The current status of karst inventories is a critical starting point for the development of the KISP. This is outlined in the following sub-sections:

- 2.1 describes current methodologies used by forest districts and regions in British Columbia,
- 2.2 reviews examples of "typical" karst inventory reports completed in British Columbia, and other karst inventories completed worldwide, and
- 2.3 summarizes the level of karst inventory–related information currently available in the publications of British Columbia government agencies.

2.1 Current Methodologies Used for Karst Inventories in British Columbia

2.1.1 General approach

Recreation resource inventories are required for planning purposes as part of the Forest Practices Code, and are usually carried out by the forest districts and licensees. A recreation resource inventory involves identifying, classifying, and recording the types and locations of recreation features, visually sensitive sites, recreational opportunities, rivers, trails, and interpretive forest sites. The recreation inventory is normally carried out at the 1:50 000 scale (or 1:20 000 on Vancouver Island and in the Lower Mainland). For most areas, karst and cave areas have been mapped as L5 polygons. More specific karst-related recreation feature codes were devised in 1996, as follows:

K00	Cave/karst features
K01	Cave
K02	Sinkhole
K03	Limestone plateau

The methods by which L5 polygon boundaries have been determined vary throughout the province. In some forest districts, after confirmation of the karst unit boundaries and adjustment of the L5 polygons, ground search methods are used to locate karst features and cave entrances. These methods include low-intensity reconnaissance walkabouts, moderately intensive grid pattern or judgemental searches, and high-intensity total search grids (see Section 5.0 for details). The ground search is usually concurrent with, or followed by, subsurface inspection of caves. This subsurface inspection can, depending on the cave resources encountered, lead to a complete multi-disciplinary subsurface inventory.

The Port McNeill and Campbell River Forest Districts have been at the forefront of karst inventory work in British Columbia, both in terms of field methodologies and in the number of karst inventories completed. Other forest districts and regions have been involved in karst inventories to a lesser extent. The sections below focus on the current karst inventory systems used by the Port McNeill and Campbell River Forest Districts.

2.1.2 Port McNeill Forest District

Reconnaissance (1:250 000 scale) cave/karst potential maps, completed in 1994, identify the main regions of karst in the Port McNeill District, and are used for strategic planning purposes (e.g., calculation of AAC net down).

L5 recreation polygons have been delineated for the entire district at a scale of 1:20 000. These are intended to include all potential surface karst areas, but, in some places, include non-karst recreational values. However, the intention for the future is that L5 (now called "K00") polygon boundaries should follow surface karst boundaries only. To obtain preliminary boundaries for L5 polygons, the boundaries of limestone-bearing units are taken from available bedrock maps (typically no finer than 1:50 000 scale) and superimposed on the boundaries of 1:50 000 scale terrain map polygons where karst has been identified (e.g., as -K on the terrain unit symbol). The resultant L5 polygon then becomes the outline of the two boundary types. Refinements to the boundaries of L5 polygons are made over time as karst inventories are carried out for particular areas and as the boundaries are checked in the field.

Approximately 20–30 karst inventories are estimated to have been carried out in the district for a range of scales—1:20 000, 1:10 000, and 1:5000. Most have focused on the location of significant karst surface features and cave entrances, and were combined with subsurface cave inspections and classification. Judgemental traverses appear to be used for ground search methods more often than grids.

2.1.3 Campbell River Forest District

The Campbell River District uses reconnaissance (1:250 000 scale) cave/karst potential maps in a similar fashion to the Port McNeill District. However, the various high, moderate, and low ratings of karst potential on the maps are occasionally used to provide some indication of areas where more detailed inventories should be focused.

Landscape-level inventories are currently done at 1:50 000 and 1:20 000 scales, and are used to refine the boundaries of karst units. This is usually done at the 5- or 20-year forest development plan stage. The boundaries are checked by field reconnaissance along creeks and roads. Once the surface extent of the karst units are known, they are mapped as L5 polygon boundaries.

Identification and mapping of karst features at the operational level is accomplished mainly by traversing the L5 polygons with grid ground searches. This is done at scales of 1:20 000 or 1:10 000. Typically, the grids are laid out by three workers, one surveying a centre line and two others (rovers) on either side zig-zagging back and forth. Karst surface features and cave entrances are identified and tied into the survey line, and subsurface inspections are carried out for cave classification. It is estimated that 30–50 of these types of karst inventories have been completed for the district.

Cave/karst impact assessment reports are required for any proposed forestry activity to assist with management decisions on karst areas. These reports may include statements on slope, terrain stability, soils, windfirmness, hydrology, vegetation, wildlife and fisheries, palaeontological values, and socio-economic concerns.

In some cases, the landscape- and operational-level inventories and the cave/karst impact assessments are combined into one detailed inventory.

2.1.4 Other districts and regions

Various data have been obtained from some of the other forest regions and districts in British Columbia. The North Coast Forest District uses the 1:250 000 karst potential maps for the Prince Rupert Forest Region to determine the location of karst areas and incorporate them into L5 recreation inventory polygons. The "K00" system now used for recreation karst inventories is not in place in the North Coast District at the present time. Operational-type karst inventory reports have not been used in the relatively few karst areas that have been identified.

The South Island Forest District has used a combination of 1:50 000 bedrock geology maps and public (e.g., caver) input to identify L5 polygons. Only a few (approximately six) operational-type karst inventory reports have been completed for the district.

The Nelson Forest Region identifies karst as part of their recreation inventory mapping, and uses the current "K00" system at a scale of 1:50 000. The recreation inventory is determined from a combination of forest cover maps, airphotos, and local karst/cave knowledge. Operational-type karst inventories have not been completed in any karst areas in the region to date.

In the Prince George Forest Region, karst information for L5 polygons has been derived mainly from bedrock geology maps and local knowledge. Only one reconnaissance/planning-type karst inventory report is known to have been completed in the region—for the Herrick Creek Watershed.

2.2 Review of Karst Inventory Reports

Reports reviewed for this section include the typical karst inventory reports completed for the B.C. Ministry of Forests and the forest industry, and examples of karst inventory reports from the rest of Canada and worldwide. The reports were examined for the following criteria:

- inventory objectives and end users,
- inventory scale,
- office review methods/materials (British Columbia reports only),
- field inventory methodologies used, and
- reporting standards/presentation (British Columbia reports only).

The review was not intended to criticize or evaluate particular methodologies or reporting styles, but rather to assess current activities. It is not anticipated that future karst inventory reports for British Columbia should be completed in a standard format, but rather that they should all include critical factors required to assess a particular karst area in a scientifically sound manner. Tables were developed to review the karst inventory reports for the criteria listed above (Tables 2 and 3). Some assumptions were made during the review process, particularly in terms of understanding objectives (not always clearly stated), the source of materials used (not always referenced), and the conclusions and recommendations made.

A general letter was sent to all regional and district offices of the B.C. Ministry of Forests, and interested parties overseas, introducing the KISP project and requesting inventory reports for review. A homepage with an annotated questionnaire survey was developed to assist correspondence with interested parties (**http://www.island.net/~subterra**).

Almost all of the British Columbia karst inventory reports reviewed were from the Port McNeill and Campbell River Forest Districts of

TABLE 2 *Review of typical karst inventory reports for the Ministry of Forests and forest industry in British Columbia*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
REPORT TYPES OR CATEGORIES																
Cave investigations (management)		X	X			X		X	X	X	X	X	X	X	X	X
Surface karst (cave entrance) management	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
Impact assessment														Z		
Karst aquifer/hydrological evaluation																
Karst ecology/biota evaluation																
Recharge/catchment area delineation								X								
Karst vulnerability/sensitivity assessment			X					X			X					
DATE OF PROJECT																
1982–1987																
1988–1992		X												X		
1993–1998	X		X	X	X	X	X	X	X	X	X	X	X		X	X
ESTIMATED PROJECT COVERAGE																
Regional (>1:200 000)																
Intermediate (>1:75 000 to <1:200 000)																
Planning (>1:15 000 to <1:75 000)											X	X				X
Detailed (>1:2500 to <1:15 000)	X	X	X	X	X	X	X	X	X	X			X		X	
Very detailed (< 1:2500)														X		
REPORT SETUP/DESCRIPTORS																
Cover/title page	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Date	Z	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Location	Z	Z	X	X	X	X	Z	X	X	X	X	X	X	X	X	X

TABLE 2 *(Continued)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Prepared for	Z	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Prepared by	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Abstract or summary	X	X	X				X	X	X	X	X		X			
Acknowledgements		X	X				X	X	X	X	X					X
Table of contents	X	X	X				X	X	X	X	X		X	X		X
Section headings	X	X	X	X	X	X	X	X	X	X	X		X	X		X
Page numbers	X	X	X			X	X	X	X	X	X	X	X	X	X	X
OBJECTIVES OF INVENTORY																
To manage forest resources	X		X			X		X	X	X	X	X				X
To increase awareness of karst resources	X	X	X			X	X	X	X	X	X	X	X	X		X
To inform land use decisions													X			
To investigate karst groundwater systems																
To assess sensitive recharge zones			Z					X					Z			
To protect domestic water supplies																
To protect downstream resources/fisheries													Z			
To assess/manage/protect caves		Z				Z	Z	Z	X	X	X	Z	Z	X	X	X
INTRODUCTION AND BACKGROUND																
Site location	X	X	X			X	X	X	X	X	X		X	X	X	X
Terms of reference/scope of work			Z			Z	X	X	X	X	X		X	X		X
Local knowledge		X	X				X	X	X	X	X		X	X		X
Pre-cutblock/road layout	X	X	X				X			X	X					
Post-cutblock/road layout				X	X	X		X	X							

TABLE 2 *(Continued)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	Fl-A19240 1st	Block Dl-10	Area 149	Fl-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Proposed harvesting methods																
Previous karst inventory work/reports		X	X					X	X	X	X		X	X		X
Regional geomorphology/geology	X	Z	Z			Z	X	Z	X	X	Z		Z	X		X
Biophysical setting	X		X			Z		X	X		X	Z		X		
Hydrological setting	X					X		Z			Z		X	X		
OFFICE REVIEW MATERIALS																
Topographical maps/data	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
Bedrock geology maps	X	X	X			X	X	X	X	X	X		X	X		X
Air photos	X	X					X	X	X	X	X		X	X		
Surficial geology/terrain maps		X	X					X								
Standards and protocols	Z	X	Z			X	X	X	X	X	X		X			
Hydrological/rainfall data																
Forest cover maps												X				
Terrestrial ecosystem/vegetation/soil maps																
Archeological surveys																
Fish/wildlife habitat maps																
Digital satellite imagery																
Photographs/videography																
Other reports (terrain stability, windthrow)																
Books and periodicals																
Unpublished records (e.g., cave surveys)																

TABLE 2 *(Continued)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
FIELD INVENTORY METHODOLOGIES																
Field personnel names	X	X	X			X	X			X					X	X
Date/time/length of field work	Z	X	X			X	X		X	X						
Weather conditions during field work						X										
Aerial searching											Z					
Ground searching - walkabout															X	
Ground searching - judgemental traverse			X					X	X	X	X	Z	X			
Ground searching - single transect												X				
Ground searching - multiple traverses/grids	X	X		X	X	X	X									
Subsurface inspection - exploration																
Subsurface inspection - MOF classification	X	X	X				X	X	X	X	X	X				
Subsurface inspection - cave survey/map			X			X		X	X	X						
Subsurface - specific resource investigation																
Description of field markings/flagging	X			X	X					X	X	X				
Field instrument description (e.g., compass)		X	X							X						
Water tracing with dyes																
Water tracing with dyes and collectors																
Water flow measurements																
Water sampling for chemistry																
Water sampling for ph, Eh, etc.																
GPS use																

TABLE 2 *(Continued)*

		Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	Fl-A19240 1st	Block Dl-10	Area 149	Fl-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
RESULTS																	
Data presentation -	Tabular		X	X			X	X	X	X	X	X		X			
	Forms (e.g., FS 311)	X	X	X				X	X	X	X	X					
	Narrative	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Map presentation of karst features -	Polygons	X		X					X			X		X	X		
	Lines			X					X			X		X	X		
	Points	X	X	X	X	X		X	X	X	X	X	X	X	X	X	
	Symbol convention		X	X				X	X	X	X	X		X			
PRESENTATION OF DATA																	
TABLES			X	X			X	X	X	X	X	X		X			
Descriptive headings			X	X			X	X	X	X	X	X		X			
Numbered sequentially			X	X			X	X	X	X	X	X		X			
MAPS/FIGURES		X	X	X			X	X	X	X	X	X	X	X	X	X	
Digitally drafted			X	X				X	X	X	X	X		X	X		
Manually drafted		X			X	X	X						X			X	
Title/heading		X	X	X			X	X	X	X	X	X		X	X	X	
Scale		X	X	X	X	X	X	X	X	X	X	X		X	X	X	
North arrow		X	X	X			X	X	X	X	X	X		X	X	X	
Legend		X	X	X			X	X	X	X	X	X		X	X		
Traverse/grid locations					X	X						X					
DATA ANALYSIS METHODOLOGIES																	
Cave/karst management zones		Z												X	X		

TABLE 2 *(Continued)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	FI-A19240 1st	Block DI-10	Area 149	FI-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Qualitative cave/karst potential																
Hydrological analysis																
Recharge area delineation			Z					Z					Z			
Karst vulnerability assessment			X					X			X					
GIS mapping techniques																
DISCUSSION AND/OR INTERPRETATION	X	X	X			X	X	X	X	X	X	X	X	X		
CONCLUSIONS	X	X	X	Z	Z	X		X	X	X	X	X	X	X		X
RECOMMENDATIONS	X	X	X	Z	Z	X		X	X	X	X	Z	X	X	X	X
ADDITIONAL DATA/INFORMATION																
REFERENCES	X	X	X				X		X	X	X		X	X		X
BIBLIOGRAPHY	X															
GLOSSARY	X	X	X			X	X		X	X	X		X	X		X
APPENDICES	X	X	X			X	X		X	X	X		X	X		
PHOTOGRAPHS		X	X			X	X		X		X	X				
Numbered		X	X				X				X					
Annotation/descriptions		X	X			X	X				X	X				
VIDEOGRAPHY																
Verbal narrative																
LIMITATIONS																
Confidentiality statements		X	X				X				X					
Accuracy and reliability statements																
Statement on any missing information																

TABLE 2 *(Concluded)*

	Cross River	Artlish River	Ransom Lake	022-Artlish	07- Artlish	NE-60/AR-165	Fl-A19240 1st	Block Dl-10	Area 149	Fl-19240 2nd	Klaskish	Nawitti	Glory'ole	Upana	Chapple	Duncan FD
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Limiting field conditions (weather, windthrow)						X										
END USERS																
B.C. Ministry of Forests	X	X	X				X			X	X	X	X	X	X	X
Other government forestry agencies																
Municipal/regional land-use planners																
Government environmental agencies																
Forest industry				X	X	X		X	X							
Public																
Cavers																
Research agencies																

A Cross River cave/karst inventory. Prepared for Ministry of Forests by Island Karst Research. Spring 1993. Unpublished report. 22 p.
B Artlish River caves/karst inventory: Report on the ground search of Karst Feature Areas 2,3,4 and 5 Conducted for B.C. Ministry of Forests. September 1990.
C Cave/karst inventory in and about Ransom Lake, F.L. A19231. Conducted for Pacific West Coast Contract Logging. June 1996.
D Cave/karst features inventory report for Block 022, Artlish, F.L. A19231. Prepared for Pacific Forest Products Ltd. June 1993.
E Cave/karst features inventory report for Block 07, Artlish, F.L. A19231. Prepared for Pacific Forest Products Ltd. July 1994.
F Cave inventory of Block NE-60 and Block AR-165. Prepared for Canadian Forest Products. January 1994.
G Cave/karst features inventory report for F.L. A19240. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. Report date: March 1993.
H Cave/Karst inventory in and about Block DL-10. Conducted for Canadian Forest Products Limited, Englewood Logging Division. Report date: September 1994.
I Cave/karst inventory in Area 149, F.L. A19240. Conducted for Western Forest Products Ltd. September 1995.
J Cave/karst ground search for F.L. A19240. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. March 1994.
K Klaskish and East Creek karst survey. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. July 1996.
L Cave/karst features inventory, Nawitti Lake and Kains Lake Forest Area. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. March 1993.
M Karst mapping for the Glory 'Ole Area Management Plan. Conducted for B.C. Ministry of Forests, Port McNeill Forest District. September 1994.
N Resource inventory and management plan for the Upana Caves, T.F.L 19, Kyuquot Provincial Forest. Prepared by the Campbell River Forest District. March 1988.
O Report on caves in the Chapple Inlet area of Princess Royal Island by Christopher Gordon. February 1996.
P Cave/karst inventory of the Duncan Forest District, B.C. Ministry of Forests. March 1993.

NOTE:
X Clearly apparent
Z Partially apparent (some judgement involved)

TABLE 3 *Review of other karst inventory reports in Canada and worldwide*

	Tuxekan	Lab Bay	Grand Rapids	New Melons	Cullagh	Interlake	White Ridge	Cougar	Nahanni	Great Bear	Snaring	Jags	Maligne	Quatsino	Regions	Grottes	Coronation
	CC	**DD**	**EE**	**FF**	**GG**	**HH**	**I I**	**JJ**	**KK**	**LL**	**MM**	**NN**	**OO**	**PP**	**QQ**	**RR**	**TT**
REPORT TYPES OR CATEGORIES																	
Cave investigatons (management)			X	X		X			X		X			X		X	
Surface karst mangement	X	X	X			X		X	X	X	X	X			X	Z	
Impact assessment				X				X		X							
Karst aquifer/hydological evaluation							X			X			X	X			
Karst ecology/biota evaluation						X		X				X					X
Water tracing for recharge area delineation	X	X			X												
Karst vulnerability/sensitivity analysis	X	X															
DATE OF PROJECT																	
Pre-1987				X			X	X	X	X	X		X	X	X		
1987–1992			X			X						X					
1993–1998	X	X			X											X	X
RANGE OF PROJECT SCALE																	
Regional (>1:200 000)														Z	X		
Intermediate (>1:75 000 to <1:200 000)		X								X		Z	Z		X		Z
Planning (>1:15 000 to <1:75 000)		X	Z	Z	X		X		X	X	Z						
Detailed (>1:2500 to <1:15 000)					X	X		X									
Very detailed (< 1:2500)			X	X		X		X	X		X	X	X	X		X	Z
STATED OBJECTIVES																	
To manage forest resources	X	X															
To increase awareness of karst resources	X	X	X			X	X	X	X		X	X	X	X	X	X	X
To inform land-use decisions				X	X			X		X		X					
To investigate karst groundwater systems										X			X	X			

TABLE 3 *(Continued)*

	Tuxekan	Lab Bay	Grand Rapids	New Melons	Cullagh	Interlake	White Ridge	Cougar	Nahanni	Great Bear	Snaring	Jags	Maligne	Quatsino	Regions	Grottes	Coronation
	CC	**DD**	**EE**	**FF**	**GG**	**HH**	**I I**	**JJ**	**KK**	**LL**	**MM**	**NN**	**OO**	**PP**	**QQ**	**RR**	**TT**
To assess sensitive recharge zones	Z	Z			X												
To protect domestic water supplies																	
To protect downstream resources/fisheries	Z	Z															
To assess/manage/preserve caves																	
FIELD INVENTORY METHODOLOGIES																	
Aerial searching									X		X	X					
Ground searching - walkabout						X					X	X			X	X	
Ground searching - judgemental traverse	X	X					X	X	X	X				X			X
Ground searching - single transect																	
Ground searching - multiple traverses/grids																	
Subsurface inspection - exploration																	
Subsurface inspection - MOF classification																	
Subsurface inspection - cave survey/map				X		X	X	X	X		X			X	X	X	
Subsurface - specific resource investigation				X		X											
Field instrument description (e.g., compass)																	
Water tracing with dyes					X												
Water tracing with dyes and collectors	X	X					X						X				
Water flow measurements					Z		X			X			X				
Water sampling for chemistry							X			X			X	X			
Water sampling for ph, Eh, T, etc.							X			X				X			
GPS equipment																	
DATA ANALYSIS METHODOLOGIES																	
Cave/karst mangement zones																	
Qualitative cave/karst potential																	

TABLE 3 *(Concluded)*

	Tuxekan	Lab Bay	Grand Rapids	New Melons	Cullagh	Interlake	White Ridge	Cougar	Nahanni	Great Bear	Snaring	Jags	Maligne	Quatsino	Regions	Grottes	Coronation
	CC	**DD**	**EE**	**FF**	**GG**	**HH**	**I I**	**JJ**	**KK**	**LL**	**MM**	**NN**	**OO**	**PP**	**QQ**	**RR**	**TT**
Hydrological system analysis							X			X			X	X			
Recharge area delineation	X	X			Z												
Karst vulnerability assessment	X	X															
GIS mapping techniques	X	X			X												
PRINCIPAL END USERS																	
B.C. Ministry of Forests																	
Other government forestry agencies	X	X															X
Municipal/regional land-use planners																	
Government environmental agencies				X	X			X	X		X	X			X	X	
Public and cavers					X	X										X	
Research agencies							X						X	X			X

CC Karst vulnerability assessment report, Tuxekan Island, Alaska. 1994. Completed for the USDA, Forest Service.
DD Final karst vunerability assessment report, Phase II – Site specific verification study, Lab Bay environmental impact statement, Prince of Wales Island, Alaska. 1995. USDA, Forest Service.
EE Karst investigations in Palaeozic carbonates of the Grand Rapids Uplands and Southern Interface. Manitoba Energy and Mines. Report of Field Activities. 1988. pp. 143–156.
FF An inventory and evaluation of the cave resources to be impacted by the New Melons resevoir project, Calaveras and Tuolumne Counties, California. Submitted to the Sacramento District Office of the U.S. Army Corps of Engineers, 1978.
GG Environmental change and land management in the Cuilagh karst, Northern Ireland by John Gunn, pages 195-207. In "Geomorphology and Land Mangement in a Changing Environment." Edited by D. McGregor and D. Thompson. 1995.
HH Caves in Manitoba's Interlake Region. From surveys conducted by the Speleogical Society of Mantioba. 1991.
II The Hydrology of an alpine karst, White Ridge, Vancouver Island. Unpublished MSc Thesis. K. Ecock. McMaster University. 1994.
JJ Cougar Valley – Nakimu Caves, Glacier National Park, British Columbia. Volumes I and II. Resource inventory and environmental impact assessment. Prepared for Parks Canada by Hardy Associates Ltd. 1978.
KK Final report upon cavern and allied researches in the First Canyon Park, S. Nahanni River, N.W.T. Completed for National Historic Parks Branch by Cave and Karst Research Group of Canada. 1971.
LL Morphology, hydrology and hydrochemistry of karst in permafrost terrain near Great Bear Lake, Northwest Territories. National Hydrology Research Institute Paper No. 11. by R.O. van Everdingen. 1981.
MM Snaring karst exploration, Jasper National Park. Joiint project by Parks Canada and Alberta Speleological Society. 1984.
NN Alsaka research areas, 2: Limestone Jags. Gen. Tech rep. PNW-GTR-237. USDA, Forest Service, Pacific Northwest Research Station. 58 p.
OO Karst geomorphology and hydrology of the Lower Maligne Basin, Jasper, Alberta. Unpublished MSc thesis by M.C. Brown, McMaster University. 1970.
PP Karst development and groundwater flow in the Quatsino Formation, Northern Vancouver Island. Unpublished MSc thesis. W.R.P. Miles. McMaster University. 1981.
QQ Theme and resource inventory study of the karst regions of Canada. Completed for National and Historic Parks Branch by D. Ford and J. Quinlan. 1973.
RR Les grottes du sud-est du Nouveau-Brunswick. Open file 94-6, Natural Energy and Resources, New Brunswick.
TT Inventory and assessment of ecological relationships between cavernicolus (cave-associated) invertebrate species and their interactions in representative karst ecosystems on carbonate terrain in the Ketchikan area Tongass National Forest. Part II Coronation Island. Completed by Karst Biosciences, Kent Carlson. 1996.

NOTE:
X Clearly apparent
Z Partially apparent (some judgement involved)

Northern Vancouver Island. One karst inventory report was obtained from the South Island Forest District. No karst inventory reports were obtained from known interior karst areas such as Prince George or Nelson. No particular methods were involved in selecting reports for review other than to obtain a cross-section of inventories completed by a variety of workers/contractors.

Other karst inventory reports reviewed included government publications, consultant reports, and research theses completed for a range of end users in Canada and worldwide. No particular method was used in the selection of the reports other than availability and, if possible, some association with forestry activities. Some of the reports focused solely on one aspect of karst (e.g., hydrology, biota, caves). Reports reviewed included the following:

- two karst vulnerability assessment reports from Southeast Alaska,
- three theses investigating karst hydrology in British Columbia,
- two karst biota inventories from Southeast Alaska,
- two karst resource inventories—Canada-wide and South Nahanni River, NWT,
- a geomorphology, natural resource, and impact assessment for Nakimu Caves, British Columbia,
- cave-oriented inventories, Manitoba (x2), New Brunswick, and Jasper National Park, and
- a cave resource impact assessment from California.

2.2.1 Review findings for typical British Columbia karst inventory reports

The main objectives of the British Columbia karst inventory reports reviewed (Reports A to O) were to assist in the forest management of surface karst features, cave entrances, and cave systems. Little or no consideration was given in the reports to karst hydrological systems, karst biota, or downstream resources and impacts. An attempt was made in three reports (C, H, and K) to assess karst vulnerability and recharge areas. Most of the reports were completed in the last 5 years. Most were completed at a detailed operational scale of 1:5000; however, two reports (K and L) were completed at the planning-level scale of 1:20 000. Two cave/karst management plans and one cave report were also included in this review (Reports M, N, and O, respectively).

Background information in the reports was confined to topographic and bedrock maps. It was assumed that airphotos were used in most cases; however, they were not always specifically referenced with a flight line, number, and year. Terrain maps and surficial geology maps were only sparingly used (Reports B and C). Other indirect background information (e.g., hydrological/rainfall data, fish habitat maps) was not addressed. The principal government standards and protocols used for the completion of the inventory reports included:

- The Cave/Karst Management Handbook for the Vancouver Forest Region, 1994, and
- A Method to Manage the Cave/Karst Resource Within British Columbia's Provincial Forest: Interim Guidelines for the Vancouver Forest Region, 1990.

Ground searching, by either judgemental traverses (based on a predetermined rationale of karst distribution) or multiple-transect grids, were the main field methodologies used (see Section 2.1). Most of the subsurface inspection work included a combination of classifying caves according to B.C. Ministry of Forests requirements (e.g., the F311 form) and maps covering the entrance and a portion of the initial cave area. No dye tracing was carried out to investigate hydrological flows. Background details of field work were generally incomplete, missing such items as weather conditions, number of days/hours in the field, and field instruments used.

The standard of reporting varied considerably, both in terms of report content and presentation. General locations of areas of interest were usually described adequately, but regional location maps were not present in all cases. In some cases, the objectives or scope of the work, detailing why the inventory was being carried out, were not present. Very few details were provided about the types of proposed forest activities, (e.g., harvesting methods and road construction techniques). Road locations appeared to be rarely assessed. In most cases, the regional geological and geomorphic setting was only partially described, with little description of limestone lithology or bedrock structures. Some bedding measurements were recorded in some reports, but no other structural bedrock data (e.g., joints/faults) were typically present.

Map presentation varied from hand-drafted maps with point locations for surface karst features to coloured digital maps with polygons depicting karst vulnerability ratings. Some maps had no legends, titles, or north arrows. The traverse or grid locations for areas covered by the inventories were commonly not present on maps, and were found only in Reports D, E, and K. This is important for assessing the coverage of a particular karst unit/cutblock/road, in order to quickly evaluate which areas have been examined and which have not.

In general, very little analysis of the karst data was done; for example, correlating subsurface features with surface features, developing management zones, providing karst vulnerability assessments, or delineating recharge areas. Exceptions to this were Reports C, H, and K, where vulnerability mapping and some recharge area delineation were carried out, and Report M, where management zones were delineated. Most reports provided recommendations for forestry activities that primarily focused on prescriptions for surface karst features, cave entrances, and cave systems.

Almost no reports provided information on any limitations of the work. For example, few detailed the areas not covered by the inventory, the reliability of the field work completed, or any limiting factors such as bad weather. Data confidentiality statements were provided in Reports B, C, G, and K.

It is apparent that the focus of most of the inventory reports was to locate and manage for specific surface karst features, cave entrances, and cave systems. Very little focus was placed on the karst system as a whole, and there was minimal recognition of karst hydrology or biota as part of a standard inventory process.

No attempts were made to analyze any of the inventory data, such as developing a suitable or simple geological/geomorphological/hydrological model for the karst system. No dye tracing was carried out, nor were any attempts made to try and understand the subsurface hydrological system. No use was made of cross-sections to interpret or understand the subsurface extent and three-dimensional nature of the karst units.

2.2.2 Review findings for other karst inventory reports in Canada and worldwide

The general objectives of these other karst inventory reports varied significantly. Some focused on specific aspects of karst (e.g., biota, hydrology, caves), while others were very broad in scope, covering a range of karst parameters. The scales also varied from regional or countrywide (e.g., Report II) to very site- and cave-specific (e.g., Report RR). The underlying objective of most reports was to increase the general awareness of karst resources. However, each report had project-specific objectives. For example, the inventories from southeast Alaska (Reports CC and DD) focused on forest management, Reports FF and GG were to help with land management decisions for the protection of cave resources, and Reports EE and RR were concerned with cave exploration within karst areas.

In terms of ground-searching methodologies, most surface karst areas were examined by a combination of walkabout and judgemental traverses; no transects or grid systems were used. Aerial searching was conducted in some of the more regional and inaccessible areas, and was used for identifying likely sites for ground searches. Cave surveying and mapping were the principal subsurface inspection methods, and were used for some of the regional inventories (e.g., Report KK). Water tracing with dyes was used in the hydrology-specific inventories (e.g., Reports II and PP), in the southeast Alaska vulnerability assessment reports (Reports CC and DD), and in a cave impact assessment report (Report GG). Water chemistry and flow measurements were taken only for the hydrology-specific reports (Reports II, LL, and OO). The end users of these reports were principally government forestry or environmental agencies, and research institutes.

Karst vulnerability analysis, recharge delineation, and GIS mapping methods were used only in the more recent reports (CC, DD, and GG). Detailed hydrological analysis was carried out only for the hydrology-specific reports.

2.3 Karst-related Information in Government Publications of British Columbia

The first objective of this sub-section is to assess and synthesize the level of karst inventory–related information currently available in the publications of British Columbia government agencies. The second is to determine what inventory methodologies could be either incorporated into the KISP or, alternatively, improved to increase the awareness of karst systems. A variety of British Columbia government publications was examined, including publications of the Resource Inventory Committee (RIC), publications of BC Environment, Forest Practices Code (FPC) Guidebooks, and British Columbia Geological Survey documents. The Cave/Karst Management Handbook for the Vancouver Forest Region, 1994, and the FPC Cave Management Guidebook (draft) also provide guidance for karst inventories (see Section 2.1), but focus mainly on cave classification and management, an area outside the scope of this project.

2.3.1 Resource Inventory Committee (RIC)

A manual and digital search (by ForestViews software) was carried out on the RIC to identify any information related specifically to karst, limestone, carbonate, or caves. Publications considered to have relevance to karst inventories were:

- Guidelines and Standards to Terrain Mapping in British Columbia,
- Standards for Terrestrial Ecosystems Mapping in British Columbia,
- Specifications and Guidelines for Bedrock Mapping in British Columbia,
- Terrain Stability Mapping in British Columbia: A Review and Suggested Methods for Landslide Hazard and Risk Mapping,
- Terrain Database Manual: Standards for Digital Terrain Data Capture in British Columbia (interim), and
- Groundwater Mapping and Assessment in British Columbia, Vols. I and II.

Guidelines and Standards to Terrain Mapping in British Columbia (GSTM-BC) The principal objective of the GSTM-British Columbia is "to define common standards and methods for the collection and presentation of terrain data." The guidelines show how this information can be used to develop secondary derivative maps (e.g., geological hazard, slope stability) for resource and land management purposes. The publication is closely linked to the Terrain Classification System of British Columbia (TCS-BC) and the Terrain Database Manual for British Columbia (TDM-BC). Karstification processes and karst features are briefly mentioned throughout. The specific terms: karst, karst depression, karst processes, limestone pavement, and sinkholes, are defined in the glossary. Features specific to karst are included in the symbols appendix at the end of the publication, and include those for cave, large sinkhole/karst depression, and small sinkhole/karst depression. Cartographic definitions and details for defining each of the features are provided.

A series of hydrological and hydrogeological features is also outlined. These include: groundwater divide, surface water divide, groundwater flow (various scales and levels of certainty), springs (various types), disappearance of surface drainage, reappearance of surface drainage, surface water drainages (dry, intermittent, perennial), surface water gullies (dry, intermittent, perennial), and swamps (big and small). These hydrological features do not appear karst-specific, but they could have some potential use for the mapping of karst hydrological systems/catchment areas.[4] Most of the methodologies for project organization, field work, and map compilation could be used to assist in the development of karst mapping/inventory procedures, particularly at the planning scales of 1:50 000 and 1:20 000. Details on how terrain mapping methods could be used at the planning level of karst inventory are provided in Section 4.0.

Standards for Terrestrial Ecosystems Mapping in British Columbia (STEM-BC) The STEM-BC is similar to the GSTM-BC in that karst is mentioned only in passing. It is primarily noted under the bioterrain mapping methods in Appendix B, where limestone or carbonate is

[4] Karst catchment – the subaerial surfaces upon which water contributes to the recharge of a karst aquifer (not to be confused with topographic watersheds and drainage basins).

identified as a bedrock unit that can contain "caves, karst, large cracks and joints, fault lines" as well as "unique flora, fauna and habitat." Bioterrain mapping methodologies rely heavily upon surficial characteristics and processes taken from the Terrain Classification System of British Columbia (TCS-BC). A useful table for the classification of sedimentary rocks is included in Appendix K. Two mentions of carbonate seepages are identified in Appendix J under the site series modifiers for IDFdm206BH- Scrub birch-Horsetail and IDFdm207SHSxw-Horsetail.

Specifications and Guidelines for Bedrock Mapping in British Columbia (SGBM-BC) The SGBM-BC publication describes a methodology for data collection and presentation, and for the production of geological bedrock maps. Karst is not specifically mentioned; however, it does recommend the use of standard geological texts for the classification of carbonates (e.g., Dunham 1962; Folk 1962). Many of the project planning procedures, field survey methods, data synthesis ideas, and map production techniques could be used for karst inventory mapping methods at the reconnaissance and planning levels (see Sections 3.0 and 4.0, respectively).

Terrain Stability Mapping in British Columbia: A Review and Suggested Methods for Landslide Hazard and Risk Mapping (TSM-BC) The TSM-BC publication is closely linked to the GSTM-BC and TCS-BC publications. No specific reference to karst is made within the TSM-BC; however, some of the mapping concepts and methodologies may have applications in developing the KISP. Of particular interest is Section 2.2, in which the various definitions of hazard, consequence, and risk are outlined. These are defined with reference to landslides, but could also be considered with respect to karst vulnerability (see Section 6.0).

Terrain Database Manual: Standards for Digital Terrain Data Capture in British Columbia (TDM-BC) This manual was compiled in conjunction with the GSTM-BC, STEM-BC, and TSM-BC. Its purpose is to establish "procedures and rules for the digital capture, storage and delivery of terrain data for GIS and data base systems so that they are suitable for digital data exchange between business, industry, the public and government." The manual covers the entry of terrain information on a terrain data form, digital data specifications for terrain mapping in GIS, and terrain data entity relationship diagrams.

Groundwater Mapping and Assessment in British Columbia, Vols. I and II (GMA-BC) These documents describe a dual-level groundwater mapping and assessment process that considers climatic, hydrologic, geologic, topographic, ecologic, and soil factors in hydrogeological settings. The Level 1 assessment gives an approximation of the groundwater regime and a qualitative overview of groundwater conditions. The parameter measurements are derived from available information, without detailed reconnaissance. The system relies on the DRASTIC model; an overlay and index method combining maps of parameters considered influential in contaminant transport. The DRASTIC acronym stands for the following parameters: D - depth to water; R - net recharge; A - aquifer media; S - soil media; T - topography or slope; I - impact of vadose zone media; and C - hydraulic conductivity of the aquifer.

The Level 2 assessment is a multi-phased study, beginning with the acquisition of existing information. The information search and analysis tasks are followed by a field reconnaissance survey of controlling factors. Water wells and springs are inventoried to determine yield characteristics and hydrochemistry. Recommendations for further study and assessment are also prepared. The DRASTIC model could potentially be used to assess the vulnerability of karst groundwater during forest management activities. Most of the parametric values for a Level 1 assessment are readily determined from existing sources of information, such as geological maps, topographical maps, terrain maps, air photos, geological reports, climatological records, spring records, and published speleological investigations. However, some workers in karst hydrology (e.g, Aley and Aley 1993) have found that while DRASTIC demonstrates that karst areas are at risk to groundwater contamination, it is not detailed enough for making integrated land-use decisions.

2.3.2 BC Environment publications

The Terrain Classification System for British Columbia: Version 2.0 (TCS-BC) outlines a scheme for "the classification of surficial materials, landforms and geological processes," and is a fundamental part of the GSTM-BC and STEM-BC. Version 2.0 was completed in 1997, and is an updated and expanded edition of a 1988 publication. It is specifically designed to provide an inventory of terrain features in a landscape to show their spatial distribution, extent, and location. The fundamental feature of the system is the "terrain unit symbol," which is comprised of a group of letters, so arranged that they provide information on the characteristics of a particular terrain polygon. This information can include descriptions of surficial material type and texture, surface expression, geological processes, and qualifying descriptors.

The symbol "-K" is used as a specific process modifier at the end of the terrain unit symbol to identify karstification on soluble bedrock, and is intended to include a broad variety of karst features (e.g., uvalvas, caves, surface etching, and limestone pavements). Of particular interest to the KISP are the "geomorphological process subclass codes" that are attached at the end of the process modifiers for mass movement (-R), avalanches (-A), fluvial (-F), and permafrost (-X). These subclass codes provide "space" in the terrain unit symbol for additional qualifiers regarding geomorphic processes, and could be possibly adapted, in a rudimentary fashion, to indicate the intensity of karst development. Bedrock classification codes have also been added to the updated version and provide detailed descriptors for various types of carbonate bedrock. The codes are intended to be added to the end of the "R" symbol that is used to indicate the presence of bedrock. Phase 2 of the planning-level karst inventory describes modifications to the TCS-BC that could be used to include further karst information (see Section 4.3).

2.3.3 Forest Practices Code (FPC) guidebooks

FPC Guidebooks are limited in their mention of karst inventory–related information. Most of the related material is in the Cave Management Guidebook (draft). However, specific aspects (indicated in italics) of other FPC Guidebooks could have some uses for karst inventory methodologies:

- Riparian Management Area Guidebook (December 1995) - *Stream, wetlands and lake classification. Channel width measurements.*
- Community Watershed Guidebook (October *1995) - Water quality monitoring.*
- Gully Assessment Procedure Guidebook (December 1995) - *Methods for measuring gully sidewalls and channels. Holistic system approach to evaluating potential gully hazards and their impacts.*
- Coastal Watershed Assessment Procedure Guidebook (September 1996) - *Measurement of stream flow and catchment areas.*
- Interior Watershed Assessment Procedure Guidebook (September 1995) - *Measurement of stream flow and catchment areas.*
- Hazard Assessment Keys for Evaluating Site Sensitivity to Soil Degrading Process Guidebook (June 1995) - *Methods for measuring soil types, thickness, texture, drainage, slope gradients, and slope characteristics*.
- Mapping and Assessing Terrain Stability Guidebook (April 1995) - *Terrain survey intensity levels, map scales, classification and mapping conventions, and terrain reports*.
- Fish Stream Identification Guidebook (July 1995) - *Methods for identifying fish streams. Measurement of channels, gradients, and reaches; and need for fish surveys.*
- Channel Assessment Procedure Guidebook (December 1996) - *Identifying and classifying surface channel reaches.*
- Biodiversity Guidebook (1995) - *Managing calcareous bedrock exposures.*

It would be valuable to include more karst-related information in FPC guidebooks and other documents as they are revised over time.

2.3.4 British Columbia Geological Survey publications

Two useful "inventory-type" documents on karst bedrock materials have been completed by the British Columbia Geological Survey Branch:

- Limestone and Dolomite Resources in British Columbia by P. Fischl (Open File 1992-18), and
- Gypsum in British Columbia by S.B. Butrenchuk (Open File 1991-15).

Both publications document the occurrence of karst bedrock materials from a mineral exploration/mining perspective. Little or no mention of surface or subsurface karst features is made; however, the publications do document the extent, location, and type of bedrock materials present, and this would assist in determining the potential for karstification. References to more detailed maps and other site-specific publications/reports are also made. Overall, this information is considered essential for the reconnaissance-level karst inventory.

Another valuable source of information on karst bedrock materials can be found on the Ministry of Energy and Mines website under MINFILE, which contains maps and data on limestone, dolomite, and gypsum occurrences in British Columbia. It is also available in hard copy at Crown Publications, Victoria, B.C.

2.3.5 Other publications

Other government publications that could supply karst inventory–related information include:

- British Columbia archeological impact assessment guidelines. 1994. (*Specific mention of landforms, caves, and springs within inventory and assessment methodology.)*
- British Columbia archeological site inventory form guide. *(The site form and guide consider potential karst features such as rock shelters, caves, and springs.)*
- Green, R.N. and K. Klinka. A field guide for site identification and interpretation for the Vancouver Forest Region. 1994. *(Specific mention of limestone bedrock and calcareous soils.)*
- Pojar, J. and A. MacKinnon. Plants of Coastal British Columbia including Washington, Oregon and Alaska. 1994. *(Specific mention of carbonate bedrock exposures, calcareous soils, calciphilic plants, caves, and crevices.)*

3.0 PROPOSED RECONNAISSANCE- OR STRATEGIC-LEVEL KISP (1:250 000 MAP SCALE)

3.1 Objectives and Approach

The principal objective of the reconnaissance- or strategic-level karst inventory is to carry out a regional 1:250 000 scale evaluation for karst potential. This inventory level provides a coarse filter in which terrain underlain by karstified bedrock is flagged and identified. Bedrock geology maps can identify the principal bedrock types and units that are likely to develop karst (i.e., limestone and dolomite). However, they give no indication of the intensity of karst development or the importance of composite geological units in which the potential karst-forming bedrock may form a significant or small portion.

Suggestion 1. At a minimum, it should be possible to obtain regional bedrock maps covering a particular forest district or region and highlight the major carbonate formations. Without any further effort this will highlight the most likely karst-bearing formations.

It is not the intention of the reconnaissance karst inventory to delineate specific cave/karst sites or features, but rather to qualitatively rate terrain for potential karst development. These maps should not be used as direct overlays for planning- or operational-level inventories, because their regional scale (1:250 000) is unlikely to provide accurate polygon boundaries/lines at more detailed scales (e.g., 1:20 000 or 1:5000). Typically, the more detailed karst inventories will require field work and/or mapping to verify the distribution of the karst units and the degree of karstification.

A preferred approach for the reconnaissance-level inventory is to develop "karst potential" maps that can predict the likelihood and level of karst development within various geological units. The karst potential mapping can be used to evaluate two principal criteria:

- **Criterion 1** - the likelihood of karst-forming bedrock (e.g., limestone) to occur within a specific geological unit (or polygon), and
- **Criterion 2** - the intensity of karst development in a particular type of karst-forming bedrock.

Distinguishing between these two criteria could be useful during forest development planning. For example, a geological unit with a small well-karstifed limestone component may require different management/ planning strategies from a similarly rated geological unit that has a large, but poorly karstified, limestone component.

Suggestion 2. For reconnaissance-level inventories of karst potential, it is suggested that the two principal criteria are examined separately: Criterion 1, the likelihood of karst-forming bedrock to occur within a specific geological unit, and Criterion 2, the intensity of karst development in a particular type of karst-forming bedrock.

Additional confirmatory criteria, such as the presence of existing karst features, including both caves and surface karst features, can be used to add a level of confidence to the karst-potential rating of a particular unit. This evidence is highly dependent on the level of inspection/assessment for a particular unit or region.

Two previous reconnaissance cave/karst potential mapping projects have been carried out for the Vancouver and Prince Rupert Forest Regions using manual overlays and analysis (Stokes 1994; 1995a; 1995b). In both projects, 1:250 000 scale NTS topographic sheets were used as base maps, while bedrock geology maps of various scales (1:50 000 to 1:250 000) and ages were used to determine the presence of limestone-bearing units. The locations of these units were transferred as polygons onto the 1:250 000 base maps. The polygons were then split or grouped to assist in assigning cave/karst attribute data. These data included the character of the limestone unit, the number of known caves, the presence of major surface karst features, and the level of inspection. The information was tabulated for each map sheet, and a judgemental estimate from low to high cave/karst potential was provided for each of the polygons. These maps are currently used by some forest districts for strategic planning purposes, and, in some cases, for identifying priority sites for landscape- (planning-) level karst inventories. A trial reconnaissance cave/karst mapping project was carried out for northern Vancouver Island (Stokes et al. 1997) using digital (GIS) mapping techniques. This project showed how it was possible to combine and analyze digital bedrock polygons with cave/karst data, and produce maps for overall cave/karst potential and individual attributes (e.g., cave density).

3.2 Methodology

In order to develop a methodology for a regional-scale evaluation of karstification, the fundamental karst-forming process of water circulation and dissolution of bedrock must be closely considered. The greater the circulation, the greater the bedrock dissolution and the higher the intensity of karst development. Hydrogeologically, this process requires: i) water rich in carbon dioxide to recharge the system, ii) sufficient permeability to allow water flow to flush through the system, and iii) a discharge area to allow water to exit from the system.[5] The hydrogeologic setting of karst is difficult to determine directly; however, it is controlled by a variety of closely inter-related attributes, including:

- bedrock lithology (BL),
- tectonic/structural setting (tss),
- unit thickness (UT),
- topographic landform position (TP),
- vegetation cover (vc),
- soil cover (sc), and
- climatic setting (cs).

These attributes are relatively easy to determine at a regional scale from mapping, published, and local sources. However, they do not take into consideration the time factor, which might have played an important role in the karstification history of a particular unit. For example, the topographic landform setting provides an indication of present-day karst development in a particular unit, but earlier karstification of the unit might have occurred under a different topographic setting and hydrological regime. Climatic setting is similar to topographic position in that only the present-day climate can be easily assessed. For example, a unit in an area with high rainfall today might have had quite a different climate ten thousand, or even a thousand, years ago. Vegetation and soil cover attributes are closely related to climate and topographic position and hence, in some respect, are time dependent.

It is anticipated that the reconnaissance karst inventory will be an office-based study involving the collation and analysis of existing data. The suggested methodology includes the identification of karst-bearing units/polygons from existing 1:250 000 digital bedrock maps, and a rating analysis of the bedrock lithology combined with other available bedrock information (e.g., structural setting, unit thickness) and terrain and environmental attributes (e.g., climate, topographic position, vegetation/soil cover).

3.2.1 Preparation of digital base map and data

Regional 1:250 000 digital bedrock maps have been completed by the British Columbia Geological Survey Branch (BCGSB) for all of British Columbia. They are as follows:

- Vancouver Island - Open File 1994-6

[5] For simplicity, karst development in elevated or mountainous terrain was assumed as the likely dominant type of hydrological system in British Columbia. In this case, meteoric water and groundwater are the principal solutions present in the system. Other site-specific hydrological systems and waters can also develop karst, such as might be related to hydrothermal activity, acidification of waters related to sulphides, and fresh and salt water interactions during changes in land and sea levels.

- Cariboo/Chilcotin Area - Open File 1994-7
- Kootenay Area - Open File 1994-8
- Nass-Skeena - Open File 1994-14
- Mid-Coast - Open File 1994-17
- Northeast British Columbia - Open File 1995-6 and 1995-24
- Northwest British Columbia - Open File 1996-11

These maps were compiled as part of the BCGSB's Mineral Potential Project and depict the distribution of geological units and major structures. Information for the maps was obtained from previously published maps of the BCGSB and the Geological Survey of Canada, and from scientific journals, unpublished theses, mineral assessment reports, and property files. The open file reports can be obtained directly from Crown Publications, Victoria, B.C., or the maps can be viewed and downloaded from the Internet at the following web site: **http://www.em.gov.bc.ca/geology**. These digital bedrock data can be readily incorporated into GIS software such as ArcView. Various layers are present within the files, including coastline, lakes, islands, boundaries of geological units, structural features (e.g., faults), and labels for geological units. The base maps used for these compilations were taken from Digital Elevation Model (DEM) data reconstructed into a Terrain Resource Information Mapping (TRIM) format at a scale of 1:250 000. Additional information on topography, river systems, and roads can be obtained in digital format if required. Forest district and regional boundaries are provided on district recreation maps and 1:250 000 NTS maps.

3.2.2 Identification and rating of potential karst-bearing units

From the bedrock legends associated with the digital maps, all potential karst-bearing units should be identified and highlighted (see Figure 4). This should include both major limestone units and units within which limestone is a component. These units are usually classified according to a stratigraphic code system based on rock characteristics, fossil content, and geological age (see SGBM-BC, pp.29–34). In practice, the most likely units encountered at a regional mapping scale would be groups, formations, or complexes. The boundaries of these units can be highlighted, and the boundaries of other non-karst-bearing units digitally dissolved.

Geological input from bedrock geologists familiar with the region should be obtained to assist in the identification of potential karst-bearing units, particularly where limestone is a small component of a geological group or formation. Geologists from the Geological Survey of Canada, the British Columbia Geological Survey, the mining/exploration industry, or local consultants could provide useful information required for determining Criteria 1 and 2.

Criterion 1 Determination - Likelihood for karst-forming bedrock to occur In order to determine the likelihood of karst-forming bedrock (e.g., limestone) occurring within a specific geological unit (or polygon), it is necessary to estimate the proportion of limestone present. In practice this is difficult, as limestone within a unit can occur in a combination of ways, such as a series of thin layers or as isolated lenses. However, a geologist familiar with a particular unit should be able to provide a "best guess"

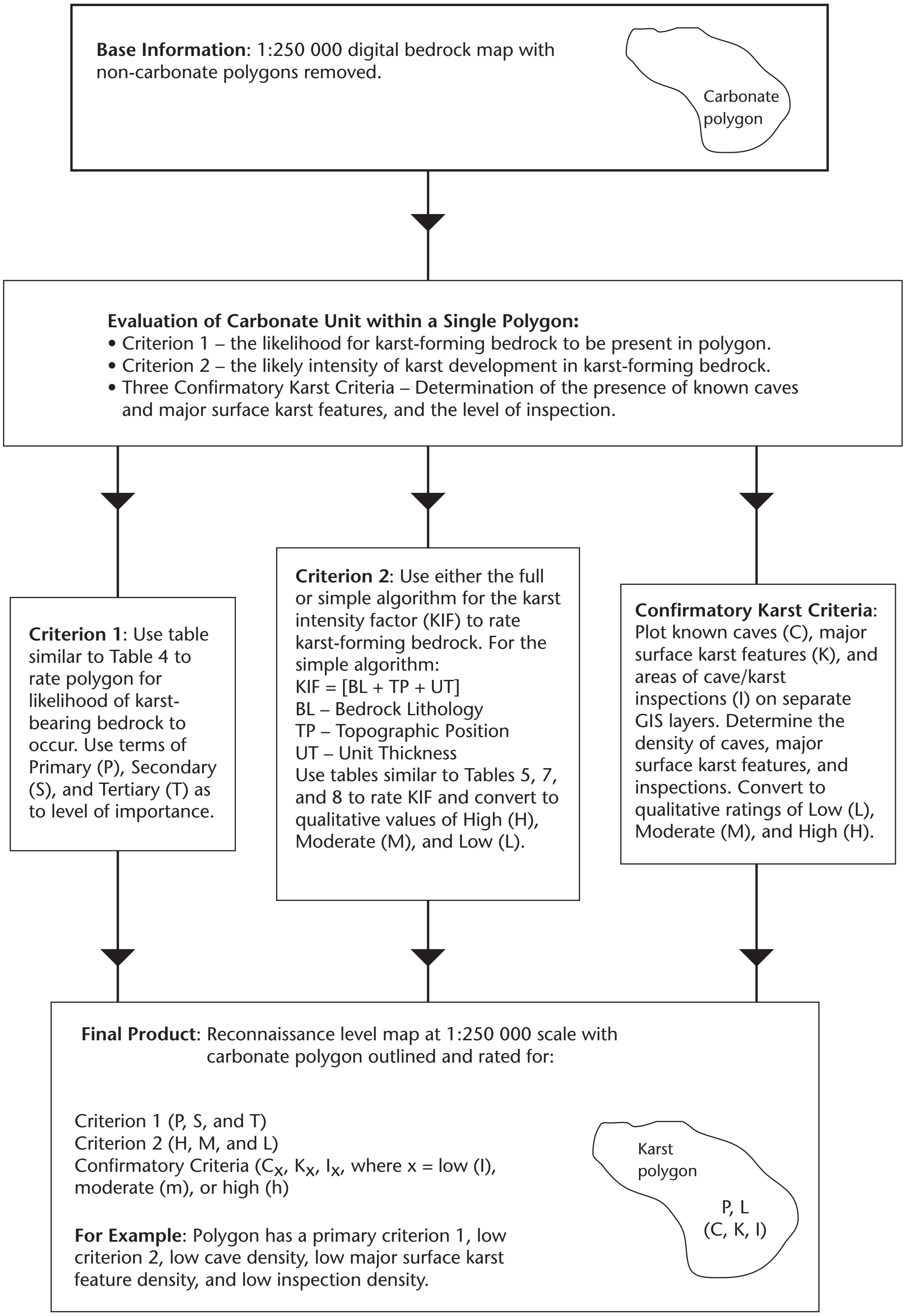


FIGURE 4 *Proposed reconnaissance-level KISP methodology.*

estimate. Typically, this might be in terms of a qualitative description (e.g., trace, minor, some, or major component). A preferable estimation would be as a percentage volume of a particular unit. It would be useful if some indication was given as to the reliability of this estimation. Table 4 provides a general guide that could be used for this purpose. It is suggested that the terms primary (P), secondary (S), and tertiary (T) be used as a qualitative rating system for this criterion. The terms primary, secondary, and tertiary are used to clearly signify the relative importance of the karst-bearing units.

TABLE 4 *The likelihood for karst-forming bedrock to occur within a geological unit (for use at a mapping scale of 1:250 000)*

Verbal estimate of karst-forming bedrock in geological unit	% estimate of karst-forming bedrock in geological unit	Qualitative rating
Major, Significant	50–100%	HIGH
Some	25–50%	MODERATE
Minor, Small	10–25%	LOW
Trace	<10%	NEGLIGIBLE OR VERY LOW

Criterion 2 Determination - Intensity of karst development In order to obtain a general idea of the potential intensity of karst development within a particular type of karst-forming bedrock, it is necessary to obtain some fundamental bedrock information on lithology type (purity/form), unit thickness, and structural setting. Bedrock lithology considers the closely related features of bedrock type (e.g., calcareous dolomite), form (e.g., massive, thick bedded, thin bedded, or interbedded), and purity (% CaCo3).[6] The first two features are typically present on map legends and in associated publications. In some places, these limestone rocks have undergone geochemical analysis so that quite accurate data on purity are available. An estimate of the stratigraphic thickness of a unit provides an indication of the amount of bedrock that is available for karst processes to work on; the greater the thickness, the more karst development that might be anticipated. Regional structural/tectonic settings can be used to provide some indication of the intensity of structural disturbance within a particular unit. This can be very approximately correlated to the amount of uplift, folding, faulting, and fracturing that might be anticipated. The greater the amount of structural disturbance, the greater the intensity of karst development (see Table 8). The above information is available from a variety of sources, such as geologists familiar with an area and government publications/open files/maps.

[6] In many cases, carbonate purity is reported in chemical analysis as %CaO (e.g., Fischl 1992). This can easily be converted to %$CaCO_3$ multiplying by a factor of 1.78.

Following information gathering, an analysis can be completed for a particular karst-forming unit using a numerical rating scheme and a suitable algorithm that combines all the attributes. Development of an acceptable set of tables and an algorithm will require further verification in a variety of carefully selected areas of British Columbia (e.g., Vancouver Island, Nelson, Prince George). For the purposes of discussion, a series of tables has been developed to outline the proposed methodology (see Tables 5 to 8). These tables have been completed for bedrock lithology, unit thickness, regional topographic position, and structural setting. Weightings for the subcategories of the attributes were provided directly into the tables. Details for climatic setting, topographic setting, vegetation, and soil cover could be obtained from the 1:250 000 biogeoclimatic maps of British Columbia. Further work is required to develop a numerical rating scheme for each of the biogeoclimatic units at the subzonal or zonal level, and to incorporate these data into the algorithm below.

In developing a suitable algorithm, bedrock lithology, topographic position, and unit thickness were considered the primary controls on karstification. The algorithm proposed, and the attributes taken into account, are as follows:

Karst Intensity Factor = [**BL + TP + UT + tss + vc + sc + cs**]

BL – Bedrock Lithology	**tss – tectonic/structural setting**
TP – Topographic Position	**vc – vegetation cover**
UT – Unit Thickness	**sc – soil cover**
	cs – climatic setting

By using this methodology, it should be possible to come up with a range of numerical values for the various karst-bearing units in British Columbia. These can then be converted into qualitative ratings for allocation to the appropriate polygons. It is suggested that the terms High (H), Moderate (M), and Low (L) be used to indicate the relative intensity of karst development.

Suggestion 3. An algorithm combining the main karst-forming attributes of bedrock lithology (BL), topographic position (TP), unit thickness (UT), tectonic/structural setting (tss), vegetation cover (vc), soil cover (sc), and climatic setting (cs) is proposed. It will provide an estimate of karst development or intensity for a particular bedrock unit.

If it is found that the general algorithm for the Karst Intensity Factor is too complex, it could be simplified to include only bedrock lithology, topographic position, and unit thickness as follows:

Karst Intensity Factor (Simple) = [BL + TP + UT]

TABLE 5 *Suggested karstification rating values based on bedrock lithology types (suitable for mapping at 1:250,000 scale)*

Lithology	**Number rating**	**Comments**
Massive, thick, or medium bedded limestone (>70% pure)	10	Most limestone units with a purity of greater than 70% limestone will develop good karst.
Thin bedded limestone (>70% pure)	9	Bedding planes play an important role in directing solutional networks.
Interbedded limestone with other sediments/volcanics	8	In many cases, interbedded limestone units can develop good conduit systems, but they are poorly connected between limestone beds.
Interbedded limestone with other	6	sediments/volcanics (<60%, but >20% limestone beds).
Interbedded limestone with other sediments/volcanics	3	(<20% limestone beds).
Argillaceous limestone (<20–30% clays)	5	Clay materials within limestone reduce the karstification process, potentially clogging channels.
Argillaceous limestone (>20–30% clays)	1	
Calcareous sandstone (<50% carbonates)	2	Extensive karst does not develop in this lithology, but it can form some features (dolines/caves).
Calcareous mudstone/siltstone (<50% carbonates)	0	Little karst development is anticipated.
Marble (metamorphosed limestone or dolomite)	7	In most cases, marble has a low porosity with negligible permeability, but most marble is jointed/faulted and can provide conduits for dissolution.
Dolomite	7	
Calcareous dolomite	8	
Dolomitic limestone	8	
Gypsum/Anhydrite	10	
Halite	10	

TABLE 6
Suggested karstification values related to unit thickness and ability to develop water circulation systems

Unit thickness (may or may not include non-karst bedrock)	Number rating	Comments
Thin (0–5 m)	1	Likely small, confined, and incomplete circulation systems.
Medium (5–20 m)	2	Small circulation systems with irregular water recharge and discharge.
Thick (20–100 m)	4	Moderate-size circulation systems with likely regular recharge and discharge.
Very Thick (>100 m)	10	Large circulation systems with complete recharge and discharge systems.

TABLE 7
Suggested karstification values based on regional topographic setting (suitable for mapping at 1:250 000 scale)

Regional topographic setting	Number rating	Comments
Upper elevation or peak areas of mountain ranges	5	In most cases, these areas occur at upper alpine/subalpine elevations. Significant hydrological head present. Excellent conditions for karst processes, providing that reasonable precipitation conditions are present.
Mid and upper slopes of mountain ranges	4	Variable soil thickness cover, but well-developed hydraulic heads. Good conditions for karst processes.
Raised plateaus	3	Can be laterally extensive, but likely to have deeper water table from ground surface than valley bottoms.
Lower slopes and valley bottoms	2	Thick surficial cover and water table near to ground surface, less hydrological circulation. Limited potential for karst processes.
Coastal flat or along shoreline	1	Relatively high water tables and less water circulation; exceptions would be where steep and high terrain occurs immediately on shore.

TABLE 8
Suggested karstification values based on regional structural setting (suitable for mapping at 1:250 000 scale)

Regional structural setting	Number rating	Comments
Subhorizonal or gently (<10°) dipping	1	In most cases, these areas would have undergone minor regional folding and faulting (thrust environments).
Moderately dipping (>10° to <30°)	2	Likely to have undergone some uplift, less faulting/fracturing than steeply dipping.
Steeply dipping (>30° to <60°)	3	Likely to have undergone significant uplift during folding and faulting.
Subvertical (>60°)	4	Likely in areas where extensive folding and faulting has occurred. Faults could be a major control on karst conduits.

3.2.3 Cave areas, major surface karst features, and inspection level confirmation criteria

Information about known cave areas and major surface karst features is useful in confirming that some level of karst development is present within a particular karst-forming unit. It could be particularly useful for verification purposes, especially in areas where limited geological information is available. However, these criteria are a function of the level of assessment/inspection of a particular karst-forming unit, and should not be considered factors that control karst processes. It is suggested that the three confirmation criteria—known cave areas, known major surface karst features, and inspection level—be treated and used differently from Criteria 1 and 2. It should be understood that these three confirmatory criteria may change with time as more cave areas and surface karst features are encountered. Information sources for these data could be obtained from existing karst inventory reports, local recreational cavers, and other industry or government files.

Other sources of information that could be used to confirm the presence of surface karst features include high-level airphotos and digital data from remote sensing satellites (e.g., infra-red, radar imagery; [Nossin 1989; Glasco 1992]). Only the largest individual karst landform features are discernable from space. Landsat MSS images, for example, provide a relatively coarse resolution of about 80 metres. However, patterns and textures associated with solution morphology in karst landscapes are discernable. Karst areas can exhibit a relatively homogeneous "pock-marked" texture when viewed in space images. The absence of a well-developed integrated surface drainage network is another reliable karst "signature." A series of commercial satellite launches is planned in the near future that will permit resolution approaching that used by military surveillance satellites. These kinds of images could prove useful in future karst inventory work.

Known cave areas with given geographic reference points could be incorporated into a suitable GIS layer, and overlain onto the polygons of karst-bearing units. Obvious issues related to security would have to be considered with the development of such a layer, and suitable precautions would be needed to ensure that the data were stored and used correctly. Possible methods for providing some level of security would be to use geographic reference points accurate to the nearest 250 m (or 1 mm on a 1:250 000 map). Cave areas would be used rather than specific cave entrances, because one cave system might have numerous entrances. By using the spatial distribution of known caves and the area of a particular karst-unit polygon, it should be relatively easy to come up with an approximate value for known cave density. Numerical ranges for cave density could be obtained and converted to a suitable qualitative rating system (e.g., high, moderate, or low density of known cave areas).

Details of known major surface karst features could be obtained and analyzed in a similar fashion to cave areas to give a qualitative density rating for these features. A separate GIS layer with point data could be compiled for this information. Typically, the types of major or macro surface karst features considered would include disappearing creeks/insurgences, significant sinkhole/grike areas, rock bridges, extensive epikarst pavements, and discharge areas. Minor or micro surface karst features would not be considered.

A qualitative rating based on the level of cave/karst inspections would also be useful to provide an indication of the amount of local knowledge of caves or major surface karst features in an area. Typically, this knowledge is gained from a combination of recreational cave visits/exploration of areas, cave/karst inventories completed for forest districts or the forest industry, and other research studies. This information could be incorporated into a separate GIS layer as either point or, more preferably, polygon data, so that an approximate percent coverage value could be obtained.

Suggestion 4. Known cave areas, major surface karst features, and the level of cave/karst inspections should be used as criteria to confirm the presence of karst areas. Maps of these three confirmation criteria can be overlain onto maps containing polygons labelled with Criteria 1 and 2.

3.3 Suggested Standards for Mapping, Data Representation, and Data Reliability

The reconnaissance-level karst inventory is primarily intended to be an office study. Field reconnaissance could be carried out, and in some cases might be recommended, to evaluate type localities of a karst-bearing unit or where few or no data are available for a unit. This type of reconnaissance could include ground work at carefully selected sites or aerial viewing. Data that could be obtained from a general field examination of a potential karst-bearing unit are: i) the proportion of carbonate within a unit (for Criterion 1), ii) the probable thickness of a unit, iii) the presence of major surface karst features, and iv) the structural setting. Representative samples of material could also be obtained for geochemical analysis of carbonate content.

Data representation for reconnaissance inventory maps should follow the mapping methodologies laid out in Part 3 of the SGBM-BC, pp. 13–23. That section provides useful information for title blocks, base map specifications, legends, map attributes, symbols, and rock terminology. Some adaptation will be required. Each karst-bearing polygon could be assigned a combination of symbols for Criterion 1 (P, S, T) and Criterion 2 (H, M, L). These maps could be overlain with maps derived from the confirmation criteria: known cave area density (C), surface karst feature density (K), and inspection coverage (I). See Figure 4 for an example.

It is recommended that short reports accompany the various projects that are completed for collecting reconnaissance information. They would detail any specific methodology, project limitations, sources of information, references, and a list of contacts.

It is recommended that the reconnaissance karst inventory work be completed by professional geoscientists familiar with karst processes and digital GIS mapping techniques.

Data reliability for this scale of inventory is primarily a function of the information available. Where possible, recognized government publications and maps should be used. Information from other sources, such as industry or consultants, should be carefully documented and referenced.

3.4 Management Implications

Reconnaissance karst inventories are critical for the long-term management of forest and karst resources, and provide a source of information for strategic planning. In addition, they can be used to flag critical areas, which may assist planners by highlighting areas where development costs might be higher. For example, it should be possible to examine a large watershed (or group of watersheds) from the reconnaissance inventory map and infer the likelihood of both encountering karst (Criterion 1) and the probable intensity of karst development (Criterion 2). These inventories will also provide baseline information for the other more detailed planning- and operational-level karst inventories. Potential end-users of the reconnaissance inventory maps and data would likely include not only forest licensees and the B.C. Ministry of Forests, but also fishery and wildlife workers, archeologists, paleontologists, First Nations, recreational cavers, mineral explorationists, and the tourism industry.

Costs for these inventories are anticipated to be relatively low, because much of the procedures are office-based. In addition, much of the required information, such as the digital bedrock data, is already available in a user-friendly format. The amount of karst and the level of knowledge of known cave areas and karst features will play a major role in determining project costs. For example, a project for Vancouver Island (with its extensive areas of karst that have undergone considerable investigation) will likely be more expensive than for the mid-coast where little karst is known and limited information is available. Estimates based on budgets prepared for a 1997 Forest Renewal BC (FRBC) proposal suggest possible average costs of $200–300 per 1:250 000 NTS map sheet.

4.0 PROPOSED PLANNING-LEVEL KISP (1:50 000 to 1:20 000 MAP SCALES)

4.1 Objectives and Approach

This section outlines the suggested methodologies for the planning-level karst inventory. These methodologies could require some adaptation, depending on the level of existing karst inventory information available in various forest regions and districts. If existing karst information is available in a suitable format, it could simply require refinement and updating to raise the information to an acceptable standard.

The aim of the planning-level karst inventory is to provide a management tool that can be used for detailed forest development planning at the landscape scale. In comparison with the reconnaissance-level karst inventory, this level is an intermediate filter in which more specific attributes controlling karst development are examined. The primary objectives of the planning-level inventory are to further delineate the boundaries and three-dimensional character of the karst units, examine the regional extent of catchment and recharge areas, identify subsurface groundwater paths, and obtain an indication of the intensity and distribution of surface and subsurface karst development.

Three phases are proposed for the planning level karst inventory (see Figure 5). These adapt two existing inventory/mapping methodologies and introduce a third. Phase 1 would use the current L5 recreation polygon data as base information to assist in delineating the boundaries of karst-bearing units and potential recharge/catchment areas. This could be done

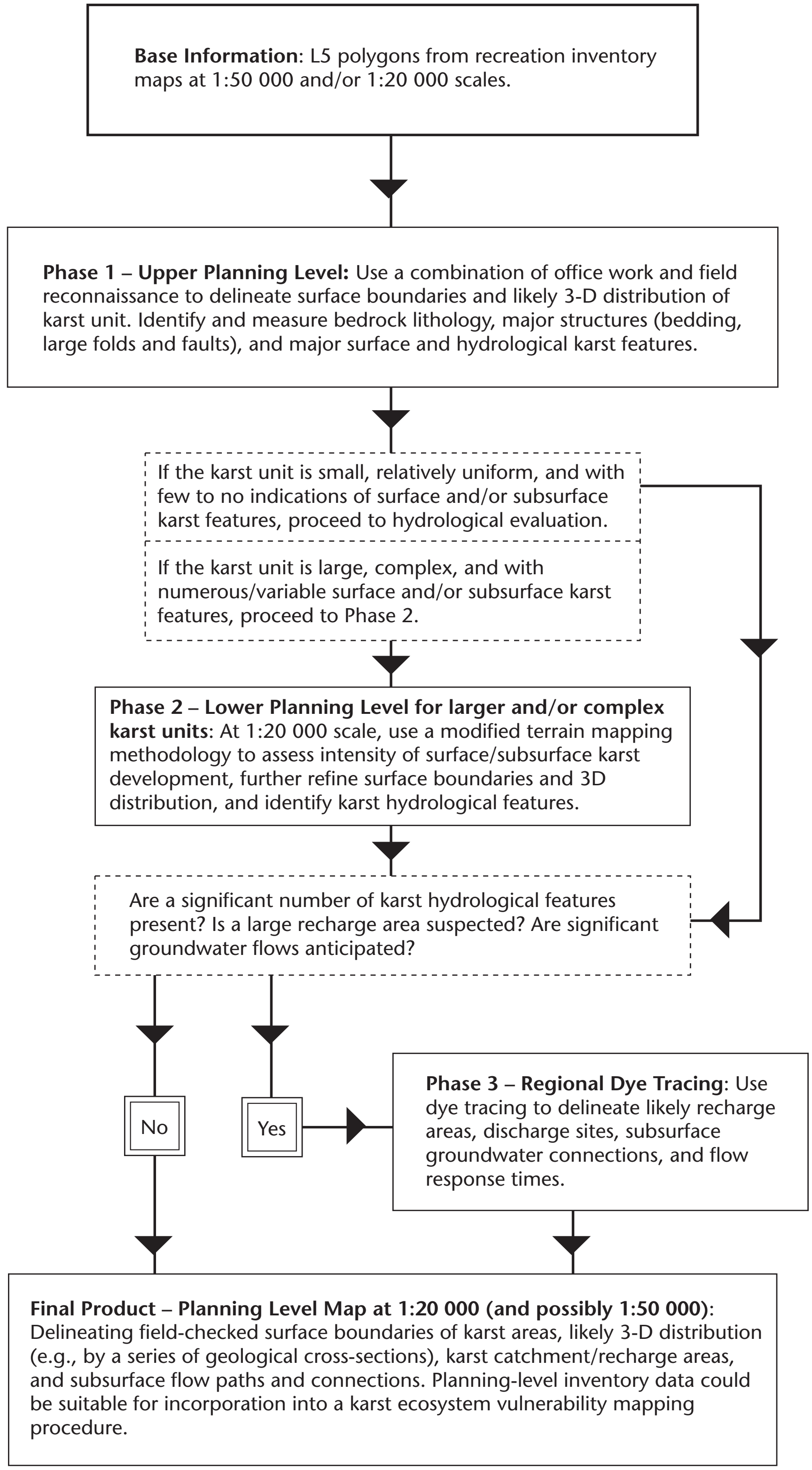


FIGURE 5 *Proposed planning-level KISP methodology.*

at a scale of 1:50 000 (or possibly 1:20 000) and be considered an upper planning level. Phase 2 is a refinement of the terrain mapping methodology, and concentrates on further delineating the boundaries of the karst-bearing units and assessing the intensity of surface/subsurface karst development. This mapping should be carried out at a scale of 1:20 000 and is considered a lower planning level. Phase 3 introduces regional dye tracing to delineate recharge and discharge areas, and likely paths for major groundwater flow.

In terms of timing, Phases 1 and 2 could be done sequentially or concurrently. Phase 3 should be completed after Phases 1 and 2, because much of the information obtained in the earlier phases will be needed (e.g., locations of swallets for dye injection sites and springs for dye samplers). However, the need to complete Phases 2 and 3 will also depend on the size and complexity of the karst unit. A large, complex karst unit with variable surface karst characteristics and numerous subsurface openings and hydrological features (e.g., swallets and springs) would probably require Phase 1 followed by Phases 2 and 3. A small, uniform karst area with no subsurface indicators or hydrological features might require only Phase 1. The advantages of completing Phase 1 at a 1:50 000 scale are that it is usually the scale of base information (e.g., bedrock geology), and it would be possible to view large contiguous karst-bearing units and catchment areas on one map.

Suggestion 5. Three phases are proposed for the planning level karst inventory. Phase 1 uses L5 recreation polygons at 1:50 000 or 1:20 000 scales to delineate the boundaries of karst units. Phase 2 uses modified terrain mapping methods at a 1:20 000 scale to delineate the intensity of surface/subsurface karst development. Phase 3 uses regional dye tracing to delineate recharge and discharge areas, and likely paths for major groundwater flow.

4.2 Phase 1 - Upper Planning Level Methodology

The general objectives of Phase 1, the upper planning level inventory, are:

- to delineate the surface boundaries of the karst unit,
- to determine the likely subsurface, three-dimensional distribution of the karst unit and its relationship to major structural features (e.g., bedding, major faults and folds) and adjacent bedrock units,
- to determine any variations in lithology of the karst unit (e.g., interbedding),
- to recognize major surface karst areas/features (e.g., cave entrances, areas of extensive epikarst, large sinkholes, sinking or reappearing streams), and
- to determine, where possible, the potential extent of both karst and non-karst catchments.

This procedure could primarily be carried out in the office, but does require some reconnaissance field work. A digital base map at a scale of 1:50 000 should be compiled from available digital TRIM data and incorporated into a suitable GIS system. This base map should include coastline, creeks, lakes, topography, and major roads.

Suggestion 6. The objectives of Phase 1, the upper planning level inventory, are to delineate the surface boundaries and three-dimensional distribution of a karst unit, determine lithological variations within the karst unit, and recognize any major surface karst areas/features. This work should be carried out through a combination of office study and field reconnaissance.

4.2.1 Office work and project initiation

Recreation L5 polygon data, along with detailed (1:50 000 scale or larger) bedrock maps and 1:50 000 terrain/surficial geological maps, should be obtained for the area and used as base information. A determination of how the L5 polygon data were compiled (e.g., office work using bedrock geology maps or some reconnaissance field work) should be made. If the data are considered geologically reliable and accurate (e.g., L5 polygon boundaries approximately match that of bedrock mapping and some field work has been done to check the karst limits), they could be compiled as a separate base layer into the GIS system defining the boundaries of karst-bearing units. If many other recreation features are included in the L5 polygons, it may be better to use the bedrock geological map as the base information. If only regional-scale bedrock mapping is available, karst information from 1:50 000 terrain mapping could be considered for base information.

An index of all bedrock mapping completed for British Columbia is available over the Internet from the British Columbia Geological Survey Branch (BCGSB) at **http://www.em.gov.bc.ca/geology/** (follow links to downloadable mineral potential files) and also in hardcopy (BCGSB Information Circular 1991-7). Most of these detailed maps have been completed by British Columbia government geologists, particularly in areas of mineral potential or mining interest. Bedrock mapping at 1:50 000 scale is not available for all parts of British Columbia, although some form of old, detailed mapping is usually available (e.g., 1:64 000, 1 inch to 1 mile). The remote northern parts of British Columbia typically do not have mapping at these more detailed scales, and may require the use of regional-scale (e.g., 1:250 000 or 1:100 000) maps. The boundaries of karst units from the regional (1:250 000) digital bedrock maps of British Columbia (see Section 3.0) were compiled at a 1:100 000 scale, and could be considered only a very approximate guide at the 1:50 000 scale. The information sources for the 1:250 000 scale compilations should be examined to see if areas of interest have been mapped in detail.

During the late 1970s and early 1980s, the Ministry of Environment produced terrain/surficial geological maps at a 1:50 000 scale for most parts of southern and central British Columbia. An index for these maps is available over the Internet from the BCGSB at **http://www.em.gov.bc.ca/geology/** or in hard copy (BCGSB Open File 1992-13). Where present, as required by the Terrain Classification System of British Columbia, karst is identified on terrain maps as a process modifier (-K). However, experience from Vancouver Island has shown that this process modifier has not always been used.

From experience, it is anticipated that the boundaries of karst-bearing units determined from bedrock mapping will probably be more accurate than those determined from terrain mapping. The reason behind this is that former mapping procedures focused specifically on bedrock relationships, while the latter concentrate on surficial materials overlying bedrock. With this in mind, it is suggested that these boundaries be kept as separate layers within the GIS, or be given different colours/linings until confirmed by field reconnaissance. In some areas, terrain mapping may be the only source of detailed mapping that has been completed, and hence could be more reliable than regional-scale bedrock maps.

High-level airphotos (e.g., >1:50 000) or remote-sensing maps could be used to assist in determining the boundaries of karst-bearing units, particularly if a distinct visual terrain attribute (e.g., vegetation change) is present. Sparsely vegetated or logged areas are likely to show karst features and terrain more readily.

4.2.2 Field work

In order to determine the general objectives of Phase 1, reconnaissance field work should be carried out using the most readily accessible sites where karst-bearing bedrock might be encountered (e.g., road cuts, exposures in logged cutblocks, and creek channels/sidewalls). In more remote areas, accessible only by air, traverses could be carried out with the intention of intersecting as much karst bedrock as possible.

In some cases, where recent 1:50 000 bedrock maps have been compiled and completed to RIC requirements (e.g., 1000 stations/1:50 000 NTS map sheet), the need to confirm the boundaries of the karst-bearing units may be low. Nevertheless, information would still be required on the general characteristics and major features of the karst unit. Confirmation of some boundaries could be carried out using maps from previous karst inventory reports. The karst inventory attributes that should be identified during the completion of Phase 1 are highlighted in Table 9 by a single asterisk.

From the distribution of bedrock exposure and bedrock contact relationships, it should be possible to develop final map boundaries for karst-bearing units. These boundaries can be indicated as defined, approximate, or inferred, according to standard bedrock map symbols (SGBM-BC, p. 21). The location, identification, and measurement of any major surface karst features encountered will assist in determining both the overall extent and intensity of karstification. Surface hydrological karst features, combined with a knowledge of the topographic catchment areas and the distribution of nearby karst units, should enable educated speculation on likely recharge and discharge areas. Recharge areas from some non-karst units could also be identified. Thus, a preliminary indication of the overall non-karst and karst catchments might be obtained from a relatively simple mapping exercise, and potential areas of hydrological concern could be identified for later investigation (e.g., provide a focus for Phase 3 work).

Regional geological cross-sections could be drawn using available topographical, lithological, and structural data. This will assist in determining the three-dimensional distribution of the karst units. Preliminary examinations of the karst hydrological system can be carried out to determine likely groundwater flow paths and discharge/recharge

TABLE 9 *Surface karst attributes and features*

Karst attribute or feature	Data measurements/requirements
	Geological and Geomorphological
Karst unit lithology*	Form (e.g., massive, thin bedded, interbedded), type (e.g., limestone, dolomite), purity (e.g., colour, chemistry)
Adjacent lithology*	Types and contact relationships with karst unit (e.g., faulted, gradational, intrusive)
Thickness of unit*	Measured from outcrop or inferred over a series of outcrops
Extent of karst unit exposed in outcrop*	Mapped using standard convention (dotted line or x)
Bedding planes*	Strike direction/dip direction
Major faults*	Fault plane strike dip, offset, slickensides
Major folds*	Fold axis, axial plane, size
Minor faults**	Fault plane strike/dip, offset, slickensides
Minor folds**	Axial plane - strike/dip, fold axis - plunge, shape, size)
Joints**	Sets, orientation, spacing, openness
General topography*	Slope gradients; mid, upper or lower slopes; benched, uniform
Detailed topographic form/character**	Concave, irregular, uniform, straight
Surficial materials**	Type (e.g., moraine, fluvial, colluvium), thickness (e.g., thin veneer, veneer <1 m, blanket >1 m, or mantle), weathering depth, drainage (e.g., well drained, poorly drained, imperfectly drained)
Forest floor/organic layer**	Type, depth to mineral soil
Major sinkholes or closed depressions*	Diameter, shape, depth, openness
Cave entrances**	Size (width, height)
Shaft or Karst Window**	Size and depth, presence/absence of water at base
Grykes**	Size (width, height, length, openness)
Natural rock bridges**	Size (width, height, length)
Canyons**	Size (width, height, length)
Cliffs**	Height, length
Surface epikarst development**	Depth of solutional openings, percentage of area/exposed bedrock, openness
Microkarst features	Karren, percentage of exposed bedrock
	Hydrological
Topographic catchment*	Size, area, boundaries
Karst recharge (including non-karst areas)***	Size, boundaries (possible, probable, definite)
Dry channels/valleys**	Length, gradient, sidewall slope
Seepages/springs**	Elevation, flow rate, temperature, pH, conductivity, oxygen content

TABLE 9 *(Continued)*

Karst attribute or feature	Data measurements/requirements
Insurgence (swallet)**	Elevation, flow rate, temperature, pH, conductivity
Disappearing streams**	Elevation, flow rate, temperature, pH, transport capability for sediment and woody debris
Diffuse and discrete recharge areas**	Size and distribution (e.g., infiltration or percolation zones)
Lakes and ponds*	Size, water inputs and outputs
Wetlands/swamps*	Size, water inputs and outputs
Surface overflow channels**	Channel width and height, transport capability for sediment and woody debris
	Natural Disturbances
Fire/burn areas**	Extent, intensity
Tree windthrow**	Orientation, age, amount
Landslides**	Location, size, materials
Rockfall and soil slumps**	Location, size, materials
Gully sidewall/channel erosion**	Location, size, materials
Surface flooding**	Level, size, frequency
	Karst Flora and Fauna
Rare or unique plants and plant communities**	Species, location
Rare or endangered surface karst fauna or habitats**	Species, location
Cave entrance habitat**	Type and conditions
	Climate and Air
Slope aspect**	Azimuth
Precipitation	Estimates of maximum, minimum, mean
Air temperature around surface karst features or depressions	Estimates of maximum, minimum, mean
Snow depth	Estimates of maximum, minimum, mean
Surface evapotranspiration	Estimates of maximum, minimum, mean

* denotes data collection possible during Phase 1 of the planning-level inventory,
** denotes collection possible during Phase 2 of the planning-level inventory,
*** denotes collection possible during Phase 3 of the planning-level inventory.
All attributes listed in the table should be collected if possible during the operational-level inventory.

sites. This information could be critical to the dye tracing procedures of Phase 3. Further modification of these cross-sections can be carried out following the more detailed assessments of Phase 2.

4.3 Phase 2 - Lower Planning Level Methodology

The primary objectives of Phase 2, the lower planning level, are:

- to assess the intensity of surface/subsurface karst development within the karst unit,
- to further refine the three-dimensional distribution of the karst unit,
- to identify further hydrological karst features suitable for Phase 3, and
- to identify, in a preliminary manner, the likely presence of any unique karst-specific biota or related habitat.

For the purposes of a lower planning level karst inventory, it is suggested that the guidelines and standards for terrain mapping at a 1:20 000 scale be followed, but that some adjustments and refinements be added for karst. The information gathered during terrain mapping focuses on data similar to those required for a karst inventory, including surficial cover type/thickness, geomorphic processes present, surface expression/topography, and specific features/on-site symbols. However, various items require modification to take into account variability in karst features and karst hydrology. Information from this mapping could then be relatively easily incorporated into a planning-level karst vulnerability rating system (see Section 6.0), providing that the appropriate data have been collected. This karst vulnerability map would then become a derivative terrain map, in a similar fashion to a slope stability hazard map.

Suggestion 7. The objectives of Phase 2, the lower planning level inventory, are to assess the intensity of surface/subsurface karst development within a karst unit, further refine the unit's three-dimensional distribution, and identify surface karst features suitable for dye tracing. This work is carried out mainly by terrain mapping with some modifications for karst purposes.

Methodologies for terrain mapping within forested areas of British Columbia are well outlined in the FPC *Mapping and Assessing Terrain Stability Guidebook*, the GSTM-BC, and the TCS-BC. Standards for digital terrain data usage are included in the TDM-BC. A summary of particular references to karst in the above publications is included in Section 2.0.

One point that must be emphasized is that terrain mapping, modified for lower planning level karst inventories, cannot alone assess the three-dimensional nature of karst. It can provide only some indication of the likely subsurface characteristics. However, in combination with additional attributes (e.g., bedrock structure) and regional dye tracing in Phase 3, it should be able to provide a relatively good idea of the distribution and intensity of overall karst development.

In practice, 1:20 000 terrain mapping may or may not have been completed for the area of interest for a karst inventory. Three possible scenarios are likely: i) no terrain mapping has been done; ii) terrain mapping has been done, but to a relatively low survey intensity level and before the existing standards; and iii) terrain mapping has been done to an acceptable standard (e.g., GSTM-BC) and survey intensity. In the first case, terrain mapping for the karst inventory area should be carried out, but would be limited by the approximate boundaries of the karst unit obtained in Phase 1. If possible, terrain mapping for the karst inventory could be done concurrently with prescribed slope stability or terrestrial ecosystem mapping. In the second case, some improvement to terrain mapping may be required, but it should be possible to use this as a base map for the karst inventory. In the third case, the terrain mapping could be used as the base map with karst details superimposed. In some circumstances where terrain mapping has been done and previous karst inventory work has been completed, this might be primarily an information transfer process.

4.3.1 Office work and project initiation

In addition to gathering the standard information required for a terrain mapping project (e.g., surfical geology maps, bedrock maps, airphotos, and other terrain maps/publications), the planning-level inventory would require the collation of any karst-related information. This could include karst inventory maps, cave maps, related publications, and input from local interest parties (e.g., cavers, B.C. Ministry of Forests recreation officers). Other useful information could be gathered from forest cover maps, forest development plans, terrestrial ecosystem maps, and fish inventory maps. Local offices of BC Environment could be contacted to determine if any karst-related biota (e.g., threatened or endangered wildlife or plants) occur within the area of interest. A working base topographic map (from TRIM data) should be compiled with coastlines, streams, lakes, and roads. A suitable set of airphotos should be chosen prior to the field work (see Sections 5 and 6 of the GSTM-BC). These airphotos should be pre-typed for terrain polygons, but should also focus on karst processes, using any additional information where required.

4.3.2 Modification of terrain attribute symbols for terrain mapping polygons

Polygons are used for terrain mapping to outline an area with relatively uniform criteria of surfical material texture/type, landform type, and processes. In some cases, these polygons are simple (no more than one element per criterion), while in others they are composite (two or three elements per criterion). However, whether the polygons are simple or composite, they can still define a homogeneous area with respect to adjacent polygons. Details on polygon definitions, boundaries, etc. are included in Section 4.0 of the GSTM-BC.

Terrain mapping polygons could be made suitable for karst inventory purposes by using a descriptive “subclass code” table for the karst (-K) process. A proposed table for this purpose is illustrated in Table 10. This table could possibly be revised to incorporate indications of subsurface karst development as well. Similar tables have been completed for mass movement, avalanche, fluvial, and permafrost processes (see Tables 12–14 in the TDM-BC).

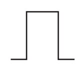
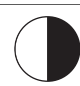
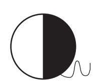
It is also suggested that additions be made to the terrain symbol list (Appendix I of the GSTM-BC) to accommodate more karst features. These could be adapted from existing karst mapping symbol standards. Features that could be included, along with existing cave entrances and large and small sinkholes, are: dry valleys, large stream insurgences, major stream exsurgences, karst bridges, karst canyons, karst springs or group of karst springs, and major grikes. Table 11 outlines examples of proposed symbols that could be added. The table is constructed in a format compatible with Appendix I of the GSTM-BC.

TABLE 10 *Suggested subclasses for karst process modifiers for British Columbia terrain classification system*

Code	Subclass name	Definitions
i	intensely developed epikarst	Ridges/peaks and depressions, extensive development of micro-karst features (e.g., karren and runnels) on numerous exposed bedrock surfaces. Occasional sinkholes and cave entrances/shafts. Average openings to >10 m. Probably visible on airphoto with distinct vegetation change or lack of well-developed vegetation.
g	gryke field	Area of well-developed epikarst with linear grykes linking depressions, development of micro-karst features on bedrock exposures, most sinkholes open at depth, >5–10 m average depth.
e	well-developed surface epikarst	Ridges and depressions with micro-karst features developed on ridge tops, depressions closed at depth and infilled with forest floor/ surficial material. >2 to < 5 m average depth.
s	sinkhole field	Numerous sinkholes encountered <50 m average spacing between centres, with occasional bedrock exposures with minor micro-karst. >2 to <5 m average depth.
t	occasional sinkholes	Occasional sinkholes >50 m spacing with few bedrock exposures, and evidence of micro-features on minor exposed bedrock. <2 m average depth.
r	rare sinkholes	Few sinkholes >100 m spacing, traces to no areas of exposed bedrock or micro-karst features. <2 m average depth.
n	insurgence sites	Area where a number of small creeks disappear either into surface epikarst or sinkholes. Too small to map as single-symbol features.
x	exsurgence sites	Area where a number of small seepages/ creeks reappear. Too small to map as single-symbol features.

TABLE 11 *Suggested additional terrain mapping symbols for karst features*

Group: Geomorphologic

Symbol description	Symbol	Positional definition	Definition/remarks
Dry valley		accurate to within 50 m	Linear gully with overflow channels and possible sinkholes
Stream insurgence		feature at centre of symbol	Single major stream flow that abruptly disappears
Stream exsurgence		feature at centre of symbol	Single major stream flow that abruptly appears
Natural karst bridge		feature at centre of symbol	Large arch spanning canyon
Karst canyon/gorge		accurate to within 50 m	Linear gully with subvertical bedrock sidewalls
Karst spring		feature at centre of symbol	Single spring from karst unit
Karst spring group		group at centre of symbol	Series of springs from karst unit
Major gryke		accurate to within 50 m	Linear depressions open at depth

Bedrock classification codes are also present in the terrain mapping system and could be utilized to identify variations in bedrock type. A system of suffixes could be added to bedrock codes to identify local variations in bedrock lithology. This could be done on an informal or local basis and should be acceptable, providing the details are well laid out in legends and text. For example, limestone "ls" could be suffixed as: ls1 for massive limestones, ls2 for massive well-bedded limestone, ls3 for thin-bedded limestone, and ls4 for interbedded limestone.

Suggestion 8. Modify the existing Terrain Classification System of British Columbia with more details for karst process descriptors/subclass codes, karst terrain symbols, and bedrock classification codes. This will assist in the modification of terrain mapping methodology for planning-level karst inventories.

4.3.3 Attributes for Phase 2

At 1:20 000 scale, a variety of karst geological, geomorphological, and hydrological attributes can be identified and measured during the Phase 2 terrain mapping field work. These attributes are highlighted in Table 9 by a double asterisk. General observations should be made with respect to any anomalous/unusual karst-associated surface flora or fauna. If such biota are encountered, the information should be relayed to other appropriate inventory specialists for further assessment.

4.3.4 Field work procedures

Field work for Phase 2 is anticipated to be similar to any other terrain mapping project and should follow the general details laid out in Section 7.0 of the GSTM-BC. These details include careful use of time, a pre-project regional reconnaissance, designated observation sites/traverses, and polygon field typing. The level of field checking required for a mapping project can be defined in terms of the Terrain Survey Intensity Level (TSIL), which provides an indication for the percentage of terrain polygons checked or the number of field checks per 100 ha (see Table 7 in GSTM-BC). The TSIL level used for a mapping project is typically a function of terrain and vegetation conditions, and the anticipated use for the terrain map. In the case of a karst inventory, particularly in forested areas, the mapping should be carried out at least to TSIL C, with 25–50% of polygons field checked. If the karst area is complex and/or it is anticipated that the data will be used subsequently for vulnerability mapping, TSIL B (50–75% of polygons field checked) or possibly TSIL A (75–100% of polygons field checked) may be required.

4.4 Phase 3 - Regional Dye Tracing

One of the unique characteristics of karst terrain is its different hydrological system compared to non-karst terrain. Most of the karst hydrological system is subsurface, with recharge areas that not only do not follow topographic divides, but in many cases, cross them. Likewise, subsurface drainage may not follow simple paths, and exsurgenences (e.g., springs) can occur in unexpected places. Groundwater systems within karst have the potential to both rapidly transmit flows through bedrock conduits, and to provide groundwater storage in permeable, fissured bedrock volumes (e.g., in epikarst areas). Hence, karst hydrological systems can be characterized as highly variable and difficult to predict from surface features. Any evaluation of these hydrological systems needs to consider differences in stage height (i.e., flow regime), because discharge directions and groundwater divides in karst can vary according to how much water is present in the system. In some cases, it may be necessary to assess karst hydrological systems under different discharge conditions. Dye tracing is a well-accepted methodology for evaluating karst hydrological systems, and can be used successfully to delineate recharge areas, assess groundwater flow paths, and identify discharge sites (Aley and Aley 1993; Gunn 1995; Doerfliger 1996).

Dye tracing is undertaken using a fluorescent dye injected into a recharge site (e.g., sinking stream), which is then tracked by sampler sites located at likely discharge locations (e.g., springs). Examples of dye tracing methods, materials and analytical procedures are provided in Appendix 1.

One of the principal concerns in karst hydrology is the transport of materials from a site of management activity to an area downstream where other resources may be affected. The materials that can typically be generated during forest development activities include sediment, logging debris, and pollutants (e.g., diesel fuel). In non-karst terrain, various methodologies/guidelines have been determined for the assessment and management of surface water bodies and downstream resources (e.g., *Riparian Guidebook, Gully Assessment Procedure Guidebook*). It is recommended that, even though water flow in karst terrain is principally subsurface and not visible, it still requires careful assessment and management.

The objectives of Phase 3 dye tracing investigations are to regionally delineate, for a particular karst unit with significant surface hydrological features and likely subsurface groundwater flows, the following:

- likely recharge areas,
- likely discharge sites,
- principal groundwater flow paths,
- likely location and connectivity of subsurface conduits, and
- likely subsurface flow response times.

Phase 3 investigations are not intended to be all encompassing, but will provide a general idea of sites that may, or may not, require further dye tracing or investigation during operational-level inventories. At the operational level, dye tracing can be focused towards assessing groundwater-related impacts to particular downstream resources or values. Where possible, regional dye tracing should be done well in advance of operational inventories or vulnerability assessments, to allow for careful planning and integration of information.

Suggestion 9. Regional dye tracing should be carried out for a karst unit with significant surface hydrological features and likely subsurface groundwater flows to identify the likely recharge and discharge areas, determine the principal groundwater flow paths, and assess the location and connectivity of subsurface conduits.

4.4.1 Office work and project initiation

Following completion of Phases 1 and 2, the boundaries of the main karst-bearing units will have been delineated for an area, the principal geomorphic and hydrological features identified, and the distribution and intensity of karst development generally understood. This would preferably be compiled in the form of GIS data with various layers of information (see below).

A conceptual design for dye tracing projects should be completed prior to field work. This design should take into consideration the findings of Phases 1 and 2. It will ensure that the overall project objectives are clarified, and will determine favourable locations for dye injections and sampler sites, and frequency of sampling. Appropriate dyes and samplers should be chosen for the site conditions. Various interested agencies (e.g., Federal Department of Fisheries and Oceans and BC Environment) should be informed of the location and time of the dye tracing.

4.4.2 Field work

Background water samples should be taken at injection and collection sites for analysis, particularly if previous dye tracing has been done in the area. Water at the injection and collection sites should be tested for temperature, pH, dissolved oxygen, and conductivity. (Conductivity can sometimes prove an important measurement for assessing the possible sources of water flow, because karst waters generally have a higher conductivity). Water flow estimates should be made at injection and sampler sites. Precipitation data should be obtained from a nearby registered rain gauge, if available. If not available, a simple rain gauge should be set up at a suitable location for the duration of the field work.

Retrieval and replacement of dye samplers should be carried out strictly according to an approved procedure. A labelling protocol and chain of custody should be implemented, with all samples being shipped directly to an approved laboratory for analysis. These samples should be prepared and analyzed according to accepted laboratory standards and procedures. Analytical results should be certified by the laboratory. Following completion of the field testing and analysis, a map (or layer in a GIS data base) should be completed, showing dye paths and travel times of groundwater flow, boundaries of the recharge areas, insurgences, and exsurgences.

4.5 Suggested Standards for Map Presentation, Reports, and Workers

For Phase 1 maps and cross-sections, presentation should be carried out to standards outlined in Part 3 of the SGBM-BC (pp. 13–23). Bedrock mapping symbols should be as indicated in the SGBM-BC, and karst features/hydrological symbols should conform to a chosen standard. For Phase 2, map presentation should be carried out to the general standards of Sections 8 and 9 in the GSTM-BC. It is recommended that mapping for all phases be integrated into a layered GIS system. This information could then be rapidly incorporated into a planning-level karst vulnerability assessment if required (see Section 6.0). Separate layers for the following are suggested: topography, creeks/lakes, boundaries and types of karst units, structural bedrock information, surface karst features, terrain mapping polygons with karst attributes, hydrological data, and subsurface flows/dye trace paths.

One report covering all phases would be acceptable if all phases were completed during a short time frame by one worker. Separate reports are suggested for each phase if they are done sequentially over a period of time or completed by different workers. The reports should cover project objectives, materials used, regional geologic/geomorphologic/hydrologic setting, office and field methodologies, discussion of results, conclusions, and recommendations. Section 11 of the GSTM-BC covers the general scope required for these types of reports. The report should also contain information with respect to data reliability, TSIL, and any limitations (areas not assessed, difficulties in dye tracing, etc.)

A variety of skills, both at professional and technical levels, will be required to carry out a planning-level inventory. It is suggested that Phase 1 be carried out by a professional experienced in bedrock/surficial mapping and karst geomorphological and hydrological processes. A suitably trained technician or professional-in-training could, under the direct supervision of a qualified professional, be employed to carry out some of the field work.

Phase 2 should be carried out by a professional experienced in terrain mapping and karst processes. It is suggested that a suitably experienced technician could be employed "in tandem" with the professional to mark and locate/measure surface karst features, and rove off the main traverse route to examine any areas of significant interest. In some cases, rapid examination and inspection of cave entrances could be made during the course of the field work. Careful radio communication between the two workers would be essential for this team to be successful.

Phase 3 requires the input of an experienced karst hydrologist during the dye tracing design and data analysis.

4.6 Management Implications

The planning-level karst inventory, as outlined by the three phases above, should be able to provide a data base and framework from which management decisions can be made during forestry activities. Data from the planning level inventory should be in such a format that they could be readily incorporated into an accepted karst vulnerability procedure (see Section 6.0) or, if required, transferred into a forest development plan. **Note:** Phase 3 dye tracing can be a useful management tool for indicating the hydrological sensitivity of both karst and non-karst catchments.

From the planning-level karst inventory, the design of cutblocks and roads for a particular watershed should be able to take into consideration potentially sensitive karst areas. These areas can be either avoided or planned for, thus avoiding possible surprises at the initiation of harvesting or road construction. The implications and costs of various harvesting systems and special road construction methods can also be considered ahead of time.

A similar planning-level karst inventory procedure could be carried out for watersheds undergoing restoration or road deactivation, because potentially well-intentioned work could cause undesirable impacts (e.g., redirection of surface flows into a critical insurgence point). Silvicultural work would also benefit from a better knowledge of the karst unit (e.g., thinning on sensitive sites or using fertilizers/pesticides in sensitive recharge areas).

Costs for the planning-level karst inventory are difficult to determine at this stage because this methodology has not been tried in the field. Costs for terrain mapping at TSIL C are typically $2–5/ha, but are highly dependent on project objectives, access, and map format requirements. If the intention is to use Phase 2 data for a vulnerability assessment, these costs could increase slightly because more detailed field checking might be required. The costs for Phase 1 are anticipated to be less than those for Phase 2, but depend on access and project requirements (e.g., helicopter time for some sites will significantly increase costs). Materials and analyses for dye tracing are relatively inexpensive (e.g., $120/dye injection and $45/sample analysis) considering the important information that can be obtained for both inventory and management purposes. Most of the costs of the dye tracing work are in the labour required for design, implementation, and reporting of results.

5.0 PROPOSED OPERATIONAL-LEVEL KISP (1:10 000 to 1:5000 MAP SCALES)

5.1 Objectives and Approach

This section outlines a proposed methodology for the operational-level karst inventory at 1:10 000 to 1:5000 map scales (see Figure 6). While this level of karst inventory can include both surface and subsurface inspection and evaluation, this section focuses on the surface. The inspection of caves is a detailed inventory in its own right and is beyond the scope of this document.

The principal objectives of the operational level karst inventory are:

- to identify resource values and features for management according to FPC requirements,
- to identify and classify surface and subsurface karst features,
- to identify the need for further specialized inventories (e.g., palaeontological, subsurface biota),
- to refine the three-dimensional nature of a specific part of a karst unit, and
- to determine the need for further detailed dye tracing, due to subsurface hydrology concerns or downstream resource impacts.

One underlying aim of the operational level karst inventory is to provide site-specific information for forest development (e.g., proposed cutblocks or roads). This level of inventory should both reinforce and expand upon the work conducted during the reconnaissance- and planning-level karst inventories.

Operational karst inventories are intended to build upon the recreation inventories normally carried out by forest districts or forest licensees. In most instances, the operational karst inventory would be initiated in support of an application for forest development at the cutblock level. Site-specific impact assessment would rely on the inventory data collected at this “fine filter” level.

The operational karst inventory would typically focus on a small area of karst that probably occurs within a larger karst system or unit. The size of the host system in relation to the karst area of interest would need to be considered before setting inventory boundaries. An important unit at this level would be the karst catchment or recharge area, which might extend beyond topographic divides. This recharge area could include both the karst hydrological system and an upland, non-karst catchment area. The regional recharge area should be delineated by regional dye tracing at Phase 3 of the planning-level inventory (see Section 4.4).

To effectively consider the karst ecosystem for management purposes, the inventory area must be “projected” underground and will require some level of subsurface inspection. This will assist in the evaluation of the three-dimensional aspects of the karst ecosystem. It is critical at this stage to recognize the linkages that exist between the surface and subsurface attributes of the karst system. The principal surface attributes that should be recorded during the operational-level inventory include all those required at Phase 1 and Phase 2 of the planning-level inventory, plus some others, as indicated with three asterisks in Table 9.

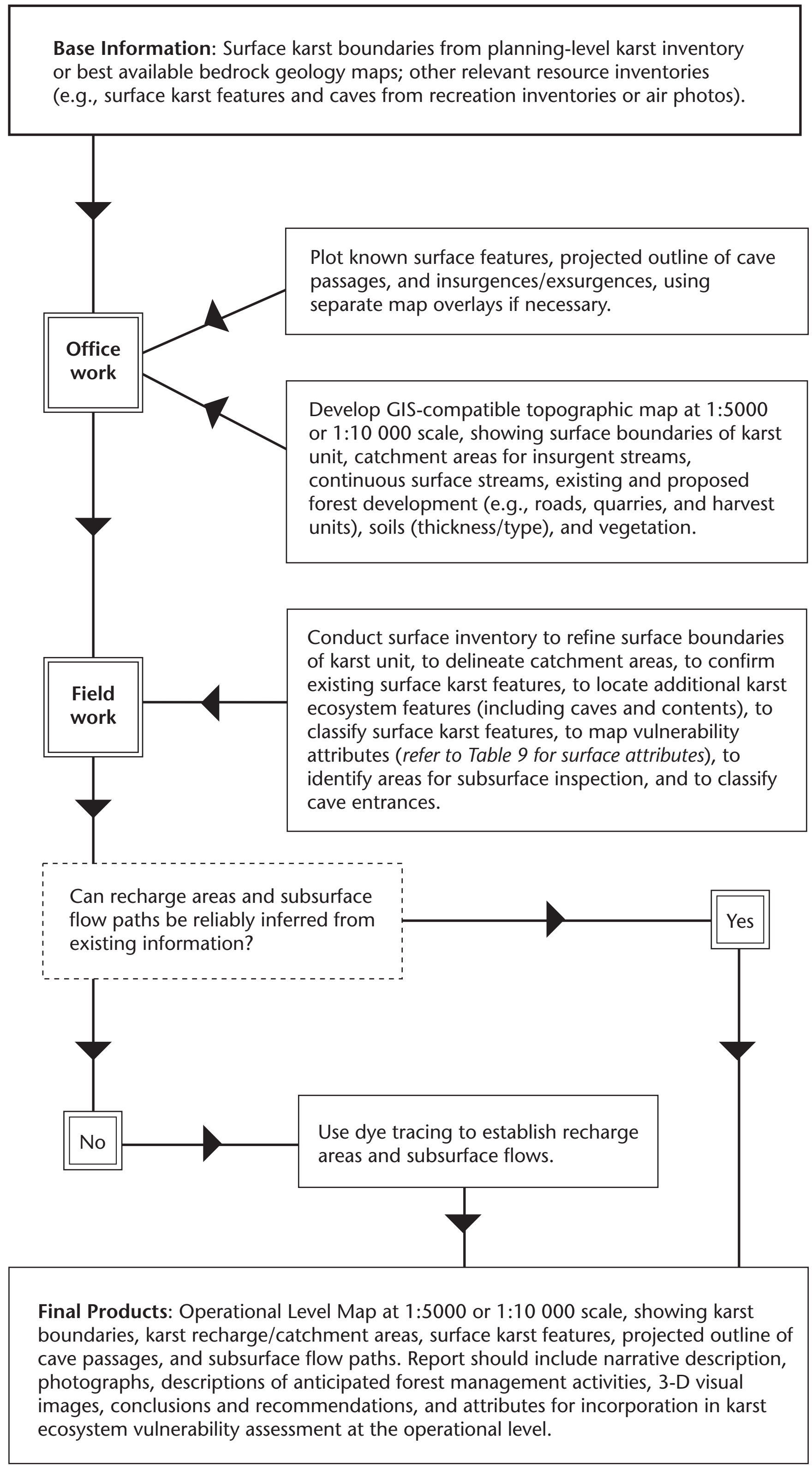


FIGURE 6 *Proposed operational-level KISP methodology.*

In some cases, there may be a need to assemble a multi-disciplinary team for very detailed inventories of significant karst ecosystems that might encompass multiple resources and values. Specialists may include geomorphologists, hydrogeologists, biologists, palaeontologists, archeologists, etc., as required by the site conditions. Knowledgeable and experienced speleologists will normally be required for the safe and efficient investigation of technically difficult and/or sensitive caves.

5.2 Methodology

The operational-level karst inventory should focus on identifying karst elements (e.g., surface karst features, soil thickness) that are relatively stable and reliably mapped. The quantity and/or quality of other, less fixed, biophysical attributes (vegetation, wildlife, etc.) should also be inventoried if the information is required for the assessment and management of a particular karst area.

In most cases, the operational karst inventory will include a combination of desktop review, field work (ground searching and subsurface inspection), data analysis, classification of surface and subsurface karst features, map preparation, and report compilation.

5.2.1 Office work phase

The office work phase of an operational-level karst inventory should involve the following tasks:

1) Reviewing the available data from reconnaissance- and planning-level karst inventories, including any dye tracing results. Obtaining any other karst inventory or cave information for both the area of interest and adjacent areas.
2) Obtaining basic information on the karst area from available air photos, and from topography, bedrock geology, and surficial geology/terrain maps.
3) Determining any relevant requirements or protocols from FPC guidelines and higher-level plans, including cave/karst management plans. Reviewing types of proposed forest activity (e.g., location of roads, harvesting methods). Obtaining any local knowledge on the area or adjacent areas (e.g., windthrow).
4) Identifying and gathering any other existing information about the karst unit's landform features, soils, topography, ecosystems, flora, and fauna using available mapping and other inventories (e.g., terrestrial ecosystem, terrain mapping, fish habitat, forest cover; see Section 7.0). (This information will assist in later land management decisions that consider possible issues related to endangered animal and plant species, biodiversity, downstream fisheries, domestic and/or livestock water supply, recreation, etc.)
5) Constructing a base topographic map at the required scale, preferably in digital format using a GIS system with a series of layers. Developing layers for bedrock geology (e.g., karst boundaries), creeks, proposed forest activity (e.g., roads/cutblocks), soils (thickness/type), and vegetation. Plotting any known surface karst features on the base map using points and approved symbol conventions. Plotting any known cave passage outlines in plan view. Plotting any known insurgences or exsurgences (e.g., swallets or springs, respectively).

6) Developing a plan for field work (e.g., task list), including appropriate methods for ground searches and subsurface inspections.

5.2.2 Field work phase

In order to complete an operational karst inventory of an area, detailed ground searching and mapping are required to both record and measure surface attributes (e.g., soil thickness, epikarst distribution, and openness). For karst inventories in forested areas, it is not practical or economically feasible to search 100% of the area. Therefore, an appropriate method of inventory sampling is required. Surface mapping is a critical part of the inventory methodology for delineating boundaries of areas or zones of equivalent attributes (e.g., soil thickness, groups of sinkholes).

The time and costs required to complete more intensive surveys are important considerations. Larger and more complex units may require many repeat visits and take several years to complete, particularly for subsurface inspection/exploration. This may also be compounded by other problems of poor access and unfavourable weather (e.g., heavy rainfall/floods hindering subsurface work).

A variety of methods for surface inventory sampling techniques can be used for both searching and mapping of attributes, including:

- reconnaissance surveys,
- judgemental surveys,
- multiple transect or grid surveys, and
- total grid surveys.

These methods can be combined, stratified, or modified to suit field conditions. Details on how each of these methods are currently used in British Columbia are included in Section 2.2. It is suggested that these methods be slightly modified and adapted to incorporate mapping of attributes as well as the location and identification of karst surface features. The surface inventory method chosen should sample the core karst attributes identified in the desktop analysis, locate further significant karst features (e.g., insurgences and discharge points), and map required attributes (e.g., soil thickness, epikarst extent, and openness).

The reconnaissance (or walkabout) sampling survey could be used as the first field phase in combination with later more detailed judgemental or grid surveys. The reconnaissance survey consists of a transverse line across the inventory area or a search along proposed road locations.

The judgemental survey is based on the recognition that karst development does not occur in a random fashion, and that it is possible to identify associations between karst development and terrain variables (e.g., the correlation between swallets and upper limestone contacts or the inverse correlation between steep hill slopes and dolines). By using this approach, an experienced field worker can predict where features are more likely to be found, and the traverse routes can be designed and optimized accordingly. This can be an effective method for concentrating field work on critical areas and avoiding detailed work in areas of less concern.

The multiple transect or grid survey is useful where cave/karst features (i.e., possible cave entrances) are spread more diffusely or randomly throughout an area, rather than being concentrated at predictable locations. The grid layout, spacing, and orientation of search lines should be based on both practical considerations (e.g., understorey thickness, terrain steepness) and an assessment of where the most information might be obtained. Typically, these grids can be constructed by a single compass person along a centre line, with rovers identifying/locating/mapping surface karst features and relevant attribute information.

The total grid method could be employed for critical areas within cutblocks. This method requires surveying a regular grid system of an appropriate size (e.g., 20 by 20 m for intensive searches). Surface karst features and other attributes are located and mapped onto a series of set point locations.

The following outlines the steps that should be considered in completing operational karst inventory field work:

1) Select an appropriate surface inventory sampling technique.
2) Locate any significant surface karst features using GPS or a compass bearing and distance to a fixed marker (e.g., survey line/falling corner). Mark in the field as required. Provide narrative descriptions, measurements, photos, etc. for all features or zones.
3) Identify, locate, and map required attributes where identified in Table 9 (e.g., epikarst zones, exposed bedrock, natural windthrow, surface overflow channels).
4) Systematically measure and record the approximate depth of soil by test pits or probing. Take measurements both on ridges and in depressions. Estimate the depth of openness in the epikarst.
5) Measure and record the electrical conductivity of water at insurgences and exsurgences with a portable meter. (This information is useful for assessing the source and nature of subsurface flows, since the higher the conductivity, the more the water has been in contact with karst.) Estimate flow rates and describe weather conditions for the previous 24 hours, if known.
6) Classify significant surface karst features (see Section 5.2.3 below).
7) Inspect cave entrances and classify as required (see Section 5.2.3 below).
8) Review the results of the initial survey to determine where more intensive ground coverage may be required.
9) Conduct detailed dye tracing, if required (see Section 7.1). **Note: At the operational level, it may be necessary to carry out dye tracing under various discharge conditions.**

5.2.3 Classification of karst geomorphic features, biota, and habitats

Several classification systems for karst geomorphic features have been advanced. Classification of karst features can be by their position, function in a hydrological regime, or genesis (Ford and Williams 1989). The placement of a given karst feature within a classification system assists in its hydrological and geomorphological interpretation.

A surface karst feature classification system has been developed by one of the authors, and is presented in Appendix 2. This classification system can be used to determine the relative significance of karst features to assist with subsequent management decisions.

The classification of subsurface karst or cave features has been addressed by the Cave/Karst Management Handbook for the Vancouver Forest Region (1994). This classification system is based on a method from New Mexico. Karst habitats or karst "biospaces" may be classified in terms of their quality or importance. They can be mapped as part of an operational level inventory to assist in karst management decisions.

5.2.4 Suggested standards for reports and data presentation

The data collected from operational karst inventories should be organized and presented spatially on a map, using a GIS system, if possible. The methods and standards for mapping should conform with those endorsed by the Resources Inventory Committee (RIC), where available (e.g., GSTM-BC). Where no RIC standards exist, methods and standards that have been previously approved by a recognized organization with jurisdiction could be used, where appropriate (e.g., UIS cave symbols). Map data should be produced in a format consistent with GIS systems used by forest districts, regions, and licensees.

The base map/data developed during the office work phase should be used to incorporate the following data into separate layers/overlays:

1) Plot new surface karst features on the base map using points and approved symbol conventions.
2) Plot new cave passage outlines in plan view.
3) Plot new surface hydrological features such as insurgence and exsurgence sites (i.e., swallets or springs), dry valleys, and overflow channels.
4) Map the distribution and depth of exposed epikarst and soil types.
5) Delineate the recharge area for both the karst system as a whole and insurgence sites, using appropriate line work to indicate known, probable, and possible limits.

The map layers developed from the operational level inventory can then be used for a vulnerability assessment (see Section 6.0).

The report completed for the operational-level inventory should cover the objectives of the inventory, the methodology, and the results, and provide conclusions and recommendations to assist operational staff, both from government agencies and forest companies, in making management decisions. They should be written in technically accurate language that is understandable to a range of possible readers from management to field operators. Rationale should be provided to support the writers' conclusions and recommendations for any suggested management prescriptions.

The report should include the following essential or critical items:

1) Inventory objectives, scope, limitations, and location.
2) Who completed the work, for whom, and when. Length of time in the field. Weather conditions. Areas examined and areas not examined, with explanations.
3) List of information used (e.g., maps, airphotos, previous karst data, guidelines).
4) Description of anticipated forestry activities (e.g., harvesting methods, road construction techniques).

5) Background description of the regional geological, geomorphological, hydrological, and biophysical setting, with particular reference to adjacent areas.
6) Description of field methodologies, classification systems, and equipment used.
7) Detailed description of karst within and adjacent to the area of interest, including comments on the distribution, types, and openness of surface and subsurface karst features, the surface and subsurface hydrology, slope, and soil conditions. Results can be in the form of narratives, tables, or figures.
8) Discussion of the potential effects of forest harvesting/road construction within the karst area of concern, including comments on the possible consequences of these activities.
9) Conclusions and recommendations for management prescriptions or mitigative measures (e.g., buffers along edges of sinking streams).

Attachments or appendices should include:

1) Regional location map (1:20 000 scale or greater).
2) Detailed 1:5000 or 1:10 000 scale map with topography, surface hydrology, karst feature distribution, likely subsurface hydrological connections, epikarst openness, and soil thickness.
3) Three-dimensional schematics or computer drawings of the karst system in perspective view (emphasizing the types/extent of surface/subsurface linkages).
4) References and glossary.
5) Photographs.

5.3 Management Implications

Operational karst inventories should provide a level of detail appropriate to the particular type of forest development proposed. Site-specific karst inventories should help decision making and ensure compliance with the Interim Karst Management Guidelines (under development). Operational-level karst inventories should also provide sufficient information for impact assessments, with respect to other resources or values (e.g., downstream fisheries).

Costs for completing operational-level karst inventories will vary greatly and are difficult to generalize. They are highly dependent upon: terrain/karst conditions (e.g., number of surface features), percentage of coverage required for an area, ground search method employed, vegetation cover (density of understorey), season, ease of access to the work area (e.g., helicopters for remote locations), and amount of subsurface inspection done or required. A base figure of $50/ha could be considered a “ballpark” estimate for a typical operational-level karst inventory on a coastal cutblock. This cost would cover the crew travel/field expenses, the location and identification of surface karst features, the examination of cave entrances, and the completion of a report/map. Costs could increase significantly if large numbers of surface features are found or if extensive subsurface inspection is required.

It is suggested that procedures be developed to ensure that sensitive karst inventory data (e.g., cave entrance locations) are kept secure. A secure/coded layer could be developed within a GIS system for cave locations to allow access to only specified personnel.

In general, the personnel who complete the operational karst inventory work should have an appropriate combination of education and experience, and be well-versed in karst and forestry processes and issues. They should be familiar with surveying and mapping procedures, and with the completion of technical reports and maps. Experienced speleologists will be required for subsurface investigations, particularly in technically difficult and/or sensitive caves.

At this stage, it is difficult to determine the specific role of, or the need for, professional involvement (e.g., RPF, P.Geo., RPBio., P.Ag., P.Eng.), but due diligence, liability issues related to the FPC, and the more detailed technical nature of the operational level inventory may make their participation an eventual requirement. The number of professionals in British Columbia with experience in karst and forestry issues is probably limited at this time. Further discussion of this particular issue is anticipated.

6.0 KARST VULNERABILITY METHODOLOGIES AND POSSIBLE APPLICATIONS FOR FORESTED KARST AREAS OF BRITISH COLUMBIA

6.1 Introduction and Background

Karst vulnerability methodologies have been extensively used for the evaluation of karst hydrological systems, particularly with respect to the pollution of karst aquifers and groundwater (Aley and Aley 1993; European Commission Report 1995). Two examples of groundwater vulnerability methodologies are summarized below.

The EPIK system for karst groundwater protection in Switzerland (Doerfliger 1996) was specifically designed to evaluate the vulnerability of karst spring catchments to natural and anthropogenic impacts. This method requires the mapping of four attributes:

- Epikarst (E). Identifying surface karst features (e.g., cave entrances, sinkholes, fractured outcrops, dry valleys).
- Protective cover (P). Categorizing soil conditions (e.g., soil type, depth, permeability).
- Infiltration conditions (I). Locating stream beds and banks, perennial and intermittent swallets, perennial and intermittent streams feeding a swallet or sinkhole, and infiltrating streams.
- Karst network development (K). Characterizing the development of the karst network (e.g., well or poorly developed).

Each of the four attributes is given a weighted numerical rating, and a spatial distribution map is created for each of the attributes using a GIS system. An algorithm for E, P, I, and K is then used to develop a vulnerability map for the catchment, identifying areas of high vulnerability (S1), moderate vulnerability (S2), and low vulnerability (S3).

Another approach for assessing karst groundwater vulnerability is hazard area mapping of recharge areas (Aley and Aley 1993). The aims of this method are to identify and characterize the recharge areas that may pose varying water quality hazards to significant cave areas. The principal technique used for this methodology is groundwater tracing using fluorescent dyes. After a thorough reconnaissance of a particular area, sites are identified where water sinks (e.g., swallets) and where it emerges (e.g., springs). Dyes are injected at the sinks and cumulative charcoal samplers are set at emergent sites. The specific recharge area for each spring can then be identified and rated, depending on downstream impacts, using four groundwater contamination hazard categories (low, moderate, high, and very high).

Karst vulnerability assessment has also been adapted for forest management purposes in temperate forested karst areas in Southeast Alaska (e.g., Aley et al. 1993; Harza 1995; Baichtal and Swanston 1996; Baichtal 1997; USDA Forest Service 1997) and Tasmania (e.g., Eberhard 1996). Examples of these methodologies are summarized below.

In southeast Alaska, a methodology used by the U.S. Forest Service, as part of the Tongass Land and Resource Management Plan (TLMP), focuses on the potential impact of forestry on karst systems (USDA Forest Service 1997). The Alaskan system is a four-step process that i) identifies potential karst lands on a regional basis, ii) conducts inventories of karst resources, iii) delineates karst hydrologic systems and catchment areas, and iv) assesses the vulnerability of karst terrain to forest management activities. Eight classification criteria are used to delineate the karst system and contributing catchments into low, moderate, and high vulnerability. Some of these criteria include epikarst depth, presence of surface karst features, soil type and depth, presence of caves, slope gradient, and connectivity to fish-bearing streams and/or domestic watersheds (see Table 12). The methodology employs a simple default system, whereby if one of the criteria listed under the high vulnerability category occurs in an area, then that area is classified as high vulnerability for forest management purposes.

The default system is largely driven by the *U.S. Federal Cave Resources Protection Act* of 1988. The Act requires the protection of caves found to be significant under the definitions of the Act. U.S. Forest Service Regulations further define what constitutes a significant cave. The standards and guidelines for karst and cave resources under the TLMP are intended to maintain the function and biological significance of karst systems, while allowing for other uses of the land. The management approach focuses on protecting the hydrologic and atmospheric connections of karst systems. Southeast Alaska's process for assessing karst vulnerability is presently under review to clarify the intent and direction of the recommended procedures (J. Baichtal, pers. comm., 1999).

In Tasmania, a zoning scheme differentiating areas into high, medium, and low sensitivity with respect to karst values has been developed for forested areas (Eberhard 1996). The principal concepts and sensitivity concerns incorporated into the zoning scheme include:

- the effects of human disturbance on karst environments and biological communities,
- the maintenance of natural karst processes, as well as individual landforms and their contents,
- the hydrological and meteorological pathways connecting karst systems,
- the karst catchments (as well as the non-karst catchments) of a system,

TABLE 12 *Vulnerability classification criteria used in southeast Alaska (taken from USDA Forest Service 1997)*

Low vulnerability karst lands

Classification Criteria. Low vulnerability karst lands are those areas where resource damage threats associated with land management activities in the areas are not likely to be appreciably greater than those posed by similar activities on non-carbonate substrate. Some characteristics of these lands are:

(a) Karst development is limited or has been modified by glaciation.
(b) Epikarst development is relatively shallow.
(c) Solutional karst features are present but not numerous.
(d) Soils are primarily mineral, soil depth is shallow to deep, soils are moderately well to well drained, parent material is the carbonate substrate, glacial till, or volcanic.
(e) No caves are present.
(f) There are no slopes > 72%.
(g) The karst hydrologic system does not contribute waters to Class I or Class II streams and/or domestic watersheds.
(h) They lie within a watershed that contributes surface waters to a karst area determined to have a low vulnerability.

Moderate vulnerability karst lands

Classification Criteria. Moderate vulnerability karst lands are those areas where resource damage threats associated with land management activities in the areas are appreciably greater than those posed by similar activities on low vulnerability karst lands. Some characteristics of these lands are:

(a) Karst systems are moderately well developed.
(b) Epikarst is up to 8 feet in depth.
(c) Solutional karst features are present but not numerous.
(d) Soils are a mosaic of both mineral and organic. Mineral soils vary from shallow to deep, and are well drained, and parent material is the carbonate substrate. Organic soils are shallow and well drained. If the soil was displaced from the bedrock, it would be retained in the adjacent solutional channels of the epikarst. The percentage of bare rock would increase but the soils would not be transported beyond the rooting depth of young conifers.
(e) No caves are present.
(f) There are no slopes > 72%.
(g) The karst hydrologic system does not contribute waters to Class I or Class II streams and/or domestic watersheds.
(h) They lie within a watershed that contributes surface waters to a karst area determined to have a low vulnerability.

High vulnerability karst lands

Classification Criteria. High vulnerability karst lands are those areas where resource damage threats associated with land management activities in the areas are appreciably greater than those posed by similar activities on low or moderate vulnerability karst lands. These are the areas contributing to or overlying significant caves and areas containing a high density of karst features. Some characteristics of these lands are:

(a) Karst systems are extremely well developed.
(b) Epikarst is greater than 8 feet in depth and may be open to the lateral karst conduits at depth.
(c) Solutional karst features are numerous.
(d) Soils are primarily shallow, well-drained organics. Exposed bedrock areas are common to extensive. If the soil is displaced from the bedrock, it may be retained in the adjacent solutional channels of the epikarst; however, the percentage of bare rock would greatly increase and the soils most likely would be transported beyond the rooting depth of young conifers. If the karst systems are extremely well developed and open, soils may not be retained within the epikarst channels. They would be rapidly transported to the lateral karst conduits at depth.
(e) Caves may be present.
(f) Karst areas may contain slopes > 72%.
(g) The karst hydrologic system may contribute waters to Class I or Class II streams and/or domestic watersheds.
(h) They lie within a watershed that contributes surface waters to a karst area determined to have a high vulnerability.

- the incomplete exploration of karst environments and the potential to enhance knowledge of cave development and hydrology, and
- the notion that the significance of karst areas is likely to change with time as more knowledge is obtained.

The Tasmanian sensitivity method used various criteria to define the different types of sensitivity. For example, low sensitivity karst zones include those areas outside the catchments of significant and sensitive karst systems. Medium sensitivity zones are areas where karst values are known or likely to be present in a catchment, and where the significance of those values is such that land-use activities could affect them. High sensitivity zones are areas that contain highly significant karst values, or where it is extremely probable that these values would eventually be found. These high sensitivity zones might include areas:

- underlain by significant caves,
- with a high density of karst features (e.g., sinkholes, stream sinks, caves),
- that suggest the presence of underlying caves (e.g., by a high density of stream sinks, cave entrances, and sinkholes),
- that are catchments to significant cave areas, and
- where lithological or structural geological considerations suggest the presence of underlying caves.

From the above and other literature, it is apparent that the term "karst vulnerability" is not well defined, and has been used by a variety of workers for different purposes. It is therefore suggested (based on ideas from the European Commission Report 1995) that, in order to provide clarity in vulnerability mapping, it is critical:

- to define the term "vulnerability" and the other terms used,
- to indicate the overall objectives of the vulnerability methodology,
- to describe the basis for the various vulnerability categories, and
- to ensure that the scale of mapping used can meet the objectives.

It is also suggested that the British Columbia karst vulnerability methodology focus on the "intrinsic" (or internal) factors of karst ecosystems, which can be defined as "the natural factors associated with, and inseparable from, the karst ecosystem" (e.g., lithology, hydrology, geomorphology, air, and biota). These intrinsic factors are separate from extrinsic factors that are imposed on a karst ecosystem by natural processes (e.g., windstorms, wildfire) or human-caused events (e.g., forest harvesting, roads).

6.2 Concepts and Definitions for a Proposed Karst Ecosystem Vulnerability Methodology for Forested Areas of British Columbia

In order to provide a comprehensive karst vulnerability mapping tool for British Columbia, all aspects of a karst ecosystem must be taken into consideration. This concept differs from the objectives of the karst vulnerability systems summarized above, in that they have focused on only selected parts of the karst ecosystem. Therefore, the prime objective of the karst vulnerability system for British Columbia must be to evaluate all four fundamental environmental states of the ecosystem: **air, water, land, and biota.**

Suggestion 10. The prime objective of the karst vulnerability system for British Columbia must be to evaluate all four fundamental environmental states of the karst ecosystem: **air, water, land, and biota.** The assessment should focus on the intrinsic or natural factors associated with, and inseparable from, the karst ecosystem.

This approach to karst ecosystem vulnerability mapping must be based on sound principles supported by scientific knowledge. It should be understood that:

- Karst ecosystems are complex, interwoven networks of attributes related to the fundamental environmental states of air, water, land, and biota.
- Karst ecosystems are sensitive to change.
- Karst ecosystems are constantly changing.
- People can be part of karst ecosystems and influence them.
- Karst ecosystems must be viewed at a variety of scales, from the very large (total system) to the very small (microcavity).

Karst ecosystem vulnerability mapping for the purposes of this report can be defined as "a hazard assessment methodology for evaluating the relative ease with which a karst ecosystem might be changed negatively (or harmed) by an imposed external activity."

Karst sensitivity can be considered as "the inherent susceptibility of a particular karst ecosystem attribute (e.g., groundwater) to change."

A karst attribute can be defined as "a feature that is part of a karst ecosystem and is related to one or more of the fundamental environmental states of the ecosystem: air, water, land, or biota."

Forestry and land-use management activities, and other extrinsic (or external) factors, such as the location of downstream fisheries, were excluded from this vulnerability methodology. These external factors could, however, be mapped out separately at a similar scale to the vulnerability mapping so that they could be viewed side-by-side or overlain on the karst vulnerability map. From the two maps, it would then be possible to assess the overall risk of proposed activities within a particular karst area.

Existing karst vulnerability methodologies vary from numerical-based algorithms (e.g., EPIK) to more simple, single-attribute controls (e.g., southeast Alaska system). Both methodologies have advantages and disadvantages. For example, the data for the EPIK system are controlled by a variety of numerically rated attributes that are summed and weighted. While the EPIK system considers a variety of factors, it could also be considered complex when compared to the non-numerical southeast Alaska system. With this in mind, it is suggested that karst ecosystem vulnerability methodology for British Columbia use a combination of these approaches. It should be simple and flexible, but also broad enough in scope to consider as much of the karst ecosystem as possible.

Karst ecosystem vulnerability assessments could possibly be done at both the planning- and operational-level karst inventories. In the former, it is suggested that the broad attributes mapped during Phase 2 of the inventory process (e.g., karst features, slope characteristics and gradient, soil cover and types) could be categorized or incorporated into a simple vulnerability rating system. This simple system would focus primarily on the land and water environmental states of the karst ecosystem, and could be used as a coarse planning tool for assessing the risk of proposed forest management activities in a karst area. A more rigorous and detailed methodology, that could easily incorporate all four environmental states of the karst ecosystem, could be used at the operational level. The basis of this methodology is detailed in the next section.

Suggestion 11. Karst ecosystem vulnerability assessments could be done during Phase 2 of the planning-level inventory to provide a broad planning tool for assessing the risk of proposed forest management activities in a karst area. A more rigorous and detailed assessment could be carried out at the operational-level inventory, and could incorporate all four environmental states of the karst ecosystem: air, water, land, and biota.

6.3 An Approach for Karst Ecosystem Vulnerability Mapping in Coastal Forested Areas of British Columbia

This section outlines an approach for karst ecosystem vulnerability mapping using data from coastal forested areas of British Columbia. The data and categories developed will probably require some refinement for the interior of British Columbia.

As stated above, karst ecosystems are complex, interwoven networks of attributes related to the fundamental environmental states of air, water, land, and biota. In order to develop a vulnerability methodology to assess this complex ecosystem, it is necessary, firstly, to break the karst ecosystem down into its four fundamental environmental states and, secondly, divide these into broad components or sub-states. These sub-states can then be categorized for vulnerability using a subjective rating system with values of low, moderate, or high. After each of these sub-states has been categorized, it should then be possible to "reconstruct" the whole ecosystem and determine an overall vulnerability rating (see Figure 7). It should be realized at the outset that this type of approach could be considered conceptually flawed because of the tightly interwoven nature of the ecosystem. Whether it is possible to break down an ecosystem and then re-build it is probably open to debate. However, it should be possible to do so, if a relatively broad, rationalized view is taken, and a focus on minute details is avoided.

The various environmental states and sub-states are discussed below and summarized in Tables 13 to 16. These tables provide site examples for low (L), moderate (M), and high (H) vulnerability categories for the various sub-states.

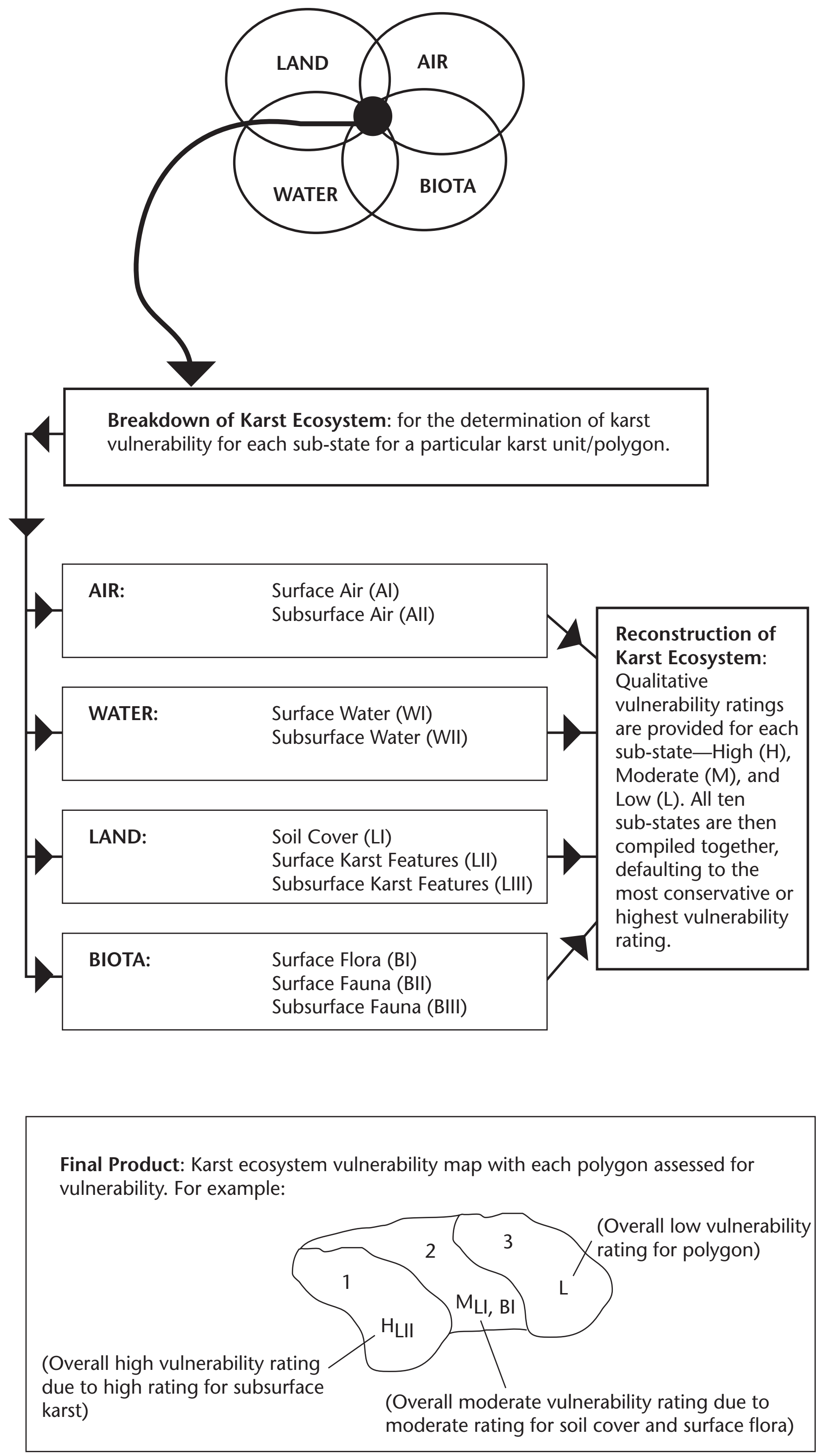


FIGURE 7 *Suggested karst ecosystem vulnerability methodology using four environmental states of the karst ecosystem.*

Air (A)

Air is the one fundamental state of the karst ecosystem that is typically given the least attention, but it can play an integral role in the well-being and health of the system. The two principal sub-states are Surface Air and Underground Air (Air I and II, respectively). The exact location where surface air ends and subsurface air begins is difficult to define, but it is assumed to be close to the boundary of light and darkness. The quality and flow rate of surface air around surface karst features (e.g., sinkholes) can be critical to climatic conditions underground, influencing faunal habitats and speleothem growth. Surface air is also critical for certain fauna and flora around the perimeter of karst features.

TABLE 13 *Qualitative vulnerability ratings for air*

Air sub-states	Objectives	Measurable paramenters	Examples of site characteristics for various vulnerability ratings	
SURFACE AIR (AI)	Air quality	Temperature range, relative humidity range, etc.	High	large, deep depressions (e.g., doline) where temperature inversion is possible
			Moderate	depressions of moderate depth
			Low	no deep, closed depressions
SUBSURFACE AIR (AII)	Air quality, natural rates of transfer	Temperature range, relative humidity range, etc.	High	atmospheric openings with known surface connections
			Moderate	narrow openings with known surface connections
			Low	no atmospheric openings

TABLE 14 *Qualitative vulnerability ratings for water*

Water sub-states	Objectives	Measurable paramenters	Examples of site characteristics for various vulnerability ratings	
SURFACE WATER (WI)	Maintain quality and quantity	Number and size of surface karst hydrological features, flow rate, pH, temperature, specific conductance, dissolved oxygen, etc.	High	springs, major sinking streams, swallets
			Moderate	"dry" sinkholes, grykes, no flowing water
			Low	soil-covered karst with diffuse infiltration
SUBSURFACE WATER (GROUNDWATER) (WII)	Maintain quality and quantity	Flow rate, pH, temperature, specific conductance, dissolved oxygen, etc.	High	cave streams, standing water, dripwater
			Moderate	intermittently dry and wet caves
			Low	dry cave systems

TABLE 15 *Qualitative vulnerability ratings for land*

Land sub-states	Objectives	Measurable paramenters	Examples of site characteristics for various vulnerability ratings	
SOIL (LI)	Maintain soil conditions within acceptable ranges	Soil thickness/ type, epikarst depth, slope (macro/micro), permeability, etc.	High	thin organic veneer over well-developed epikarst
			Moderate	moderate soil thickness
			Low	thin blanket or mantle
SURFACE KARST (LII)	Maintain natural rates of dissolution integrity, etc.	Identification/ number of features, feature size	High	extensive areas of deep epikarst, large sinkhole with steep sideslopes
			Moderate	small surface karst features mantled with variable soil cover
			Low	buried (i.e., soil-covered) karst
SUBSURFACE KARST (LIII)	Maintain cave quality, structural integrity, etc.	Cave entrance width/ height, depth of overlying bedrock, etc.	High	well-decorated caves
			Moderate	caves with features/significant between high and low
			Low	caves with no unusual resource contents or values

TABLE 16 *Qualitative vulnerability ratings for biota*

Biota sub-states	Objectives	Measurable paramenters	Examples of site characteristics for various vulnerability ratings	
SURFACE FLORA (BI)	Maintain natural communities, populations, and habitats	Species diversity/ density, dominant taxa, presence of unique flora	High	significant areas of unique or rare plants occurring on limestone
			Moderate	some areas of unusual plants, but not extensive or endangered
			Low	deep soils, no unique plants
SURFACE FAUNA (BII)	Maintain natural communities, populations, and habitats	Habitat indicators, presence of unique fauna	High	rare mammals using surface karst habitat
			Moderate	some rare usage of minor surface karst habitats
			Low	no known surface karst-dependent fauna
SUBSURFACE FAUNA (BIII)	Maintain natural communities, populations, and habitats	Habitat indicators, presence of troglobites	High	bat hibernaculum or rare, unique fauna site
			Moderate	suitable habitat, but no evidence of fauna
			Low	active, seasonally flooded caves of limited extent

Water (W)
Water is one of the more studied environmental states of the karst ecosystem and could be considered as the fundamental driving force in the karst dissolution process. In this case, two sub-states are considered, Surface Water and Subsurface Water (Water I and II, respectively). Again the boundary between these two states is not well defined. For example, it is possible to have a stream that disappears and reappears along its length. However, the same light and darkness boundary used for dividing surface air from subsurface air is considered reasonable. As with air, the principal concerns are the sensitivity of water to changes in quality and quantity.

Land (L)
For simplicity, the land (or terrestrial) environmental state can be divided into three sub-states: Soil Cover, Surface Karst Features, and Subsurface Karst Features (Land I, II, and III, respectively). Soil Cover can be considered as any unconsolidated materials overlying the karst bedrock, and includes both genetic surficial materials and weathered bedrock fragments. The distinction between Soil Cover and the other two sub-states is obvious. The distinction between Surface and Subsurface Karst Features is a more difficult boundary to define, but the light and darkness boundary is considered a reasonable guide.

Biota (B)
Karst biota can be divided into three sub-states: Surface Flora, Surface Fauna, and Subsurface Fauna (Biota I, II, and III, respectively). For simplicity, all subsurface biota are considered as fauna because no chlorophyllic biota (e.g., plants) are naturally present underground. The principal aim of categorizing biota is to evaluate an area for unique or rare flora or fauna associations.

Following the rating of sub-states, each of the four states (air, water, land and biota) is assigned the highest rating obtained from the respective sub-states. For example, if the sub-states Surface Flora, Surface Fauna, and Subsurface Fauna for a particular site give a rating of low, moderate, and low, respectively, then the overall rating for Biota would be moderate. A subscript could be used after the rating to indicate which sub-state is the controlling factor (in the above case it would be BII). From the ratings of the four states, it should then be possible to obtain an overall vulnerability rating for a particular karst ecosystem unit or site. Again, the most sensitive value assigned one of the four states is used. For example, if the states for Air, Water, Land, and Biota for a particular site had ratings of low, low, low, and moderate, respectively, then the overall vulnerability rating for the site would be moderate. To be more specific, the overall vulnerability rating could be given a suitable subscript to identify what state and sub-state has driven the rating. The above example would provide an overall vulnerability rating of moderate due to biota associated with surface fauna (MBII). If more than one of the sub-states is the controlling factor, then these could be listed in order of air, water, land, and biota.

One way to obtain a very high vulnerability rating for a particular area would be when two (or possibly three) environmental states all indicate a high rating. In addition, the use of a vulnerability assessment system with annotated subscripts for the various ratings of ecosystem sub-states would allow forest management prescriptions to address particular concerns at a site.

Suggestion 12. It is suggested that the four environmental states of the karst ecosystem (air, water, land, and biota) be divided into ten sub-states for the vulnerability assessment as follows: Surface Air (Air I), Subsurface Air (Air II), Surface Water (Water I), Subsurface Water (Water II), Soil Cover (Land I), Surface Karst (Land II), Subsurface Karst (Land III), Surface Flora (Biota I), Surface Fauna (Biota II), and Subsurface Fauna (Biota III). These sub-states should be individually rated as low, moderate, or high for a particular karst unit. The overall vulnerability rating for the karst unit would then default to the highest sub-state rating.

6.4 Data Presentation, Integration, and Analysis

To date, this approach to karst ecosystem vulnerability assessment has not been applied in practice. It will, therefore, require considerable testing and refinement. It is intended that the assessment be applied as a mapping procedure incorporated into a GIS system with various layers compiled for each of the environmental sub-states. Data for these layers could be obtained from the appropriate levels of karst inventory information. The karst inventory data could also be refined to assist in developing a suitable format for incorporating them into the sub-state layers. The sub-state layers could then be analyzed by the GIS system to produce a map with an overall karst ecosystem vulnerability rating. This type of mapping methodology would be most useful at planning-level inventory scales.

A possible alternative to the GIS system, particularly at proposed cutblock or road-building scales, would be the development of a tabulated form approach. Each of the sub-states could be set out on a field form and the cutblock or area of interest categorized for each of the sub-states. An overall vulnerability rating could then be obtained relatively quickly for simple sites. For example, a cutblock underlain by carbonate bedrock, with no evidence of subsurface openings or rare surface karst biota, and a blanket (i.e., >1 m) of soil cover, could be evaluated and rated rapidly with little need for GIS mapping techniques.

6.5 Limitations, Strengths, and Weaknesses of the Suggested Approach

Issues such as data collection intensity, data limitations, subjectivity of results, and data reliability will need to be examined further. Additional work will be required to ascertain which measurable attributes and features are needed to categorize the sub-states. British Columbia–based karst research, scientific consensus on results, and field trials may eventually support the ideas proposed above.

In terms of strengths, the proposed methodology for karst ecosystem vulnerability is flexible and well suited to the attributes that occur at any or all levels of the karst inventory process. The methodology can be considered holistic in that it attempts to address the complete karst ecosystem, in contrast to other vulnerability assessments that focus on only parts of the ecosystem. The methodology is applicable to long-term evaluation of the cumulative impacts of different forest management activities (or successive phases of an activity) and for harvesting rotations. It can also be readily updated as new information becomes available (e.g., a new cave area is discovered).

In terms of weakness, the methodology could be considered excessive because of all the data required to complete the vulnerability assessment. However, in many cases, particularly where no subsurface karst features are evident, the data required could be minimal.

7.0 INTEGRATION OF PROPOSED KARST INVENTORY SYSTEM AND SUGGESTIONS FOR FURTHER WORK

Any well-integrated inventory system developed for differing scales of data collection should have closely knit internal linkages. These internal linkages are required so that the methods of data collection, assimilation, and analysis are systematic, progressing from regional, overview scales (e.g., 1:250 000) to more detailed site-specific scales (e.g., 1:5000). These well-defined linkages are also important for consistency during the exchange of data between the various scales of inventory.

The objectives of this final section are:

- to summarize the linkages between the reconnaissance-, planning-, and operational-level karst inventories,
- to summarize how the proposed karst ecosystem vulnerability assessment could be carried out and used within this framework,
- to show how the three inventory levels might be linked, both in terms of data collection and completion, with other inventory procedures, and
- to outline a series of suggestions for further work to both refine and improve the proposed karst inventory and vulnerability assessment methodologies.

7.1 Summary of Internal Linkages within the Proposed Karst Inventory System

The various scales chosen for the three inventory levels are based on standard geographic mapping scales used in Canada (NTS system with 1:250 000 and 1:50 000 maps), and the currently used mapping scales of the British Columbia forest industry and provincial government (1:20 000, 1:10 000 and 1:5000). The change in scale from reconnaissance- to planning-level inventories is significant, with a five-fold increase in detail from 1:250 000 to 1:50 000 scales and a twelve-and-a-half-fold increase from 1:250 000 to 1:20 000 scales. Significant errors in the transfer of line and polygon data could occur in both of these cases. The change in scale from the planning level inventory (1:20 000) to the operational level (1:10 000 or 1:5000) is less (two- and four-fold, respectively). Therefore, less potential error in the transfer of line and polygon data between the planning and the operational levels is anticipated.

The first stages in determining the karst potential for a region, assuming no existing karst information is available, is to complete a reconnaissance-level inventory (see Section 3.0). From the reconnaissance-level karst inventory (at 1:250 000 scale), it should be possible to determine