REFERENCES

ABS – Australian Bureau of Statistics (2003). *Demography - Local Government Area (LGA) population for each State and Territory.* www.abs.gov.au.

Atapur, H. and Aftabi, A. (2002) Geomorphological, geochemical and geo-environmental aspects of karstification in the urban area of Kerman City, south-eastern, Iran, *Environmental Geology,* **42:** 783-792.

Bastian, L. V. (1991) *The hydrology and speleogenisis of Yanchep.* Proceedings of the 18th Biennial Speleological Conference, Margaret River, W.A. December 30, 1990 to January 5, 1991. Australian Speleological Federation Inc.

Bastian, L. V. (1996) Residual soil mineralogy and dune subdivision, Swan Coastal Plain, Western Australia, *Australian Journal of Earth Science,* **43:** 31-44.

Bastian, L. V. (2003). *pers. comm.* Perth, Western Australia, 10/03/2003.

Devilbiss, T. S. (1995) *A local government approach to mitigating impacts of karst.* Proceedings if the Fifth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Gatlinburg, Tennessee. 2-5 April, 1995. A.A. Balkema Publishers, Netherlands

Ford, D. and Williams, P. (1989) *Karst Geomorphology and Hydrology*, Unwin Hyman Ltd, London.

Gillieson, D. and Spate, A. (2003). *Karst of Australia.* http://wasg.iinet.net.au/karsts.html, 26/03/2003.

Gozzard, J.R. (1982a) *Muchea Sheet 2034 I and part 3134 IV, Perth Metropolitan Region*, Environmental Geology Series, Geological Survey of Western Australia.

Gozzard, J.R. (1982b) *Perth Sheet 2034 II and part 2034 III and 2134 II, Perth Metropolitan Region*, Environmental Geology Series, Geological Survey of Western Australia.

Gozzard, J.R. (1982c) *Yanchep Sheet 2034 IV, Perth Metropolitan Region*, Environmental Geology Series, Geological Survey of Western Australia.

Jansinska, E. J. and Knott, B. (1990) *The importance of caves at Yanchep, Western Australia, with a comment on cave research.* Proceedings of the 18th Biennial Speleological Conference, Margaret River, W.A. December 30, 1990 to January 5, 1991. Australian Speleological Federation Inc.

Jennings, J. N. (1971) *Karst,* Australian National University Press, Canberra.

Komatina, M. (1975) Development conditions and reionalization of karst *in Hydrogeology of Karstic Terrains* (Eds, Burger, A. and Dubertre, L.) International Associated of Hydrogeologists, Paris.

Playford, P. E., Cockbain, A. E. and Low, G. H. (1976) *Geology of the Perth Basin,* Geological Survey of Western Australia Bulletin, Perth.

Salvati, R. and Sasowsky, I. D. (2002) Development of collapse sinkholes in areas of groundwater discharge, *Journal of Hydrology,* **264:** 1-11.

Semeniuk, V. and Johnson, D. P. (1982) Recent and Pleistocene beach/dune sequences, Western Australia, *Sedimentary Geology,* **32:** 301-328.

Teichert, C. (1967) Age of coastal limestone, Western Australia, *Australian Journal of Earth Science,* **30:** 71.

Tharp, T. M. (1999) Mechanics of upward propagation of cover-collapse sinkholes, *Engineering Geology,* **52:** 23-33.

Thomas, B. and Roth, M.J.S. (1999) Evaluation of site characterization methods for sinkholes in Pennsylvania and New Jersey. *Engineering Geology,* **52:** 147-152.

White, W. B. (1988) *Geomorphology and Hydrology of Karst Terrain,* Oxford University Press, New York.

Williams, P. W. (1993) Environmental change and human impact on karst terrains: An introduction, *Catena Supplement,* **25**.

Wilson, W. L., Mylorie, J. and Carew, J. L. (1995) *Caves as a geologic hazard: A quantitative analysis for San Salvador Island, Bahamas.* Proceedings of the Fifth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts on Karst, Gatlinburg, Tennessee. A.A. Balkema Publishers. Rotterdam, Netherlands

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.

REFERENCES

Atapur, H. and Aftabi, A. (2002) Geomorphological, geochemical and geo-environmental aspects of karstification in the urban area of Kerman City, southeastern, Iran, *Environmental Geology*, **42:** 783-792.

Currens, J. C. (2002) *Kentucky is Karst Country! What you should know about sinkholes and springs*, Kentucky Geological Survey, Kentucky.

Ford, D. and Williams, P. (1989) *Karst Geomorphology and Hydrology*, Unwin Hyman Ltd, London.

Forth, R. A., Butcher, D. and Senior, R. (1999) Hazard mapping of karst along the coast of Algarve, Portugal, *Engineering Geology*, **52:** 67-74.

Jennings, J. N. (1971) *Karst*, Australian National University Press, Canberra.

Salvati, R. and Sasowsky, I. D. (2002) Development of collapse sinkholes in areas of groundwater discharge, *Journal of Hydrology*, **264:** 1-11.

Sparks, B. W. (1986) *Geomorphology*, Longman Scientific and Technical, New York.

Sweeting, M. M. (1972) *Karst Landforms*, The Macmillian Press, London.

Tharp, T. M. (1999) Mechanics of upward propagation of cover-collapse sinkholes, *Engineering Geology*, **52:** 23-33.

Thomas, B. and Roth, M. J. S. (1999) Evaluation of site characterization methods for sinkholes in Pennsylvania and New Jersey, *Engineering Geology*, **52:** 147-152.

WASG (1996). *Poor/Inappropriate development or use leading to damage of caves/karst.* http://wasg.iinet.net.au/baddev.html, 27/03/2003.

White, W. B. (1988) *Geomorphology and Hydrology of Karst Terrain*, Oxford University Press, New York.

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.