Delineation of a Karst Watershed on Prince of Wales Island, Southeast Alaska

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Karst systems have developed in the extensive areas of carbonate bedrock underlying portions of the Tongass National Forest, southeast Alaska. Karst development includes losing streams, sinks, caves, grikes, and resurgence streams. Many of the resurgence streams maintain productive salmon populations important to local culture and economics. Identifying source areas of resurgence streams is crucial to protecting water quality and watershed planning in karst ecosystems. Historically, watershed assessments have only considered topographic boundaries when defining various watersheds. This method is difficult in karst areas where surface waters are rare. Two projects on northern Prince of Wales Island, part of the Thorne Bay Ranger District, have employed tracer dye studies to illustrate the complexity of karst systems, and help redefine watershed boundaries to assist in watershed planning efforts. Through dye trace tests we were able to identify subsurface flow pathways, identify downstream effects, and better assess cumulative effects on a watershed scale. Success of groundwater tracing efforts hinged on locating the springs that feed coastal streams. This required careful inventory of shorelines and margins of the carbonate outcrops. Activated charcoal packets were anchored within these streams and springs to absorb dye. Tracer dye injection points were generally discrete karst features where surface waters enter the systems. The charcoal packets were recovered at intervals to allow time for the dye to move through the systems. Tracking the locations of dye injection and recovery helped identify specific subsurface water flow pathways and measure minimum flow velocities. Identification of these subsurface pathways enabled us to delineate karst watershed boundaries, understand the downstream effects of proposed management, and better manage karst areas.

Keywords: *karst, insurgence, resurgence, dye trace, watershed delineation*

Introduction

Karst is a geomorphologic term describing the topography resulting from the chemical dissolution of carbonate bedrock. In southeast Alaska, karst refers to areas where this distinct geomorphology has developed from the dissolution of limestone or marble bedrock. Karst characterization includes grikes, caves, insurgence and resurgence streams, and extensive areas where runoff does not exist on the land surface. Instead, these waters infiltrate into the subsurface environment (insurgence) and may re-appear many miles away (resurgence). This process of surface waters appearing and disappearing is just one of the distinct features of karst watersheds.

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Southeast Alaska has over 869 square miles (2,228 km^2) of known karst (Figure 1). Of this area, 731 square miles (1,874 km^2) are on national forest land as part of the Tongass National Forest. Within the Thorne Bay Ranger District, 283 square miles (725 km^2) of karst are located on northern Prince of Wales and surrounding islands (Baichtal and Swanston 1996) (Figure 1). The development of karst is dependent upon many influences such as volume of precipitation, water temperatures, water chemistry, vegetation, soils, and in the case of southeast Alaska, elevation relative to past glaciations.

The coastal temperate rainforest environment of southeast Alaska is essential to the development of karst. With annual precipitation ranging from 100 to 200 inches (254 to 508 cm), and average annual air temperatures of around 45°F (7.2°C), the climate is ideal for carbonate dissolution. In addition, the role of glaciers in modifying existing karst features and depositing glacial till has a significant effect on karst development. Where glacial till was deposited, infiltration is limited, peatlands have

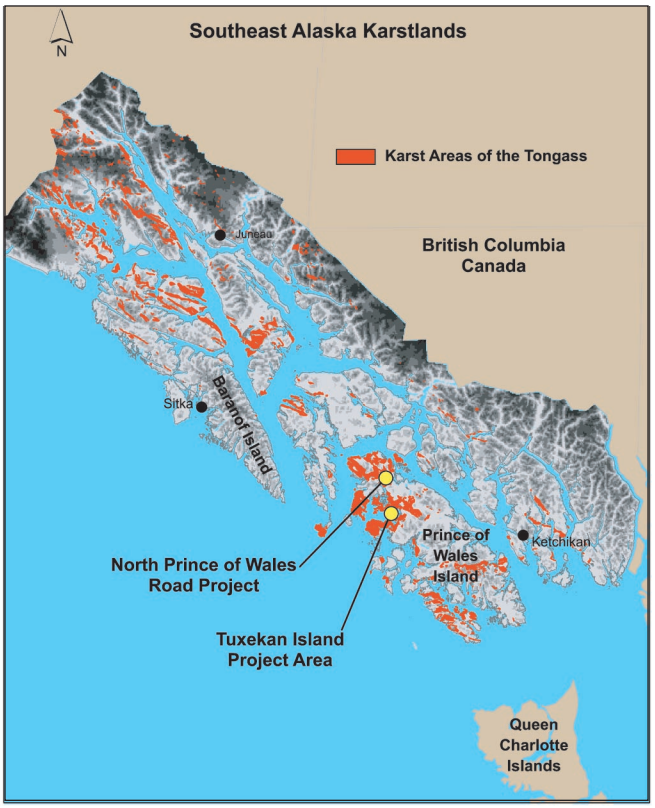


Figure 1. Project area locations in the Prince of Wales Island area, southeast Alaska.

developed and hence acidic soils are present. With the development of the peatlands on poorly drained areas and the acidic waters that flow from them, a system of vadose caves and vertical shafts have developed. These have combined with pre-existing subsurface conduits and cave systems to form the current drainage networks.

The carbonate that underlies the study areas consist of Upper Silurian aged (419-423 million years old) Heceta Limestone of the Alexander Terrane. This unit consists of light gray, massive, sublithographic limestone, with abundant amphiporoid corals, dasycladacean algae, oncoids, and brachiopods. Limestone also contains subordinate stromatoporoids, gastropods, pelecypods, bryozoans, trilobites, graptolites, conodonts, and aphrosalpingid sponges. Algal, coralline, and microbial buildups are interpreted to represent platform margin reefs, with carbonate turbidites, debris flows, and slump deposits that accumulated in deeper water off the shelf margin (Soja 1991). Contact with underlying Ordovician to Silurian aged Descon and Luck Creek Breccia Formations is generally conformable, but limestone detritus resembling the Heceta in polymictic conglomerate that conformably underlies Heceta in several places indicates that carbonate sediments were deposited, lithified, and eroded in the Early Silurian prior to the main period of Heceta Limestone deposition. The Heceta Limestone is overlain by the Early Devonian aged Karheen Formation, composed of sandstone, shale, and pebble, cobble, and boulder conglomerate, characterized by redbeds, calcareous cement, and crossbedding (S. Karl, USGS, personal communication).

Structural features within the Alexander Terrane are complex. These structures consist primarily of northwest-to-southeasterly strike slip faults and shear zones and secondary faulting and shearing in a east-to-westerly direction. These formations have been further modified by extensive thrust faulting and localized folding. Dissolution in limestone is accelerated along fault and shear zones, therefore solution channels and lineaments are common along the major and secondary fault zones.

The project areas (located on northern Prince of Wales Island [NPOW] and Tuxekon Island) were last glaciated during the Wisconsin glacial advance from the north and northeast 21,000 to 14,000 years ago. Karst existed on Prince of Wales and surrounding islands prior to the last glacial advance. Recent phreatic passages in two pre-Wisconsinan caves have dissolved through Tertiary paleokarst breccias (Aley et al. 1993). Older passages have been plugged or collapsed by debris from past glacial episodes. Most caves predate the most recent glaciation, based on the presence of glacial clays, glacial sediments, wood, Pleistocene vertebrate remains, and possibly ancient ice. Such evidence clearly suggests that glaciation modified a pre-existing karst landscape, collapsing some passages and systems, gouging into others, and filling some with sediments. The epikarst (surficial karst), which is exceptionally well developed at higher elevations, has been destroyed at lower elevations by the scouring of the most recent glaciation.

METHODS

The methods used to delineate watersheds in karst are drastically different from those methods used in non-carbonate environments. Surface water runoff in non-carbonate environments flows across the ground surface and is ultimately controlled by topography. However, in carbonate environments where surface waters are rare, insurgences and resurgences must be located on the ground, and where possible, these waters must be traced through the subsurface environment, to identify flow paths, and hence watershed boundaries. Although runoff in both carbonate and non-carbonate areas generally flows down gradient, those waters in carbonate environments don't necessarily flow downhill relative to surface topography. The following methods describe ways to determine flow paths using both geomorphic and dye trace methods.

Mapping of Hydrogeologic Features

Success of tracer projects in karst areas hinges on the ability to identify and map all features that influence runoff. These mapped features include streams, significant sinkholes (those that are open to the subsurface), insurgences, resurgence caves and springs, and any other features where runoff flows into or out of the subsurface environment. Aerial photo interpretation, contour maps, field reconnaissance, and a general understanding of the bedrock geology, are essential in successful identification and mapping of features. All features identified on the ground or through map or photo interpretation were mapped, labeled, and characterized regarding feature type and characteristics (Figures 2 and 3). In some cases, water quality parameters, such as pH, temperature, and conductivity, were collected and used in planning the dye trace.

Aerial photographs were used in this study to identify runoff features and track runoff patterns. Streams, sinkholes, lineaments, geologic contacts, and large closed basins can be identified through aerial photo interpretation. Depending upon the scale and degree of forest canopy, karst features can be more or less evident through a stereoscope. In some cases sinkholes and karst lineaments can be very obvious from aerial photos.

Contour maps were also used to determine where surface drainage features were located on the landscape. Closed depressions, or large internally drained basins, can be identified as areas that contain no drainage outlet. In some cases, digital imagery such as LIDAR can be used to color-code negative contours for identifying sinkholes and closed depressions (Baichtal and Langendoen 2001; Langendoen and Baichtal 2004)

Extensive field reconnaissance was performed to confirm features identified from map or photo work, and to explore for additional drainage features. Surface water streams were walked to determine contributing area, or source at the headwaters, and to determine if the waters dissipated or disappeared into the subsurface. Karst lineaments and geologic structural boundaries were investigated in the field for potential insurgence or resurgence features. Bedrock contacts are logical locations for water to appear or disappear, depending upon the bedrock and the nature of surface runoff. Features identified along these contacts were characterized and mapped. All wetland boundaries proximal to carbonate bedrock were also scouted to determine drainage and to identify additional karst features.

Planning Dye Traces

Dye trace methods used in this project followed those outlined in Aley and Fletcher's Water Tracers Handbook (1976). These methods use several different fluorescent dyes for tracing. The methods also describe the use of activated charcoal packets for adsorption and the laboratory analysis process for detection.

Planning is a crucial element in a successful dye trace, and in delineating watershed boundaries. Both the NPOW and Tuxekan project areas were separated into five distinct sets of insurgence locations that were chosen for dye introduction. For NPOW, the introduction points were determined according to their location relative to each other and proximity to a proposed road project. Points were far enough separated that two of the five traces could be done simultaneously using the same dyes. On Tuxekan, the five distinct areas were structurally separated, and were capable of handling five sets of four dye introductions all at once. Generally, the dye trace plan must separate out insurgences according to the number of dye tracers available, and the geologic, or structural boundaries between areas, to limit contamination between traces. Where clusters of insurgences are in close proximity, one or several of the more significant features were chosen for dye injection.

Collection of Background Data

To ensure that no prior trace of the proposed dyes existed in the drainage system scheduled for tracing, background water chemistry information was collected. A set of charcoal packets was placed in all resurgence locations for seven to ten days to collect baseline water chemistry. Packets were placed under rocks within the normal flow section of stream, were bound by a cord, and tied to the stream bank. All packets were placed for easy access during all flow levels, and placed to ensure packets would remain underwater during low flows, yet not be moved, or carried away, during high flows.

Dye Introduction

After all background packets had been replaced with fresh packets, dyes were introduced into designated insurgences. Transport and introduction were undertaken with care to prevent contamination of the injector's body or clothing by the dye materials. There was no handling of charcoal packets following dye injection without full cleansing of hands and a change of clothing. The dyes used in this study were purchased from Ozark Underground Laboratories Inc. , and included Rodamine

WT, Fluorescein, Eosine, and Sulferodamine dyes. Each of these dyes is characterized by a distinct wavelength when placed in a fluorophotospectrometer; therefore each can be chemically distinguished. The packets contain activated charcoal enclosed in a mesh pouch and anchored to the streambed of a resurgence stream. As runoff in the resurgence zone flows through the dye packet, the charcoal adsorbs the dye and retains the chemical trace for analysis. These tracer packets were recovered from the resurgence area and sent to Ozark Underground Laboratories for analysis. Laboratory reports state the concentration of each dye that is recovered for each site.

The time provided between dye trace introductions is dependent upon the volume of water that is available to flush the dyes. When a dye is introduced into a system, it must be fully flushed before introducing that same dye into the same drainage network. In this study, dye traces were performed between August and November when large storms are generally back-to-back, soils are saturated, and flushing of the drainage networks is rapid. Times between dye tracer introductions ranged from one to three weeks, depending upon flow volumes and access opportunities. The process of packet replacement for the NPOW project generally took a day with two groups of two people, and an additional day for dye introduction. The Tuxekan project required several days for packet replacement and several days for dye introductions.

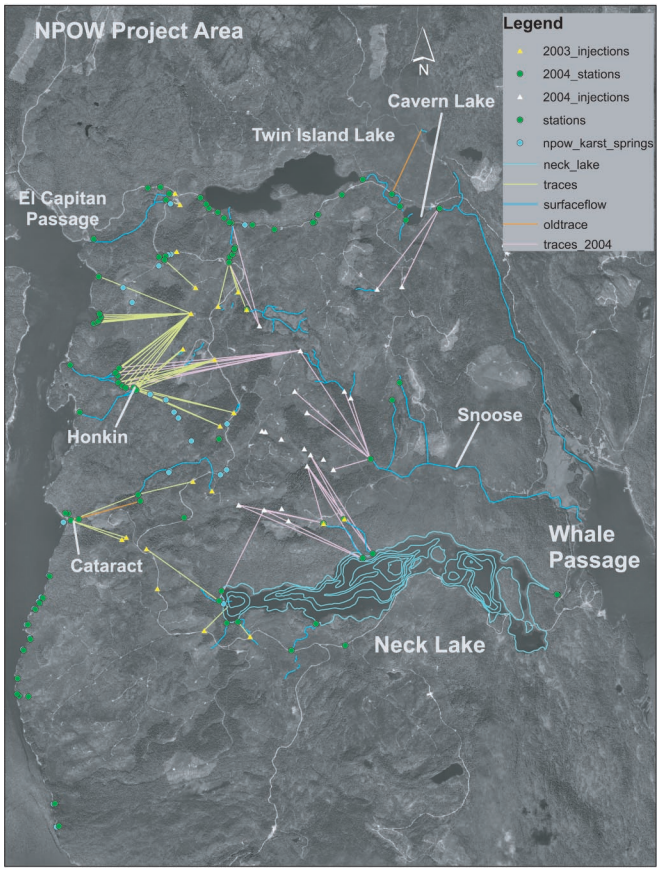


Figure 2. North Prince of Wales Island project area, insurgence and resurgence locations, and dye trace results.

Plotting Dye Trace Results and Modifying Remaining Traces

When performing a multi-year dye trace, there is opportunity to adjust dye traces according to results of previous work. In the case of the NPOW project, the results of the work performed in 2003 led to increased investigation and an expanded project area for 2004. Because there were no east-west watershed divides identified in the 2003 work, additional field work was done prior to the 2004 work to identify insurgences that might lend information to this question. Trace results in 2004 provided insight to the watershed divide, which better defined the watershed boundary.

RESULTS

Ozark Underground Laboratories performed charcoal packet analysis for both of these studies. The results of the analysis included type and concentration of each dye recovered. The NPOW project area covered approximately 36 square miles (93 km^2). Over a two-year sampling period, 38 dye traces were introduced. Thirty-six of these traces were recovered at 65 springs (Figure 2). In the smaller Tuxekan project area, covering approximately 28 square miles (72 km^2), 14 dyes were introduced during one sampling season. Thirteen of these dyes were recovered at 20 springs (Figure 3).

North Prince of Wales Island

Dye was recovered at resurgence areas near Neck Lake and Snoose Creek in the southern portion of the project area, Honkin Spring and Cataract Spring in the western portion of the project area, and Twin and Cavern Lakes in the northern portion of the project area (Figure 2). All source areas, where dye was introduced, were located along the high karst plateau of the project area. Resulting dye paths trended northeast, northwest, southeast, and southwest, with no dominant trend direction.

The 2003 dye introduction points were largely along the mainline road system (National Forest System Roads 15 and 20). This road is located along the western flank of the high plateau, trending north-south. The 2004 dye introduction locations were concentrated along the eastern flank of the high plateau and dispersed in a northern, central, and southern trend, focusing on key insurgence features.

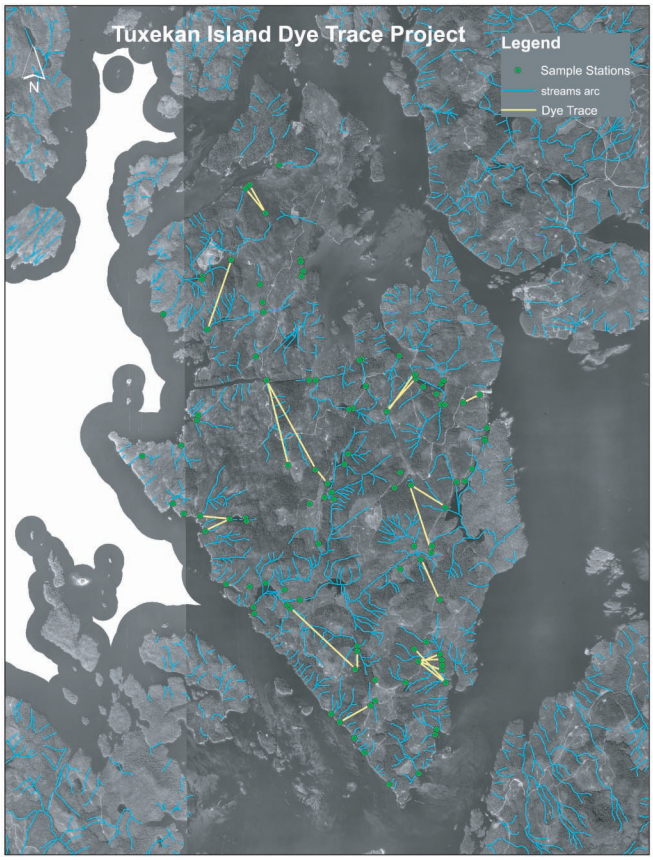


Figure 3. Tuxekan Island project area, insurgence and resurgence locations, and dye trace results.

All but three of the 2003 dye introductions eventually entered El Capitan Passage. Most of the 2004 dye introductions eventually entered Whale Passage. The few dyes that crossed this trend were used to delineate the east-west boundary along the high karst plateau. All springs in the western portion of the project area, including Cataract and Honkin, flow into El Capitan Passage, along the western shoreline of Prince of Wales Island. Twin Island Lake flows into Cavern Lake, which flows into 108 Creek, and eventually out into the estuary of Whale Passage. Snoose Creek, a significant drainage in the central portion of the project area, also flows into Whale Passage. Snoose Creek enters Whale Passage slightly south of 108 Creek and within the estuary. Neck Lake outfalls into Neck Creek, which flows a short distance before entering Whale Passage.

A large percentage of the 2003 dye was recovered at Honkin Spring, centrally located along the western portion of the project area. The Honkin Spring Cluster, a series of springs proximal to Honkin Spring, gained source waters from four different insurgences in 2003, and an additional insurgence in 2004. All these source waters are located along the western flank of the high Plateau in 2003, and with the exception of a small sink located in the northern portion of the eastern flank of the project area in 2004. Dye from this small sink (84) was the only dye recovered along the eastern resurgences in 2004. Neck Lake received dye from the southern portion of the eastern flank of the project area in 2004 and received one hit of dye from along the road in 2003. Snoose Creek collected dye from the central portion of the eastern flank of the project area in 2004. Dye recovery was not monitored in the Snoose Creek area in 2003. Twin Island Lakes received dye from the Beaver Falls area, in the northern portion of the eastern flank of the project area. Cavern Lake is downstream of Twin Island Lake and received dye from upslope within its topographic watershed, insurgences 91 and 92.

Several significant resurgences did not receive dye in either year of sampling. For example, resurgences 86 and 87 located in the central portion of the project area, which flow into Snoose Creek, were monitored during the 2004 season and received no dye. The resurgences in the southwestern portion of the project area, 35 to 38, were monitored during the 2003 season and received no dye.

Tuxekan Island

The Tuxekan Island project area was more linear in shape than the North Prince of Wales project area and a greater number of significant structural features separated the areas of delineation. This allowed a single dye to be introduced in numerous locations within the project area without contaminating adjacent watersheds. Of the 14 dyes that were introduced, 13 were recovered in 20 springs (Figure 3). Similar to the North Prince of Wales project area, Tuxekan resulted in no significant trend for dye recovery. Dye traces follow northwest, northeast, southwest, and southeast flow paths.

Most dyes were recovered less than a mile (1.6 km) away from and within topographic boundaries of, the introduction points. The few exceptions include I-2, which was recovered southwest at 87; I-5, which was recovered northwest at 60; and I-12, which was recovered northwest at 12; all greater than a mile in distance from introduction points. Topographic boundaries were crossed at introduction point I-12, where dye was recovered in two separate watersheds; I-6, where dye was recovered across a topographic boundary to the southeast; and I-2, where dye was recovered across a topographic boundary to the southwest.

Discussion

Results of these dye traces revealed underlying flow paths. These subsurface flow paths are combined with surface water flow paths to delineate watershed boundaries. The complexity of delineating watersheds is confirmed in

the results of these two projects. This complexity lies in the inter-relationship and processes controlling topography, structural geology, and runoff, or flow volume.

Topography

Topography played a large role in the runoff patterns of both project areas. Many of the topographic watershed boundaries remained unchanged. Those boundaries that did change resulted from dye trace information. Delineation of watershed boundaries must be an iterative process in karst areas because of the influence of subsurface flow paths, and hence dye trace results. Prior to dye tracing, karst watershed boundaries followed topographic divides. With each additional dye trace, the boundary can change to reflect source area. In some cases, the source area of the introduction point became the watershed boundary. In other cases, the watershed boundary was altered, just slightly, to reflect additional source areas.

Structural Geology

Outcrop pattern, bedrock contacts, structure, and glacial deposits and scouring control landform development and the subsurface flow paths. Spring locations are associated with fault and shear zones, bedrock contacts, and sea-level stance associated with isostatic adjustment after the last glacial advance. In both study areas, the large northwest-southeast faults control the individual drainage basins and the associated east-west shear zones tend to control groundwater flow pathways. Bedrock geology and generalized fault patterns are shown in Figures 4 and 5.

High and Low Flows

The volume of runoff affected the direction of flow in at least one location on both project areas. On NPOW, dye from insurgence location 87 was recovered at the Honkin Spring cluster and at Headwaters resurgence (Figure 2). Honkin Spring flows west into El Capitan Passage, while Headwaters Cave flows east into Snoose Creek, and eventually Whale Passage (Figure 2). This evidence indicates a watershed that extends the entire width of Prince of Wales Island. On Tuxekan Island, I-5 flows north to Scott Lagoon and south to Karheen Lake (Figure 3). The geology and dye trace results suggest that normal flow in these cases would be in one direction. Overflow during larger storm events would then flood the

Figure 4. Bedrock geology, structure, and dye trace results, North Prince of Wales Island project area.

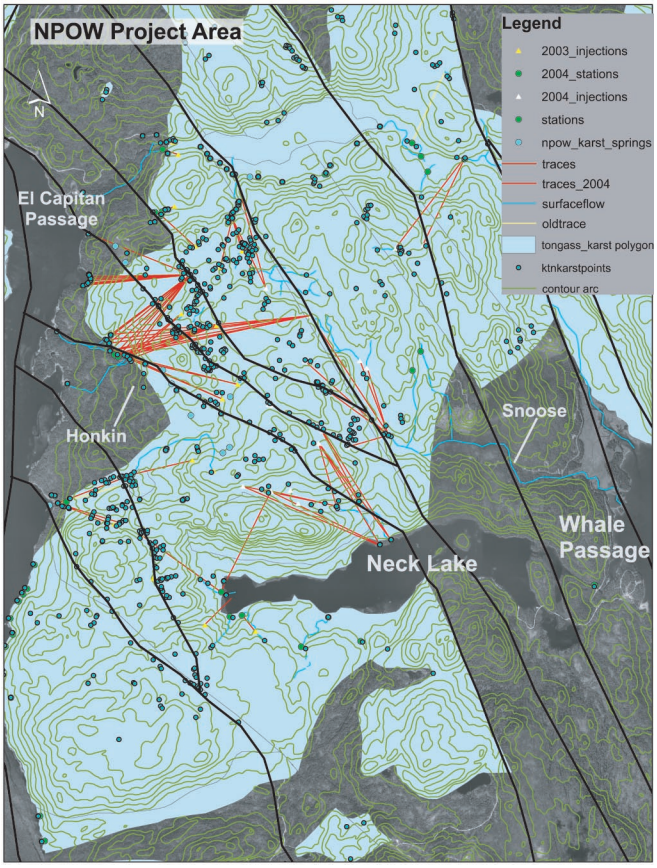
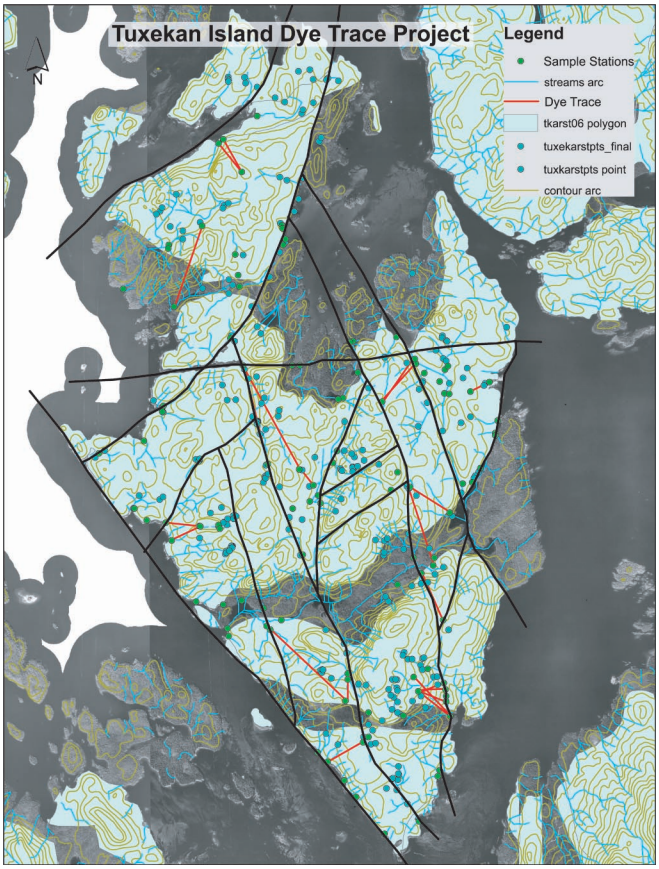


Figure 5. Bedrock geology, structure, and dye trace results, Tuxekan Island project area.



dominant passages and spill over into a secondary set of flow passages. Additional dye traces aimed to measure flow velocity may suggest dominant flow paths, and at what flow volume the dominant flow paths are exceeded.

Conclusions

Tuxekan and NPOW project area watershed boundaries were delineated using the usual tools available for surface topographic watershed boundaries, while also incorporating dye trace results. Topography was the dominant characteristic in the delineation of the boundaries; however, structural geology and flow volume played a large role. Studies with dye tracers revealed subsurface flow paths and helped account for the majority of runoff in the study watersheds. Dye tracers are valuable in delineating karst watersheds and identifying subsurface flow paths in complex geologic structures. Now that the primary karst groundwater basins have been established for these areas, more in-depth studies are planned to determine high and low flow velocities and dominant flow paths.

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