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.

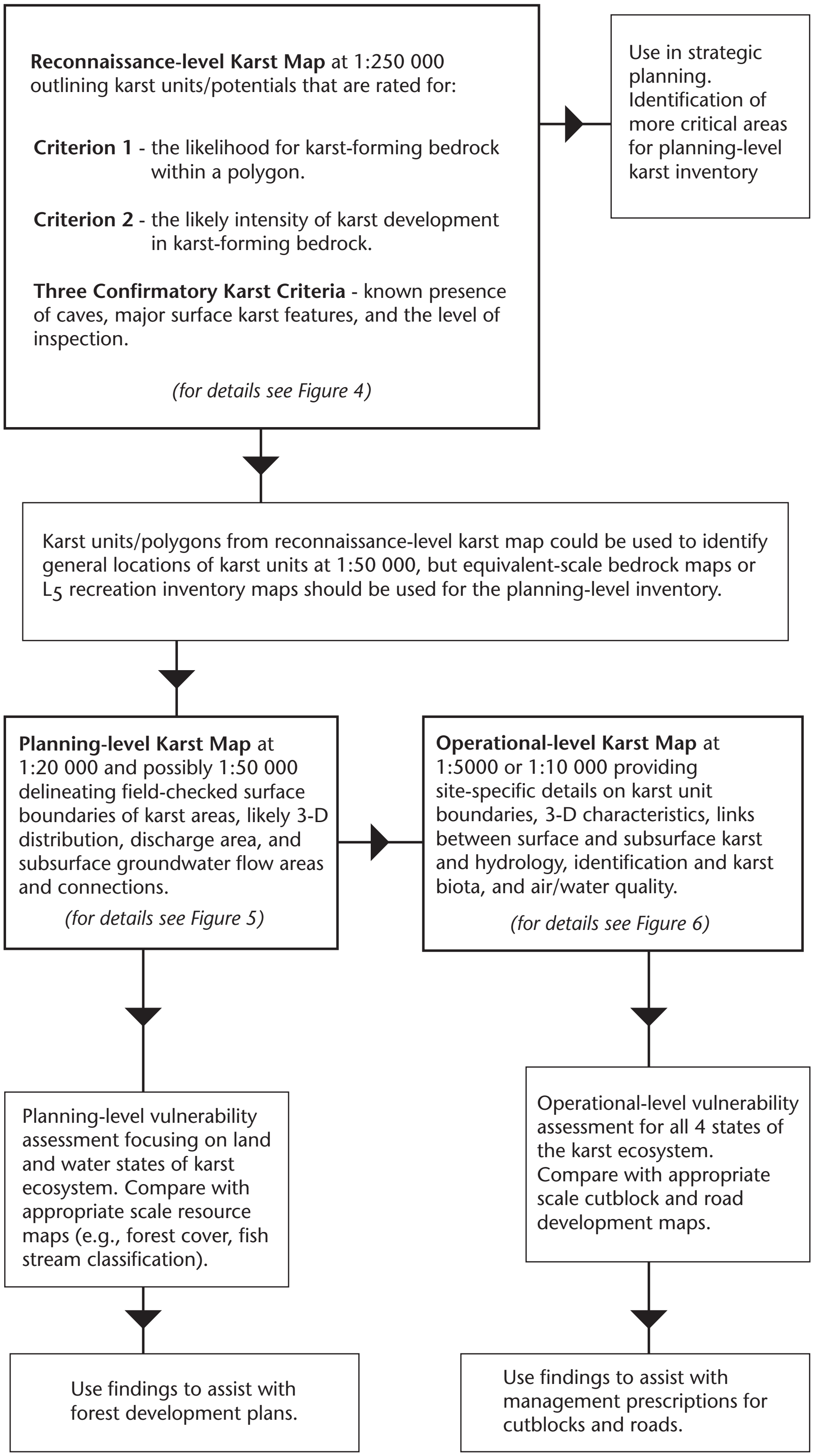
The first stages in determining the karst potential for a region, assuming no existing karst information is available, is to complete a reconnaissance-level inventory (see Section 3.0). From the reconnaissance-level karst inventory (at 1:250 000 scale), it should be possible to determine which particular bedrock units are likely to be the most significant in terms of karst presence (Criterion 1) and intensity of karst development (Criterion 2). The confirmatory criteria for known caves, surface karst features, and inspection level will add confidence to this information.

Figure 8 is a summary flow chart for the proposed karst inventory system, starting at the reconnaissance level, leading on to the planning and operational levels, with final links to the karst vulnerability assessment methodology.

The boundary lines for the 1:250 000 scale karst unit polygons, taken from the digital bedrock maps of British Columbia, will be reasonably accurate down to a scale of 1:100 000. However, if used directly for Phase 1 or Phase 2 at the planning-level inventory (1:50 000 or 1:20 000), significant boundary errors are likely to occur. To reduce these errors, it is suggested that the original, detailed bedrock maps (with variable scales and coverage), which were the basis for the 1:250 000 digital compilation, be sourced and used at the planning level. These original maps will also probably provide additional information on bedrock lithologies and major structures. To assist sourcing of these original maps, it is suggested that their references be included in the legends of the reconnaissance karst inventory maps. An inset map could also be included on the reconnaissance maps to show the coverage, scales, and overlaps of the original maps. The attributes of bedrock lithology and unit width, determined at the 1:250 000 reconnaissance level, could be used as a preliminary guide at the planning level for bedrock lithology conditions and karst unit widths. However, these data are office-based and will likely require verification and field checking at the planning level.

The planning-level inventory uses a phased approach to assist in data gathering and in defining the direction of work (see Section 4.0). Phase 1, at scales of 1:50 000 or 1:20 000, focuses on identifying the types and boundaries of a karst unit, the adjacent bedrock lithologies, major bedrock structures, and major surface karst and hydrological features. This information can be readily used, or incorporated into Phases 2 and 3, as required. The decision on whether Phase 2 is required or not depends on both the size and complexity of the karst areas under investigation. Phase 2 may not be required for small areas of karst with relatively uniform characteristics. Phase 1 for a small area might be able to readily obtain the karst feature and attribute data suitable for easy incorporation into the vulnerability assessment procedure. For larger and more complex areas (e.g., units with varying intensities of surface epikarst and soil thickness), Phase 2 should be carried out to stratify these areas into sub-areas (polygons) using a modified terrain mapping system. Regional dye tracing (Phase 3) should be carried out only following Phases 1 and/or 2.

The requirement for dye tracing depends on whether: i) recharge areas or subsurface flows can be inferred from existing information (be it surface or subsurface observations), ii) significant karst hydrological features are present (e.g., sinking streams or major springs), and iii) significant or complex subsurface flow paths are present. If the recharge areas and subsurface flow paths are apparent, and there are no significant karst hydrological features, there may be no need to conduct dye tracing. On the other hand, dye tracing may be the only way to investigate complex subsurface hydrological networks (see Section 4.4).



Reconnaissance-level Karst Map at 1:250 000 outlining karst units/potentials that are rated for:

Criterion 1 - the likelihood for karst-forming bedrock within a polygon.

Criterion 2 - the likely intensity of karst development in karst-forming bedrock.

Three Confirmatory Karst Criteria - known presence of caves, major surface karst features, and the level of inspection.

(for details see Figure 4)

Use in strategic planning. Identification of more critical areas for planning-level karst inventory

Karst units/polygons from reconnaissance-level karst map could be used to identify general locations of karst units at 1:50 000, but equivalent-scale bedrock maps or L5 recreation inventory maps should be used for the planning-level inventory.

Planning-level Karst Map at 1:20 000 and possibly 1:50 000 delineating field-checked surface boundaries of karst areas, likely 3-D distribution, discharge area, and subsurface groundwater flow areas and connections.

(for details see Figure 5)

Operational-level Karst Map at 1:5000 or 1:10 000 providing site-specific details on karst unit boundaries, 3-D characteristics, links between surface and subsurface karst and hydrology, identification and karst biota, and air/water quality.

(for details see Figure 6)

Planning-level vulnerability assessment focusing on land and water states of karst ecosystem. Compare with appropriate scale resource maps (e.g., forest cover, fish stream classification).

Operational-level vulnerability assessment for all 4 states of the karst ecosystem. Compare with appropriate scale cutblock and road development maps.

Use findings to assist with forest development plans.

Use findings to assist with management prescriptions for cutblocks and roads.

FIGURE 8 *Summary of linkages between proposed karst inventory levels and vulnerability assessment.*

At the end of the planning-level inventory, a 1:20 000 map should be completed and marked with: the field-checked surface boundaries of the karst areas, the karst catchment/recharge areas (this could include upslope non-karst areas), subsurface flow paths and connections, major surface karst features, cave entrances, and karst hydrological features. The karst areas should be mapped into various polygons with similar intensities of karst development. (Appropriate geological cross-sections would assist in understanding the three-dimensional character of the karst unit and its hydrology.) These inventory data could then be incorporated into a planning-level vulnerability assessment, and compared to maps with proposed forest activities and adjacent (or downstream) resources to assist in management planning and decision making.

Data obtained from the planning level karst inventory could be readily incorporated into the operational-level karst inventory at the desktop phase. Detailed field examination of karst areas (within proposed cutblocks or along roads) should focus on the location and classification of specific surface and subsurface features or resources. Dye tracing could be carried out during the operational-level inventory to answer specific questions on recharge areas or subsurface flows that might have significant management implications. Examples of such questions could include: i) which parts of the recharge area for a karst unit are more critical in terms of impact on downstream fish habitat, ii) what size of buffer should be left on a particular sinking stream, and iii) where will groundwater flows from a particular quarry site go?

At the end of the operational inventory, a 1:5000 or 1:10 000 scale map should be completed and marked with: the karst unit boundaries, overall recharge area for the karst unit (may require a 1:20 000 scale map), local recharge areas for specific sinking streams/insurgence sites, surface karst features (point locations or mapped zones), projected outlines of subsurface cave passages, and subsurface flow paths and conduits. Profiles or cross-sections could be used to display the three-dimensional nature of the karst areas. Data collected during the operational level inventory could be used for an operational vulnerability assessment. This could be done by: i) using and refining vulnerability polygon boundaries developed during the planning vulnerability assessment, ii) developing new map polygon boundaries within a layered GIS system for the various ecosystem sub-states, and iii) incorporating the data into a prescribed field form (see Section 6.4). A risk assessment could then be carried out using the operational vulnerability ratings in conjunction with proposed activities and adjacent or downstream resources.

7.2 Linkages between the Proposed Karst Inventory System and Other Inventory Procedures

Both regional bedrock geological mapping (see SGBM-BC) and 1:250 000 terrestrial ecosystem mapping include data that can be incorporated into the reconnaissance-level karst inventory. However, it is unlikely that these inventories could use the specific data obtained from the reconnaissance-level karst inventory.

Planning- and operational-level karst inventories have a greater number of linkages with other inventory programs (see Figure 9). At least seven complementary inventories were identified:

- Terrain Stability Mapping,

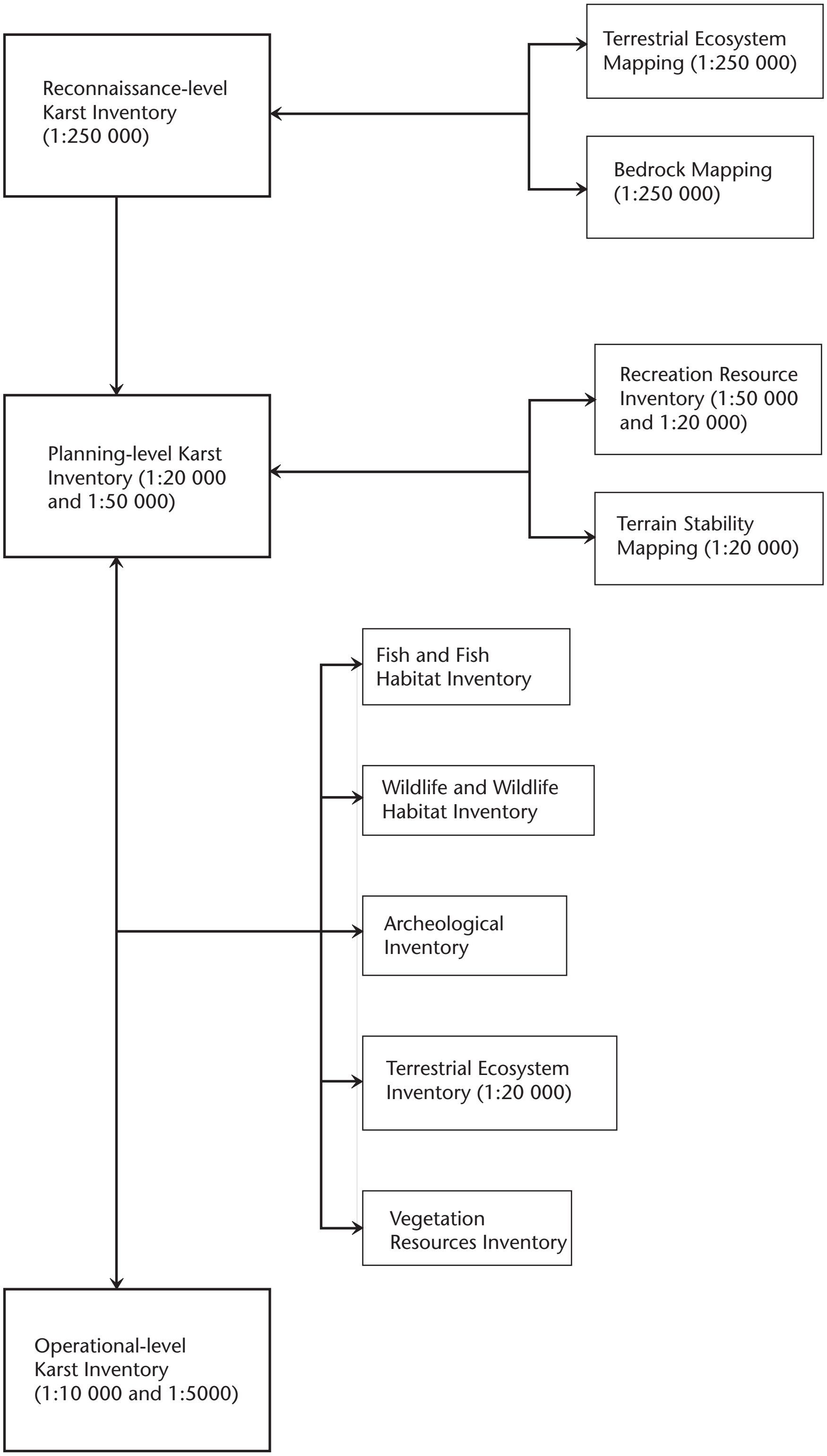


FIGURE 9 *Likely linkages between proposed karst inventory levels and other inventories.*

- Terrestrial Ecosystem Mapping,
- Vegetation Resources Inventory,
- Recreation Resource Inventory,
- Archaeology Inventory,
- Wildlife and Wildlife Habitat Inventory, and
- Fish and Fish Habitat Inventory.

Terrain Stability Mapping

Terrain stability mapping identifies unstable and potentially unstable land areas by inventorying the character and distribution of surficial materials, and inventorying active geomorphological processes that can lead to instability. Terrain stability mapping is best linked to karst inventories at the planning scale (see Section 4.3). The planning-level karst inventory would be more cost-effective if it was integrated with terrain stability mapping. Terrain stability mapping is also linked to terrestrial ecosystem mapping in some circumstances. Concurrent terrain stability mapping and terrestrial ecosystem mapping with karst inventories is probably also cost-efficient.

Terrestrial Ecosystem Mapping

Terrestrial ecosystem mapping is used for interpretations related to forest, range, wildlife, soils and biodiversity management. The landscape is stratified into map units based on ecological criteria (e.g., climate, physiography, surficial material, soils and vegetation). This mapping combines biogeoclimatic ecosystem classification and ecoregion classification in order to map homogeneous areas. Terrain ecosystem mapping (at 1:20 000 scale) could be used as a first pass biota stratification for the planning-level karst inventory. It would be both useful and cost-efficient for field personnel to collect information that could be used for karst inventories during terrestrial ecosystem mapping.

Vegetation Resources Inventory

The vegetation resources inventory describes vegetation cover and other non-timber characteristics of the landscape, using the British Columbia Land Cover Classification Scheme (RIC Standard). These inventories identify harvest status, stand treatments, wildfires, insects, and disease, and are used to provide a basis for wildlife habitat mapping. Procedures and standards for ground sampling are described in the RIC publication, *Vegetation Resources Inventory Draft Sampling Procedure*. Linkages exist for the vegetation resources inventory to be conducted concurrently with terrestrial ecosystem mapping. Initial polygon delineation from terrestrial ecosystem mapping can be directly applied to the vegetation resources inventory. The surficial ecological data could also be used within the planning-level karst inventory.

Recreation Resource Inventory

Recreation inventories are initiated and maintained to meet FPC planning requirements and RIC standards. A recreation resource inventory involves identifying, classifying, and recording the types and locations of amenity resources. This inventory actually encompasses the recreation features inventory, visual resources inventory, visual sensitivity inventory, and recreation opportunity spectrum (ROS) inventory, as well as inventories of rivers, sites, trails, caves, and interpretive forest sites. The recreation resource inventory is normally carried out at a 1:50 000 scale (1:20 000 on Vancouver Island and in the Lower Mainland). Karst features are linked to recreation inventories by a series of recreation feature codes that denote karst/cave areas within L5 polygons. The codes are: K00-cave/karst features, K01-cave, K02-sinkhole, and K03-limestone plateau. Recreation karst information is most useful at the planning-level inventory, where it can be used as base information. However, final planning-level inventory maps could also be used to update recreation inventories.

Archeological Inventory

There are two types of archaeological inventories: Archeological Overview Assessments (AOA's) and Archeological Inventory Studies (AIS's). AOA's can be used at the forest development planning level, and to position AIS's. The AOA is used to estimate or predict an area's potential for archeological resources. The results are used to determine the need for subsequent impact assessments and management studies before the approval of forest development activities. The AIS's are field surveys used to locate and record archaeological sites within a proposed study area. They can provide baseline information on archaeological site locations in a variety of biophysical settings.

AOA's and AIS's must be consistent with the *British Columbia Archaeological Impact Assessment Guidelines* (Apland and Kenny 1994). In addition, AIS's must be consistent with the *British Columbia Archaeological Site Inventory Form Guide*. All work is completed at a scale of 1:20 000 and thus could be readily linked to the planning-level karst inventory, if required.

Wildlife and Wildlife Habitat Inventories

Wildlife and wildlife habitat inventories include broader ecological values that require a comprehensive habitat inventory. These inventories are required to provide information in support of forest development and logging plans, and are designed to produce information that complies with FPC wildlife regulations. The distribution of red- and blue-listed species and habitats at risk, or a particular management concern, can be identified during these inventories. The habitat information is typically derived from species/habitat models in conjunction with terrestrial ecosystem and vegetation resource mapping. When conducting wildlife habitat mapping, methods must follow the RIC standards for ecosystem mapping as set out in the STEM-BC. Priority inventories are carried out in areas of high wildlife value where little information exists, in areas where active planning is in progress, or in areas where species are at risk.[7] Planning- and operational-level karst inventories could be linked to wildlife and wildlife habitat inventories when specific karst-related fauna are identified.

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[7] "Species at risk" refers to: any wildlife species that is threatened, endangered, sensitive or vulnerable; any threatened or endangered plant or plant communities requiring protection; and regionally important wildlife.

Fish and Fish Habitat Inventories

Fish and fish habitat inventories provide information about fish distribution and the condition and capability of supporting habitats. The purpose of fish and fish habitat inventories at the planning level is to assist in the compilation of forest development plans, logging plans, and silviculture prescriptions. Intensive inventories at an operational level generate additional information required for managing species and designating habitats at risk. Karst inventories would be linked to these inventories when fish habitats occur within karst areas, or when downstream fish habitats are likely to be influenced by upland karst units.

7.3 Suggestions for Further Work to Refine and Improve the KISP

Further work is required to both refine and improve the preliminary KISP at all three inventory levels, particularly because many of the procedures suggested have not been extensively tested or used. The proposed vulnerability assessment procedure is still in a conceptual form and needs considerable refinement and testing. However, once further developed, it could provide a useful and powerful management tool.

The reconnaissance-level karst inventory could be tested and refined in a number of areas. One primary concern is the use of a numerical rating system that has to be developed into an acceptable province-wide format. A number of carefully selected karst areas (e.g., northern Vancouver Island, Nelson, Prince George) could be chosen and the methodology applied. In addition, work is needed to determine exactly how the biogeoclimatic information could be suitably incorporated into the methodology. GIS data systems should be examined so that information gathering, analysis, and display is completed in a well-organized and systematic fashion.

Of the three karst inventory levels, the planning level (particularly Phases 2 and 3) is the one that probably requires the most testing. Phase 2 requires the mapping of karst areas using a modified terrain mapping methodology. This methodology needs field testing to check that it is both reliable and cost-effective. Phase 3, dye tracing, is a well-recognized procedure for assessing karst hydrology, but it has not been used extensively in forested areas of British Columbia. To demonstrate both the uses and applications of dye tracing in forest management, it is suggested that a series of field trials be carried out in carefully selected representative areas.

The operational-level karst inventory is probably the level at which most work on coastal karst areas has been carried out in the past. However, there are still parts of the methodology that could benefit from testing, including: i) a controlled field trial for the various ground search methods to test them for accuracy, precision, efficiency, and costs, ii) investigating suitable methods for graphical representation of three-dimensional karst data in GIS, and iii) investigating suitable classification schemes and symbology for surface karst and hydrological features.

The karst ecosystem vulnerability methodology could be tested and refined in a number of ways. The schemes developed for the various karst ecosystem states should be expanded to include more details on measurable attributes and examples of site characteristics. At the planning level, the vulnerability assessment procedure should be adapted and applied to polygons obtained from the karst-modified terrain mapping methodology.

The vulnerability assessment at the planning level should be evaluated to see whether it could be used as an effective planning tool. At the operational level, possible options/formats for carrying out the vulnerability assessment should be investigated. For example, would a GIS-based mapping system be effective, would a simple field form format be acceptable, or would a combination of both be required?

One of the principal concerns for the KISP it that it must be developed for all areas of British Columbia. At present, it has been developed primarily on experience and information from coastal forested areas. Some adaptation and refinement will probably be required for forested areas in the interior of British Columbia and, if used in non-forested areas, for alpine and grassland settings.

Another major concern is the management and secure storage of karst inventory information. Appropriate storage of information should be carried out at the various administrative levels (e.g., forest district, forest region, and province). The purpose would be to ensure accessibility only by authorized resource planners, to ensure inventory standardization, and to promote general administrative efficiency. Further investigation is required to assess the data requirements for setting up such a system.

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9.0 GLOSSARY

Anhydrite	A mineral; anhydrous calcium sulphate.
Anthropogenic	Caused by or resulting from the acts of humans.
Biogenic	Of biological origin; organic.
Biospace	The separated or interconnected network of “spaces” as air- or water-filled cracks, pipes, vertical channels, tubes, voids or microcavities, horizontal conduits, and larger cavities, including caves, that are inhabited by invertebrates, including in the interstitial medium and saturated zone.
Biota	All living organisms of an area, taken collectively.
Calcareous	Containing calcium carbonate; from the Latin word *calcarius*, meaning “of lime.”
Calciphilic	Biota that prefers calcareous soils or rock.
Calcite	A mineral composed of calcium carbonate, like aragonite but differing in crystal form; the principal constituent of limestone.
Carbonate	A salt or ester of carbonic acid, such as calcium carbonate. A rock consisting mainly of carbonate minerals, such as limestone or dolomite.
Catchment	The surface area drained by various-sized watercourses.
Caver	A person who explores caves as a hobby or for recreation.
Chert	Light-cream or grey to black rock composed of silica, found occurring as nodules or layers in limestone, or as a replacement of limestone.
Closed depression	A general term for any enclosed topographic basin having no external drainage, regardless of origin or size.
Conductivity	A measure of the ability of water to conduct electricity.
Conduit	A subterranean stream course filled completely with water and always under hydrostatic pressure.
Cutblock	A specific area, with defined boundaries, authorized for timber harvest.

Doline	A basin or funnel-shaped hollow in limestone ranging in diameter from a few metres to a kilometre, and in depth from a few to several hundred metres. May be distinguished as "solution" or "collapse" if precise origin is known.
Dolomite	A mineral composed of calcium magnesium carbonate. Rock chiefly composed of the mineral dolomite. Also called dolostone.
Dry valley	A valley that lacks a surface water channel.
Epikarst	The upper zone of a karst area that extends downward as sinkholes, fractures, fissures, and other surface karst features to where the natural porosity of the bedrock is located. Epikarst can range from almost non-existent to tens of metres deep.
Evaporite	A sediment that is deposited from aqueous solution as a result of extensive or total evaporation of the solvent.
Exsurgence	Point at which an underground stream reaches the surface if the stream has no known surface headwaters.
Grike, gryke	A vertical or subvertical fissure in a limestone pavement developed by solution along a joint.
Gypsum	A mineral; hydrated calcium sulphate.
Insurgence	The point at which water sinks into the ground.
Interbed	A typically thin bed of rock material alternating with contrasting thicker beds.
Karren	Channels or furrows, separated by ridges, resulting from solution of carbonate rock on the surface or under soil layers.
Karst	A terrain, generally underlain by limestone, in which the topography is formed chiefly by the dissolving of rock, and which is commonly characterized by karren, closed depressions, subterranean drainage, and caves.
Karst bridge	A natural bridge or arch in limestone.
Karst canyon	A natural steep-sided canyon in limestone.
Karst catchment	The subaerial surfaces upon which water contributes to the recharge of a karst aquifer. Also known as true catchment or geologic catchment.
Karst hydrology	The drainage phenomena of karstified limestones, dolomites, and other slowly soluble rocks.

Karst spring	A spring emerging from karstified limestone. See also exsurgence and resurgence.
Karstification	Action by water, mainly chemical but also mechanical, that produces features of a karst topography, including such surface features as dolines, and karren, and such subsurface features as caves and shafts.
Limestone	A sedimentary rock consisting mainly of calcium carbonate.
Limestone pavement	A bare plane surface of limestone, parallel to the bedding, commonly divided into blocks (clints) by solutionally widened joints (grikes), and pitted by solution pans.
Lithology	The physical characteristics of a rock, generally as determined megascopically or with the aid of a low-power magnifier. The microscopic study and description of rocks.
Marble	Limestone recrystallized and hardened by pressure and heat.
Microcavity	Predominantly an air-filled cavity, usually referring to voids in the epikarstic region of the unsaturated zone and considered to include all cavities not large enough to be defined as caves.
Paleontology	The study of life of the past by interpreting fossil remains of plants and animals.
Recharge	The process involving the input or intake (absorption) of water into the zones of saturation in karst aquifers; also relates to the quantity of water added to the saturation zone.
Resurgence	The point at which an underground stream reaches the surface and becomes a surface stream; the term is reserved for the re-emergence of a stream that has earlier sunk upstream. The term exsurgence is applied to a stream without known surface headwaters.
Sink, sinkhole	General terms for closed depressions. They may be basin, funnel, or cylindrical shaped. Also closed depression, doline, swallet, swallow hole.
Sinking creek (stream)	A small stream that disappears underground. See also swallet.
Solution	With reference to karst, the chemical alteration of bedrock from the solid to the liquid state through combination with water.

Speleological	Pertaining to the scientific study, exploration, and description of caves and related features.
Speleologist	A scientist engaged in the study and exploration of caves, their environment, and their biota.
Speleothem	A secondary mineral deposit formed in caves, such as a stalactite or stalagmite. Also known as a cave formation.
Stratigraphic	Pertaining to the formation, composition, sequence, and correlation of stratified rocks.
Swallet	A place where water disappears underground in a limestone region. A swallet may refer to water loss in a streambed even though there is no depression. A swallow hole generally implies water loss in a closed depression or blind valley. See also sinking stream.
Troglobite	An animal living permanently in the dark zone of a cave and unable to live outside the cave environment.
Understorey	Any plants growing under the canopy formed by other plants, particularly herbaceous and shrub vegetation under a tree canopy.
Uvala	Large closed depression formed by the coalescence of several dolines; compound doline.
Vadose	Pertaining to the zone where voids in the rock are partly filled with air and through which water descends under gravity.

DELINEATION AND HAZARD AREA MAPPING OF AREAS CONTRIBUTING WATER TO SIGNIFICANT CAVES

Taken from *Proceedings of the 1993 American Cave Conservation Association*, pp. 116–122.

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ABSTRACT

The recharge area for a cave is that area which contributes water to the cave. In some cases the recharge area is little more than the land which overlies the cave. However, in many cases (and especially when the cave contains streams or lakes) the recharge area may encompass several square miles.

Groundwater tracing is a fundamental tool for recharge area delineation. The general approach is to introduce fluorescent tracer dyes at points where surface waters sink into the groundwater system and then sample for these dyes at springs, significant caves, and other relevant points.

Hazard area assessment and mapping is a management approach for identifying and characterizing those areas which pose the greatest water quality threats to significant caves. Hazard area delineation integrates the hydrologic functioning of particular units of land with the uses of those lands. This paper will help resource managers understand the benefits of recharge area delineations and hazard area mapping and understand characteristics of technically sound investigations.

INTRODUCTION

The area which contributes water to a cave is called the recharge area. With few exceptions, identifying the recharge area for a significant cave represents fundamental management information. Recharge area delineations are particularly important for caves with important aquatic cave faunas.

The purpose of this paper is to provide resource managers with a workable understanding of how cave recharge areas are delineated and how hazard area mapping is done. While there is no single “right” way there are clearly many ineffective or undesirable ways to accomplish this work.

Cave Mapping and Topographic Studies

While cave maps can provide useful data, they seldom provide an adequate basis for recharge area delineation. We sometimes see assumptions that the area overlying a cave plus some arbitrary narrow "buffer zone" on the order of 100 to 300 feet is the sole source of recharge waters for that cave. This assumption is questionable (and often wrong) even when the cave contains neither streams nor lakes, and where only drippage waters are present. The assumption is frequently wrong even when the dip the bedding is taken into account. A major reason that this approach is often in error is that flow paths in the epikarstic zone (the weathered and corroded zone beneath the soil) are highly complex, may be dramatically different from the dip, and may involve lateral water movement over substantial distances.

Water infiltrates the epikarstic zone more rapidly than it infiltrates beneath it; this results in appreciable water storage in the epikarstic zone and lateral water movement through the zone since lateral permeability is routinely much greater than vertical permeability.

It is sometimes assumed that groundwater flow directions and divides are identical, or very similar to, surface flow directions and topographic divides. In our experience this assumption is commonly false. An exception could be a cave in the bottom of an intermittent surface stream channel, although such caves may also receive water from points not tributary to the surface stream. Even when it appears that the recharge area for a cave may be estimated from surface features, actual delineation studies should be conducted for verification.

Equipotential maps, which are contour maps of the water table elevation, can be developed for areas. In most (but not all) karst areas these maps are not of great utility in delineating cave recharge areas. One reason is that the data points are generally widely scattered and poorly distributed; the resulting maps are thus gross generalizations. Well depths vary substantially in many karst areas, and water level elevations are significantly affected by the geologic units in which the well is developed. In one cave area we routinely encountered differences in water level elevations of over 100 feet between nearby wells 125 feet deep and those 300 feet deep. Differences are generally not this great, yet the differences are commonly sufficient to readily produce incorrect interpretations.

Groundwater Tracing

Realistic recharge area delineation requires groundwater tracing. The tracing is generally conducted with fluorescent tracer dyes. Other tracing agents exist, but their use is substantially more difficult than tracing with the fluorescent dyes. Some of the other tracing agents, such as sodium chloride, are likely to create adverse impacts. Groundwater tracing techniques are described in detail by Aley and Fletcher (1976) and by Aley et al. (1992). There have been major improvements in analytical techniques since the Aley and Fletcher (1976) publication.

The most effective and most commonly used tracer dye is sodium fluorescein (Acid Yellow 73, Color Index [ICI] Constitution Number 45350). It is commonly simply called fluorescein in the United States; it is sometimes called uranine (especially in Europe). It is most commonly sold in a powder form which has a strong reddish color. When added to water the dyed solution is a brilliant yellow-green color. Visual detectability is significantly affected by background color in the dyed water and other factors. An experienced observer can commonly detect fluorescein in the field in concentrations as low as about 30 micrograms per litre (parts per billion).

The concentration of fluorescein in dye mixtures sold by various supply houses varies substantially. Some of the liquid mixtures contain less than 5% fluorescein. Powder mixtures generally contain more fluorescein than liquid mixtures, but they also vary widely. In order to achieve a uniform product and, in some cases, to enhance the ease of dyeing a product, it is conventional to add diluents (cutting agents) to technical grade dyes. This is standardization, not adulteration. The diluent most commonly used with fluorescein is sodium sulfate.

Rhodamine WT (Acid Red 388) is also a commonly used tracer dye. Rhodamine WT should not be confused with other Rhodamine dyes; some of the other Rhodamine dyes have undesirable properties. Rhodamine WT is commonly sold as a 20% dye solution. When added to water the dyed solution is pinkish orange. As with fluorescein, visual detectability of Rhodamine WT is affected by background color in the dyed water and other factors. An experienced observer can commonly detect Rhodamine WT in the field in concentrations as low as about 50 micrograms per litre (parts per billion).

Various optical brighteners have also been used in groundwater tracing. These are pale blue fluorescent dyes commonly used in laundry soaps and detergents to make “whites appear whiter.” Because of their use in soaps and detergents the optical brighteners may already be present in cave waters; this limits their utility for recharge area delineation studies. However, sampling for background concentrations of optical brighteners can be useful in indicating sewage contamination of the cave waters (Aley 1985). We find background sampling for optical brighteners to be a very useful approach during a recharge area delineation study. It should be noted that the absence of background optical brighteners in cave waters may result from their adsorption onto fine textured soils; sewage effluents may be present even if optical brighteners are absent.

Direct Yellow 96 (Diphenyl Brilliant Flavine 7GFF) is a fluorescent yellow dye which has been successfully used in a number of groundwater traces in Kentucky. Other fluorescent dyes which have received some use in the United States include Pyranine (CI 59040; CI solvent green 7, D&C green 8); Lissamine FF (CI 56205; CI acid yellow 7); and Eosine Sodium (CI 45380). Amino G Acid, a dye intermediary, has also been used. Anyone competently using any of these dyes will almost certainly also be using fluorescein, Rhodamine WT, and probably optical brighteners.

Of the four most commonly used dyes, fluorescein is generally the best for groundwater tracing and Rhodamine WT is the second best. Fluorescein is more subject to destruction or alteration in sunlight than is Rhodamine WT, optical brighteners, or Direct Yellow 96. Significant dye losses by adsorption onto charged soil particles can occur with any of the dyes; in our experience dye losses to adsorption increase in the order of fluorescein, Rhodamine WT, optical brighteners, and Direct Yellow 96. Use of optical brighteners and Direct Yellow 96 is unlikely to be successful in groundwater systems where appreciable adsorptive losses occur. Other considerations are also involved in the selection of the dye or dyes to use.

There are sometimes sources of background fluorescence which can interfere with the detection of tracer dyes. Additionally, the tracer dyes (or similar dyes) may be components of compounds already present in the area. Fluorescein is used in a few household products and as the coloring agent in antifreeze. It can sometimes be detected in runoff waters from parking lots and city streets. Pyranine is used in more household products than fluorescein; these dyes cannot be readily separated visually or with a fluorometer, but they can be separated with a spectrofluorophotometer operated with a synchronous scan protocol. A dye which cannot be fluorescently distinguished from Rhodamine WT (it is probably Rhodamine B) is used as the coloring agent in many hydraulic fluids. It is routinely present in the waste water from manufacturing plants which use hydraulic equipment. Additionally, Rhodamine B has also been used to color seed corn to prevent it from accidentally being fed to livestock.

Cumulative samplers capable of absorbing passing dyes are commonly used in recharge area delineation studies. Activated carbon samplers are used to adsorb dyes such as fluorescein, Rhodamine WT, and some of the less commonly used dyes. Cotton samplers are used to adsorb optical brighteners and Direct Yellow 96 "grab samples" of water can be collected for dye detection, but the frequency of sampling necessary to insure that a pulse of tracer dye is not missed limits the general utility of this approach. Grab samples of water collected simultaneously with the collection of activated carbon samplers can provide valuable data on actual dye concentrations at particular points in time if the analysis protocol is capable of providing credible quantitative results.

Cumulative samplers are typically collected and new samplers placed about once a week, although the frequency can be varied depending upon the nature of the study. Activated carbon samplers are eluted with a strong base, alcohol, and water solution. Moderate to large concentrations of fluorescein can be detected visually in the eluting solution. Visual detection of Rhodamine WT in the eluting solution is difficult; this dye should not be used in groundwater tracing unless analytical equipment is available. Simultaneous tracing with fluorescein and Rhodamine WT can be done with the use of a spectrofluorophotometer operated in a synchronous scan mode. It should not be attempted with a fluorometer since large concentrations of one dye will create an apparent detection of the other dye with this type of instrument.

Cotton samplers are washed with jets of clean water and then examined either under an ultraviolet light or in an appropriate analytical instrument. Experience and care are essential in visual analysis. Optical brighteners and Direct Yellow 96 can mask one another unless both are present in large concentrations. These dyes can be used simultaneously if analysis is done with a spectrofluorophotometer operated in a synchronous scan mode.

The common groundwater trace utilizes cumulative samplers. Background sampling, prior to any introduction of tracer dyes, is generally conducted to demonstrate the absence of fluorescence interference or to characterize the magnitude of the interference. The extent of background sampling is largely determined by the nature of land use in the area.

A well designed delineation study for an important cave is characterized by thorough field work to identify potential dye injection sites and caves or springs through which the injected dye may subsequently pass. Simply studying topographic maps and aerial photos alone will seldom be sufficient. These approaches generally miss many important springs. Groundwater tracers seem to have a propensity to discharge from springs that were not sampled. Some of the missed springs may be in the channel of surface streams. As a result, surface streams must be sampled to address this possibility. Multiple sampling stations are routinely needed along surface streams since tracer dyes deteriorate and are adsorbed as they are transported down the stream channel. In delineation studies, a trace that goes to the "wrong" spring provides valuable data for the delineation of the cave or spring of concern. It is always better to know where the trace went than to simply know where it did not arrive. This is not always possible; an example would be an area where many springs are beneath the surface of large lakes.

The easiest sites for injecting tracer dyes are points where water always or almost always sinks into the groundwater system. Sites near roads, on public land, or on property of landowners known to be friendly are always nice. The easiest sites are frequently not those most useful for a good delineation study. The good delineation study must gather the data needed rather than the data that are more easily available.

A good delineation study must be dynamic; one should seldom plan more than one or two traces in advance. The results from one trace must be incorporated into the planning for the next. Tracing should take advantage of weather conditions. Some highly desirable tracer injection sites have flowing water only a few days out of the year. Unless one can haul substantial volumes of water, these sites must be used when the water is present. Sometimes one can place the tracer dye where it will enter the water the first time flow occurs; this must be done very carefully.

Another characteristic of a good delineation study is that many of the dye injection sites are located in areas where contaminants enter (or might enter) the groundwater system. We routinely select injection sites which receive waters from dumps and landfills; sewage and sewage effluent discharges; commercial and industrial operations; highways, railroads, and product pipelines; and major sources of animal wastes. The failure to recover dye from such traces in the cave of concern is always an important finding; however, important caves are not immune to impacts from these types of land uses.

A good delineation study should include groundwater traces which are recovered in the cave of concern plus some traces which are recovered at sites other than the cave. If all of the traces are recovered in the cave of concern you have probably not identified the boundary of the recharge area.

Water that enters the karst groundwater system at a particular point does not always flow only to one cave or spring. The flow may be to two or more caves or springs. In one study Aley (1988) found radial groundwater flow throughout a large area in northwestern Arkansas. Not only can the flow be shared among several caves or springs, but the relative quantity moving to each site can vary with flow rates and other groundwater conditions.

We often find that a particular cave (or spring) has some recharge areas which contribute waters only to that cave. Often there are some recharge areas which share water between the cave of concern and other caves or springs. The total recharge area includes both the exclusive recharge area and the shared recharge area. Where feasible, each should be delineated separately and their hydrologic interactions characterized. Shared recharge areas are commonly located near recharge area boundaries; however, distributaries can exist closer to the discharge points for the groundwater system. An illustration of distributaries is provided by the springs which drain the main stream in Tumbling Creek Cave, Missouri. These springs extend for 2,000 feet along Big Creek; none of these springs is more than a mile from the cave stream.

Identification of shared recharge areas routinely requires more comprehensive sampling, good analytical approaches, and project direction by experienced groundwater professionals. Some shared recharge areas deliver water to a cave of concern only during moderate to high flow conditions. Fantastic Caverns near Springfield, Missouri is an illustration of this condition. During low flow conditions the recharge area comprises about 7 square miles. During high flow conditions the recharge area comprises about 20 square miles; at least six springs share portions of this recharge water.

Even a small cave stream may have a large recharge area because of shared recharge areas. Fire Hydrant Cave on the Current River in Missouri is an illustration. This cave shares water with Pulltite Spring and other springs in the area. While the mean flow rate of this spring is relatively small, dye injected in a losing stream segment of Big Creek 13.1 miles straight line distance from the cave was recovered in the cave.

How large are recharge areas for significant caves likely to be? This is a bit like asking the length of a typical piece of string, yet resource managers concerned with potential recharge area delineation investigations need some understanding of the size of areas likely to be involved.

The caves with the largest recharge areas are generally those which contain cave streams or lakes. As a general rule, the greater the mean annual flow of water through the cave the larger the recharge area. If a recharge area is shared by multiple caves and springs the recharge area is likely to be larger than if the cave has an exclusive recharge area. Caves which receive recharge waters from a significant surface stream have recharge areas which include the entire topographic basin of the stream upstream of the recharging point plus any other areas contributing water to the cave stream.

We have delineated the recharge areas for about 25 caves in seven states. Six biologically significant caves had recharge areas of 0.2 to 2.5 square miles; none of these received recharge waters from any appreciable surface streams. Six other biologically significant caves had recharge areas of 7 to 24 square miles; all but two of these involved either appreciable surface streams or recharge areas shared with other caves or springs. Caves in the Western United States do not necessarily have larger or smaller recharge areas than caves in the Midwest or East.

Hazard Area Mapping

The hydrologic functioning of the land is not uniform. The hydrologic impacts of land use are also not uniform. It is clear that the combined impacts of these conditions on a cave or spring are also variable. Because of these conditions we can develop maps which depict qualitatively different groundwater quality risks posed to a significant cave. This is the foundation for a karst-specific approach which we call hazard area mapping.

We initially developed the approach in 1976 for use in recharge area delineation studies for major springs on the Ozark National Scenic Riverways in Missouri (a National Park unit). We have subsequently applied the approach in many of the delineation studies we have conducted over the last 15 years, and believe it to be a very useful management tool. It has been applied elsewhere in Missouri and in Arkansas, Oklahoma, Wyoming, Kentucky, and Alabama.

A nationally used mapping approach for assessing groundwater contamination risks was developed by the National Water Well Association and the U.S. Environmental Protection Agency (Aller et al. 1987) and is called “DRASTIC.” It is a useful approach, but is neither a karst-specific nor a cave resource–sensitive approach. The DRASTIC approach demonstrates that karst areas are readily subject to groundwater contamination but does not provide for more detailed discrimination nor for integrating land use conditions.

We develop somewhat different criteria for hazard area classes for each region (and sometimes for each cave) studied. We typically use three or four categories, although one or more may be absent in particular recharge areas. In a typical hazard area mapping the categories will include low, moderate, high, and extremely high groundwater contamination hazard categories. Situations associated with the higher risk categories include:

1) Areas in close proximity to the cave.
2) Sinkhole areas, losing stream segments, and areas within 300 feet of mapped fracture traces and lineaments.
3) Localized areas where substantial volumes of water enter groundwater.
4) Areas with shallow or very rocky soils.
5) Areas where land uses of concern exist or are likely to exist. Point sources are routinely identified, assessed, and shown on the maps with an index number.
6) Areas which exclusively recharge the cave of concern.

SUMMARY OF GOOD RECHARGE AREA STUDY CHARACTERISTICS

1) The study should be conducted by, or be under the technical direction of, a karst hydrologist who has successfully conducted previous recharge area delineation studies. A person who has previously conducted groundwater traces does not automatically qualify since recharge area delineation and hazard area assessments requires more than simple groundwater tracing. However, the person directing the study should have background or experience in groundwater tracing. Once a year the National Water Well Association offers a week-long professional short course entitled "Practical Karst Hydrogeology with Emphasis on Ground Water Monitoring." This course provides the type of background needed to supplement the conventional background of most groundwater hydrologists. Recharge area studies lie well outside the field of expertise of the typical registered geologist or engineer.
2) Thorough field reconnaissance precedes the start of groundwater tracing. Background sampling is conducted before tracer dyes are injected. Numerous sampling stations are established to insure that the injected dyes are recovered. Dyes appropriate to conditions in the study area are selected and the quantities used are adequate to insure that the failure to recover dye at the cave of concern is credible evidence that a hydrologic connection does not exist. Depending upon conditions, adsorptive losses may cause the failure of groundwater traces conducted with Direct Yellow 96, optical brighteners, and Rhodamine WT.
3) The delineation study should be adequate to detect and assess recharge areas which the cave of concern shares with other caves or springs. The good study will not be limited to just the simple and easy groundwater traces, but will instead include traces from areas where data are needed. The good study will routinely conduct traces to assess sites which pose potentially significant water quality threats to the cave or spring being studied. The study will be dynamic; the results from previous traces must be incorporated into the planning for those subsequently conducted.
4) State of the art analysis for tracer dyes uses a scanning spectrofluorophotometer operated with a synchronous scan protocol. Successful groundwater tracing can be done using visual and fluorometric methods, but these approaches slow the tracing program because of dye interferences and the necessity of using more dye to insure positive results. Increasing the quantity of dye increases the duration of the dye pulse and, in turn, the time between traces. Field time is generally the most expensive part of a recharge area study. In our experience, state of the art analysis generally maximizes the number of groundwater traces conducted; it also produces the most credible results. Several firms have this type of equipment; at least two of these firms will routinely conduct dye analysis work on samples shipped to them. Similar equipment exists at a few universities or other state agencies, yet experienced operators and acceptable protocols for dye analysis often limit the utility of this equipment.
5) Hazard area assessments and the development of hazard area maps should be a routine component of recharge area delineations.

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DYE TRACING IN FORESTED KARST TERRAIN: A CASE STUDY ON VANCOUVER ISLAND, BRITISH COLUMBIA

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Abstract: This paper presents the findings of a groundwater dye tracing study that was carried out in the Glory'Ole Cave/Karst Management Area (GCMA) of Northern Vancouver Island, British Columbia. The objectives of the project were to delineate the groundwater flow paths and recharge areas of the GCMA, and to demonstrate how this information could be used to assist in forest management. Four fluorescent dyes (fluorescein, rhodamine WT, eosine, and pyranine) were simultaneously injected into flowing water at four different locations: three sinking streams and a surface stream. Charcoal samplers and grab water samples were taken from springs and streams at lower elevations and analyzed for the presence of dyes. All four dye traces were detected at the Tsulton Rising, the principal discharge point for groundwater flow in the GCMA. Most of the non-karst recharge areas upslope of the GCMA contribute to the groundwater discharge at Tsulton Rising. Careful forest management planning and prescriptions are required in these recharge areas to protect water quality and quantity.

1 INTRODUCTION

Karst terrain is the three-dimensional landscape that develops from the weathering of soluble bedrock (Fig. 1). These bedrock types primarily include carbonates such as limestone and dolomite, or evaporites such as gypsum and halite. It has been well documented that karst terrain (or systems) function very differently in geology, hydrology and biology than non-karst, and that karst exhibits a range of significantly different values (Ford and Williams 1989; White et al. 1995). Karst terrain, derived predominately from limestone and dolomite, underlies many of the forested areas of British Columbia (Fig. 2). On Vancouver Island, coastal temperate rainforests occur in conjunction with some of the most well-developed karst terrain and largest cave systems in both British Columbia and Canada (Griffiths 1991). Industrial forestry activities on karst areas can have significant impacts on karst recreational resources, karst flora and fauna, karst soils, karst surface features and karst hydrology (Stokes 1996; Baichtal in press; Baichtal and Swanson 1996; Kiernan 1993). On

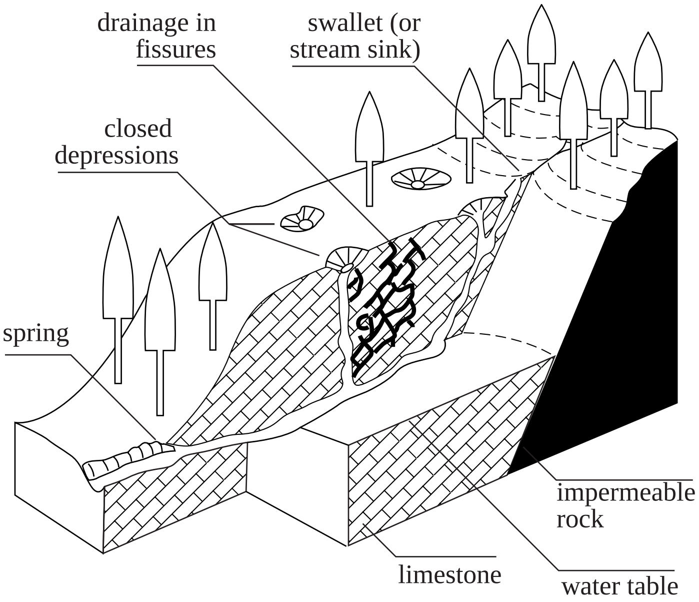
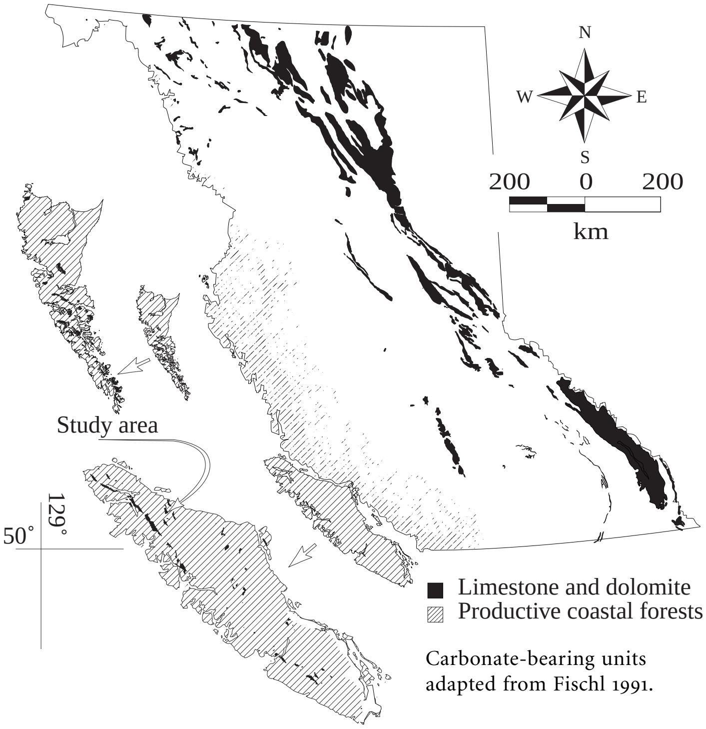


FIGURE 1 *The three-dimensional karst landscape. (Adapted from Cooke and Dornkamp 1990.)*



Carbonate-bearing units adapted from Fischl 1991.

Biogeoclimatic zones of British Columbia from Ministry of Forests, Research Branch.

FIGURE 2 *Location of study area within British Columbia and the regional distribution of carbonate bedrock and productive forested zones.*

Vancouver Island, past forest management practices on karst terrain have focused on the identification and protection of significant caves and karst features (B.C. Ministry of Forest 1994). Recent work by the Research Branch of the B.C. Ministry of Forests is focused on a broader ecosystem approach to karst management (B.C. Ministry of Forests 1997).

Karst hydrology, one of the fundamental components of the karst ecosystem, requires careful investigation, as changes to the quality and quantity of upstream karst waters can have significant impacts downstream (e.g., drying and flooding of caves, altering sensitive microclimate and habitats, and the clogging of subsurface conduits with debris). The hydrological system in karst is significantly different from non-karst as much of the system is subsurface, with recharge areas that commonly do not follow topographic divides. Groundwater flows within karst have the potential to rapidly transmit water through bedrock conduits, and to provide groundwater storage in less permeable, highly fissured bedrock volumes (e.g., in epikarst areas). Hence, karst hydrological systems can be characterized as highly variable and are difficult to predict from surface features and topography.

Subsurface investigation of karst hydrological systems can be carried out remotely using dye tracing. Dye tracing is a well accepted and practiced technique that has been used successfully to track the dispersal of contaminants, delineate recharge areas for springs, determine groundwater flow paths, and identify discharge sites (Aley and Aley 1993; Doerfliger 1996). Dye tracing has also been used in the forested karst terrain of southeast Alaska as one of the tools for karst vulnerability mapping (U.S. Forest Service 1996). The basic concept of a dye trace test is simple. A fluorescent dye is injected into an insurgence (e.g., a sinking stream), and then sampled at likely exsurgent sites (e.g., springs). Typical dyes that are used include fluorescein, rhodamine WT, eosine, and pyranine, These dyes are all considered environmentally safe at the concentration levels used for testing (Field et al. 1995; Smart 1984). Sampling for dyes can be carried out by either grab water samples or by charcoal samplers which accumulate traces of the dye over a predetermined period of time. The charcoal samplers are 4 g of activated carbon granules sealed in a fibre mesh packet. Both the elutant from the charcoal samplers and grab water samples can be analyzed with a spectrofluorophotometer. Each of the dyes has a different and diagnostic excitation peak wavelength, with pyranine, fluorescein, eosine, and rhodamine WT having peaks of 502, 512, 535, and 563 nanometres, respectively. Dye concentrations in samples are calculated by comparing the area within the excitation peak to a standard of known dye concentration. Detection limits vary among the dyes, but they are all within the parts per trillion range.

2 STUDY AREA

The Glory'Ole Cave/Karst Management Area (GCMA) was proposed as a study area by the Port McNeill Forest District to test the applicability of dye tracing as a forest management tool. The GCMA was considered a suitable study area because of its cave/karst exploration history, its significant cave/karst resources, and its past and present forestry activities. The general objectives of this project were to determine:

1. The principal groundwater flow paths and likely recharge areas for known springs in the GCMA;
2. What dye tracing methods and dyes are most applicable to conditions on northern Vancouver Island; and
3. How dye tracing could play a role in assisting forest management decisions.

Two site-specific objectives were: i) to determine the groundwater source for the P-1 Spring (a sensitive cave system discharge point); and ii) to provide preliminary information on groundwater flow conditions below a proposed timber cutting block on the west side of the GCMA (Cutblock 154-1). Detailed precipitation and water budget analysis were considered beyond the scope of the study.

The GCMA is located approximately 25 km to the south of Port McNeill on the east side of Nimpkish Lake. Most of the area is located on east- to northeast-facing slopes of the Hankin Range, and is in the upper catchment area of the Tsulton River. Small portions of the GCMA to the south and southwest are in catchment of the Noomas River. The GCMA is within the Coastal Western Hemlock biogeoclimatic zone, and has a relatively high mean annual precipitation of 100-250 cm with mean daily temperatures of less than 16°C (B.C. Ministry of Forests 1992)

The GCMA is situated on Crown land between two Tree Farm Licences (TFL s), TFL 37 of Canadian Forest Products Ltd. (CANFOR), and TFL 47 of TimberWest Forest Ltd. Most of the GCMA is crossed by a dense network of forest roads and was harvested during the mid 1980's. Numerous cave systems were discovered in the area during the late 1970's and early 1980's. Mapping and exploration of the cave systems occurred during harvesting of the area from the mid 1980's to early 1990's. A cave/karst management plan, which delineates the boundaries for the GCMA, was completed in 1995 to resolve issues between caving groups, the B.C. Ministry of Forests and forest companies (Griffiths 1994; B.C. Ministry of Forests, 1995).

The GCMA occurs near the southeastern end of a limestone belt that is part of the Quatsino Formation and is Triassic in geological age. At this location the limestone belt dips 15–30° to the east-northeast and forms the western limb of a major syncline. The axis of the syncline trends NW-SE and is located approximately 600–800 m to the east of the project area. Mafic volcanic rocks of the Karmutsen Formation conformably underlie the Quatsino Formation along the west side of the GCMA. To the east the Quatsino Formation is conformably overlain by volcanic and sedimentary rocks of the Bonanza Group. The southwest side of the area is bounded by granitic rocks of the Island Intrusives. Most of the east and southern slopes of the area are comprised of irregular benches and depressions, with till (and/or colluvial) veneers and blankets overlying bedrock. Numerous small bedrock bluffs are present and in some cases form low north-south ridges. Steeper slopes are present along the eastern part of the area and lead down to gentle and moderate slopes to the northwest.

Significant areas of surface and subsurface karst development are present within the GCMA (Fig. 3). In total at least eight cave sites are found within the area including: Arch, Treasure, Crown Pot, P-1, Glory'Ole, Hanging Sump, Resonance, and Tsulton Rising (B.C. Ministry

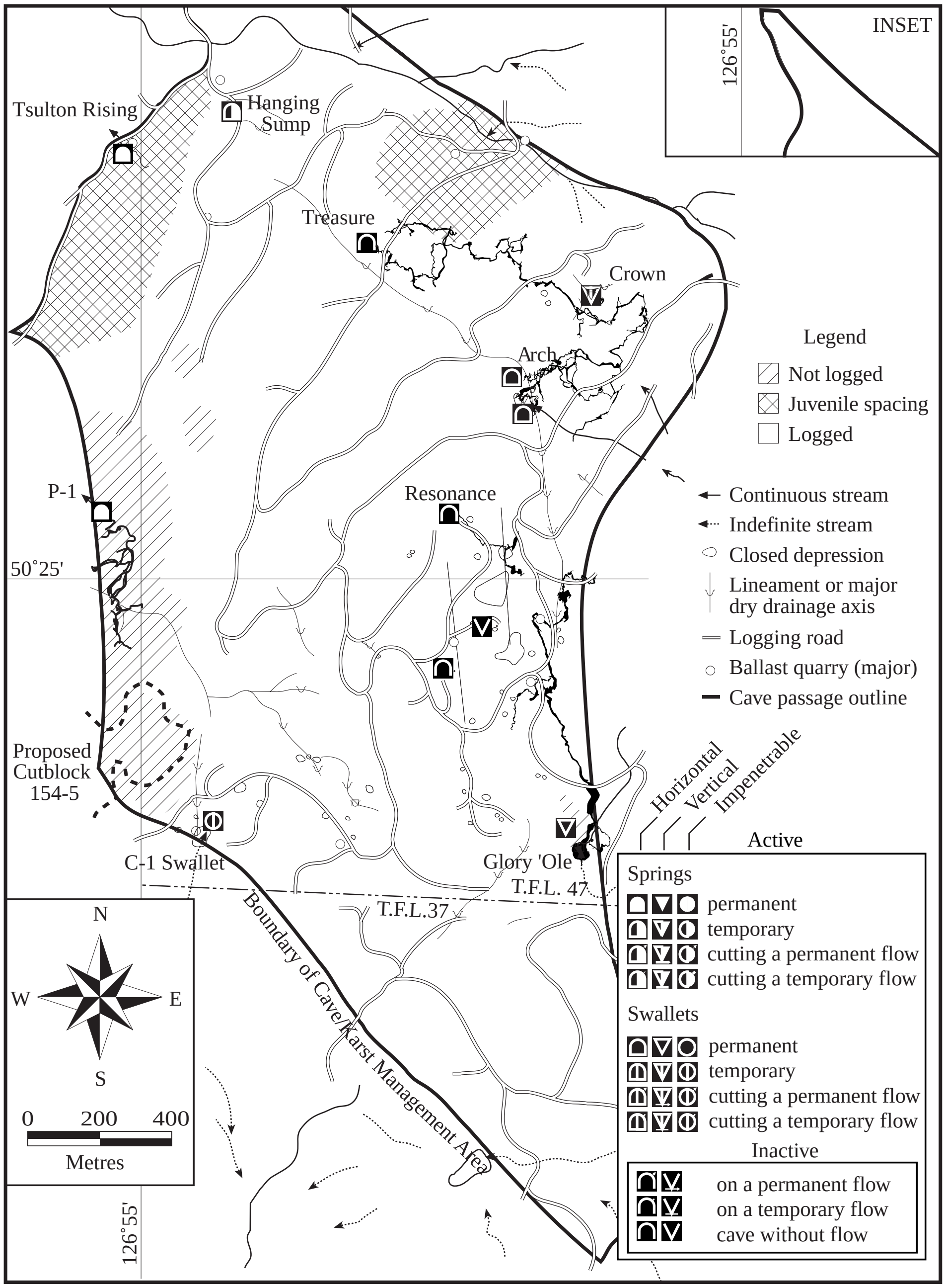


FIGURE 3 *Caves, major surface features and forestry activity.*

of Forests 1995). Most of these caves are significant in terms of their dimensions, speleothems, biota, and palaeontological content. Numerous sinkholes and depression are present throughout the area, particularly on the irregular and benched slopes. The largest sinkholes occur near the D1(Uvala) to the east and at the C-1 Swallet. The area is also crosscut by at least four dry valleys.

Streams flowing off non-karst areas onto the GCMA disappear at or near the upper limestone contact. Two of the larger streams disappear into the Glory'Ole and Arch caves. A smaller stream flows into the C-1 Swallet. Two major springs, Tsulton Rising and P-1, occur along the lower slopes of the area, while another major spring (Lunar Spring) occurs to the northwest of the GCMA. Square Corner Creek is located along the northern boundary of the GCMA and drains into the Tsulton River. The Tsulton River continues to the north along a broad valley and eventually enters the sea at Beaver Cove.

3 DYE TRACING METHODOLOGY

3.1 Design

A preliminary, office-based design for the dye tracing test was developed for the GCMA, using available topographical and geological maps, airphotos, and existing cave/karst information. A brief field reconnaissance was carried out to verify the design, and minor adjustments were made to the locations of injection and sample sites. The four injection sites chosen included: three streams along the upper limestone contact which flow into the Glory'Ole Cave, the Arch Cave and the C-1 Swallet, and a road crossing in the upper reaches of Square Corner Creek. A total of seventeen sample sites were chosen both inside and outside of the GCMA, providing as complete hydrological coverage as possible. The sample sites chosen included: known spring locations (Tsulton Rising, P-1 Spring, and Lunar Spring), seepages encountered adjacent to the main springs (e.g., Stn. #3 and #4), streams on non-karst areas nearby (e.g., Stn. #10 to #14), and the lower stream reaches some distance from the injection sites (e.g., Stn. #16 and #17). A critical part of the design was to determine which of the four dyes to place where, as all the dyes would be injected at approximately the same time. Dyes with nearly similar wavelength peaks (e.g., pyranine and fluorescein) can, in some cases, produce signatures that overlap and thus hinder interpretation. To avoid this problem, these two dyes are placed as far apart as possible, with fluorescein at Square Corner Creek and pyranine at the C-1 Swallet. Dye mobility, a function of adsorption properties onto either soil or bedrock materials, was also taken into consideration. Eosine, one of the more mobile dyes, was used at the Glory'Ole injection site, as a relatively large subsurface hydrological system was anticipated.

3.2 Implementation

The field work for the initial sampler layout and four dye injections was carried out in the early spring between March 15 and 17, 1998. At each sample location two charcoal samplers were carefully tied to either a rock or metal plate using plastic-covered steel wire. (The purpose of two charcoal samplers was to ensure that if one was lost the other would likely be recovered.) The charcoal samplers were placed into flowing water and, in places of potential high water flow, attached by a cord to a nearby tree to assist recovery. Grab water samples were taken at each location for background analysis. Sterilized plastic bottles were used, and each was labeled with the station number, date and time. At each sample and injection site the water temperature, pH and specific conductance was measured along with an estimate of flow rate. The dissolved oxygen content was measured at the three main karst springs using a portable oxygen meter and probe.

Following layout of the charcoal samplers, the four dyes were introduced at approximately the same time (within 2–3 hours) into flowing water at the injection sites. Eosine (Trace 98–01) was introduced into a stream leading into the Glory'Ole Swallet, pyranine (Trace 98–02) was introduced into a small stream draining into the C-1 Swallet, rhodamine WT (Trace 98–03) was placed into one of the streams leading into Arch Cave, and fluorescein (Trace 98–04) was placed into an upper road crossing of Square Corner Creek.

Two subsequent visits were made to the sample sites, one and two weeks following the dye injections, March 24, 1998 and April 2, 1998, respectively. The two charcoal samplers from each site were collected and placed in labeled sterile plastic bags. If one of the charcoal samplers was found in better position (e.g., one in the water flow and one out) it was preferentially chosen for analysis. Grab water samples were also taken at each site during sampler retrieval and collected in a small sterilized plastic bottle. After the first retrieval new charcoal samplers were then placed at each site, ready for the second retrieval a week later. All the charcoal samplers and grab water samples collected were sent by overnight courier to the Ozark Underground Laboratory (OUL) for analysis.

3.3 Laboratory Preparation and Analysis

The charcoal samplers and grab water samples on reaching OUL were immediately refrigerated at 4°C until time for analysis. Firstly the charcoal samplers were washed with water to removed sediment and organic debris. One of the two charcoal samplers was taken for analysis and the second was put into frozen storage. The dye was firstly removed (or eluted) from the charcoal sampler by a solution of aqua ammonia and isopropyl alcohol. The resulting solution (or elutant) that contains traces of dye materials was subjected to analysis by a Shimaddzu RF-5000 U spectrofluorophotometer under a synchronous scan protocol. Figure 4 shows examples of fluorescent peaks obtained of a background water sample and a charcoal sampler taken from Tsulton Rising. Details on all analytical data are available in Stokes (1998).

4 RESULTS

No dyes were detected in the background grab water samples that were taken during the initial sampler layout. These results were anticipated, as the area has no record of significant dye tracing, but was done as standard procedure. Findings from the four dye injections are summarized below and shown diagrammatically on Figure 5.

Eosine, injected into one of the sinking streams of the Glory'Ole Cave (Trace 98–01), was detected in all charcoal samplers from Stn.#1 (Lunar Spring), Stn.#2 (Slot Canyon Outlet), Stn.#8 (Tsulton Rising) and Stn.#17 Downstream Tsulton River. Eosine was detected in all of the first set of grab water samples, but none of the second.

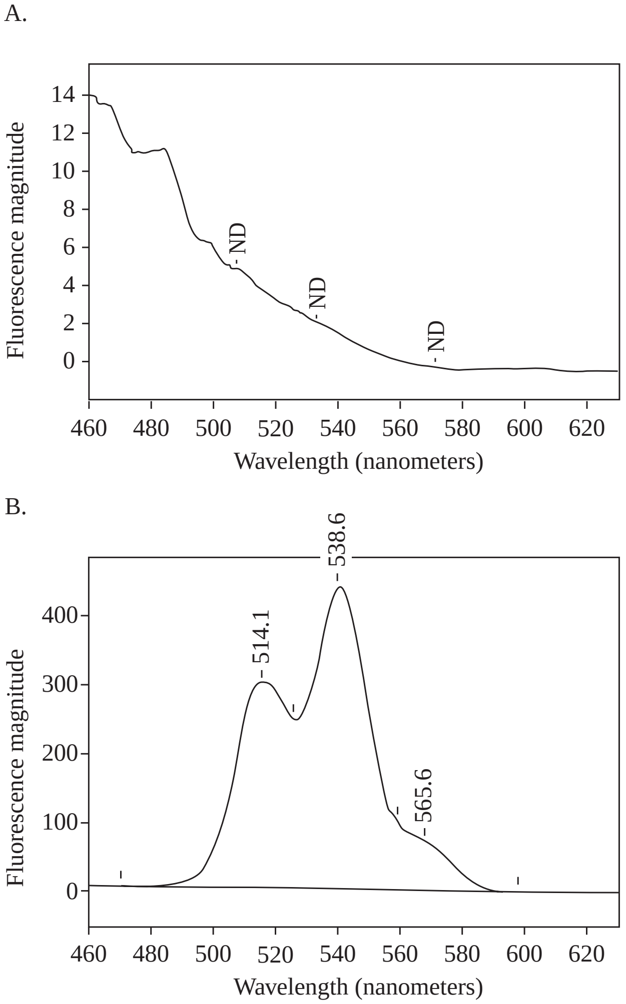


FIGURE 4 *Example of typical fluorescent spectra from dye analysis with the spectrofluorometer. A – background grab sample from Tsulton Rising (HI545) taken prior to dye injection. B – charcoal sampler from Tsulton Rising (HI875) taken one week after dye injections. Distinct peaks obtained for fluorescein (514.1), eosine (538.6) and rhodamine WT (565.6). Peak for pyranine (at 501) masked by fluorescein.*

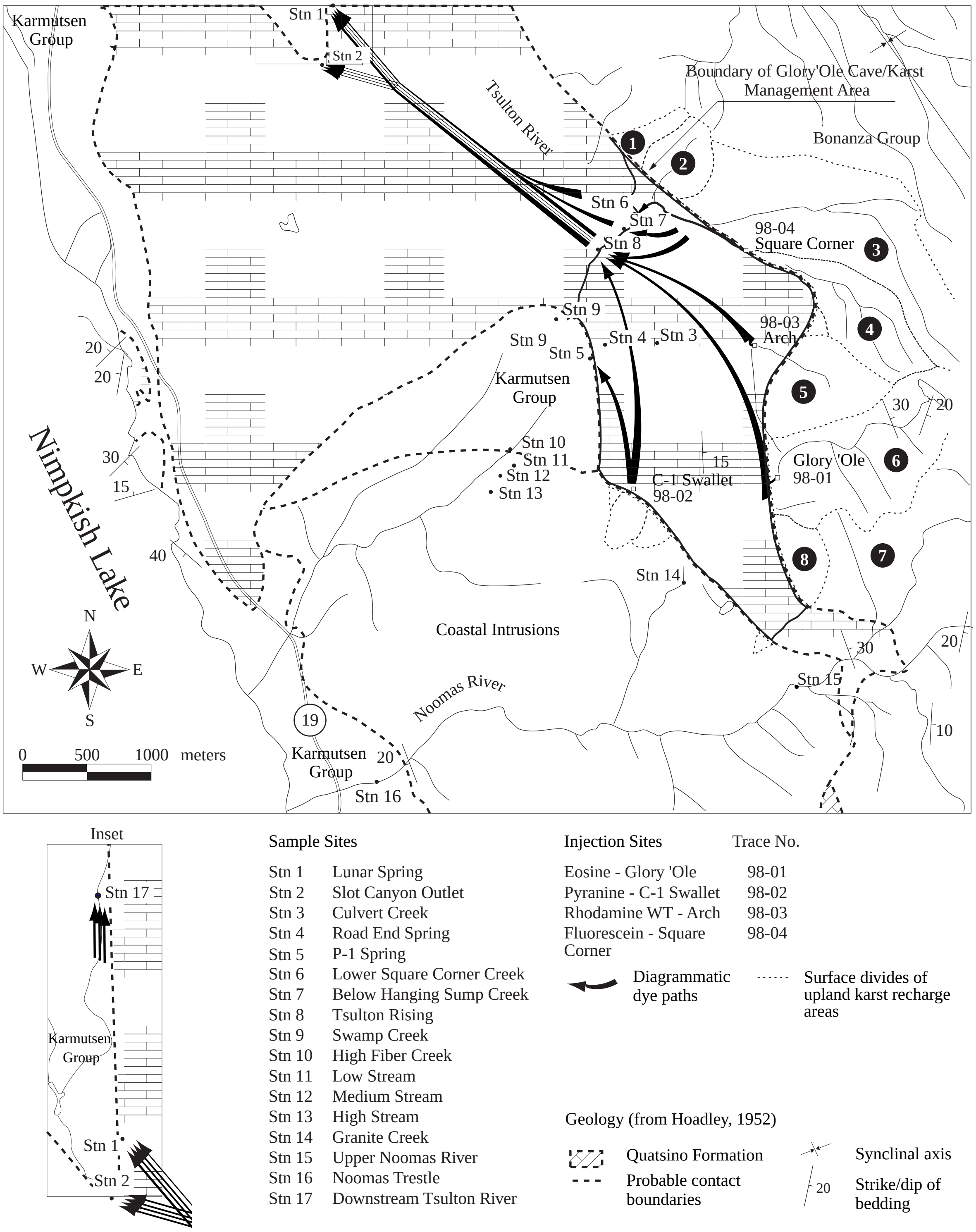


FIGURE 5 *Diagrammatic groundwater flow paths and recharge areas of the Glory'Ole Cave/Karst Management Area.*

Pyranine, injected into the C-1 Swallet (Trace 98–02), was recovered from all charcoal samplers from Stn.#1 (Lunar Spring), Stn.#2 (Slot Canyon Outlet), Stn. #5 (P-1 Spring), and Stn.#8 (Tsulton Rising). Some interference in the pyranine peaks occurred due to the presence of fluorescein detected at Stns. #1, #2 and #3. This interference limited the determination of dye concentrations at these stations. Pyranine was detected in the two grab water samples taken at Stn. #5 (P-1 Spring).

Rhodamine WT, injected into the Arch Cave Tributary Stream (Trace 98–03), was recovered from all the charcoal samplers at Stn.#1 (Lunar Spring), Stn.#2 (Slot Canyon Outlet), Stn.#8 (Tsulton Rising) and Stn.#17 Downstream Tsulton River. Rhodamine WT was only detected in the first set of grab water samples from Stn. #8 and Stn.#17.

Fluorescein, injected into Square Corner Creek (Trace 98–04) was detected in all the charcoal samplers at Stn.#1 (Lunar Spring), Stn.#2 (Slot Canyon Outlet), Stn. #6 (Lower Square Corner Creek), Stn. #7 (Below Hanging Sump Creek), Stn.#8 (Tsulton Rising) and Stn.#17 (Downstream Tsulton River). Fluorescein was detected in most of the first set of grab water samples, but none of the second set.

No dyes were detected in charcoal samplers or grab water samples taken from Stn.#3 (Culvert Creek), Stn.#4 (Road End Spring), Stn.#9 (Swamp Creek), Stn.#10 (High Fiber Creek), Stn.#11 (Low Stream), Stn.#12 (Medium Stream), Stn.#13 (Low Stream), Stn. #14 (Granite Creek), Stn.#15 (Upper Noomas River), and Stn.#16 (Noomas Trestle).

Water temperature measurements taken at the sampler and injection sites varied from 0.8–6.6°C. pH readings varied from 7.4-8.6 units. Dissolved oxygen content from the three main springs indicate that the discharge waters were at or close to their saturation point with respect to oxygen. These measurements were not considered particularly useful tools for assessing these karst waters, but could indicate any abnormal conditions important for dye analysis.

The specific conductance measurements, taken at all the sample and injection sites, were more useful. (Specific conductance measures the ability of water to conduct electricity and increases with dissolved $CaCO_3$ content.) Typically, waters that occurred within or downstream from karst areas of the GCMA gave high readings, between 80–140 micromhos/cm, while waters draining non-karst areas typically gave measurements <10 micromhos/cm. This information provides a useful and inexpensive field tool for rapidly identifying karst-related waters, and can assist in the design and interpretation of dye trace studies.

5 GROUNDWATER FLOW PATHS AND RECHARGE AREAS

From the four dye traces it is apparent that the principal discharge point for subsurface flow in the GCMA is at the Tsulton Rising (Stn.#8). The dye traces, in conjunction with speleological knowledge of cave passages, suggest that the Glory'Ole, Arch and Treasure cave systems are probably hydrologically linked. Stream flows into the Glory'Ole and Arch Caves are the likely major sources of this water within the three cave systems. However, the dye trace at the C1-Swallet (Trace 98–02) also indicates a hydrological connection with Tsulton Rising. The dye trace from Square Corner Creek (Trace 98–04) displays a subsurface hydrological link to below Hanging Sump (Stn.#7) and Tsulton Rising (Stn.#8). This subsurface flow is probably the result of an insurgent point (or points) located along the channel of Square Corner Creek below the injection site at Trace 98–04. This emphasizes the point that surface creeks adjacent to, or crossing, karst areas can lose (or conversely gain) water flow along their length, and that these creeks warrant dye tracing along with sinking streams.

A subsurface hydrological link was also confirmed between the C1-Swallet and the P-1 Spring (Stn.#5) from Trace 98–02. However, there was some imbalance in the apparent flow rates between the C-1 Swallet and the P-1 Spring, with relatively small flows in the C-1 Swallet as compared to the P-1 Spring. This suggests that subsurface water for the P-1 Spring probably comes from other sources as well. Possible sources include the disappearing streams that occur to the south of the Glory'Ole Cave and/or the dry valley southeast of the P-1 Spring. The area extent of this dry valley appears sufficient for recharge of the P-1 Spring by precipitation alone.

All four dyes were detected at Slot Canyon (Stn.#2) and at Lunar Spring (Stn.#1). From the dye concentrations obtained it was apparent that greater amounts of fluorescein (and corresponding low amounts of eosine and rhodamine WT) were detected in the samplers from Lunar Spring (Stn.# 1) as compared to Tsulton Rising (Stn.#8). This suggests that most of the flow of Lunar Spring is probably derived from Square Corner Creek, and that at some point (or points) between Tsulton Rising (Stn.#8) and Slot Canyon (Stn.#2) water flow is probably redirected subsurface towards the Lunar Spring (Stn.#1). From this information it is apparent that successful dye tracing requires looking outside the area of specific interest to ensure that the full extent of the karst hydrological system is investigated.

Fluorescein, eosine and rhodamine WT were all detected at Downstream Tsulton River (Stn.#17) which is approximately 7-8 km from the injection sites. This shows the good mobility of these three dyes, which can travel significant distances without major losses onto organics, soil or rock. From this result it is apparent that sample sites could be located a significant distance away from injection sites, and could be particularly useful where access to areas is limited. Pyranine was not detected at Downstream Tsulton River (Stn.#17), but did however reach Slot Canyon (Stn.#2). Pyranine was also not detected as might have been anticipated below the P-1 Spring (Stn.#5) at Swamp Creek (Stn.#9). This might be a function of pyranine's tendency to be more readily adsorbed onto organic materials and vegetation as compared to the other dyes. Out of the four dyes used pyranine is probably the least preferred.

No dye was detected in the samplers along Noomas drainage to the south (Stns.#14, #15 and #16) and the other creek system to the southwest of the area (Stns.#10, #11, #12 and #13). This confirms that none of the four dye injection sites within the GCMA is hydrologically linked to these water courses. These data are compatible with the low specific conductance readings taken at these locations and suggests limited contact of the water with limestone.

The lack of dyes detected at Culvert Creek (Stn.#3) and Road End Spring (Stn.#4) indicate that these water flows are not connected to any of the injection sites. These sites of water flow are both probably expressions of discharge from localized catchment areas upslope (e.g., small gullies or draws).

Recharge catchment areas on non-karst terrain occur upslope of the GCMA and contribute water to sinking streams that enter the karst groundwater system. This water eventually discharges at springs a significant distance away from the recharge areas. The topographic divides for each of these non-karst recharge catchment areas upslope has been delineated on Figure 5. Recharge Areas 6 and 5 occur immediately upslope of the injection sites of the Glory'Ole Cave (Trace 98-01) and Arch Cave (Trace 98–03), respectively, and both contribute to the groundwater systems that discharges at Tsulton Rising. The recharge areas of Square Corner Creek, and its tributary to the north (Areas 4 and 3, respectively) also contribute to discharge at Tsulton Rising. A small recharge area contributes to the C1-Swallet and is shared between the P-1 Spring and Tsulton Rising. Recharge areas for the Tsulton Rising and P-1 Spring within the GCMA itself are difficult to determine without site-specific dye tracing of water input sites.

In summary, the dye tracing results indicate relatively rapid response times occur between the insurgent and exsurgent points of the groundwater system within the GCMA. In all likelihood turbulent water flows could develop in this type of groundwater system, which would be capable of transporting significant amounts of sediment and debris. The results obtained are considered consistent with the recovery of all the dyes from the four traces. No significant undetected losses outside of the project area were anticipated.

6 IMPLICATIONS FOR FOREST MANAGEMENT

Dye tracing provides an important insight into the groundwater systems of karst terrain and can have significant implications for forest management. One of the principal concerns during the forestry activities of harvesting or road construction is the changes to terrain conditions and hydrology, which can have significant impacts on water quality and quantity. In non-karst areas most of the water flow occurs as surface overland flow which collects along road ditches, and originates from intersected streams and seepages. Typically, in non-karst areas there is some potential for attenuation of the surface overland flow between the area of activity and downstream resources (e.g., vegetation along banks of streams catching sediment). In karst terrain water flow rapidly enters natural openings on the surface (e.g., swallets, sinkholes, epikarst) and drains vertically into subsurface conduits. Water and any entrained materials (e.g., sediment, logging debris and contaminants) can be transported a considerable distances downstream with little to no attenuation. These "piped" materials can cause detrimental impacts to a variety of instream and downstream resources, such as fisheries or community water supplies. Changes in peak flows or flow direction (by harvesting or road construction) can alter the volumes of water entering into subsurface conduits and result in subsurface flooding or drying, and variations to spring discharge rates.

Some preliminary information on the subsurface hydrological conditions below Cutblock 154-5 can be inferred from the dye tracing and available geological maps. The lower slopes of the cutblock appear to have no karst hydrological concerns, as they are underlain by granitic bedrock and drain away from the limestone contact. The upper part of the cutblock is underlain by limestone and is located midway between the C-1 Swallet and the P-1 Spring. In this area further dye tracing would be required to determine its hydrological significance, as it is potentially in the recharge area of the P-1 Spring. A "dry set" dye introduction could be carried to confirm this. (A dry set is where dye is placed in such a manner as to be taken into solution by the first surface flow reaching the site.)

Qualitative sensitivity ratings for non-karst recharge can be determined once the karst groundwater flow paths are known and the downstream resources evaluated. For example, the non-karst recharge catchment areas immediately upslope of the Glory'Ole Cave, Arch Cave, Square Corner Creek and its northern tributary (Areas 3, 4, 5 and 6) all contribute water flow to the Tsulton Rising. These four areas could therefore be considered more hydrologically sensitive than Areas 1, 2, 7 and 8. This application of dye tracing information can be used as a guide for responsible forest management. Forestry activities in the more sensitive areas might require limitations on the size, number and shape of cutblocks; the location and density of roads; and the harvesting methods (e.g., heli-logging, ground-based or cable systems). Special prescriptions may be required for sensitive creeks (e.g., sinking streams), with the development of riparian reserves and the careful construction of road crossings. At present some forest companies are using variable retention as a method of harvesting, as opposed to larger clearcuts. This approach might be suitable for sensitive recharge areas.

7 CONCLUSIONS

1. The dye tracing project at the GCMA has demonstrated that a significant amount of information can be obtained about non-karst recharge and karst groundwater flow paths. Dye tracing appears a useful tool for investigating groundwater issues related to forest management in karst areas, particularly where activities might have any impact on water quality or quantity.
2. All four dyes were detected at Tsulton Rising, the principal discharge point for subsurface flow in the GCMA stream flow into the Glory'Ole and Arch Caves and along Square Corner Creek are probably the major sources of this water. Dye from the C1-Swallet indicates a subsurface hydrological link to the P-1 Spring.
3. All four dyes were detected at Slot Canyon (Stn.#2) and at Lunar Spring (Stn.#1). From the dye concentrations it is apparent that most of the flow of Lunar Spring is derived from Square Corner Creek, and is probably the result of an insurgent point (or points) along the channel.

4. Fluorescein, eosine and rhodamine WT were detected 7-8 km below the injection sites at Downstream Tsulton River (Stn.#17), indicating the good mobility characteristics of these dyes.
5. Non-karst recharge catchment areas upslope of the Glory'Ole Cave, Arch Cave, Square Corner Creek and its northern tributary all contribute to the groundwater systems that discharge at Tsulton Rising. These recharge areas are considered hydrologically sensitive to disturbance by forestry activities, and site-specific prescriptions are required for careful forest management (e.g., riparian reserves).
6. In terms of completing future dye tracing projects in similar forest karst areas it is recommended that: i) professional direction be used for their design and implementation, ii) fluorescein, eosine and rhodamine WT be used in preference to pyranine, iii) specific conductance measurements be taken, and iv) streams adjacent to and crossing the karst areas be considered, along with sinking streams, as potential dye injection sites.

8 ACKNOWLEDGEMENTS

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APPENDIX 2 Classification system for discrete mesoscale and microscale surface karst features

Taken from *Part A of Method for Managing Discrete Surface Karst Features*, Cave Management Services, Campbell River, British Columbia, 1993 (Unpublished).

GENERAL

The evaluation criteria include dimensional characteristics, function (e.g., hydrology), actual or potential resource values, and "intangibles" such as the visual quality of the individual feature. These criteria require varying degrees of subjectivity and judgement.

The subset criteria presented are not necessarily applicable to all features. For example, hydraulic characteristics such as sinking stream incisement or catchment size are not applicable to microscale surface karst features such as grikes or karren. Nor are the criteria listed in the order of importance that is applicable to all features.

The criteria may change with time as new values evolve, or as the number of remaining undisturbed or "pristine" features diminishes.

Timing The significance of surface karst features is determined prior to roadbuilding and harvesting plan preparation, and after an acceptable level of ground searching. Until this evaluation takes place the features are regarded as "potentially significant" and managed accordingly. Neither roadbuilding nor harvesting is approved during this interim period.

METHODOLOGY

The highest numerical ranking (1 through 3) *for any one value* determines the significance of the feature. For example, based on volume only, a doline is a significant feature (i.e., Type 3), without any further evaluation.

(Refer to Figure 1 for classification flow.)

The sum of numerical rankings for each value can be used in a matrix table for comparison between two or more features.

CRITERIA

Dimensional Characteristics Widths, lengths, and depths are readily determined for closed depressions. Sinkhole and doline diameters are measured and ranked accordingly. It should be possible to generate and maintain a database of the largest dolines on Vancouver Island.

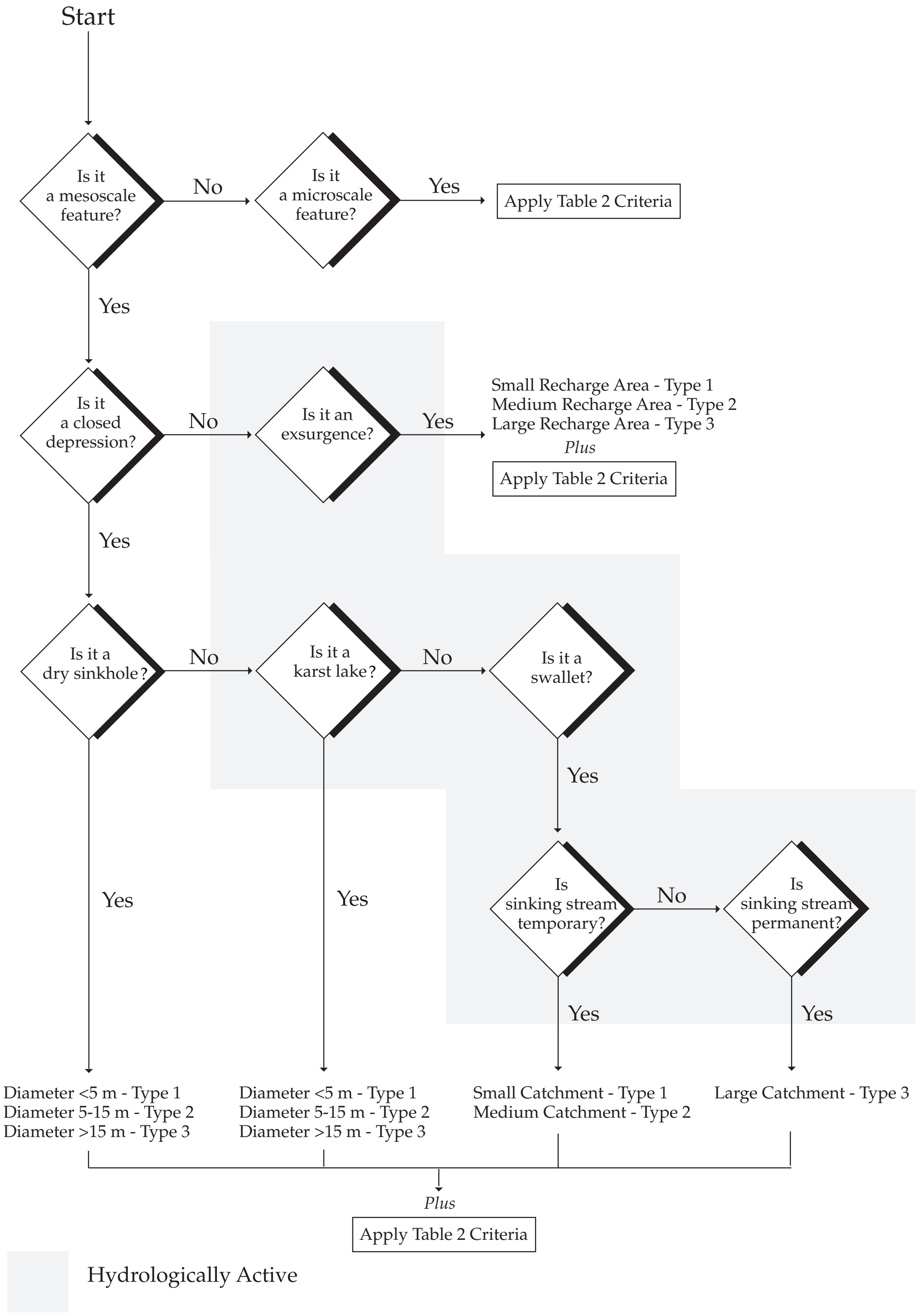

FIGURE 1 *Classification flow for discrete surface karst features.*

HYDROLOGY

Karst Lakes and Ponds

The size of the enclosed body of standing water is the principal determinant of significance. Symmetry and depth of water are also considered where appropriate.

Swallets

The catchment of a sinking stream is considered in determining the significance of a swallet. Swallets with intermittent or ephemeral (i.e., temporary) sinking streams are less significant than those with permanent streams. Permanent sinking streams with catchments exceeding 100 ha are most significant. Catchment size is estimated from contour mapping, field checking, or influent channel morphology. Beds of permanent sinking streams with large catchments show evidence of flowing water, a gravel, pebble, rocky, or sandy bed, an obvious gully, or short steep banks. Sinking streams that are known to resurge as productive surface streams or as domestic water supplies are also significant. Sinking streams suspected to contribute to productive surface waters or domestic water supplies will be managed as Type 3, until proven otherwise by dye tracing or other appropriate methods.

Exsurgences

More difficult to assess is the recharge area of exsurgences. The exsurgent channel morphology can provide some information, but the knowledge obtained from underground exploration and dye tracing is more precise. Exsurgences that rise as productive surface streams or domestic water supplies are significant.

GEOLOGY

The uniqueness of the geological setting is established from field identification of the host carbonate bedrock. Features that are found in uncommon geological strata are the most significant.

BIOLOGY

The assessment of the biological value (e.g., biodiversity) of a feature may necessitate evaluation by taxonomists and other specialists. The utilization of the feature as habitat for wildlife would involve other disciplines. The presence of rare or endangered flora or fauna is a significant value. In particular, the ability of refugial biota to recolonize other features, should a disturbance occur, is an important consideration. The presence of elevational gradients of biota, such as occur in large closed depressions, is of high significance. Unique or rare habitats for large mammals and fur-bearers and water sources for the same are significant.

Ecological Zones The ecological classification of a surface karst feature is determined from the published biogeoclimatic mapping. The abundance of the feature in the particular ecological zone is checked against the database. The presence of a surface karst feature within a karst ecosystem that is poorly represented within a particular ecological zone is of special interest.

ARCHAEOLOGY

Determining the significance or potential archaeological significance of a surface karst feature may require archival research or archaeological surveys. This normally requires cultural heritage expertise.

HISTORICAL OR CULTURAL VALUES

The determination of the historical or cultural values of a surface karst feature may require consultation with local inhabitants, including native groups, and the B.C. Heritage Conservation Branch. Features that are presently recognized by the general public or the caving community as having value are most significant.

TABLE 1 *Classification system checklist for closed depressions and exsurgences*

Dimensional Characteristics – Closed Depressions

	Type 1 ▼	**Type 2** ▼	**Type 3** ▼
	Sinkholes (dry)		Dolines (dry)
Diameter at rim	☐ *<5 m*	☐ *5-15 m*	☐ *>15 m*
	Karst Ponds		Karst Lakes
Diameter of enclosed body of standing water	☐ *<5 m*	☐ *5-15 m*	☐ *>15 m*

Hydrology – Swallets

	Type 1 ▼	**Type 2** ▼	**Type 3** ▼
	Sinkhole		Doline
Sinking stream type	*temporary*		*Permanent*
Catchment size	☐ *small*	☐ *medium*	☐ *large*[1]

Exsurgences

	Type 1 ▼	**Type 2** ▼	**Type 3** ▼
Recharge area	☐ *small*	☐ *medium*	☐ *large*

[1] large sinking stream catchment size (>100 ha) or multiple sinking streams

SCIENTIFIC, EDUCATIONAL, OR RECREATIONAL VALUES

The assessment of the scientific, educational, or recreational value of a surface karst feature can extend beyond the consideration of contemporary benefit or use, and accessibility. The *potential* future use of a feature (e.g., interpretative karst viewing) is considered. Paleontological features are of significant scientific and educational value.

COMMERCIAL VALUE

Surface karst features may provide significant opportunities for commercial tourism. Exsurgences may have significant present or future value for commercial spring or mineral water production.

VISUAL QUALITY

The pristine character of the surface karst feature is significant. The association of certain features with an advanced stage of natural forest growth, such as climax forest, is usually of the highest visual value.

ABUNDANCE

The abundance criterion is applied to the individual feature, but it is equally applicable for determination of significance of an individual feature, or cluster of features, at a local, regional, national, or international level.

CONNECTIVITY

The connectivity between the feature and other significant surface karst features or caves within the same karst ecosystem contributes to the significance of the feature.

TABLE 2 *Classification system checklist for all discrete mesoscale and microscale surface karst features*

	Type 1 ▼	**Type 2** ▼	**Type 3** ▼
Geology	☐ common	☐ uncommon	☐ unique or rare
Biology	☐ low	☐ moderate	☐ high
Archaeology	☐ low	☐ moderate	☐ high
Historical or Cultural	☐ low	☐ moderate	☐ high
Scientific, Educational, or Recreational	☐ low	☐ moderate	☐ high
Commercial	☐ low	☐ moderate	☐ high
Visual Quality	☐ low	☐ moderate	☐ high
Abundance	☐ common	☐ uncommon	☐ unique or rare
Connectivity	☐ low	☐ moderate	☐ high