Karst Geomorphology, Hydrology, and Management

TIM STOKES, PAUL GRIFFITHS, AND CAROL RAMSEY

INTRODUCTION

The term “karst” applies to a distinctive type of landscape that develops from the dissolving action of water on soluble bedrock (Figure 11.1)—primarily limestone and marble but also dolostone, gypsum and halite.

Karst landscapes are characterized by fluted and pitted rock surfaces, shafts, sinkholes, sinking streams, springs, subsurface drainage systems, and caves. The unique features and three-dimensional nature of karst landscapes are the result of a complex

FIGURE 11.1 *Limestone: a soluble rock. (Photo: P. Griffiths)*

interplay between geology, climate, topography, hydrology, and biological factors over long time scales. Globally, examples of karst topography can be found at all latitudes and at all elevations, with rock types potentially containing karst covering approximately 20% of the Earth's land surface (Ford and Williams 2007). British Columbia's karst landscapes are of particular interest because they support coastal temperate rainforests (Figures 11.2 and 11.3), which are found only in a few other regions of the world such as southeast Alaska, Tasmania, New Zealand, and Chile (Ford and Williams 2007).

Limestone, marble, and dolostone are all examples of carbonate rocks. Carbonate rocks are primarily made up of carbonate minerals, such as calcite ($CaCO_3$) in the case of limestone and marble, and dolomite ($CaMg[CO_3]_2$) in the case of dolostone. The formation of karst landscapes in carbonate bedrock involves the "carbon dioxide (CO_2) cascade" (Figure 11.4).

In this process, rain falls through the atmosphere and picks up CO_2, which then dissolves into rain droplets. Once the rain hits and infiltrates the ground, it percolates through the soil and picks up more CO_2 and forms a weak solution of carbonic acid ($H_2O + CO_2 = H_2CO_3$). This slightly acidic water then exploits any existing joints or fractures in the bedrock, gradually dissolving the bedrock and creating larger openings or conduits for the water to flow through. Over many thousands of years, this process eventually creates underground drainage systems and caves. Mechanical processes such as stream corrasion (abrasion) also come into play once subsurface conduits are of a significant size.

Carbonate bedrock underlies approximately 10% of British Columbia (Figure 11.5), but this presence of carbonate bedrock alone does not necessarily indicate the presence of karst. The formation of karst depends on attributes such as bedrock type and purity,[1] physiographic location, and biogeoclimatic set-

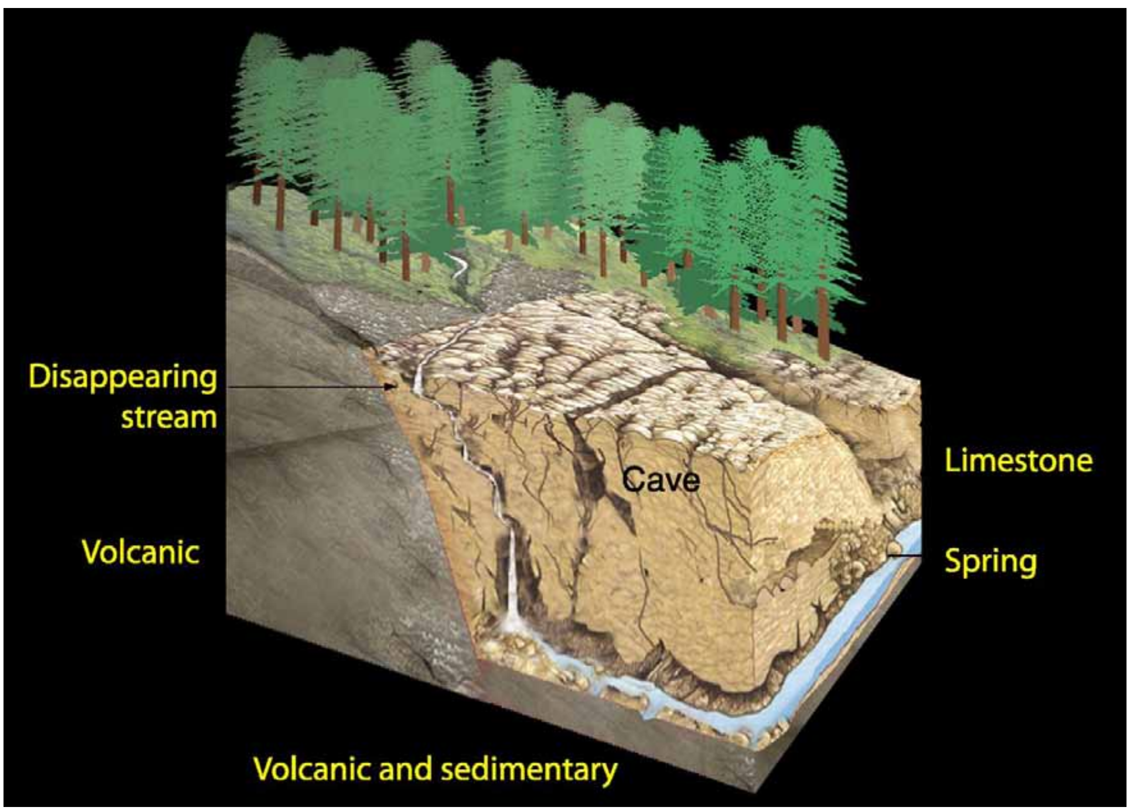

FIGURE 11.2 *A forested karst landscape system (P. Griffiths).*

1 Limestone purity (%$CaCO_2$) is one of the most important controls on karst development, the purer the limestone, the higher its potential for karst development. Karst development in carbonate rocks requires a calcium carbonate ($CaCO_3$) content of 70% or greater (Ford and Williams 2007).

FIGURE 11.3 *Forest-covered karst with small sinkhole (centre). (Photo: P. Griffiths)*

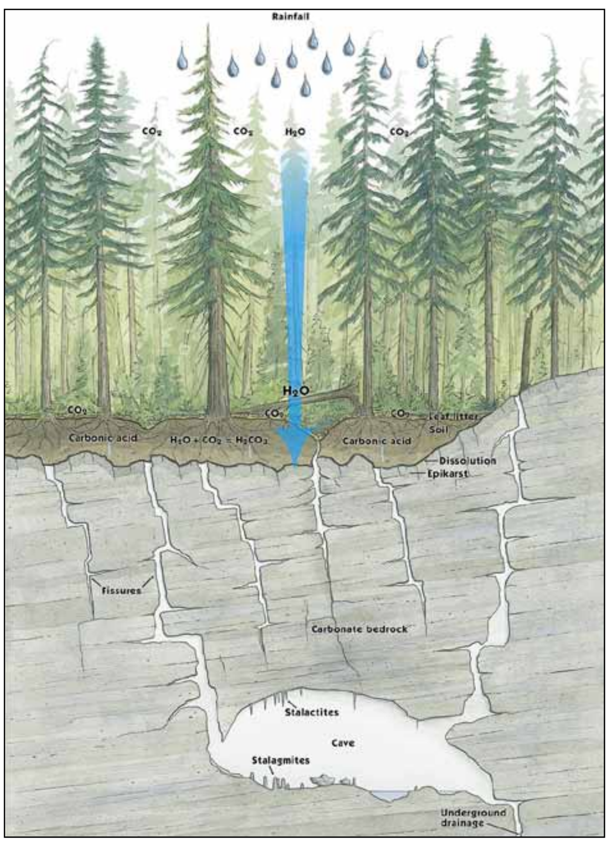

FIGURE 11.4 *The "carbon dioxide (CO_2) cascade" in the forested karst environment (B.C. Ministry of Forests 1997).*

ting and hence its development across the province is highly variable (Stokes and Griffiths 2000).

Extensive areas of alpine karst occur in the northern and southern Rocky Mountains. Well-developed karst areas are associated with carbonate units on Vancouver Island and Haida Gwaii (Queen Charlotte Islands), and smaller, isolated pockets of karst are known along the north and mid-Coast, Texada and Quadra Islands, the Sechelt Peninsula, and near Chilliwack. Less well-known karst areas occur in northwest British Columbia (e.g., Atlin, Stuart, and Babine Lakes, as well as along the Stikine, Nakina, and Taku Rivers), and in the Interior (such as the Purcell and Pavilion Mountains). Approximately 4% of Vancouver Island is underlain by limestone and much of it is forested. Vancouver Island's karst mostly occurs in the north within long and continuous belts of limestone 1–10 km wide and 10–100 km long (Figure 11.6).

A number of cave and karst parks have been established on Vancouver Island, including Horne Lake Caves Park, Clayoquot Plateau Park, Weymer Creek Park, White Ridge Park, and Artlish Caves Park (Figure 11.6).

A wide range of international material is available on the science of caves and karst. Particularly relevant to this province is the *Karst in British Columbia* brochure (B.C. Ministry of Forests 1997). The B.C. Ministry of Forests and Range's karst webpage

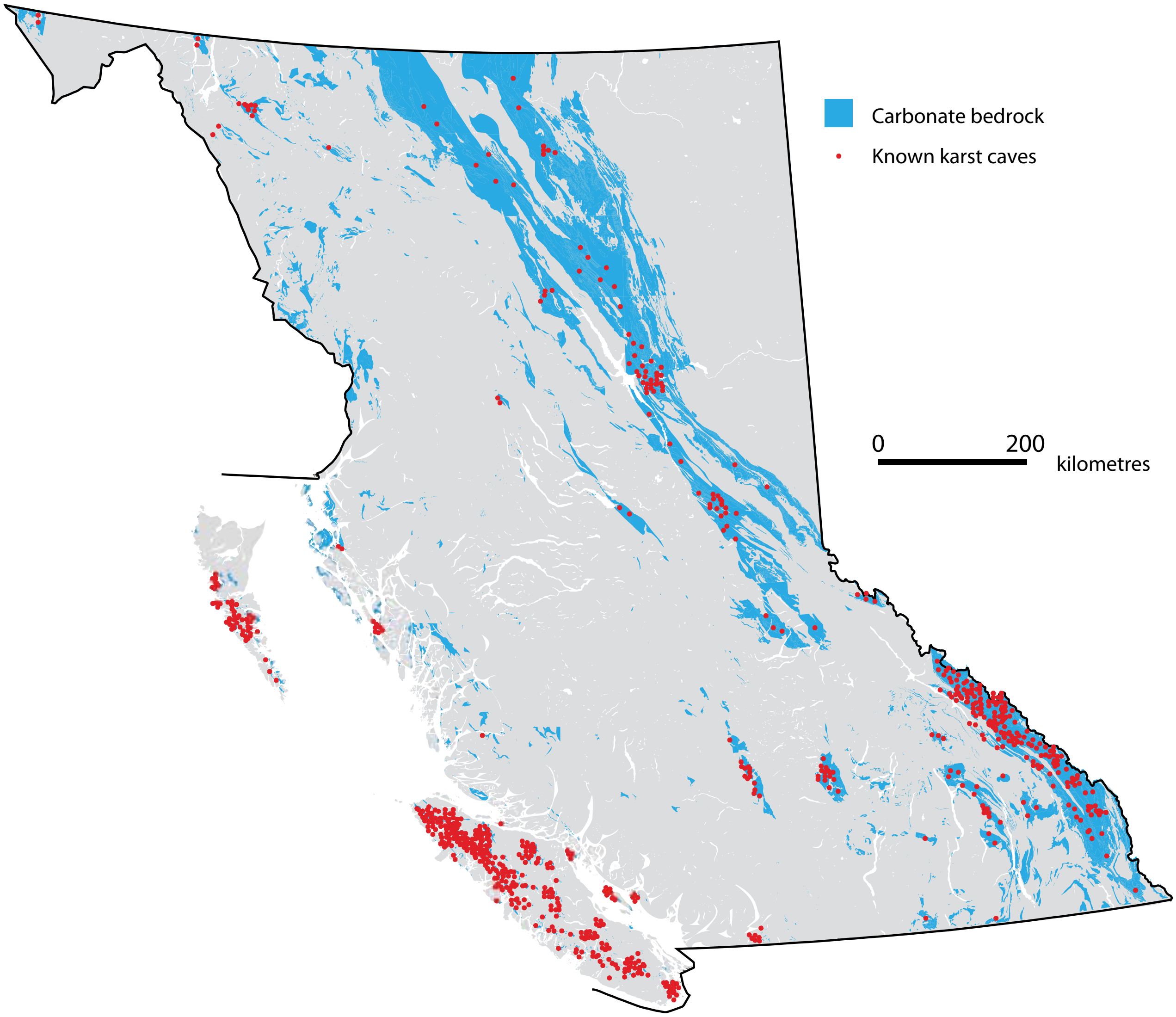

FIGURE 11.5 *Distribution of carbonate bedrock, potential karst lands, and known karst caves within British Columbia (P. Griffiths and B.C. Ministry of Forests 1997).*

is another source of useful information (see www.for.gov.bc.ca/hfp/values/features/karst/index.htm). Papers that provide good summaries of cave/karst landscape issues and processes include those of Baichtal and Swanston (1996) and White et al. (1995). Textbooks on caves and karst science include those of Jennings (1985), White (1988), Ford and Williams (2007), Gillieson (1998), Finlayson and Hamilton-Smith (2003), and Palmer (2007). Gunn (2004) provides an extensive and well-illustrated encyclopedia that covers all aspects of cave and karst science.

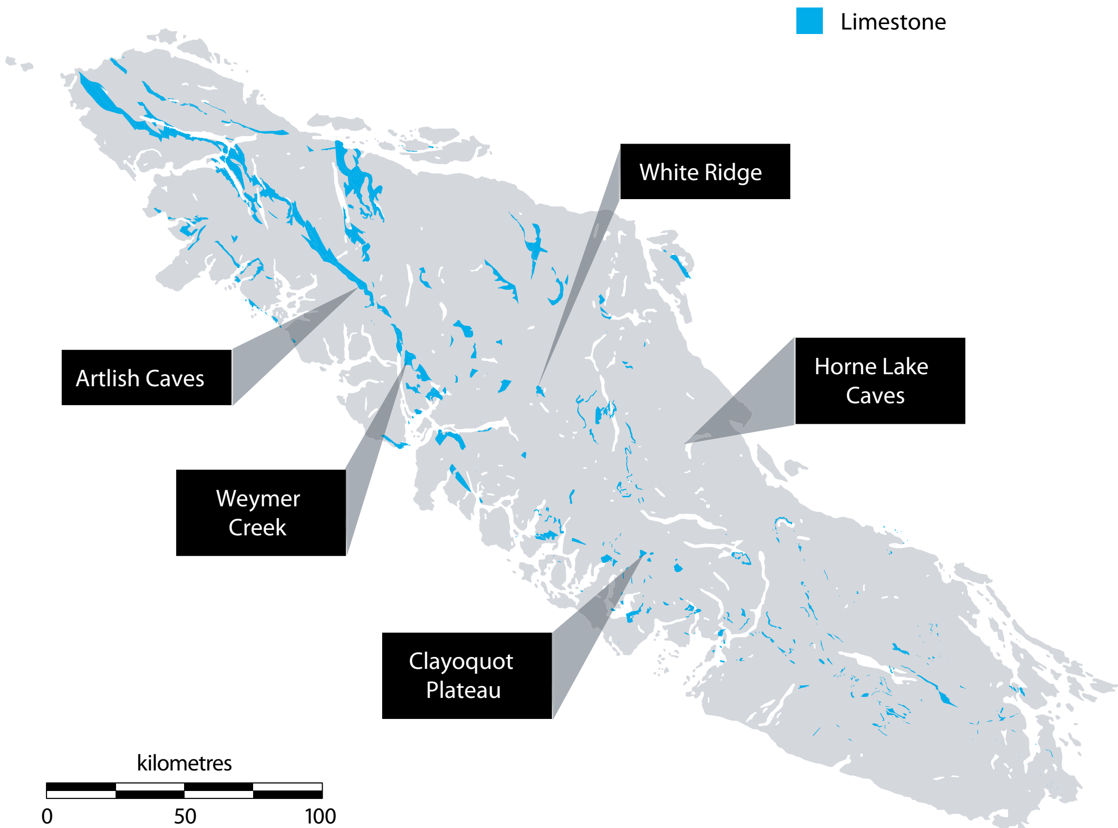

FIGURE 11.6 *Cave and karst parks of Vancouver Island.*

KARST LANDSCAPES AS FUNCTIONING SYSTEMS

All landscapes (e.g., desert, glacial, mountain, and karst) work as functioning systems, exhibiting continual movements of materials, energy, and biota, which in turn constrain the natural processes and balances of these environments. However, the complexity of systems associated with karst landscapes is enhanced because these landscapes include distinctive subsurface environments consisting of solutionally enlarged fractures and cavities that directly link the surface to the subsurface and vice-versa. These micro- to mesoscale fractures and cavities provide pathways for easy transfer of water, air, soil, rock, organic matter, and biota. The processes by which these materials are moved are integral to the character, and functioning of a karst system. Interruptions to these processes can result in adverse impacts to both the surface and subsurface environments (Baichtal 1995; Baichtal and Swanston 1996). Thus, karst can pose additional management considerations, challenges, and constraints relative to other types of landscape.

Karst systems are distinct from non-karst systems because of the processes of karst dissolution, the permeability of the solutionally developed landscape surface, the presence of a well-developed and open subsurface, fewer surface streams, and an overall calcium-rich environment (White et al. 1995; Gunn 2004). Given these differences, it is perhaps not surprising that specialized surface and subsurface biota can inhabit karst landscapes (Figure 11.7).

These can range from calcium-dependent flora on the exposed bedrock surface to cave-adapted fauna in the subsurface (e.g., *Stygobromus quatsinensis,* a rare freshwater crustacean found in underground pools on Vancouver Island; Holsinger and Shaw 1987). Some subsurface fauna in karst ecosystems

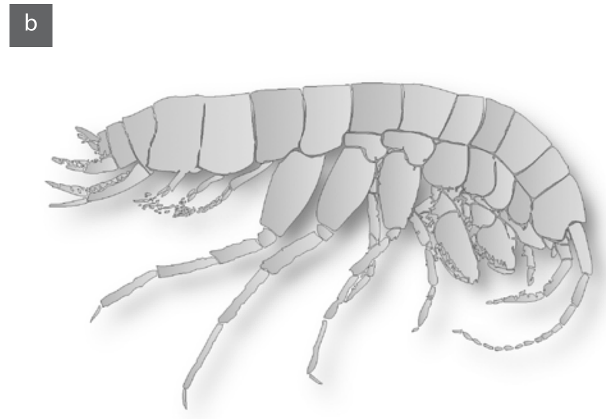

FIGURE 11.7 *Examples of karst fauna: (a) a cricket commonly found in caves; and (b) a cave-adapted crustacean. ((a) photo: P. Griffiths; (b) modified from Holsinger and Shaw 1987)*

have evolved over long time periods in this very stable and dark environment, resulting in adaptations such as reduced pigment and eyesight (Finlayson and Hamilton-Smith 2003). Such organisms, termed "troglobites," are obliged to live their entire lives in the subterranean world.

IDENTIFYING KARST LANDSCAPES FEATURES

A karst landscape unit, or more simply a "karst unit," is defined for the purposes of this chapter as "a three-dimensional belt or block of soluble bedrock area surrounded by other less soluble rock types." The first step in investigating a karst unit is to confirm the extent or intensity of karst development and to delineate its boundaries. Some understanding of bedrock geology is critical to determine the likely extent and boundaries of a karst unit. Bedrock geology maps[2] can be consulted to identify limestone or other soluble bedrock units. In many cases, the scale of bedrock mapping is not sufficient to outline the soluable bedrock unit in detail, and therefore field investigation is required to confirm the unit boundaries.

In the field, carbonate bedrock exposures such as limestone or marble are often visible in rock cuts, along creeks, under windthrown trees, or along topographic highs or bluffs. Carbonate bedrock can be readily identified by characteristics such as its white to grey colour, solutionally weathered surfaces, bedding layers, presence of fossils, and relative softness compared to other rocks. Carbonate rock types can be confirmed by dropping a small amount of dilute hydrochloric (HCl) acid onto its surface.[3] If the rock sample is limestone or marble, the HCl solution will effervesce (or bubble) with a visible and audible chemical reaction that gives off CO_2. Dolostone may require powdering of the rock and a more concentrated acid solution to produce effervescence. A useful tool for delineating the presence of carbonate bedrock at the regional level is to look for float material (e.g., cobbles and boulders of limestone) in larger creeks that drain these areas. In addition, the presence of anomalously high electrical conductivity values in streams as measured using a handheld electrical conductivity meter can indicate the occurrence of water that has been in contact with carbonate bedrock for extended periods; such water might emerge from a karst spring.[4]

2 In British Columbia, websites such as MapPlace BC (www.mapplace.ca) can be a good place to start.
3 Dilute HCl or muriatic acid is readily available from pharmacies and is commonly used by geologists for this purpose.
4 Water in contact with carbonate bedrock generally contains more free ions, owing to the chemical reactions that have dissolved the bedrock; therefore, when tested with a handheld conductivity probe, this water provides a high reading compared to water from non-carbonate rocks. As a general rule, karst waters have 5–10 times higher electrical conductivity values than non-karst waters.

Bedrock geology, in combination with surface contour maps, can assist in delineating karst units. Aerial photographs, high-resolution satellite imagery, and (in some cases) lidar can also be useful to identify diagnostic surface karst features (e.g., large sinkholes and disappearing streams or springs), distinct differences in bedrock lithologies (e.g., white marbles), or disrupted surface drainage patterns. In some aerial photographs and satellite images, forest cover may hinder the identification of these features; however, many characteristics of a karst landscape can be identified in recently harvested cutblocks or in areas above the tree line (B.C. Ministry of Forests 2003a).

Karst landscapes are usually recognized in the field by the presence of diagnostic surface karst features. Karst features that can readily be observed on the surface include: solutionally rounded or sculpted bedrock exposures; sinkholes; cave entrances; streams that disappear at discrete openings or sink points; and springs that emerge from bedrock openings or conduits. These types of surface karst features are common in karst areas of coastal British Columbia where relatively pure carbonate bedrock is present and precipitation levels are high (e.g., Vancouver Island, Haida Gwaii, and the mid-Coast). However, these diagnostic features can be more difficult to identify and confirm in the Interior where precipitation levels are generally lower and (or) the landscape is overlain by thick mantles of glacial material (Stokes and Griffiths 2000).

Surface karst features can vary dimensionally from small-scale features (millimetres to centimetres) to large-scale features that measure in the hundreds of metres (Ford and Williams 2007). Small-scale features on soluble rock outcrops can include distinctive linear channels or grooves known as "karren" (Figure 11.8) that are classified by dimensions and morphology (Gunn 2004).

Examples commonly found in coastal British Columbia include *rundkarren* (rounded channels separated by rounded ridges) and *rillenkarren* (shallow channels with sharp ridges 2–3 cm apart). Larger-scale surface karst features are commonly

FIGURE 11.8 *Karst solutional grooves or karren on steeply sloping bedrock surfaces. (Photo: P. Griffiths)*

encountered when traversing a karst landscape (Figure 11.9). In most cases, these larger features are classified by morphology, shape, and dimensions rather than genetic origin; however, in some cases, the feature's function (e.g., input/output of water and air) is used as part of the classification. Table 11.1 presents examples of some of the most common surface karst features.

Details on the types of surface karst features typically encountered within the forests of British Columbia are available in the appendices of the *Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia* (B.C. Ministry of Forests 2003a) and in the *Karst Management Handbook for British Columbia* (B.C. Ministry of Forests 2003b). Additional details about the origins and functions of various types of surface karst features are available in Jennings (1985), White (1988), and Ford and Williams (2007).

In the broadest sense, the three-dimensional nature of a karst landscape can be broken down into three parts: (1) exokarst, (2) epikarst, and (3) endokarst (Figure 11.10).[5]

FIGURE 11.9 *Examples of karst features found in forested regions of coastal British Columbia: (a) a sinking stream at a vertical sink point (or swallet); (b) a series of small sinkholes; (c) a karst spring; and (d) a dry karst canyon. (Photos: P. Griffiths)*

5 Although the terms "exokarst" and "endokarst" are rarely used, these terms are useful to illustrate the upper surface and subsurface components of the karst landscape.

TABLE 11.1 *Common surface karst features*

Dry valley	A valley that generally lacks a stream, although one may occasionally form during peak rainfall events.
Grike	A narrow and deep slot formed by dissolution along a pre-existing fracture in bedrock.
Karst canyon	A steep-sided canyon in karst sometimes exhibiting distinctive surface solutional rocky relief features (e.g., scalloping).
Karst spring	A site where an underground stream emerges from a karst conduit or cave.
Polje	A large, flat-bottomed karst depression with water periodically present across its floor.
Sinkhole	A topographically closed depression that is circular or elliptical in plan view, with enclosing sidewalls that can range from shallow and gradually sloping toward a central drainage focus to steep or almost vertical.
Solution tube	A circular or elliptical steeply inclined tube formed by dissolution, which is sometimes found on karst bedrock exposures.
Swallet	A point where a stream of any size sinks underground. In some cases, a swallet can also be a cave entrance.

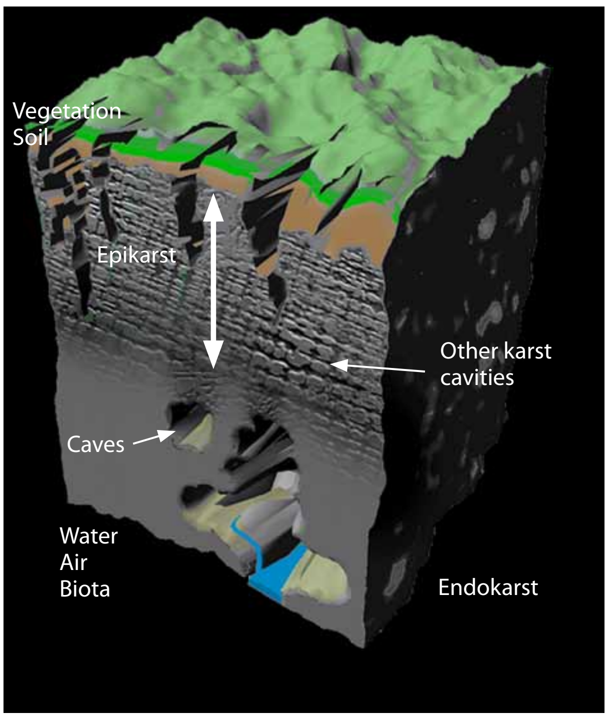

FIGURE 11.10 *The linkage between epikarst and endokarst; note that exokarst is the surface of the karst landscape (P. Griffiths).*

Exokarst describes all features found on the surface of the karst landscape, ranging from small-scale to large-scale features (e.g., from karren to sinkholes to poljes). Epikarst is the zone of solutionally enlarged openings or fractures that extends from the surface (the exokarst) down as much as 10–30 m below the surface to the underlying endokarst. The endokarst describes all deeper components of the underground karst landscape, including the smallest cavities, cave speleothems,[6] cave sediments, and cave passages. The epikarst zone therefore plays a critical role in the karst system, allowing water, air, and other materials (sediment, organic debris, and nutrients) to be readily transferred from the surface to the subsurface.

The term "cave" is often defined as "a natural cavity within the earth's crust that is connected to the surface, is penetrable by a human, and includes a zone of permanent and total darkness" (B.C. Ministry of Forests 2003a:72). Most people correctly associate caves with karst, although in the context of karst systems, caves tend to acquire a disproportionate amount of public attention. Caves are undeniably very important features and can contain a range of significant values and resources, including the geomorphological, paleontological, archaeological, and biological. A number of references are available that provide a more extensive discussion of these values and resources, plus the related cave management issues (e.g., Kiernan 1988; International Union for the Conservation of Nature 1997; New Zealand Department of Conservation 1999; Ramsey 2004). However, caves as karst features should also be placed into the

6 A speleothem is any form of secondary deposit in a cave that forms by mineral precipitation (usually of calcite) and includes such features as stalagmites, stalactites, and draperies.

perspective of other subsurface openings in the karst system, as the vast majority of these openings or voids are not large enough for humans to enter but are, nevertheless, important biospaces with their associated eco-hydrological functions (Figure 11.11). As such, caves typically make up only a small portion of the cavities within a karst system (e.g., less than 0.01%; Ford and Williams 2007).

Caves may appear as complex or random patterns when displayed in maps or as cross-sections, but these features typically exhibit three basic components: (1) passages, (2) chambers, and (3) one or more entrances. In most cases, geological or hydrological factors dictate the location of a cave by defining its shape, extent, and dimensions. A cave's significance is not necessarily related to its size; even a very small cave can contain significant resource contents or values.

Regionally, Vancouver Island has the highest density of recorded caves of any karst region in Canada, as well as 5 of the 10 longest and deepest caves in Canada (e.g., Weymer Cave System is more than 13 km long and Thanksgiving Cave is over 400 m deep). Caves on Vancouver Island are predominantly found in carbonate bedrock units that are steeply dipping, and occur from sea level, on forested lower and middle slopes, and up to the highest peaks 2000 m above sea level. Many of these caves consist of multiple chambers and passages with associated vertical drops of up to 50 m, whereas other caves occur along river drainages with discrete sink points and emergences (e.g., Artlish River Cave). Calcium carbonate deposits, or speleothems, in the form of stalactites, stalagmites, soda straws, draperies, and helictites are present in many British Columbia caves, as are cave fills or sediments (e.g., layered clay, sand, gravel, and rubble deposits). Both speleothems and cave sediments contain important information for understanding scientific issues such as ancient flora/fauna, past glaciation events and climates, and, past human activities (e.g., migration patterns).

Because caves can occur in geological environments other than karst, caves are not necessarily diagnostic karst features. Non karstic examples include lava caves found in basalt flows, glacier caves, crevice/fracture caves along faults, sea caves caused by wave action and erosion, and talus caves under rock debris (Palmer 2007).

FIGURE 11.11 *Examples of the cave environment: (a) an active underground stream; (b) a sinking river and large swallet; and (c) viewing from within a cave passage towards a cave entrance. (Photos: P. Griffiths)*

Water is the key to understanding the formation and functions of a karst landscape. As precipitation falls on a karst landscape, it generally infiltrates downward through the soil towards the soil–bedrock contact (Figure 11.12). The water then percolates through the epikarst zone along small fractures or solutionally enlarged openings in the bedrock, gradually moving downward until it reaches larger conduits and (or) caves below. In general, the upper unsaturated (or vadose) part of a karst aquifer is where water partially fills openings or voids, and the lower saturated (or phreatic) part of the aquifer is where all voids are water filled. Water may be stored in these voids within conduits and fractures and, depending on flow stage, will eventually leave the karst landscape system at outflow sites such as springs. Some obvious hydrological features that distinguish karst from other types of landscapes include a general lack of surface drainage or streams, the presence of discrete sink points where streams disappear (swallets), and the occurrence of springs where water emerges.

An important characteristic of many karst landscape systems is the presence of an aquifer suspended above the phreatic zone and located within the epikarst zone (Williams 2008). The porosity and permeability of epikarst is typically greatest at the surface and decreases with depth (i.e., from 1 m down to 10 m below the surface). The net result is that rainfall can be temporarily detained and stored in the rock matrix and fractures of the epikarst before infiltrating downwards into the lower parts of the karst aquifer (Williams 2008). Water on reaching the lower part of the karst aquifer moves into larger subterranean conduits that not only provide the main flow paths for water within the aquifer but also allow flow into and out of fractures (Gillieson 1998; Gunn 2004; Williams 2008). In general, the storage of water in the rock matrix and fracture porosity is considered a longer-term phenomenon, and water storage in conduits is a shorter-term phenomenon.

Streams will run over the surface of karst when and where water flow exceeds what can infiltrate into the channel bed or into sink points within the karst landscape. Karst streams are often inactive during low flow periods and active only during high flow events. Year-round surface flow on well-developed

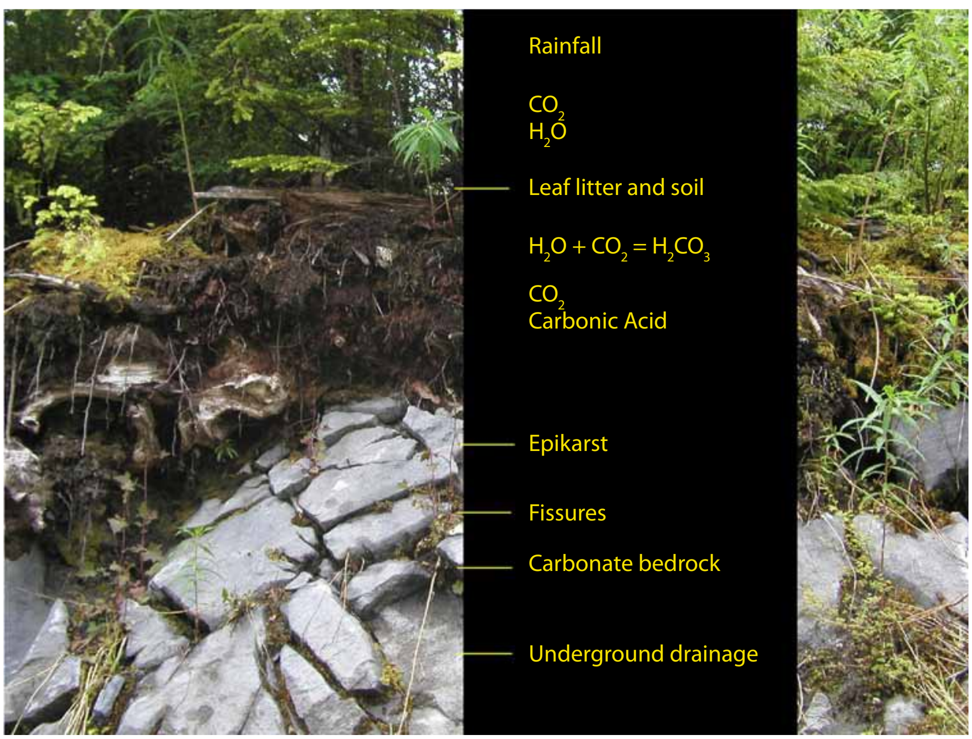

FIGURE 11.12 *Infiltration of water through soil and the epikarst. (Source: Griffiths and Ramsey 2009)*

karst landscapes is rare but can occur where the karst is covered by thick and (or) impermeable sediment cover (e.g., till). Some of the most spectacular features associated with karst streams are karst canyons, where water has dissolved the soluble bedrock, creating steep and sometimes overhanging sidewalls.

The recharge of karst aquifers can be either autogenic, allogenic, or a combination of the two (Figure 11.13; White et al. 1985; Ford and Williams 2007). In autogenic recharge, water falls directly onto the karst and infiltrates the soil and epikarst, and then enters into the underlying aquifer. In some cases, this autogenic recharge flow can be concentrated at point-input features such as sinkholes. Allogenic recharge occurs when water falls on adjacent or nearby non-karst landscapes and is transported onto a karst unit via surface streams.

This water may eventually disappear underground if it reaches discrete sink points in the karst unit such as swallets or sinkholes. The characteristics of water from allogenic recharge sources can vary depending on conditions upstream, but this water generally has lower electrical conductivity and lower pH values compared to water that has flowed through a karst system. In some cases, allogenic water can be very aggressive (acidic) when derived from non-karst wetlands or bogs. When such water encounters carbonate bedrock, it can result in more intensive karst development. On Vancouver Island, allogenic streams draining from non-karst slopes to a karst unit can form a line of swallets or sink points along the upper karst unit boundary.

An important concept in karst hydrology is the notion of the "karst catchment" (i.e., the drainage area that contributes water to a particular karst landscape unit).[7] Karst catchments can cross beneath topographic divides because the water flowing in underground conduit systems is not necessarily constrained by surface topography, and hence the catchment for any particular karst unit may bear little or no relation to the surrounding topographic divides. Water from adjacent or adjoining non-karst landscapes can also contribute significantly to the catchments of karst units (Figure 11.14; B.C. Ministry of Forests 2003a).

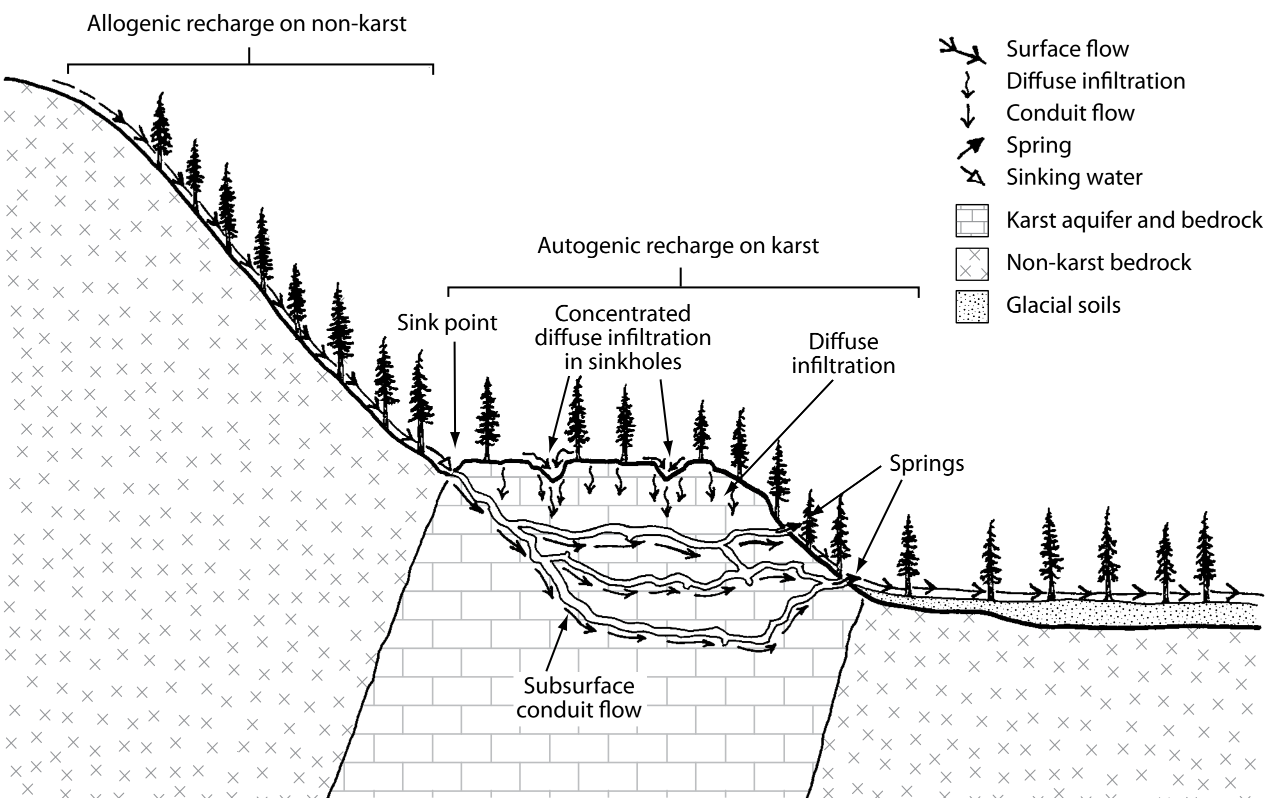

FIGURE 11.13 *Autogenic and allogenic recharge of karst aquifers (T. Stokes).*

7 The term "karst catchment" is used instead of "karst watershed," primarily because watershed implies a strong topographic control (i.e., watershed boundaries that occur along topographic divides). This is commonly not the case for karst landscapes.

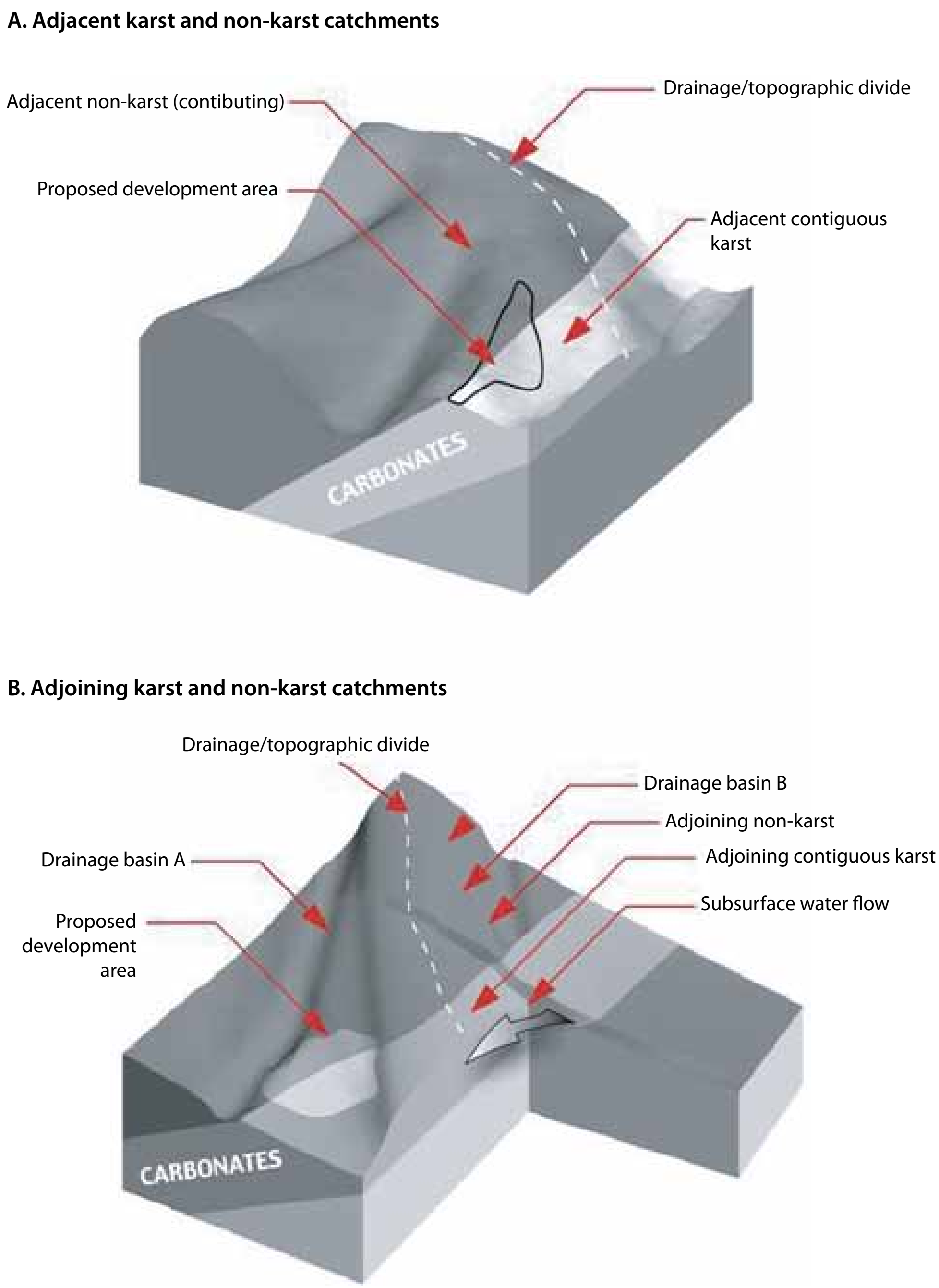

FIGURE 11.14 *Karst catchment hydrology; note the differences between the contributing catchment areas of the adjacent and adjoining karst, plus the adjacent and adjoining non-karst; also note the subsurface flow under topographic divide (B.C. Ministry of Forests 2003a).*

Techniques such as water tracing using fluorescent dyes are often required to fully determine a karst catchment's full extent (Stokes et al. 1998; Prussian and Baichtal 2007).

Water typically leaves karst aquifers by way of karst springs, which represent water that has flowed through a carbonate bedrock from a source area at a higher elevation. Karst spring discharges can range from small trickles of water to raging rivers tens of metres in width. Typically, karst springs are located at lower elevations—along valley floors, sides of lakes, or coastal shorelines. In some cases, these springs can occur beneath water bodies. Karst springs differ from those occurring in other rock types in that these springs are mostly fed via conduits. Discharge waters from karst springs are also used to infer some of the physical and chemical characteristics of a karst aquifer (Gunn 2004). Springs with continuous year-round flow suggest that the aquifer has some potential for storage relative to the amount of water flowing through the system. These springs typically occur at low elevations and are termed "outflow springs." Springs that are more active during high flows, or that have seasonal or intermittent flows, are termed "overflow springs." Overflow springs are typically at sites of slightly higher elevation than the corresponding outflow springs.

Although often overlooked in Canada, karst aquifers are recognized globally as important natural resources. An estimated 25% of the world's population depends on water from karst aquifers for daily use (Ford and Williams 2007). Subterranean karst aquifers have been included in the RAMSAR Wetland Classification System since 1971 (New Zealand Department of Conservation 1999), and provide habitat for underground-adapted aquatic fauna known as "stygobites" (Pipan 2005; Ford and Williams 2007; Pipan and Culver 2007). Research in southeast Alaska suggests that aquatic ecosystems associated with streams fed by karst waters can be more productive than those that are not. Streams flowing through or from karst landscapes have distinct water chemistry and appear to support more fish than non-karst streams (Baichtal et al. 1995; Bryant et al. 1998). This research likely has important implications for fisheries and karst landscapes of coastal British Columbia.

KARST LANDSCAPE UNITS: TWO CASE STUDIES FROM VANCOUVER ISLAND

To illustrate the typical conditions and characteristics of forested karst landscape units in British Columbia, we describe two case studies for Vancouver Island—one at a low elevation and one at a high elevation. In general, most of the karst landscapes on Vancouver Island are within the limestone of either the Quatsino or the Mount Mark formations. Generally, these limestone formations occur as moderately to steeply dipping linear belts less than one kilometre to tens of kilometres in length and hundreds of metres to kilometres wide. The limestone of both the Quatsino and Mount Mark formations is of a relatively high purity—typically greater than 90% $CaCO_3$. Karst development is also controlled by elevation and slope gradient. In general, high-elevation areas are more likely than low-elevation areas to develop a steep hydraulic gradient, and hence have a greater potential for karst development. Gentle slopes (e.g., benches) are also preferable to steep slopes for karst development, possibly as the former allows more time for water infiltration (Stokes 1999; B.C. Ministry of Forests 2003a). Figure 11.15 shows an example of a lower-elevation karst landscape unit on Quadra Island, which is one of the Northern Gulf Islands just to the east of Vancouver Island.

In this location, a belt of Triassic Quatsino Formation limestone extends north to south through the centre of the island. The karst unit is approximately 15 km long and 1–2 km wide, varying in elevation from sea level to approximately 100 m above sea level. The limestone unit is bounded by basaltic volcanic rocks to the west and by granitic rocks to the east, and is steeply to moderately dipping. Most of the limestone is located in or near a topographic low that is mantled by glacial materials. Based on reconnaissance mapping, the limestone in this region is considered to have high potential for karst development (Stokes 1999). Small (< 10 m diameter) sinkholes are common but variable in concentration. Large sinkholes (up to 40 m in diameter) do occur but are rare. Solution holes and grikes also occur on exposed epikarst sites, which are typically found on karst bedrock highs (e.g., hums) and (or) occasional ridges. A number of karst springs occur on the mid- and lower-elevation slopes, with at least one used for domestic water supply. Caves occur in several

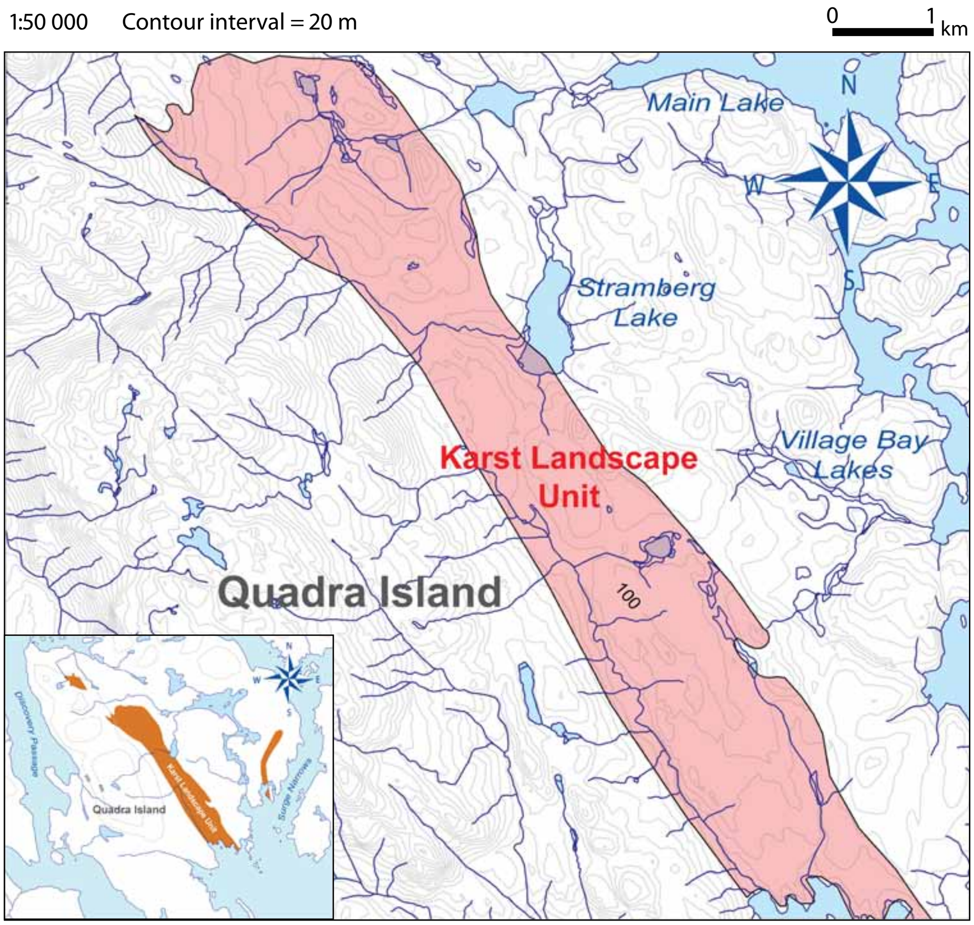

FIGURE 11.15 *Quadra Island karst unit, northern Gulf Islands (P. Griffiths).*

locations but are not of great length or depth. Most of Quadra Island was logged and forest stands consist of second-growth trees of various ages. Active logging continues both on and off the karst unit. In our experience, no systematic, planning-level karst inventory has been completed in this region, but a number of operational-scale karst field assessments linked to cutblock planning and development were carried out.

Figure 11.16 shows a higher-elevation example of a karst landscape unit to the east of Nimpkish Lake in the Noomas Creek and Kinman Creek areas of northern Vancouver Island. At this location, the karst occurs in a 10–15 km long, 4–5 km wide, northwest–southeast trending limestone unit of the Quatsino Formation, bounded by volcanic rocks to the east and west and by intrusive rocks to the south. This unit varies in elevation from approximately 700 to 1300 m above sea level and has variable soil cover. Significant portions of the unit were logged but some old-growth stands remain. The area has a high potential for karst development based on the reconnaissance mapping of British Columbia performed by Stokes (1999). Regional evaluation of the unit was carried out as part of a planning-level inventory of Tree Farm Licence 37 for Canadian Forest Products Ltd.[8] This project defined the limits of the karst unit, identified some of the major karst features, and stratified the karst unit into areas of different karst vulnerability potential. The unit contains a number of extensive cave systems such as Arch Cave and Glory'ole—both of which have provincial and national significance. In addition to these significant caves, the unit also includes several large and

8 Stokes, T.R. and P.A. Griffiths. 2003. Planning-level karst inventory for TFL 37 and FL A19233, northern Vancouver Island. Prepared for Canadian Forest Products Ltd. Unpubl. report.

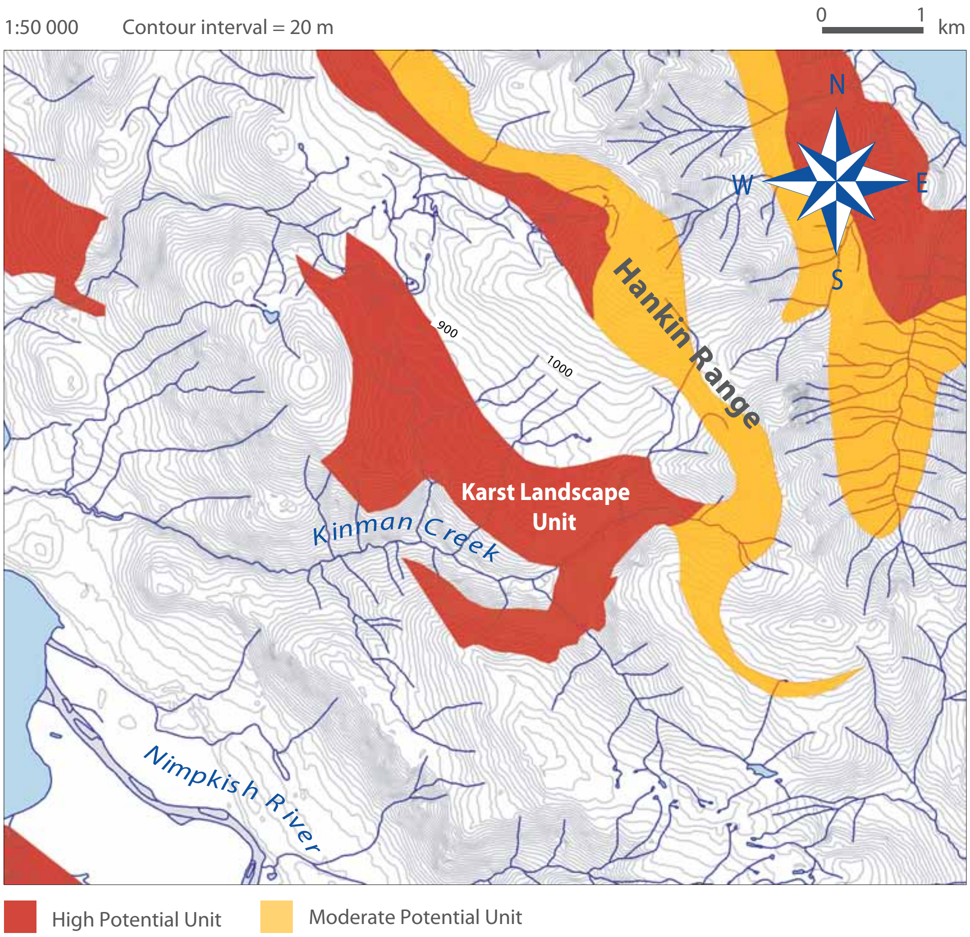

FIGURE 11.16 *Noomas Creek and Kinman Creek karst units, northern Vancouver Island (P. Griffiths).*

significant springs. Epikarst, visible on some exposed bedrock surfaces, is slightly to moderately well developed. A wide range of different karst features such as sinkholes, karst canyons, grikes, and swallets are also present. Dye tracing carried out at the northern end of the unit linked sink points associated with cave entrances and important cave systems to downslope springs. As well as defining the various subsurface flow paths, the dye tracing also identified potentially sensitive non-karst catchments upslope (Stokes et al. 1998).

IMPACTS OF FORESTRY ACTIVITIES ON KARST LANDSCAPES

Overall, forestry activities have a range of impacts on the karst landscape, including disturbance to surface karst features, subsurface environments, karst waters, and karst biota (Figure 11.17). These disturbances can also affect water quality and flow regime, scientific values (e.g., archaeological, paleontological, geological), recreation (both surface and subsurface), visual quality, and fisheries. Because of the inherent low-energy transfers present at these sites, impacts to subsurface environments and caves take hundreds to thousands of years to recover and restore to their previous states (Gillieson 1998). On the surface, as with non-karst landscapes, recovery of forest conditions after disturbances will also occur over time; however, soil loss into vertical solution openings or epikarst can significantly slow this process (Harding and Ford 1993). Removal of the forest canopy on well-developed karst during logging or other forestry activities can:

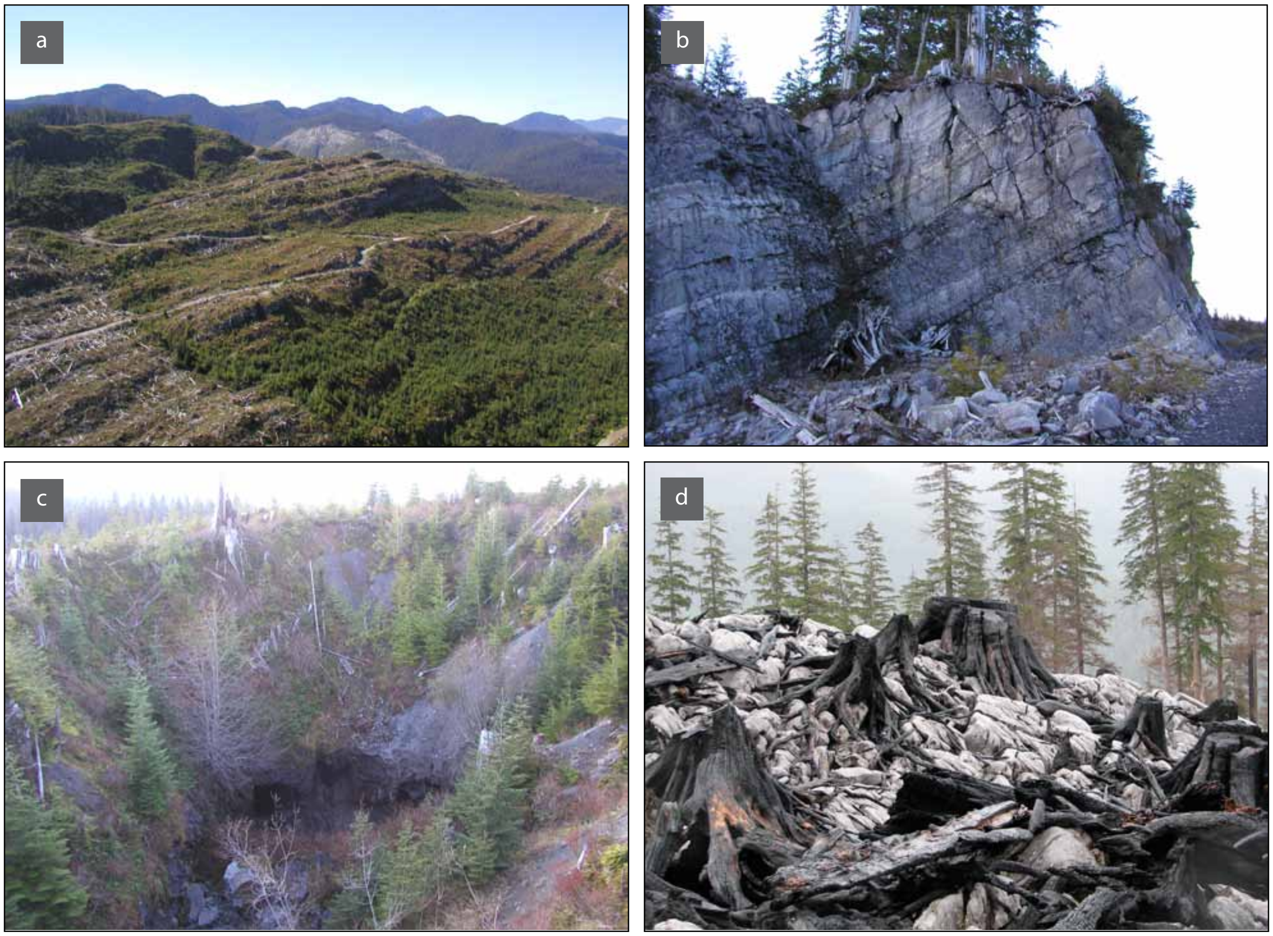

FIGURE 11.17 *Examples of past and potential disturbances to karst by forestry activities: (a) a contiguous clearcutting of karst lands; (b) a quarry excavated into karst; (c) a large sinkhole with destabilized sidewalls following logging activities; and (d) soil loss and burning on well-developed epikarst. (Photos: P. Griffiths)*

- change hydrology by redirecting surface flows that can dewater or flood subsurface conduits;
- increase input of organic debris and sediment into subsurface cavities;
- alter microclimates of larger surface features (e.g., a > 20 m diameter sinkhole);
- alter microclimates of shallow subsurface cavities; and
- increase surface desiccation and loss of thin surface soils into well-developed karst.

One of the key differences between karst landscapes and other types of landscapes is the presence of subsurface biota, of which little is really known, particularly in British Columbia. Detailed inventory information on the biodiversity of forested karst lands on Vancouver Island and in the rest of British Columbia is limited. Studies in other karst areas outside of British Columbia show that the better developed a karst landscape (i.e., the more openness between the surface and subsurface environments), the greater the likelihood of finding life forms that have adapted to it. In effect, the greater the variability (or topographical roughness) of the karst landscape, the more likely it is to possess a greater diversity of life forms that have developed in isolated niches. Caves and other karst cavities can host and support a wide range of cave-adapted life forms (e.g., blind and de-pigmented crustaceans; Gillieson 1998).

Karst Inventories in British Columbia

A framework for carrying out karst inventories in British Columbia is outlined in the *Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia* (B.C. Ministry of Forests

2003a). Under this framework, inventory activity can take place at three levels: (1) reconnaissance, (2) planning, and (3) operational.

The intent of these three different inventory levels is to provide a filtered approach to the karst inventory process, going from broader information to progressively greater detail. In 1999, a reconnaissance-level karst inventory project was carried out for all of British Columbia (Stokes 1999). During this project, all potential soluble bedrock units (i.e., limestone, dolomite, marble, and gypsum) were identified at a 1:250 000 scale using a series of digital bedrock geology maps. These soluble bedrock units were then rated for the potential to develop karst. Knowledge of specific cave and (or) karst features was also incorporated into the mapping.

Planning-level karst inventories can be carried out at the 1:20 000 or 1:50 000 scales, and are intended for the strategic management of forestry activities in karst landscapes. The primary aims of planning-level karst inventories are to:

- stratify the sensitivity or vulnerability of the karst landscape;
- identify major surface karst features; and
- provide a preliminary delineation of the karst catchments.

To date, only two planning-level inventory projects have been completed in British Columbia, both on northern Vancouver Island.[9] In both cases, considerable bedrock mapping was required in the field to verify the extent and boundaries of the karst units. Geographic Information System (GIS) analysis was also used to rapidly identify areas of differing karst vulnerability potential by using the attributes of elevation and slope gradient.

Operational-level inventories primarily involve the use of Karst Field Assessments (KFAs) carried out at 1:5000 or 1:10 000 scales. A KFA is a detailed evaluation of the karst attributes and features in the cutblock area. It covers not only the area of potential or suspected karst units within a proposed cutblock, but also other areas outside the cutblock. The process for completing operational-scale inventories is discussed below and is outlined in the *Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia* (B.C. Ministry of Forests 2003a).

Cave inspections can be done as part of a KFA, and in some cases more detailed inventories may be required to determine a cave's significance and vulnerability to disturbance. These should be undertaken only by qualified personnel (Kiernan 1988; Ramsey 2004).

At the cutblock level, KFAs may include karst areas 100 m beyond the cutblock boundaries, as well as reaches of sinking streams or watercourses outside of the cutblock, depending on various circumstances (see B.C. Ministry of Forests 2003a). Typical KFA field activities (Figure 11.18) include:

- identifying geological contacts and inferring or delineating the extent of potential karst units;
- locating, classifying, and evaluating surface karst features for relative significance;
- evaluating attributes such as the level of epikarst development, soil thickness and texture, density of surface karst features, roughness of the karst surface, and subsurface karst potential;
- assessing streams to see whether they sink or lose water into the subsurface;
- inspecting and mapping caves;
- identifying unique or unusual flora and fauna and (or) habitats; and
- identifying potential geomorphic hazards that could affect the karst unit (landslides, windthrow, etc.).

The data collected during a KFA can be used to broadly stratify the karst unit of interest into polygons of similar karst characteristics, which are then rated for vulnerability as low, moderate, high, or very high. Karst vulnerability is defined as the susceptibility of a karst ecosystem to change. Karst vulnerability ratings are determined by a four-step procedure (Figure 11.19) and are used to guide the selection of appropriate best management practices as outlined in the *Karst Management Handbook for British Columbia* (B.C. Ministry of Forests 2003b).

9 These projects are: (1) Stokes, T.R. and P.A. Griffiths. 2002. Planning-level karst inventory of TFL 19, Nootka Region, B.C. Prepared for Western Forest Products. Unpubl. report; and (2) Stokes, T.R. and P.G. Griffiths. 2003. Planning-level karst inventory for TFL 37 and FL A19233, northern Vancouver Island. Prepared for Canadian Forest Products. Unpubl. report.

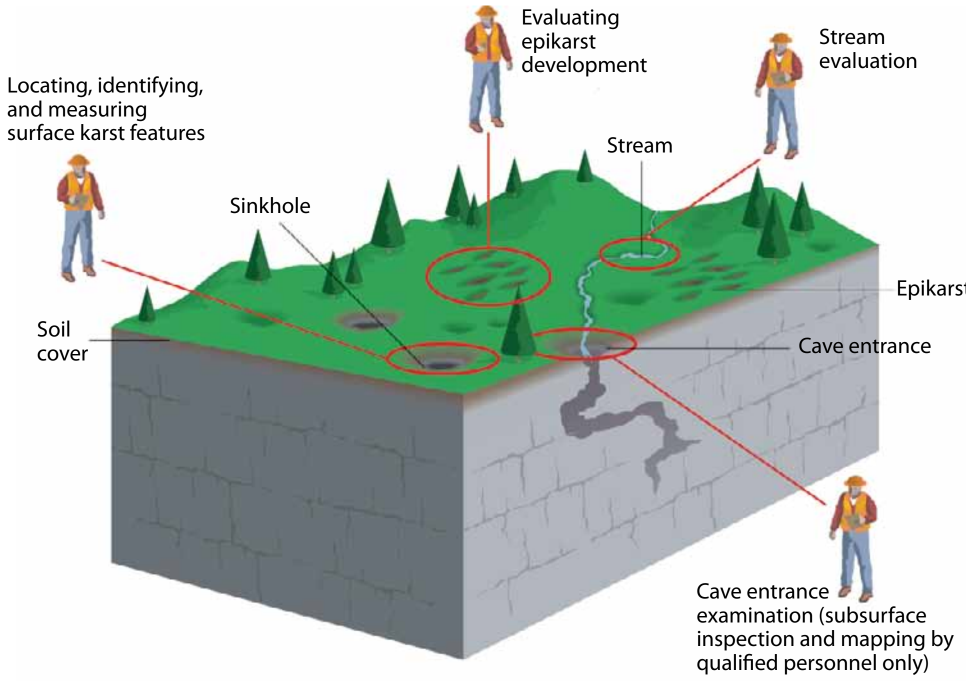

FIGURE 11.18 *Karst field assessment activities (B.C. Ministry of Forests 2003a).*

Karst Management and Best Management Practices for Forestry Activities on Karst Landscapes

The B.C. Ministry of Forests first acknowledged karst landscapes as complex ecosystems in 1997 (B.C. Ministry of Forests 1997; Beedle 1997), recognizing that management efforts should focus on protecting the integrity of the whole karst system rather than individual karst features and caves. This new approach to managing karst resources was embodied within a series of significant government initiatives and associated publications (i.e., Stokes and Griffiths 2000; B.C. Ministry of Forests 2003a, 2003b). These documents are available on the B.C. Ministry of Forests and Range website at www.for.gov.bc.ca/hfp/values/features/karst/index.htm.

A Preliminary Discussion of Karst Inventory Systems and Principles for British Columbia (Stokes and Griffiths 2000) proposes a scientific framework for a standardized inventory system for karst landscapes in British Columbia. The *Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia* (B.C. Ministry of Forests 2003a) outlines standards and procedures for evaluating and inventorying karst landscapes at various scales. The first version of this document was published in 2001.

The *Karst Management Handbook for British Columbia* (B.C. Ministry of Forests 2003b) provides best management practices for harvesting and forest road construction where these forestry operations impinge upon:

- surface karst features (e.g., sinkholes, karst springs, epikarst exposures, cave entrances);
- cave systems;
- sinking streams and sinking watercourses; and
- the broader karst landscape.

Some specific examples of best management practices include:

- developing reserve and management areas for more significant surface karst features and above shallow caves or caves with exceptional features;
- realigning roads and carefully designing road drainage systems to avoid sinkholes;
- using overlanding[10] road construction techniques with coarse rock fill to bridge small-scale karst

10 Overlanding is a construction technique whereby fill is imported to build the road up to a level grade rather than using conventional cut and fill.

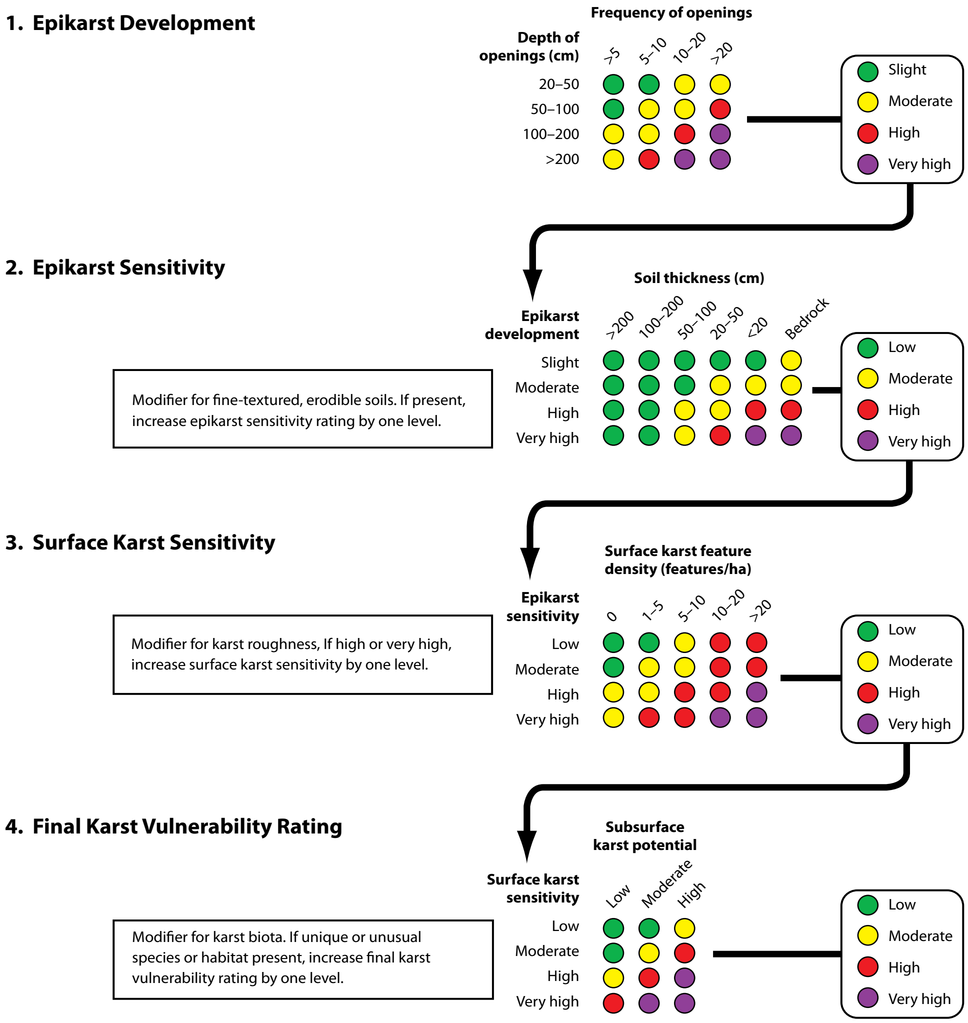

FIGURE 11.19 *The four-step karst vulnerability rating system (B.C. Ministry of Forests 2003a).*

features such as grikes or epikarst zones; and
- developing buffers along the edges of sinking streams that contribute to significant recipient features.

The best management practices for the broader karst landscape are linked incrementally to the four karst vulnerability ratings, such that the higher the level of karst vulnerability the more numerous and comprehensive the management practices (see Figure 11.20).

Case Studies of Karst Management Practices on Forested Cutblocks

To illustrate how inventories, best management practices, and harvesting or road construction activities are completed on cutblocks underlain by karst in the province, we provide three case studies from Vancouver Island.[11]

Case study 1: Large sinkholes and small caves

Site conditions This rectangular 17-ha cutblock is located near a ridge top in an old-growth forest stand. The northern half of the cutblock is underlain by Quatsino Formation limestone. The cutblock is at an elevation of approximately 200–300 m above sea level. A road was built to access the cutblock from the north. The landscape is characterized by gentle to moderate rolling topography with occasional limestone outcrops and interrupted drainage linears. Glacial sediments cover much of the cutblock area.

11 For expediency and to allow comments and opinions on the results of harvesting and road construction activities, we have excluded the location of the cutblocks and names of licensees.

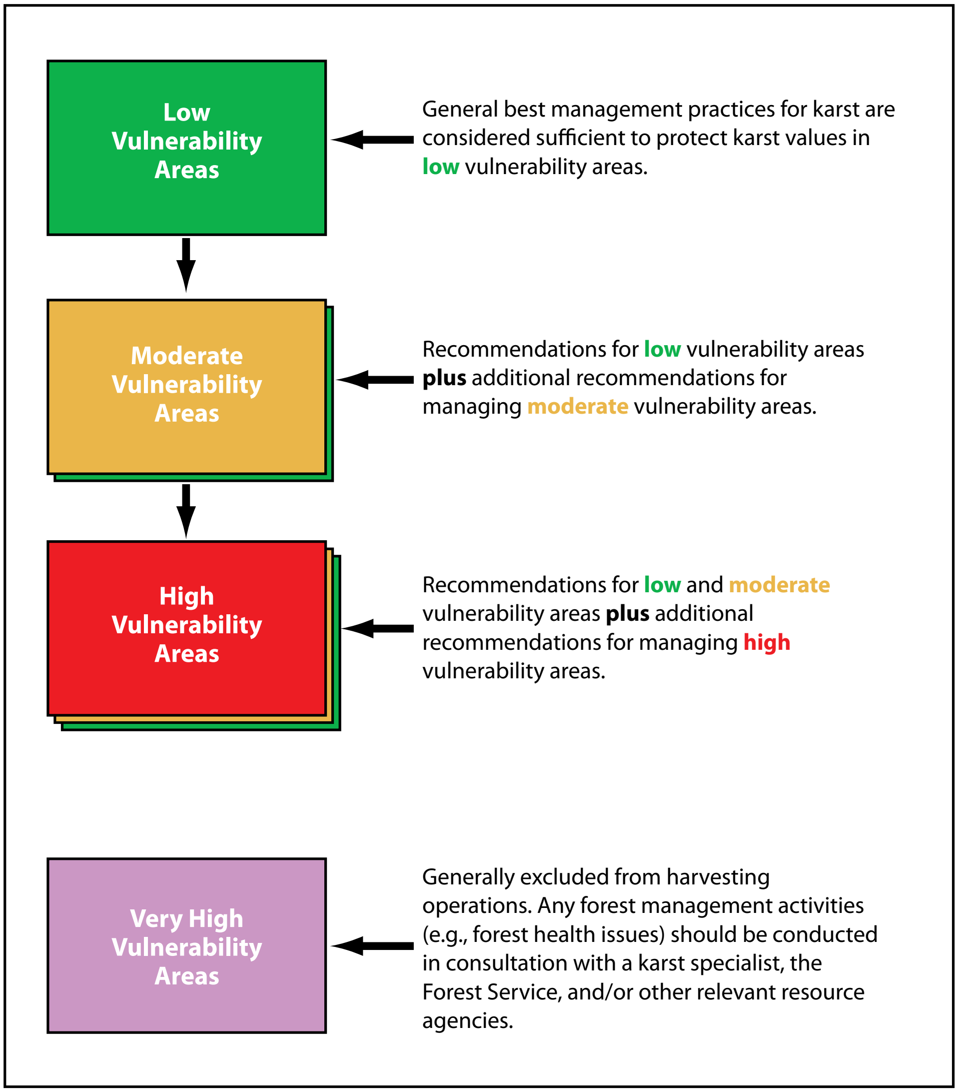

FIGURE 11.20 *Framework for best management practices and karst vulnerability ratings for broader karst landscapes (B.C. Ministry of Forests 2003b).*

Karst attributes A detailed KFA was carried out for this cutblock during 2005. The greater portion of the unit received a moderate karst vulnerability rating, with localized areas of high vulnerability. Approximately 10 karst features were encountered within or adjacent to the cutblock. These features consisted primarily of sinkholes of various sizes. Two larger sinkholes with cave entrances were found along the proposed access road leading to the cutblock, and two other large (15–20 m diameter) sinkholes were found within the cutblock near to the proposed road (see Figure 11.21).

Pre-harvest recommendations It was recommended that harvesting and road construction practices over the broader karst landscape follow those outlined for karst areas with moderate karst vulnerability ratings. For the two sinkholes with cave entrances and associated shallow caves situated outside of the cutblock, minor changes to the alignment of the access road were recommended to avoid these features. For the two larger, significant sinkholes within the cutblock, the preferred option was to develop suitable windfirm reserves with surrounding management areas to protect the structural, functional, and ecological integrity of these features. Development of these reserves and surrounding management areas would require some adjustment of the road alignment within the cutblock.

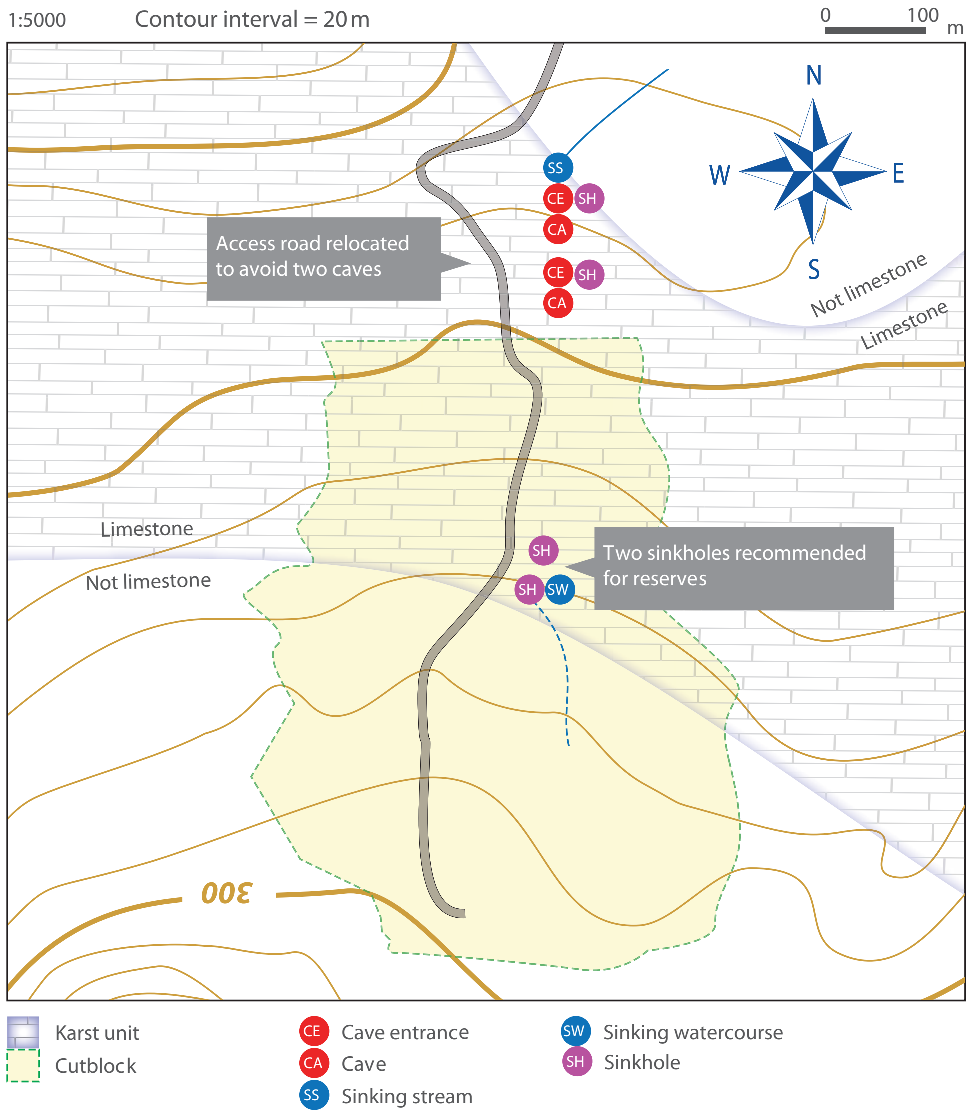

FIGURE 11.21 *Case study 1: Cutblock with large sinkholes and small caves along access road and potentially significant sinkholes within cutblock (P. Griffiths).*

Results of harvesting and road construction A follow-up visit to the site confirmed that the alignment of the access road to the cutblock had been adjusted to avoid the sinkholes and associated cave entrances. Within the cutblock, however, no reserves or management areas had been left around the larger sinkholes. Falling and yarding away from these sinkholes had been carried out with no notable disturbance to these features' sidewalls. From subsequent discussions with the licensee, it was apparent that windthrow hazard near the proposed reserves and management areas around the two sinkholes was considered high, and that the licensee was unable to realign the road at this location.

Post-harvest issues for further consideration Although management of the larger sinkholes outside the cutblock appeared to have been successfully carried out by realigning the access road, tree retention around the two larger sinkholes within the cutblock had not occurred. In hindsight, it would have more efficient and effective to have completed a KFA before cutblock and road design so that the karst issues could be more readily addressed and alternatives for forest development considered more thoroughly.

Case study 2: Karst drainage linears

Site conditions A 7-ha cutblock is located on east-facing slopes at elevations of 100–150 m and is within a well-developed second-growth stand. Two well-defined karst drainage linears trending east to west occur immediately outside of the cutblock boundaries to the north and south, respectively.

Karst attributes A detailed KFA was not carried out for this cutblock; however, a field review of the cutblock and associated report were completed in 2007. The two karst drainage linears were both associated with interrupted streams, as well as a number sink points, springs, and small caves (Figure 11.22).

Approximately 1–1.5 km downslope from the cutblock, a number of other springs occur and a nearby homeowner uses one of these springs as a domestic water supply. A cluster of smaller sinkholes was encountered within the cutblock and along the proposed road alignment.

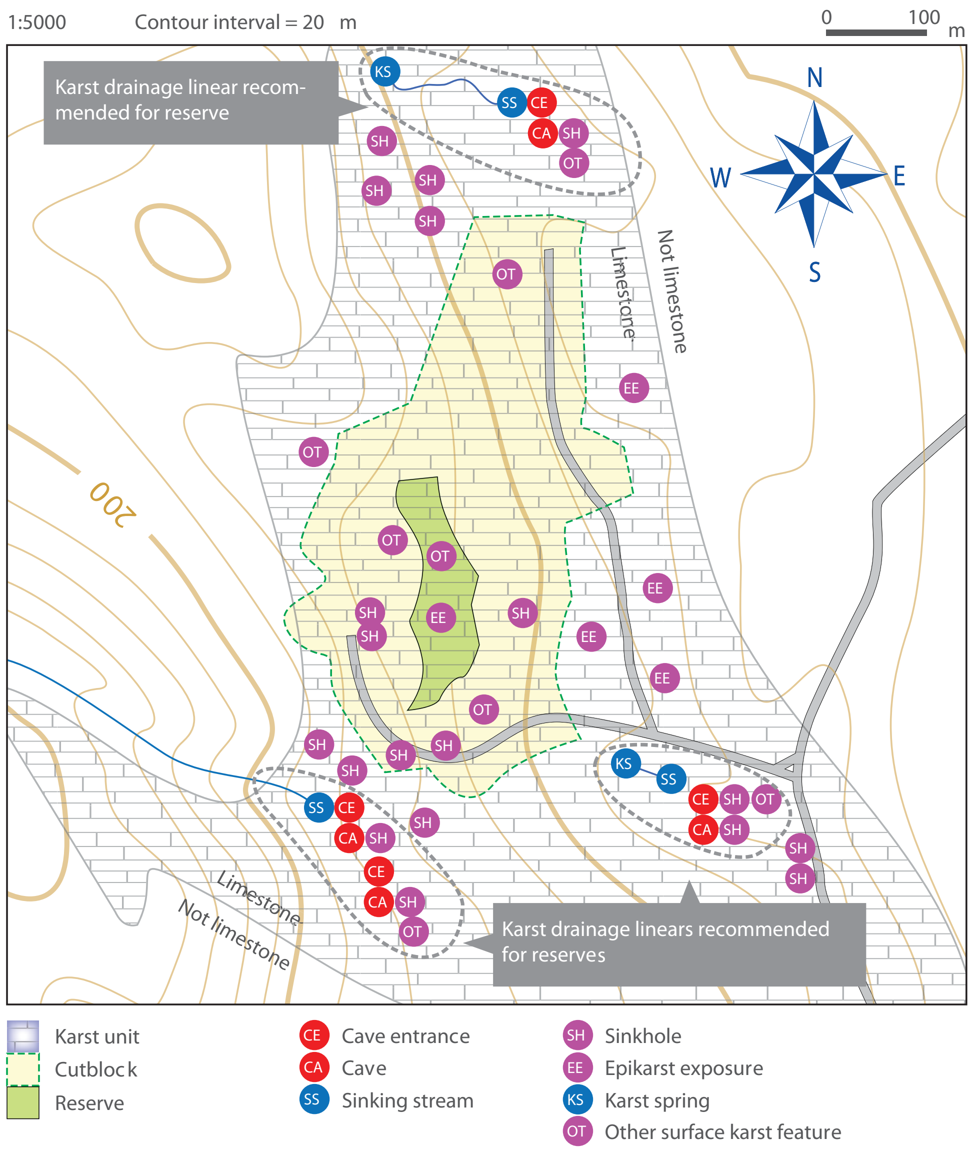

FIGURE 11.22 *Case study 2: Cutblock between two major and significant drainage elements (P. Griffiths).*

Pre-harvest recommendation Both drainage linears were identified as sinking streams with significant recipient features that warranted reserves. The recommended minimum buffers were 20 m from the drainage linears, and up to 80 m for some of the significant karst features associated with the linears. It was also recommended that road builders avoid a group of smaller sinkholes.

Results of harvesting and road construction Harvesting and road construction were carried out in 2008. Reserves were left around the drainage linears and associated significant karst features as recommended. Road construction did encroach on a number of the smaller sinkholes, some of which were infilled with road ballast and surfacing material. Significant sandy fines were also exposed along road cuts in proximity to karst features and drainage linears.

Post-harvest issues for further consideration Retaining buffers along the drainage linears was considered important in this cutblock, particularly as possible hydrological connections existed to springs at lower elevations, one of which is used as a domestic water supply. The significant karst features associated with the drainage linears were adequately buffered, although windthrow along the buffer edges may be a future concern. Therefore, windfirming these boundaries may warrant consideration. A need also exists to ensure that fine sediment exposed along the roads does not enter the karst drainage linears. Infilling the smaller sinkholes is not a good practice as this will obviously affect the hydrology and function of the sinkholes. Knowing more about the water subsurface connections and flow paths between sink points and springs at this block is likely the key issue, particularly as a spring is used as a domestic water supply. A good pre-harvest option would have been the completion of a dye tracing study.

Case study 3: Sinkhole clusters and surface streams
Site Conditions: A 40-ha cutblock is located on a south-facing slope at an elevation of about 600 m above sea level and has slope gradients of 20% or less. The cutblock is blanketed by thick glacial sediments (mainly weathered till) and has dense stands of small, second-growth trees. The entire cutblock is underlain by karst but with only one limestone outcrop exposed. Small surface streams drain across the cutblock and flow into a small wetland, which in turn flows into a larger stream that eventually crosses other possible karst areas some distance downslope to the north.

Karst attributes A detailed KFA was carried out in 2007. Numerous sinkholes were found throughout this cutblock and appear to occur in clusters, most of which were aligned along a linear band extending across the cutblock. Some of the sinkholes were enclosed within broad and shallow depressions. A number of large (> 15 m diameter) and potentially significant sinkholes were present, some of them possibly large enough to sustain microclimates.[12] Most sinkholes were infilled with 40- to 50-year-old woody debris from previous logging. Some of the streams crossing the cutblock were considered permanent, whereas others were intermittent. Two minor sink points and two possible small springs were identified along or near these streams. An area with significant caves is located approximately 1 km to the northeast of the cutblock, but this area does not appear to have any direct hydrological connection to the cutblock or to the stream draining the cutblock.

Pre-harvest recommendations The large sinkholes and areas of closely spaced sinkholes were grouped into four clusters and were recommended as retention areas, with the retention boundaries to be located 15–20 m away from the rims of the sinkholes or shallow depressions enclosing the sinkholes (Figure 11.23). Windfirm treatment of the retention boundaries was recommended, if the licensee considered the site to have a risk of windthrow. Careful harvesting of the smaller isolated sinkholes was considered acceptable. Minimizing the input of fine sediment and logging debris was recommended for the two larger streams in the cutblock, particularly as these are connected to a swamp and larger stream that flows toward other potential karst areas to the north, of which little is known.

Results of harvesting and road construction No harvesting has been carried out as yet.

12 Large karst sinkholes with microclimates include those that exhibit a distinctive temperature and relative humidity gradient from the rim to base along the sideslopes, and may include higher biodiversity or habitat values (B.C. Ministry of Forests 2003b).

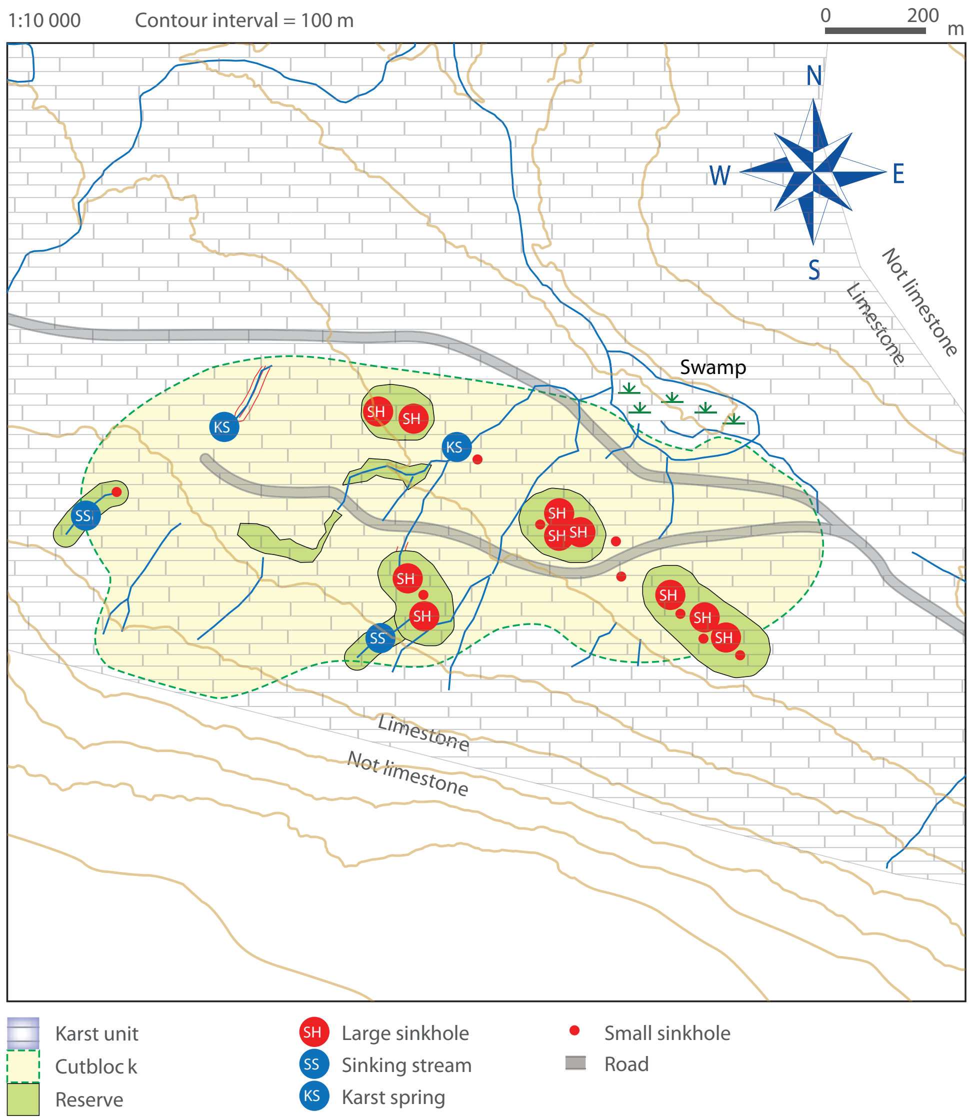

FIGURE 11.23 *Case study 3: Cutblock with clusters of sinkholes and development of retention areas (T. Stokes and P. Griffiths).*

Other issues for consideration The retention areas should be of sufficient size to retain the structure, function, and ecological integrity of many of the identified sinkholes. Though the significant caves to the northeast do not appear to have an obvious hydrological connection to the cutblock area, other karst features of concern (e.g., sink points with cave entrances) may exist along the larger stream to the north; therefore, significant care should be taken when harvesting in and around the streams within the cutblock to limit sediment and debris input.

SUMMARY

British Columbia has a wide range of karst landscapes, many of which are forested and occur in areas with ongoing forestry activities. Consequently, a real need exists to manage the province's forested karst resources carefully with the understanding that karst landscapes function as integrated systems and are valuable resources for biodiversity, water, scientific research, and recreation.

Since 2004, when the *Forest and Range Practices Act* (FRPA) was adopted in British Columbia, karst has become a subset of FRPA's "resource features" value—one of 11 specified forest and environmental values that must be maintained. Under FRPA's Government Actions Regulation (GAR), the surface and subsurface elements of a karst system can now be legally established by government orders as resource features by type or category (e.g., caves, significant surface karst features, high or very high vulnerability karst terrain) and may be restricted to a specified geographic location (see Griffiths et al. 2005). Currently, six GAR orders have been established for karst in six of British Columbia's coastal forest districts—North Island–Central Coast, South Island, Campbell River, Chilliwack, Sunshine Coast, and Haida Gwaii.

The Forest Resource Evaluation Program (FREP) was established in 2003 to assess the effectiveness of FRPA in meeting government's objectives for each of the 11 resource values. The objectives of the FREP karst program are to evaluate the condition of karst resource features and the adjacent management areas following forestry activities of harvesting and road construction, and to determine whether FRPA standards and practices have achieved the desired level of protection for these features. The development of a checklist and detailed protocol for Karst Routine Evaluations has been initiated (see www.for.gov.bc.ca/hfp/frep/indicators/table.htm).

The Earth Science Department of Vancouver Island University is currently carrying out several research projects to investigate the characteristics of karst landscapes in the forested environment. Projects include: examining the microclimate of large sinkholes,[13] investigating soil development and hydrological processes in and around sinkholes, and evaluating and monitoring karst springs and the associated recharge areas and aquifers (Stokes et al. 2008).

An important first step in karst management is the completion of a careful inventory and evaluation, without which it is not possible to consider suitable management strategies or apply best management practices. The existing *Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia* (B.C. Ministry of Forests 2003a) and *Karst Management Handbook for British Columbia* (B.C. Ministry of Forests 2003b) provide guidance for completing karst inventories and carrying out karst management using best management practices. However, standards in forested karst management are evolving (e.g., ecosystem-based karst management; see Griffiths and Ramsey 2009) and therefore these publications are becoming outdated. Revisions to these documents should incorporate the important lessons learned in karst management over the last decade.

13 Stokes, T.R., P. Griffiths, and C. Ramsey. 2007. Preliminary microclimate study of forested karst sinkholes, Nimpkish River Area, Northern Vancouver Island, British Columbia, Canada. Poster presented at 17th Australasian Conference on Cave and Karst Management, Buchan, Victoria.

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