Forest Practices Board

Forest Sinkhole Manual

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This forest sinkhole manual constitutes the technical note referred to in the Forest Practices Code entitled
Some Operational Considerations In Sinkhole Management

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INTRODUCTION

The Forest Practices Code (FPC) recognises that "Soils, water quality and flow, air quality, site productivity, biodiversity, landscape, cultural heritage and landforms are potentially affected by forest operations and will be considered at the planning stage" (p. 3). *Karst* is defined in the Code (p. 98) as:

> *…a landscape that results from the high degree of solubility in natural waters of the bedrock. Underground drainage, sinkholes and limestone caves are the best known components of karst.*

The management of karst features such as sinkholes is addressed by specific provisions in the FPC. The purpose of this document is to consolidate the various provisions for the management of sinkholes (also known as dolines) and related karst terrain that are scattered through the FPC, and to provide practical guidance as to how compliance with FPC provisions can be achieved.

The particular focus of this manual is on the management of sinkhole areas. A sinkhole is defined in the FPC as being:

> *A closed depression draining underground in karst, of simple but variable form e.g. cylindrical, conical, bowl or dish-shaped. From few to many hundreds of metres in dimensions.* (FPC p. 100)

Even if there are no known negotiable karst caves, the presence of a sinkhole implies that the underlying rock is karstified and that certain related karst geohazards are likely to exist to some degree.

Sinkholes are the most familiar type of topographic depression found in karst environments. The FPC requires that natural depressions in karst areas should be avoided during forest operations. However, the wording is sometimes very general and questions may arise. For example, the FPC requires that "natural depressions in karst areas will be avoided". But in what way and by what distance? - the FPC does not define precisely what their avoidance means in practical terms. Similarly, the FPC requires that "watercourse classifications will not be downgraded where there is loss of water underground" – but how should classification and position of the underground streams be determined?

The purpose of this Technical Note is to clarify how avoidance should be achieved, and to provide sufficient background information to allow Forest Practices Officers and other land managers to make informed decisions in situations where flexibility may be required. Karst is a highly interactive environment, and informed management of sinkholes requires an understanding of their relationship to other aspects of karst systems. Such understanding is particularly important in situations where discretion and judgement are required. This document replaces an earlier edition of *Some Operational Considerations in Sinkhole Management* that has been in use for over five years under the umbrella of the 1983 edition of the FPC, and provides an update consistent with the 2000 edition of the FPC and current knowledge.

Scope of these guidelines

While sinkholes are only one form of karst depression the management requirements for the various types of karst depressions are similar. Hence, for the sake of simplicity and brevity of expression, the term *sinkhole* is used here as a shorthand term to cover all types of *karst depression*, as defined in the FPC:

> *Karst depression - a depression in a karst landscape caused by the dissolution of soluble bedrock by water that has drained underground; variable in shape and size and may be formed in rock or in sediments that overly karstic rocks; includes:*
>
> - *various types of sinkholes, sinkhole complexes and slots or shafts that can be defined by a closed depression contour;*

Table 1.

Location and nature of provisions in the *Forest Practices Code* (FPC) 2000 that are specific to sinkhole terrain and karst. Note that other provisions of the FPC are also applicable to karst areas.

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- *linear depressions with no closed contour such as apparently "dry" valleys or channels that occur in areas where subsurface soil water seeps underground, or where an underground watercourse may resume a surface course when the capacity of the underground conduits is exceeded under wet conditions.* (FPC p. 98)

Again to facilitate brevity of expression, the word *limestone* is employed in this document as an umbrella term to cover all the soluble rock types in which karst may occur (limestone, dolomites, evaporites etc.) but readers should remain alert to the fact that a site need not be mapped specifically as limestone for a karst hazard to potentially exist. Reference should be made to the report *An Atlas of Tasmanian Karst*, and relevant geological maps and other sources, and advice sought from experts when in doubt.

This Technical Note addresses only matters specific to karst. Provisions of the FPC specific to karst are summarised in Table 1. However, other provisions of the FPC that relate to the planning and conduct of operations are generally also relevant to forest management in a sinkhole area. It is therefore important that this Technical Note be read in conjunction with the Forest Practices Code.

The primary focus in this document is upon the responsible stewardship of soil and water values that are considered under the Code to comprise a landowner's Duty of Care. It does not provide specific advice with respect to the conservation of natural and cultural heritage values in karst. Measures proposed here are unlikely to be sufficient where important natural and cultural heritage values are also involved, hence, the Forest Practices Code must again be consulted in these cases, and other relevant documents such as the *Threatened Fauna Adviser* for threatened cave fauna.

PART I.
PRINCIPLES UNDERLYING SINKHOLE MANAGEMENT

A. SINKHOLES: THE BASICS

An understanding of the principles that underpin sinkhole management is useful before considering the specific approaches outlined here. Successful sinkhole management requires an understanding of sinkhole function and processes, and that the relationship of sinkholes to soil cover, vegetation and drainage are properly understood and taken into account.

The basic reason for the formation of sinkholes is that relatively soluble rocks such as limestone are dissolved over geological time, leaving an open space in the rock mass. The cavity may be a large limestone cave similar to those developed for the tourist industry, but more commonly it is of very much smaller dimensions - the scientific definition of a karst cave requires simply that it is a solutional opening that is greater than 5-15 mm in diameter or width, the effective minimum aperture size for turbulent water flow to occur through the cavity. Once such a cavity has formed, the process of sinkhole formation can start, as material above that cavity may then collapse or be washed into it, resulting in collapse or subsidence of the land surface.

a. Basic types of sinkhole

There are six basic types of sinkhole, albeit with many shades of grey (Figure 1). All sinkholes have relevance for land managers, but one type in particular, suffosion sinkholes, poses perhaps the greatest hazard for managers of Tasmanian karst environments. Most sinkholes have not formed simply due to collapse of the ground surface into a limestone cave, as is commonly assumed.

Solution sinkholes form in areas where limestone is the uppermost bedrock type. Water seeping downwards into fractures in the limestone progressively dissolves them open into natural funnels which capture increasing amounts of seepage as their mouths broaden. They sometimes evolve into blind valleys. In Tasmania, solution sinkholes form very slowly over geological rather than human time scales.

Collapse sinkholes form due to simple collapse of a cavity in the underlying bedrock. They may be very pronounced features in the landscape, often with stark rock walls. Most form suddenly, but in the Tasmanian context the frequency of new collapse sinkholes appearing is extremely low. However, they are the natural last phase in the evolution of a cave in bedrock, and premature collapse can be triggered by interference with the tension dome of maximum shear above a cavity.

Subjacent karst collapse sinkholes. In some cases the uppermost bedrock may not be limestone at all, but limestone may occur at greater depth beneath it. If a sufficiently large cavity forms in the limestone its collapse may be propagated upwards into the overlying rock type causing it to also collapse. In Tasmania some very large sinkholes have formed by this process, notably in basalt and in Permian sedimentary rocks. One example formed in basalt is nearly 40 m deep and extends over several hectares. Many probably form suddenly although fortunately not too frequently.

Subsidence sinkholes are similar to collapse sinkholes insofar as they involve failure of a cavity at depth in the rock mass, but in this case the ground surface subsides relatively gently, squashing the cavity without significant rupturing of the rock beds.

Suffosion sinkholes form where unconsolidated sediments or soils overlie limestone that contains solution cavities. Grains from the soil are washed into solution cavities that have formed in the bedrock beneath it, causing a cavity to form in the soil. Ground surface collapse occurs because the roof of the cavity in the soil ultimately collapses. The bedrock cavity into which the soil grains were lost may be some distance from the site of the soil cavity and resulting sinkhole. Sinkholes of this kind are widespread in Tasmania. They

are generally smaller than some of the other types of sinkholes but they can form very rapidly, are often triggered by land use practices, and can cause inconvenience, expense and significant environmental harm.

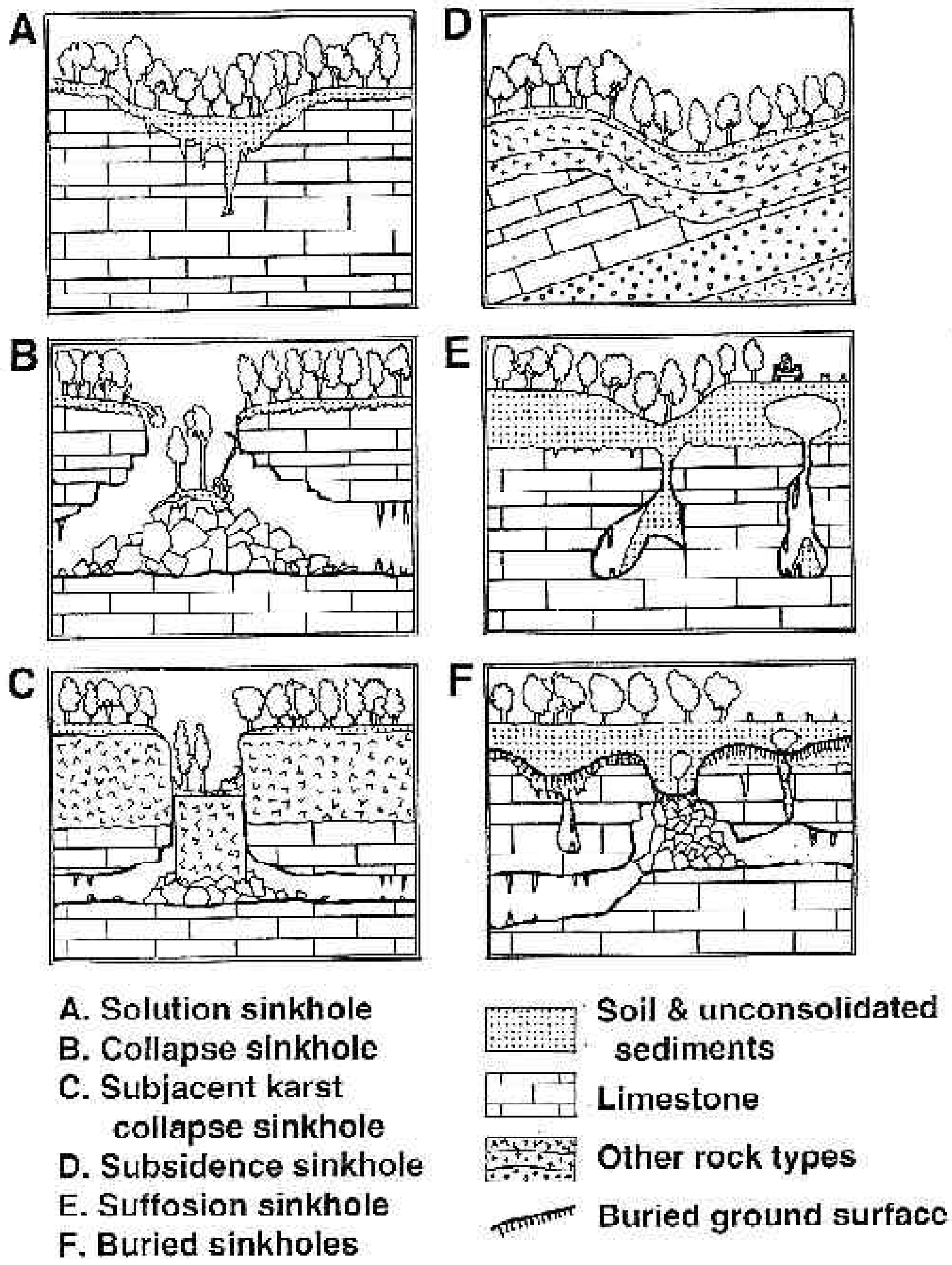


Figure 1. Basic types of sinkhole.

Buried sinkholes are former enclosed depressions that are no longer visible in the landscape because they have become filled by sediment. Generally they are detectable only by the application of specialised geophysical techniques. Although they cannot be seen they may be very abundant. One American researcer found buried sinkholes to occur at densities of 56-250 / km^2 on ridges thickly mantled by soil, and 460-3400 / km^2 at 10 thinly mantled sites. For every one visible sinkhole there were 16-70 buried sinkholes. Buried sinkholes remain of significance to land managers because even though they are not detectable on the surface they can remain potentially unstable. Test borings undertaken in the same study suggested 6-50% of all buried sinkholes were currently subject to unravelling of the fill by subsurface erosion.

Once a sinkhole has formed, it continues to evolve and to play a role in ongoing evolution of the landscape in which it occurs – its hydrological processes, its geomorphological processes, and its colonisation by plants and animals, including use by humans. Buried sinkholes in particular emphasise this fact. It is seldom easy to discern between some types of sinkholes, so it pays to seek specialist advice and be cautious.

b. How sinkholes work

1. A sinkhole is an integral part of the drainage system in which it occurs.
Karstic depressions such as sinkholes reflect the movement of water from the surface environment down through the soil to the upper part of an underlying soluble rock unit (epikarst) and ultimately down into the deeper groundwater system, from where it may flow to springs or diffuse more generally.

2. The water flowing underground via a sinkhole may not be obvious visually – but it is there.
Because water in karst need not flow across the ground surface, surface water may not be visible in a sinkhole. However, the continued development or long term persistence of any sinkhole implies there is active flow through or beneath the soil mantle.

3. Soil cover is an important variable.
The nature of the soil cover, including the manner in which it transmits water underground, its suitability as a medium to support plant growth and its inherent erodibility, all have a significant influence on the potential for sinkhole formation. The thicker the soil the greater the size of the cavity that can form within it, and collapse (Figure 2).

Figure 2. Most Tasmanian limestone areas are mantled by alluvial, glacial or other sediments that may hide the presence of subsurface karst. Artificial stripping of the covering sediments prior to limestone quarrying at this site has revealed highly karstified limestone showing residual pillars of rock between deep solution crevices down which water and sediment are lost into the karst.

4. Active collapse implies water flows at a sinkhole site are erosionally active

An actively collapsing sinkhole implies that material is being eroded from the base of the sinkhole much more rapidly than it is being replaced by inwash. In undisturbed natural environments collapse results from entirely natural processes. Instances of active collapse are only rarely seen in undisturbed forest. A very much greater degree of active collapse is seen in some disturbed environments where natural soil / vegetation / water relationships have been disturbed. An actively collapsing sinkhole can reasonably be regarded as being akin to a soil erosion gully in non-karst terrain. One single sinkhole collapse event does not imply soil cavity formation is at an end at that site (Figures 3 and 4).

Figure 3. The first evidence of a potential sinkhole problem may be the appearance of small holes formed by collapse of cavities formed in the soil due to finer particles having been washed away into subsurface karst.

Figure 4. Once a sinkhole is initiated, increasing volumes of water and sediment are likely to be engulfed as drainage routes become more open. Once this sort of positive feedback is operating, stabilisation can be very difficult.

c. Relationship of sinkhole hazard to soil erosion hazard

1. Sinkholes and karst soil erosion – two sides of the same coin.
The FPC recognises that "in karst areas soil can be eroded directly downward into subsurface drainage channels without surface runoff occurring, causing progressive and potentially total soil loss ... " (FPO p. 52). This same process of soil grains being washed underground can cause sinkhole formation if the soil cover is thick enough to allow cavities to form within it.

2. All karst soils are vulnerable by virtue of their setting
In karst areas the soil may be no more than a film of relatively unconsolidated sediment stretched across the top of an upturned sieve. Where karst development has not advanced far, or there are large volumes of sediment able to clog cavity systems in the limestone, soil loss down through the sieve may be relatively inefficient. But quite often there are well developed deep fissure systems or natural shafts in the underlying bedrock which, although not detectable from the surface, nevertheless serve as natural pitfall traps down which soil particles may fall readily. Hence, it is important to recognise that a soil surface is potentially at risk simply because it is in a karst area, irrespective of the level of vulnerability that might normally be accorded that soil type in a non-karst setting (Figure 5).

Figure 5. Loss of soil into subsurface karst may be revealed by the exposure of limestone outcrops that exhibit rounded solution fluting (karren) of kinds that originally form beneath a soil cover and are exposed by soil loss. The presence of fluting of this kind on limestone outcrops implies the presence of karst and potential for sinkhole problems.

3. Soil erosion in karst may not be visually obvious
The pattern of soil erosion in karst environments is different to the norm. When water flows down through a soil into drainage systems dissolved in the underlying bedrock it is able to erode soil grains directly from the *bottom* of the soil profile and flush them down into the cavities in the bedrock. This is opposite to the usual pattern of soil erosion in non-karst environments where soil is stripped from the *top* of a soil surface by water flowing across it.

4. Ground surface slope angle does not provide a reliable guide to soil erosion risk in karst
In non-karst landscapes we generally assume that soil erosion hazard is greatest on steep slopes and least and gentle slopes. This is because the angle of slope determines the hydraulic gradient and hence steep slopes allow water to flow faster and strip particles from the soil surface most effectively. However, in karst landscapes the water is often flowing directly downwards into the ground rather than across it, so the hydraulic

gradient can be effectively vertical – the ultimate steep slope – even though the land surface itself may be horizontal and appear to pose little risk of soil erosion.

5. Most sinkholes imply a particular focus of soil erosion at one point
Only relatively few of the karst depressions visible at the surface are formed directly in bedrock. Most form in sediments or soils that overlie karstified bedrock, and are due to particles being washed out of the soil and into cavities dissolved into the limestone or dolomite at greater depth. The weakly supported soil surface is then left prone to collapse.

6. A thicker soil does NOT imply a lesser sinkhole hazard
A very thick soil over bedrock that has been subject to only minor karstification may provide sufficient sediment to clog cavity systems in the limestone, at least temporarily. However, the potential for cavities to form in a soil is constrained in part by the thickness of the soil. In general, the thicker the soil the larger the cavities that can form. One wide-ranging study found that newly formed sinkholes were generally largest where the soil cover over the bedrock was 30-60 m thick; the sinkholes were smaller where the soil was less than 10 m thick and infrequent where the cover thickness exceeded 60 m.

7. Consider both the vertical and horizontal sediment trajectories
Sinkhole formation will cease and a sinkhole become filled by sediment if the bedrock crevices into which the soil is being lost become filled by sediment, or if the deeper cavity in the limestone into which they deliver that sediment ultimately becomes filled. Unless the cavity in the bedrock is extremely large, the persistence of a sinkhole requires that the movement of soil particles downward by infiltrating water is accompanied by that sediment then being shifted out of the cavity by underground water flows that follow a more horizontal route. The sinkhole risk is particularly great if these horizontal streams and their channels are sufficiently well developed that large volumes of sediment can be evacuated along them. It is important to recognise the level of sinkhole risk is a function of both these potential sediment trajectories, vertical and horizontal. Even if the volume of water vertically infiltrating the soil might appear limited at a particular site, the sinkhole hazard can still be extreme if there are large underground streams flowing horizontally beneath it.

8. Low, seasonally flooded land can be at especially high risk
Soil cover subsidence or collapse is often particularly pronounced in areas where sinkholes become ponds in the wet season. This is because when the water-table fluctuates through the base of a sinkhole the process generally enhances the flushing of sediment downwards through the sinkhole floor and enhances cavity formation in regolith through which the water table fluctuates. Hence, low relief plains can be as prone or more prone to sinkhole development and soil loss into sinkholes as more elevated terrain.

9. *Direct disturbance of sinkholes or sinkhole vegetation can cause problems*
The soil in a sinkhole may be rather like the sand in the upper chamber of an hour-glass, prone to slip away through the constriction into the space below if disturbed. Whether time also runs out for the land manager depends upon how effectively stability is maintained. Vegetation often plays a critical role in maintaining soil stability because tree roots help bind the soil together, and transpiration by the vegetation reduces the amount of water that would otherwise be able to flush soil grains down into the karst. When sinkhole vegetation is cleared the reduction in transpiration allows more water to seep underground, increasing pore water pressures and the potential to lose the soil plug in the top of the cavity. The potential for accelerated sinkhole formation may be compounded when the tree roots rot out because this reduces the reinforcement of the soil grains at the very time the increased pore water stress is being applied to the soil plug (Figure 6). Holes left when tree roots rot out or are burnt out can provide routes for rapid infiltration of water into the karst.

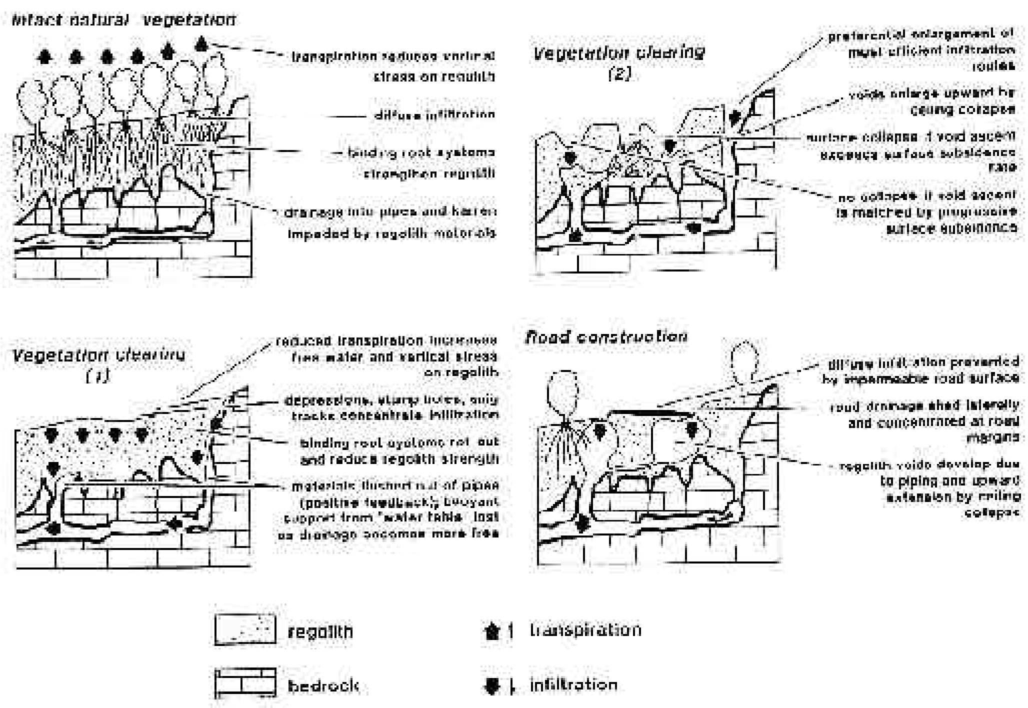


Figure 6. Some processes that may result in accelerated formation of suffosion sinkholes.

d. Relationship of sinkholes to broader drainage systems

1. A sinkhole is a special type of tributary watercourse – a stream channel tipped up on end

In essence, sinkholes can reasonably be regarded as stream channels tipped up on end. It may be useful to think of them as the "tributary valleys" of the main underground streams. The slope of a sinkhole can be regarded as analogous to a stream bank.

2. A lack of visible surface water doesn't mean a stream doesn't exist

In karst environments water generally flows through underground channels dissolved in the limestone rather than across the land surface in conventional watercourses. Sinkholes are the means by which water from the surface is delivered into these subsurface stream systems.

3. Which way does the drainage go? Don't be fooled by the surface topography!

The FPC cautions that "subsurface drainage directions in karst may be different to those suggested by topographic maps or observations on the surface. Subsurface drainage should be assessed before any forest operation occurs in a karst area or its catchment" (FPC p. 52).

4. Where exactly do the underground streams run?

Major linear concentrations of sinkholes may reflect the approximate position beneath which major subsurface streams are located, but subsurface streams also exist beneath ground where sinkholes are more dispersed, their precise location potentially harder to discern.

5. In some cases "losing streams' leak into inconspicuous sinkholes in their bed.

Where streams maintain a surface course across limestone or sediment-mantled limestone there may be a progressive loss of water into the stream bed. The only clue may be a downstream decline in the volume discharged by the stream. Hence there may be subsurface flows and sinkhole hazards beneath and beside some streams of this kind. Sometimes establishing small farm dams along the course of such streams can trigger collapse that suddenly drains the dam or diverts the stream underground into a new colapse upstream of the dam.

e. How significant is a particular sinkhole?

1. Sinkholes imply activity
Virtually all sinkholes reflect continuing loss of water and soil down into the karst. If material does not continue to be mobilised through the floor of sinkholes they will ultimately fill up with sediment.

2. Small sinkholes do not imply lesser hazard
The fact that a particular sinkhole may have a small diameter is not necessarily indicative of any lesser risk because even a very small diameter sinkhole may represent the "tip of an iceberg". It is commonly small sinkholes, often only a metre or two in diameter, that give initial surface expression to the presence of large cavities that have formed in the soil.

3. The form of sinkholes is not a reliable indicator of hazard
The most active of sinkholes are often steep-sided with soil exposed in their sides. In some cases they are fairly deep relative to their width though this is not always the case. Wide, more open sinkholes with very gentle, vegetated edges and no deeper sub-basins enclosed within them are suggestive of more stable sub-surface conditions, but this stability may be only a temporary stage in their development, and may cease due to land-use changes that change soil drainage conditions. Alternatively, instability may increase due simply to intrinsic changes as the system evolves naturally.

4. An appearance of stability can be misleading
It is not uncommon for the bottom to suddenly fall out of a sinkhole that appears to have been stable for years or decades, but where that apparent stability on the surface has hidden the fact that cavities have been forming progressively over the years within the soil. In other cases where no sudden collapse is observed, sober monitoring may reveal this to have been due to sinking of the soil surface having occurred slowly and evenly in compensation for the progressive washing-out of subsurface soil grains.

5. You may not see some of the most significant sinkholes and potential sinkhole sites
Buried sinkholes and subsurface solutional crevices in the bedrock that may become foci for sinkhole formation and pose potential groundwater contamination problems cannot generally be detected without specialised geophysical surveys. Remember, overseas studies of this kind have shown that for every visible sinkhole there may be 16-70 unseen buried sinkholes and 1,300-42,000 dissolutional openings in the top of the bedrock. It is important to recognise that sinkhole risk extends over entire karst areas, and that it cannot be assumed to be localised just to areas near visible sinkholes.

f. Recognising subtle karst depressions

1. *Sinkholes may not always be conspicuous by having a clearly closed contour on their downslope edge.*
Incipient sinkholes or sinkholes that have been filled by material deposited from upslope may appear simply as shallower-gradient steps along the axis of a valley, or as small terraces on slopes, often with an amphitheatre-like embayment into the hillslope behind them.

2. *In some cases it may not be entirely clear whether a depression or break of slope is karstic.*
Depressions may also form due to some other cause such as the structure of rock beds or a past landslide, but limestone bedrock may be buried beneath thick soil or unconsolidated sediments. Be suspicious of any depression or break of slope if limestone or other soluble bedrock may be present.

3. *It is important to recognise that whatever the original cause of a depression having formed, if there is soluble bedrock beneath it is likely to have become a focus for infiltration of water into the soil, and hence to have become a likely site for accelerated limestone dissolution and sinkhole formation.*

Even such recent depressions as some World War II bomb craters in European karsts have since evolved into sinkholes. The formation of sinkholes along valley axes provides one obvious case of sinkholes evolving from the floor or pre-existing non-karstic depressions. Other examples include sinkholes formed along the back edge of river terraces, in flood channels, or in slump hollows. In some cases sinkholes may underpin the existence of other hazards (Figure 7) such that landforms are of composite origin.

Figure 7. Sinkholes may trigger more widespread slope instability. Loss of sediment into this small sinkhole (arrowed) at Mole Creek is removing toe support from slope deposits further upslope, leading to intermittent landslide activity on the hill above the sinkhole (dashed line elipse).

g. Very large karst depressions

1. Some karst depressions can be very, very large.

The largest types of karst depressions are known as poljes, and in some parts of the world these can attain widths of some kilometres. Somewhat smaller but still extensive depressions formed by the coalescence of sinkholes are known as uvalas, and these commonly have smaller sinkholes of various types nested within them. Poljes are rare in Australia and that rarity is such that the few relatively undisturbed poljes that exist are of very high geoheritage conservation significance. Uvalas are less rare, and in Tasmania one has formed in basalt that overlies limestone. In most cases the geoheritage value of Australia's largest karst depressions has already been sufficiently compromised that management concern is now largely confined to the potential hazards they may pose. The response to these soil and water management concerns in very large karst depressions is encompassed by a landowner's duty of care.

2. Recognising very large karst depressions

Some very large karst depressions in Tasmania have the general appearance of conventional valleys and hence they may not always immediately be recognised as being karst features. The Mayberry basin north of Standard Tier in the Mole Creek area provides one example. However, a consideration of the geological setting and drainage characteristics will confirm their identification as karst features. Some of these very large depressions have been developed for agriculture, causing their geoheritage values to be severely compromised, but they continue to pose karst-related land and water management issues.

3. Very large karst depressions imply very considerable karst activity

For a polje or uvala to form implies the evacuation of a large volume of soluble rock through karstic channels over a long period. This in turn implies very well developed subsurface cavity and channel systems. Hence, even if sinkholes are not abundant on the floor of a polje or uvala it must be managed with the utmost care. Because poljes generally occur at lower altitudes in the landscape their floors are often thickly mantled by unconsolidated sediments and soil. Hence, suffosion sinkholes may indicate significant land management risks. There may also be streamstrinks, springs, and lengths of surface watercourse that are active seasonally or ephemerally.

PART II.
SOIL AND WATER DUTY OF CARE ISSUES IN SINKHOLE AREAS

B-1. GATHERING INFORMATION AND ASSESSING ISSUES

a. Data Gathering

1. Know the full potential for significant environmental harm
Acquiring the level of information regarding subsurface drainage patterns that is required to permit responsibly informed land management may take significant time, effort and expense. However, if an adequate understanding is not obtained the consequences can include serious land degradation; the possible blocking of subsurface routes by eroded sediment (sometimes possibly causing a reversion to surface flow and erosion on the surface by overland runoff); and significant harm to the groundwater environment, which may include contamination by sediment or chemicals.

2. Never consider an operation in karst unless you fully understand the drainage system.
A topographic map is the most basic fundamental tool available to any responsible land manager or forest planner, because it permits determination of the drainage pattern, catchment characteristics and potential downstream affects. No responsible forest planner or manager would proceed without such an understanding in conventional, non-karst terrain. Similarly, no operation should proceed in any karst area if the drainage pattern and characteristics have not been ascertained. Understanding the drainage pattern and drainage system characteristics is particularly critical because underground streams in karst are much more highly prone to sustaining environmental harm than are most conventional stream systems.

3. Never rely solely on topographic maps in assessing the likely drainage pattern
Topographic maps can be grossly misleading in karst areas because the streams are often mostly underground, and these underground streams tend to follow hidden geological structures and to be largely unconstrained in their directions of flow by the surface topography and the valley systems depicted on maps. It is not uncommon for cartographers to misinterpret karst depressions in forested areas to be valleys. The streams commonly assumed by cartographers to flow down any valley and which they depict on maps as doing so often simply do not exist where the area is karstic.

4. Remember that a stream does not cease to exist simply because it flows underground
The FPC requires that “watercourse classifications will not be downgraded where there is a loss of water underground into subsurface conduits including karst streams or slope deposits” (FPC p. 57).

5. Always verify the appropriate classification for any karst watercourse
The Forest Practices Code provides a classification scheme for watercourses, but its application in karst areas typically requires considerable detailed inventory work by specialists. In some Tasmanian karsts the water that flows in small valleys with relatively small apparent topographic catchments originates more than 10 km away in entirely different valleys. In some cases the true catchments for those streams are up to fifty times larger than their catchment areas as suggested by topographic maps. In some cases in Tasmanian karst areas streams pass across or beneath the floor of one valley en route from one entirely different valley to another entirely different valley! Cases exist in Tasmania where small valleys that appear capable of carrying only Class 4 watercourses actually contain Class 2 or Class 1 streams (as defined by the FPC). Erring on the side of caution is recommended.

6. Integrate classification of watercourses with classification of sinkholes

Because sinkholes are vertical tributaries to underground streams it is appropriate that they be classified in a similar manner to streams wherever possible.

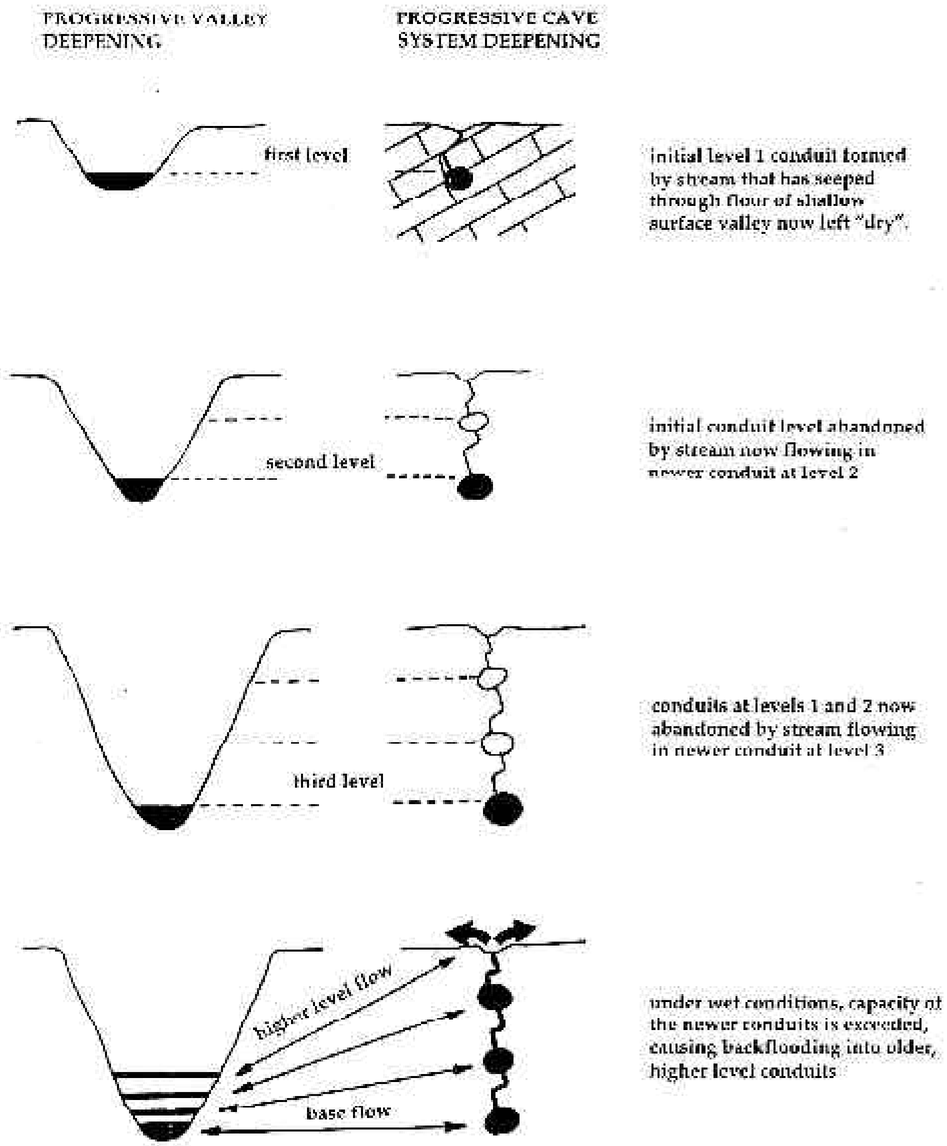
7. Never take springs at face value
The Code provides that "significant springs will be treated as Class 3 or 4 watercourses. Subsurface conduits emerging as springs may require extra protection upslope eg. extension of machinery exclusion zones" (FPC p.57). This is a general provision for springs, not one specific to karst. Numerous points at which water emerges from the ground in small Tasmanian valleys are not simple springs from soil seepage water but are *resurgences* of streams that sink underground many kilometres distant, sometimes in entirely different valleys. For example, one stream that emerges from a resurgence in a very small valley of less than 1 km^2 extent in northern Tasmania actually rises on mountain slopes more than 8 km away and has a catchment of 30 km^2. Hence, this particular stream warrants classification as no less than a Class 2 watercourse. Water-tracing experiments are essential because they may allow the origin and destination of an underground stream to be determined, and hence contribute to its accurate classification.

8. Respect and avoid apparently "dry" valleys and other depressions
Drainage systems in karst are three dimensional, with water running in pipe systems at different depths in the limestone. Just as some surface streams that flow across non-karst terrain have braided channel networks rather than a single channel, so too do braided channel systems occur in karst. But in the karst case the braiding can be vertical as well as horizontal. In a conventional valley, progressive incision by the river leads to deepening of the valley, and heavy rainfall may result in simple progressive rises in stream level. But karst watercourses evolve through successively deeper pipes being dissolved in the limestone, and the active lowermost pipes may be insufficient to cope with the flow during heavy rains. At these times, the capacity of these newest and least developed karst pipes is often exceeded, causing overflow into older abandoned pipe systems at a higher level in the rock mass. But there is still less space available than in an open surface valley, so ultimately all the pipes may become full, causing overflow across the ground surface. Hence, an apparently dry channel may suddenly become the most geomorphologically energetic part of a Class 3, 2 or 1 watercourse. It may discharge water flows across the surface that have the capacity to cause serious erosion of land (Figure 8).Remember too that runoff or infiltration may be greater after clearfelling.

9. Be aware of the limitations in being able to determine accurately the position of underground streams
Water tracing commonly allows the origin and destination of underground streams to be determined, but water tracing alone does not permit the exact underground course of a stream to be pinpointed. Expert advice will be required, and this needs to be planned and budgeted for. There are obvious practical difficulties entailed in establishing exactly where an underground stream is running at a reasonable cost, but some assessment needs to be made. Interpretation of geological structures, mapping of sinkhole distribution, dye tracing, cave exploration and remote sensing techniques are among the means that may be employed.

10. Remember that even a small subsurface drainage pipe can be significant
Particular caution is required because natural underground pipe systems in karst often permit speedy transmission of contaminants. Flow through natural underground karst pipes does not allow the sort of "natural purification" that can sometimes ameliorate poor water quality in surface channels. The pipes need not be of large diameter for a hazard to exist – consider for example the very small diameter of household water pipes but the potentially rapid and serious effects of introducing a contaminant. So too with karst pipes.

In the same way that streams cut progressively deeper valleys over time, so do cave streams cut caves progressively deeper in a rock mass. But rainfall that may cause only a modest rise in the level of a surface stream may cause severe flooding in a cave system where only confined spaces are available to accommodate the water. Karstic "dry" valleys may be reactivated and surface flooding may occur.



If the subsurface conduits become totally water-filled under flood conditions, water may flood back up tributary cave passages and substantial runoff may be redirected into the "dry" valleys on the surface. If a cave stream is left with no underground route to follow because all subsurface spaces are water-filled, all runoff may be discharged across the surface. If the stream has a sufficiently large catchment, a "dry" valley may suddenly carry a Class 3, 2 or 1 watercourse.

Figure 8. Protection of "dry" valleys in karst environments.

11. Assessment requirements
Information necessary for planning operations in karst areas includes: (a) a map of the karst that depicts landforms, bedrock geology, surficial geology and regolith thickness, soil types, possible catchment areas and relevant sub-catchments; (b) an interpretative hydrogeological map that includes likely groundwater recharge and discharge areas, any proven subsurface flow connections, interpreted flow routes, and karst sensitivity zoning relative to forest operations under consideration; and (c) the proposed layout of operations and reserve areas. Assessment reports must be based on appropriate natural system boundaries rather than artificial cadastral or logging unit boundaries. Where special natural or cultural values are also present there may be additional assessment requirements, but resolution of any such issues is likely to be greatly expedited by adequate completion of these basic karst soil and water requirements.

12. Role of the forest planner
The forest planner can contribute to expediting assessments by remaining alert to possible issues, accurately documenting sinkhole locations and plotting them on geological maps, and sometimes assisting in water-tracing experiments, cave surveys or other investigations initiated by the specialist consulted.

13. Allow sufficient lead time
Knowledge of subsurface drainage patterns may or may not be immediately available. It is essential that allowance is made for sufficient lead time for inventory work, and appropriate resourcing of the inventory process.

b. Soil vulnerability classification in karst areas

1. Unconsolidated material on karstified bedrock may not be just soil – some implications
For simplicity and in view of operational issues involved, the Forest Practices Code defines a karst soil simply as "residual or transported soils in a karst area; an accumulation of materials deposited above a soluble bedrock parent material". It does not require that the material has been subject to pedogenic processes as required by the conventional textbook definition of a soil. The material involved may imply a need to consider other issues. For instance, where sinkholes occur in terrain mantled by basalt slope deposits, threshold slope limits may also need to be taken into account (FPC p. 54).

2. Remember all soils in karst areas are vulnerable simply because of their setting
It is important to recall that virtually any type of soil in a karst area derives a degree of vulnerability simply by virtue of its karst setting. It may be akin to a membrane of soil stretched across the top of a an upturned colander.

3. Consider the severity of the vulnerability at each site
Recognising that all soils in karst areas are vulnerable because of the karst context, the Forest Practices Code identifies two levels to that vulnerability:

- "vulnerable karst soils, comprising [a] thin residual soils derived *in situ* from decay of limestone; [b] thin or high or very high erodibility soils derived from other parent materials; [c] [soils in] Medium Sensitivity Zones in Category A or B karst areas and specified locations in Category C and D karst areas (as described in *An Atlas of Tasmanian Karst*).
- karst soils of lower vulnerability, not included in the definition of 'vulnerable karst soils" including [a] thick soils on limestone or dolomite; and [b] [soils in] Low Sensitivity Zones in Category A karst areas". (FPC, p. 101)

4. Ascertain and employ the appropriate Karst Sensitivity Zone
Sensitivity zones are referred to in the FPC (p. 101) but are not defined in that document. There are specific requirements with respect to Medium Sensitivity Zones (MSZs) and while High Sensitivity Zones (HSZs) are not mentioned the precautions should be not less, and indeed significantly greater than, those stipulated for MSZs. The zoning system referred to is that developed for the Junee-Florentine area. In its original context it was designed primarily to safeguard natural and cultural heritage values. However, it

employs certain objective criteria that nevertheless provide useful indicators for the degree of karst development in any karst area. Hence, it may be used to assist in prediction of the potential for geohazards to be present in a karst. Where no sensitivity zoning is yet available for a specific karst, and until such time as a more general Karst Vulnerability system is developed, the Junee-Florentine system should be employed:

> **LSZ**: areas of low or negligible sensitivity from a karst management perspective. Specifically, areas outside the catchments of significant and sensitive cave systems on the basis of current knowledge. No special provisions for karst geohazards are required but normal Forest Practices Code requiremen ts still apply.
>
> **MSZ**: areas where karst values are known or likely to be present in the catchment, and where the significance of those values and the potential for land-use activities to impact upon them suggests the need for a higher level of protective management than is appropriate in the case of the LSZ. MSZ areas require detailed planning of the kinds referred to in sections of this manual to take account of karst.
>
> **HSZ**: areas already known to contain highly significant karst values or where it is extremely probable that significant karst values will ultimately be found to be present, and where the potential for land use activities to impact upon those values is high. Specifically: areas known to be underlain by significant caves; areas containing a high density of karst features, particularly caves, streamsinks and sinkholes; areas where surface landforms such as cave entrances, streamsinks and sinkholes strongly suggest the presence of underlying caves, the catchment areas of significant caves, areas where lithological considerations….and / or geological structures…suggest the existence of underlying caves, and sites of high natural hazard risk where those hazards have the potential to impinge upon the conservation of significant karst values. Forest operations are not compatible with sustainable management of karst.

c. Management of very large karst depressions

1. Consider relative impact

Very large karst depressions in Tasmania are identified in the *Atlas of Tasmanian Karst*. While the Forest Practices Code prohibits operations within karst depressions, the magnitude of the potential disturbance relative to the extent of the depression may be a legitimate consideration in evaluating reserve boundary requirements and sinkhole reserve management. Removal of a small area of forest from the margin of a very large karst depression may conceivably involve a lesser relative impact than removing a single tree from the margin of a small sinkhole. On this basis it may be possible for some operations to occur inside normal reserve boundaries for the very largest types of karst depression (apart from geomorphologically intact poljes which are inevitably of geoheritage significance), provided the operation is well removed from any watercourse and that its relative impact is below some theoretical standard. However, such cases will require special approval from the Chief Forest Practices Officer.

2. Remember that very large karst depressions cannot be managed as if they are normal non-karst valleys

It is not adequate simply to regard a polje as being no more than a special sort of valley, because the karst setting and the probable presence of an efficient system of natural subsurface pipes means the environmental risk is never low, anywhere within even a very large karst depression.

3. All very large depressions must be classified as sensitive and special management guidelines developed

No site within a very large karst depression can legitimately be regarded as being of less than Medium Sensitivity, and most should be regarded as High Sensitivity, irrespective of the erodibility class of the soil within them.

B-2. SINKHOLE CLASSIFICATION AND SINKHOLE EXCLUSION ZONES

a. Fundamentals of classification and exclusion boundary design

1. Link sinkhole classification to stream classification
Assessment of the appropriate classification for particular sinkholes must be linked to an assessment of their proximity to subsurface streams of various sizes and the appropriate classification for that underground stream. Because sinkholes are essentially stream channels tipped up on end it is appropriate to link their classification to the classification of the streams to which they are tributary.

2. Sinkholes are often bigger than you think
It is important to recognise that the surface expression of sinkholes is seldom if ever exactly equivalent to their subsurface bedrock / hydrological boundaries. The bedrock and / or hydrological boundaries of a sinkhole is sometimes significantly larger than the surface expression of the sinkhole, and this must be taken into account in sinkhole management (Figure 9).

3. Remember proximity to an underground trunk stream is an important consideration
It is not always immediately clear which "stream" classification category is appropriate for a particular sinkhole. It might seem appropriate to regard a very small sinkhole as akin to a Class 4 stream channel, but if that sinkhole lies in close proximity to a large underground stream that is hidden from view, then protecting it as if it were a category 4 stream may be inadequate. This issue is addressed later.

4. Reserve a sinkhole buffer just as you would provide a buffer to any watercourse
As a simple first approximation, apply similar reserve boundary requirements to those required adjacent to watercourses of the same classification as the sinkhole (FPC p. 57), provided you are sure that will provide adequate protection.

5. Remember to take account of potential windthrow of retained trees
The objectives of retaining vegetation in sinkholes will be compromised if excessively close harvesting allows retained trees to be toppled by the wind, tearing up their roots and the surrounding soil. Exclusion zones must be sufficiently wide to preclude this happening. The minimum boundary requirements presented later in these guidelines may need to be extended at exposed sites, consistent with the FPC requirement (p. 57) that wider streamside reserves should be specified to protect areas at significant risk of windthrow.

b. Exclusion zone widths assuming a near-horizontal surface

1. The minimum buffer width is 10 m
A buffer of not less than 10 m width should be established around any sinkhole. Reserve width should be measured from the "edge" of the sinkhole, ie. outwards from where the slope exceeds 5° (Figure 10). A minimum 10m buffer in these cases is necessary to take safe account of those many situations where the subsurface bedrock / hydrological sinkhole exceeds that of its surface expression. This approach is also useful where the precise topographic margin of a sinkhole is difficult to define, and as an aid to reducing the potential for damage to sinkhole slopes due to windthrow of isolated retained trees. Where this approach does not seem practical, perhaps because sinkholes are very large, the inner boundary of the buffer may be established at the principal upper break of slope leading into the sinkhole, providing that the slope leading into the sinkhole remains less then5°.

2. Wider reserves may be necessary
Note that 10 m is a minimum width. The FPC requires that wider reserves, including reserves on class 4 watercourses, should be specified where necessary to protect karst (FPC p. 57). A wider buffer may be considered by the FPO to be appropriate in some circumstances (e.g. where there is evidence of instability on the margin of a sinkhole, or to better address potential windthrow problems).

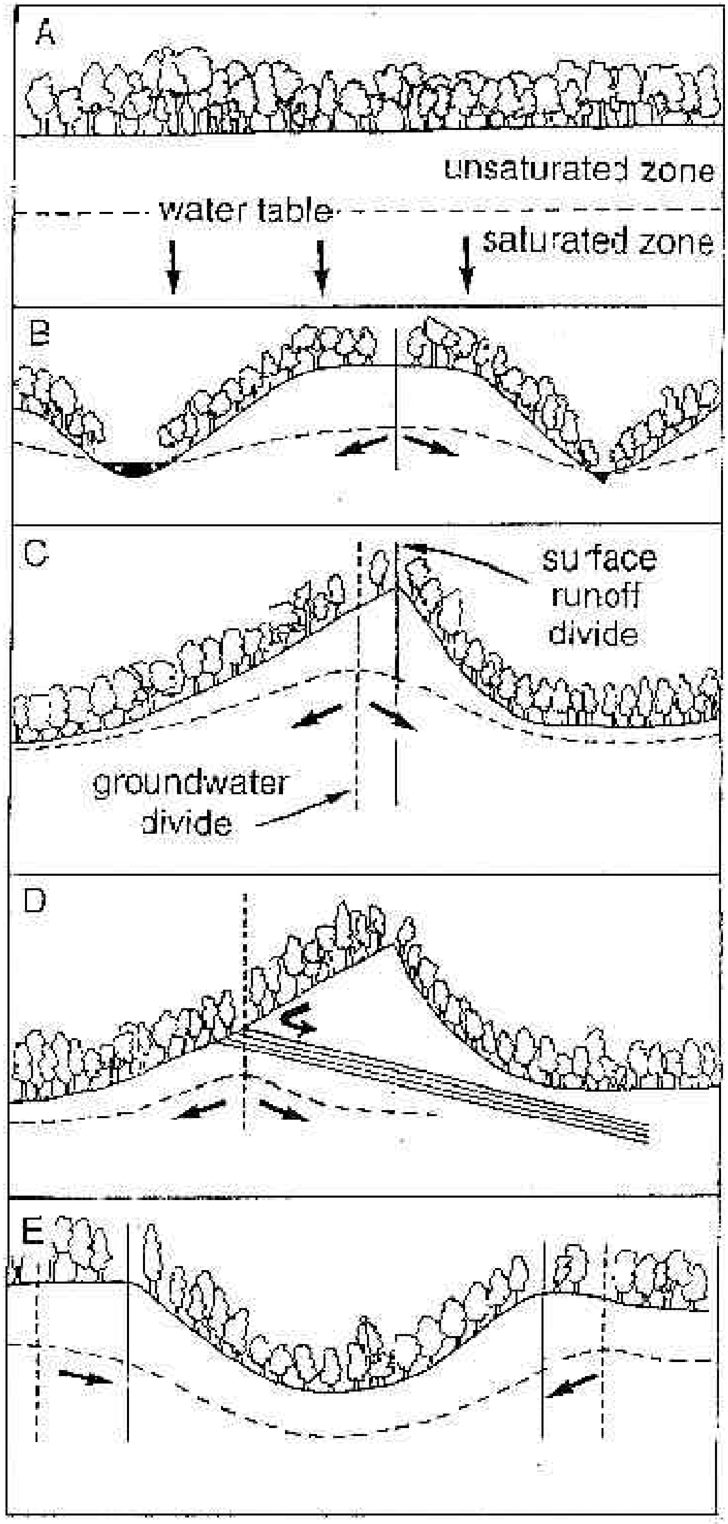


Figure 9. Potential inconsistencies between groundwater divides and surface drainage divides. Diagram A depicts situation on flat land, and diagram B depicts a symmetrical hill where groundwater and surface topographic divides coincide. The water table is higher beneath hills than beneath valleys, but because water is not as rigid as rock a “water table hill” cannot closely mimic sharp changes in the contours on the surface. Hence, the water table hill “averages out” the contours. Diagram C depicts an asymmetrical hill beneath which the crest of the groundwater divide will not coincide exactly with the surface contours. In case D an impermeable rock bed further confuses the situation. Diagram C illustrates potential implications on the margin of a sinkhole.

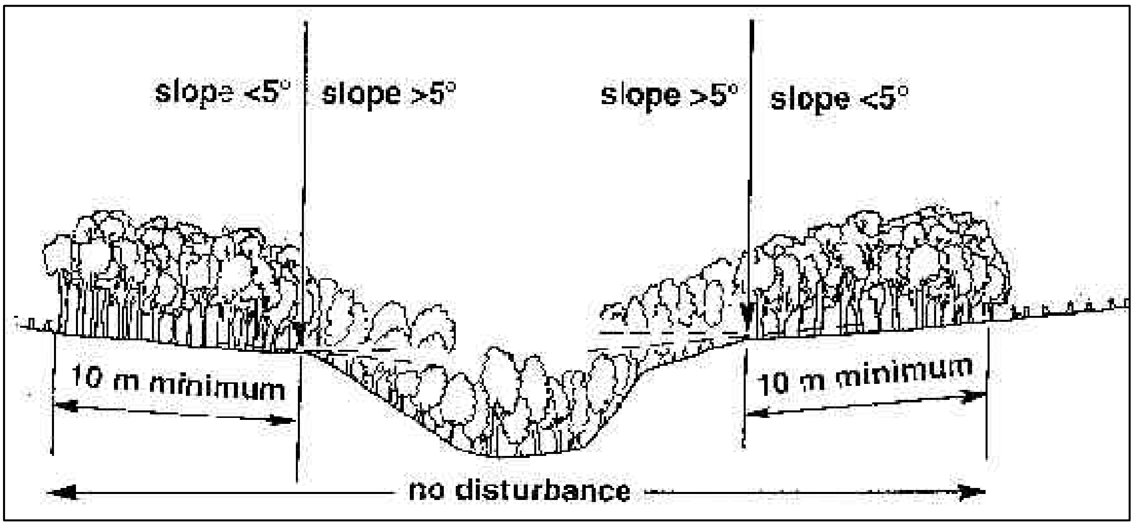


Figure 10. Defining the inner margin of a sinkhole exclusion zone.

Remember too that wider buffers may be needed where other natural or cultural values are involved.

3. Link buffer width to degree of anticipated impact of proposed land use.
The suggested 10 m minimum buffer width is appropriate for selective harvesting of native forest but may be insufficient where clearfelling and broad scale hot burning for natural regeneration is envisaged, or where it is proposed to clearfall for plantation or pasture development.

4. What if there are sinkholes everywhere?
Application of the sinkhole buffer widths recommended in this Technical Note may preclude operations in polygonal karst ("egg carton topography") where all slopes lead into sinkholes. In most such situations this is the appropriate course of action.

5. Consider sinkhole stability
In assessing necessary buffer width, attention should be paid as to how stable or otherwise each sinkhole appears to be. Torn turf or small scarps on the sinkhole slopes are often indicative of active subsidence. In the case of sinkholes that fill with water at times, if they are not particularly active then sediment accumulation within them should tend to smooth the basal contours. If this smoothing has not occurred, is there evidence of water-table fluctuations flushing sediment down into the deeper karst?

6. No sinkhole is less than Class 4.
Because the persistence of sinkholes implies the flow of water underground, no sinkhole should be given less protection than that required for a Class 4 stream. In the case of sinkholes that do not occur immediately proximal to large underground streams (Class 4 sinkholes) avoidance is best achieved in the field by establishing a buffer of intact vegetation at least 10m wide with no machinery entry. Its inner margin should be located at the drainage divide outside of which surface run-off would no longer flow into the sinkhole. Remember that water flowing into the base of a sinkhole may fall almost immediately from the base of that sinkhole via an open vertical shaft system directly into the underground stream.

7. Class 3 sinkholes and required buffer design
The Code defines Class 3 streams as "watercourses carrying running water most of the year between the points where their catchment is from 50-100 ha", and stipulates a minimum streamside reserve width of 20 m. But a karst environment is three-dimensional, which introduces a vertical component to the streamside reserve requirement. Only the very largest types of karst depressions might appear to qualify for

20 m reserve boundaries, but the stream into which they drain may well be a Class 3 watercourse. If a subsurface Class 3 stream is flowing at less than 20 m depth in a karst area then for consistency a "streamside" reserve would be required on the ground surface above it. Sinkholes proximal to that underground stream that can reasonably be assumed to drain into it should be accorded Class 3 status and given reserve boundaries of Class 3 width.

8. Class 2 sinkholes and required buffer design
In non karst terrain a Class 2 watercourse requires a streamside reserve at least 30 m wide. Hence, where such a stream flows at less than 30 m depth beneath the ground surface a reserve on the surface above the stream is appropriate and essential. In the case of a Class 2 stream the minimum protection requirement ought to include a reserve of no less than Class 2 width (30 m) around all sinkholes within 30 m of the inferred position of the underground watercourse.

9. Class 1 sinkholes and required buffer design
There is no effective differentiation in the Code between Class 2 and Class 1 streams that require a reserve width of 40, the criterion for a Class 1 stream being simply that it be a "river" generally named on 1:100,000 topographic maps. Some streams named as "rivers" in that map series have significantly lesser discharge than some karst streams.

10. Large isolated sinkholes and required buffer design
In some cases a large sinkhole may occur on its own with few if any other features nearby to provide a context and allow the sinkhole to be classified in accordance with its proximity to a stream of known size. However, the fact that such a sinkhole exists implies that a karst drainage system is present and hence that the sinkhole cannot be treated as if it is truly isolated. In such cases the recommended approach is to apply an arbitrary classification based on the size of the sinkhole, and assuming the size of the stream that is likely to be required for the formation or persistence of as sinkhole of that size. The uncertainty that exists in such cases means that extreme caution is required. As a broad guide, an isolated sinkhole up to 5 m diameter or 2 m depth should be given a minimum Class 4 designation, sinkholes 5-10 m diameter or up to 5 m deep given a Class 3 designation, sinkholes 10-20 m diameter or up to 10 m deep given a Class 2 designation, and sinkholes any larger in size designated as Class 1. Arbitrary designation of sinkhole class is permissible only when efforts to determine the broader drainage relationships have not been successful. The written approval of the Chief Forest Practices Officer is required and sinkhole class designation should be undertaken in consultation with the FPB Senior Geomorphologist.

c. Exclusion zone widths for sinkholes on slopes

1. Sinkholes on slopes imply upslope catchments
The minimum sinkhole reserve widths proposed above are based on the assumption that the sinkhole occurs on a relatively flat surface, and that the sinkhole catchment is protected by a reserve of the stipulated width. However, where a sinkhole occurs on a sloping surface, its catchment is not encompassed by a buffer of arbitrary width extending outwards from the closed contour, because the closed contour will lie well inside the upslope area that still drains into the sinkhole.

2. Upslope catchments imply a need for upslope buffering
Where sinkholes occur on slopes, there is a need to extend the width of the reserve on the upslope side (Figure 11). The steeper the slope, the greater the risk of lateral soil erosion or slumping. A sinkhole margin may imply a local increase in slope angle to above landslide threshold limits (FPC, p. 54) (and see Figure 7).

3. Appropriate upslope boundary widths increase in regular increments
In the case of a small Class 4 sinkhole, the width of the reserve on the upslope side should be increased to 20 m minimum where the slope is 5- 10°, to 30 m for slopes of 10-15°, and then increased in width by 10 m for each 5 degree slope increment above that

(the maximum landslide threshold slope angle is 19° where dolerite or basalt slope deposits overlie the limestone, and less steep for some other rock types). Where the sinkholes are Class 3 or 2 then the minimum reserve widths should be increased accordingly.

4. Where is the upslope margin of a sinkhole on a slope?
The position at which the slope locally steepens to an angle greater than the mean for the adjacent hillslope can be taken as the upslope edge of the sinkhole.

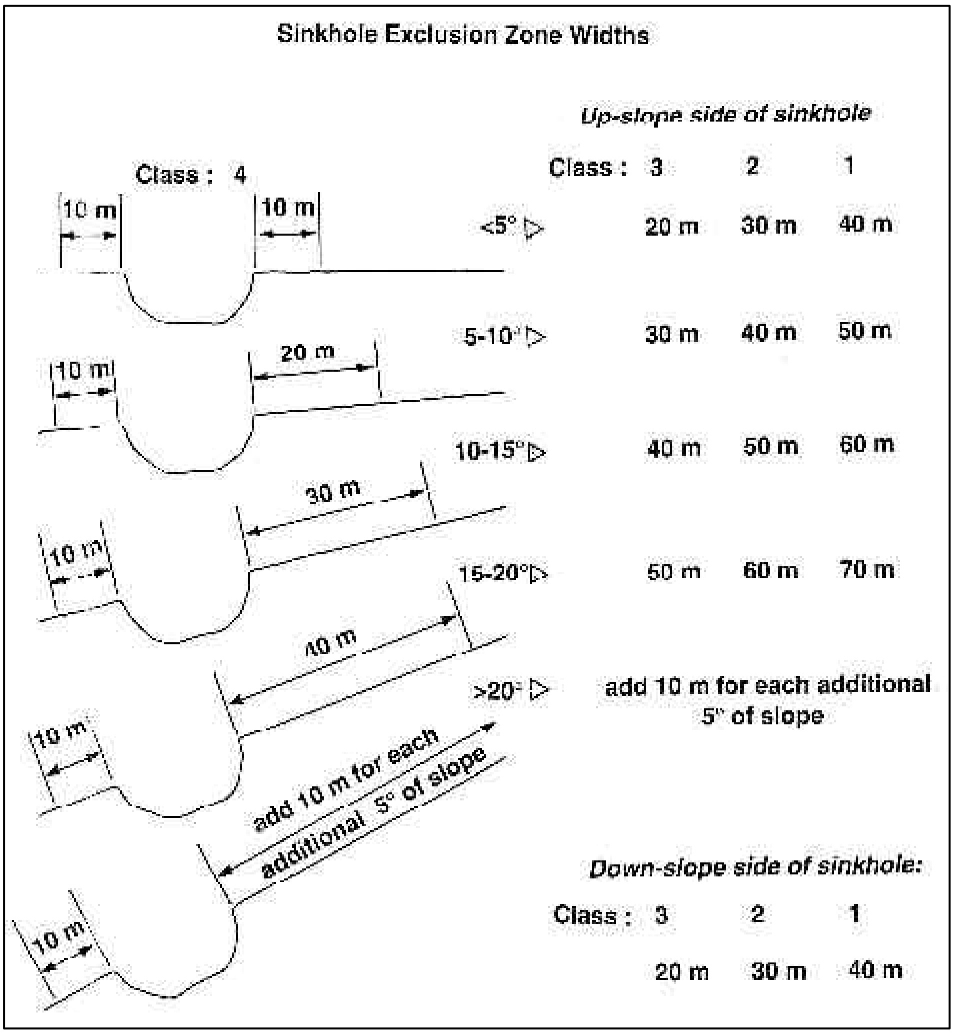


Figure 11. Defining exclusion zones for sinkholes on slopes.

d. Classification of subsurface streams needed for sinkhole classification

1. Procedure for assessment of stream class where there is no obvious streamsink.
Where a clearly defined streamsink exists upstream from a spring and there is (a) no apparent discrepancy between discharge from the spring and the volume of water entering the streamsink and (b) no hydrogeological evidence suggests the situation may involve more than a single linear conduit, then determination of catchment extent may proceed by conventional means, and may be undertaken by a forest planner in consultation with a karst specialist.

2. Procedure where there is no obvious streamsink.
If the classification of a subsurface stream cannot be ascertained by reference to an identified sinking or losing stream with an identifiable catchment because the water sinks more diffusely into slope deposits, classification should be based on specialist advice in order to ensure compliance with the relevant clause in the FPC (p. 57). Such advice will include assessment of all relevant hydrogeological evidence including geological structure, landforms, and the volume of water discharging from any spring

(taking into account the possibility that spring discharge may merely represent overflow from a deeper conduit system).

3. Assessment of the likely exact plan position of an underground stream.
In some cases accessible caves will allow direct access to an underground stream thus permitting survey of its subsurface course, but in many cases access to an underground watercourse will be limited. In these cases, interpretation must be based upon as informed a professional judgement as can be obtained, in which the specialist consulted will take account of such access to subsurface streams as can be obtained in combination with water tracing results, surface landforms, geological structures and such other data as can be brought to bear.

4. Assessment of the likely vertical depth at which an underground stream occurs.
The difference in altitude between a land surface on which a forest operation is proposed and the altitude of any spring or accessible stream which drains that land surface provides a first approximation of the maximum likely depth of the stream beneath the land. If a streamsink occurs within or close beside the operation area, assessment of its likely depth beneath any part of that area should be guided by the assumption that the stream descends at an even gradient from its sinking point to the spring or accessible segment of cave stream. Account must also be taken of the likelihood that older upper level cave passages developed earlier in the process of cave stream incision may occur above the present stream passage. These may still become active during rains when the capacity of the deeper stream passage is exceeded, and may facilitate rapid infiltration from the surface.

5. If in doubt, lift the stream classification one class
It is important to recognise that vertical flow from the base of a sinkhole straight down open solution slots in the limestone and into an underground stream can be very rapid. It does not offer the degree of buffering by slow flow across relatively low gradient vegetated terrain upon which the width of streamside reserves in non-karst terrain is predicated. For this reason, there may be a case for adopting a buffer width one category higher than would be required were a surface stream involved. Where very direct connection to a subsurface stream is suspected a wider reserve must be established.

6. Procedure to be followed where greater uncertainty remains
Operations should not be undertaken where the relationship to the drainage system is not well known. In special cases where the CFPO may for some reason approve an operation despite some uncertainty about the precise position of underground streams, wider exclusion zones will be required.

B-3. PLANNING AND CONDUCT OF FOREST OPERATIONS IN SINKHOLE AREAS

These remaining paragraphs draw attention to other provisions of the Forest Practices Code that relate specifically to forest operations of various kinds in sinkhole areas.

a. Building access to the Forest

1. Plan roads to avoid karst hazards
The FPC requires that "roads will be located to avoid caves, sinkholes, streamsinks and springs" (FPC p.7).

2. Do not allow fill to enter sinkholes
The FPC specifically requires that "fills will be contained so that material does not enter sinkholes in karst areas" (FPC p. 13).

3. Never direct a culvert discharge into a sinkhole
Concentration of runoff into a sinkhole can be expected to accelerate the flushing of sediment from the sinkhole base into the deeper karst. This can sometimes even threaten the stability of the road itself because the road formation becomes undermined (Figure 6). The FPC requires that "Drainage will not be concentrated into sinkholes and vegetation will be retained on the margin of sinkholes" (FPC p. 14). There must be **at least** 10 m of ground vegetation between a culvert exit and the margin of a sinkhole.

4. Remember that roads may stimulate formation of new sinkholes
When a road formation is cut into soil on karstified limestone the mat of soil draped over the solution cavities in the bedrock is made thinner, and the entry of water into the karst made easier and more rapid. In addition, the vegetation that previously helped bind the soil together is lost. Relatively diffuse infiltration under natural conditions may be replaced by more concentrated runoff from unvegetated surfaces and impermeable road surfaces into ditches, which can become a focus for more concentrated seepage of water underground, flushing soil particles from beneath the road margin. This can lead to potentially serious environmental and safety problems, and may sometimes lead to the collapse of the road that triggered the problem (Figures 12, 13 and 14).

Figure 12. Sinkhole formed in a logging road in the Junee-Florentine karst. Sinkhole formation on road margins can occur due to changes in patterns of drainage and infiltration caused by road construction. In this case the cavity was formed in dolerite-rich slope deposits many metres thick and none of the underlying limestone is visible. The formation of large cavities beneath the road can pose a serious safety hazard. In this case collapse occurred long after logging operations had ceased and been replaced by public use of the road to gain access to recreation sites.

Figure 13. Sinkhole that formed suddenly in the main Mole Creek-Gowrie Park road after heavy rain in the early 1970s. Collapse occurred into basalt-rich slope deposits mantling limestone. A small spring at this site is reported to have been blocked during construction of the road many years earlier. Further road surface failures have occurred at this site over subsequent decades.

Figure 14. Further road collapse at the site depicted in Figure 7, two decades after “repairs” had been made, highlighting the long term problems that may be initiated by inadequate attention to potential sinkhole problems.

5. Deflection of road drainage away from surface streams in sinkhole terrain
Any surface stream that may be present in a sinkhole area may maintain its surface course only briefly before vanishing into a sinkhole. Because of its potential impact upon the quality of karst groundwater, it is particularly important to ensure that the natural quantity and quality of surface streams is maintained. The FPC requires that "During the last 50 m before a road crosses a watercourse where practicable road drainage flowing towards the watercourse will be diverted from table drains directly into the surrounding vegetation before entering the watercourse…..where not practicable diversion into the surrounding vegetation by means of a culvert ….will be undertaken for Class 1, 2 and 3 watercourses (including surface karst channels that may usually be dry)" (FPC p. 17).

6. Dispersal of road drainage in sinkhole terrain
Focussing of drainage onto a particular point on a road margin can initiate sinkhole development even if a sinkhole is not already present. In one recent case in Tasmania the discharge of a culvert onto fill containing logs impeded downslope flow and encouraged seepage downwards into the soil thereby causing accelerated sinkhole formation.

7. Special risks exist where roads are cut into limestone bedrock
Where caves exist in unfractured bedrock of relatively homogeneous strength, a tension dome of maximum shear stress extends upwards for about 1.5 times the diameter of the cavity. Additional loading in this zone can cause collapse of the ground surface. Excavation of a road formation into limestone can shift the ground surface downwards into the shear zone where the passage of heavy vehicles may be sufficient to trigger collapse. The depth and size of the cavity and the inherent strength of the rock mass above it are the key variables in determining the height of the tension zone. Limestone is seldom unfractured. Where the limestone has been weathered and joints have been opened by solution activity, the rock may be very weak and the tension zone may extend much higher above the cavity than 1.5 times the cavity diameter. Closely-spaced test borings are the most reliable method of determining foundation integrity but they may need to extend to 30 m or more depth. Serious collapses have occurred where shallower test boring revealed only intact limestone which was then largely removed by excavation, such that final construction occurred within the tension zone of large cavities at greater depth that were not identified by the drilling.

8. *Quarries in sinkhole terrain*
Quarrying of loose surface materials that overlie karstified limestone can allow water to infiltrate into the karst at an accelerated rate, with the potential to generate significant environmental harm. Quarrying of limestone commonly also requires some stripping

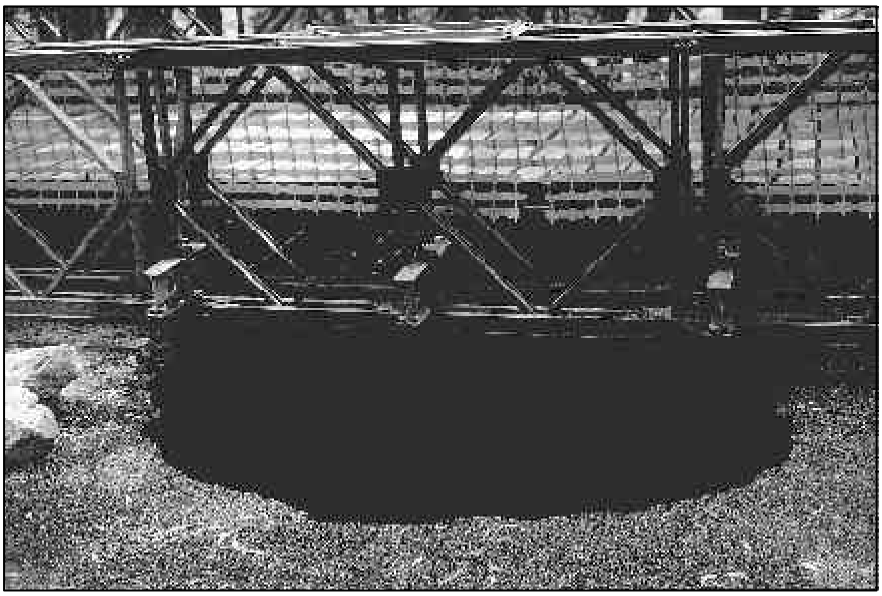


Figure 15. One temporary engineering solution following collapse of a Tasmanian road into a sinkhole.

back of the soil cover and can also result in damage to subsurface caves and disturbance of cave ecosystems. The FPC provides that "The Chief Forest Practices Officer will be consulted before quarries are opened in karst areas or in the catchment of a Category A or B karst area (as indicated in *An Atlas of Tasmanian Karst*)" (FPC p.21).

b. Harvesting of Timber

1. Clearfelling is not permitted on defined vulnerable karst soils
The FPC stipulates that "Clearfelling will not be permitted on areas with vulnerable karst soils unless authorised by the Chief Forest Practices Officer. Clearfelling should be avoided in other karst areas if high conservation or water supply values are present" (FPC p. 27).

2. Harvesting equipment and acceptable slope angles in sinkhole areas
The FPC stipulates that "In karst areas ground-based harvesting systems will be limited to slopes below 20°. On vulnerable karst soils harvesting on slopes above 9° will be restricted to uphill cable harvesting. No harvesting will be permitted on slopes above 20°" (FPC p. 32).

3. Wet weather limitations apply in sinkhole areas
Soils in karst areas are all inherently vulnerable to removal by water flowing down into the karst via sinkholes and smaller solution crevices in the limestone. Water quality is also easily damaged due to the rapidity with which sediment or any other contaminant may disperse through the groundwater system. For this reason, the FPC stipulates that "harvesting on vulnerable karst soils…will only be permitted in dry season conditions" (FPC p.33).

4. Snig tracks in sinkhole areas
Snig tracks are a potentially major source of soil disturbance which may have implications for infiltration, land surface stability and groundwater quality in karst. For this reason the FPC requires that "Snig tracks will not cross mapped caves that are near the surface, enter any karst depression…. or divert any watercourse in a karst area. Concentration of drainage will be avoided" (FPC p. 37).

5. Discovery of previously unrecorded sinkholes during the course of a forest operation
With proper site inventory it is unlikely that sinkholes will be encountered after a forest operation has commenced. However, the FPC provides that "New caves or streamsinks found during harvesting will be avoided and the Chief Forest Practices Officer advised as soon as possible" (FPC p. 37). Hence there is a requirement to notify the CFPO only if the sinkhole has a visible stream sinking into it, otherwise it is only necessary to ensure that the buffer zones required around the sinkholes is maintained. You may however feel it prudent to set your mind at rest by discussing the situation with the relevant FPB specialist.

6. Landings in sinkhole areas
Landings can be located in forests that contain sinkholes but must be sited so as to ensure that no sinkhole is compromised. The FPC requires that "Landing size will be minimised in karst areas and landings will not be located near karst depressions or sinkholes" (FPC p. 41). Because a sinkhole is a watercourse, no landing should be located within 40 m of a sinkhole (FPC p. 42) or a Class 4 machinery exclusion zone (p. 56) "unless designated in a Forest Practices Plan and provided specific measures (e.g. marking the landing boundary, drainage controls), are placed in the Plan to protect water quality." (FPC p. 42)

7. Drainage requirements where landings are established in sinkhole areas
The FPC requires that "Landings in areas with vulnerable karst soils will be drained into effective sediment traps which are properly maintained" (FPC p. 41).

c. Establishing and maintaining forests

1. Soil requirements where plantations are established in sinkhole terrain
Remember that all soils in karst areas are potentially at risk from disturbance because they may be little more than a veneer of relatively unconsolidated material stretched across a rock mass that may be riddled with numerous solution crevices down which potentially erosive water is constantly infiltrating. For this reason the FPC stipulates that "Plantations will not be permitted on sites with vulnerable karst soils…unless authorised by the Chief Forest Practices Officer" (FPC p. 81).

2. Proximity of approach to sinkholes by site preparation machinery
Site preparation has the potential to exacerbate loss of soil materials into subsurface karst, thereby accelerating sinkhole formation. The FPC requires that "Mapped caves that are near the surface, karst depressions and streamsinks will be avoided by site preparation machinery. The technical note *Some Operational Considerations in Sinkhole Management* will be consulted where appropriate" (FPC p. 81).

d. Establishing plantations on previously-cleared land

1. Reafforestation of degraded karst can be an important rehabilitation technique.
In cases where an area has been converted to pasture, past management of sinkholes has often been less that optimal. In such cases sinkhole forms are often already somewhat degraded and the soil and groundwater resources have often already been compromised (Figure 16). Under these circumstances plantation establishment can often be considered to involve a degree of site rehabilitation, an interpretation that allows some flexibility, but some constraints exist regarding suitable sites and appropriate future practices.

2. The sinkhole exclusion provisions applicable to Native Forest are generally applicable to plantations.
Reafforestation is one thing, but intensive plantation forestry can be another. The "rehabilitation" argument applies only temporarily. While soil and water management is improved by the re-establishment of a substantial vegetation cover, the day will come when harvesting occurs. In degraded karst there has commonly already been loss of soil into subsurface cavities. Rounded solution fluting of a kind that forms only beneath a soil cover has often become exposed due to this soil loss. Once this form of land degradation becomes established it can be impossible to reverse fully because a positive feedback system develops – the more sediment is lost into the sinkhole the more free the drainage becomes, and the more rapid infiltration allows still more soil to be lost.

3. Both on-site and off-site rainfall and response must be considered.
Reafforestation may slow or arrest the process of soil loss into the deeper karst, but the remaining soil is still likely to hold only a tenuous grip. The sudden increase in vertical infiltration of free water when the trees are removed, and the types and patterns of ground disturbance and surface drainage changes that occur with logging, may all have the potential to undo the good done by reafforestation. High rainfall events after logging can be very significant in this context. Not only may soil be flushed down into crevices, but very large volumes of sediment may be evacuated from the base of the crevices by horizontally-flowing underground streams that commonly originate off-site. The removal of that sediment not only makes space for more sediment to accumulate in the cavity, but its removal may also take away toe support from a sediment column in a crevice, triggering a positive feedback loop of accelerating soil and water movement down the crevice

4. Consider potential windthrow
Planting of lower-growing non commercial species in sinkhole exclusion zones may assist in reducing potential windthrow problems. It may be feasible in some cases to seek assistance under Landcare-type programs.

5. Minimise the time between clearing and reafforestation.
Reafforestation should be undertaken promptly to minimise the time that karst soils are left exposed without vegetation cover. The soil is under most stress when removal of soil moisture by evapotranspiration has been reduced due to forest cutting, and in the period between the old tree roots rotting out and the advent of a new binding root system. It may be appropriate to consider planting advanced stock in some cases.

e. Plantations adjoining watercourses in previously-cleared land

1. Relationship of sinkhole provisions to conventional riparian provisions
Recognising that sinkholes are vertical watercourses and that they may deliver water very rapidly straight into underground streams, it is appropriate to link the provisions for plantation establishment adjoining sinkholes in recently cleared land to the Code provisions for establishing plantations adjoining watercourses in previously cleared land (FPC pp. 81-84). The basic principles within that section of the Code are broadly appropriate for sinkhole margins. Upper catchments where runoff from other rocks first encounters limestone are particularly sensitive.

2. Closeness of approach to sinkholes and their long term management
Where plantations are established within a Class 1, 2 or 3 streamside reserve the FPC stipulates that “no machinery will be permitted within 10 m of any watercourse except at points designated in a Forest Practices Plan” (FPC p. 82) and that “trees established within 10 m of a class 1, 2 or 3 watercourse will not be available for future harvest” (FPC p. 82). To emphasise physically the intended buffer areas, it would be useful if they were planted with non-commercial species to guard against future disturbance.

3. Cultivation on slopes adjacent to sinkholes
The Code also specifies that “if slopes are over 11° or soils are of high or very high erodibility only spot cultivation will be permitted in order to establish plantations in the zone between 10 and 20 m from any watercourse” (FPC p.82). This same provision is appropriate for sinkholes.

4. Entry to sinkhole exclusion zones
However, in the case of plantations within 10 m of a Class 4 watercourse the Code provides that “if slopes are over 11 degrees, or soils are in the high or very high erodibility classes machinery will not enter within 10 m of the watercourse (except at designated crossing points….), and cultivation will not be permitted” (FPC p. 83). It also stipulates that “in other situations…spot cultivation and debris removal may be undertaken by excavators reaching to within 5 m of the watercourse” [and assume sinkhole margin], “provided patches of native vegetation are not damaged” and that “on cleared land (i.e. pasture, developed or undeveloped agricultural land), spot cultivation by excavators to establish plantations may occur to within 2 m of streambanks provided the excavator remains at least 5 m from the streambank: (FPC p.83). Given that any soil in a karst setting is vulnerable by virtue of its karst setting, this last concession is **NOT** considered appropriate for sinkhole boundaries.

5. These entry provisions do NOT apply in native forest
Because intensive forestry is not an environmentally optimal landuse on karst the protective measures that would normally apply on naturally forested karst should again be implemented. Modified measures suggested for situations where major rehabilitation is involved should not be taken as a precedent for logging operations in existing forest where the history of past land management is different and the soil and groundwater systems have not been compromised in the same way or to the same degree.

6. Visibly active sinkholes
From a management perspective, it is reasonable to consider active sinkholes to be a special form of active soil erosion gully. The appropriate course of action is to seek to stabilise the site by achieving an improved vegetation cover and reducing unnaturally

large volumes of water draining into the sinkhole. Planting with non-commercial species is encouraged. Some assistance may be obtainable under Landcare-type programs.

f. Use of chemicals

1. The same care that is required using chemicals near streams is required using chemicals near sinkholes

There are many other situations where the similarity between sinkholes and surface watercourses should be borne in mind in applying the Code, such as the requirement that chemicals not enter watercourses, and the provision that "Techniques such as wick-wiping and spot or shrouded strip application should be considered next to watercourses" (FPC p. 89).

2. Specific requirements near sinkholes

The introduction of chemicals into waters that enter aquifers via sinkholes can lead to groundwater pollution, and contaminants may be transmitted considerable distances very rapidly. For this reason the FPC stipulates that the "application of chemicals will not be permitted close to karst watercourses or known cave entrances" (FPC p. 90) and that "fertiliser application will be planned and carried out so as to minimise the chance of fertiliser being dropped or drifted onto any surface waters, including streams and wetlands" (FPC p.90).

3. Sinkholes are the means by which energy is transferred into very sensitive wetlands.

The reference on p. 90 of the FPC to avoiding fertiliser being dropped or drifting into wetlands has specific relevance to sinkholes. The atmosphere in Tasmanian caves is characteristically very humid. Much invertebrate cave fauna is effectively aquatic in character and highly dependent upon maintenance of these very humid atmospheric conditions. In recognition of this, Resolution V1.5 from the 1996 Ramsar Convention on the Conservation of Wetlands and Waterfowl determined that subterranean karst and cave hydrological systems should be added to the Ramsar Wetland Classification System. As a signatory to the Ramsar Convention, Australia has international legal responsibilities to protect cave and karst "wetlands".

g. Fire management

1. Fire management plans in karst

Fire can have a significant impact in karst areas, especially where vegetation is burnt in and around sinkholes, which may lead to an increase in pore water pressure because vegetation is no longer actively transpiring. If the vegetation is killed and the binding root systems rot out the strength of the soil cover may be insufficient to counteract the additional stress applied by the water load. The FPC requires that "a fire management plan should be prepared by the landowner for all consolidated areas of commercial forest over 50 ha" (FPC p. 91) and that this "should be based on a simple map and a consideration of….natural and cultural values (e.g….. karst sinkholes and dolomite knolls…)." (FPC p.91)

2. Specific requirements for burning in sinkhole terrain

Special provisions for burning in sinkhole areas include requirements that "burning near cave entrances and sinkholes will be avoided" (FPC p. 92) and that "high intensity burning will be avoided where degradation of significant karst features is likely to result, such as sites with vulnerable karst soils…. on slopes above 12°" (FPC p.90).

3. Plan the burn when planning harvesting boundaries

It is imperative that the practicalities of meeting the requirements for sinkhole protection during regeneration burns or other planned post-harvesting fires are considered fully before the harvesting unit boundaries are finalised.

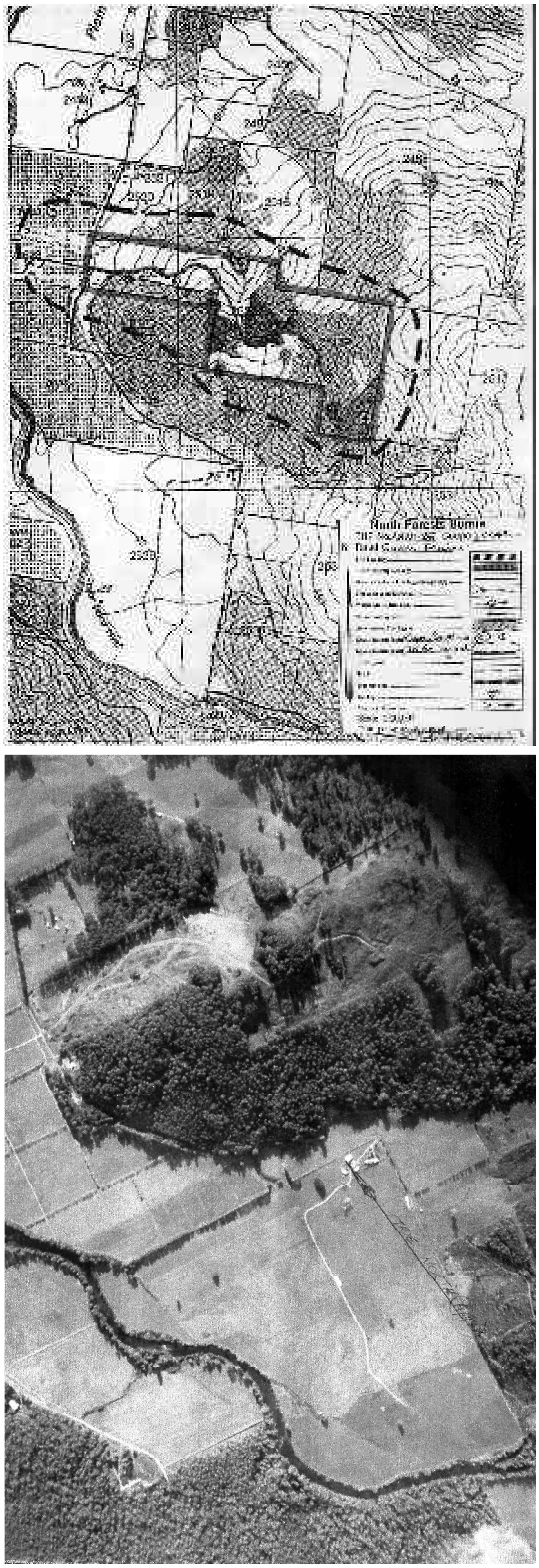


Figure 16. Planning of a new forest plantation on karst at Gunns Plains, Tasmania, to take account of sinkholes and related karst features: (a) map from Forest Practices Plan; (b) aerial photograph of successful final result. (Illustrations courtesy B. Graham)

h. Management of fuel, oils, rubbish and emissions

1. Use of fuel, grease and oils: Waste materials must never be disposed of near or into sinkholes
Because sinkholes are the tributaries of underground streams, waste materials disposed of into sinkholes may readily reach the groundwater system and cause contamination that may spread rapidly and widely. The FPC requires that "fuel, grease and oils will be stored in a location where any inadvertent leaks will not enter….karst systems either directly or indirectly" (FPC p.94). Equipment should not be serviced in the proximity of sinkholes. In the event of any spillage contaminated soil may need to be carted away. Advice of the FPB Senior Geomorphologist must be sought.

2. Smoke, noise and dust: *Avoid the introduction of atmospheric contaminants into sinkholes*
Water is the most obvious fluid that may drain into karst systems through sinkholes but another equally important one is air. A variety of factors cause air to be exchanged between the subsurface and surface environments through routes large and small. This air transfer can occur quite vigorously and quickly. Atmospheric contaminants may accumulate in depressions such as sinkholes where they may have effects on site or may be carried underground with the potential to allow serious or material environmental harm. Possible effects include impacts on sinkhole or cave biota, potential hazards for recreational cavers if gases accumulate underground, and discolouration of actively growing speleothems (stalactites etc.) when particles that adhere to them become encased in calcium carbonate thus permanently binding them into the structure of the speleothem. The FPC requires that such serious or material environmental harm not be permitted to occur (FPC p. 95).

PART III.
CONSERVATION OF NATURAL AND CULTURAL HERITAGE IN SINKHOLE AREAS

A. SINKHOLES HOST A DIVERSE RANGE OF VALUES

This technical note has been directed primarily towards responsible stewardship of soil and water values that represent a landowners Duty of Care under the provisions of the Forest Practices Code (FPC p.52). However, it is important also to bear in mind that in some cases important natural or cultural heritage conservation values may exist in and around sinkholes.

The Code provides that "conservation of environmental diversity (including geodiversity) will be principally catered for in a systematic reserve system on public land, by a voluntary private land reserve system, and by management prescriptions in production forests. It requires that natural and cultural values in adjacent reserves should be considered during the planning and conducting of forest operations "(FPC p. 51).

While this Sinkhole Manual has focused upon soil and water issues, the conservation of geoheritage sites such as important karst caves may require additional consideration by karst area planners and managers. FPOs should bear in mind that other values may also need to be taken into account in sinkhole management. For example,

- *Zoological issues* may exist where elements of any cave fauna feed outside at night, or where the micro-environment of the sinkhole itself may offer important habitat;
- *Botanical values* may exist due to the microclimate or substrate;
- *Archaeological values* may exist in rockshelters, caves or at water sources in sinkholes; and
- *Visual landscape values* may arise in some cases.

Sinkholes play an important role in sustaining ecosystem support essential to the survival of animal life in caves, including rare and threatened species. In the case of cultural heritage, the Forest Practices Code requires that "the cultural heritage of all ethnic groups (eg. Aboriginal and other Australians) will be considered in all stages of forest management" (FPC p. 70). Known archaeological sites in Tasmanian karst areas include both prehistoric and historic sites of Aboriginal and non-Aboriginal origin occurring both in caves and above ground, in the latter case often being related to scarce water supply sources in karst. The FPC recognises that karst areas are archaeological High Sensitivity Zones and requires that surveys will be completed prior to the commencement of forest operations if site conditions are suitable.

Where such natural or cultural heritage values may exist the FPO should consult with the appropriate FPB specialist for more specific advice. The revised *Threatened Fauna Adviser* provides prescriptions for sinkhole management where there are known localities for listed threatened species.

The FPC provides that "the sustainable management of natural and cultural values within production forests under the forest practices system will be determined in accordance with …the duty of care of landowners under the provisions of this Code, which is defined as the fundamental contribution of the landowner to the conservation of natural and cultural values that are deemed to be significant under the forest practices system. The landowners duty of care includes:

- all measures that are necessary to protect soil and water values as detailed in this Code;
- the reservation of other significant natural and cultural values. This will be at a level of up to 5% of the existing and proposed forest on the property for areas totally excluded from operations. In circumstances where partial harvesting of the reserve area is compatible with the protection of the values, the level will be up to 10%. The conservation of values beyond the duty of care is deemed to be for the community benefit and should be achieved on a voluntary basis or though compensation mechanisms where available" (FPC p. 52).

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