REVIEW OF KARST HAZARDS IN THE WANNEROO AREA, PERTH, WESTERN AUSTRALIA

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EXECUTIVE SUMMARY

Within the Perth region, a karst belt lies 5 km inland from the coast and stretches for approximately 24 km in a north-west to south-east direction (Figure 2.1). This area comprises one main geological unit; the Tamala Limestone surrounded by residual sands formed from the erosion of the limestone.

The Tamala Limestone is a porous rock prone to solution by weakly acidic water such as groundwater and rainfall. These waters circulate though cracks and pores within the limestone aiding the Carbonic acids in these waters to remove the calcium carbonate from the limestone by solution. This process is known as karst weathering

There are many distinctive landform features that define karst terrains including: sinkholes (dolines), caves, dry valleys, tube structures, vaults and solution flutes.

Known karst hazards in Wanneroo include; holes developing on private property, a rock fall, exposed caves with inappropriate coverings, and roads and houses built over caves and pinnacles. These hazards pose a risk to the community as personal, structural and environmental damage may occur.

A karst hazard map of the Wanneroo area, Perth, W.A, has been developed as numerous lakes, caves and sinkholes exist. Increased housing developments and the subdivision of land pose a threat to the Wanneroo rural community as education regarding karst terrains is limited.

There are numerous ways of minimising the risk of karst hazards and they include education, completing geotechnical reports and placing warning signs, fences and barriers in cavernous areas. The subdivision of land should rely on karst knowledge as well as a karst hazards database.

The karst hazard map and report are intended to provide regional karst awareness within the Wanneroo Local Government Area and to promote the need for proper karstic documentation, hazard management and prevention measures. The information provided is only a start to the documentation process and does not include all karst features, as approximately 750 caves exist in the Yanchep and Wanneroo region. A Karst Hazard brochure has also been developed to educate communities within Australia about the risk of living on karst terrains.

ACKNOWLEDGEMENTS

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As well as Lex, I would also like to thank Bob Gozzard, from the Geological Survey of Western Australia for inputting his invaluable knowledge of karst terrains. The time you both took to show me karst hazards around Perth, W.A. was greatly appreciated.

A thank-you goes to Phil Calley and Phil Thompson from the Wanneroo Council. The provision of information about Wanneroo and karst concerns was highly valued.

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INTRODUCTION

1.1 BACKGROUND

Geoscience Australia's Urban Geohazards Group is assessing the risk of natural hazards to the Perth community through its Risk Modelling Project and Cities Perth Project. Natural hazards including flood, earthquake, landslide, severe wind and storm tide are studied on a regional scale in collaboration with State and Local Government Departments, the Fire and Emergency Service Authority of Western Australia (FESA), the Bureau of Meteorology and local stakeholders. The Project aims to increase awareness and understanding of natural hazard impacts. It also examines better ways in addressing the risks posed by natural hazards by providing policy makers and hazard managers with tools and information that will assist in mitigation. The ultimate outcome is the reduction of loss of life, property damage and economic disruption associated with natural hazards.

1.2 URBAN/REGIONAL SETTING

The City of Wanneroo is situated approximately 20 km north of Perth, Western Australia and has an approximate population of 88,401. The Local Government Areas (LGA's) in Perth increased in population by 7.3% during 1996-2001 (ABS, 2003). The pressure of new developments and the subdivision of land pose a risk to the Wanneroo community due to its geological setting. Numerous lakes, caves and sinkholes exist in Wanneroo as a result of the underlying carbonate bedrock which contains karst features. Urbanisation of karst regions is a geological hazard affecting 10% of the global population (Jennings, 1971).

In Australia, approximately 15% of the continent is karstic. However, due to a thick blanket of Quaternary sediments, only around 4% is exposed and mapped (Figure 1.1), (Gillieson & Spate, 2003). Australia's karstic areas are concentrated along the southern margin with the Nullarbor karst being one of the largest karst regions in the world. Small karstic regions are intermittently distributed around the eastern and western margins of Australia.

Figure 1.1 Distribution of karst in Australia

1.3 HAZARDS ASSOCIATED WITH URBANISATION ON KARSTIC AREAS

Karst terrains are driven by the hydrological cycle and generally refer to limestone regions with distinctive hydrology and landforms, resulting from increased rock solubility and heightened secondary porosity (Ford and Williams, 1989). Karstification results from geochemical, climatological and geomorphological processes that affect and expose soluble rock, soil and alluvium (Atapur and Aftabi, 2002).

Karst regions are sporadically distributed over the Earth and are generally located between 30º and 50º latitude north (Komatina, 1975). However, karst is encountered at all elevations and geographic latitudes that favoured the right climatic and geotectonic environments for carbonate deposition, followed by flowing water (Komatina, 1975).

There are many distinctive landform features that define karst terrains including: sinkholes (dolines), caves, dry valleys, tube structures, vaults and solution flutes (Figure 1.2a and b). Deep water tables, large springs and disappearing streams are also common characteristics (Atapur and Aftabi, 2002).

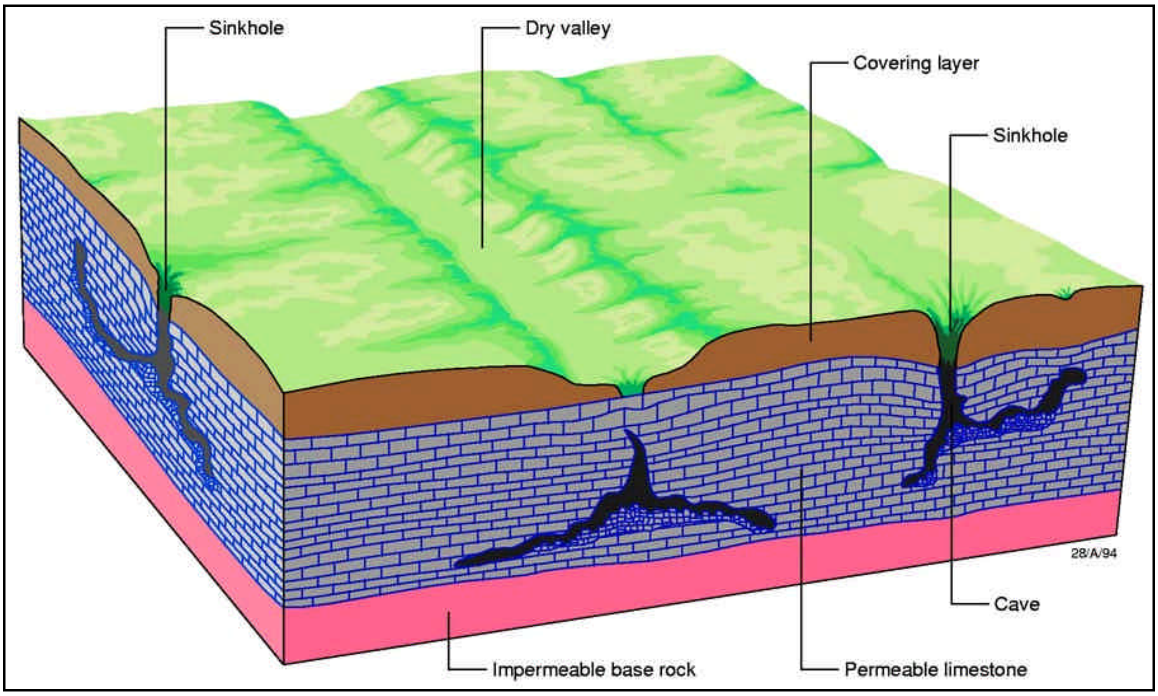

Figure 1.2a Block diagram of a karst terrain with varied karstic features and topography.

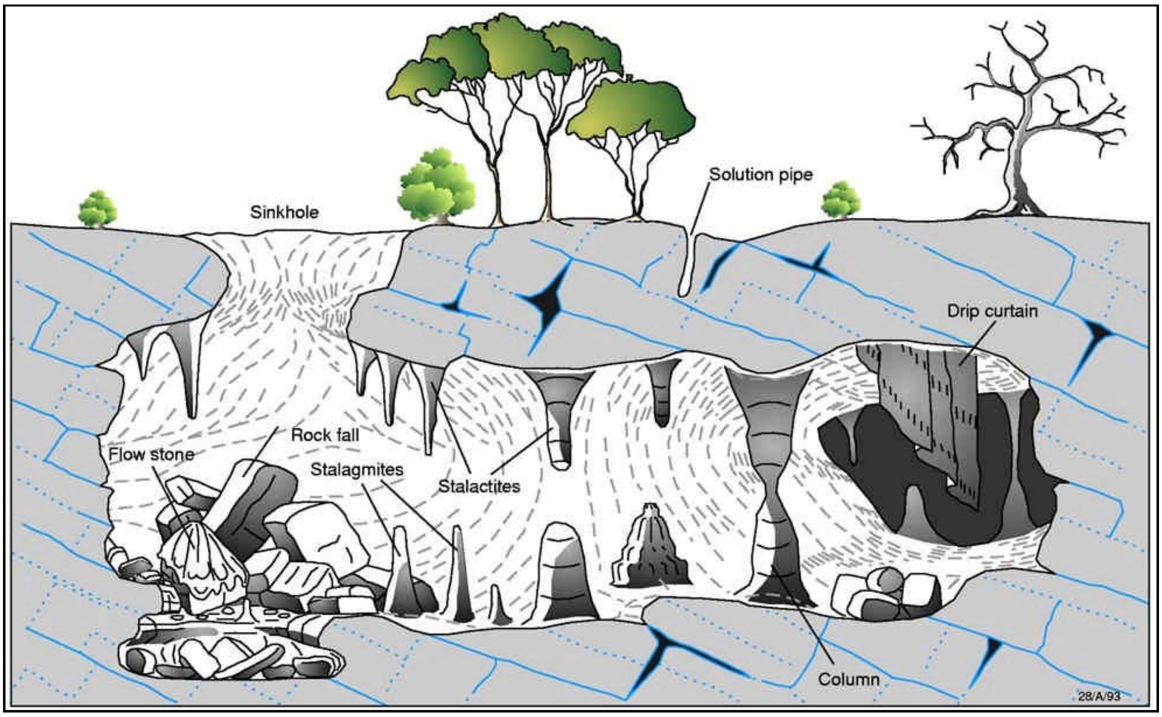

Figure 1.2 b Schematic diagram of a 2-D, karst terrain with caves, solutions pipes and sinkholes

Often it is hard to separate human and natural impacts. However, human impacts occur at a faster rate than natural ones (Williams, 1993). Human induced impacts in karst environments have occurred due to cave occupation, deforestation, quarrying, mining, water exploitation, agriculture, urbanisation, tourism and recreation (Williams, 1993).

Human made impermeable surfaces such as highways, roofs and parking lots redirect runoff into various sinks posing a threat when the water table is low (Ford and Williams, 1989). Rerouting of stormwater can cause soil piping under neighbouring properties and damage properties outside their margins (White, 1988). Sinkholes can be associated with building failure, groundwater contamination and the draining of lakes and ponds (Thomas and Roth, 1999). Urbanization of karst terrains has caused flooding, pollution and ground collapse (Ford and Williams, 1989).

Surface collapse can be triggered by various mechanisms such as: wetting - including rainfall and snowmelt; droughts which result in drying; shaking by earthquakes; and loading by construction (Salvati and Sasowsky, 2002). However, a void must pre-exist. Loading events of small magnitude are a common cause for the formation of sinkholes. Human induced dynamic loading, blasting, vibrating equipment and vibro-compaction are frequent triggers, as are small earthquakes (Tharp, 1999). Air pressure sent transiently through a cave system produces stress below the soil voids and frequently causes partial soil structure collapse. This increases pore pressure, resulting in greater pore pressure gradient at the surface (Tharp, 1999). When structural failure occurs, it most likely related to pre-existing cavities or voids or overburden (Atapur and Aftabi, 2002).

Caves represent potential ground stability hazards to surface structures and engineering work (Wilson *et al.*, 1995). Caves and karst regions have been globally recognised as a geologic hazard with collapse and subsidence being of greatest concern (White, 1988). Collapse potential can only be evaluated by the nature and distribution of cave types within the region (Wilson *et al.*, 1995).

1.4 AIMS

This project has been carried out as part of Geoscience Australia's Graduate Program. The City of Wanneroo expressed concerns to the Geohazards Group regarding the hazards associated with urbanisation on karstic areas. Limited published work exists for the Wanneroo region and most knowledge is anecdotal. Therefore the aims of this project are:

- To identify the hazards associated with urbanisation of karstic areas in Wanneroo
- To identify ways at reducing karst-associated hazards
- To produce a karst hazard map (Appendix 2)

This report is intended to provide regional karst awareness within the Wanneroo Local Government Area and to promote the need for proper karstic documentation, hazard management and prevention measures. In addition to the report, a brochure 'Karst Hazards' was developed to promote karst awareness in Australia.

CHAPTER TWO

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GEOLOGICAL SETTING

2.1 INTRODUCTION

Within the Perth region, a karst belt lies 5 km inland from the coast and stretches for approximately 24 km in a north-west to south-east direction (Figure 2.1). This area comprises one main geological unit; the Tamala Limestone surrounded by residual sands formed from the erosion of the limestone. This unit has been mapped at a scale of 1:50,000 by the Geological Survey of Western Australia (GSWA) in their Environmental Geology Series (Gozzard, 1982a,b,c).

2.2 REGIONAL GEOLOGY

The Tamala Limestone (LS1 on the Environmental Geology Series) is composed of medium to course grained Aeolian calcareous sandstone to sandy limestone (calcarenite). The Tamala limestone's carbonate content varies dramatically, ranging from 30% to greater than 80%. However, the Tamala limestone averages 60-70% carbonate, containing molluscs and foraminifers, as well as minimal quartz and feldspar (Semeniuk and Johnson, 1982). The limestone was formed from the Spearwood Dune System by cementation of calcium carbonate (Playford *et al.*, 1976).

The Spearwood Dune System is a late Pleistocene formation, believed to have formed during the Pleistocene Wurm Glacial Period when sea levels were lower than the present (Teichert, 1967). Within the Perth Basin, the formation was deposited as a series of coastal sand dunes representing successive lines of late Pleistocene dunes. The most extensive being the Spearwood Dune System (Playford *et al.*, 1976).

The dunes follow an east-west trend and correspond to the ridges within the Spearwood Dune System and groups of ridges within the younger Bassendean Dune System. This trend shadows the ages of residual sand after the dissolution of carbonate from the dune ridges that formed behind Pleistocene shorelines (Bastian, 1996). Residual sand may accumulate over the limestone due to continuous exposure. The thickness of sand is inversely proportional to the grade of the limestone. A low-grade limestone usually has a thick sand cover due to its high concentration of insoluble material (Bastian, 1996).

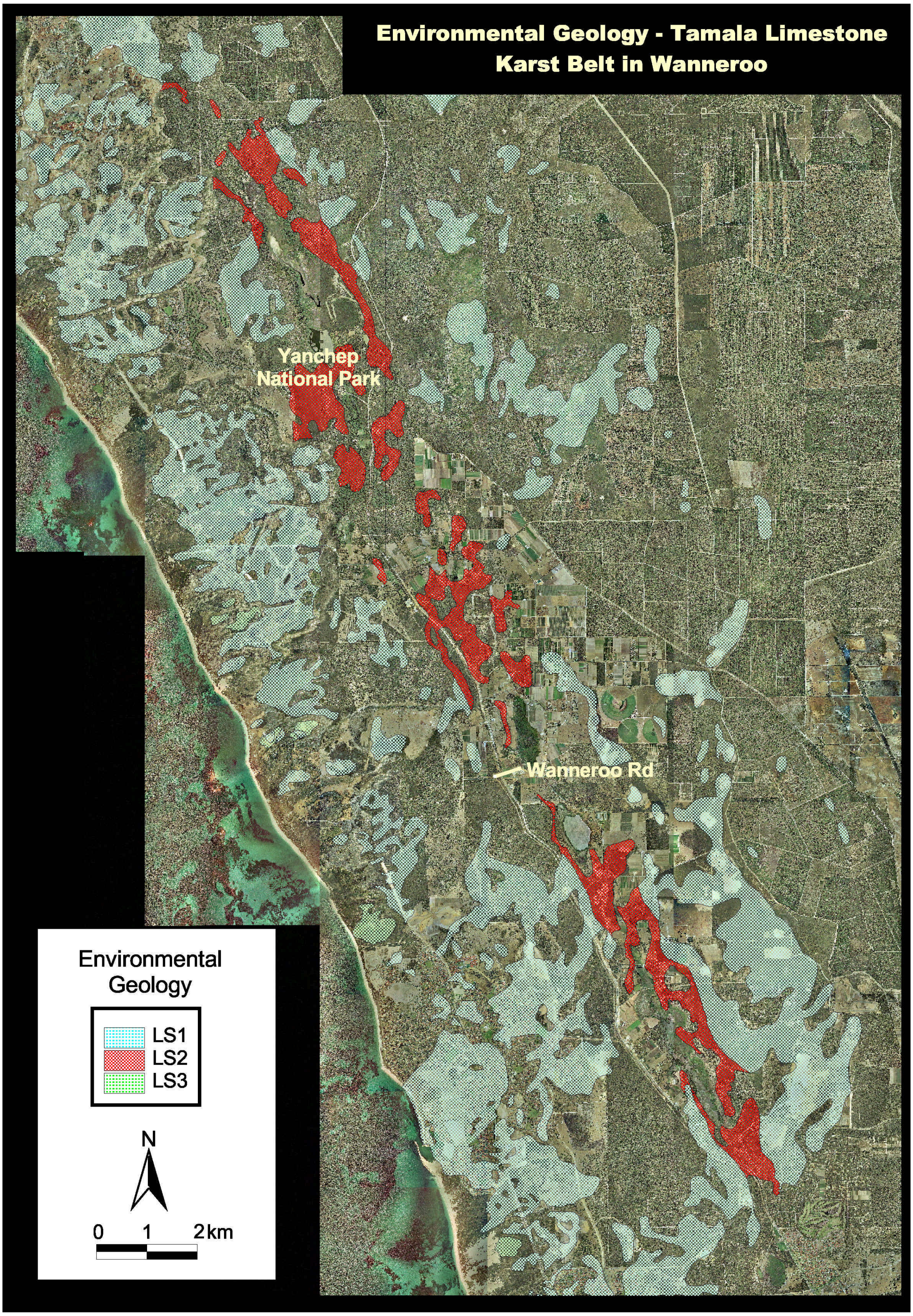

Figure 2.1 Karst belt in Wanneroo. LS 1-3 represents the Tamala Limestone. LS2 marks the karst belt.

At the surface, the Tamala Limestone is frequently leached resulting in a residue of yellow to white quartz sand. The contact between unleached limestone and the residual sand is irregular (Playford *et al.*, 1976). Calcium carbonate is leached out from the upper levels of the dune system and is redeposited around tree and plant roots. This blocky calcrete layer, known as kunkar, eventually thickens to form pinnacles (Figure 2.2), pipes and cap rock (Bastian, 1996).

Figure 2.2 Typical exposure of pinnacles within the Tamala Limestone.

Within the upper layers of the dune, calcified plant root systems (rhizoconcretions) are common and display strong evidence for the youth of the dune system. With depth, their abundance decreases. Pinnacles from older dune belts are exposed revealing substantial vertical erosion of the limestone from the original dune surface level (Bastian, 1996).

In the easternmost region of the dune system, cave development is not common as the watertable is in the Sand Formation below the base of the limestone (Bastian, 1991).

2.3 KARST GEOLOGY

The Tamala Limestone is a porous rock prone to solution by weakly acidic water such as groundwater and rainfall. These waters circulate though cracks and pores within the limestone aiding the Carbonic acids in these waters to remove the calcium carbonate from the limestone by solution (Appendix 1). This process is known as karst weathering.

LS2 in the Environmental Geology Series (Gozzard, 1982a,b,c) marks a karst belt displaying sinkholes and caves. As karst landforms are prone to rapid change due to weathering processes, LS2 may presently cover more area than what was mapped in 1982. The compositions of LS1 and LS2 are the same. However, LS2 has a greater carbonate content (~ 80%), enabling it to go into solution easily (Bastian, 2003).

Within the Spearwood Dune System, the karst belt runs in a south-west to north-east direction and represents an interdune swale. This area is prone to karst features as the low topography enabled groundwater to interact with the limestone. On the neighbouring dunes, the limestone sits higher and therefore limits limestone-groundwater contact. At present, karstification processes are not active due to extremely low groundwater levels. Karst features may still appear due to climate and environmental changes as well as varied land use practices (Bastian, 2003).

The point that marks the contact between the groundwater and the base of the limestone is associated with dramatic topographic and vegetative changes (Figure 2.3). As groundwater attacks the limestone, epiphreatic cave development proceeds (Bastian, 1990).

In Wanneroo, karstic activity has been dominated by previous high groundwater levels (Bastian, 2003). This has caused many caves and sinkholes to form. Overtime, some of these karst features have been blanketed with sand and soil, hiding their appearance and covering up potential hazards.

Figure 2.3 The rounded and smooth limestone at the base of the cave wall marks the contact where groundwater used to flow.

CHAPTER THREE

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REVIEW OF KARST HAZARDS IN WANNEROO

3.1 INTRODUCTION

Wanneroo Rd marks the western boundary of the karst belt, mapped out by Gozzard, 1982a,b & c. The karst belt extends from Yanchep National Park to the south of Flynn Drive. This area is predominantly rural comprising of hobby farms and national parks. The study area has been limited to the eastern side of Wanneroo Rd between Bernard St and Flynn Dr. Examples of hazards in Yanchep National Park have also been included as they exemplify potential hazards that could occur within the Wanneroo rural karst zone.

Detailed mapping by Lex Bastian revealed a karst hazard zone in the Carabooda region (Figure 3.1), (Bastian, 2003). Due to development pressures, the subdivision of land in this zone is highly sought out and no formal documentation process for karst hazards has been implemented. Consequently, there is an absence of published knowledge of karst hazards within this region. The following case studies, documented by Lex Bastian, will provide an insight to the hazards associated with development in karstic areas.

3.2 HOLES/COVER COLLAPSE SINKHOLES

3.2.1 Case Study 1 - Tintara

On the 22nd November 1999, a 3m x 2m hole developed on Tintara - a property on the eastern side of Wanneroo Rd. The sprinkler system was left on for hours and during this time, the hose detached from the sprinkler, saturating the top half meter of soil. Below this zone the soil was dry. The hole developed in the middle of a grassy area (Bastian, 2003). For this to have happened, a pre-existing cavity must have been present, in-filled with soil. The excess water concentrated within a small area, washing and draining the soil down the cavity. Limestone boulders and soil were used by the owner o fill up the hole.

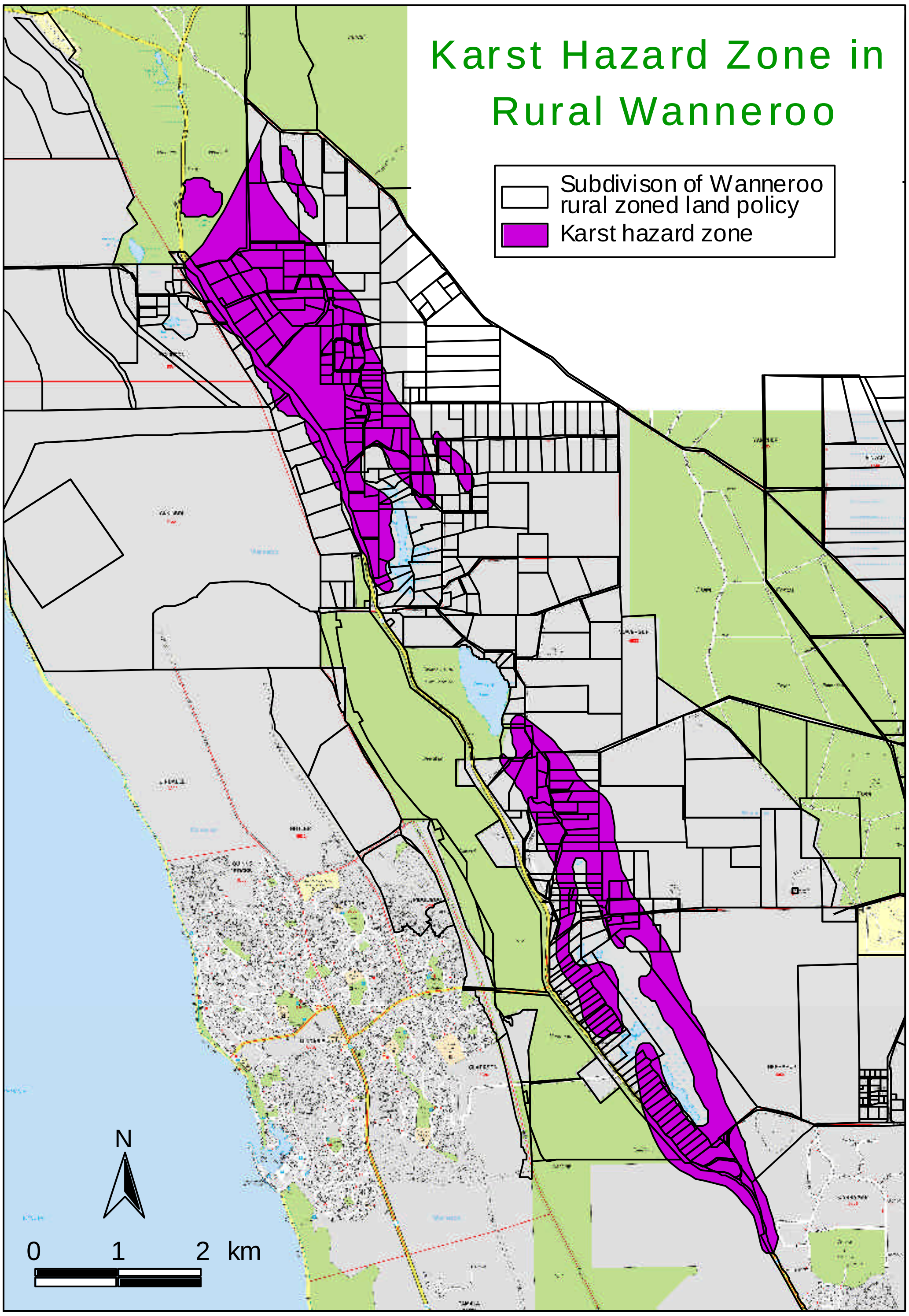

Figure 3.1 Karst Hazard Zone in rural Wanneroo. (Mapped by Lex Bastian).

3.2.2 Case Study 2 – Trian St

On the 4th January 1999, a 6.3 m deep hole developed next to a shed entrance on a property in Trian St (Figure 3.2). This hole was 2 m in diameter and formed when a water pipe burst, flooding the area. The area was flooded overnight and in the morning the hole was observed (Bastian, 2003). The hole formed in a similar way to Case Study 1 and was filled up by the owner with limestone blocks and soil, leaving a slight depression.

Figure 3.2 Photo and schematic picture of the hole on the Trian St property. The white circle marks a slight depression where the hole formed.

3.2.3 Case Study 3 – Yanchep National Park

A sandy road leads to the workshop compound at Yanchep National Park off Yanchep Beach Rd. Within the workshop area, a bitumen road is present; allowing trucks access to the workshop. In July 1997, a hole 4m deep and one meter in diameter, opened up in the road within the workshop compound (Figure 3.3), (Bastian, 2003). Unlike Case Study 1 and 2, this hole did not form from water saturation. A pre-existing cavity must have been present and it can be surmised that the soil had poor soil structure due to the bitumen covering. Vibrations from vehicles entering and leaving the workshop most likely loosened the soil, allowing it to move down the cavity until all soil had piped down and left the road above the hole unsupported. Eventually, the unsupported road gave way, leaving a hole.

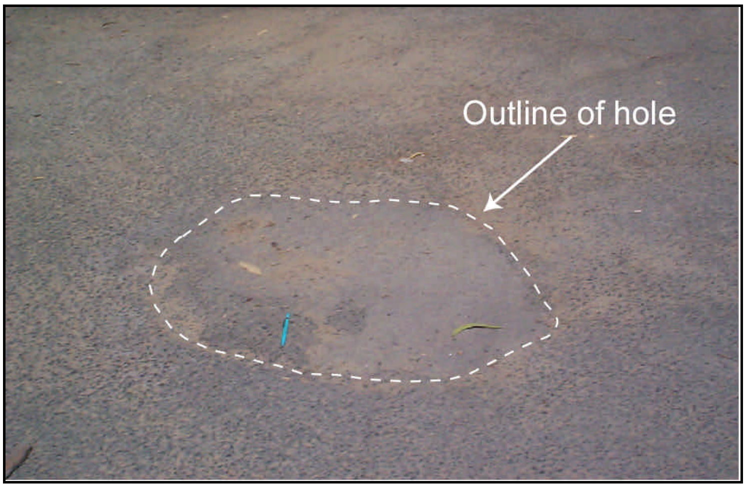

Figure 3.3 Photo of where the hole in the Yanchep workshop compound was.

3.3 ROCK FALL

2.3.1 Case Study 1 - Cabaret Cave

On the 9th June 1995, a major rock fall occurred at Cabaret Cave, Yanchep National Park (Bastian, 2003). This site was undergoing construction at the time, but no-one was injured as the rock fall occurred overnight. Tree roots gradually wedged the rock apart causing limestone boulders up to 2.5m in diameter, to tumble down the rock face (Figure 3.4).

Figure 3.4 Rock fall at Cabaret Cave in Yanchep National Park

3.4 EXPOSED CAVES

Over the last decade, Lex Bastian has mapped out most of the caves within the Wanneroo Local Government Area (LGA). There are approximately 750 caves within this region, ranging in size from the large show caves at Yanchep National Park to small caves around 1m in height and depth (Bastian, 2003).

Caves occur on both private and state property in the Wanneroo area. Usually, large caves do not pose a hazard as their locations are obvious to the eye. However, smaller caves can be hidden by shrubs, grass or other human made objects which can increase the hazard as most are not marked or fenced.

3.4.1 Case Study 1 – Tintara

The Tintara property, has exemplified many karst features including fissures, holes and caves. Most of the caves are fissure type, resembling a chimney straight into the ground. Two caves in Tintara were covered up by a broken sheet of asbestos with shrub and grass growing over the top (Figure 3.5a). This is a hazard as the caves are partially concealed and not fenced or signed. Moreover, the current cover would probably not support the weight of an adult person (Figure 3.5b).

Figure 3.5a Cave on Tintara with broken covering and shrubs **Figure 3.5b** Current covering is inefficient

3.4.2 Case Study 2 – Emerald Estate

Emerald Estate is a new housing development within the rural karst belt of Wanneroo. It borders Yanchep National Park and has a high concentration of karstic features. Within the estate, approximately 48 caves have been identified (Figure 3.6). Upon entering Emerald, there are no warning signs about caves or other karst features. None of the caves are marked, signed or fenced. This is a hazard as both property owners and visitors may be unaware of the terrain, potentially leading to injury. Lighting at night is scarce and walking through properties is unsafe.

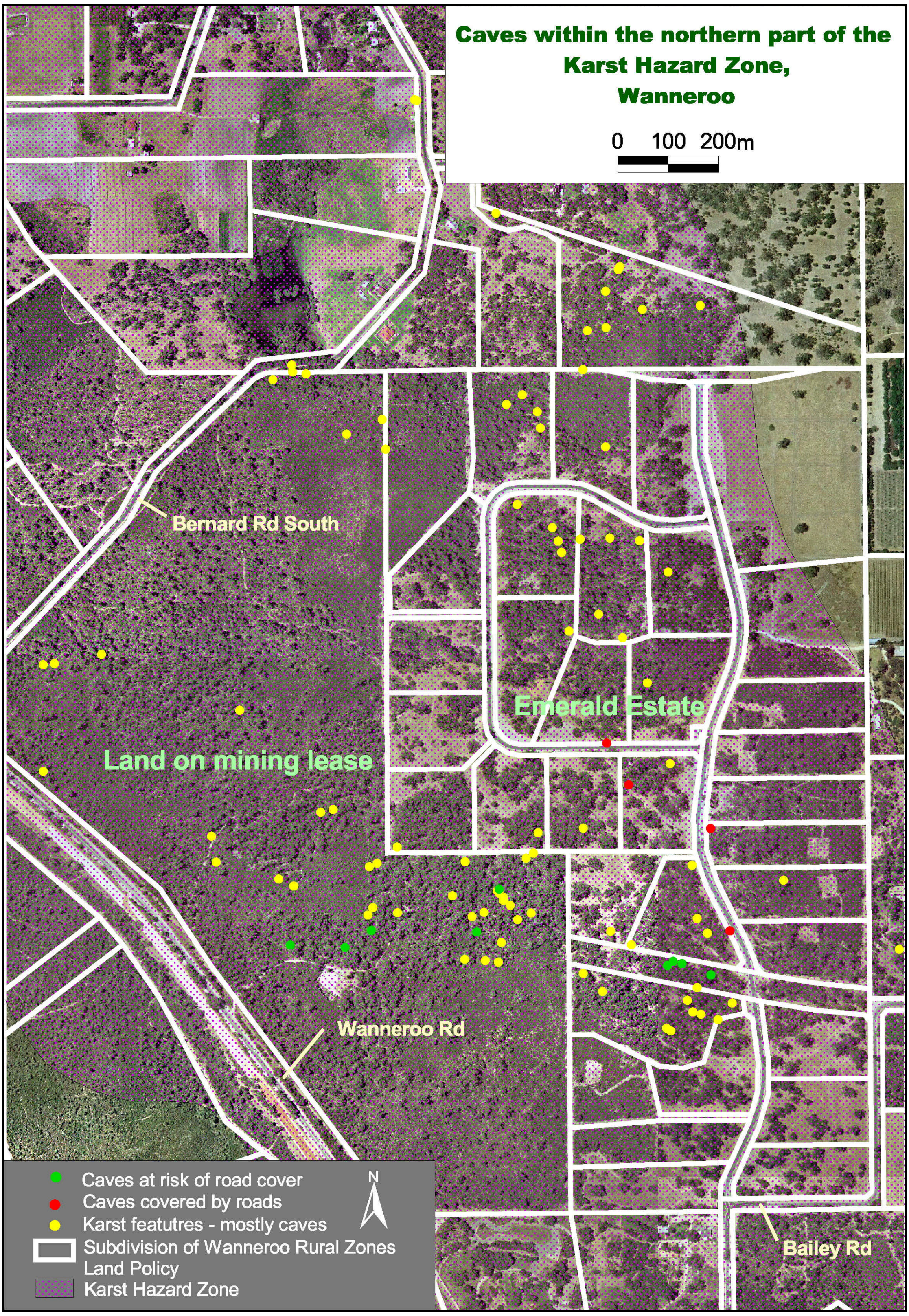

Figure 3.6 Location of caves within Emerald Estate (mapped by Lex Bastian)

A small sinkhole at Emerald, roughly 2m in diameter was filled with rubble. Within the sinkhole a cave approximately 8m in depth exists (Figure 3.7). The entrance hole to the cave was originally small (child size), sloping into the cave. However, by tipping rubble into the sinkhole, the cave entrance increased in size and currently an adult can fit through the hole (Bastian, 2003). The rubble has also caused the cave entrance to now be vertical. This feature has now been left in a more dangerous condition due to the partial filling of the hole and changing the size and gradient of the cave entrance.

Figure 3.7 Sinkhole with limestone rubble and vertical cave entrance

3.4.3 Case Study 3 - Bernard Rd South

A fissure type cave, 4m in depth is situated approximately 50cm off Bernard Rd South (Figure 3.8). It is not marked or covered and could be a hazard if cars were to pull over or park on the side of the road. Vibrations from cars could alter the cave structure, enlarging it or causing it to cave in.

Figure 3.8 Fissure type cave bes ide Bernard Rd South

3.4.4 Case Study 4 – Mining lease land

The block of land adjacent to Emerald Estate is currently controlled by a mining lease. Numerous small caves occur on this land and most are partially concealed due to a covering of grass (Figure 3.9).

Figure 3.9 Typical exposure of a discreet caves

This block of land is highly vegetated and contains caves with numerous openings. Figure 3.10 shows one of the eight entrances to Tuarts cave. These vertical openings are fissure type and are up to 5m in depth. As this land is adjacent to Emerald Estate, it may be hazardous if members of the community explore the land as no signs or barriers exist around caves.

Figure 3.10 One of the eight entrances to Tuarts Cave

3.5 GROUND SUBSIDENCE

When groundwater levels are high, the karst weathering process occurs at the base of caves - where limestone and groundwater interact. When calcium carbonate goes into solution, gradual subsidence occurs.

3.5.1 Case Study 1 – Cabaret Cave

The pillars at the entrance of Cabaret Cave exemplify gradual subsidence within this cave system. These pillars, made of limestone blocks, were human made and were joined to the base and roof of the cave. Over time, gradual subsidence has led to gaps forming between the roof of the cave and the top of the pillars (Figure 3.11).

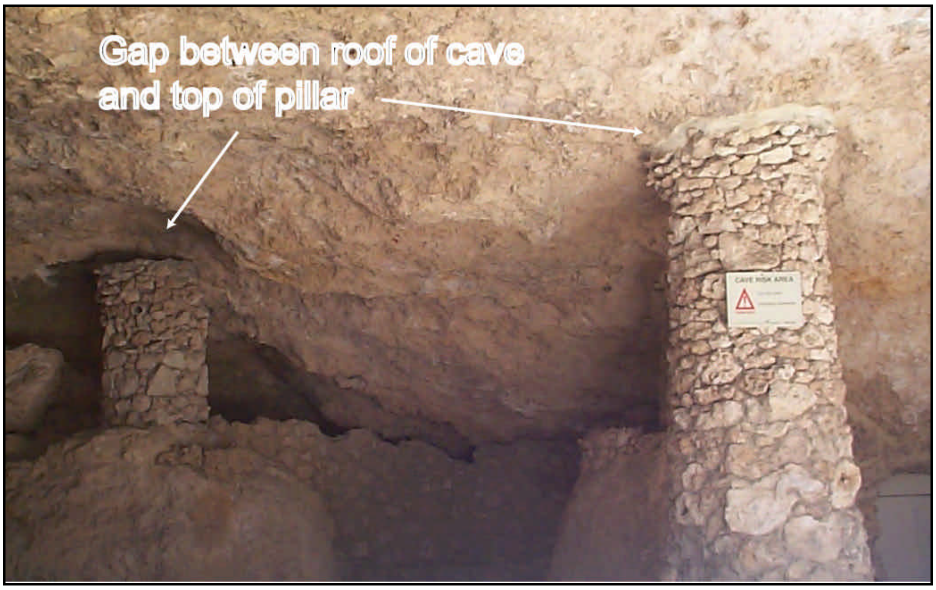

Figure 3.11 Pillars at Cabaret Cave. The left pillar has a gap between the roof of the cave and the top of the pillar. The pillar on the right does not have a gap as it has been filled in.

3.5.2 Case Study 2 - Rural land use

There are many hobby farms within Wanneroo and land use plays an important role in karst hazard prevention. Vegetated land holds soil together as well as increases soil structure. When the ground is bare, there is nothing holding the soil together and with increased rain or floods (natural or human made), the soil has a greater potential to be washed down a pre-existing cavity. This could lead to holes forming in the ground, similar to those described in Section 3.2. During parts of the year, the soil within the hobby farms is bare (Figure 3.12).

Figure 3.12 Un-vegetated land between plantings in hobby farms within Wanneroo

The holes that formed on the rural properties in Section 3.2 occurred due to an increase in water, concentrating on a small area of land. These case studies demonstrate that water should not be concentrated to one spot on karstic land. Figure 3.13 shows an inefficient sprinkler system off Bernard Rd South. The green grass shows that water is concentrated in these areas. With increased watering, subsidence may occur. However, this can only happen if is a pre-existing cavity is below.

Figure 3.13 Inefficient sprinkler system concentrating water within a small zone

Ground subsidence can cause structural damage to roads and houses. The tilting of fence posts as well as cracks along mortar joints and in pavements are indicators for ground subsidence (Figure 3.14).

Figure 3.14 Schematic diagram representing cracks in masonry and tilting fences due to ground subsidence.

3.6 INFRASTRUCTURE OVER KARST FEATURES

3.6.1 Building on pinnacles

The limestone within the Wanneroo area contains an abundance of pinnacles. When developing infrastructure it is important that these pinnacles are identified. With increased rain or erosion, the soil between the pinnacles can be removed causing a cavity. Figure 3.15 depicts how pinnacles are situated in the ground. The lines down the cutting are solution flutes which provide a method for transporting water and soil. Building over pinnacled ground, can cause structural damage from subsidence.

Figure 3.15 Most pinnacles in Wanneroo and below ground level. This photo depicts how pinnacle are situated in the ground with solution flutes running down the cutting.

3.6.2 Houses over caves

Within Emerald Estate, a house was built over a fissure type cave (Bastion, 2003). Although the surface of the cave was filled in, movement down the fissure may occur. If the caves structural integrity is reduced then structural damage to the house will possibly occur, similar to Figure 3.13. However, more damage may occur if the cave collapses as the structural foundations to the house will be removed.

3.6.3 Roads over caves

Caves represent zones of potential structural failure. Bastian (2003), revealed that the main road that runs through Emerald Estate passes over at least two caves. Both cave entrances have been covered up in the construction of the road. This is a hazard as monitoring the cave's stability cannot occur and structural failure cannot be predicted. The proposed road alignment of Alkimos Drive potentially covers approximately 5 caves (Bastian, 2003).

Figure 3.16 is a photo of a road collapse in Two Rocks. This site is on Holocene Limestone which is a lot more friable that the Pleistocene limestone within the karst belt. Nevertheless, it depicts the hazards associated with road collapse and potential social, economic and environmental disruption.

Figure 3.16 Road collapse in Holocene limestone at Two Rocks

CHAPTER FOUR

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MINIMISING KARST HAZARDS IN WANNEROO

4.1 INTRODUCTION

Following the Gracetown tragedy in 1996, local councils have focused on coastal cliff collapse, employing geotechnical consultants, signing coastal hazard zones and producing brochures on shore safety. Attention to inland karst hazards has not been given much attention as no major incident has occurred resulting in loss of life. However, the hazards associated with the inland rural karst belt have the potential to be great unless preventative measures are implemented in order to reduce economic, social and environmental disruption.

4.2 MINIMISING INLAND KARST HAZARDS

Local governments place a crucial role in tackling the environmental and engineering impacts of karst. Monitoring and mitigation opportunities are available as the majority of local governments control land use including subdivision, planning and land development (Devilbiss, 1995).

There are several preventative measures that can be implemented to reduce the hazards associated with karst in Wanneroo. These measures are discussed below.

4.2.1 Education

Public and community education is one of the greatest measures that can be implemented to reduce the risk of karst hazards. If landowners are educated about karst terrains, more caution would be given to development and land use practises.

At present, there is a lack of community education or acknowledgement of karst hazards. Whilst visiting the landowners that developed holes on their properties, it seemed that the attitude to the hole formation incidents were "it just happened and we don't know why".

It is important that emergency services are also educated about karst terrains. The fire brigade and State Emergency Services were unaware of the abundance of caves in the Wanneroo Area. If an emergency situation was to occur at night, they would be put at great risk as personal injury could occur due to lack of knowledge regarding karst features and locations.

It would be beneficial to educate the community through community presentations and school visits. The availability of information in the form of pamphlets or posters is equally important. An example of this type of pamphlet is the 'Karst Hazards" brochure produced by Geoscience Australia (Appendix 3). However, a more localised educational pamphlet, directed at Wanneroo, would directly benefit the community.

This pamphlet should inform the community about the hazards in Wanneroo, identifying karst hazards and provide information about how the community can minimise the risk of karst hazards. This would educate landowners on land use practices and what to do if a hazard occurred. It would also provide local contact details.

4.2.2 Geotechnical Reports

There have been no geotechnical reports documenting the stability of the rural karst limestone. If geotechnical consultants were employed to inspect and assess the hazards, recommendation would be made regarding community safety as well ways to reduce risk to the local council. All geotechnical reports completed for the Wanneroo Council have currently focused on coastal limestone hazards, not inland.

4.2.3 Warning signs, fences and barriers

Within Wanneroo, there are no warning signs, fences or barriers warning people to be careful when walking in the rural karst belt. Preventative signs such as “Keep Out” or “No Entry” are absent and informative signs such as “Caves and holes occur on this property. Be careful!” do not exist.

Signs and barriers inform people of the dangers and hazards associated with entering an area. However, they do not guarantee that these warnings will be observed. Signs within the rural karst belt should not be used to deny public access but should aid and alert people of the dangers associated with karst. For example, a sign at the entrance of Emerald Estate would inform people that this area is highly cavernous.

Protective barriers or fences should be placed around caves on private property. For example, a cave on Tintara has a well covering (Figure 4.1). This reduces the risk of falling into a cave and ensures that the cave remains protected. The council should make sure that caves on public land are marked, signed or fenced. For example, the cave alongside Bernard Rd South should have a fence or a sign marking the cave in order to alert drivers not to stop in this area.

Figure 4.1 Cave with well covering on Tintara. This ensures that the cave is not damaged or covered up and provides access into the cave for explorers.

4.2.4 Development and subdivision of land

When developing land within karstic terrains two questions must be asked: Firstly, will the proposed land use trigger sinkhole formation? And, Will in-filled sinkholes remain passive through the anticipated lifetime of the proposed land use? (Wilson *et al.*, 1995)

When subdividing land within the rural karst zone of Wanneroo, increased hazards may occur due to heightened development and infrastructure. It is important that geotechnical surveys are completed before planning and subdivision approval. Roads should not cover up caves, nor should houses. Karst features should be identified before developing land in order to prevent and minimise personal and infrastructure damage.

4.2.5 Karst hazard database

A karst feature and hazard database would benefit the local council as well as the emergency services as location of caves and hazards would be documented. Prior to this report, the Wanneroo council was unaware of the holes that developed on private property. There is no reporting or recording system of karst hazards implemented by the council.

A database would not only be useful for preventing current hazards. It would also aid town planners in the future as land use changes may occur. Knowing the location of caves or other karst features would also aid the council in determining if subdivision plans or development will be approved.

Setting up a page on the City of Wanneroo website for reporting sinkholes or hazards would aid in collating information about local incidents.

4.2.6 Cave protection

Caves have been scientifically and culturally recognised as integral components of the national ecosystem. Planned economic development as well deliberate vandalism has contributed to cave degradation (Jasinska and Knott, 1990).
Damage to caves should be considered and prevented when developing land. This would not only reduce the risk of structural failure but would protect the caves for the local and speleological communities.

Koala Cave contains the only koala fossils in Perth. This cave is both culturally and scientifically significant and it provides one of the only insights that koalas used to be part of the natural ecosystem in Perth. They are currently extinct. The proposed road alignment of Alkimos Drive covers this cave. By respecting the significance of this cave and others in the area, their protection would not preserve the cave but it would reduce the potential hazards of road collapse.

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APPENDIX ONE

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- LITERATURE REVIEW - KARST FORMATION, FEATURES AND GEOHAZARDS

INTRODUCTION

Karst terrains are driven by the hydrological cycle and generally refer to limestone regions with distinctive hydrology and landforms, resulting from increased rock solubility and heightened secondary porosity (Ford and Williams, 1989). Karstification results from geochemical, climatological and geomorphological processes that affect and expose soluble rock, soil and alluvium (Atapur and Aftabi, 2002).

There are many distinctive landform features that define karst terrains including: sinkholes (dolines), caves, dry valleys, tube structures, vaults and solution flutes. Deep water tables, large springs and disappearing streams are also common characteristics (Atapur and Aftabi, 2002).

Karst environments are vital for maintaining ground-water resources. However, they cause structural failure and sinks below urbanized areas; challenging urban planners and engineers. Consequently, karst environments are a serious geohazard as hazards occur impulsively and instantaneously (Atapur and Aftabi, 2002). They occupy approximately one quarter of the earth's surface (Thomas and Roth, 1999).

CARBONATE DISSOLUTION

Carbonates including calcite, aragonite, magnesium-calcium or dolomite are the main components of limestone. Carbonate rocks form at the final point of deposition in intrabasinal terrestrial marine environments and are prone to alteration post deposition (Sweeting, 1972). Karst limestone is predominantly 80 % or more calcite with some karst regions developed on dolomitic or magnesium limestone's (Sweeting, 1972). Calcium carbonate diffuses slowly in water and the diffusion rate is proportional to temperature. However, the speed and the turbulence of water is a controlling factor, as the diffusion of CO_2 cannot occur in a closed system where water is restricted to openings within the rock unit with limited oxygen (Jennings, 1971).

Vadose and phreatic waters circulate into soluble rock, producing cavities by solution (Atapur and Aftabi, 2002). In limestone, the circulation of water occurs in cracks, fissures and pore spaces within the unit. Therefore, regardless of the type of pore space, highly fissured rocks may be more soluble than less fissured ones (Sweeting, 1972). Poorly developed karsts occur in soluble rocks with great primary porosity. In contrast, soluble rocks with minor primary porosity that develop heightened secondary porosity, support well developed karst features (Ford and Williams, 1989). Within a rock mass, rock fractures represent planes of weakness, indicating potential flow channels for water movement (Forth *et al.*, 1999).

Karst terrains are usually a combination of autogenic and allogenic systems (Ford and Williams, 1989). Autogenic systems are composed entirely of karstic rocks which solely derive their waters from precipitation. In contrast, allogenic systems accumulate runoff water from neighbouring non-karstic catchment areas (Ford and Williams, 1989). Drainage patterns within karst conduits resemble similar patterns to streams and their tributaries that flow over insoluble rock and above ground (Currens, 2002). Chemical erosion in limestones alter surface drainage patterns, promoting runoff to drain down solution holes and flow through channels opened up by solution (Sparks, 1986). Alternatively, water can also recharge karst aquifers permeating through the regolith overlying the limestone bedrock (Currens 2002).

Regolith, in an undisturbed state, generally overlies limestone bedrock at a thickness of <20 m (Salvati and Sasowsky, 2002). The regolith/bedrock interface usually displays a hydraulic connection such as joint growth, allowing regolith to be transported into the aquifer. The transportation of sediment occurs due to gravitational forces on sediment particles in conjunction with the force of water penetrating the regolith (Salvati and Sasowsky, 2002). Voids are created as sediment is removed from the cover material.

SINKHOLES (DOLINES)

Sinkholes or dolines in the USA, are defined as shallow bowel-shaped depressions ranging in diameter and depth from 1m, to more that 1000m (White, 1988). Karst terrains dominated by sinkholes, usually develop on uplands within the recharge zone of carbonate aquifers (Salvati and Sasowsky, 2002). Sinkholes may serve as recharge points for aquifers governed by conduit flow, allowing regolith to be transported aiding incessant subsidence (Salvati and Sasowsky, 2002). Sinkhole formation is common after rain and is prone to areas affected by the unnatural re-routing of runoff such as along highway ditches and in stormwater retention basins. Faulty piping and leakage from drainage pipes and water supplies are a common cause in the formation of sinkholes (Tharp, 1999).

Within karst environments, three grades of fracture permeability exist and are rated high, moderate and low (Forth *et al.,* 1999). High fracture permeability involves an efficient subsurface fracture system in which groundwater travels rapidly within the rock mass. Due to its efficiency, sinkholes rarely develop (Forth *et al.,* 1999). In contrast, moderate fracture permeability involves the removal of carbonate material in solution due to longer residence times in the rock mass and slower moving groundwater (Forth *et al.*, 1999). Sinkhole formation is unlikely to occur in rock masses with low fracture permeability as dissolution of carbonates is minimal and water percolates into areas that are heavily fractures (Forth *et al.*, 1999)

Solution sinkholes form at the bedrock/soil interface and are due to the dissolution of carbonate rocks within voids or cavities (Salvati and Sasowsky, 2002). If the depression is in-filled by regolith, the solution sinkhole’s topographic expression is either smooth or absent (Salvati and Sasowsky, 2002). Moreover, cavern collapse sinkholes form when the rock roof of an underlying cave fails. A high water table provides hydrostatic uplift to the overlying bedrock of a cavern roof or a cave that has been filled by regolith. When the water table is lowered, it catalyses karstification features, promoting sinking due to gravitational collapse as the hydrostatic uplift is lost (Atapur and Aftabi, 2002). Cavern collapse sinkholes generally display steep, rocky walls and contain voids greater that 1 m in the underlying rock (Salvati and Sasowsky, 2002). Lastly, cover collapse sinkholes are caused by the erosion of regolith that overlies carbonate bedrock. Regolith is transported downwards within the bedrock, eventually causing surface failure (Salvati and Sasowsky, 2002).

CAVES

Karst caves form by solution and are openings that are greater than 5-15 cm in dimeter or width (Ford and Williams, 1989). Karst caves vary in their geometry and range in size from single room to linked, long and short passages to shafts and chambers. Caves range in length from a few meters to a couple hundred metres to over 100 km (Jennings, 1971). Large show caves in Australia include the Buchan Caves in Victoria and the Jenolan Caves in NSW, where the average cave length is approximately 400m. These areas as well as the Yanchep area in Perth, W.A, contain smaller caves averaging up to 15m.

Caves form in all topographic environments. However, steep ridges tend to form poor caves due to lack of infiltration as runoff favours the gradient (Jennings, 1971). Deep potholes and caves favour high plateaux regions due to extensive vertical development. In contrast, horizontal developed caves form on low plateaux (Jennings, 1971).

Local solution is needed to produce caves. They can be produced by bacterially assisted oxidation of organic matter within the groundwater or by sulphide minerals in the limestone. Alternatively, mixture corrosion is another mechanism involving two streams with different limestone quantities mixing, hence the total amount of limestone able to dissolve increases (Sweeting, 1972).

DRY VALLEYS AND SOLUTION FLUTES

Dry valleys are defined as valleys with absent or temporary watercourses. They consist of numerous undefined features and represent past drainage networks. Karstic dry valleys are usually steep-sided with flat of U-shaped floors, favouring sinkhole development as small pools of water flow into fissures and joints (Sweeting, 1972).

Solution flutes or chimneys are irregular in shape and structurally controlled. They can be up to 320 m deep and usually represent fissures, incorporating sloping and horizontal pathways (White, 1988).

KARSTIC GEOHAZARDS AND URBANISATION

Karst drainage systems provide many pathways for soil erosion. Vegetation traps and retards soil into solution cavities. However, with tillage and agricultural practices, soil loss occurs due to the removal of vegetation (White, 1988). Trees and large bushes are indicative of deep soil cover and in karst terrains this may determine sinkholes that have been filled in by regolith. Isolated clusters of vegetation within areas of no vegetation also indicate regions with greater soil depth occur. Lawn gardens may be indicators of potential cavity formation due to high irrigation (Forth *et al.*, 1999).

Surface collapse can be triggered by various mechanisms such as: wetting - including rainfall and snowmelt, droughts which result in drying, shaking by earthquakes and loading by construction (Salvati and Sasowsky, 2002). However, a void must be pre-existent.

Manmade impermeable surfaces such as highways, roofs and parking lots redirect runoff into various sinks posing a threat when the water table is low (Ford and Williams, 1989). Rerouting of stormwater can cause soil to pipe under neighbouring properties and damage properties outside their margins. Sinkholes can be associated with building failure, groundwater contamination and the draining of lakes and ponds (Thomas and Roth, 1999). Urbanization of karst terrains has caused flooding, pollution and ground collapse (Ford and Williams, 1989).

Figure 1, is a photo of a road collapse at Liena in Northern Tasmania. This road was constructed above a water drainage line. This hole had already been filled and resurfaced and once again, failed (WASG, 1996).

Figure 1 Road collapse due to inappropriate location of road. (Photograph courtesy of Elery Hamilton-Smith)

Loading events of small magnitude are a common cause for the formation of sinkholes. Human induced dynamic loading, blasting, vibrating equipment and vibro-compaction are frequent triggers, as are small earthquakes (Tharp, 1999). Air pressure sent transiently through a cave system produces stress below the soil voids and frequently causes partial soil structure collapse. This increases pore pressure, resulting in greater pore pressure gradient at the surface (Tharp, 1999). When structural failure occurs, it most likely related to pre-existing cavities or voids or overburden (Atapur and Aftabi, 2002). Soil voids form by the transportation and movement of regolith into openings within the underlying bedrock. These openings are generally 10-40 cm in diameter and precede the formation of surface sinkholes (White *et al.*, 1984 in Tharp, 1999).

CONCLUSIONS

Karst environments form by solution in Limestone and display many different landform features with dolines and caves being most prominent. As karstic areas occupy one quarter of the globe it is important that they are managed and conserved as urbanisation of karstic areas is a serious geohazard. Urbanisation such as roads and construction are catalysts for karst formation and due to the karst's instantaneous nature, hazards can occur.

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GLOSSARY

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This Glossary has been adapted from the
'*Glossary of Speleological and Caving Terms A – Z Complete*'.

AEOLIAN	Pertaining to the wind. Used for landforms generated by the wind, or sediments transported by the wind
AQUIFER	A body of rock saturated with water that is capable of allowing the subterranean water to be stored or transmitted and is capable of absorbing recharge water. It can yield water through a well or a spring.
AUTOGENIC DRAINAGE	Underground karst drainage that is derived entirely by absorption of meteoric (atmospheric) water into the karst rock surface
BARE KARST	Karst with much exposed bedrock
BASIN	A segment of the earth's crust which has been down-warped. When filled with sediment they increase in thickness towards the centre.
BEDROCK	(1) In a cave, a portion of the native rock strata that has not undergone collapse. The walls and roof of caves are often in bedrock. (2) In karst, the rock that underlies the limestone strata.
BIOCLASTIC	Containing grains composed of fragmented and transported organic material, eg. Shell fragments.
CAINOZOIC	The last of the geological eras, includes Tertiary and Quaternary Periods. Extending from about 65 million years ago up to present.
CALCARENITE	An indurated sand composed mainly of detrial calcium carbonate fragments. A limestone or dolomite composed of coral or shell sand, or of sand derived from the erosion of older limestones, with sand sized particles.
CALCAREOUS	Made of limestone or calcium carbonate.
CALCIFICATION	Calcified. To become hard or stony by being impregnated with calcium.
CALCITE	The common (trigonal) crystal form of Calcium carbonate mineral and the main constituent of limestone, with different crystal forms in the rhombohedral subsystem. Occurs in caves as massive or finely crystalline speleothems or other crystal forms.
CALCIUM	$CaCO_3$ – see calcite

CABORNATE	
CALCRETE	An indurated surface formed by weathering processes involving cementation of the surface soils and weathered rock by calcite, drawn to the surface by capillary action.
CANYON	A deep valley with steep to vertical walls. In karst, often formed by a river rising in impervious rocks outside the karst area.
CAPROCK	A surface composed of Calcrete, especially where it is separated from the underlying rock by a clay or similar layer.
CAVE	A natural cavity in rock, large enough to be entered by people. May be water filled. May also be blocked partly or fully by sediment or ice. Commonly formed by solution in Limestone. Caves also form in many other rock types and by many other processes.
CAVE DEVELOPMENT	Equates to cave genesis, the process that work together to produce caves.
CAVE SYSTEM	A collection of caves linked by enterable passages, or linked hydrologically. Or a large cave with extensive complex of chambers and passages.
CAVERN	A large chamber within a cave. Also used poetically to denote a larger than average cave.
CHAMBER	The name for the largest space in a cave. Compared to other parts of the cave they generally have greater width, length and height.
COLLAPSE DOLINE	A doline which has formed chiefly by the collapse of rock strata.
CONDUIT	An underground stream course (often circular or elliptical in cross section) completely water filled and under hydrostatic pressure.
COVERED KARST	Karst where the bedrock is mainly covered by soil or superficial deposits.
CROSS BEDDING	Sets of inclined layers or beds, typically seen in dunes.
DEAD CAVE	A cave without streams or drips of water.
DOLINE	A closed depression draining underground in karst, formed by solution and/or collapse of underlying rock strata. Shape is variable, but often conical or bowl shaped.
DOLINE KARST	Karst dominated by closed depressions, chiefly dolines, perforating a simple surface.
DRY CAVE	A cave without a running stream or a lake.
DRY VALLEY	A valley in karst terrain without a surface flow of water. The talweg of such a valley may undulate with many closed depressions, and there may be no longer a distinct channel.
EPIPHREATIC ZONE	The zone immediately above the permanently flooded Phreatic zone. Referring to water moving with some speed

	during floods that are too large for the usual conduits.
EROSION	The wearing away of bedrock or sediment by mechanical and chemical actions of all moving agents. Eg rivers, wind, and glaciers.
FISSURE	An open crack in rock or soil.
FISSURE CAVE	A narrow vertical cave passage, often developed along a joint but not necessarily so. Usually due to solution but sometimes to tension.
FORMANIFERA	A subclass of Sarcodina, unicellular animals that secrete tests of Calcium carbonate. Their remains accumulate to form forminiferous limestone.
GEOLOGY	The study of the earth, its rocks and how it changes, or has changed. Includes earth science, such as geology, geophysics, earth history, stratigraphy and mineralogy.
HABITAT	The immediate surroundings of a plant or animals, with everything necessary to sustain life.
HOLOKARST	Having bare surfaces on thick deposits of limestone that extend below sea level and have little or no surface drainage.
KARST	Terrain with special landforms and drainage characteristics due to greater solubility of certain rocks in natural waters than is common. Name derived from a province in Slovenia, where this type of landform was first described.
KARST GEOMORPHOLOGY	The scientific study of karst landforms (both on the surface and underground) and the processes which contribute to their development.
KARST HYDROLOGY	The scientific study of the movement of water through a karst system, and the storage of water in it.
KARSTIC	Pertaining to karst.
KARSTIFICATION	A periodic or cyclic process where phases of active solutional development of karst are followed by infilling of karst conduits and voids.
LAKE	In caving, a body of standing water, no matter how small, in a cave.
LIMESTONE	A sedimentary rock consisting mainly of calcium carbonate derived from the deposition of the calcareous remains of animals. Usually of marine origin but can be of freshwater origin.
LIMESTONE CAVE	Limestone is relatively soluble and is the most common rock type in which caves develop.
MORPHOLOGY	The study of the physical form of lands or regions. Also the form and structure of any natural phenomena.
PHREATIC WATER	Water below the level at which all voids in the rock are completely filled with water.
PHREATIC ZONE	The zone that is below the water table (except at times of

	drought) where voids or tubes in the rock are completely saturated with water.
PILLAR	A bedrock column from roof to floor left by the removal of surrounding rock.
PINNACLE KARST	Tropical landscape of near vertical sided spires.
POROSITY	The property of rock or soil having small voids between the constituent particles. The voids may or may not interconnect. If they connect, the permeability of the rock will be higher. There are three classes of porosity.
POTHOLE	A vertical of nearly vertical shaft or chimney open to the surface.
PSEUDOKARST	Terrain with landforms (and caves) which resemble those of karst but are not the product of karst solution processes.
QUATERNARY	The youngest geological period, extending from the end of the Tertiary, 1.6 million years ago to the present. Divided into Pleistocene and Holocene, which is the last 10,000 years. A time of great ice ages with widely fluctuating climates and sea levels.
RECHARGE	The process involving the input or intake of water into the saturated zone in karst aquifers. Relates to the quantity of water added.
RESURGENCE	A spring where a stream, which has a course higher up on the surface, reappears lower down at the surface.
SATURATED	Water which has dissolved as much limestone or other material as it can under the prevailing conditions.
SATURATED ZONE	The zone below the water table composed of shallow, deep and stagnant phreatic zones.
SEDIMENT	Material deposited by water, ice, and wind or precipitated from water.
SHOW CAVE	A cave that has been made accessible to the public for guided visits.
SINK	A place where a surface water course disappears underground.
SINKHOLE	In Australia, used for sites of sinking water in karst areas. Sinkholes also include swallets. This term is synonymous with the term DOLINE in the USA.
SOLUTION DOLINE	A doline formed by solution processes and not modified by collapse.
SOLUTION PIPE	A vertical cylindrical shaft, often about 0.5 m across and up to 20 m deep, which is a characteristic of syngenetic karst areas.
SOLUTION TUBE	May equate to blowhole, but solution tubes are often filled with sediment, which falls to a cave floor and forms a mound
SPELEOLOGY	The study of caves and their contents. The exploration,

	description and study of caves and related phenomena.
SPRING	A natural flow of water from rock or soil onto the land surface or into a body of surface water.
SUBSIDENCE DOLINE	Formed by the downward movement of limestone by solution and of loose surface material such as soils into an underground cavity.
SWALE	A linear hollow or depression found between dunes or beachridges. Generally marshy or swampy, or may contain small lakes.
SWALLET	They may empty into open or choked cave features (eg shafts, avens). Swallets may simply be a portion of streambed from which there is a gradual downward percolation of surface water.
TERTIARY	The geological time between Cretaceous and Quaternary, from about 65 to 1.6 million years ago. It occupies the bulk of the Cainozoic era. From oldest to youngest, the subdivisions are Palaeocene, Eocene, Oligocene, Miocene, and Pliocene.
VADOSE WATER	Water in the vadose zone.
VADOSE ZONE	That part of the cave environment that lies or once lay above the water table. Also refers to the erosional processes that act in that zone.
WATERTABLE	The surface between phreatic water which completely fills voids in the rock, and ground air, which partially fills higher voids.
WELL	A deep rounded hole in a cave floor or on the surface in karst.
ZONATION	The division of a cave into a series of zones relating to the extent of light penetration, influence of external environmental factors and degree of internal stability. Examples of cave zones are the twilight zone, transition zone and dark zone.