Land use in karst terrain: review of impacts of primary activities on temperate karst ecosystems

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ABSTRACT

There is an acknowledged lack of information available to managers of New Zealand's karst estate on the impacts of primary activities on these sensitive environments. A review of the international literature was undertaken to begin to address the issue. Subjects of particular interest were identified by Department of Conservation staff and included, in order of priority: forestry, agriculture and quarrying, followed by a second range of activities including landfilling, groundwater chemistry changes, urbanisation, cave climate and near-entrance vegetation change, and also conservation legislation. While there is a volume of literature on karst, it is largely devoted to the science of karst processes rather than the impacts of primary activities. In many cases the science is robust and the likely impacts of primary activity can be adequately assessed. In the future, improved communication by karst managers and researchers and the people living on, and in contact with karst landscapes on a daily basis will lead to better informed and directed research on the impacts of human occupancy on karst ecosystems.

Keywords: temperate karst, primary industry, management, impacts, protection, conservation, legislation

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1. Introduction

1.1 RATIONALE

Much of the karst[1] scientific literature is relatively inaccessible to managers of karst environments both within and outside New Zealand. Yet much of this literature is potentially applicable and useful in management. Over time, little consultation has occurred between karst scientists and potential end users of the research product, i.e. land/conservation managers. Certain notable examples of more applied research do exist (Kiernan 1998, 1989a) and much of this has been undertaken in New Zealand and Australia (Williams 1975, 1980; Gunn 1978; Wilde 1985; Bunting 1998). However, the prevailing situation is mainly for research to be driven by the scientific community rather than the management community. This project is a first attempt at bridging the gap between the science of karst and the practice of karst management. The project draws from a very rich and diverse literature to begin to answer some important questions being raised by the managers of karst environments. The overall rationale therefore is to deduce from the scientific literature the potential impacts of primary activities (defined below) on the short- and long-term sustainability of karst environments. Imbedded within this overarching rationale is an attempt to provide an avenue whereby accessible knowledge of particular, science-based studies can influence and support policy formulation for the preservation, conservation or sustainable use of New Zealand's karst heritage.

This research project was initiated in discussion with Dave Smith (Department of Conservation, Maniapoto Office, Te Kuiti) concerning issues faced by managers of New Zealand's karst estate. We attempted to discern the particular needs of New Zealand's karst managers when confronting various legislative polices. We wished to link these issues with current environmental thinking, both theoretical and applied. We grouped the original set of issues under headings representing 'activities of concern', 'management' and 'processes and features', then ranked the issues according to 'level of concern'. This provided a focus to review the literature comprising close to 5000 potentially relevant works.

Further input on these categories was sought by email from DOC staff involved in the management of karst terrain in New Zealand, but none was forthcoming.

1.2 CATEGORIES

The following categories were derived, in part, from a brief assessment of works by particular karst scientists. The matrix devised by Williams (1993) was particularly helpful (Fig. 1).

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[1] Karst refers to landscapes formed through the solution of rock, most commonly 'limestone and its close relatives' (Gillieson 1986). Common elements of karst environments include macro features such as cave systems, lack of surface water, pinnacles, closed depressions and limestone-derived soils.

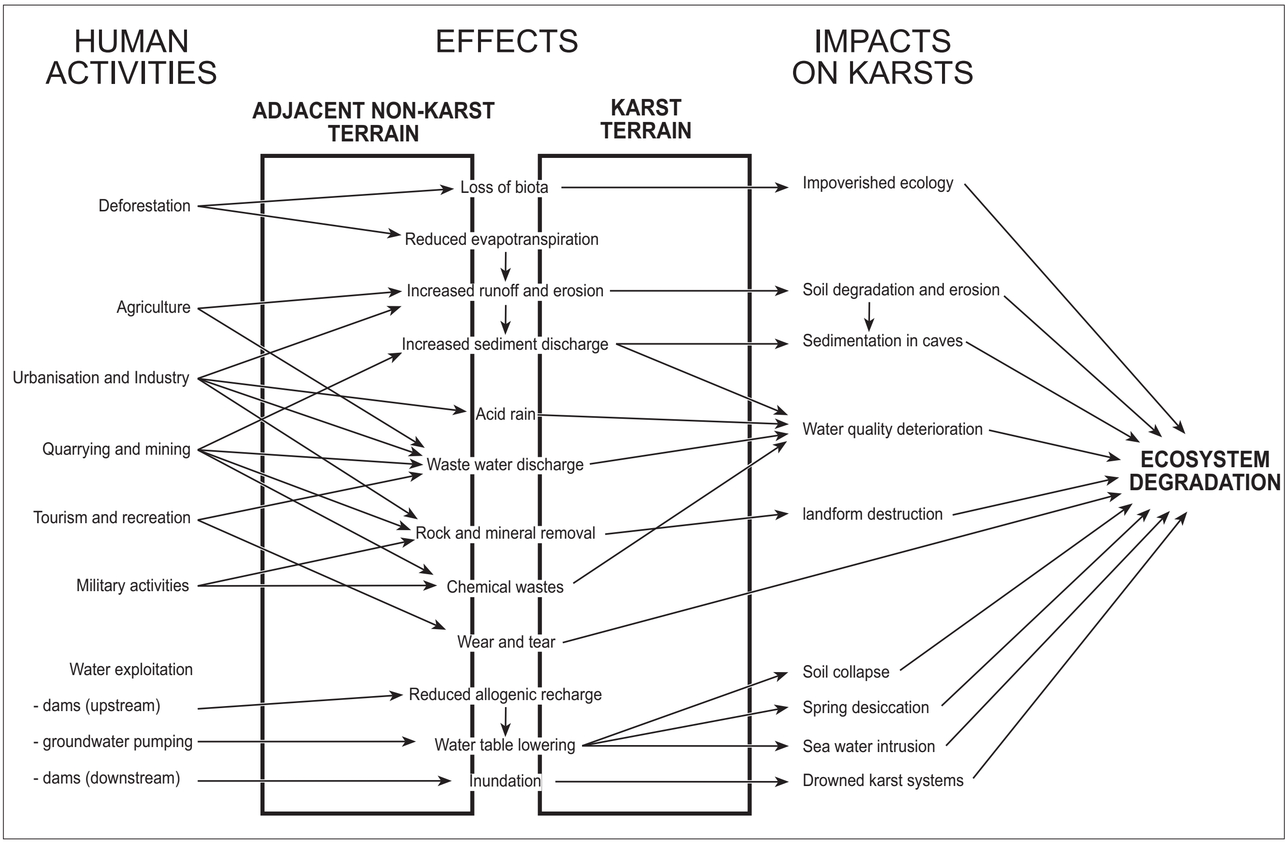

Figure 1. Matrix of anthropogenic activities, effects and impacts on karst terrain. (Source: Williams 1993. Reproduced with permission.)

For the present literature review, a more refined matrix was devised in order to address the needs of karst managers in New Zealand. The categories for consideration were grouped under three headings:

Activities of general concern in New Zealand:

- *Pastoral farming*: conversion, species and stocking rates, soil chemistry, percolating water chemistry, soil erosion, agrochemicals and sedimentation rates.
- *Forestry*: species and stocking rates, clear felling, selective logging, soil chemistry, percolating water chemistry, leaf litter, soil biology, harvesting, soil erosion, and sedimentation rates , effects of 'rotating' of impacts.
- *Cropping systems* (maize, viticulture, etc.): groundwater contamination, soil compaction, soil erosion, irrigation.
- *Quarries and landfills*: groundwater contamination, sediment movement, groundwater pumping.
- *Urban development*: subdivision, storm water management, contaminants, surges.
- *Dams*: hazards, effects of water level control (dams above karst).

Management of karst terrains—current knowledge:

- *Measurement and management*: anything pertaining to temperate karst.
- *Remedial measures*: strategies, outcomes and impacts.

Specific processes and features of karst-based activities and impacts:

- *Percolation water*: effects of vegetation type.
- *Doline management*: erosion control, gallery vegetation.
- *Cave entrance flora*: vegetation (microclimate, light/temperature penetration and airflow with change in vegetation cover) change in flows of energy (organics), air, water through vertical entrances.
- *Cave fauna*: sensitivity of stygobites to water quality, epigean aquatics (solids and contaminants), organic content of allogenic streams and changes to cave riparian communities.
- *Speleothems*: effects of change in water quantity and quality.
- *Epikarst processes*: effects of erosion and change in water quantity and quality.
- *Flooding*: quantity and quality of floodwater and effects on speleogenesis.

While all the above issues were perceived to be important, the available literature did not support such a detailed analysis. A second framework was therefore devised for the purposes of this review, with forestry and agricultural activities carrying the most weight.

1.3 METHODOLOGY

Examined literature sources included professional journals, conference proceedings, books and government reports.

The University of Waikato library and the Internet provided electronic access to Firstsearch's GEOBASE and GEOREF.

GEOBASE covers worldwide literature on ecology, geography, geology, human geography, international development and related disciplines. Over 2000 journals are covered fully, and 3000 selectively in addition to coverage of more than 2000 books, monographs, conference proceedings and reports. GEOBASE contains more than 600 000 records with *abstracts* maintained from 1980 on.

The GEOREF database is the most comprehensive geosciences database, providing access to over 2.2 million *references* related to geoscience journal articles, books, maps, conference papers, reports and theses.

These two major databases were supplemented by a search of the UNCOVER REVEAL online database. UNCOVER is a database containing current article information from well over 18 000 multidisciplinary journals. UNCOVER also contains brief descriptive information for over 8 800 000 articles which have appeared since late 1988.

Search terms were uniformly applied to all databases. These terms included 'karst' and 'limestone' in combination with the following descriptors: environment, development, epikarst, formations, stalactite, stalagmite, sediments, quarry, aquifer, pollution, agriculture, impact, fauna and flora. The search was conducted for keywords and abstracts in order to search as widely as possible to capture references electronically using the Endnote Version 3.0 computer program. A total of 4762 references were placed in a searchable file in Endnote. The references were then sorted off-line. Titles and available abstracts were assessed with respect to their applicability in addressing the questions posed in the objectives noted above. Papers with potential to address the questions raised in the objectives were placed in a second database and sought through libraries. Personal contacts or the American Geographical Society collection at the University of Wisconsin-Milwaukee, where I was based for one month, provided additional works. A total of 142 referenced research works were obtained and form the basis for this literature review.

1.4 OVERVIEW

Karst environmental change occurs both on the surface and underground. The activities that alter karst environments may be direct or indirect in nature, and may occur within the karst environment or beyond its boundaries, entering and impacting upon it. There is an urgent need for a better understanding of the linkages between primary activities such as agriculture, mining and forestry (amongst others), and both the short and long-term impact these activities can and do have on New Zealand's karst heritage.

Environmental damage in karst landscapes is carried through the karst system either rapidly with great impact, or sometimes slowly with little readily apparent impact (Fig. 2). The slow accumulation of change in the karst environmental system is important. By definition, karst systems are typically ancient, defined and moulded by eons of entrophic change ('natural' environmental processes). Hence, slight changes in groundwater chemistry, while not immediately and dramatically evident, may become so over a longer time frame. Many karst scientists argue that this time frame needs to be considered in all assessments of primary activity impacts in a karst environment system.

Most karst studies have been focused on the engine of karst development—water; scientific studies have generally focused on the issue of water and its chemistry, role in karst development, flow patterns (traces) and water quantity and quality in an anthropogenic sense. Hardwick & Gunn (1990) comment 'the impacts on limestone cave geoecosystems of surface change resulting from human activity have not been well documented'. Therefore, this literature review tried initially to capture a large volume of literature that might broadly relate to topics of interest to those managing New Zealand's karst. Although not directly comparable, international knowledge of karst environmental processes is broadly applicable to New Zealand conditions on a case-by-case basis.

This literature review has been arranged as 'blocks of knowledge'. Where an article touches on issues that are relevant to different parts of this review, I have dealt with each part separately, rather than through the single review of a referenced work. For example, it is common for a researcher to address sampling methods, findings and management outcomes, perhaps in terms of legislative requirements, in one paper. I have distributed these ideas into the relevant subsections of this review, with a comprehensive bibliography at the end. A glossary of technical terms is appended. The use of technical terms has been minimised.

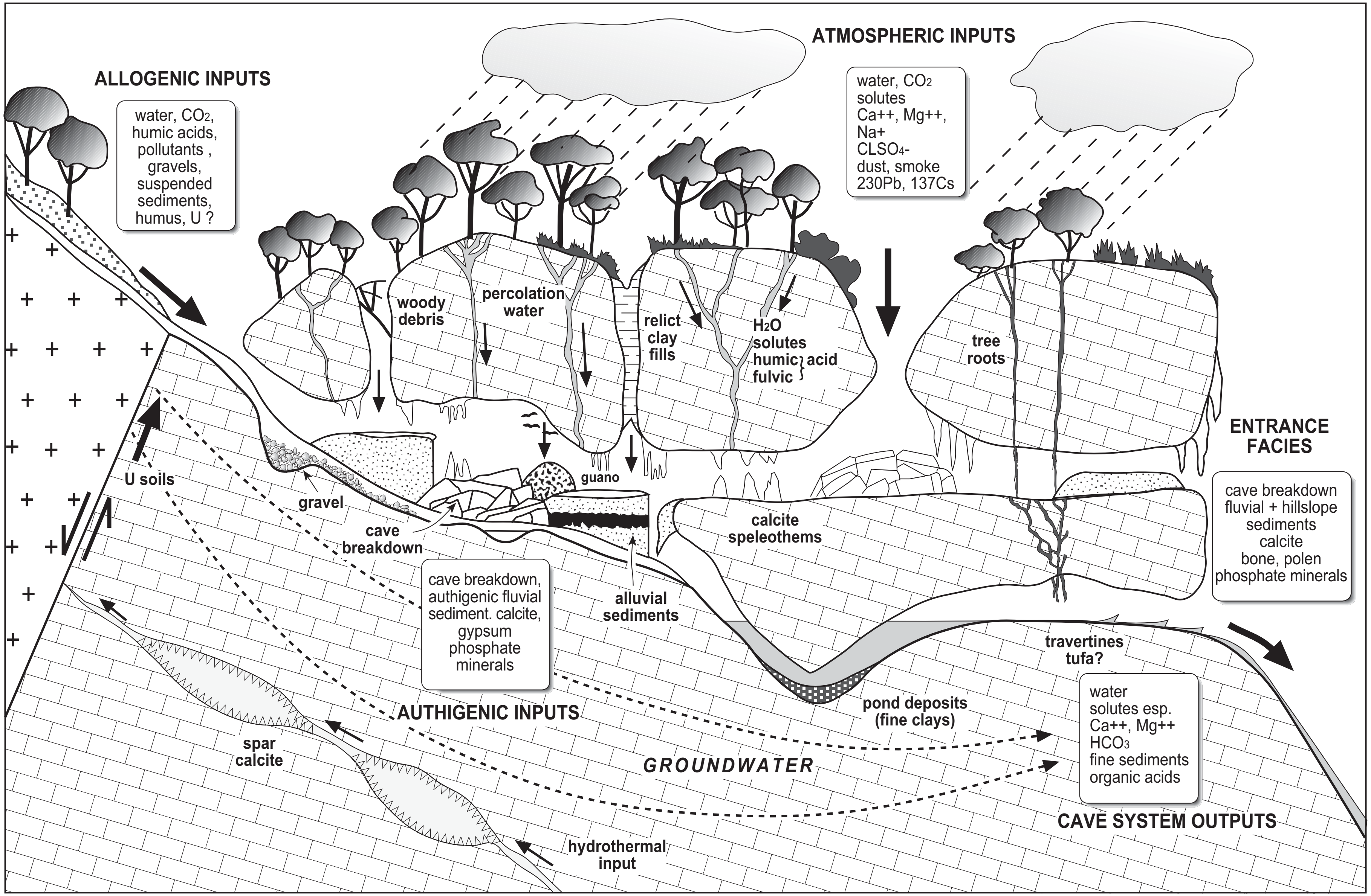

Figure 2. A model karst system. (Source: Gillieson 1996. Reproduced with permission.)

2. Impact of primary activities

2.1 FORESTRY

Felling of trees in experimental catchments has repeatedly shown that runoff increases by an amount equivalent to previous losses by evapotranspiration from the forest stand. In temperate rainforest, such as that occurring on the Waitomo karst in New Zealand, which receives an annual rainfall of about 1800 mm, annual runoff can increase by up to 700 mm (over 35%). This represents a very large increase in kinetic energy available for erosion and transportation of soil and debris. Such increases result in downslope movement of soil, especially where the protective ground cover is disturbed by burning or machines. At Waitomo (Central North Island, New Zealand), the bottoms of cleared solution dolines became the repositories of forest debris and soil, which occurred despite the fact that increased runoff impeded transmission of flow to springs (Gunn 1978). In the lower Waitomo valley, floodplain sedimentation of 2.1–4.3 m has occurred since forest clearance for agriculture commenced about a century ago (Williams 1980). This is 40 to 80 times the average Holocene sedimentation rate in that valley. The local soils are principally derived from a thick blanket of volcanic ash. Hence, the karst still remains largely soil-covered. This contrasts markedly with regions that are dependent only on karst-derived soils. In the latter case, forest clearance can lead to the complete stripping of the thin soil that may have existed.

There is some confusion regarding the impact of forest clearance on speleothem development. There is little doubt that groundwater recharge is a major control on speleothem growth and development processes; calcite cannot be deposited in absence of recharge. However, Kiernan (1988) has presented two interesting cases from Tasmania, Australia. A decrease in recharge following a change of vegetation cover from pasture to pine forest was associated with subsequent desiccation and 'fossilisation' of speleothems in underlying caves; yet in another cave in Tasmania, forest clearance above resulted in renewed calcite deposition. If forest cover was the natural ecosystem in these areas of karst development, then forest cover appears to mitigate speleothem development; advocating the regeneration of forest to preserve the underlying karst ecosystem may be remiss. Important research remains to be done on the impact of the composition of forest species and complexity of the forest cover and litter and karst processes. In the Tasmanian case noted above, monocropping of *Pinus radiata* appeared to be detrimental to the karst; however the condition of the cave prior to the development of the plantation forest was not discussed.

Any change in the volume and chemical or physical state of flowing water or air may also have a profound effect upon cave decoration (Kiernan 1988). Kiernan further notes that any disturbance of the soil mantle can lead to dehydration and a change in the continuity of formation development. There have been cases in Tasmania where sealing roads and carparks at tourist cave locations has actually led to the degradation of the spelothems that attracted tourists in the first place (Skinner 1972 in Kiernan 1988). It is becoming more evident that local hydrology must be taken into account during all phases of development in karst areas, and that this must occur at a variety of scales in order to recognise interconnectivity of systems. As will be discussed later, both the cave and entrance area atmosphere conditions must also be considered. As Kiernan (1988, 1989b) noted, this issue can have important implications for management. For example, the removal of forest cover can raise soil temperatures and subsequently alter soil CO_2 levels, and ultimately lead to the development of more acidic and hence aggressive seepage water entering the cave environment, which could corrode decorations. Kiernan also details a case where the opposite may occur, when salts are released in regeneration burning which causes the opposite trend but notes that hard data to prove this is lacking.

Unfortunately, these claims are largely anecdotal since no data are available. One study of the impacts of forest clearance on these parameters is underway in Tasmania, Australia, but results cannot be expected in the short term (Kiernan, pers. comm.).

Evidence from Norway is also inconclusive with respect to the role of forest cover in its influence on water chemistry, i.e. carbon dioxide levels in the epikarst zone. In the Norwegian example, there was a difference in carbon dioxide levels in water debouching above and below the tree line. A definitive correlation between forest cover and CO_2 was not possible, owing to intervening factors such as flood pulses and reduced sampling levels (Bakalowicz 1984). As discussed elsewhere in this report (cf. percolation waters), the sampling methods used in assessing the aggressiveness or depositional capacity of karst waters are hotly debated.

The northern half of Vancouver Island, Canada, features steep limestone slopes that were still glaciated up to 12 000 years ago. Following deglaciation, coniferous forest grew upon the veneers of the outwash laid down upon the ice-scoured rocks. The dominant species were western hemlock (*Tsuga heterophylla*), silver fir (*Abies amabilis*) and western red cedar (*Thuja plicata*). Clear-cutting involving the removal of all trees and burning of the slash and dead wood began around 1900, but increased in intensity with mechanisation in 1960. Land that was cleared was left to re-seed naturally. Harding & Ford (1991) established that 'clear cutting led to significant soil losses on both limestone and volcanic rock slopes but that losses were much greater on the limestone'. In the limestone area, there was a mean reduction in soil depth of 25% five years after logging. This increased to 60% after ten years. The mean percentages of bare limestone also increased, with virtually none under virgin forest. Bareness increased from between 10 and 20% after five years to between 20 and 30% after ten years. Soil losses on limestone were significantly greater where deliberate burning of slash and dead wood followed cutting. Burning was not as significant on the volcanic rocks. Eroded soil on the limestone bedrock was deposited in the epikarst and in shallow micro-caves.

Regrowth was very limited. Evidence to date shows that there will be no growth of large trees on the longer, bare limestone slopes. For example, even in the site clear-cut in 1911, which was much flatter than more recently logged areas and thus retained more soil, the area had regained only about 17% of the original volume of timber (Harding & Ford 1991).

2.2 FOREST RECOVERY

Discussion in the forestry literature related to karst is dominated by the negative effects of deforestation on the karst ecosystem and the subsequent impact on the sustainability of economic activities (Urich 1996). Researchers and managers of the karst estate are also concerned with rehabilitation of endemic forest cover when and where possible, in order to preserve karst systems. Several studies have explored the underlying conditions necessary for, and constraints on the rehabilitation of forest cover (Rivera & Aide 1998; Urich & Reeder 1999).

The study by Rivera & Aide (1998) was conducted in Puerto Rico where karst covers 20% of the island. At the peak of deforestation just after WWII, native forest covered only 6% of the island. Other studies of forest recovery rates had been conducted in non-karst environments. Rivera & Aide's study was the first to explore the issue in karst terrain. The researchers sought to answer two questions:

- How do the different types of land use affect forest regeneration in terms of basal area, density and species diversity?
- How does the composition of seedling regeneration compare with the composition of adult trees in abandoned pastures and coffee plantations?

These authors predicted that species diversity and stem density would recover faster in pasture, and that basal area would be greater in abandoned coffee plantations. Historically, coffee was planted below shade trees. Recovery in an area with a close canopy should restrict the establishment and growth of shade-intolerant species. On the other hand, pasture sites may be colonised by species with a wide range of light requirements.

They found that densities were higher in abandoned pastures than in coffee plantation sites, but there was no difference between the two land uses in basal area. The major differences between these land uses were the vegetation structure at the time of abandonment, age since abandonment, valley width and light environment. The coffee plantation sites were all abandoned around 35 years ago. The pasture sites were younger and were abandoned at different times (range 15–35 years ago). It appears that coffee plantation sites reached a stable phase in terms of density and basal area, while the pastures were still in the thinning (density) and increment (basal area) phases. Valley width was significantly higher in abandoned pastures than in abandoned coffee plantation sites. The wider valleys received more light, while the light environment in the abandoned pastures would have been much greater at the time of abandonment. The coffee plantations were all planted under shade trees where light levels in the understory were relatively low.

Rivera & Aide compared the findings of their study with those of researchers working in other geologic settings in Puerto Rice. They found that secondary forests in the karst region recover faster than secondary forest in other geological/soil formations. In the karst region, the mean basal area in the abandoned pastures (age 15–35 years) was nearly double the mean basal area in pastures of similar age (15–37 years) in eastern Puerto Rico. Another study reported a similar mean basal area in pastures that were at least twice the age (60 years) of those in the karst region. Abandoned coffee plantations in the karst region's subtropical moist forest also recovered faster. In Rivera & Aide's study, basal areas in 35-year-old abandoned coffee plantations were again nearly double those of similar plantations in other geologies, namely volcanic areas. The differences in the recovery rate in these abandoned coffee plantations could have been due to different climates, but the authors believed that the topography of the karst region may also have contributed to the recovery.

The unique topography of karst landscapes may be the most important factor contributing to the rapid recovery of secondary forest. Karst topography often consists of long narrow valleys surrounded by hills with steep slopes. This topography protects the valleys from strong winds. In addition, the accumulation of soil and organic matter in the valley bottoms creates better conditions for plant growth. The long narrow valleys protected the soil from direct sunlight (maintaining high humidity) and soil erosion (high nutrient inputs occur from runoff from the surrounding hills) in contrast with other non-karst soils.

The encouraging findings of Rivera & Aide in relation with the ability of limestone environments to recover secondary forest cover are echoed in the findings of Urich & Reeder (1999) in the Philippines. They found that micro-geomorphic factors appear to influence both tree survival and growth rates. Each hill they studied had micro-geomorphic features that included slope angle, slope length, breaks in slope, and the size and distribution of talus, which influenced the rates of erosion and deposition. In their case study, trees were planted on a preset grid, and hence in a wide range of micro-geomorphologic environments with no apparent regard for micro-topography. Soils were both deeper and moister toward the toeslope of the mogotes. This is to be expected, since overland flow transports eroded soil to the toeslope and, combined with lateral unsaturated flow, keep this soil moist. For these reasons, generally higher survival rates and more vigorous growth can be expected to occur at the toeslope rather than at the mid-slope or on summits. These analyses indictate that there is a fairly strong relationship between tree growth and landscape position.

Additionally, and in support of the work of Rivera & Aide (1998), Urich & Reeder (1999) found that previous land-use history plus length and intensity of land cultivation following the clearance of primary forest were critical to the survival rate and vigour of secondary forest growth.

Unfortunately, similar studies to those above have not been conducted in temperate karst environments such as New Zealand. Particularly useful in the context of this review is the evidence that karst environments can, in some instances, support the growth of secondary forest cover. Secondly, karst environment appears to support more rapid secondary forest growth than other environments of different geology, topography and soil types as noted by the work of Rivera & Aide. Similar constraints on rates and success of secondary forest recover such as history of deforestation and subsequent land use should apply in New Zealand's karst environments.

2.3 AGRICULTURE AND CROPPING SYSTEMS

As in the case of forestry, the primary impact on the karst environmental system from the conversion of natural land cover, be it forest, grassland or any other biome, is the resultant change to the characteristics of the water entering the karst system either allogenically or autogenically.

Williams (1993) addressed this in a general way. Water supplies in karst areas are very susceptible to degradation by both point source and diffuse or non-point source pollutants and, consequently, their ecosystems are correspondingly susceptible to irreparable damage. This is largely due to the nature of karst hydrologic systems. Natural treatment of water-borne contaminants is often relatively ineffective in these systems. Ford & Williams (1989) identify five reasons for this:

- The surface area available for colonisation by natural micro-organisms, and for adsorption and ion exchange, is much less in dense, fractured karst rocks with shallow soil than in porous elastic sediments with deep soil covers. Consequently, percolating water that diffusely recharges karst has relatively little opportunity for self-purification.
- Rapid infiltration into karst also reduces the opportunity for evaporation, a process that is particularly important for the removal of volatile substances such as solvents and pesticides.
- The transmission of particulate contaminants right through the karst systems to springs is assisted by the turbulent flow regime that is characteristic of well-developed karst aquifers. Point recharge occurs via stream-sinks (ponors) and dolines. Sinking rivers penetrate rapidly and deeply into the karst. Drainage from the bottom of individual dolines is on a smaller scale, but their frequent use as rubbish pits permits rapid transport of debris and leachate down opened joints into groundwater systems. A similar but larger-scale problem arises when abandoned limestone quarries are used as landfill sites.
- Physical filtration is relatively ineffective through rocks with highly developed secondary porosity and patchy, shallow soils.
- Flow velocities are very high and flow-through times correspondingly short compared with most other groundwater systems. Consequently, pollution elimination processes that are time-dependent are less effective. There is usually insufficient time, for example, to permit the die-off of pathogenic organisms, which may therefore emerge at karst springs.

Soil erosion is often intensified when soils are disturbed for agriculture and other primary land uses such as highly mechanised forestry. Increased sediment loads impact on speleothems, speleogens and clastic sedimentary deposits. This may result in sediment accretion and either total or partial infilling of cave passages, and possibly the burial of *in situ* speleothems, speleogens and clastic sediments.

Hardwick & Gunn (1990) conducted a review of the impacts of soil erosion on cavernous limestone catchments (Fig. 3). They soon noted that reports on soil erosion in limestone catchments are obscure and require careful scrutiny. They found this unfortunate, since the formulation of land use strategies for karst terrain should require consideration of soil erosion and its environmental impact on cave systems and limestone aquifers. Hardwick & Gunn's analysis is divided into two components: soil erosion on limestones overlying caves and

Surface changes	IMPACTS ON CAVE GEOECOSYSTEMS: GEOMORPHOLOGY MICROSCALE	GEOMORPHOLOGY MACROSCALE	WORK ENVIRONMENT	MICRO CLIMATE	ECOLOGY	AGRICULTURAL OPERATIONS WHICH MAY PRODUCE THIS TYPE OF CHANGE
Direct changes to water quality	Speleothem growth & development / Contamination of unwashed & In-situ sediments		Gas hazards Explosion hazards	Toxic & explosive gases (from petroleum products) CH_4, CO_2 & O_2 changes from decomposition of sewage/silage/slurry	Hypogean fauna / Stream fauna	Fertilisers (incl. Irrigation) Agrichemicals Slurry / silage leaks Petroleum Products Septic Tank leaks
Indirect changes to water quality	Speleothem growth & development				Hypogean fauna / Stream fauna	Field Drainage Land Drainage (Open Ditching) Ploughing Afforestation Practices
Direct changes to water quantity	Speleothem growth & development	Boulder choke stability	Flood hazard	Humidity / Humidity, Airflow, Air/Water Temperature	Hypogean fauna / Stream fauna, Trogloxines	Field Drainage Land Drainage (Open Ditching) Irrigation Water extraction
Indirect changes to water quantity	Speleothem growth & development		Flood hazard	Humidity / Humidity, Airflow, Air/Water Temperature	Hypogean fauna / Stream fauna, Trogloxines	Afforestation Practices Ploughing Crop Changes
Indirect changes in sediment loads	Speleothem growth & development / Burial of Speleothems, speleogens & In-situ Sediments	Infilling of cave passages & blockage of cave entrances	Flood hazard	Humidity, Airflow, Temperature / Humidity, Airflow, Temperature	Hypogean fauna / Stream fauna - habitat loss, Trogloxines - access loss	Field Drainage Land Drainage (Open Ditching) Afforestation Practices Ploughing Construction (roads, buildings)
Direct alteration of cave entrances	Speleothem growth & development	Blockage of cave entrance	Loss of access to cave health hazards e.g. Leptospirosis (From rats/livestock)	Humidity, Airflow, Temperature / Humidity, Airflow, Temperature	Trogloxines - access loss	Waste Disposal Deliberate Infilling Capping for Water Supply
Indirect alteration of cave entrances	Speleothem growth & development	Blockage of cave entrance	Loss of access to cave	Humidity, Airflow, Temperature / Humidity, Airflow, Temperature	Trogloxines - access loss	Afforestation Practices Ploughing Construction (roads, tracks, buildings) Heavy Mechanisation

Figure 3. Matrix modelling the impacts of agricultural activities on the cave geoecosystem. (Source: Hardwick & Gunn 1990. Reproduced with permission.)

the transport of derived sediments underground by autogenic water on one hand, and inputs of sediments to caves from the catchments of allogenic feeder streams on the other.

In many areas, superficial deposits of allogenic origin, on which mineral soils have developed, overlay limestones. There are also extensive areas of bare limestone where intervening fissures and underlying caves frequently contain substantial amounts of sediment (eroded in previous phases of land use change). For example, the bare appearance of much of the Mediterranean karstlands, including the 'classic' karst of Yugoslavia, is believed to be a result of human-induced deforestation and subsequent soil erosion. In England, early agriculture in the northern Pennines may have provoked large-scale soil loss, hence leaving bare limestones in that area. The shallow soils, patchy vegetation and large areas of bare rock of the Burren karst plateau of Ireland have been ascribed to glacial erosion. However, Drew (1983) argued that the area was once well populated and forested, with an extensive cover of mineral soil which was removed by erosion as a result of forest clearance in the late Bronze Age.

There is also evidence from areas where modern intensive agriculture is practised. Lewis (1981), in a study of CO_2 levels in Coldwater Cave, Iowa, USA, noted that large amounts of mud and fine organic debris were washed into the cave from the overlying farmland during storm events. Similarly, Weirsma et al. (1986), in their study of Wisconsin's Door County karst, noted the impact on groundwater quality of soil loss into dolines. Moreover, agricultural productivity was reduced by a loss of tillable area.

In many cases, the ultimate destination of eroded material must be the underlying cave and conduit systems. The speed and mode of transmission are poorly understood. Hardwick & Gunn (1990) identify three points on the basis of physical size of conduits: shaft flow with thin films of water flowing down the walls of openings more than 1 m in diameter; vadose flow with meteoric water mostly flowing solutionally enlarged fissures and joints 0.01–1.00 m in diameter; and vadose seepage of water percolating through tight fissures and fractures, or moving as intergranular flow. Shaft flow and most vadose flows are turbulent, and capable of transporting soil and rock particles underground.

Once boulders, rocks, pebbles and sediment reach the larger cave conduits, the process of their movement is very similar to that of surface fluvial systems (Gillieson 1996). The primary difference is that the sediments are confined to a conduit. Gillieson (1996) commented that this resulted in the following effects:

- There can be rapid changes in water level from flooding or the morphology of the cave passage and this results in steep gradients and the rapid change in the energy available for reworking sediments along the cave passage. This can lead to a greater diversity in sediment textures per unit length than in surface systems.
- There can also be the complete reworking of sediments whereby previous deposited sediments may be completely removed with a subsequent high-intensity event (flood). Thus the life history of a parcel of cave sediment is one of periodic reworking until its identity is lost, its volume become negligible or it is placed in a very low-energy environment.

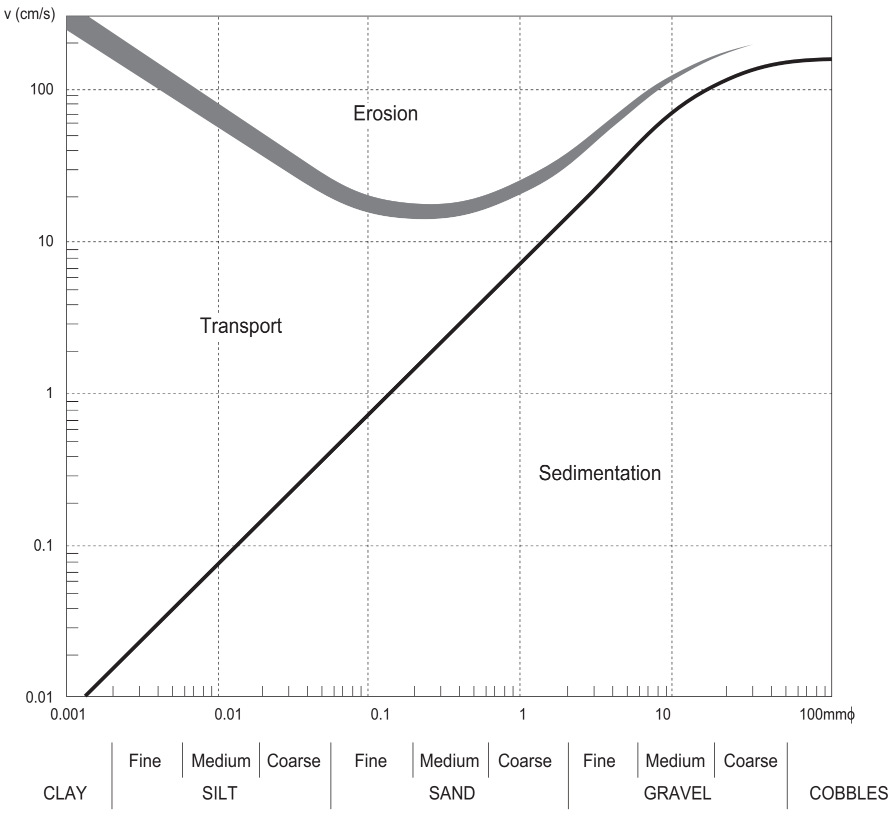

Figure 4. Potential for movement of various types of material with changes in the volume of flow in a confined system as defined by the Hjulström curve. (Source: Gillieson 1996. Reproduced with permission.)

As Gillieson further noted, the reworking of cave sediment will be largely determined by the texture of the sediment, i.e. large boulders and very fine and cohesive clays will not be easily transported once they are emplaced in a cave.

When these fine clays are in place they tend to be resistant to erosion; but once they are disturbed and become suspended sediment, they are easily transportable in line with the model defined by the Hjulström curve (see Fig. 4). As reported by Gillieson, based on the work of Bull, after settling from suspension these fine-grained sediments can 'accrete at steep angles, draped on underlying rock, flowstone or sediment surfaces'. These sediments have in some cases been found to be ancient and offer opportunities to study paleoclimatic conditions and land cover change through attached pollen.

Some authors suggest that eroded sediments will be removed to the subcutaneous (epikarst) zone and thus remain locally. For example, it had been noted that the products of soil erosion in the Burren, Co. Clare, Ireland were deposited in fissures in the limestone. Similarly, Trudgill (1985) considered that there was little evidence of significant inputs from autogenic recharge to caves deposits. However, the studies by Kogovsek & Habic (1980) and Kogsevsek (1982) provide clear evidence of substantial inputs of clastic material into the Postojna and Planina caves in Yugoslavia.

Some limestone areas receive substantial point sources of allogenic recharge from adjacent non-carbonate rocks, e.g. Waitomo karst in New Zealand. Sinking streams can carry erosion products from their catchments into the karst drainage systems. Major sediment deposits are frequently found in cave systems where flow velocities are rapidly reduced, for example at a constriction or where a narrow vadose stream meets a wider, slower phreatic flow. Many such deposits are characterised by depositional cycles of bedload to suspended sediment. Gillieson (1986) studied allogenic slopewash sediments from limestone rock shelters in the Papua New Guinea highlands. These suggested that late Pleistocene erosion rates under stable primary forest were minimal but erosion increased significantly from 6000 B.P. on, and especially from 300–400 B.P. owing to horticultural intensification.

In temperate regions, Tucker (1982) noted continuing accretion of up to several metres of agriculturally derived sediment in Kentucky caves. Several authors (e.g. Williams 1975; Hawke 1982) have documented rapidly increasing sediment levels in cave systems that are due to anthropogenic activities in the catchments of allogenic streams in New Zealand. Public road maintenance and deforestation activities in surface catchments are just two possible reasons for the artificial raising of stream levels downstream, which can reduce the hydraulic gradient of the system, leading to further depositions of sediment. In some cases blockage and disruption of underground drainage routes can also create problems, particularly flooding, within their surface catchments (Dougherty 1983).

2.4 IMPACTS OF SOIL EROSION ON KARST

The impacts of soil erosion in karst catchments can be severe. Soil erosion can result in the partial or complete infilling of cave passages and the burial of older clastic deposits, some of which may be of scientific importance. With the choking of passages, backflooding may result and access to caves or parts of cave systems may be permanently lost. However, the rehabilitation of an allogenic catchment to natural or semi-natural vegetation may have unforeseen consequences, with downcutting of cave sediment infills resulting from increased stream competence (Kranjc 1979; Dougherty 1983). Sediment infill may also lead to long-term changes on cave passage morphology.

Adverse impact of soil materials transported by autogenic recharge on speleothem growth and development has been demonstrated by Jakucs (1977). He found that speleothems beneath barren and deforested karst were inactive and usually yellowy, brown or ochre in colour. When surface vegetation died off or was removed, there was a marked change in colour of speleothem growth layers, usually towards red, and this was attributed to the inwashing of terra rossa soils and deposition of clay minerals on the speleothem surface. If afforestation recommenced, speleothems grew lighter with fresh deposition of white or translucent calcite.

Anthropogenically induced allogenic sedimentation may also impact on cave ecosystems. For example, silting of Mammoth Cave, Kentucky, USA is known to have affected the geographical distribution of hypogean Asselidae communities (Lewis 1981), since pool and riffle sequences, plus gravel areas that were lost, were essential for the species' reproduction and survival. Similarly, sedimentation is known to have reduced the breeding sites of a species of glow worm at the Waitomo glow-worm grotto, in New Zealand (Pugsley 1981). There is also the case of the impact of differential deposition of clay minerals on the hypogean fauna in Belgium (Tercafs 1988). Thus, localised movement of soils may have a profound impact on hypogean communities.

In the conclusion of their review, Hardwick & Gunn (1990) noted that modern agricultural practices may increase the material taken underground by allogenic streams, and may also increase the rate of this material further removal by autogenic recharge. A continued dependence on agrochemicals to maintain soil fertility may promote long-term soil degradation owing to the loss of organic material from soil matrices (Luoma 1989). The presence of underlying joints and fissures is likely to facilitate the evacuation of soils from the surface. This can be exacerbated by soil disturbance and compaction during soil cultivation. The application of liquid sewage sludge as fertilisers using irrigation techniques may accelerate soil erosion, owing to rapid subsurface runoff via the subcutaneous zone.

Since catchment disturbance is likely to lead to increased sediment loads in insurgent streams, consideration needs to be given to agricultural activities in allogenic catchments. This raises a further problem with the present system for the designation of Cave Sites of Special Scientific Interest in Britain under the 1981 Wildlife and Countryside Act, since 'only land overlying known or hypothesized caves, not the allogenic catchment, is included in the site' (Hardwick & Gunn 1990).

2.5 AGRICULTURAL CHEMICALS

Berryhill (1989) provided a general overview of the potential impact that changing agricultural practices might have on the karst environment. His focus was on particular nutrients and their movement and impact. He considered one of the critical issues to be that of plant nutrients such as nitrogen. Sources of contamination include fertilisers and manure applied to fields for crop production, as well as manure storage facilities, feedlots, dairy parlours, poultry and hog houses. Activities that may exacerbate nutrient losses include excess fertiliser and manure application, improper timing of application, poor manure storage management and failure to supervise areas where livestock may concentrate. Other activities include inappropriate tillage practices such as up-and-down-hill ploughing just before heavy rainfall, and allowing livestock access to sinking streams, cave entrances and sinkholes.

Conservation practices may also increase nutrient loss. Reduced tillage techniques, which leave a crop residue cover on the soil surface, can increase infiltration and cause loss of soluble nutrients to groundwater. Level terraces can more than double groundwater nitrate loading compared with contour farming (Johnson et al. 1982).

Nitrate is recognised as a major karst groundwater pollutant, owing to its adverse health effects. In infants, nitrate can be reduced to nitrite, causing methemoglobinemia, the 'blue-baby' syndrome (Grow 1986). Levels of nitrate above the United States Environmental Protection Agency drinking water standard of 10 mg/L have been documented in karst groundwater in Minnesota (Grow 1986; Smolen et al. 1989), Pennsylvania (Kastrinos & White 1987) and Iowa (Mitchem et al. 1988). Kastrinos & White (1987) showed a linear relationship between mean nitrate concentration in karst spring water and agricultural land use coverage. In their study of the Conestoga Headwaters RCWP project area (about a third of which is underlain by carbonate rocks) wells in the carbonate-rock portion showed higher nitrate levels than non-carbonate wells.

Phosphorus is not considered a groundwater pollutant, since it has no adverse health effects and does not migrate far into soils before it is immobilised (White 1988). However, if excessive loadings of phosphourous (usually from manure) exceed the adsorptive capacity of a soil, leaching to ground water is possible (Johnson et al. 1982) and direct entry and passage of phosphorus through conduit drainage to resurgences may occur. The major adverse environmental effect of high phosphorus levels is the eutrophication of surface waters (Johnson et al. 1982).

The link between changing agricultural land use and impacts on the underlying karst have been most thoroughly studied in the context of human effluent and manure lagoons and silage storage. Alexander & Book (1984) examined the notorious case of the Altura Minnesota lagoon collapse in 1976, studying the massive failure of a series of effluent and aeration ponds holding concentrated human waste. The lack of understanding of the number and extent of sinkholes underlying the lagoon area was implicated as the cause for the disaster. Moreover, the presence of a thin, poorly indurated and jointed sandstone layer overlaying a thick carbonate unit was not discovered in pre-construction surveys. The problem arose when sandstone collected solutionally aggressive vadose water and concentrated it on the underlying bedrock exposures. The aggressive, differential solution of the underlying carbonate produced enlarged voids in which the overlaying materials collapsed. The stored effluent then drained into the underlying carbonate karst aquifer.

Drew (1996), working in the Burren country of western Ireland, investigated the threat of farm-related effluents on the underlying karst groundwater system. It was discovered that a large proportion of silage piles produced a potent form of effluent that greatly exceeds the other more commonly examined types of effluent in terms of its biological oxygen demand (B.O.D.) (Table 1). Cattle slurry was also found to be highly concentrated and of considerable concern. However, systems to manage cattle slurry were better developed and were incorporated into agriculturalists' management practices compared with the management of silage effluent which was poor to non-existent—nearly half of the surveyed silage piles were drained directly into the karst aquifer via some sort of karst window.

Drew's findings are highly relevant to the New Zealand situation. Most notable is the expansion of dairying, and concomitant row cropping of corn and silage production in the Waitomo district. The Ministry of Agriculture and Fisheries

TABLE 1 BIOLOGICAL OXYGEN DEMAND, NITROGEN AND PHOSPHOROUS INPUT FROM VARIOUS POLLUTANTS (DREW 1996).

SUBSTANCE	B.O.D. mg/L	NITROGEN mg/L	PHOSPHOROUS mg/L
Silage effluent	65 000	2700	560
Cattle slurry	17 000	4000	700
Soiled farmyard water	1500	300	30
Untreated sewage	400	55	15
Clean water	<4	<1	0.005

(Hamilton) reported an increase in dairy operations from 44 to 51 in the Waitomo district between 1991 and 1992 (Begg 2002). Since 1992, the trend toward increased dairy cow numbers per unit area and the number of new operations has increased rather than diminished.

Related to the increase in row cropping of corn with the expansion of dairying is the risk of contamination of karst groundwater owing to the use of agricultural chemicals. Most modern herbicides move in the dissolved phase. In Iowa karst, of the atrazine found in groundwater, 55 to 85% arrived there via infiltration through the soil (Mitchem et al. 1988). Maas et al. (1984) and other authors including Boyer & Pasquarell (1996, 1999) and Pasquarell & Boyer (1996) identified the following primary routes of bacteria and/or pesticide transport to karst aquatic systems: by direct application to water surface; in runoff: either dissolved, granulated or adsorbed on to soil particles; aerial drift; volatilisation and subsequent atmospheric deposition; and through uptake by biota and subsequent movement through the food web. Sources of pesticide contamination in karst include excessive or improper application, poor timing of application, incorrect choice of chemicals, and improper cleanup and disposal practices. Pesticides in groundwater not only affect drinking water wells and springs adjacent to the point of use, but also may kill fish and other aquatic life (Maas et al. 1984) and affect municipal water supplies and surface water bodies downstream. Hallberg et al. (1985) reported year-round concentrations of atrazine in Iowa karst ground water of 0.2 to 0.5 μg/L. The levels of atrazine reached a maximum in 1984–85 but dropped after cleanup efforts (Klein 1989 quoted in Berryhill 1989).

Quinlan & Alexander (1987) conducted a comprehensive survey of atrazine flow through a karst environment. Their study addressed the unique hydrodynamics of recharge storage, and also discharge in a karst aquifer and its influence on the distribution of pollutant maxima during various water input scenarios (both meteoric and snow melt). The study challenged the applicability of sampling methods for monitoring groundwater quality that were designed to satisfy regulatory requirements. Such methods, he discovered, commonly assume that there are no significant short-term changes, and he concurred with Bender (1986) that very few publications address water-sampling strategy and related problems of sampling frequency.

Quinlan & Alexander found that nitrate may reach a maximum or minimum which neatly coincides with the hydrographic peak, but this depends upon the season and whether a significant amount of recharge infiltrates through the soil. The lag between the hydrograph maximum and the atrazine maximum is a consequence of the rise in stage which is caused by groundwater being pushed out of the cave by 'piston-flow' of storm water behind it. The hydrographic peak in the nitrate has a similar origin. It is water which was stored in joints and fissures, but which is also being pushed out before the storm water runoff attunes at the monitoring site.

Importantly, the time span for pollutant variability ranges from months to years, and is a response to the frequency and duration of wet periods versus dry periods. During dry periods, the pollutants accumulate in the soil and epikarst zone (Williams 1985; Hobbs & Smart 1986; Smart & Friederich 1986). Hence, pollutant concentration detected in springs and relevant wells in the active flow zone decreases. Since flow is also less during dry periods, the total amount of pollutants moving through the system decreases too. In wet periods, however, more pollutants are washed through the soil and epikarst zone and are detected at springs and monitoring wells which intercept conduits flowing to them. Therefore, the total amount of pollutants, as well as their concentrations reaching these monitoring points, is much higher during wet periods. Short-term, event-related fluctuations of pollutant concentration are superimposed on these long-term fluctuations.

2.5.1 Monitoring and assessment of pollution pathways

Adequate monitoring of a pollutant source in a karst characterised by conduit-flow and concentrated recharge requires both frequent sampling (in some settings) as often as hourly during a storm or other precipitation event as well as long-term sampling (regularly, over a period of years). Adequate monitoring also requires continuous recording, inspection and interpretation of stage data and also adjustment of sampling frequency, so that it is possible to know the approximate times of parameter maxima during a storm event. Additionally, it must be possible to know and interpret antecedent soil-moisture conditions, since they strongly influence the hydrograph response.

Different sampling problems are encountered in karst aquifers dominated by diffuse-flow through fractures. Quinlan & Alexander (1987) demonstrated that daily sampling of numerous springs and wells was necessary to detect one-way 'pulses' of dye that randomly appeared one week to even months after injection at a proposed landfill on a ridgetop. It must be noted that this was a case where a precise throughput time was required rather than simply proving a hydrologic connection.

As alluded to in Quinlan & Alexander's work, soil type, depth and characteristics of the soil profile bear heavily on the movement of water, and hence pesticides, into the epikarst zone. Veni (1999) discussed in some detail the role played by soil when conducting environmental impact assessments in karst areas. Veni asserts that surface karst features containing no sediment or soil, or only A horizon-type soils, are far more likely to transmit contaminants rapidly into aquifers than features containing soils of the B and C horizons. In karst areas however, the thickness and permeability of sediments and soils can vary dramatically over short distances. Conditions assessed in one feature should not be generalised to other features and locations.

2.6 PERCOLATING WATER

Landscapes and their vegetation type can have important implications for the formation of particular biokarst features. Hence, attention must be given to alterations in the vegetation cover in areas where biokarst features occur. The main biokarst features that have been researched in the context of changing vegetation cover are tufa dams and micro-pits (Jie at al. 1997). Two areas of interest are commonly referred to in the discussion of the role of biokarst in karst landscape development. One area applies to erosional elements such as lichen and mosses, which in effect play a catalytic role in eroding limestone.

Small, micro-scale features ‘etched’ into exposed limestone are the result. These are considered to be minor factors in the meso- and macro-scale formation of karst landscapes. Local exceptions must of course be considered, e.g. karstic coral islands, as important examples of the potential of this type of activity. Identified as more important are the depositional biokarst processes. These are represented by the deposition of calcite on the surface in the form of tufas. Considerable debate surrounds the process of tufa accumulation. Jie et al. (1997) proposed a model based on research conducted in Sichuan Province, China. They discovered that the role of algae and mosses in karst deposition has, in turn, an important role in tufa formation. The management implication of this study is that site-specific bacteria, algae and mosses prevalent in the wider karst area or hydrological catchment must be identified and protected if the natural process of karst deposition on the surface as tufa deposits is to continue. This research also supports arguments made elsewhere on the role of bio-agents in the epikarst zone and karst erosion and deposition.

A two-year study of a karst spring in the peri-Mediterranean karst system in southeast France yielded some interesting results that are relevant for karst area managers. Lastennet & Mudry (1997) attempted, through longer–term study, to determine the nature of the variability in karst water chemistry debouched by one spring. By studying the area for two years, the effects of drought and flood could be assessed. The authors discovered considerable variability in the chemical composition of the water debouched from the system, especially as related to ‘discrete’ and ‘unusual’ climatic events. One of the important findings was that small events in the catchment appeared to have little or no impact on the entire karst hydrological system (or the effects were so small that they were undetectable). Major events, however, such as large floods, had great and potentially lasting impacts on the system. These lasting impacts usually resulted because of the gross change effected on the composition of the autogenic input sites in the karst basin by substantial movement of regolith either into the system or the entrances of caves. Similarly, the blocking of exit points by debris and sediment had the potential to force a longer-term change in the flow regime of the hydrological system, and thus alter the chemical makeup of the water.

A second and equally important finding was the variability discovered in water chemistry in relation to storm events. Special emphasis was placed on chemicals recognised as influential in the karstification process. These were total dissolved solids, i.e. bicarbonates; chloride and nitrate (tracers of shallow water systems); and silica and magnesium (tracers of water from the saturated zone). Concentrations of these compounds were highly variable in relation to storm events. Consequently, the authors emphasised the importance of a rigourous water sampling methodology in most studies of karst groundwater. This is highly relevant to managers of karst environments in New Zealand, where climatic variability across time and space is significant. When water chemistry data form a vital input into the database on which management decisions are to be made, it must be ensured that these data are rigorous and appropriate for the type of karst being considered.

As an example, Quinlan & Alexander (1987) devised a set of parameters to determine the frequency at which water samples should be taken when assessing the impact of pollutants from agricultural, waste disposal and spill sites in karst terrain. The authors implore agencies to consider these recommendations in order to have accurate information 'to defend against their [environmental zealots] frequently unjustified attacks'. Quinlan & Alexander state that 'the conventional practice of using four conveniently located monitoring wells (one up-gradient and three down-gradient), as commonly required by regulatory agencies (in the United States) for granular aquifers, but honorably, naively, and erroneously also required for karst terraces, is likely to be a waste of time and money'. Moreover, the sampling of water collected quarterly, semi-annually and annually is also invalid in karst terrain. The authors advocate much more frequent monitoring. It is argued that the distinctive characteristics of the karst aquifer under investigation must be considered on a case-by-case basis. The unique hydrodynamics of recharge, storage, and discharge and their influence on the distribution of various pollutants must account for variability in climatic events. The requirements in place in the United States for monitoring groundwater are simple and straightforward, but do not account for the variability that can occur in karst aquifers. The assumption in the USA regulations is that there will be little short-term change in an aquifer and that testing for any short-term change will not be cost-effective.

The importance of frequent sampling was reinforced by the results of Quinlan & Alexander (1987) study of Moth Spring in Minnesota, USA. In the conduit flow-type situation they studied, concentrations of pollutants can range from 100 to 10 000 times higher than antecedent levels within a few hours or days. Admittedly, this is in a conduit-flow situation (more rapid and hence more likely to have concentrated pulses of contaminants), which the authors recognise as one end of the continuum of karst aquifer development, with diffuse-flow and dispersed recharge aquifers at the other end. In essence, pulses driven by precipitation or runoff events account for one set of effects. The maxima for different contaminants can be out of phase with each other and the hydrograph peak. For example, with non-point sources of pollution such as herbicides that may be carried by surface runoff, this component may reach a maximum early in the hydrograph peak at the spring discharge. However, nitrate is often carried by the diffuse component of recharge. Nitrate may reach its peak or trough along with the hydrograph peak, depending on the intensity of a given rainfall event, soil moisture conditions and seasonality. In some cases, the maximum contamination can occur before the peak hydrograph as contaminants stored in joints and fissures are 'pushed out' by the rising pulse of the storm surge.

The second scale of analysis determined by Quinlan & Alexander is over a longer time frame. This correlated with either wet and dry periods or longer duration over months and years. Since flow during extended dry periods is less, the amount of contaminant discharged in such periods also decreases. Conversely, at the end of a dry period and with the onset of a wetter period, the amount of water and contaminants debouched from a spring will rise. The variability of the aforementioned short-term events is superimposed on these wet and dry period fluctuations.

In summary, Quinlan & Alexander suggest that for adequate pollutant monitoring in a karst area characterised by a conduit-flow system and concentrated recharge, sampling should occur hourly during storm or other significant precipitation events, and also longer term over several years. In conjunction with water chemistry, attention must be given to regular collection of reliable stage data so that researchers can characterise an aquifer and predict the impact of individual rainfall events with reasonable certainty. Accuracy of predictions is also enhanced by the collection and interpretation of soil-moisture conditions, since these strongly influence hydrograph behaviour.

The monitoring of karst groundwater is critical for assessment of risk associated with the use of karst landscapes for primary production. Problems do arise however, when data attained in the comprehensive study of a karst aquifer are released to the public. A commonly asked question, one posed by Quinlan & Alexander is: 'Is a temporary high concentration of parameter "X" during a storm a real problem as contrasted with merely a theoretical one? . . . does such an event constitute a significant risk to the health and welfare of people, cave fauna, or other life?' What if, for example, it were possible to avoid the use of the contaminated groundwater debouched during a storm event that is likely to have a high concentration of contaminant(s)? Risk analysis cannot, by itself, provide a panacea for unequivocally determining issues of public safety and health (or of the impact on the flora and fauna of the karst environment). At best, as Quinlan & Alexander note, risk assessment offers some guidance for policy decision, as does common sense.

2.7 QUARRIES, LANDFILLS AND MINING

Two significant forms of point pollution in karst areas are sinkhole dumping and the act of quarrying and subsequently employing disused quarries as sites for solid waste disposal. In this section, the focus is on the issue of quarrying and use of disused quarries for waste management, or in limited cases as sites for landscape rejuvenation.

2.7.1 Quarrying

In aesthetic terms, limestone quarrying is the most 'obvious and, in both process and landform terms, the most dramatic anthropogenic impact on karst terrain' (Gunn & Bailey 1991, 1993). The quarrying of limestone has both geomorphological and ecological impacts. The work of Gunn & Bailey (1991, 1993), Gunn & Hobbs (1999) and Hess & Slattery (1999) detailed these impacts in a British context. However, many of their findings are applicable to quarrying in any environment.

In essence, quarrying represents an intensification of the erosion process. In the case of Britain, the volume of material excavated would have taken up to 10 000 years to erode naturally. It is the rate of change that has dramatic and equally rapid impacts on hydrology and karst ecology. One of the more common impacts of quarrying is the drawdown of water in the subcutaneous zone surrounding the quarry. In some cases, this has led to doline formation. In other cases, the entire subcutaneous zone may be removed by quarrying activities and in such cases the impacts on local water resources and karst processes can be profound. When groundwater pumping is required to maintain a quarrying operation, the impacts typically affect a greater area than when pumping is not required. Groundwater drawdown can influence groundwater discharge from springs in the region of the quarrying operation, in terms of both quantity (seasonality) and quality of debouched water.

The stripping of forest cover and soil for quarry development destroys the karst ecology of the area earmarked for quarry development. Deposition of the spoils from these activities can also influence karst processes. The size and depth of the quarry has implications for the subsequent recolonisation of the environment by surrounding vegetation. With an increase in depth, it is correspondingly likelier that a different limestone composition will be exposed. Upon abandonment, the soil formed from this parent material could be significantly different from the surrounding environment, obviating the development of a complementary plant assemblage (Ruthrof 1997).

Gunn & Bailey (1991) assert that the size of a quarry is of less impact than its situation. They describe three possible locations for quarry development: on flat ground, along or into the side of a valley, or into a hill. Quarries developed in flat areas have less impact and this is restricted to the destruction of local karst features. Valleyside and hillside quarries are, however, favoured for their economy; it is easier and cheaper to work material laterally rather than vertically. Generally, hillside quarries have a greater geomorphological impact than valleyside operations. Cases of complete hill removal through quarrying have been documented (Stanton 1990; Urich et al. 2001).

2.7.2 Anthropogenic landforms

Gunn & Bailey (1991) describe three anthropogenic features that may result when quarrying ceases.

- Enclosed or semi-enclosed rock basins have formed when quarrying occurred in a generally flat landscapes in morphometric terms, they are comparable to very steep-sided collapsed dolines.
- Valleys with both sides modified by quarrying result in a steepening of the valley sides and a widening of the valley floor. Resulting valleys have a shape usually found after glacial sculpting.
- Artificial dry valleys can result when quarrying activities work in, rather than along a slope.

The landforms described above can, and should be considered 'permanent' in that it will take considerable geologic time for the modified landscape and the surrounding environment to evolve to become a unified system. The return to a more 'natural' geomorphological condition can be hastened by the importation of foreign material (land fill), with its own set of ecological ramifications.

2.7.3 Reclamation

Given that the evolution of quarried landscapes to a more natural condition may take hundreds of thousands of years, there has been a movement to hasten the process through the use of rehabilitative techniques. In Britain, it is now mandatory that a reclamation plan be included with any application for a quarrying permit.

2.7.4 Landfilling

Bodhankar & Chatterjee (1994) examined an interesting case of land filling in a disused quarry in Madya Pradesh, India. They considered a water-quality problem in their study. The problem was first discovered when a variation in the colour of the groundwater was noticed, owing to the presence of suspended sediments. The water had been supplied by tube wells in a residential locality near an abandoned limestone quarry. This abandoned quarry was used as an urban waste disposal site. The problem only occurred during the rainy season, when the quarry filled with precipitation and surface runoff water. This phenomenon was overlooked and the people continued using water. After some time, many nearby residents had to be hospitalised owing to waterborne diseases such as cholera, dysentery and gastroenteritis. Jaundice, malaria and typhoid were also on the rise.

A study showed that groundwater from the wells and water within the now garbage-filled quarry were linked. Four other sources of contamination were also identified:

- Domestic waste disposal: the prevailing practice was the direct disposal of domestic waste into surface sewers, which flow into the natural drainage system within the watershed area. Sewage was also dumped in sinkholes within the highly porous and permeable soil capping the limestone. Unregulated waste disposal in slums and newly urbanized areas without a planned sewage disposal system led to the formation of cess pools, which were potential sources of contamination.
- Water conservation structures: there were approximately 35 water conservation structures in and around Raipur City. These were in the form of natural lakes and ponds, and artificially constructed stop dams, and acted as groundwater recharge sites. The inflow into these reservoirs included precipitation and surface runoff water. Most hazardous was the surface runoff water that carried dissolved and suspended solids such as food wastes, animal faeces, fertilisers, pesticides, grease and oil.
- Landfills: there were more than 25 active or abandoned urban waste disposal sites in Raipur City. Dumped waste consisted of garbage, and at some landfills there was also incineration of combustible refuse in abandoned limestone quarries. Landfill material included paper products, food wastes, construction debris, septic tank sludge, plastic, glass and chemicals.
- Water wells: domestic dug wells were of small capacity and tapped the shallow water. Many of these shallow wells had dried owing to lowering of the groundwater level. These dried dug wells were in places used as community dump sites. Deeper tube wells for private and municipal water distribution were of a higher capacity and tap deep-seated aquifers. Surface and groundwater percolation from outside the casing may also have occurred, leading to contamination.

The case of quarry use for landfill, and its consequences, were graphic in Raipur City. Similar cases and impacts are also common in so-called developed areas. In some cases in the United States, it is not the solid wastes that are of the greatest concern. Liquids, mainly in the form of industrial chemicals, have been dumped in disused quarries and other landfills developed in karst areas. Contamination of the groundwater supply is common, with potentially disastrous consequences for public health and aquifer integrity. See the works of Hoenstine et al. (1987); Edwards & Smart (1989); Slifer & Erchul (1989); Hall et al. (1995); Davis (1997) for details that parallel those of the Raipur City case study.

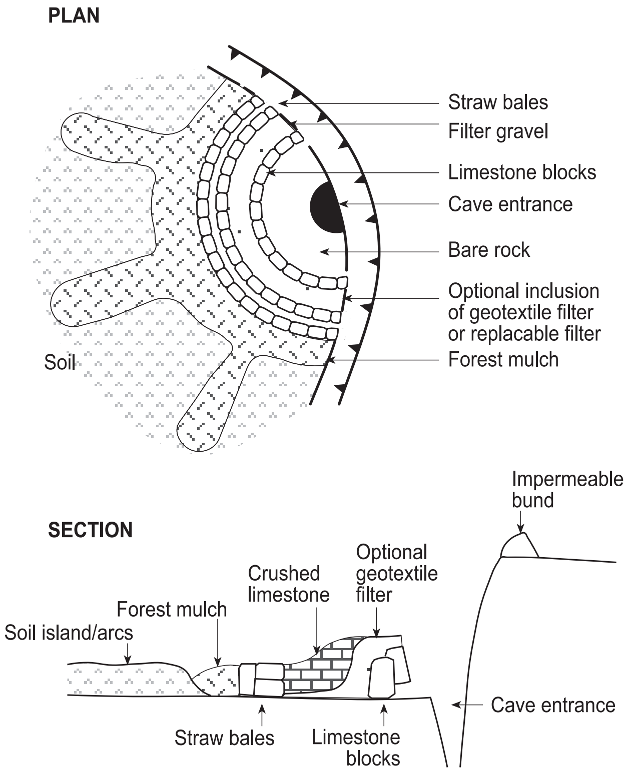

Figure 5. Technical features incorporated in the Lune River Quarry rehabilitation project. (Source: Gillieson & Household 1999. Reproduced with permission.)

2.7.5 Restoration and closing of quarries and landfills

The Tasmanian Lune River limestone quarry is one of the best-described quarry rehabilitation projects in the literature. As previously mentioned, most resource conflict over limestone concerns visual and water pollution, as well as loss of recreational amenity and conservation values. Quarry rehabilitation in Australia is occurring in three karst sites: Mount Etna in central Queensland, Wombeyan in southern New South Wales and Lune River in the Tasmanian Wilderness World Heritage Area.

The impacts of quarrying on the karst at Lune River have been profound (Gillieson & Household 1999).

- Removal of cave passages and their contents by quarrying
- Destruction of palaeokarstic fills by quarrying
- Increased sedimentation of fine clays in Little Grunt Cave (underlying the quarry) and the hydrologically connected Eastern Passage of Exit Cave
- Recurrent turbidity in Eastern Passage and Exit Creek
- Changes in pH, conductivity and sulphate ion concentrations in passages draining the quarry
- Re-solution of speleothems by acidified drainage waters due to oxidation of sulphides from paleokarst fills
- Reduced densities of indicator species of hydrobiid molluscs (*Fluvidona* spec. nov.) in passages draining the quarry.

An attempt was then made to rehabilitate the quarry and the affected parts of the cave without further impacting the karst values and ecosystems (Fig. 5). Reshaping of the quarry by the commonly used technique of restoration blasting was rejected, owing to the sensitivity of both the geomorphology and biology of the cave (Gagen & Gunn 1987).

The World Heritage values of the Exit Cave system was identified as a primary objective. It was then deemed necessary to return the ecosystem processes within the quarry area to as close as possible to their original state. In terms of rehabilitation, the integrity of the underground drainage was set as the main priority, followed by water quality and finally the cave invertebrate populations. A secondary objective was also identified: the project proponents wished to re-establish a high degree of interconnected secondary porosity in the quarry so as to effectuate appropriate recharge and to simulate as much as possible the original polygonal karst drainage and forest cover.

The detailed objectives were as follows (Gillieson & Household 1999):

- Restore the hydrology of the site by simulating as much as possible the drainage characteristics of the unimpacted karst.
- Reduce peak runoff by the creation of small internal drainage basins which simulate dolines in polygonal karst as an effective way of restoring near-natural infiltration rates and their spatially diverse patterning to allow soil and subcutaneous zone recharge.
- Control sediment movement at source by the use of control structures and filters, and construct adequate filters at stream sinks to prevent entry of sediment into the karst hydrological system.
- Control active soil erosion and sediment entry to the karst system by stabilising the soil surface (using hydromulching on steep areas) at the sediment sources and encouraging cryptogam growth, which is the soil's first defence against erosion.
- Establish a stable vegetation cover, preferably of perennial plants. A diverse vegetative cover with viable seed and the right structure to maintain geomorphic and biotic processes is not only aesthetically pleasing, but also will effectively moderate karst processes in the long term. The quality of substrates used in rehabilitation is critical.
- Reactivate the soil biology. Allowing colonisation of the site by soil biota, especially the colonial insects necessary for litter breakdown, will enhance the recovery of nutrient cycling and produce a good soil structure for plant seedling establishment and water infiltration.
- Monitor progress above and below ground. The success or failure of the rehabilitation can only be assessed with meaningful data, preferably collected on an event basis in order to allow calculation of loads of solutes and sediments entering the karst drainage system.
- The complex nature of drainage and filter structures means that daily supervision is mandatory during machine work phases. Plant operators may be unfamiliar with karst rehabilitation principles, and environmentally costly mistakes may be made inadvertently.

A monitoring system was established at Exit Cave to quantify the effects of the quarry rehabilitation strategy. To date, the researchers have found that hydrograph peaks and the transfer of solutes and fine sediments have declined. A more controlled and diffuse infiltration of surface water is occurring, which has led to a decrease in the introduction of sulphite-rich clays to the subterranean environment. It is still too early to assess the impact the changes have had on the cave fauna.

A model of sorts for designing, implementing and monitoring the closing of a quarry landfill comes from Missouri in the United States (Hall et al. 1995). The landfill in question was situated within a mature dolomite karst system, which included numerous sinkholes, springs, cave systems, and streams which lost flow to the bed through fissures in the underlying limestone bedrock or gained flow from water seeping up through the bed. The investigation and closure of this site was conducted utilising a set of innovative techniques including fracture trace analysis, natural-potential and resistivity surveys, regional potentiometric data analysis, structural information, stream/spring gauging, monitoring well installations and dye-tracing studies. It was determined that well-connected karst conduits were the structural features that control the movement of groundwater in the vicinity of the landfill. Final landfill closure included the use of such methods as seep remediation and a landfill cap to limit through-flow of meteoric water, plus the sealing of an on-site sinkhole. Groundwater monitoring continues to assess the success of the project.

2.8 URBAN DEVELOPMENT (USA)

A considerable amount of research has been conducted on the impact of urban development on underlying karst aquifers. The greater part of this research has been conducted in the United States, where large urban agglomerations are sited atop important karst aquifers.

2.8.1 Sinkhole flooding

Nicholas Crawford, who heads the Karst Waters Research Unit at Western Kentucky University, studied the impact of sinkhole flooding and surface water contamination on the karst underlying the urban area of Bowling Green, Kentucky (Crawford 1984). The city of Bowling Green is located entirely upon a sinkhole plain, with underground streams flowing through solutionally enlarged caves within the shallow carbonate aquifer. The landscape resembles large funnels (sinkholes) that direct storm water runoff into the underlying caves. Flooding of sinkholes in this karst region is a part of the natural hydrologic system.

The urban storm water runoff flowing into By-Pass Cave exceeded the surface water criteria for public water supplies for faecal coliform, oil and grease, chromium, lead and iron. Grab samples revealed that levels of ammonia, 5-day Biological Oxygen Demand (BOD5) and total dissolved solids were also high enough to be considered pollutants or indictors of pollution during the first flush of storm water into the cave. In addition, suspended solids (e.g. plastic bags) were a significant pollutant; the refuse had a high potential for clogging cave passages and exacerbating flooding.

Crawford concluded that any attempt to keep urban storm water runoff out of caves under Bowling Green was impractical or impossible, even though it carries pollutants into the underground streams.

In one part of the city, a watershed systems approach had been made to solve a particular sinkhole flooding problems. This problem resulted from increased storm water runoff associated with primarily residential developments. Sinkholes were filled by developers and homeowners, and runoff was directed into adjacent sinks which were unable to handle the increased discharge. Overflowing sinkholes during storms produced an unchanneled surface-flowing stream that wound its way through residential property for about 2.5 km before sinking completely. The watershed approach with a thorough mapping of cave conduits and capacities was deemed a success and reduced local flooding. In the future, developers need to be made aware of the nature of the underlying geology and be restricted in their practice of infilling sinkholes (which block underground flow). Avoiding the movement of surface water in this urban development into the karst aquifer is impractical, but can be better managed.

2.8.2 Groundwater withdrawal

A similar case of urban development in a fragile karst with a risk to its groundwater and surface collapse was studied in the northwestern part of Augusta County in Virginia. The area is flanked by the Blue Ridge Mountains of the Ridge and Valley Physiographic Province. Groundwater resources are plentiful in Augusta County, particularly along the toe of the Blue Ridge in what is known as the Lyndhurst-Grottoes alluvial corridor, immediately adjacent to the study area. To meet future water-use demand in the county, a groundwater supply well was developed and a 48-hour pump test conducted at 11 356 litres per minute. Although groundwater reserves proved plentiful, a 45-cm-deep sinkhole developed about 198 m from the well, farm ponds 457 m away receded and residential wells 244–610 m away incurred reduced water levels. Residents feared a risk of damage to homes, loss of their water supply and degradation of drinking water quality (Destephen & Benson 1993). Groundwater and surface water testing included inorganic water-quality also and microbiological parameters. The latter included particulate analyses and the presence of protozoan parasite *Giardia lamblia* and coliforms, which were used to evaluate the connection between groundwater and local surface water bodies. Although results of the study indicated a low potential for structural damage, owing to future sinkhole activity, it showed that the water quality of some residential wells might be degraded.

Since particulate analyses confirmed that groundwater feeding into the supply well is under the direct influence of surface water, it was recommended that certain residents be placed on an alternative water supply prior to production pumping, and that filtration be provided for the well in accordance with the Surface Water Treatment Rule. A mitigation plan was implemented, which included crack surveys. The more comprehensive plan included a long-term settlement station monitoring programme, and limitation of the groundwater withdrawal rate to 3.78 million litres per day (mgd) and a maximum production rate of 5670 litres per minute. The residents who could have been adversely impacted by groundwater resource exploitation were satisfied by the outcome of this investigation and the subsequent management plan. In this case, a thorough study of the impacts of groundwater extraction averted human suffering and the associated high mitigation costs.

2.9 DAMS

The impacts of large dams in karst areas are well established (Herak et al. 1970; Nicod 1991; Breznik 1998).

Karst terrain presents several risks related to development of not only dams, but also other large structures such as buildings and landfills (Destephen & Wargo 1992). The risks include: highly variable rock surface with pinnacles and slots; 'enhanced weathered zones'; and solution voids and cavities. The first can cause differential settlement and unanticipated construction costs and delays. The others can result in either sudden or ongoing subsidence. When designing foundations in karst (for buildings or dams), the risks of potential future subsidence must be defined for potential owners so that they can make rational decisions about the amount of risk they are willing to accept.

Seismic instability may also be more likely in karst areas where dams and large reservoirs are created. In China, 19 cases of reservoir-induced seismicity have been acknowledged and 15 of these are associated with karst (Chen & Talwani 1998). For example, the Wujiangdu dam, with a height of 165 m is the highest built dam in a karst area of China. A temporary seismic network was set up 40 km upstream from the dam. The results indicate that epicentres were distributed along the immediate banks, composed of karstified carbonate, and focal depths were only several hundred metres. Most of the focal mechanisms were of thrust and normal faulting. Chen & Talwani suggested that karst may be an important factor in induced seismicity, since karst landscapes provide the hydraulic connection to change the saturation and pressure that can lead to weak planes, and hence dislocation and induced seismicity. In effect, dams raise water levels, which increases the water pressure and forces water into bedding planes of limestone—thus lubricating and expanding joints leading to earthquakes.

In south-east Andalusia, Spain, the Guadalfeo and Adra Rivers drain the crystalline massif of the Sierra Nevada and, before reaching the sea, cross a mountainous region occupied by permeable Triassic carbonate materials. The Beninar Reservoir is situated in this karst area on the Adra River. The reservoir is less efficient in part owing to considerable seepage through a series of sinkholes in the carbonate outcrops (Benavente et al. 1993). A new reservoir, on the Guadalfeo River, is planned in a similar, but more complex hydrogeological context. The study of the area by Benavente et al. (1993) suggested that the permeability of the proposed dam site obviated the rationale for dam development.

In one case, the flooding of downstream springs resulted when a dam was constructed further upstream. The construction of a reservoir on the Neretva River in Yugoslavia influenced the flow regime of three springs 1 km downstream from the dam (Bonacci & Jelin 1988).

2.9.1 Remedial measures when damming

The potential for leaks to develop in reservoirs created by damming rivers in karst terrain is widely understood. Technologies have been used to mitigate such risks, although not always with great success, as the following examples describe.

The first evidence of possible foundation problems at Wolf Creek Dam on the Cumberland River of Kentucky, USA were noted in 1962, when a cluster of wet areas appeared on the downstream toe of the embankment. In 1968, sinkholes began to develop and muddy flows could be seen in the tailrace. A series of studies was initiated to determine the cause and investigate the need for remedial treatment. The investigations indicated that the sinkholes and muddy flows were the result of piping that moved through an extensive network of solution channels in the dam foundation. It was found that serious defects existed in the foundation of the dam, and that grouting (then the common cure) could not be relied upon for long-term protection. Instead a concrete diaphragm wall was constructed along the upstream crest of the embankment, for a distance of about 683 m. The method was deemed successful (albeit costly) for rehabilitating the Wolf Creek Dam (Hejazi 1987).

The Logan Martin Dam is a hydroelectric project on the Coosa River in Alabama, USA. As in the previous case, the project was initiated in the early 1960s. Seepage beneath the dam required several remedial measures to be implemented. The dam was underlain by highly fractured and solutioned dolomite and limestone (Williams & Robinson 1993). Subsequent hydrogeological investigations identified key leakage zones and indicate that the original (1960s) and the remedial (1970s) grout curtains did not extend deeply enough to intercept the predominate seepage paths. The grouting was extended to a depth of nearly 122 m to seal the entire known permeable zone underneath the dam (Williams & Robinson 1993).

3. Best management practices (BMPs)—current knowledge

Although carbonate rock-derived soils in karst areas are rich (White 1988) and in relatively flat topographical settings such as parts of the North American Mid-west make excellent cropland, in other areas soils are shallow and rocky, and fields are small and steep. Small farms raising livestock and poultry are more prevalent in the mountainous karst area of the eastern United States. Discussions follow of some 'Best Management Practices' (BMPs) that may be helpful on cropland, and for livestock and poultry operations. Many of the conservation practices developed in recent years are applicable in karst regions, especially those for management of fertiliser, pesticides, animal wastes and erosion. Those which increase infiltration are contraindicated if they also increase groundwater loading of nutrients and pesticides.

Two BMPs that especially apply to karst include Planned Grazing Systems and Livestock Exclusion (Soil Conservation Service 1987). Planned Grazing refers to rotation of pastures with rest periods to allow ground cover to regenerate. The efficacy of planned grazing with respect to improvement of groundwater quality was demonstrated by Van Keuren et al. (1979) who compared the effects of rotational summer grazing and continuous winter grazing by a herd of beef cattle in a two-year study. There was no measurable soil loss from the three summer pastures, although round 1600 kg/ha per year was eroded from the one winter grazing and feeding area. Average annual surface runoff from the summer areas (13.2 mm) was reduced by 85% from the winter value (90.4 mm). Infiltration was slightly greater in summer under the rotational-grazed system (407 mm compared with 388 mm), as was subsurface transport of nitrogen and soluble salts. This study was made in a non-karst region. More research is needed on the effects of different grazing systems on karst soils and waters.

Livestock exclusion is one practice of keeping animals away from water bodies and areas subject to erosion. In karst, sinkholes and cave entrances should be declared off-limits (Berryhill 1989). Laurel Creek Cave in Monroe County, West Virginia, USA was an obvious case where livestock exclusion was not practised. Several years ago, the low, wide entrance of a cave was a favorite resting area for cattle. During storms, however, the cave took large volumes of water, as evidenced by a highway bridge that had been washed deep inside the cave. The potential for pollution from cattle effluent of the aquifer recharged by this cave entrance could have been greatly reduced by a few feet of fencing.

Other suggestions for livestock are paved animal living spaces, means for flushing or scraping daily buildup of manure in stock holding areas, leak-proof feed and manure storage facilities, and unitary means to dispose of dead animals. They also include runoff control structures and vegetative filter strips for erosion and nutrient control. In the Garvin Brook, Minnesota, USA, these measures were used to keep feedlot runoff from entering sinkholes (Barryhill 1989). Some cattle operations in the upper Mid-west of the USA rely on unlined lagoons and pits for manure storage. These should not be considered BMP in karst, unless local soils and underlying bedrock have been tested and found to be acceptably impermeable. The worst possible case would be a swine waste lagoon over cavernous limestone in an area of active sinkhole collapse.

3.1 EXAMPLES OF BMP AND CAVE PROTECTION

Cave protection has been addressed more widely in the literature. The most comprehensive karst assessment process to date is that of Doerfliger & Zwahlen (1995), who proposed identifying hydrologically vulnerable areas in karst spring drainage basins through the use of air photo interpretation, tracer tests, geophysical data and geomorphological mapping. Their EPIK system uses the resulting data to define an area's 'Epikarst' (surface karst features), 'Protective' cover (soil), 'Infiltration' conditions and 'Karst' drainage degree of solutional conduit development. The characteristics of an assessed karst watershed area are matched to a category under each EPIK factor. Categories have numerical values, which are multiplied by a constant for the EPIK factor, and the results are summed to identify the area's degree of sensitivity, primarily with respect to groundwater contamination. This vulnerability mapping method has a broad application and should be conducted whenever possible. However, its reliance on tracer testing and hydrologic data invalidates it as a strictly geomorphological Environmental Impact Assessment (EIA) methodology. Moreover, it assumes uniform geomorphological interpretations when no standard methods have been proposed.

Many of the methods described above are widely used, and all are based on the accepted theories of cave, karst and speleothem development presented by White (1988) and Ford & Williams (1989). However, the primary goal of Veni (1999) was to offer a standard, yet flexible approach to developing karst EIAs and to show how geomorphological methods can be used to develop more comprehensive and quantifiable EIAs in karst areas. Veni tests this method in a detailed study of over 700 caves and 650 karst features along the south-eastern margin of the Edwards Plateau, Texas, USA.

Veni (1999) advocated particular methods for EIA development in karst terrain, both in terms of data collection and analytical phases of data assessment. Two particular features of his method are extensive use of excavation of fractures to check karst permeability, and assessments using several lines of evidence of epikarst development. The study area in the case of this paper was a subdued semi-arid karst, where many features are subtle or cryptic, and the caves had small surface catchments, with epikarst and fractures providing significant recharge. While the data gathered primarily concerned geology/geomorphology and hydrology, they were supplemented with biological and archaeological information. On the basis of this data, development/exclusion zones were proposed around specific caves and fractures, including the assessed surface and epikarst catchment areas, and a buffer zone beyond these. This model for cave protection was based on concentric rings of 'exclusion' defined through the application of environmental impact assessment guidelines.

These concentric zones protected rare cave fauna and other features, as well as preventing contamination of the main site of recharge. This was deemed critical as the aquifer fed by the study area supplied water to over one million people.

Veni (1999) accepts a maximum figure of 15% for impervious cover (buildings, roads, paved areas etc.) within karst areas. When impervious cover exceeds this figure, there is a significant adverse effect on karst water quality.

While the Veni example represents, to a large degree, isolated cave and epikarst environments (boundaries relatively easily identified), these situations are not common in New Zealand (where karst tends to be more integrated with lateral cave conduits linking to larger systems). Yet the general thrust of his argument is applicable to karst EIA planning in New Zealand. The basic emphasis on epikarst assessment applies to extensive cave systems as well; however, in the New Zealand context this could be controversial as it could result in pressure being placed on private landholders to alter landuse practices owing to the presence of cave passages on their land (perhaps with little or no evidence of their presence) and outside the currently DOC-managed estate.

4. Specific processes and features of karst-based activities and impacts

4.1 DOLINE MANAGEMENT

Specific literature assessing the impact of changed vegetation on the epikarst zone and, in many cases, caves associated with dolines is non-existent. Yet much of the other literature reviewed and discussed elsewhere points to the strong relationship between entrance ways, climate and air movement and impacts on the near-entrance cave environment. Hence changes in the vegetation in dolines or sinkholes (tomo) that often form around the entrances to caves should be carefully considered when management concerns the underlying karst formations. With the lack of specific studies of landuse change and its impacts on issues such as sediment movement into caves from the typically steep and erosive doline surfaces, I attempted to adapt other studies (primarily riparian vegetation strip management) to the task. Ultimately, specific studies of individual dolines should be conducted, however the methodological considerations in devising a research strategy would be daunting (finding controls, altering doline vegetation, finding comparable examples etc.).

Widespread interest in improving the quality of surface waters has led to an emphasis on best management practices for controlling agricultural non-point source pollution. Physical reasoning coupled with limited data has led to the conclusion that non-point source pollution is best controlled on-site, where flows are not concentrated into channels. Thus, control of sediment and chemicals is best accomplished while the flow is still classed as shallow overland flow, i.e. in the soil and regolith of dolines.

To augment information from previous studies, the objective of research by Barfield et al. (1998) was to develop a database focused on the trapping of sediment and chemicals in natural grass riparian vegetation where inflows and outflows were carefully measured. In addition, these authors estimated the partitioning of trapped chemicals from those adsorbed and those sediments and chemicals infiltrated. Studies were conducted in an area of karst geology with very high infiltration rates.

When tested to the point where water would flow through all the grass strips to the outlet, infiltration rates were still extremely high, as evidenced by a high fraction of runoff which infiltrated in the grass strip. The trapping efficiency increased dramatically as the percentage of runoff that infiltrated, increased as it moved downslope. One would anticipate that much of the trapping was a result of infiltration into the soil matrix. The improvement in trapping efficiency is not significant when filter length was increased from 4.57 to 9.14 m. However, the better performance of the 13.72 m filters over 9.14 m filters was found in this study. The increase in trapping efficiency with filter length is due to an increased opportunity for runoff infiltration and chemical adsorption. The length of plot upslope from the filter strips also had a strong effect on trapping efficiency.

An important evaluation is the impact of riparian vegetative filter strips on peak concentration of contaminants in runoff across the filter strips. A decrease in peak concentration would result in a lower peak discharge in the receiving stream (the stream in the case of this review representing a cave receiving runoff from a doline slope) and, possibly, a lower impact. An example of the impact of the riparian grass vegetation on the concentrations of atrazine for the 4.56 m filter strips in the Barfield et al. was provided. The results show a greatly reduced peak discharge concentration. The ratio of peak outflow to peak inflow concentration was evaluated for all tests in the study. Based on peak concentrations only, it is obvious that the filter strips had a significant impact on water quality for all chemicals except phosphorus. The 4.57 m plots had higher ratios than the two longer plots, except for phosphorus which had similar ratio regardless of the plot size.

Erosion plots were treated with atrazine, nitrogen and phosphorus. Simulated rainfall was applied to the plots. Runoff from the erosion plots was directed on to the vegetative filter strips and measurements were made of flow into and off the individual strips. The results showed that the filters trapped over 90% of sediment and chemicals. Trapping efficiency is generally improved when the length of the filter strips is increased. Estimates were made of distribution of trapping between infiltration mass and storage, and adsorption on the soil surface layer. It was determined that the major trapping mechanism was by infiltration, followed by adsorption in the surface layer.

This testing site bears resemblance to a doline's slopes and thus is, given the paucity of other sources, one of the few examples of the importance of vegetative cover in sloping limestone areas that may direct water into the cave environment. The relevance is particularly great where the doline vegetation has been cleared and cultivation with application of fertilizers and herbicides may be occurring. The presence of longer vegetative sequences greatly increases the chances for dangerous chemicals to be trapped and volatised before entering a cave or karst groundwater system. The situation in forest-covered karst and doline environments is less clear. Disturbed forest would certainly lead to a disruption of the doline environment and would logically lead to at least an initial burst of soil movement downslope and possibly into the cave. Numerous examples of sediment-choked dolines and cave's passages have been noted in the literature. Clearly, the natural forest cover in limestone areas should be preserved if managers wish to limit any possible degradation to the doline and underlying cave and karst environment. There is an intimate relationship between the near-surface vegetation and the micro-climate of the cave entrance and the fauna supported by the light, moisture and other organic material washed into the cave through natural processes. Any disruption in this natural system would have an impact on the cave environment and should be avoided if at all possible.

4.2 CAVE FAUNA

Many types of activity threaten cave fauna. Gillieson (1996) reviewed the range of impacts:

- Caves are used for legal and illegal dumping of refuse
- Although relatively few animals can survive in refuse or garbage, cave faunas are especially sensitive. Increased resource levels may allow non-cave dwelling species to thrive and outcompete the obligate cave species
- Inadequate sewage treatment may pollute groundwater sediments, leading to local extinction and/or replacement of cave species by surface species
- Cave entrances are vulnerable to closure on account of landfills, housing developments or road construction
- Deforestation or land-use change may affect water flow and sedimentation rates
- Pesticides and herbicides in agricultural area may impact both cave vertebrate and invertebrate populations
- Mining and quarrying remove cave habitats
- Human visitors impact the cave fauna in many ways.

Many caves have only limited numbers of individual endemic species, which often occupy a very narrow range and are intolerant of change. Therefore, they can be very susceptible to the impacts of pollution entering that environment.

There have been several studies of specific primary activities and their impact on groundwater resources (Quinlan & Ewers 1985; Wheeler et al. 1989; Waterhouse 1984) but only a handful have linked this and other types of human activity with cave faunal declines (Sket 1997). Hamilton-Smith (1970) discussed the linkages between the extinction of cave fauna with trampling, water pollution and shifts in cave micro-climates. Pride et al. (1989) studied the relationship between urban runoff and cave invertebrates in three springs in Tennessee, USA. All sites had a history of contamination but the more heavily polluted sites had increases in some species that were markers for higher pollution levels; 'cleaner' caves fed by more diffuse recharge had higher biodiversity and contained species eliminated from other caves and recognised as sensitive to higher levels of pollution. Sket's study (1997) was more regional in nature and incorporated an historical approach to landuse change and legislation in the famous Dinaric Karst of Slovenia. Such a long-term approach throws up some interesting contradictions in terms of soil protection and biodiversity. Sket found that as landuse in the Dinaric Karst changed from rather species-poor forest cover to species-rich human modified landscapes, the faunal resources in the karst also diversified. With the introduction of monocropping, particularly *Pinus radiata* plantings, the diversity is being lost both in flora and fauna. Sket has advocated the protection of traditional landuses in order to 'protect the high diversity of the man-made landscape'.

Tercafs (1988) stated that there was very little research on changes in faunal populations in cave environments and the underlying implications for their conservation. Within this narrow definition of his interests Tercafs was correct. Few studies have comprehensively quantified the decline in species numbers and linked this with particular activities and their intensity. To remedy this, Tercafs studied widely-visited caves in Belgium.

Tercafs notes that existing biomass in any given cave is limited. Almost all available energy is contributed by one of two functions: the vegetative matter and small organisms carried into the cave environment by water (both via percolation and free flowing); and the regular visits of non-consumer active organisms (trogloxenes) which come and go in the subterranean environment. Cave fauna should be a high priority for preservation because of their unique characteristics of diversity and ability to coexist in an environment poor in energy resources.

Tercafs (1988) defines three types of cave fauna. The **trogloxenes** inhabit caves on a temporary basis for particular physiological needs, often linked to seasonal variations with prolonged periods of inactivity, such as hibernation, aestivation (slowing of activity in summer owing to heat and dryness, often associated with snails) or diapause. The use of the subterranean environment is in no way obligatory for these species, since similar and appropriate epigeous (above-ground) niches exist. Importantly, no morphological differences are noted between trogloxenes and other above-ground individuals. **Troglophiles** are elective subterranean guests, but display no typical morphological modifications. They are apt to live in underground environments because these suit their behaviours and they may have a physiological predisposition to caves; principally, this is linked to diet. Their entire life cycle takes place underground. **Troglobites** are permanent, obligatory occupants of the subterranean environment and cannot live outside of it. These species typically display some types of regression characteristics such as the absence or major reduction of the eye and cutaneous pigments, and also a slowing of growth and development.

Tercafs states that the biology of the underground environment 'is, as yet, only partially known and necessitates special measures in conservation'. Subterranean environments have suffered from voluntary and involuntary destruction owing to quarrying, water pollution, damage caused by speleologists' visits and, in some cases, vandalism. To assist in determining the conservation value of particular cave fauna, Tercafs developed a complex methodological framework consisting of faunal and ecological factors denoting some values for these through various sections of a cave system with more than 200 000 visits per year by tourists.

The key points of the methodology that need to be considered were an abundant cave fauna, an extended and diverse cave and karst network (extensive cave system) and heavy recreational use. It must be noted that only anecdotal evidence is provided to explain why the census of cave fauna changed over a period of round 50 years. Other variables in the model included faunal and ecological factors and the recreational use factor, the latter consisting of the length of the route taking by visitors through the cave, the aesthetic value of different formations and lookout points and the accessibility of various ecological zones through the cave. A coefficient of biological value was placed on the 17 trogloxenes, 91 troglophiles and 6 troglobites occurring in the cave. A weighted value was made for each species based on its ecological status. An ecological fragility coefficient was expressed as a function of the tourist activity and associated infrastructure (lighting, cement paths etc.). Species were then classified as non-sensitive, slightly sensitive, sensitive, very sensitive and organisms that could not stand the slightest disturbance.

Changes in cave fauna were found to have occurred over the 50 years from the original comprehensive survey of cave fauna. Many of the changes were related to differences in survey method, including non-systematic sampling in the original survey conducted in 1939. Tercafs noted the impact of cave visitations on clay deposits and the negative impact this had on three species that are linked to clay deposits in their life cycle. However, he added a caveat that this conclusion was tentative and may be linked to other phenomena. The strength of Tercaf's article was its comprehensive and well-explained methodology, and the emphasis in the conclusion on the importance of troglobites and their apparent decline in the Belgian case. The susceptibility of troglobites to disturbance of their environment is highlighted by their occupation of a relatively narrow tension-zone and even a slight modification of that environment can have a detrimental effect. Troglobites have only underground populations (they cannot be augmented by the introduction of individuals from outside the cave, such as with trogloxenes and troglophiles), and they also have low reproductive capacities. This further limits their ability to recover from an ecological shock and reduction in their population.

The management outcomes of the research by Tercafs are clear. Specific routes through the tourism cave were classified by seasonal variations in the presence of species, the aesthetic value and, above all, the great susceptibility of the cave fauna to disturbance. Behaviour could then be modified so that the impact on species diversity could be greatly reduced, if not eliminated. In Belgium, the visits by sport cavers to unregulated (i.e. unmanaged) cave environments led to a 'profound deterioration of the subterranean heritage' (Tercafs 1988); the chances of preserving cave species were much improved in the managed cave environment, which accommodated many visitors.

4.3 SPELEOTHEMS

Much of the work on speleothem development has concentrated on the possible developmental changes that can occur owing to changes in the relative humidity of the cave environment. Two studies from the Southwestern United States have explored the issue of relative humidity using very accurate methods. Their findings are very important for managers interested in the impact of cave entrances on cave air and also that of vegetation composition near entrances to caves. As will be discussed below, the relative humidity of the cave environment determines to a large degree (along with air movement) the rate of calcium carbonate deposition within caves that result in cave formations (stalactites and stalagmites etc.).

An excellent study of microclimate was conducted at Kartchner Caverns in Arizona, USA (Buecher 1999). The study of microclimate was conducted to assess the potential impact of opening Kartchner Caverns to the public. The researchers discovered that development of the cave for public viewing would greatly increase evaporation owing to multiple entrances, induced airflow and increased heat from visitors' lights. Drying of the cave could result in permanent damage to many of the features that make Kartchner Caverns so attractive. This process had already been observed in many other show caves; in Kartchner, however, the arid Arizona climate aggravated the problem.

4.3.1 Methods and monitoring

Surface climate monitoring provided a record of external variations that frequently drive micro-environmental changes within a cave (Buecher 1999). The following study was conducted in an ice cave at Kartchner Caverns, Arizona.

A surface weather station which included a thermograph, hydrograph and microbarograph, was placed in a standard instrument shelter on the south side of Gaidani Wash, 165 m south-east of the natural entrance. A recording rain gauge was also installed near the Breather station. Surface climate data was collected continuously from June 1989 to June 1991.

A lower limit on the amount of moisture reaching this particular ice cave was determined by surveying the whole cave for active drips. In each room, the researchers listened and counted the number of drips in a fixed length of time. This single 'whole cave' drip rate was adjusted to the average annual drip rate by using the eight monitored drips as an index of conditions at the time of the 'whole cave' survey. Using the average drip volume, an over-influx of drip water was determined to be equivalent to an accumulated depth of 4.3 mm/yr. This method was reinforced by the use of pans and measuring the amount of water collected after correcting for evaporation losses. This method yielded drip water input of 6.9 mm/yr. The third and final method to triangulate the study was an evaluation of evaporation rates in the driest portions of the cave.

From these three approaches the amount of water reaching the cave in the form of drip water was estimated at 4.3 mm/yr, 6.9 mm/yr and 12.4 mm/yr respectively. The mean of these figures, 7.9 mm/yr, was used as a reasonable estimate for input from drips. Therefore, of an annual precipitation of 448 mm, less than 2% reached the cave.

Relative humidity (RH) has a profound impact on moisture conditions within the cave, since it largely determines the rate of evaporation. Higher humidity results in lower evaporation. For example, if the relative humidity falls from 99.5% to 99.0%, the evaporation rate will double.

A total of 318 measurements were taken throughout the cave, using a dewpoint meter. The recorded RH varied from 96.32% to 100.00%, averaging 99.42%. The distribution was highly skewed toward relative humidities approaching 100%.

A high RH also means that only a small drop in air temperature is necessary for water to condense from the air. For the majority of conditions observed within the cave, a temperature of <0.1°C will bring the air to saturation point, and any additional cooling of the air will cause condensation to occur.

4.3.2 The entrance environment and cave climate

The existing natural entrance to Kartchner Caverns was the only known connection to the surface. Early observations indicated that the natural entrance had a profound influence on conditions throughout the cave. This prompted an intensive data gathering exercise to deduce the probable impact of either changes to the entrance or the possible development of a second entrance for tourism purposes. Seven dry-and-wet bulb temperature probe stations were connected to a computer data logging system and temperatures were recorded each hour from March 1989 to June 1990.

It was believed that airflow from the entrance into the cave was strongly related to other processes within the cave, since the exchange of air altered the concentrations of carbon dioxide and radon gas. It was discovered that the management of carbon dioxide and radon levels in the cave might contradict the most effective means of controlling cave moisture. Increasing air exchange rates would lower gas concentrations, but would also increase evaporation, and thus dry out the cave, potentially leading to damage.

A second detailed cave air study was recently conducted at Torgac Cave, New Mexico, USA (Forbes 1998). Dried conditions were encountered close to the entrance, where old, dense winter air sank into the main entrance, drying the cave passages below as the air warmed. Forbes discovered that the cave generally became progressively drier throughout the winter months, then became warmer during the summer. This was in response to inflow of surface water from summer thunderstorms and the stable thermal stratification of the cave atmosphere during the warmer months, which restricted the density-driven influx of outside air.

Torgac Cave has two known entrances, including a large main (west) entrance and a smaller east entrance. Since the large sinkhole surrounding the main entrance acts as a cold trap for outside winter air, the air temperature in the cave is noticeably colder than in other caves in the vicinity. Cavers noted that some areas of the cave were much colder than others. Minimum temperatures occur at about 8:00 a.m., and maxima at about 2:00 p.m.; cave air temperature fluctuations appeared to correlate with external temperature cycles, the coldest cave temperatures occurring near dawn at the end of a cold night. The room where these measurements were taken is located approximately 75 m from the main entrance. Pulses of outside air are able to penetrate to this distance.

The findings of both these studies confirm that ‘the climate in caves is often described as being constant, in reality this is found only in deep interiors where there is a minimal interaction between the cave and the outside environment’ (Tarhule-Lips & Ford 1998). While these ice cave environments have few corresponding examples in New Zealand, it was the quality of the research on moisture, temperature and air movements that is of relevance. A solid and well implemented research methodology provided important insights into the fragility of cave environments to changes in the cave atmosphere.

It is therefore, possible to infer from these studies that the surface morphology and orientation of individual caves (horizontal v. vertical) and their entrance and near-entrance environments can have a profound effect on temperature, airflow patterns and relative humidity over time. Any changes to the number of entrances and/or size of an entrance for tourism or other development purposes could affect the entire cave (e.g. the Waitomo Glow Worm cave experience in New Zealand). Similarly, changes to the soil and vegetation of the entrance environment could be significant, since only very slight changes in the cave atmosphere, and the temperature and moisture of air flowing into the cave on a seasonal basis, can disrupt the cave’s equilibrium and alter the rate of cave formation.

4.4 EPIKARST PROCESSES

Epikarst hydrology is a relatively new field of study that is often overlooked in karst assessments. Veni (1999) noted that, in most areas, the only published data relating to epikarst are regional soil surveys. In the context of environmental impact assessments, it is argued that the thickness and permeability of local soils can be mitigating factors in environmental impact by their retention or delay in transmission of contaminants to an aquifer. In areas with thick soil mantles, it is suggested that road cuts and quarries be examined for cross-sectional views of the soil-bedrock interface. The common situation in karst of irregular or pinnacled surfaces suggests relatively rapid recharge through the soil.

Veni noted other indicators of the role of soil in the epikarst. For example, sinkhole ponds should not be regarded as signs of possible poor permeability throughout the karst, although they usually account for just a small percentage of the total number of sinkholes. However, floors of sinkholes have often been rendered less permeable by the input of colluvium by forest clearance, for example Waitomo karst of New Zealand (Williams 1980), and/or by livestock trampling and soil compaction.

Solutional features within caves may be used to estimate epikarst extent and permeability. Active recharge into caves through a permeable epikarst is demonstrated by caves with micro-conduit networks such as honeycombed solutioned beds; anastomosed and solutionally widened bedding planes and fractures; passage features such as drip-pitted walls and floors; vertically fluted veils; and water-cut channels in passage floors. The micro-conduits and features of lesser permeability are what White (1969) described as the diffuse flow component of karst aquifers. In the vadose zone, its most intensive development occurs adjacent to horizontally extensive caves, and where cavernous limestone crops out at the surface. Micro-conduits and epikarst permeability are laterally extensive near caves, since caves are sites of flow-path convergence and chemically aggressive clay can be injected into cave walls during floods. In the phreatic zone, such solutionally enlarged features often serve as the extensive and permeable diffuse flow system that supplies most groundwater to wells.

A rapid and nearly unimpeded recharge of deeper groundwater aquifers in karst areas that occurs along fractures in the limestone bedrock can infer that an area has underdeveloped epikarstic groundwater storage. In such cases, most vadose water is stored well below the epikarst within and along fractures, bedding plane partings, other minor voids from the top of the water table or major groundwater perching horizon. This water usually appears in caves as seeps, drips, or moisture on cave walls. This moisture may provide the baseflows of some cave streams.

Hardwick & Gunn (1993) have produced a comprehensive overview of the interrelationships between landscape change and impacts on the underlying karst features, since changes in water quality are likely to affect calcite deposition and hence speleothem growth and development. This is because calcite deposition is dependent on the presence of either saturated or supersaturated hydrogen carbonate (HCO_3) ions in recharge waters. This issue has been little studied, although Kevin Kiernan is currently overseeing an ongoing study of this relationship in the context of the anthropogenically induced forest cover change in Tasmania, Australia. Hardwick & Gunn suggest that 'geochemical process studies carried out on surface water systems and in laboratory experiments suggest that calcite deposition may be influenced by the presence of other ions'. Notably, ions of phosphate, fulvic acids and humic acids have been implicated as influential in crystal growth (Reddy 1977; Morse 1983; Lorah & Herman 1988). Latham (1981) has also suggested that organic matter and other debris washed into caves can influence crystal forms and to a lesser degree perhaps the shape ('gross morphology') of speleothems. Reference is made to speleothem colour variation within caves as direct evidence of the presence of various ions, acids or organic matter.

The impact of global change on epikarst processes must not be discounted (Assaad & Jordan 1994). Under normal conditions, rain has a pH of 5.5–6.0, as measured in Greenland ice from the time before the Industrial Revolution. Since then the concentration of hydrogen ions has increased owing to the combustion of hydrocarbon fuels and/or exhalation of aerosols, which are carried upward, incorporated into the air moisture and precipitated into soils and groundwater.

The acidified rain leads to acid deposition. Aerobic decay of organic matter in the soil, together with the metabolic processes of the soil micro-organisms produce carbonic acids together with other acids that corrode limestone, all of which affect karstification (Jakucs 1977).

Limestone has a natural alkalinity, but this may be neutralised by the acidic infiltrates through corrosion. The quantification of limestone corrosion carried by acid precipitation is dependent on many complicated factors, namely the level of precipitation and its pH value, temperature, global radiation, effective catalysts, buffer capacity of the soil, soil moisture and geological features of the saturated zone. The problem of the greenhouse effect may intensify karstification. On the other hand, the depletion of the ozone layer and the increase of CO_2 (25% during the last 50 years), together with CH_4 (nearly 1% per year) and NO_x (nearly 0.2% per year) may lead to a warmer climate and shift the warm climate zone to the Northern Hemisphere rather than the Southern Hemisphere. Hence this may intensify the process of karstification more in the Northern than in the Southern Hemisphere (Assaad & Jordan 1994).

Of course, one of the main problems encountered when trying to ascertain the environmental impact of human activities on the karst natural system is the difficulty of distinguishing changes caused by ongoing natural processes, including global warming, from those induced by human activities. This is possible only if the workings of the natural system and its robustness or vulnerability are well understood. Naturally occurring and human-induced environmental changes in karst are more easily ascertained in certain cases, and these tend to be the larger-magnitude, short-duration-type events such as water-table lowering with deforestation or sediment inflows from watershed forest clearance. The often more subtle chemical changes are less apparent and it is more difficult to ascribe causes to them.

5. Legislating for karst management

Local government units, regional political bodies and in some cases nation states are increasingly adopting laws to address the issues highlighted in this literature review. The comprehensiveness of the legislation is patchy at best. In many cases, karst terrain is not singled out as the target of the legislation, but rather is subsumed within a larger 'blanket' policy to cover, for example, 'protected areas' and 'groundwater resources'. When legislation is of this 'macro' variety, the inherent distinctiveness of limestone environments tends to be overlooked and the legislative thrust can have little or no impact on such areas (LaMoreaux et al. 1997). The USA has had the greatest experience in the area of local government lawmaking with reference to karst terrain (Bade & Moss 1997; LaMoreaux et al. 1997). The presence of the relatively large array of local government ordinances in the United States is a response to the decentralised type of government. Much of the experience has to do with landfills (Davis 1997) and groundwater issues (Bowles & Arsuffi 1993) rather than the more recent trend to protect distinctive karst environments for their aesthetic and tourism potential (Day 1996).

Some initiatives are truly local in nature (Devilbiss 1995). For example, in Carroll County, Maryland, community groups are actively involved in sinkhole monitoring, mapping and repair, as well as new construction evaluation and mitigation. The programme is implemented with a non-regulatory approach. However, based on the groups' experience, more formal, regulatory functions are being considered.

In one case, the cost of disregarding the potential risks of construction in karst areas motivated researchers to design a model karst ordinance for uptake by local government units (Dougherty 1989). Karst subsidence was identified as a growing problem in the Lehigh Valley, the portion of the Great Valley of the Appalachians that cuts diagonally from north-east to south-west across Pennsylvania. More than US$1 million in damage had occurred each year. In addition, groundwater pollution endangered the productive aquifers of the area. Dougherty's paper was based on the premise that the best way to prevent the occurrence of subsidence and groundwater problems was to have safeguards in place in local zoning ordinances, comprehensive plans and subdivision ordinances. It was discovered that few municipalities had zoning ordinances with karst precautions. In order to overcome the lack of information, a model ordinance was created for one township in the hope that other local government units would adopt it.

In Clinton, New Jersey, a lay, legal and technical group prepared a geotechnically oriented ordinance which mandated consideration of the problem of karst in a multi-disciplined, multi-phased investigation (Fischer & Lechner 1989). The Township Planning Board and an experienced geotechnical consultant reviewed the results of a developer's investigation. To date, the ordinance appears to function as intended, has been well received by the township officials and is generally accepted by the developers (Fischer 1997).

In the United Kingdom, specific karst features have been protected. The Wildlife and Countryside Act 1981 was passed to provide strengthened such environmental features and threatened wildlife. Limestone pavements (exposed, extensive areas of limestone bedrock) were included specifically in Section 34 of this Act because their unique features were being damaged or destroyed through various causes. Limestone Pavement Orders (LPOs) are made under this act (Goldie 1993).

6. Conclusion

This literature review has raised several important issues and provides the evidence from scientific literature on which to base management decisions or direct future research projects. There are some clear and readily assessed dangers to karst viability from activities in primary industry. In addition, a multitude of less subtle and, I would argue, no less important issues exist that still await the development of adequate methodologies for assessment.

It is clear that environmental damage in karst terrain is transmitted through the karst, in many cases to a point far from the area of initial impact. This is a distinctive characteristic of the karst environment, with its hydrological processes that operate underground and, unfortunately, out of sight of many policy makers. The result, as this literature review has repeatedly shown, is that serious environmental damage has been detected too late, when the damage was already well advanced or, in some cases, catastrophic. As Williams (1993) noted, it is often difficult to predict the pathways that pollution will follow, given the complexity and variability of karst hydrologic systems. These systems are arguably the most complex of any known geologic structure, because they combine laminar and turbulent regimes and are dynamic in nature.

Related to the above point is the need when managing the country's landscapes to recognise the interconnectedness of systems. In New Zealand, karst landscapes frequently occupy just one or more parts of larger watersheds. Therefore the activities outside of the limestone environment but within the watershed may have important impacts when the water derived from the other geologies enters the limestone zones. The impact of the water can sometimes be easily seen, such as bedload and suspended sediments, but it may also and more critically involve dissolved materials that can affect the rate of limestone dissolution, or disrupt important bacteria and algae communities distinctive to the particular karst environment.

Within karst landscapes there is clear evidence that alteration of vegetative communities of any sort can lead to substantial and potentially irreversible impacts on the karst processes operating in that area. This is most clearly manifest with changes in vegetation near the entrances to caves which may alter the cave's climate, and the large-scale conversion of native forest to other uses: be it plantation forestry with exotic species or agricultural activities and associated changes to soil chemistry and subsequently groundwater chemistry.

On a more optimistic note, the literature does provide examples of the resilience of karst landscapes. The type of disturbance, its scale and duration and the subsequent form of intervention to rehabilitate the disrupted karst landscape all interact to influence the pace and success of karst landscape and karst process rejuvenation. More work is being carried out in this important area with some solid evidence emerging of the ability for some karst systems to be successfully rehabilitated in a relatively short period of time.

Nevertheless the specific literature that is available to shed light on the issues defined by the managers of New Zealand's karst estate is scant. While much research has been done on aspects of karst processes, very little of this can be directly applied to karst management.

The review is taking a highly anthropocentric position, because humans are impacting the environment even when claiming to be 'saving' it. Our actions, for example to attain 'sustainability', are just another form of intervention. In the case of management of karst landscapes, given their complexity, our interventions will have to be 'best guesses' at this point rather than plans devised with a clear and incontestable scientific grounding. This discussion is not intended to denigrate the work of scientists working in karst environments, nor the interventions proposed by those entrusted with their management. It is from their work that important management decisions will have to be devised, implemented and monitored, since this is the best information available at this time.

The process of moving from the literature to planning is a more overt political process. While the literature is patchy, it can assist in many of the important decisions that must be made when individuals, communities and societies decide to engage in the management of karst terrains.

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8. References

Alexander, E.C.; Book, P.R. 1984: Altura Minnesota lagoon collapses. Pp. 311–318 in Beck, B.F. (Ed.) Sinkholes: their geology, engineering, and environmental impact: Proceedings of the first multidisciplinary conference on sinkholes, Orlando, Florida, 15–17 October 1984. A.A. Balkema, Rotterdam and Boston.

Assaad, F.A.; Jordan, H. 1994: Karst terranes and environmental aspects. *Environmental Geology 23*: 228–237.

Bade, J.; Moss, P. 1997: Studies and regulations in the Southwestern Illinois karst. Pp. 439–442 in Beck, B.F.; Stephenson, J.B. (Eds) The Engineering Geology and Hydrogeology of Karst Terranes: Proceedings of the sixth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, Springfield, Missouri, 6–9 April 1997. A.A. Balkema, Rotterdam.

Bakalowicz, M. 1984: Water chemistry of some karst environments in Norway. *Norsk Geografisk Tidsskrift 15(3–4)*: 208–214.

Barfield, B.J.; Blevins, R.L; Evangelou, V.P. 1998: Water quality impacts of natural filter strips in karst areas. *Transactions of the American Society of Agricultural Engineers 41(2)*: 371–381.

Begg, M. 2002: Dairy farm women in the Waikato. Unpubl. DPhil. Thesis, Department of Geography, University of Waikato.

Benavente, J.; Cardenal, J.; Cruz-Sanjulian, J.; Garcia-Lopez, S.; Nevot, A. 1993: Karstic hydrogeological investigations for the construction of the Rules Reservoir (Granada, Spain). Pp. 25–31 in Gunay, G.; Johnson, A.I.; Back, W. (Eds) International Association of Hydrological Sciences; Publication, 207: *Hydrogeological Processes in Karst Terranes*. Wallingford, Oxfordshire, Reino Unido.

Bender, S.S. 1986: Effluent sampling for biological effects testing. Pp. 81–91 in Bergman, H.L.; Kimerle, R.H.; Maki, A.W. (Eds) *Environmental Hazard Assessment of Effluents*. Pergamon Press, New York.

Berryhill, W.S. 1989: The impact of agricultural practices on water quality in karst regions. Pp. 159–164 in Beck, B.F. (Ed.) Engineering and Environmental Impacts of Sinkholes and Karst: Proceedings of the third multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, St. Petersburg Beach, Florida, 2–4 October 1989. A.A. Balkema, St. Petersburg Beach.

Bodhankar, N.; Chatterjee, B. 1994: Pollution of limestone aquifer due to urban waste disposal around Raipur, Madhya Pradesh, India. *Environmental Geology 23*: 209–213.

Bonacci, O.; Jelin, J. 1988: Identification of a karst hydrological system in the Dinaric karst (Yugoslavia). *Hydrological Sciences Journal/Journal des Sciences Hydrologiques 33(5)*: 483–497.

Bowles, D.E.; Arsuffi T.L. 1993: Karst aquatic ecosystems of the Edwards Plateau region of central Texas, USA: a consideration of their importance, threats to their existence, and efforts for their conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems 3*: 317–329.

Boyer, D.G.; Pasquarell G.C. 1996: Agricultural land use effects on nitrate concentrations in a mature karst aquifer. *Water Resources Bulletin 32(3)*: 565–573.

Boyer, D.G.; Pasquarell, G.C. 1999: Agricultural land use impacts on bacterial water quality in a karst groundwater aquifer. *Journal of the American Water Resources Association 35(2)*: 291–300.

Breznik, M. 1998: *Storage reservoirs and deep wells in karst regions*. A.A. Balkema, Rotterdam; Brookfield, VT. P. 251.

Buecher, R.H. 1999: Microclimate study of Kartchner Caverns, Arizona. *Journal of Caves and Karst Studies 61(2)*: 108–119.

Bunting, B. 1998: The impacts of recreational caving on the physical environment of wild caves. Unpubl. MSc thesis, University of Waikato. 171p.

Chen, L.; Talwani, P. 1998: Reservoir-induced Seismicity in China. *Pure and Applied Geophysics 153 (1)*: 133–149.

Crawford, N.C. 1984: Sinkhole flooding associated with urban development upon karst terrain: Bowling Green, Kentucky. Pp. 283–292 in Beck, B.F. (Ed.) Sinkholes: Their Geology, Engineering, and Environmental Impact: Proceedings of the first multidisciplinary conference on sinkholes, Orlando, Florida, 15-17 October 1984. A.A. Balkema, Rotterdam and Boston.

Davis, S.B. 1997: Interstate assessment of governmental regulations on landfills in karst areas. Pp. 433–438 in Beck, B.F.; Stephenson, J.B. (Eds) The Engineering Geology and Hydrogeology of Karst Terranes: Proceedings of the sixth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, Springfield, Missouri, 6–9 April 1997. A.A. Balkema, Rotterdam.

Day, M. 1996: Conservation of karst in Belize. *Journal of Cave and Karst Studies 58(2)*: 139–144.

Destephen, R.A.; Benson C.P. 1993: Assessment of ground water withdrawal impacts in a karst area. Applied karst geology. Pp. 157–165 in Beck, B.F. (Ed.) Proceedings of the 4th conference on sinkholes and the engineering and environmental impacts of karst. A.A. Balkema, Panama City.

Destephen, R.A.; Wargo R.H. 1992: Foundation design in karst terrain. *Bulletin—Association of Engineering Geologists 29*: 165–173.

Devilbiss, T.S. 1995: A local government approach to mitigating impacts of karst. In Beck, B.F.(Ed.) Karst GeoHazards: Engineering and Environmental Problems in Karst Terranes. Proceedings of the Fifth Multidisciplinary Conference on Sinkholesand the Engineering and Environmental Impacts of Karst. A.A. Balkema, Rotterdam.

Doerfliger, N.; Zwahlen, F. 1995: EPIK: a new method for outlining of protection areas in karst environment. Pp. 117–123 in Gunay, G.; Johnson, I. (Eds) Proceedings of the 5th International symposium field seminar on karst waters and environmental impacts. Antalya, September 1995. A.A. Balkema, Rotterdam.

Dougherty, P.H. 1983: Valley tides—land-use response floods in a Kentucky karst region. Pp. 3–15 in Dougherty, P.H. (Ed.) *Environmental Karst*. Geospeleo Publications, Cincinnati Ohio.

Dougherty, P.H. 1989: Land use regulations in the Lehigh Valley: zoning and subdivision ordinances in an environmentally sensitive karst region. Pp. 341–348 in Beck, B.F. (Ed.) Engineering and Environmental Impacts of Sinkholes and Karst: Proceedings of the third multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, St. Petersburg Beach, Florida, 2–4 October 1989. A.A. Balkema, St. Petersburg Beach.

Drew, D.P. 1983: Accelerated soil erosion in a karst area: the Burren, western Ireland. *Journal of Hydrology 61*: 113–124.

Drew, D. 1996: Agriculturally induced environmental changes in the Burren Karst, western Ireland. *Environmental Geology 28*: 137–144.

Edwards, A.J.; Smart, P.L. 1989: Waste disposal on karstified carboniferous limestone aquifers of England and Wales. Pp. 165–182 in Beck, B.F. (Ed.) Engineering and Environmental Impacts of Sinkholes and Karst: Proceedings of the third multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, St. Petersburg Beach, Florida, 2–4 October 1989. A.A. Balkema, St. Petersburg Beach.

Fischer, J.A. 1997: Limestone ordinances of New Jersey and Pennsylvania: A practitioner's experiences. Pp. 463–466 in Beck, B.F.; Stephenson, J.B. (Eds) The Engineering Geology and Hydrogeology of Karst Terranes: proceedings of the sixth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, Springfield, Missouri, 6–9 April 1997. A.A. Balkema, Rotterdam.

Fischer, J.A.; Lechner, H. 1989: A karst ordinance—Clinton Township, New Jersey. Pp. 357–361 in Beck, B.F. (Ed.) Engineering and Environmental Impacts of Sinkholes and Karst: Proceedings of the third multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, St. Petersburg Beach, Florida, 2–4 October 1989. A.A. Balkema, St. Petersburg Beach.

Forbes, J. 1988: Air temperature and relative humidity study: Torgac Cave, New Mexico. *Journal of caves and karst studies. 60(1)*: 27–32.

Ford, D.; Williams, P. 1989: *Karst Geomorphology and Hydrology*. Unwin Hyman, London. P. 601.

Gagen, P.; Gunn, J. 1987: A geomorphological approach to restoration blasting in limestone quarries. Pp. 457–461 in Beck, B.F.; Wilson, W.L. (Eds) Karst Hydrogeology: Engineering and Environmental Applications: proceedings of the second multidsciplinary conference on sinkholes and the environmental impacts of karst, Orlando, Florida, 9–11 February 1987. A.A. Balkema, Rotterdam and Boston.

Gillieson, D.S., 1986: Cave Sedimentation in the New Highlands. *Earth Surface Processes and Landforms 11*: 533–543.

Gillieson, D. 1996: Caves: processes, development and management. Blackwell, Oxford, UK. 324 p.

Gillieson, D.; Household, I. 1999: Rehabilitation of the Lune River Quarry, Tasmanian Wilderness World Heritage Area, Australia. Pp. 201–205 in Drew, D.; Hotzel, H. (Eds) Karst hydrogeology and human activities: impacts, consequences and implications. A.A. Balkema, Rotterdam.

Goldie, H.S. 1993: The legal protection of limestone pavements in Great Britain. *Environmental Geology 21(3)*: 160–165.

Grow, S.R. 1986: Water quality in the Forestville Creek karst basin of southeastern Minnesota. MSc Thesis (Geology), University of Minnesota, Minneapolis. 219 p.

Gunn, J. 1978: Karst Hydrology and Solution in the Waitomo District, New Zealand. Unpubl. PhD Thesis, University of Auckland, Auckland.

Gunn, J.; Bailey, D. 1991: Limestone quarrying and limestone quarry reclamation in Britain. Pp. 69–76 in Sauro, U; Bondesan, A; Meneghel, M. (Eds) Proceedings of the International Conference on Environmental Changes in Karst Areas—I.G.U.—U.I.S., Universita di Padova, Italy, Quaderni del Dipartimento di Geografia 13.

Gunn, J.; Bailey, D. 1993: Limestone Quarrying and Quarry Reclamation in Britain. *Environmental Geology 21*: 167–172.

Gunn, J.; Hobbs, S. 1999: Limestone quarrying: hydrogeological impacts, consequences, implication. Pp. 192–201 in Drew, D.; Hotzel, H. (Eds) Karst hydrogeology and human activities: impacts, consequences and implications. A.A. Balkema, Rotterdam.

Hallberg, G.R.; Libra, R.D.; Hoyer, B.E. 1985: Nonpoint source contamination of ground water in karst-carbonate aquifers in Iowa. Pp. 109–114 in *Perspectives on Nonpoint Source Pollution Proceedings*. Kansas City, MO. 19–22 May 1985. Epic 42UJ/5-85-001. United States Environmental Protection Agency, Office of Water Regulations and Standards. Washington, DC.

Hall, P.J.; McCusker, A.J.;Bingham, C.T. 1995: Site investigation, monitoring, and successful landfill closure within a karst terrain. B.F. Beck, Balkema.

Hamilton-Smith, E. 1970: Biological aspects of cave conservation. *Journal of the Sydney Speleological. Society 14 (7)*: 157–164.

Harding, K.; Ford, D. 1991: A study of the impact of primary deforestation upon limestone slopes in Northern Vancouver Island, Canada and of natural rates of forest regrowth. Pp.411 in Sauro, U.; Bondesan, A.; Meneghel, M. (Eds) Proceedings of the International Conference on Environmental Changes in Karst Areas—I.G.U.—U.I.S., Universita di Padova, Italy, Quaderni del Dipartimento di Geografia 13.

Hardwick, P.; Gunn, J. 1990: Soil erosion in cavernous limestone catchments. Pp. 301–310 in Borqadman, J.; Forester, D.L.; Dearing, J.A. (Eds) Soil erosion on agricultural land. John Wiley and Sons Ltd, London.

Hardwick, P.; Gunn, J. 1993: The impact of agriculture on limestone caves. Pp. 235–249 in Williams, P.W. (Ed.) Karst Terrains, environmental changes, human impact. *Catena Supplement 25*.

Hawke, D.V. 1982: Fluvial Processes of the Upper Waitomo Catchment. Unpubl. PhD Thesis, University of Auckland.

Hejazi, H.A. 1987: Use of a concrete diaphragm wall to prevent cavernous underflow at a dam. Pp. 463–469 in Beck, B.F.; Wilson, W.L. (Eds) Karst Hydrogeology: Engineering and Environmental Applications: Proceedings of the second multidsciplinary conference on sinkholes and the environmental impacts of karst, Orlando, Florida, 9–11 February 1987. A.A. Balkema, Rotterdam and Boston.

Herak, M. 1970: Problems relative to the construction of dams and reservoirs in karst areas. Pp. 899–908. General paper no. 10. Paris, Yugoslavia. National Committee on Large Dams.

Hess, J.W; Slattery, L.D. 1999: Extractive industries impact. Pp. 187–192 in Drew, D.; Hotzel, H. (Eds) Karst hydrogeology and human activities: impacts, consequences and implications. A.A. Balkema, Rotterdam.

Hobbs, S.L.; Smart, P.L., 1988: Heterogeneity in Carbonate aquifers—A case study from Mendip Hills, England. Pp. 734–730. Proceedings of the 21st Congress, Karst Hydrogeology and Karst Environment Protection, Geological Publishing House, Beijing, China.

Hoenstine, R.W.; Lane, E.; Spencer, S.M.; O'Carroll, T. 1987: A landfill site in a karst environment, Madison County, Florida—A case study. Pp. 253–258 in Beck, B. F.; Wilson, W. L. (Eds) Karst Hydrogeology: Engineering and Environmental Applications: proceedings of the second multidsciplinary conference on sinkholes and the environmental impacts of karst, Orlando, Florida, 9–11 February 1987. AA Balkema, Rotterdam and Boston.

Jakucs, L.Q 1977: *Morphogenetics of Karst Regions*. Adam Hilger, Bristol. 283 p.

Jennings, P. 1968: Cave and Karst Terminology. http://www.wasg.iinet.net.au/terminol.html. Additions by Rauleigh Webb 1995,1996 As published in Australian Karst Index 1985. First published in ASF Newsletter 83 (1979). Replaces list in Speleo Handbook (1968).

Jie, Z.; Shenfeng, L.; Yinkang, Z. 1997: On bio-effects on karst landscape in Jiuzhaigou conservation, Sichuan Province, China. *The Journal of Chinese Geography 7(3)*: 1–13.

Johnson, D.D.; Kreglow, J. M.; Dressing, S.A.; Maas, R.P.; Koehler, F.A.; Humenik, F.J.; Snyder, S.K.; Christensen, L. 1982: *Best Management: Practices for Agricultural Nonpoint Source Control. I. Commercial Fertiliser*. North Carolina Agricultural Extension Service, and Agricultural Engineering Department, N.C. Stand University, Raleigh, N.C.

Kastrinos, J.R.; White, W.B. 1987: Seasonal, hydrogeologic, and land-use controls on nitrate contamination of carbonate ground waters. Proceedings, Environmental Problems in Karst Terranes and Their Solution, Bowling Green, Ky., 1986. National Water Well Association, Dublin, Ohio.

Kiernan, K. 1988: *The management of soluble rock landscapes: an Australian perspective*. Sydney, The Speleological Research Council Ltd. 61 p.

Kiernan, K. 1989a: Karst, caves and management at Mole Creek, Tasmania. Department of Parks, Wildlife and Heritage. Occasional Paper No. 22. 130 p.

Kiernan, K. 1989b: Human impacts and management responses in the karsts of Tasmania. Pp. 69–92 in Gillieson, D.; Smith, D.I. (Eds) *Resource Management in Limestone Landscapes: International Perspectives*, University College, Australian Defence Force Academy, Department of Geography and Oceanography.

Kogovsek, J. 1982: Vertical percolation in the Planina Cave. *Acta Carsologica Krasoslovni Zbornik 10*: 107–125.

Kogovsek, J.; Habic, P. 1980: Study of vertical water percolation in the case of Planina and Postojna Caves. *Acta Carsologica Krasoslovni Zbornik 9*: 133–148.

Kranjc, A. 1979: The influence of man on cave sedimentation, Actes du symposium international sur l'erosion karstique. International Union of Speleology, Aix en Provence-Marseilles-Nimes, 117–123.

LaMoreaux, P.E.; Powell, W.J.; LeGrand, H.E. 1997: Environmental and legal aspects of karst areas. *Environmental Geology 29(1/2)*: 23–36.

Lastennet, R.; Mudry, J. 1997: Role of karstification and rainfall in the behavior of a heterogeneous karst system. *Environmental Geology 32(2)*: 114–123.

Latham, A.G. 1981: Muck spreading on speleothems. Pp. 356–357 in *Proceedings of the 8th International Speleological Congress*, Kentucky, 1981.

Lewis, W.C. 1981: Carbon dioxide in Coldwater Cave. Pp. 91–92 in *Proceeding of the 8th International Speleological Congress*, Kentucky.

Luoma, J.R. 1989: Soil is not a factory. *Audubon 91(6)*: 61–63.

Lorah, M.M.; Herman, J.S. 1988: The chemical evolution of a travertine depositing stream: geochemical processes and mass transfer reactions. *Water Resources Research 24(9)*: 1541–1552.

Maas, R.P.; Kessling, S.A.; Spooner, J.; Smolen, M.D.; Humenik, E.J. 1984: *Best Management Practices for Agricultural Nonpoint Source Control. IV. Pesticides*. North Carolina apicultural Extension Service, Biological and Agricultural Bngineering Department, N.C. State University, Raleigh, N.C.

Mitchem, P.S.; Hallberg, G.R.; Hoyer, B.E.; Libra, R.D. 1988: Ground-Water Contamination and Land Management in the Karst Area of Northeastern Iowa. Pp. 442–458 in Collins, A.G.; Johnson, A.I. (Eds) *Ground-Water Contamination: Field Methods*, ASTM STP 963 American Society for Testing and Materials, Philadelphia.

Morse, J.W. 1983: The kinetics of calcium carbonate dissolution and precipitation. In Reeder, R.J. (Ed.) *Mineralogy and Chemistry: Reviews in Mineralogy 11*. Mineralogical Society of America.

Nicod, J. 1991: Natural hazards and engineering impacts in the karsts of Mediterranean France. Proceedings of the International Conference on Environmental Changes in Karst Areas—I.G.U.—U.I.S., Universita di Padova, Italy, Quaderni del Dipartimento di Geografia. Pp. 9–16.

Pasquarell, G.C.; Boyer, D.G. 1996: Herbicides in karst groundwater in Southeast West Virginia. *Journal of environmental quality 25(4)*: 755–765.

Pride, T.E.; Ogden A.E.; Harvey M.J. 1989: Biology and water quality of caves receiving urban runoff in Cookville, Tennessee, USA. Pp. 27–29 in *Proceedings of the 9th International Speleological Congress*, Budapest.

Pugsley, C. 1981: Management of a biological resource—Waitomo Glowworm cave, New Zealand. Pp. 489–492. *Proceedings of the 8th International Speleological Congress*, Bowling Green, Kentucky.

Quinlan, F.; Ewers, R.O. 1985: Ground water flow in limestone terranes: strategy, rationale and procedure for reliable, efficient monitoring of ground water quality in karst areas. Pp. 197–234. National symposium and exposition on aquifer restoration and ground water monitoring, proceedings. Worthington, OH: National Water Well Association.

Quinlan, J.F.; Alexander, E.C. 1987: How often should samples be taken at relevant locations for reliable monitoring of pollutants from an agricultural, waste disposal, or spill site in a karst terrane? A first approximation. Pp. 277–286 in Beck, B.F.; Wilson, W.L. (Eds) Karst Hydrogeology: Engineering and Environmental Applications: proceedings of the second multidsciplinary conference on sinkholes and the environmental impacts of karst, Orlando, Florida, 9–11 February 1987. A.A. Balkema, Rotterdam and Boston.

Reddy, M.M. 1977: Crystallisation of Calcium Carbonate in the presence of trace concentrations of phosphorous containing ions. 1. Inhibition of phosphate and glycerophosphate ions at pH 8.8 and 25 degrees Celsius. *Journal of Crystal Growth 41*: 287–295.

Rivera, L.W.; Aide, T.M. 1998: Forest recovery in the karst region of Puerto Rico. *Forest ecology and management 108(1/2)*: 63–75.

Ruthrof, K.X. 1997: Improving the success of limestone quarry revegetation. *Cave and Karst Science 24(3)*: 117–125.

Sket, B. 1997: Biotic diversity of the dinaric karst, particularly in Slovenia: History of its richness, destruction, and protection. Pp. 84–98 in Sasowsky, I.D.; Fong, D.W.; White, E.L. (Eds) Conservation and protection of the biota of karst. Karst Waters Institute Special Publication 3.

Soil Conservation Service. 1987: *National Handbook of Conservation Practices*. U.S. Department of Agriculture, Soil Conservation Service. Washington, D.C.

Slifer, D.W.; Erchul, R.A. 1989: Sinkhole dumps and the risk to ground water in Virginia's karst areas. Engineering and Environmental Impacts of Sinkholes and Karst: Proceedings of the third multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, St. Petersburg Beach, Florida, 2–4 October 1989. B.F. Beck, St. Petersburg Beach, A.A. Balkema: 207–212.

Smart, P.L.; Friederich, H. 1986: Water movement and storage in the unsaturated zone a maturely karstified Carbonate aquifer Mendip Hills, England. Proceedings of the Environmental Problems in Karst Terranes and Their Solutions Conference, October 28–30, Bowling Green, Kentucky. Pp. 59–87.

Smolen, M.D.; Humenik, F.D.; Brichford, S.L.; Spooner, J.; Bennett, T.B.; Lanier, A.L.; Coffey, S.W.; Adler, K.J. 1989: *Annual Report: Status of Agricultural Nonpoint Source Projects*. Biological and Agricultural Engineering Department, N.C. Agricultural Extension Service N.C. State University, Raleigh, N.C. 122 p.

Stanton, W.S. 1990: Hard limestone: too valuable to quarry. *Minerals Planning 43*: 3–9.

Tarhule-Lips, R.F.A.; Ford, D.C. 1998: Condensation corrosion in caves on Cayman Brac and Isla de Mona. *Journal of caves and karst studies 60(2)*: 84.

Tercafs, R. 1988: Optimal management of karst sites with cave fauna protection. *Environmental Conservation 15(2)*: 149–166.

Trudgill, S.T. 1985: Limestone Geomorphology. Longman, London. 196 p.

Tucker. N.L. 1982: Nonpoint Agricultural Pollution in a Karst Aquifer: Lost River Groundwater Drainage Basin, Warren County, Kentucky, Unpubl. MSc Thesis, Western Kentucky University, Bowling Green, Kentucky.

Urich, P.B. 1996: Deforestation and declining irrigation in Southeast Asia: A Philippine case. *International Journal of Water Resources Development 12(1)*: 49–63.

Urich, P.B.; Day, M.; Lynagh, F. 2001: Policy and practice in karst landscape protection: Bohol, the Philippines. *Geographical Journal 167(4)*: 305–323.

Urich, P.B.; Reeder, P. 1999: Plantation forestry in tropical limestone uplands: environmental constraints and opportunities. *Professional Geographer 51(4)*: 493–506.

Van Keuren, R.W.; McGuinness, J.L.; Chichester, F.W. 1979: Hydrology and Chemical Quality Flow from Small Pastured Watersheds; I. Hydrology. *Journal of Environmental Quality 812*: 162–166.

Veni, G. 1999: A geomorphological strategy for conducting environmental impact assessments in karst areas. *Geomorphology 31*: 151–180.

Waterhouse, J.D. 1984: Groundwater in the Mount Gambier area. Department of Mines and Energy, Adelaide. 12 p.

Weirsma. J.H.; Steiglitz, R.D.; Devayne, L.C.; Metzer, G.M. 1986: Characterisation of the shallow groundwater system in as area with thin soils and sinkholes. *Environment Geology Water Sciences 8(1–2)*: 99–104.

Wheeler, B.J.; Alexander, E.C.; Adams, R.S.; Huppert, G.N. 1989: Agricultural land use and groundwater quality in the Coldwater Cave groundwater basin, upper Iowa River karst region, USA. Pp. 249–60 in Gillieson, D.; Smith, D.I. (Eds) Resource Management in Limestone Landscapes: International Perspectives Special Publication no. 2, Department Geography & Oceanography University Colleges Australian Defence Force Academy.

White, W.B. 1969: Conceptual models for carbonate aquifers. *Ground Water 7(3):* 15–21.

White, W.B., 1988: *Geomorphology and Hydrology of Karst Terrains*. Oxford University Press, New York. 464 p.

Wilde, K.A. 1985: An historical review of cave and karst management in New Zealand 1889–1985. Pp. 163–206. Proceedings of the Sixth Australasian Conference on Cave Tourism and Management.

Williams, B.E.; Robinson R. 1993: Grouting beneath an existing dam founded on karst terrane. Pp. 255–258 in Beck, B.F. (Ed.) Applied karst geology. Proceedings of the 4th conference on sinkholes and the engineering and environmental impacts of karst. AA Balkema, Panama City.

Williams, P.W. 1975: Report on the conservation of Waitomo Caves. *New Zealand Speleological Bulletin 5(93)*: 373–396.

Williams, P.W. 1980: From Forest to suburb: the hydrological impact of Man in New Zealand. Pp. 103–124 in Anderson, A.G. (Ed.) The Land Our Future. Auckland. Longman Paul. Chapter 7.

Williams, P.W. 1983: The role of subcutaneous zone in karst hydrology. *Journal of Hydrology 61*: 45–67.

Williams, P.W. 1985: Subcutaneous hydrology and the development of doline and cockpit karst. *Zeitschrift fuer Geomorphologie 29(4)*: 463–482.

Williams, P.W. 1993: Environmental change and human impact on karst terrains: an introduction. In Williams, P.W. (Ed.) Karst Terrains, environmental changes, human impact. *Catena Supplement 25*: 1–19.

9. Glossary

Active cave A cave which has a stream flowing in it.

Allogenic Allogenic water enters the karstic system through the capture of streams that form on insoluble rocks at higher elevations.

Arthropods The most common group of animals inhabiting caves, including insects, crustaceans, spiders, millipedes etc. They have jointed limbs and external skeletons.

Autogenic Ground water is derived from within a catchment that is all carbonate rock.

Bare karst Karst with much exposed bedrock.

Bedding-grike A narrow, rectilinear slot in a karst rock outcrop owing to solution along a bedding-plane.

Bedding-plane A surface separating two beds, usually planar.

Calcite The commonest calcium carbonate ($CaCO_3$) mineral and the main constituent of limestone.

Cave A natural cavity in rock large enough for human entry. It may be water-filled. If it becomes full of ice or sediment and is impenetrable, the term still applies but needs qualification.

Cave breathing (1) Movement of air in and out of a cave entrance at intervals. (2) The associated air currents within the cave.

Cave ecology The study of the interaction between cave organisms and their environment, e.g. energy input from surface, climatic influences.

Cave fill Transported materials such as silt, clay, sand and gravel which cover the bedrock floor or partially or wholly block some part of a cave.

Cave system A collection of caves interconnected by passages that can be entered or linked hydrologically, or a cave with an extensive complex of chambers and passages.

Cenote A partly water-filled, wall-sided doline.

Clasitic sediments Fragments of rock derived through physical or chemical weathering processes.

Cockpit karst Conekarst in which the residual hills are chiefly hemispheroidal and the closed depressions often lobate.

Colluvium Rock detritus and soil accumulated at the foot of a slope.

Conduit flow Water flowing through an underground stream course completely filled with water and under hydrostatic pressure.

Conekarst Karst, usually tropical, dominated by its projecting residual relief rather than by its closed depressions.

Corrasion The wearing away of bedrock or loose sediment by mechanical action of moving agents, especially water, i.e. Corrosion and abrasion.

Corrosion Synonym for solution.

Dead cave A cave without streams or drips of water.

Doline A closed depression draining underground in karst, of simple but variable form, e.g. cylindrical, conical, bowl- or dish-shaped. From a few to many hundreds of metres in dimension. Also known as sinkholes.

Doline karst Karst dominated by closed depressions, chiefly dolines, perforating a simple surface.

Dolomite A mineral consisting of the double carbonate of magnesium and calcium, $CaMg(CO_3)_2$ *or* a rock made chiefly of dolomite mineral.

Dry cave A cave without a running stream. Cf. dead cave.

Epikarst The upper/outer layer of karstified carbonate rock in the unsaturated zone, immediately below the soil layer.

Epiphreatic Referring to water moving with some speed in the top of the phreatic zone or in the zone liable to be temporarily in flood, thus becoming part of the phreatic zone.

Erosion The wearing away of bedrock or sediment by mechanical and chemical actions of all moving agents such as rivers, wind and glaciers at the surface, or in caves.

Grike A deep, narrow, vertical or steeply inclined, rectilinear slot in a rock outcrop owing to solution along a joint.

Groundwater Synonym for phreatic water.

Karren The minor forms of karst owing to solution of rock on the surface or underground.

Karst Terrain with special landforms and drainage characteristics owing to greater solubility of certain rocks in natural waters than is normally common. Derived from the geographical name of part of Slovenia.

Laminar flow Streamline flow of ground water whereby it moves in layers without fluctuations or turbulence so that successive water molecules passing the same point have the same velocity.

Limestone A sedimentary rock consisting mainly of calcium carbonate, $CaCO_3$.

Mogote An isolated, steep-sided, commonly asymmetrical hill or ridge composed of limestone.

Percolation water Water moving mainly downwards through pores, cracks and tight fissures in the vadose zone.

Permeability The property of rock or soil permitting water to pass through it. Primary permeability depends on interconnecting pores between the grains of the material. Secondary permeability depends on solutional widening of joints and bedding planes and on other solution cavities in the rock.

Phreatic water Water below the level at which all voids in the rock are completely filled with water.

Phreatic zone Zone where voids in the rock are completely filled with water.

Planar flow A shallow lense of water flowing over the land surface during heavy rainfall events.

Porosity The property of rock or soil of having small voids between the constituent particles. The voids mayor may not interconnect.

Sediment Material recently deposited by water, ice or wind, or precipitated from water.

Sink hole A closed depression draining underground in karst, of simple but variable form, e.g. cylindrical, conical, bowl- or dish-shaped. From a few to many hundreds of metres in dimension. Also known as dolines.

Solution In karst study, the change of bedrock from the solid to the liquid state by combination with water. In physical solution, the ions of the rock go directly into solution without transformation. In chemical solution, acids take part, especially the weak acid formed by carbon dioxide (CO_2).

Speleogens Cave features formed erosionally or by weathering during cave enlargement such as scallops, rock pendants or canyons.

Speleology The exploration, description and scientific study of caves and related phenomena.

Speleothem A secondary mineral deposit formed in caves, most commonly calcite.

Stalactite A speleothem hanging downwards from a roof or wall, of cylindrical or conical form, usually with a central hollow tube.

Stalagmite A speleothem projecting vertically upwards from a cave floor and formed by precipitation from drips.

Subcutaneous zone The uppermost layers of rock below the soil on a karst. The zone is distinguished from lower zones by a higher porosity and storage capacity for water as a result of the presence of many solutionally enlarged fissures.

Tomo A hole or shaft.

Towerkarst Conekarst in which the residual hills have very steep to overhanging lower slopes. There may be alluvial plains between the towers and flat-floored depressions within them.

Troglobite A cavernicole unable to live outside the cave environment.

Troglophilic Animals characterised by their ability to complete their entire life cycles within a cave, but that may also be found in cool, moist habitats outside of caves.

Trogloxene A cavernicole which spends only part of its life cycle in caves and returns periodically to the epigean domain for food.

Tufa Spongy or vesicular calcium carbonate deposited from spring, river or lake waters.

Vadose flow Water flowing in free-surface streams in caves.

Vadose water Water in the vadose zone.

Vadose zone The zone where voids in the rock are partly filled with air and through which water descends under gravity.

Water table The surface between phreatic water which completely fills voids in the rock, and ground air, which partially fills higher voids.

Source: Cave and karst terminology (Jennings, http://www.wasg.iinet.net.au/terminol.html)