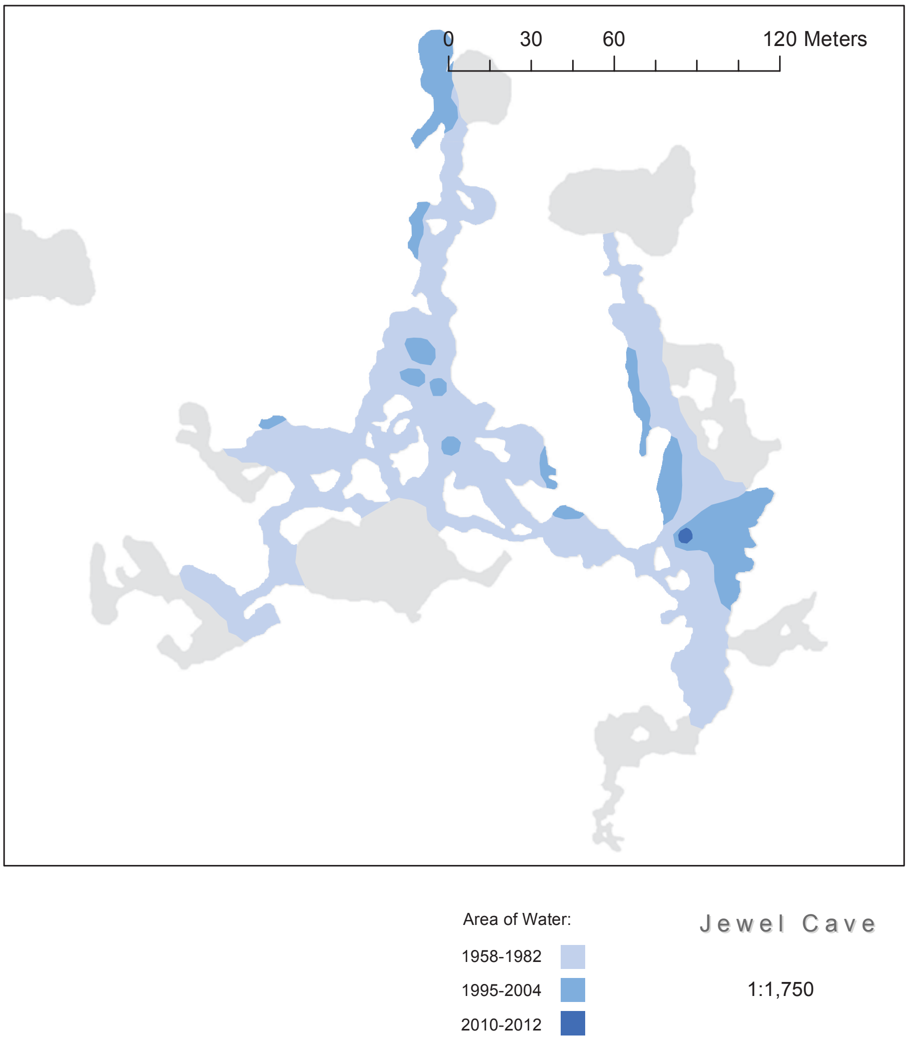

Figure 19: Water quantity change over time in Jewel Cave represented in three distinct periods, "wet" = 1958- 1982, "drying" = 1995-2004 and "Dry" = 2010-2012. (Composite map created by Simon Neville). Jewel Cave map courtesy of Peter Bell; adapted from Eberhard (2004).

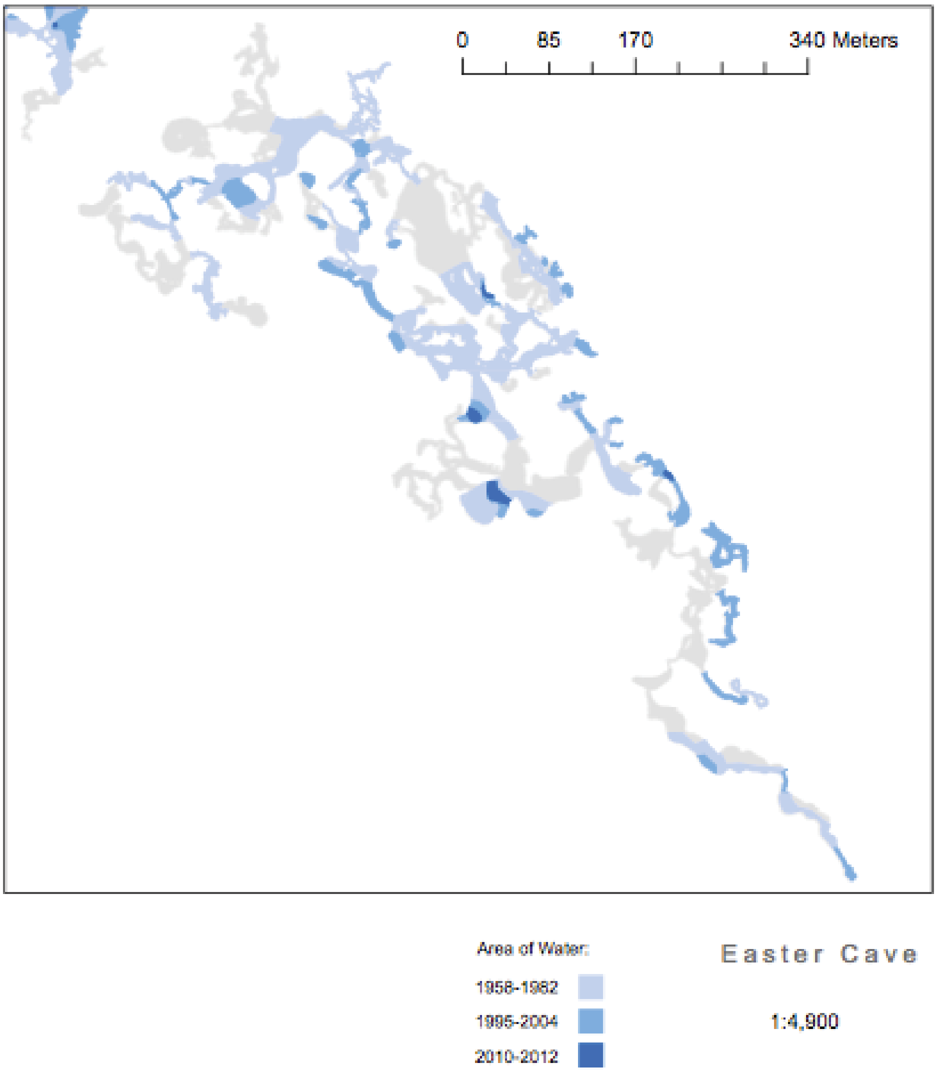

Figure 20: Water quantity change over time in Easter cave represented in three distinct periods, "wet" = 1958- 1982, "drying" = 1995-2004 and "Dry" = 2010-2012. (Composite map created by Simon Neville). Easter Cave map courtesy of Augusta Margaret River Tourism Association; adapted from Eberhard (2004).

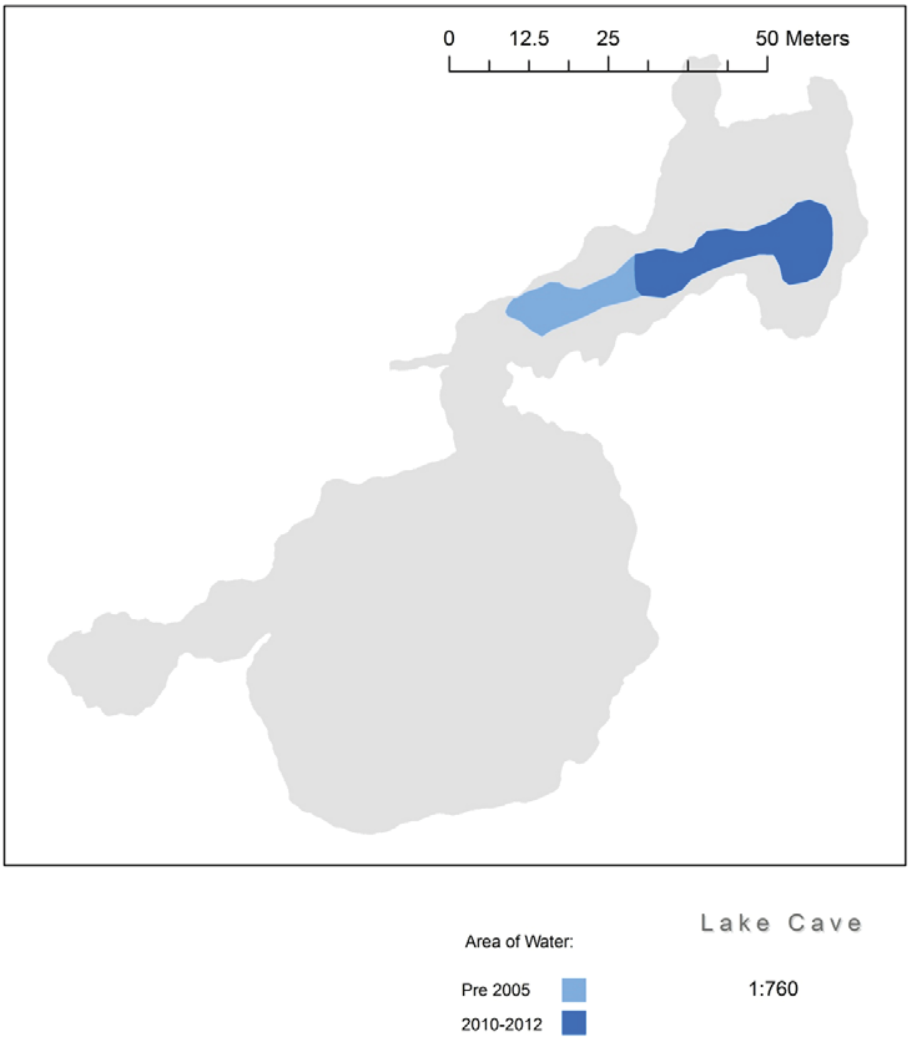

Figure 21: Water quantity change over time in Lake cave represented in two time periods, "wet" = Pre-2005 and "drying" = 2010- 2012. (Composite map created by Simon Neville). Lake Cave map courtesy of Augusta Margaret River Tourism Association.

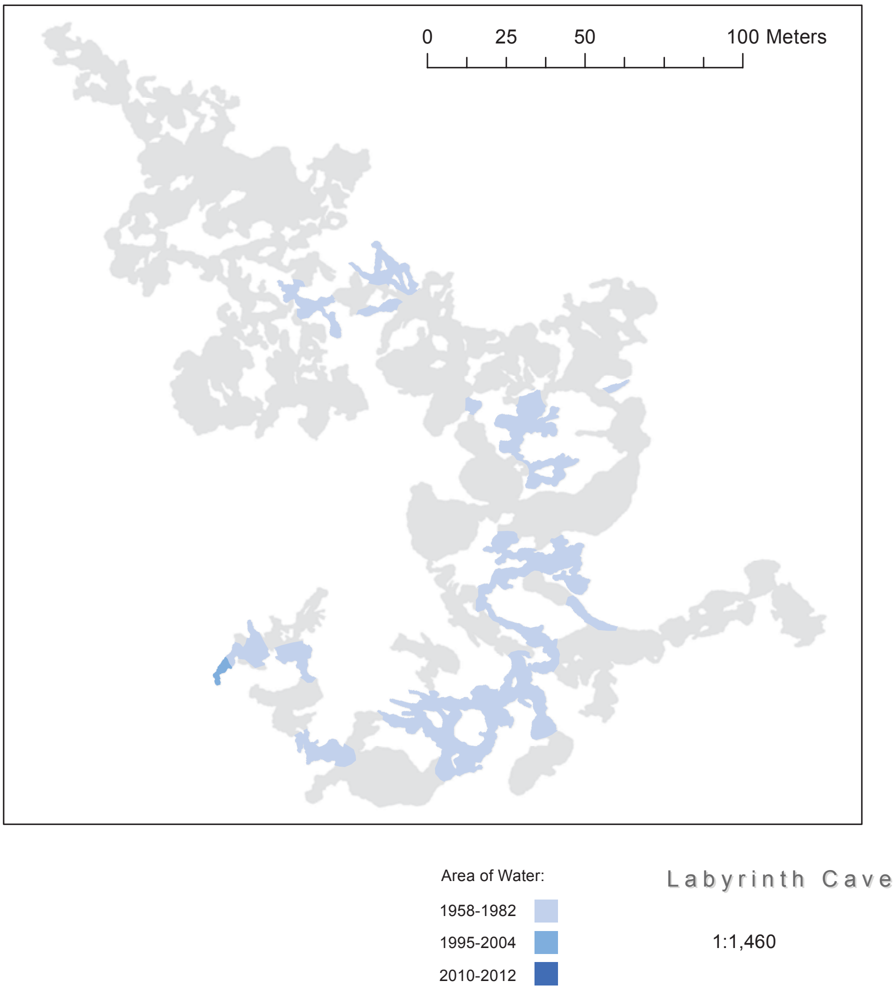

Figure 22: Water quantity change over time in Labyrinth cave represented in three distinct periods, "wet" = 1958- 1982, "drying" = 1995-2004 and "dry" = 2010-2012. (Composite map created by Simon Neville). Labyrinth Cave map courtesy of Augusta Margaret River Tourism Association; adapted from Eberhard (2004).

3.2 *Groundwater Quality in caves*

The ionic composition in Jewel-Easter and Labyrinth caves differed from Lake cave and Yanchep cave systems between 1993-2012 (Fig.23). These differences were mainly attributed to magnesium and nitrate concentrations (Figures 24 and 25). Jewel-Easter and Labyrinth magnesium ranged between 39-54 mg/L and Yanchep caves ranged between 4-17 mg/L. Jewel-Easter and Labyrinth nitrate concentrations ranged between 0.1-1.6 mg/L, with a noticeable increase in nitrate levels from 1-3.9 mg/L between 2000-2004 in Twilight cave. Figures 26-32 represent other physicochemistry concentrations recorded in Leeuwin Naturaliste Ridge and Yanchep caves between 1993-2012.

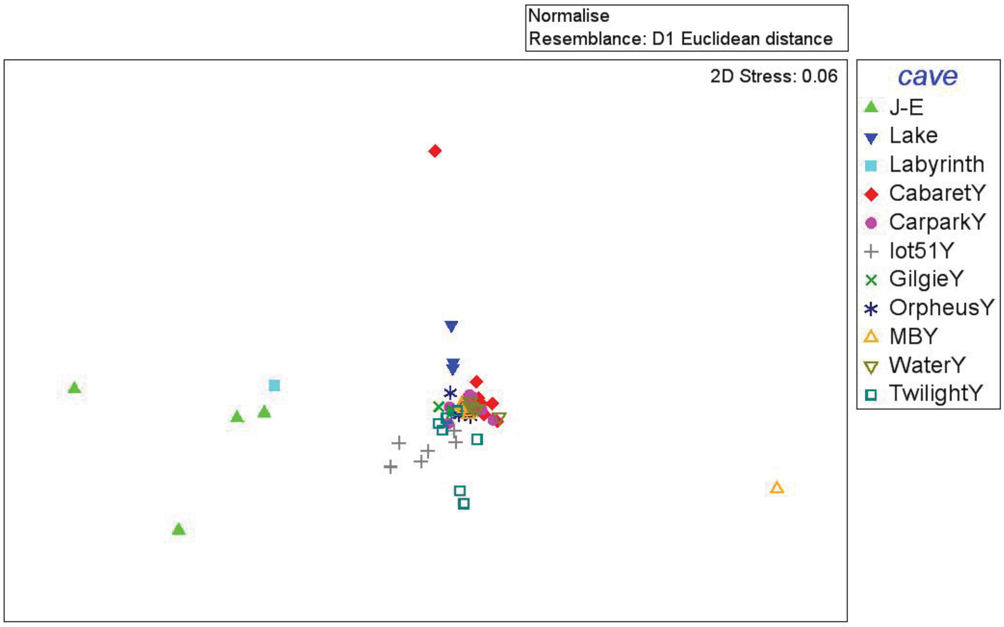

Figure 23: MDS plot representing differences in the physico-chemical environment between the Leeuwin Naturaliste Caves including, Jewel Easter (JE), Labyrinth (Augusta Water Table Caves) and Lake with Yanchep (Y) caves between 1993-2012.

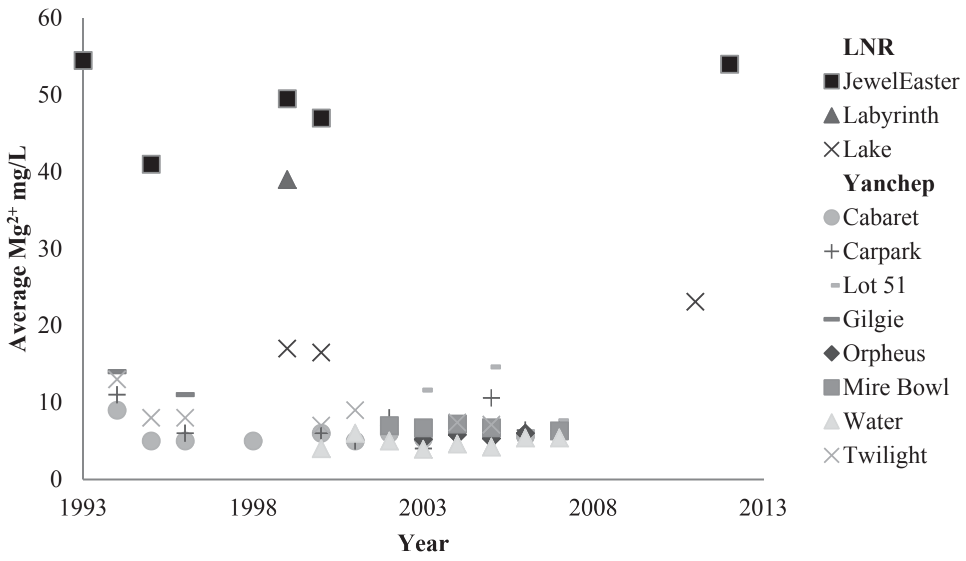

Figure 24: Recorded average magnesium (Mg^{2+}mg/L) concentration for LNR and Yanchep cave systems between 1993-2012.

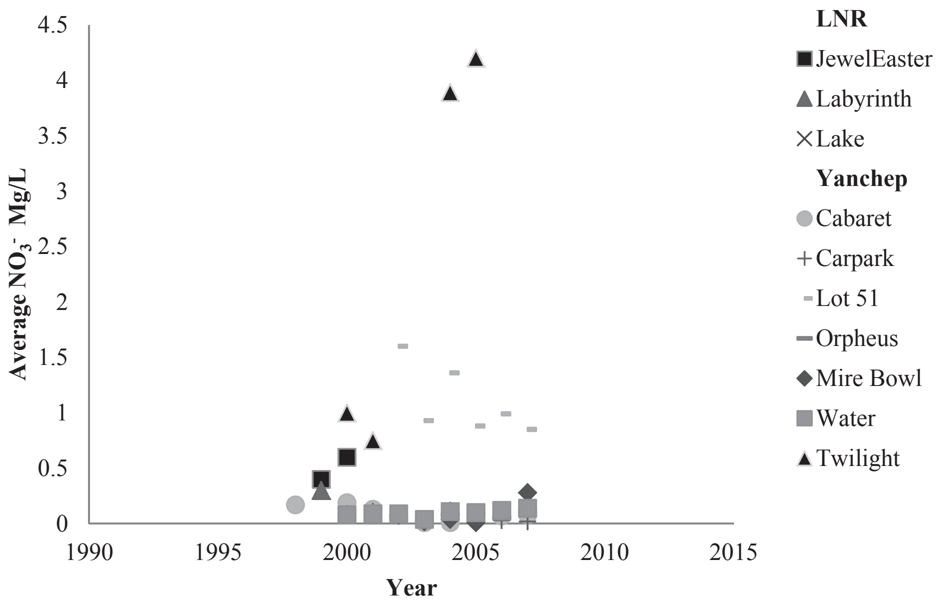

Figure 25: Recorded averages for nitrate (NO^{3-} mg/L) concentration in Leeuwin Naturaliste Ridge and Yanchep cave systems between 1993-2012.

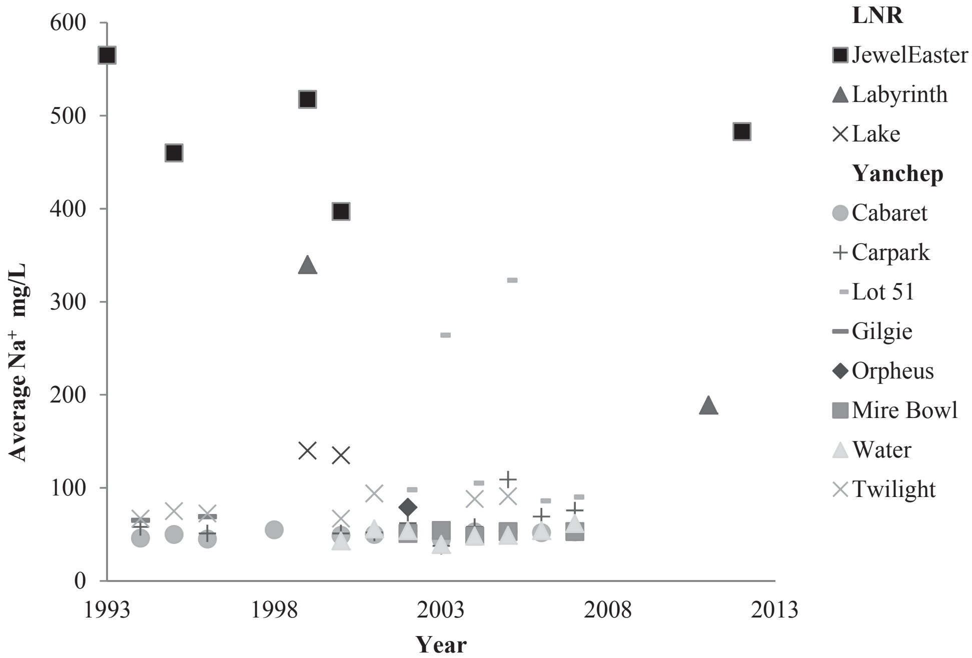

Figure 26: Recorded average sodium (Na^+ mg/L) concentration in Leeuwin Naturaliste Ridge and Yanchep cave systems between 1993-2012.

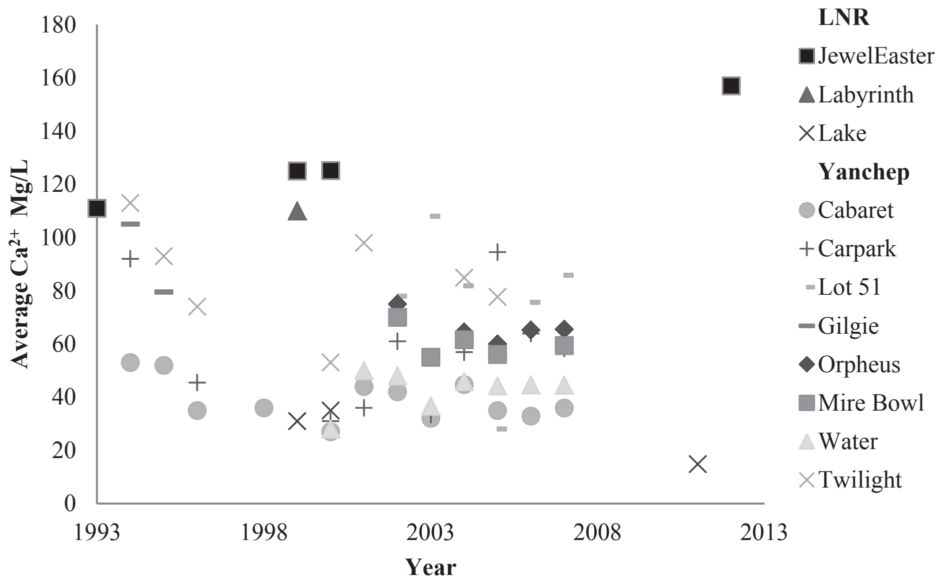

Figure 27: Recorded average calcium (Ca^{2+} mg/L) concentration in Leeuwin Naturaliste Ridge and Yanchep cave systems between 1993-2012.

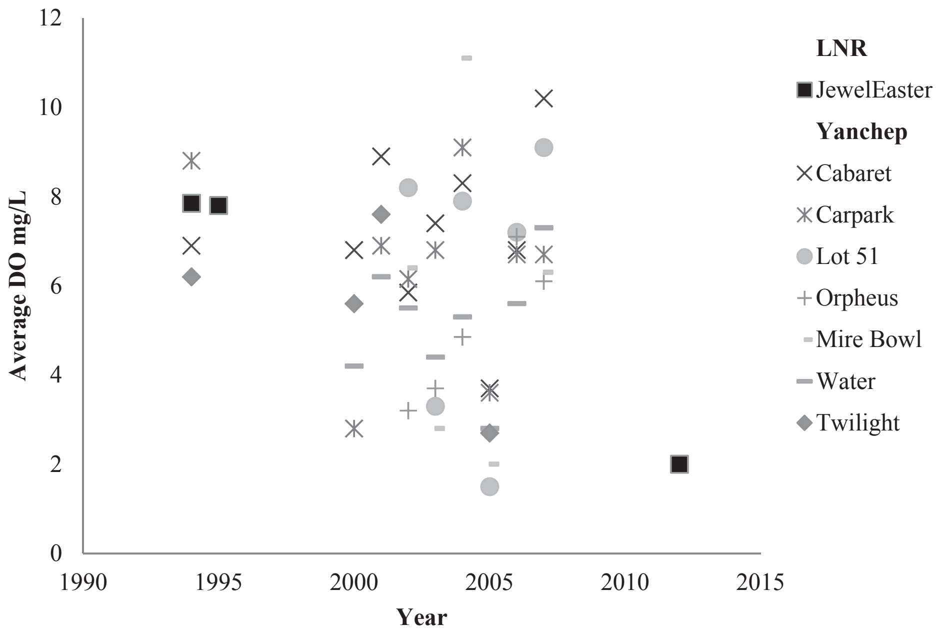

Figure 28: Recorded averages of Dissolved Oxygen (DO mg/L) in Leeuwin Naturaliste Ridge and Yanchep cave systems between 1993-2012.

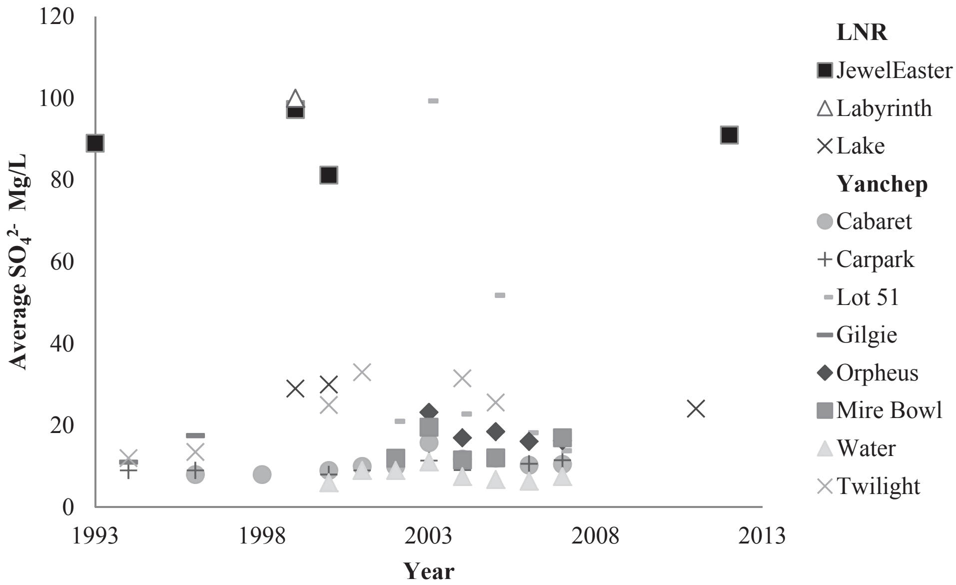

Figure 29: Recorded averages of sulfate (SO_4^{2-} mg/L) concentration in Leeuwin Naturaliste Ridge and Yanchep cave systems between 1993-2012.

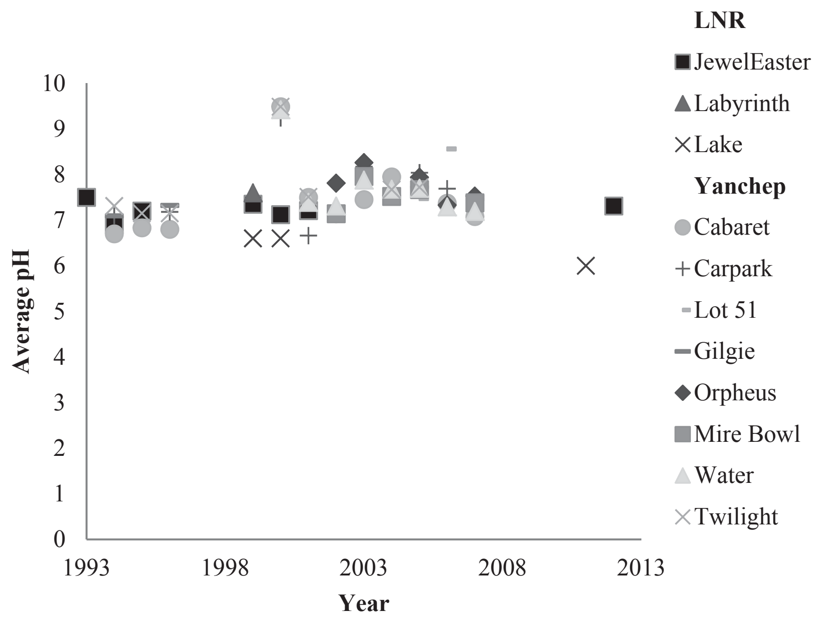

Figure 30: Recorded average pH levels in Leeuwin Naturaliste Ridge and Yanchep cave systems between 1993-2012.

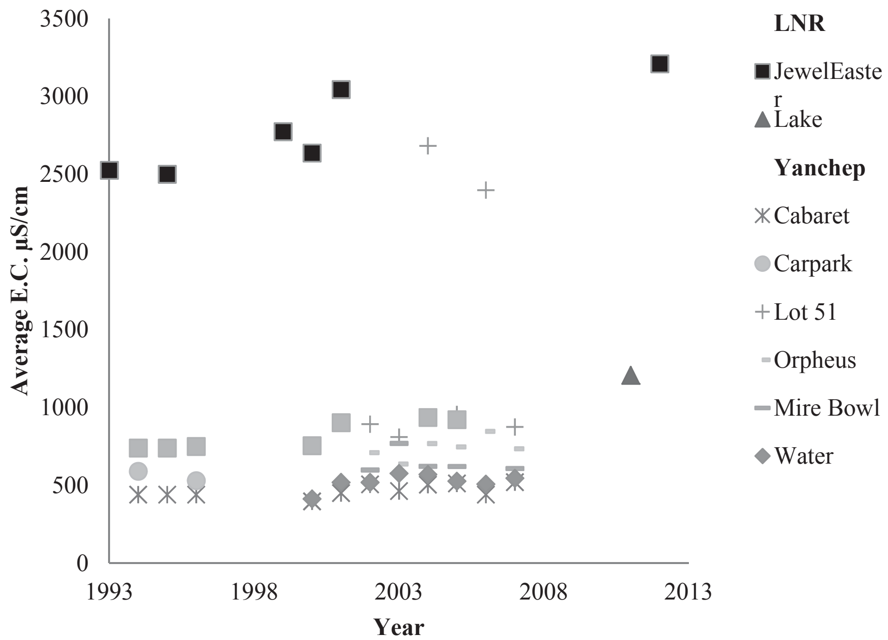

Figure 31: Recorded average Electrical Conductivity (E.C.) in Leeuwin Naturaliste Ridge and Yanchep cave systems between 1993-2012.

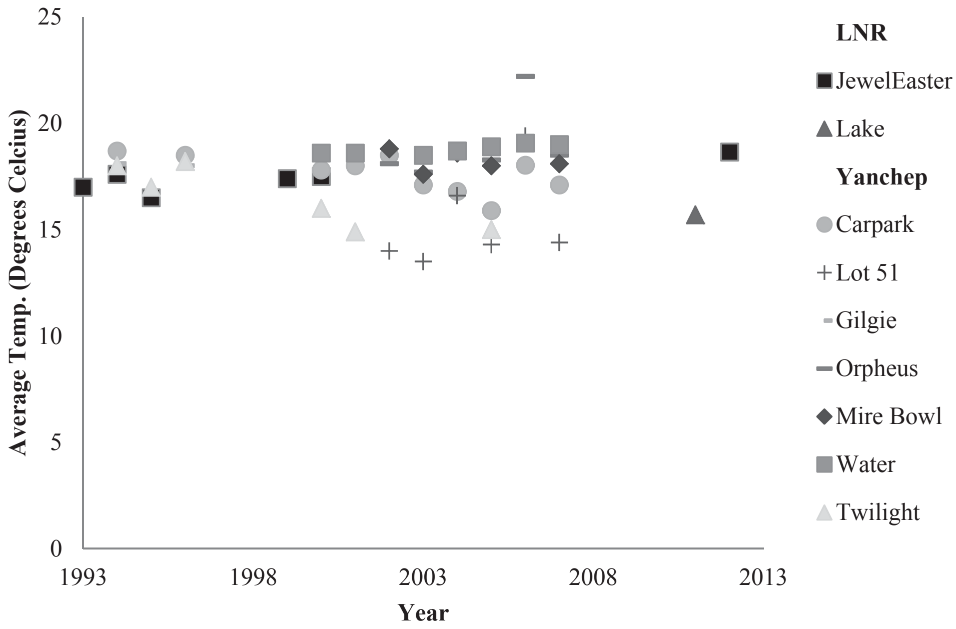

Figure 32: Recorded average Temperatures (Degrees Celsius) in Leeuwin Naturaliste Ridge and Yanchep cave systems between 1993-2012.

3.3 Stygofauna compositions in caves

Stygofauna community compositions differed between cave systems across LNR and Yanchep caves. As seen in Figure 33, the clearest observation is observed in the distinct faunal composition of Jewel-Easter. Labyrinth also contains relatively close faunal similarity to Jewel-Easter. Twilight faunal assemblage appears to be different each time it was sampled. Yanchep caves including, Mire Bowl, Water, Orpheus and Lot 51 did not show much change in faunal assemblages over time (Fig.33).

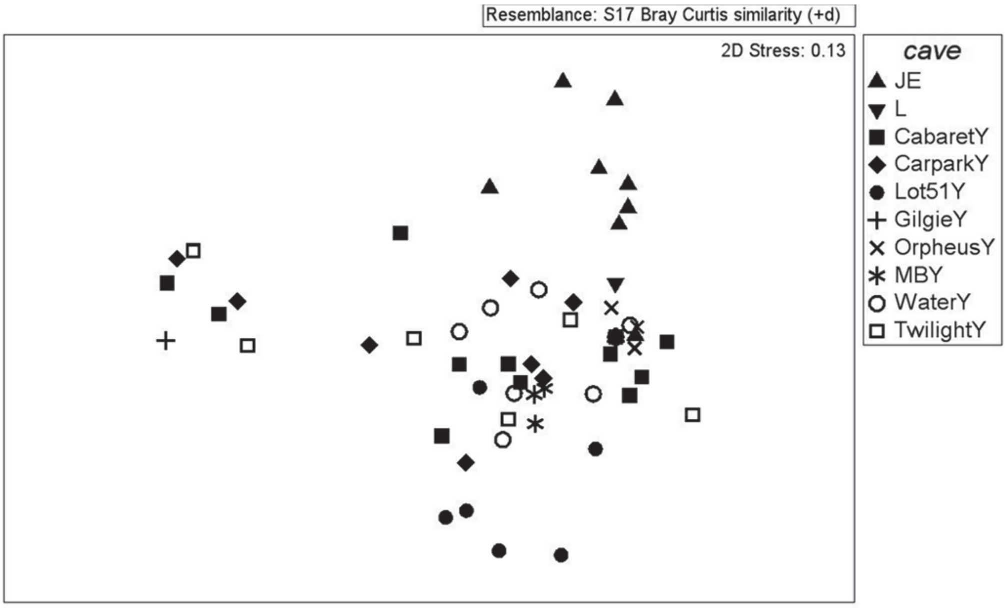

Figure 33: MDS plot representing faunal composition differences between the Leeuwin Naturaliste Caves including, Jewel Easter (JE) and Labyrinth (Augusta Water Table Caves) with Yanchep (Y) caves, 1993-2012.

Leeuwin Naturaliste Ridge and Yanchep caves are characterised by a unique community composition and dominant set of species. (Table 9). There is basically no overlap in species composition per cave, with Twilight showing the most independent contributing species. These are the species that characterize a particular cave, which is represented by the probability of presence (in brackets) of finding that species in a particular cave system and the species independent contribution to the fauna within the cave system.

Table 9 shows that all Yanchep caves except Orpheus were dominated and characterized by the presence of Nematodes, with no less than 10% independent species contribution found across Cabaret, Lot 51, Mire Bowl, Water and Twilight and up to 47.34% found in Carpark cave. Jewel-Easter cave however, was not dominated by Nematodes, but by a distinct group of fauna not found in any other cave system. The only species to show a smaller independent contribution in nematodes than any other taxa was Lot 51, which displayed a higher independent contribution of *Candona* sp. Jewel Easter cave groundwater systems were dominated by *Perthia acutitelson*, *Uroctena,* Caranoctydae and Copepoda.

Table 9: Probability of presence (in brackets) and percentage of independent contribution for species assemblages per Augusta Water Table and Yanchep cave system.

	Jewel Easter	**Cabaret**	**Carpark**	**Lot 51**	**Orpheus**	**Mire Bowl**	**Water**	**Twilight**
Nematoda		(0.55) 38.12 %	(0.55) 47.43%	(0.30) 10.08%		(0.40) 48.71 %	(0.30) 30.96 %	(0.36) 28.28 %
Rotifera								(0.18) 1.80 %
Dalyellioida sp.1								(0.18) 1.80 %
Oribatida		(0.27) 6.89 %					(0.20) 10.21 %	
Rhabdocoela		(0.27) 2.19 %						
Copepoda	(0.22) 1.48 %							
Ceratopogonidae								(0.18) 1.80 %
Crangonyctidae	(0.56) 16.52 %							
Enchytraeidae sp. 1								(0.18) 1.80 %
Enchytraeidae UWA1							(0.20) 10.21 %	
Hydrobiidae				(0.30) 8.06 %				
Hypsibiidae		(0.27) 2.13 %						
Janiridae							(0.20) 13.61 %	(0.27) 8.05 %

	Jewel Easter	**Cabaret**	**Carpark**	**Lot 51**	**Orpheus**	**Mire Bowl**	**Water**	**Twilight**
Paramelitidae Gen. 2						(0.30) 21.19 %		
Paramelitidae Gen.nov					(0.30) 100 %			
Parastacidae		(0.27) 2.13 %	(0.27) 3.04 %				(0.20) 11.67 %	(0.18) 1.80 %
Phreatoicidae				(0.40) 16.75 %				
Phreodrilidae		(0.27) 5.60 %	(0.27) 7.59 %					(0.18) 3.70 %
Phreodrilidae sp.1			(0.27) 3.43 %					(0.27) 8.05 %
Tipulidae		(0.36) 15.10 %						
Tubificidae sp.1		(0.27) 2.30 %						
Aeolosoma aff. Leidyi								(0.18) 1.80 %
Aeolosoma sp.2								(0.18) 1.80 %
Australoeucyclops sp.nov (primus?)				(0.30) 10.67%		(0.30) 23.65 %	(0.20) 11.67 %	
Austrochiltonia subtenius		(0.27) 2.13 %						
Bostokia porosa		(0.27) 2.13 %						
Candona sp.				(0.50) 40.65%				

	Jewel Easter	**Cabaret**	**Carpark**	**Lot 51**	**Orpheus**	**Mire Bowl**	**Water**	**Twilight**
Cherax crassimanus Riek (1967)							(0.20) 11.67 %	
Cherax quinquecarinatus		(0.27) 2.13 %	(0.27) 3.04 %					(0.18) 1.80 %
Gomphodella aff. maia			(0.36) 9.99 %					(0.27) 8.05 %
Gyratrix hemaphroditus								(0.18) 1.80 %
Huryleya								(0.18) 1.80 %
Macrostomum sp.								(0.18) 3.34 %
Perthia acutitelson (Williams & Barnard 1988)	(0.78) 36.68%							
Soldanellonyx monardi Walter			(0.27) 3.04 %					(0.27) 8.05 %
Stenostomum sp.		(0.27) 7.52 %	(0.27) 13.37 %					(0.18) 3.70 %
Sternopriscus sp.		(0.27) 2.13 %						
Uroctena n. sp.	(0.78) 36.68%							
Westrapyrgus sp.nov				(0.30) 8.06 %				

The species composition has changed over time between each sampling period in Leeuwin Naturaliste Ridge and Yanchep caves (Fig.34). The pattern of samples is presents a 2D stress value of 0.04, indicating that this is a good representation of the species composition data. Points that sit closer together symbolise caves with species that are more similar than the points that are further apart. Jewel and Yanchep caves are showing fewer and fewer species over time. A progression in Yanchep caves from right to left between 1996-2007 (except for 1998 which contains the addition of year 2000 data) is repeated in Lake cave from 2002-2012 shows a strong trend in reduced species diversity. The decline in species diversity over time in Leeuwin Naturaliste Ridge and Yanchep is further demonstrated in Figure 35.

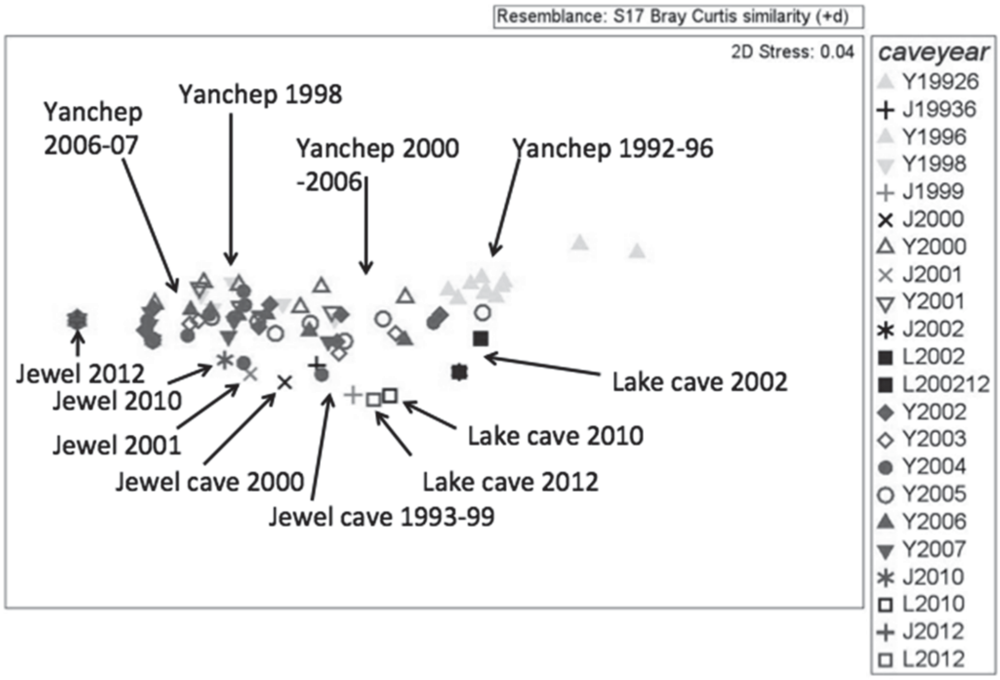

Figure 34: MDS plot representing changes to faunal composition differences of the Leeuwin Naturaliste Caves between 1992-2012 including, Jewel Easter (JE) and Labyrinth (Augusta Water Table Caves) and Yanchep (Y) caves. (Jewel cave samples from 1992, 1993, 1994, 1995 and 1996 are all represented as 19926 and Lake cave samples are represented between 2002-2012 as 200212) Yanchep 1998 data was collapsed with Yanchep 2000 data.

3.4 Simper Analysis: Dissimilarity percentage

Labyrinth and JE cave system showed 77.09% dissimilarity in species composition, but the difference in species composition between Labyrinth and Yanchep caves was locked at 100% and no less than 98% between Jewel-Easter and Yanchep Caves (Table 10) further indicating that the JE and Yanchep systems are very distinct in their fauna composition.

Table 10: Average dissimilarity percentage of species contributions between Augusta Water Table and Yanchep Caves.

	Cabaret	Carpark	Gilgie	Lot51	Orpheus	Mire Bowl	Water	Twighlight
Jewel Easter	99.06	99.14	98.82	99.31	98.45	98.83	99.42	99.12
Labyrinth	100	100	100	100	100	100	100	100

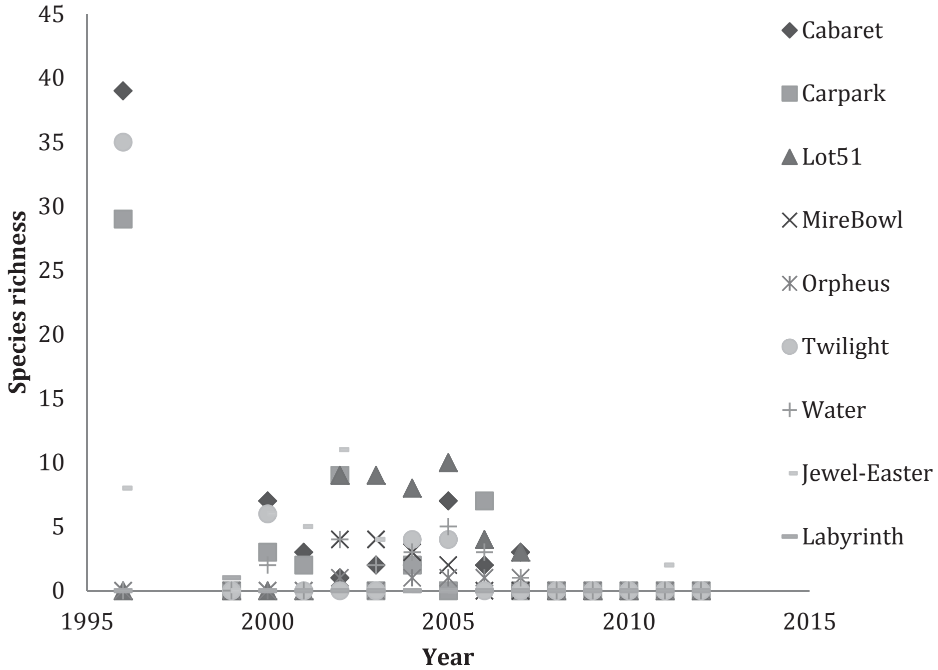

Figure 35: Diversity of species present in Leeuwin Naturaliste Ridge and Yanchep caves between 1993-2012.

Stygophiles, stygobites, and epigean species, dependent and independent on tree root mats, were found in cave groundwater habitats of LNR between 1993-2003 (Fig.36). Most distinctively, species that could not be determined as stygophile, stygobite, stygoxene or epigean and were absent from tree roots, were found to be equally as dominant as epigean species that were found in the absence of tree roots. The number of individuals per ecological group is summarised in Figure 36 and a list of individual species identified in each ecological group can be found in Table 11.

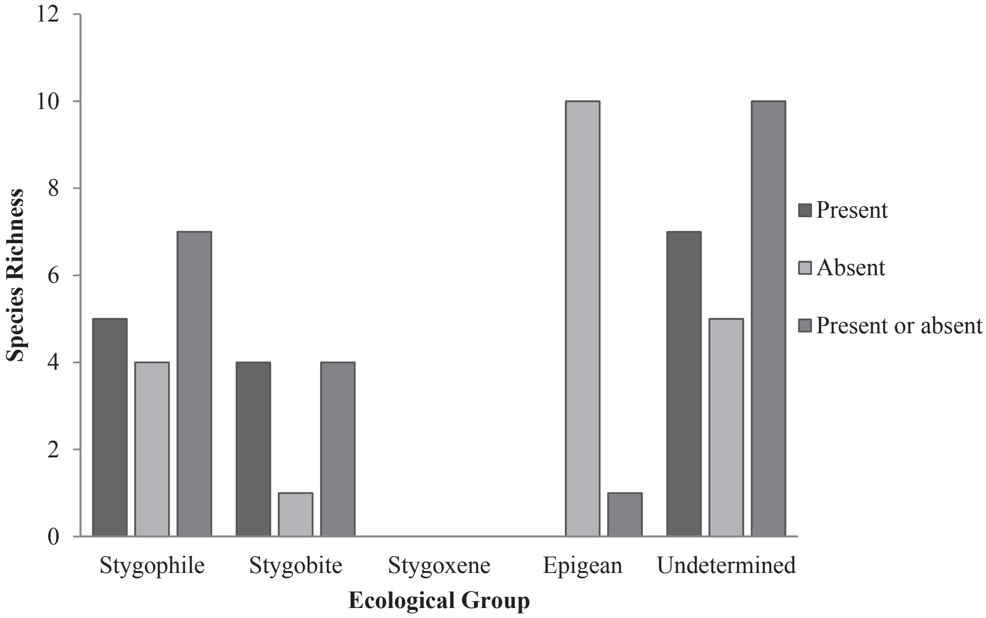

Figure 36: Species richness per ecological group, found in the Leeuwin Naturaliste Ridge cave systems between 1993-2003. Species were found in the presence (Present) or absence (Absent) of tree roots tree roots were present, or in separate habitat with and without tree roots (Present or absent).

Table 11: Aquatic cavernicoles from lowest-highest taxonomic level, extracted from site and subs-site specific samples from Eberhard (2004). Ecological groups found in the presence or absence of tree roots in the groundwater habitat of Leeuwin Naturaliste Ridge (Data sourced from Eberhard 2004). Data represented by Eberhard (2004) but previously identified by Jasinska (1997) is represented with *. Samples were extracted from vadoze seepage waters, phreatic zones; cave streams, interstitial and hyporhoes waters. The ecological groups are keyed as follows: Stygophile=1, Stygobite=2, Stygoxene=3, Epigean=4, Undetermined data=5, is noted as undetermined in the source from which it has been collected. Presence or absence of tree roots are keyed as P=present, A=absent and B=both, referring to a species that was found both in the presence and absence of tree roots. For a comprehensive study of species and their particular cave groundwater habitats, refer to Eberhard (2004).

Taxon	Ecological Group	Tree Roots Present-Absent
Acandona admiratio Karanovic, 2003	2	B
Aeolosoma	5	B
Ainudrilus nr. WA14	1*	B
Antarctodrilus micros (Pinder & Brinkhurst 1997)	5	B
Australoeucyclops sp.nov (primus?)	4	A
Candonocypris cf. Novaezelandie (Baird, 1843)	1	A
Candonoposis tenius (Brady)	4	A
Cherax crassimanus Riek (1967)	1	B
Cherax preissi (Erichson, 1864)	5	A
Diacyclops humphreysi n. ssp.	2	P
Gomphodella aff. maia	4	A
Insulodrilus lacustris s.l	5	P
Macrocyclops albidus (JURINE, 1820)	1	P
Macrostomum sp.	5	B
Mesocyclops brooksi PESCE et al., 1996	1	B
Mucronothrus sp. Malitapil & Blyth, 1982	5	P
Nitokra lacustris pacifica YEATMAN, 1983	5	A
Paracyclops fimbriatus	4	B
Parastenocaris eberhardi	2	P
*Parastenocaris sp **	2	P
Penthesilenula brasiliensis (Pinto and Kozian)	1	P
Perthia acutitelson (Williams & Barnard 1988)	1	B
Perthia acutitelson (Williams & Barnard 1988)	5	B
Peza	4	A
Pristina aquisita Bourne, 1891	5	P
Pristina longiseta Ehrenberg, 1828 sensu lato	1	B
Pristina WA4	5	A
Soldanellonyx monardi Walter	1	P
Stenostomum sp.	5	P
Thermocyclops sp.	4	A

Taxon	Ecological Group	Tree Roots Present-Absent
Uroctena n. sp.	2	B
Chironomidae	1	B
Culicidae	1	A
Enchytraeidae	5	P
Enchytraeidae sp. 1	5	A
Enchytraeidae sp. 2	5	B
Enchytraeidae sp. 3	5	B
Enchytraeidae sp.4	5	A
Janiridae sp. indet	4	A
Ilyopridae	4	A
Parabathynellidae	2	B
Paramelitidae Gen.nov	1	A
Phreodrilidae	5	P
Phreodrilidae WA26	5	P
Phreodrilidae WA26 sp. nov. ?	1	B
Tubificidae sp. indet	5	B
Tubificidae WA12 sp. nov. ?	5	B
Bathynellacea	2	B
Coleoptera	4	A
Cyclopoida	2	A
Diptera	1	A
Harpacticoida	2	P
Megadrile	1	P
Oribatida	1	P
Trichoptera	4	A
Tricladida	5	B
Nematoda	5*	B

3.5 Relationship between groundwater quality and stygofauna

The relationship between groundwater quality and stygofauna was examined with BIOENV in Primer (Version 6) to relate the species assemblage data to water quality. The assemblage data and water quality data were significantly correlated and the water quality data explained 39.4% of the variation in the species assemblage data (Rho = 0.394, P <0.001). Only two water quality variables were responsible for this correlation: nitrate and magnesium ions. Magnesium ionic concentration was much higher concentration in the Jewel-Easter cave than in the other caves, while nitrate ionic concentrations were highest in Twilight and Lot 51 of Yanchep (Figures 24 and 25).

3.6 Relationship between groundwater quantity and stygofauna

As the groundwater decline in Jewel-Easter has occurred, species richness has declined. This is clearly shown in Figure 37, as groundwater has declined since sampling efforts in 1999 where species richness was 12 and in the last survey (2012), the total number of species found was 2.

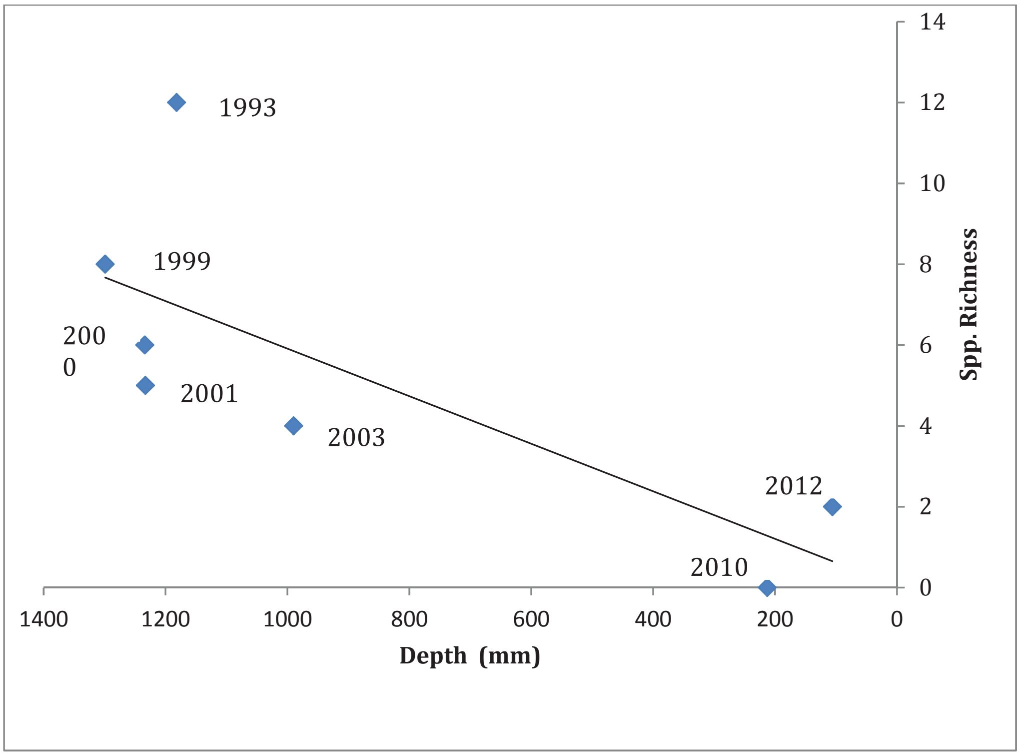

Figure 37: The number of invertebrate taxa plotted against water depth for those years where both variables were recorded in Jewel-Easter Cave. Each data point is labeled with the year of sampling. Three clusters of data points are evident: higher species counts and water levels in the 1990s, lower water levels and species richness 2000-03, and very low water levels with no taxa recorded in 2010 (as no stygofauna sampling took place) and only 2 species recorded in 2012.

The relationship between groundwater depth and stygofauna composition was also depicted in a Bayesian Belief Network (BBN). The BBN links groundwater depth to the physical ecosystem structure that is represented as tree-root-coverage by groundwater. This gives a percent value of overall stygofauna health. At a level of 24 m AHD in Jewel Easter cave, 80% of tree roots would be submerged and at least 85% of root mat dependent species (rootMatdepend, (Fig. 38) would be able to persist. However, 100% of root mat independent species (rootmatindepend, (Fig. 38) would be able to persist, because there would be enough groundwater for them to survive regardless of the presence or absence of tree roots. Similarly, 100% of species that live in cracks in the caves cracks (Fig. 38) below would be able to survive.

Species are either dependent on tree roots and groundwater or they are not, so there is no ‘declining’ scale. This works out to a percentage of 88.1% to be at a “good” level of health and with a high chance of survival.

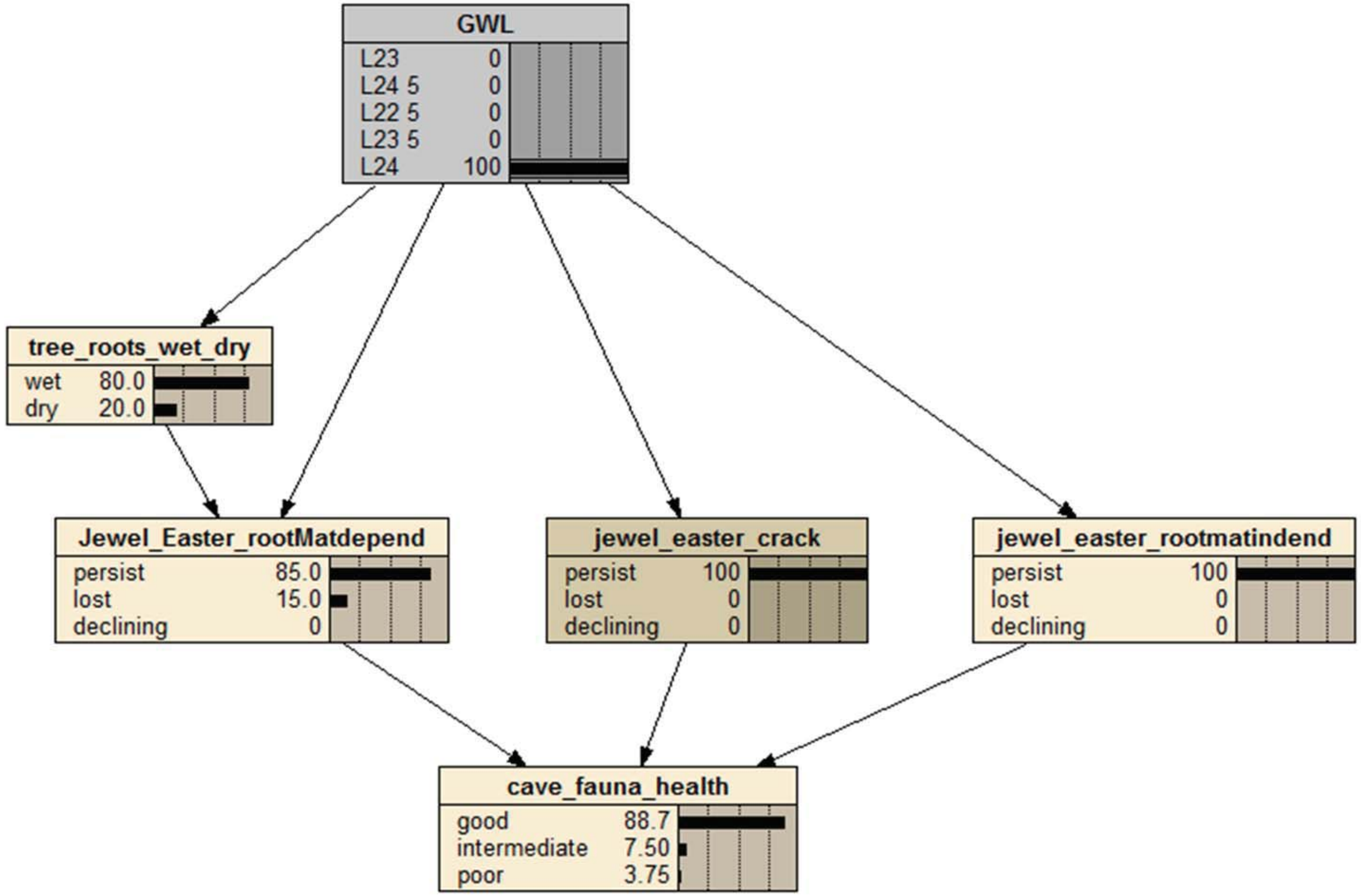

Figure 38: Bayesian Belief Network shows the effects of a scenario of groundwater decline if the groundwater level (GWL) is at 24 (m AHD) in Jewel Easter cave. The variables in the cave groundwater BBN are 1, groundwater, 2, tree root state; "wet or dry", 3, the effect on tree roots dependent species and tree root independent species and 4, overall cave stygofauna health.

The Cumulative Rainfall Departure (CRD) analysis (Fig. 38) shows a measured decline in rainfall over time, but a simulated rainfall decline shows a different pattern to what has actually been measured/exhibited in Jewel Cave. Therefore, the 'simulated' line shows a trend in groundwater decline according to background variations, while unanticipated peaks and troughs are represented by the 'measured' trend line. This can be compared with the information received from Lindsay Hatcher and Gabriel Maygar of AMRTA, who outline major changes to the Jewel-Easter catchment and cave system between 1958-present (Fig. 39).

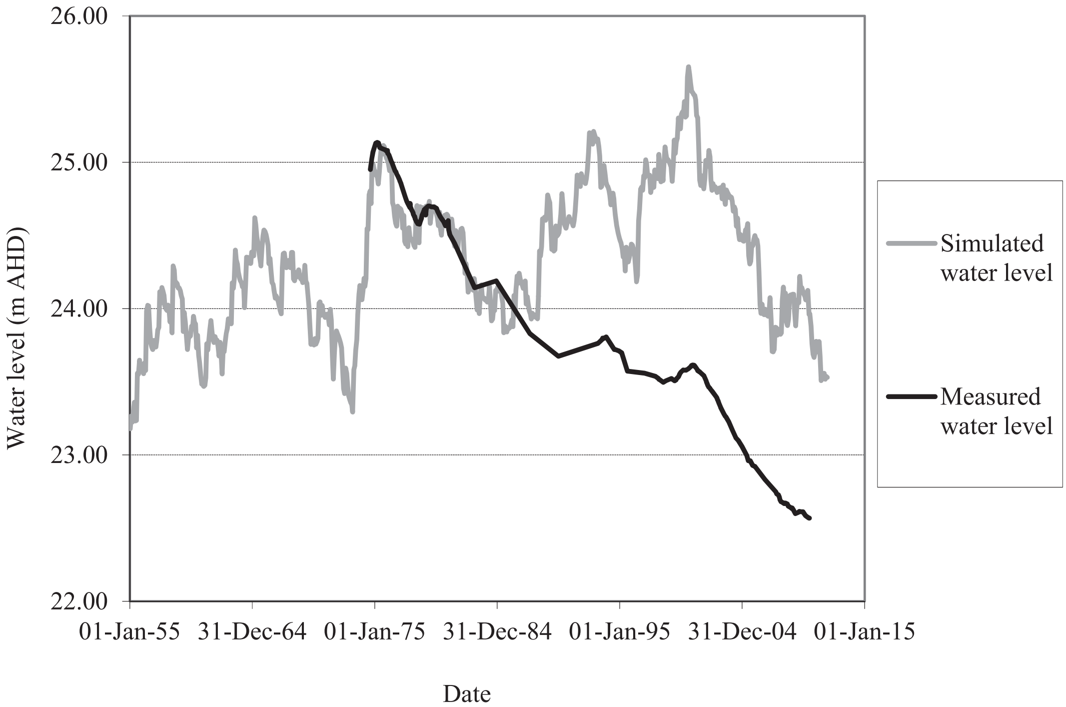

Figure 39: Jewel Cave Cumulative Rainfall Departure (CRD) diagrams displays measured groundwater levels in Jewel Cave against compared with simulated levels according to climatic data between January 1955- 2012 (Data source courtesy, Steve Appleyard).

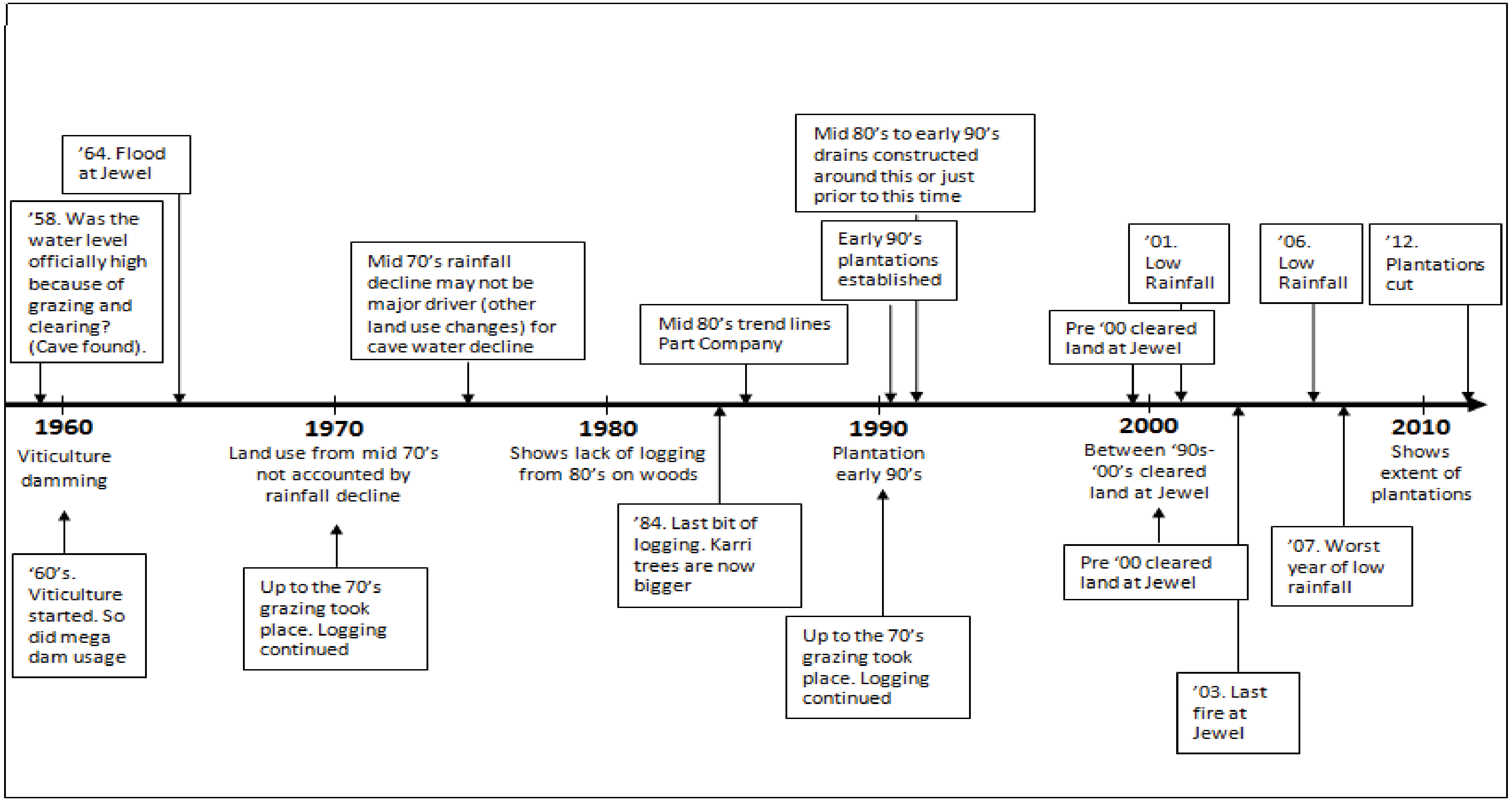

Figure 40: Timeline of changes to the Jewel-Easter catchment and cave system between 1958 and the present day following personal communication with Lindsay Hatcher and Gabriel Maygar (AMRTA).

4. DISCUSSION

This thesis is the first time that the water quantity, quality and species assemblage data for the Augusta-Margaret River and Yanchep Caves have been collated. The aims of the thesis were therefore essentially exploratory, to try to identify any patterns in each type of data over time, and any correlations between them. For this reason, I did not test hypotheses, but looked for relationships and this inherently means that causality cannot be directly determined; that is, it is not possible to state that changes in one set of variables caused changes in another. However, clear correlations between water quality and stygofauna assemblages showed that different caves had different water quality and very different stygofauna assemblages, and these are likely to both be products of the environmental history of the caves over time scales longer than covered by these datasets. There is also a clear trend of declining water level and declining species diversity over time in the Jewel-Easter cave system.

4.1 Water quality

Water quality in the aquatic cave environment highly reflects on the physico-chemical properties of the water source. Generally, these properties are influenced by the chemical elements involved in precipitation, leeching, infiltration and mineral compositions in subsurface rock (Camacho et al., 2006). The groundwater quality between Jewel-Easter Cave and Yanchep Caves were remarkably distinct in their ionic composition, which shows that Jewel Easter Cave is truly unique compared to that of Yanchep caves in their physicochemical environments. Labyrinth cave also represented similar physico-chemistry to Jewel-Easter, however this groundwater habitat is already dry. Once Jewel-Easter has lost its groundwater, this will be the last habitat of this physico-chemical condition (Fig.23).

The main contributing factors to this ionic distinction between caves were magnesium and nitrate ionic concentrations (Figures 24 and 25). Elevated magnesium concentration distinguished the Jewel-Easter and Labyrinth groundwater environments from all the other groundwater environments while raised nitrate levels were the main physico-chemical properties characterizing the groundwater environments of Twilight Cave and Lot 51 in Yanchep.

4.2 Water quality and contributing factors

Different rocks possess varied levels of magnesium and are therefore present in groundwater bodies in varying amounts, depending on the hydrogeological interaction between subsurface rocks and groundwater (Camacho et al., 2006). It is possible that the elevated magnesium concentrations relate to the properties of Leeuwin Naturaliste Ridge, a long hydrogeological history and interaction between rock and water of Augusta Water Table Caves (Jewel-Easter and Labyrinth). These concentrations are different to those observed in Lake Cave, where magnesium levels are closer to those in Yanchep (Figure 24). Elevated nitrate levels may be an indication of surface catchment activities that have influenced an influx of organic nutrients into the caves (Knott et al., 2008). These effects are likely to become accelerated if nutrient loading continues as water level becomes increasingly shallow (Knott et al., 2008), but overall, groundwater level does not seem to influence a change in background groundwater ionic concentrations. Therefore, the loss of groundwater from the cave systems appears to be the primary threat to stygofauna communities as there is little evidence of a decline in water quality as a result of groundwater decline in the caves over time (English 2000).

4.3 Water quantity changes over time

Undoubtedly, loss of groundwater in cave systems is accelerated by climate change induced rainfall decline in the southwest Western Australia (Eberhard 2004). Between 1979-1980, groundwater recharge rates of Jewel-Easter had reduced by 29%, following a 20% decrease in winter rainfall from 1968 (Eberhard 2005). Cape Leeuwin has continued to exhibit drying conditions with increased temperatures and reduced rainfall throughout recent history, which is reflected in reduced groundwater levels in Leeuwin Naturaliste Ridge.

The measured groundwater level in Jewel-Easter Cave shows a series of peaks and troughs that are replicated, although slightly muted, with background variations projected from the 'simulated' Cumulative Rainfall Departure trend (Fig. 38). The 'measured' trend shows a decline in rainfall in 1987 that steers away from the 'simulated' trend. At this time, Cape Leeuwin rainfall increased from 1010.8mm between 1987-1993 to 1105mm between 1988-1992. This trend of increasing rainfall is not reflected in the 'measured' groundwater trend, but is actually represented as a decline instead at this time (Fig. 39). By the early 90's the measured groundwater level has clearly parted with the trend of the simulated water level, indicating a severe drop in groundwater level, far lower than the simulated water level (Fig. 39). This groundwater decline proposes consideration for anthropogenic factors, such as tree plantations and changes to fire regime that are speculated to contribute to the abstraction of cave groundwater (English 2000, Giller et al., 2004).

4.4 Water quantity and stygofauna

The data presented in this thesis suggest that groundwater is likely the most crucial factor influencing the presence or absence of stygofauna (Fig. 36) (Eberhard 2002) as stygofauna depend on a sustainable source of groundwater to survive (Eberhard 2004, English 2000, Jasinska 1997). In each location sampled in Leeuwin Naturaliste Ridge and Yanchep caves, biodiversity has decreased dramatically over time and has paralleled diminishing groundwater levels. Decreased biodiversity, especially in confined ecosystems, is known to negatively affect ecosystem function (Gamfeldt et al., 2008). Stygofauna of Jewel-Easter Cave has become critically endangered in the last 28 years due to a drop in groundwater level of more than 1 metre (Eberhard 2005). It appears that all caves are producing the same pattern of reduced biodiversity to a point where there will soon be no species left as groundwater completely diminishes, however, Jewel-Easter system will be the first to have no stygofauna left.

Species with undetermined ecological grouping (stygophile, stygobite, stygoxene or epigean) were found to be most common, which is likely associated with the limited knowledge on each species surveyed in Leeuwin Naturaliste Ridge. Stygoxenes were not listed as an ecological group found in the caves, but may be represented by 'undetermined' (Fig. 36). The most highly adapted species, stygobites, are most commonly found in the absence of tree roots. Interestingly, this was also the case for epigean species, which are not adapted to cave environments. This may be because species from surface habitats had not yet found a food source in the cave environment. However, stygophilic species, which are also less adapted to subterranean habitats, are most commonly found in tree roots, although they do possess some forms of adaptation (Eberhard 2004). As groundwater declines, the amount of potential food energy will decrease and the habitat for tree root dependent and tree root independent species will diminish, causing stress in an already stressful environment (Howarth 1993, LefÉBure et al., 2006). Furthermore, stygofauna are unlikely to recolonise after a period of drought because of the separation between cave systems, which makes dispersal impossible between cave habitats (Bayly 1975, Eberhard 2004, English

2000, Howarth 1993, Humphreys 1995, Townsend 1980) rendering species vulnerable to extinction. Jewel-Easter cave also sits on underlying granite basement rock, which suggests there is no further refuge for stygofauna inhabitants once groundwater is completely lost (Eberhard 2004).

4.5 Water quantity and contributing factors

Two main factors thought to contribute to reduced groundwater levels in the caves are changes to the landscape including the development of tree plantations and changes to fire regimes. It is possible that groundwater recovery levels have been challenged by the development of plantations around 1990 in the Jewel Easter catchment, 1km down gradient of Jewel-Easter Caves (Fig. 7) (Eberhard 2011). Additionally, a lack of fires in the karst catchment has increased interception and evapotranspiration of rainfall before the water can reach the cave system (Eberhard 2005).

Figure 40 shows a flow chart that represents various contributing factors to the health of a GDE. It shows that climate is the driver of the ecosystem, influencing rainfall and fire regime. Groundwater dependent species are able to live with adequate groundwater amongst groundwater dependent vegetation, or tree root mats. This provides energy to the ecosystem, shelter, a habitat and a chemical balance, i.e.- dissolved oxygen and a structure for the food web. When the groundwater declines, these tree roots are unable to reach the groundwater and are unable to form the basis for the ecosystem. From here, the ecosystem suffers, as a major ecosystem engineer is lost.

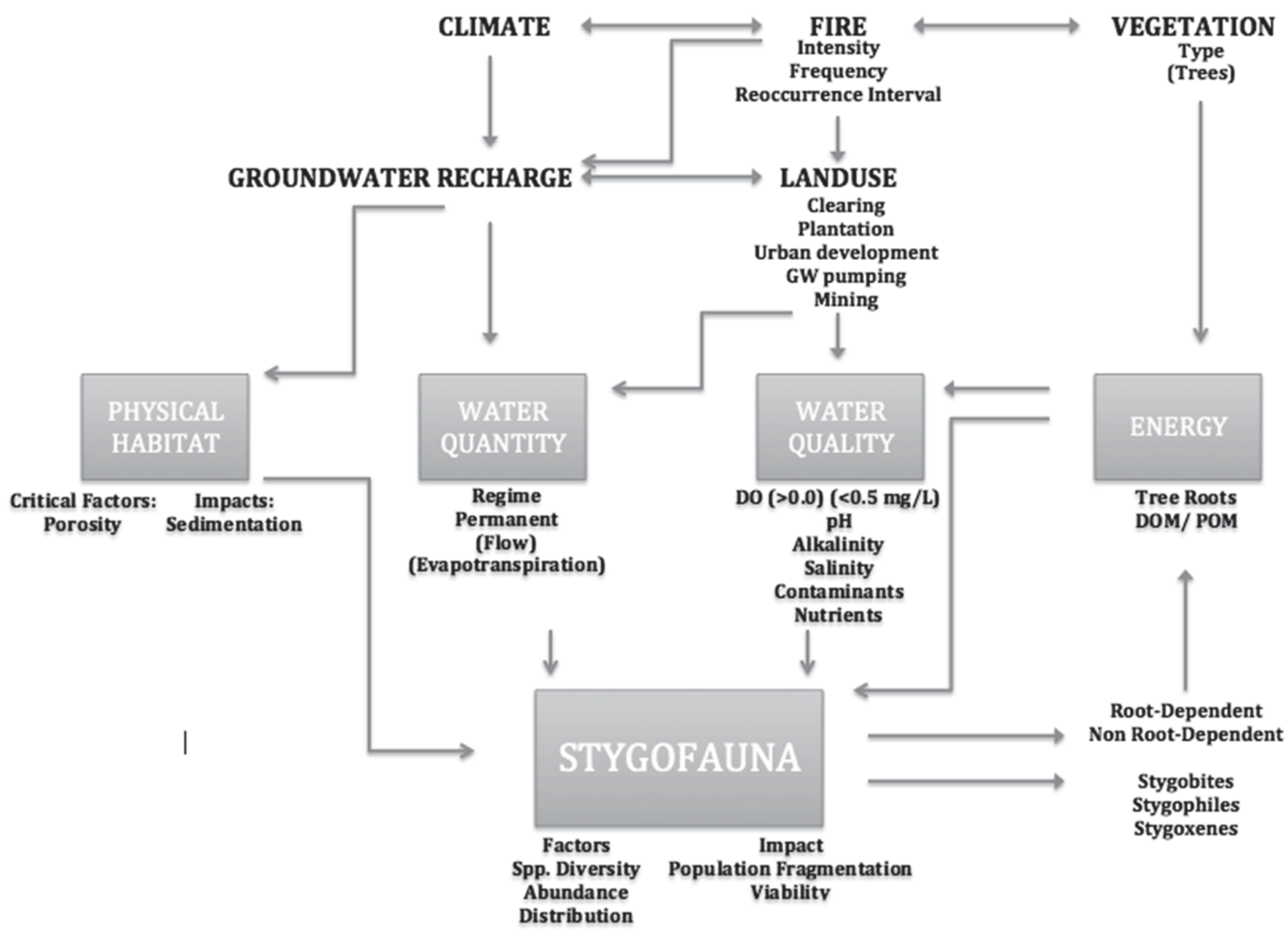

Figure 41: Major contributing factors to the health of GDE's. Climate and vegetation type are major drivers of the fire regime, which directly affect groundwater recharge quantity and quality as well as the presence of groundwater dependent vegetation, which in turn creates a stable environment for stygofauna.

5. RECOMMENDATIONS

All groundwater dependent ecosystems should be considered as individual entities, based on the unique physicochemical and faunal assemblages found in each system. In the case of Leeuwin Naturaliste Ridge root mat communities, each cave contains a different community composition and at least one species that is found in no other cave (English 2000). Therefore, development of management plans should address the properties of each ecosystem respective to these factors.

As the development of dense pine plantations are likely to contribute to a lowered water table if placed within the hydrological watercourse of the caves (English 2000), appropriate catchment management and planning should encompass further studies of cave geohydrology before allowing land owners to progress with plantation development. Another aspect of groundwater dependent ecosystem conservation should involve a dedicated approach to public awareness to prevent catchment mismanagement where possible (Boulton 2010).

6. CONCLUSION

This study successfully analysed the impacts of climate change on groundwater characteristics as well as changes to fauna over time in the Leeuwin Naturaliste Ridge karst area. In summary, the groundwater depth in the caves of Leeuwin Naturaliste Ridge has changed over time, in some instances, to the point that groundwater is no longer present in some caves. The physico-chemistry of each cave appear to be unrelated to changes in groundwater level, unless shallow groundwater habitats experience anthropogenic influences of organic nutrient loading. Faunal community composition in the caves has changed drastically over time, which is a likely reflection of declining groundwater level. Groundwater physico-chemistry in the caves does not appear to have changed over time or affected the presence of stygofauna communities.

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APPENDIX 1

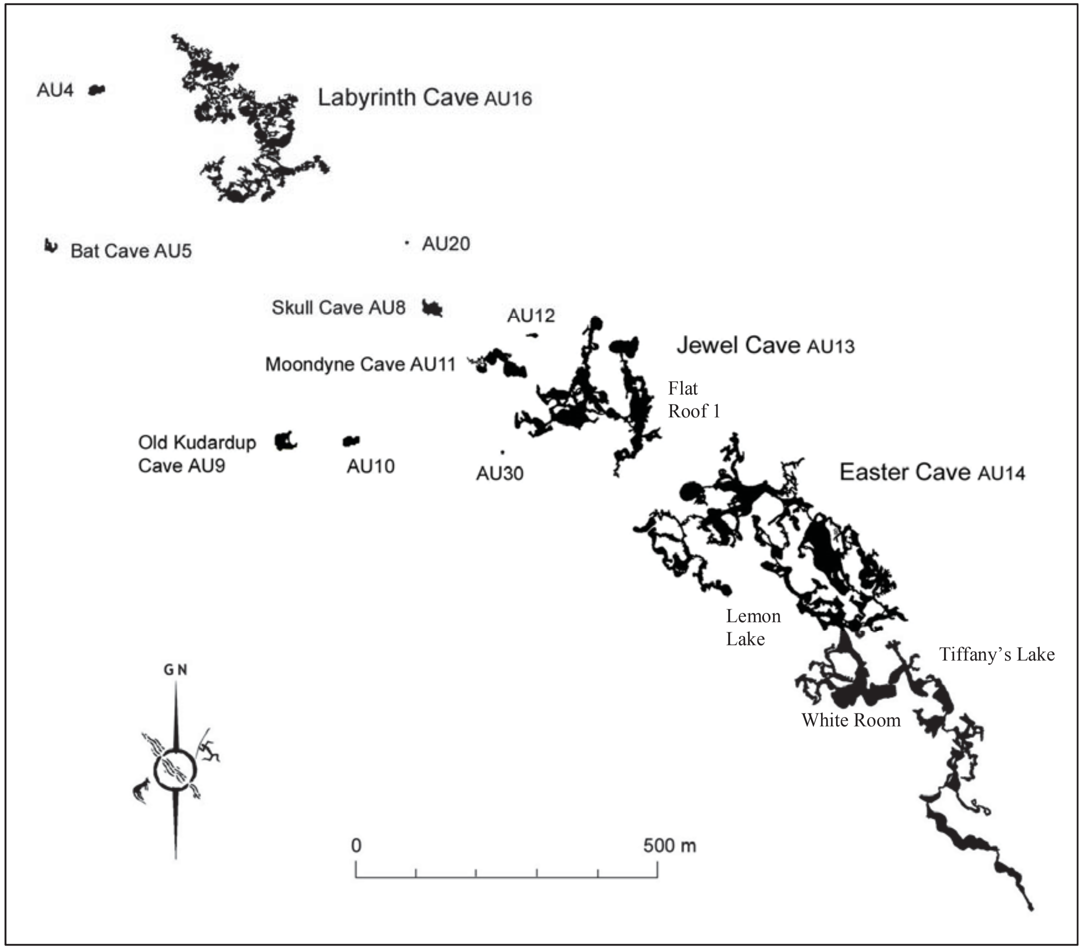

Figure A1. Augusta Water Table Caves with subsystems of Jewel Easter and Labyrinth with sampling locations from the July 2012 Survey, Easter Cave; Lemon Lake, Tiffany's Lake and White Room, and depth monitoring location of Flat Roof 1, Jewel Cave. Image adapted from Eberhard (2004).

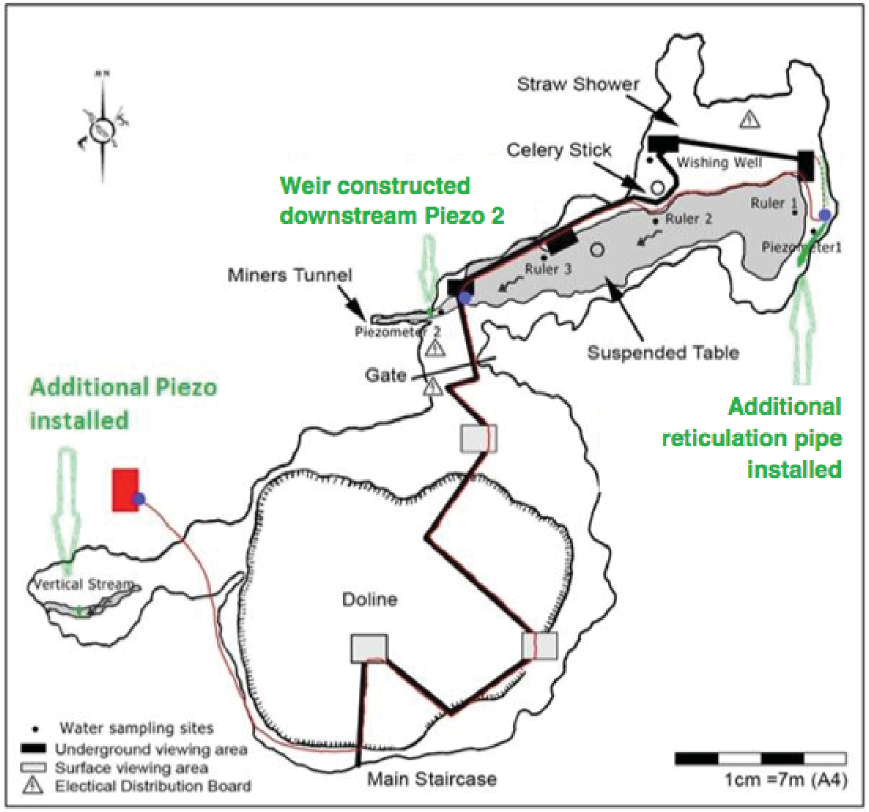

Figure A2. Lake Cave sampling sites, Ruler 1, Ruler 2, Ruler 3. Source; (Subterranean Ecology Pty Ltd and Augusta Margaret River Tourism Association 2011).

APPENDIX 2

Table A1. Preservatives used for fauna samples in Jasinska (1997), Eberhard (2004) and the most recent 2012 survey in Lake Cave.

	Preservative				
Study	**Acarina**	**Annelida, Mollusca, Platyhelminthe**	**Crustacea, Rotifera**	**Insecta, Tardigrada (in oart)**	**Nematoda, Tardigrada (in part), Cnidaria**
Jasinska (1997)	10% Acetic acid, 40% Glycerol, 50% Distilled water	Alcoholic Bouins (Brazil fluid) 2g Picric acid, 300mL Alcohol, 120mL Formalin, 30mL Acetic Acid	70% Alcohol, 5% Glycerol, 25% Distilled water	70% Alcohol, 30% Distilled water	30% Alcohol, 10% Formalin, 1% Propionic acid, 59% Water
Eberhard (2004)	50% glycerol, 10% acetic acid and 40% water.	Oligochaetes were preserved with Bouins solution (see above) for 1-3 days and then transferred into 70% ethanol.	Not identified	Not identified	Not identified
AMRTA, Subterranean Ecology	100% Ethanol (Lake Cave)	100% Ethanol (Lake Cave)	100% Ethanol (Lake Cave)	100% Ethanol (Lake Cave)	100% Ethanol (Lake Cave)

APPENDIX 3

Table A2. Compressed physico-chemistry dataset used for Primer analysis. Jewel and Easter data are grouped together as 'Jewel Easter'. Data between 1993-1996 is condensed. LNR= Leeuwin Naturaliste Ridge, Y= Yanchep, Sub.Ecol= Subterranean Ecology, AMRTA= Augusta Margaret River Tourism Association. E.C.= Electrical Conductivity.

Year	Data Source	Location	Av. pH	Av. Ca^{2+} mg/L	Av. Mg^{2+} mg/L	Av. Na^{2+} mg/L	Av. K^{+} mg/L	Av. SO_4^{2-} mg/L	Av. NO_3^{-} mg/L	Av. EC µS/cm	Av. D.O. mg/L	Av. Temp°
1993-1996	Jasinska	JewelEaster/LNR	7.2	111	47.75	512.5		89		2513	7.825	17
1999	Eberhard	JewelEaster/LNR	7.35	125	49.5	517.5	10.75	97.25	0.4	2773		
2000	Eberhard	JewelEaster/LNR	7.12	125.2	47	396.7	9.3	81.2	0.6	2636		17.4
2012	AMRTA/Sub.Ecol.	JewelEaster/LNR	7.31	157	54	483	16	91		3209	2	18.65
1999	AMRTA/Sub.Ecol.	Lake/LNR	6.6	31	17	140	4	29				
2000	AMRTA/Sub.Ecol.	Lake/LNR	6.6	35	16.5	135	3	30				
2011	AMRTA/Sub.Ecol.	Lake/LNR	6	14.8	23.1	189.8	3.8	24.1		1207		15.7
1999	Eberhard	Labyrinth/ LNR	7.6	110	39	340	10	100	0.3			
1994	Jasinska	Cabaret/Y	6.72	53	9	46	2			440	6.9	19
1995	Jasinska	Cabaret/Y	6.83	52	5	50	2			440		18
1996	Jasinska	Cabaret/Y	6.8	35	5	45	2	8		440		19
1998	K.S.T	Cabaret/Y		36	5	55	2	8	0.17			
2000	K.S.T	Cabaret/Y	9.49	27	6	49	2	9	0.19	397	6.8	16.9
2001	K.S.T	Cabaret/Y	7.5	44	5	50	2	10	0.13	450	8.9	16
2002	K.S.T	Cabaret/Y	7.14	42	6	53	3	10	0	506	5.85	17.8
2003	K.S.T	Cabaret/Y	7.45	32.1	5.3	44.6	1.4	15.8	0.01	463	7.4	13.4
2004	K.S.T	Cabaret/Y	7.95	44.7	6.3	52.8	1.9	11.8	0.01	504	8.3	16.8
2005	K.S.T	Cabaret/Y	7.72	35	5.8	53	2.2	12	0.09	512	3.7	14.6
2006	K.S.T	Cabaret/Y	7.37	32.9	5.6	51.8	2.2	10.3	0.07	440	6.8	15.74
2007	K.S.T	Cabaret/Y	7.08	35.9	6	52.8	2.3	10.5	0.08	520	10.2	15.5

Year	Data Source	Location	Av. pH	Av. Ca^{2+} mg/L	Av. Mg^{2+} mg/L	Av. Na^{2+} mg/L	Av. K^{+} mg/L	Av. SO_4^{2-} mg/L	Av. NO_3^{-} mg/L	Av. EC µS/cm	Av. D.O. mg/L	Av. Temp°
1994	Jasinska	Carpark/Y	7.1	92	11	58	2	9		590	8.8	18.7
1996	Jasinska	Carpark/Y	7.18	45.5	6	51	2	9		530		18.5
2000	K.S.T	Carpark/Y	9.24	31	6	51	2	8	0.09		2.8	17.8
2001	K.S.T	Carpark/Y	6.66	36	5	52	3	9	0.11		6.9	18
2002	K.S.T	Carpark/Y	7.3	61	8	62	2	11	0.07		6.15	18.5
2003	K.S.T	Carpark/Y	8.17	33.4	4	37.7	1.3	11.4	0.04		6.8	17.1
2004	K.S.T	Carpark/Y	7.64	56.9	5.8	57.9	1.8	9.1	0.12		9.1	16.8
2005	K.S.T	Carpark/Y	8.04	94.5	10.6	109	3.6	18.3	0.07		3.6	15.9
2006	K.S.T	Carpark/Y	7.69	63.9	6.4	69.1	2.2	10.6	0.03		6.7	18.03
2007	K.S.T	Carpark/Y	7.25	58.3	6.2	75.7	2.5	11.5	0.02		6.7	17.1
2002	K.S.T	Lot 51/Y	6.65	78	6	98	2	21	1.6	893	8.2	14
2003	K.S.T	Lot 51/Y	7.86	108	11.6	264	1.6	99.3	0.93	810	3.3	13.5
2004	K.S.T	Lot 51/Y	7.67	81.8	6.5	105	1.8	22.8	1.36	2682	7.9	16.6
2005	K.S.T	Lot 51/Y	7.47	128	14.6	323	2.1	51.8	0.88	956	1.5	14.3
2006	K.S.T	Lot 51/Y	8.56	75.6	6.2	85.9	2	18.2	0.99	2397	7.2	19.4
2007	K.S.T	Lot 51/Y	7.46	85.8	7.6	90	1.9	13.8	0.85	875	9.1	14.4
1994	Jasinska	Gilgie/Y	7.09	105	14	65	2	11		740		18.1
1996	Jasinska	Gilgie/Y	7.32	79.5	11	69	3	17.5		810		18
2002	K.S.T	Orpheus/Y	7.81	75	7	79	3	19	0.05	710	3.2	18.1
2003	K.S.T	Orpheus/Y	8.26	55	5.2	61.7	1.7	23.2	0.03	636	3.7	17.7
2004	K.S.T	Orpheus/Y	7.54	64.5	5.8	71.3	2.3	17	0.08	768	4.85	19.01
2005	K.S.T	Orpheus/Y	7.94	60	5.3	76	2.3	18.5	0.09	746	2.7	18.27
2006	K.S.T	Orpheus/Y	7.33	65.2	6	67.7	2.3	16.1	0.05	846	7.1	22.2
2007	K.S.T	Orpheus/Y	7.53	65.5	6.3	72.9	2.4	16.3	0.11	734	6.1	18.5
2002	K.S.T	Mire Bowl/Y	7.14	70	7	51	2	12	0.08	598	6.4	18.8
2003	K.S.T	Mire Bowl/Y	7.96	55	6.7	54.3	2	19.6	0.02	769	2.8	17.6

Year	Data Source	Location	Av. pH	Av. Ca^{2+} mg/L	Av. Mg^{2+} mg/L	Av. Na^{2+} mg/L	Av. K^{+} mg/L	Av. SO_4^{2-} mg/L	Av. NO_3^{-} mg/L	Av. EC µS/cm	Av. D.O. mg/L	Av. Temp°
2004	K.S.T	Mire Bowl/Y	7.52	61.6	7.2	48.2	2.4	11.6	0.04	621	11.1	18.6
2005	K.S.T	Mire Bowl/Y	7.67	56.1	6.7	53.1	2.7	12.1	0.01	620	2	18
2006	K.S.T	Mire Bowl/Y	0	0	0	0	0	0	0	0	0	0
2007	K.S.T	Mire Bowl/Y	7.38	59.4	6.3	53.1	3.5	17	0.28	607	6.3	18.1
2000	K.S.T	Water/Y	9.42	28	4	43	2	6	0.08	413	4.2	18.6
2001	K.S.T	Water/Y	7.39	50	6	56	2	9	0.09	519	6.2	18.6
2002	K.S.T	Water/Y	7.31	48	5	54	2	9	0.09	519	5.5	
2003	K.S.T	Water/Y	7.88	36.6	3.9	39.3	1.4	11.1	0.04	576	4.4	18.5
2004	K.S.T	Water/Y	7.68	45.8	4.6	48.4	2.1	7.5	0.11	570	5.3	18.7
2005	K.S.T	Water/Y	7.7	44.2	4.2	49	2.3	6.8	0.1	526	2.8	18.9
2006	K.S.T	Water/Y	7.29	44.6	5.4	54.1	3.3	6.4	0.12	508	5.6	19.07
2007	K.S.T	Water/Y	7.19	44.5	5.4	61.8	2.6	7.5	0.14	545	7.3	19
1994	Jasinska	Twilight/Y	7.31	113	13	67	2	12		740	6.2	18
1995	Jasinska	Twilight/Y	7.15	93	8	75	2			740		17
1996	Jasinska	Twilight/Y	7.15	74	8	72.5	2.5	13.5		750		18.2
2000	K.S.T	Twilight/Y	9.49	53	7	67	2	25	1	755	5.6	16
2001	K.S.T	Twilight/Y	7.51	98	9	94	2	33	0.75	902	7.6	14.9
2004	K.S.T	Twilight/Y	7.67	84.9	7.4	88	2.3	31.5	3.89	936		
2005	K.S.T	Twilight/Y	7.72	77.7	7.1	91	2.3	25.6	4.2	922	2.7	15

APPENDIX 4

Table A3. Physico-chemistry dataset of Jewel Easter with expanded values between 1993-1996 and subsequent data. LNR= Leeuwin Naturaliste Ridge, AMRTA= Augusta Margaret River Tourism Association. E.C.= Electrical Conductivity.

Year	Data Source	Location	Max Depth mm	Av. pH	Av. Ca^{2+} mg/L	Av. Mg^{2+} mg/L	Av. Na^{2+} mg/L	Av. K^{+} mg/L	Av. SO_4^{2-} mg/L	Av. NO_3^{-} mg/L	Av. E.C. µS/cm	Av. D.O mg/L	Av. Temp°
1993	Jasinska	JewelEaster/LNR	1413	7.5	111	54.5	565		89		2525		17
1994	Jasinska	Jewel Easter/LNR	1349	6.9								7.85	17.6
1995	Jasinska	Jewel Easter/LNR	1255	7.2		41	460				2500	7.8	16.5
1996	Jasinska	Jewel Easter/LNR	1179										
1997	AMRTA	Jewel Easter/LNR	1157	.	.	.	.	.	.	.	.	.	.
1998	AMRTA	Jewel Easter/LNR	1142	.	.	.	.	.	.	.	.	.	.
1999	Eberhard	Jewel Easter/LNR	1182	7.35	125	49.5	517.5	10.75	97.25	0.4	2773	.	17.4
2000	Eberhard	Jewel Easter/LNR	1234	7.12	125.2	47	397	9.3	81.2	0.6	2636	.	17.5
2001	Eberhard	Jewel Easter/LNR	1233	7.21	.	.	.	.	.	.	3044	.	.
2003	Eberhard	Jewel Easter/LNR	990	.	.	.	.	.	.	.	.	.	.
2004	AMRTA /Sub.Ecol.	Jewel Easter/LNR	785	.	.	.	.	.	.	.	.	.	.
2005	AMRTA /Sub.Ecol.	Jewel Easter/LNR	612	.	.	.	.	.	.	.	.	.	.
2006	AMRTA /Sub.Ecol.	Jewel Easter/LNR	540	.	.	.	.	.	.	.	.	.	.
2007	AMRTA /Sub.Ecol.	Jewel Easter/LNR	367	.	.	.	.	.	.	.	.	.	.
2008	AMRTA /Sub.Ecol.	Jewel Easter/LNR	331	.	.	.	.	.	.	.	.	.	.
2009	AMRTA /Sub.Ecol.	Jewel Easter/LNR	256	.	.	.	.	.	.	.	.	.	.
2010	AMRTA /Sub.Ecol.	Jewel Easter/LNR	213	.	.	.	.	.	.	.	.	.	.
2012	AMRTA /Sub.Ecol.	Jewel Easter/LNR	106	7.31	157	54	483	16	91	.	3209	2	18.65

APPENDIX 5

Table A4. Fauna and physico-chemistry data that has been grouped or removed in order to increase the integrity of the data.

Year	Data source	Cave	What happened
1992	Jasinska (1997)	Easter	1992-1996 has been labelled 1996 so it can be matched up with fauna dataset
1993	Jasinska (1997)	Easter	1993 in the MDS plot represent 1993-1996, but are only named 1993 for ease of visual interpretation.
1994	Jasinska (1997)	Easter	The value for SO_4^{2-} was moved from 1996 to 1994 and is now just called 1994
1994	Jasinska (1997)	Carpark	Values from Carpark 1995 have been removed and were added to 1994 so it matches with fauna data
1994	Jasinska (1997)	Twilight	Have grouped pysico-chemistry 1992-1996 data under 1994
1996	Jasinska (1997)	Gilgie	Only using this data for physico-chemistry to match it up with a single set of fauna data
1998	Knott, Storey, Tang (2007)	Carpark	The fauna data of 1998 has been placed in Carpark 1994-1996 so that all species are accounted for
2000	Eberhard (2004)	Jewel	The two groups of data obtained were pushed into one set. (One of the sets included 3 species and one included 6, the 3 species were pushed into the set with the other 6)
2001	Jasinska (1997) /Knott Storey Tang (2007)	Orpheus	Fauna data removed for the period of 1996-2001
2001	Jasinska (1997) /Knott Storey Tang (2007)	Mire Bowl	Fauna data removed for the period of 1996-2001
2003	Knott, Storey, Tang (2007)	Twilight	Fauna data removed
2004	Knott, Storey, Tang (2007)	Twilight	Fauna data removed
2006	Knott, Storey, Tang (2007)	Twilight	Fauna data removed
2007	Knott, Storey, Tang (2007)	Twilight	Fauna data removed

APPENDIX 6

Table A5. Average recorded magnesium concentrations in each LNR and Yanchep cave between 1993-2012.

$Mg2^{+}$ (mg/L)	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
JewelEaster	54.5		41				49.5	47												54
Labyrinth							39													
Lake							17	16.5											23.1	
Cabaret		9	5	5		5		6	5	6	5.3	6.3	5.8	5.6	6					
Carpark		11		6				6	5	8	4	5.8	10.6	6.4	6.2					
Lot 51										6	11.6	6.5	14.6	6.2	7.6					
Gilgie		14		11																
Orpheus										7	5.2	5.8	5.3	6	6.3					
Mire Bowl										7	6.7	7.2	6.7		6.3					
Water								4	6	5	3.9	4.6	4.2	5.4	5.4					
Twilight		13	8	8				7	9			7.4	7.1							

Table A6. Average recorded nitrate concentrations in each LNR and Yanchep cave between 1993-2007. Data for nitrate samples post 2007 was not possible to obtain for the timeframe of this project. Note that there is no Lake cave nitrate data.

$NO3^{-}$ (mg/L)	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
JewelEaster							0.4	0.6												
Labyrinth							0.3													
Cabaret						0.17		0.19	0.13		0.01	0.01	0.09	0.07	0.08					
Carpark								0.09	0.11	0.07	0.04	0.12	0.07	0.03	0.02					
Lot 51										1.6	0.93	1.36	0.88	0.99	0.85					
Orpheus										0.05	0.03	0.08	0.09	0.05	0.11					
Mire Bowl										0.08	0.02	0.04	0.01		0.28					
Water								0.08	0.09	0.09	0.04	0.11	0.1	0.12	0.14					
Twilight								1	0.75			3.89	4.2							

Table A7. Average recorded sodium concentrations in each LNR and Yanchep cave between 1993-2012.

$Na2^+$ (mg/L)	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
JewelEaster	565		460				517.5	397												483
Labyrinth							340												189	
Lake							140	135												
Cabaret		46	50	45		55		49	50	53	44.6	52.8	53	51.8	52.8					
Carpark		58		51				51	52	62	37.7	57.9	109	69.1	75.7					
Lot 51										98	264	105	323	85.9	90					
Gilgie		65		69																
Orpheus										79										
Mire Bowl										51	54.3	48.2	53.1		53.1					
Water								43	56	54	39.3	48.4	49	54.1	61.8					
Twilight		67	75	72.5				67	94			88	91							

Table A8. Average recorded calcium concentrations in each LNR and Yanchep cave between 1993-2012

$Ca2^+$ (mg/L)	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
JewelEaster	111						125	125.2												157
Labyrinth							110													
Lake							31	35											14.8	
Cabaret		53	52	35		36		27	44	42	32.1	44.7	35	32.9	35.9					
Carpark		92		45.5				31	36	61	33.4	56.9	94.5	63.9	58.3					
Lot 51										78	108	81.8	28	75.6	85.8					
Gilgie		105	79.5																	
Orpheus										75	55	64.5	60	65.2	65.5					
Mire Bowl										70	55	61.6	56.1		59.4					
Water								28	50	48	36.6	45.8	44.2	44.6	44.5					
Twilight		113	93	74				53	98			84.9	77.7							

Table A9. Average recorded Dissolved Oxygen in each LNR and Yanchep cave between 1993-2012. Note there is no D.O. data available for Lake or Gilgie caves.

D.O. (mg/L)	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
JewelEaster		7.85	7.8																	2
Cabaret		6.9						6.8	8.9	5.85	7.4	8.3	3.7	6.8	10.2					
Carpark		8.8						2.8	6.9	6.15	6.8	9.1	3.6	6.7	6.7					
Lot 51										8.2	3.3	7.9	1.5	7.2	9.1					
Orpheus										3.2	3.7	4.85	2.7	7.1	6.1					
Mire Bowl										6.4	2.8	11.1	2		6.3					
Water								4.2	6.2	5.5	4.4	5.3	2.8	5.6	7.3					
Twilight		6.2						5.6	7.6				2.7							

Table A10. Average recorded sulfate concentrations in each LNR and Yanchep cave between 1993-2012.

SO42⁻ (mg/L)	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
JewelEaster	89						97.25	81.2												91
Labyrinth							100													
Lake							29	30											24.1	
Cabaret				8		8		9	10	10	15.8	11.8	12	10.3	10.5					
Carpark		9		9				8	9	11	11.4	9.1	18.3	10.6	11.5					
Lot 51										21	99.3	22.8	51.8	18.2	13.8					
Gilgie		11		17.5																
Orpheus											23.2	17	18.5	16.1	16.3					
Mire Bowl										12	19.6	11.6	12.1		17					
Water								6	9	9	11.1	7.5	6.8	6.4	7.5					
Twilight		12		13.5				25	33			31.5	25.6							

Table A11. Average recorded pH in each LNR and Yanchep cave between 1993-2012.

pH	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
JewelEaster	7.5	6.9	7.2				7.35	7.12	7.21											7.31
Labyrinth							7.6													
Lake							6.6	6.6											6	
Cabaret		6.7	6.83	6.8				9.49	7.5	7.14	7.45	7.95	7.72	7.37	7.08					
Carpark		7.1		7.18				9.24	6.66	7.3	8.17	7.64	8.04	7.69	7.25					
Lot 51													7.47	8.56	7.46					
Gilgie		7.09		7.32																
Orpheus										7.81	8.26	7.54	7.94	7.33	7.53					
Mire Bowl										7.14	7.96	7.52	7.67		7.38					
Water								9.42	7.39	7.31	7.88	7.68	7.7	7.29	7.19					
Twilight		7.31	7.15	7.15				9.49	7.51			7.67	7.72							

Table A12. Average recorded Electrical Conductivity in each LNR and Yanchep cave between 1993-2012.

E.C.	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
LNR																				
JewelEaster	2525		2500				2773	2636	3044											3209
Lake																			1207	1480
Yanchep																				
Cabaret		440	440	440				397	450	506	463	504	512	440	520					
Carpark		590		530																
Lot 51										893	810	2682	956	2397	875					
Orpheus										710	636	768	746	846	734					
Mire Bowl										598	769	621	620		607					
Water								413	519	519	576	570	526	508	545					
Twilight		740	740	750				755	902			936	922							

Table A13. Average recorded temperature (degrees Celsius) in each LNR and Yanchep cave between 1993-2012.

Temp	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
JewelEaster	17	17.6	16.5				17.4	17.5												18.65
Lake																			15.7	
Cabaret		19	18	19				16.9	16	17.8	13.4	16.8	14.6	15.74	5.5					
Carpark		18.7		18.5				17.8	18	18.5	17.1	16.8	15.9	18.03	17.1					
Lot 51										14	13.5	16.6	14.3	19.4	14.4					
Gilgie		18.1		18																
Orpheus										18.1	17.7	19.01	18.27	22.2	18.5					
Mire Bowl										18.8	17.6	18.6	18		18.1					
Water								18.6	18.6		18.5	18.7	18.9	19.07	19					
Twilight		18	17	18.2				16	14.9				15							

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