WHEN THE SURVEY IS NOT ENOUGH: TEMPERATURE, SALINITY, AND DYE TRACING REVEAL FLOW PATHS

Patricia A. Beddows
McMaster University
P.O. Box 25, 1280 Main St. West
Hamilton, ON L8S 1C0, Canada
beddows@mcmaster.ca
905-526-8637

Melissa R. Hendrickson
Department of Geography
University of Western Ontario
London, ON, Canada

Abstract

Tourism-driven development along the Caribbean coast of the Yucatán Peninsula is resulting in a nearly continuous 200 km urban corridor stretching from Cancún to south of Tulum. There is an urgent demand for hydrogeological knowledge in this area, where cave diving exploration is revealing a dense network of more than 700 km of flooded cave passages. The widespread speleothem deposits below the water table indicate that the caves are polygenetic, having been drained and re-flooded. The distinct depth levels of passages are tied to speleogenesis at past sea levels and climate conditions. Where older sections of cave have been re-flooded, these often show varying degrees of hydrodynamic disequilibrium with modern boundary conditions. Consequently not all explored caves are necessarily hydrologically active. Temperature and salinity profiles along a major trunk passage in Sistema Aktun Ha, upstream of Cenote Car Wash, have helped map out distinct water masses. Dye releases in two locations confirm two distinct hydrological regimes, and that the water does not flow along the biggest apparent flow path. These results show the value of cost-effective physico-chemical mapping of water masses and modified dye tracing techniques in translating cave surveys and maps into valuable hydrological knowledge.

Key words: hydrology, cave diving, Mexico, dye tracing, water chemistry, mapping

Introduction

Sistema Aktun Ha is a water filled complex of two caves located ~8.6 km inland from the Caribbean coast on the Tulum-Coba highway (Figure 1a). The system is comprised of a "spring side" explored to a length of 1467m, extending NW from the central entrance sinkhole, called Cenote Car Wash, while on the coastward "siphon side" there is a water-filled cave explored for 1342 m. Cenote Car Wash is an open basin of water while the other two cenotes are naturally small and sediment choked. All three are post-genetic offset collapses, such that the actual point of entry into the water is offset from the apparent principal flow path. This cave system was one of the first explored and mapped in detail in the region, with a published survey in 1990 by J.G. Coke and T.M. Yong (1990). No exploration or survey data have been compiled for this cave since 1999, despite this having been one of the more popular cave dives in the whole region.

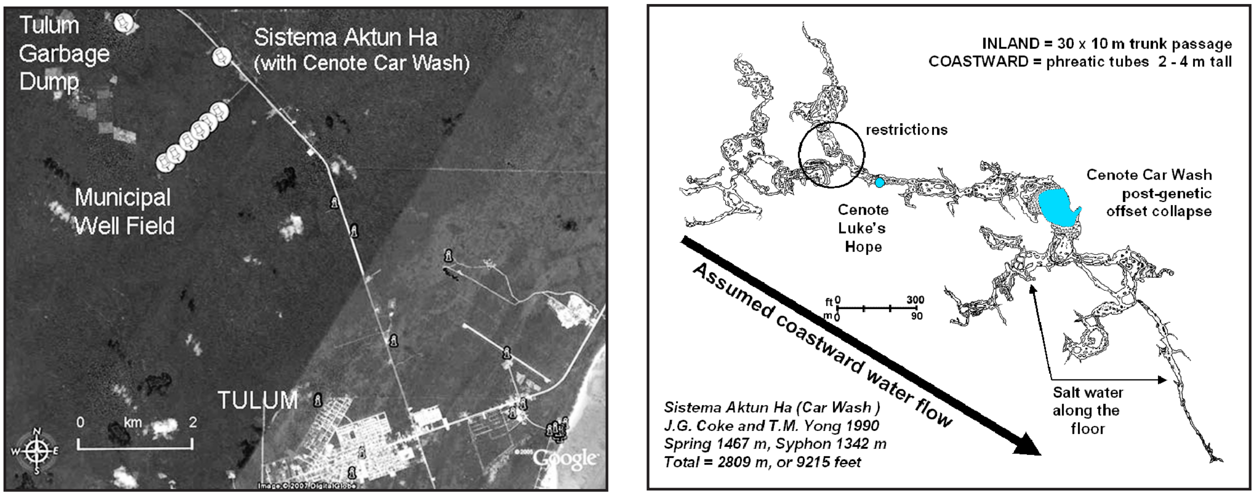

Figure 1(a) Location of Cenote Car Wash within the Sistema Aktun Ha at 8.6 km straight line distance inland from the Caribbean Sea on the Tulum-Coba highway. The locations of the individual wells of the Tulum municipal well field, as well as the Tulum garbage dump are indicated.

(b) Survey of Sistema Aktun Ha with annotations (Coke and Yonge 1990).

The cave system is flanked within 2 km by the Tulum municipal well field, while inland is the municipal unregulated garbage dump (however, it is reported by word of mouth that the dump has been closed in the last two years; Figure 1b). The dominant orientation of the cave complex is NW-SE, consistent with the dominant direction of most cave development in the region (Smart et al., 2006), and suggesting that the cave acts as a conduit for groundwater from the area of the dump and coastward to the well field. This is further supported by the orientation along the hydraulic gradient of the region, although this is exceptionally low at 10^{-5} (Beddows 2004).

Discrimination of Distinct Water Masses

From 2000 through 2007, a number of vertical physico-chemical profiles have been obtained in most areas of the cave using multi-parameter probes (Hydrolab M5, or YSI600XLM). These profiles are collected at discrete locations by a cave diver extending the probe out horizontally and descending slowly and smoothly from the ceiling to the floor, all while moving slowly forward into undisturbed water mass (Figure 2a). The data pertaining to the profile is extracted from the whole dive data, and then plotted in relation to depth. At shallow depths (< 7 m) in Sistema Aktun Ha, like other cave systems of the region, pockets of isolated water are often encountered within the cenotes with distinct temperatures from rapid recharge of storm water or from direct insolation, and coloration due to algal blooms or organic acids (tannins). These surface waters are affected by top-down processes, and are not part of the active circulation of groundwater through the cave. The mixing zone between the fresh and saline water in this density stratified aquifer is encountered at ~20 m in Sistema Aktun Ha and below that is saline water which can only be accessed in the coastward sections of this cave.

Distinct water masses are shown by temperature and specific electrical conductivity (SpC) profile data from 2007 at depths of 9-12 m below the water table (Figure 2b) from five locations on the inland side of Cenote Car Wash (as indicated

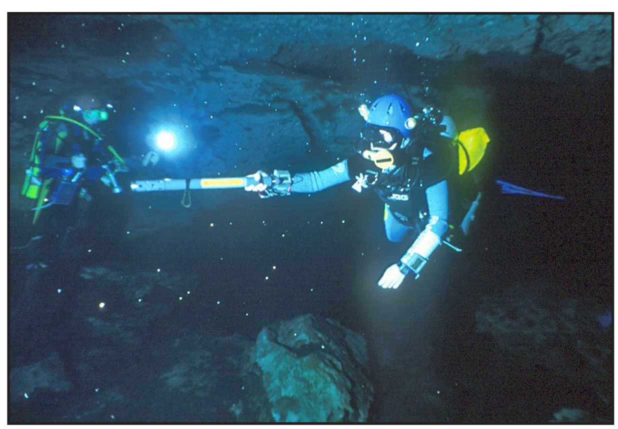

Figure 2(a). Collection of multi-parameterprofile data by a cave diver (Photo by A. Kuecha).

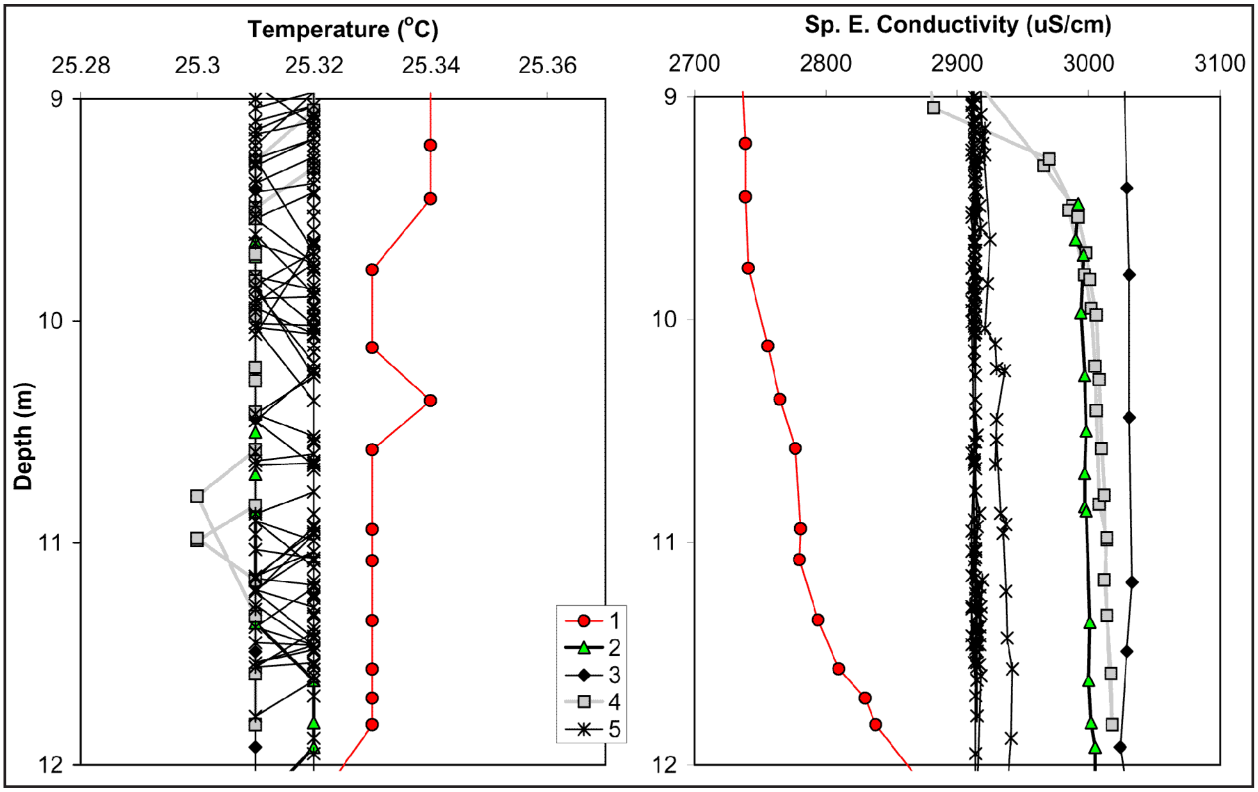

Figure 2(b) *Temperature and specific electrical conductance (SpC) between 9 and 12 m depth below the water table from five locations in Sistema Aktun Ha as identified in Figure 2(c).*

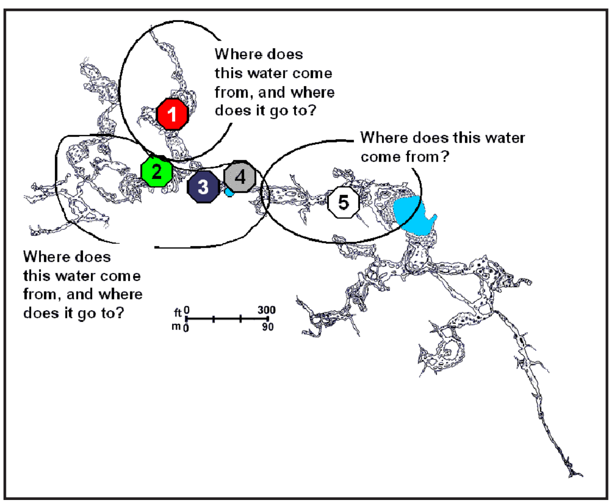

Figure 2(c)

in Figure 2c). This depth increment is selected here since it is within the principal depth of conduit development in this cave system along which the fresh water may flow. Almost all of the water throughout the cave is at the same temperature (25.31-25.32 °C) except for Profile 1 from the inland NE section of the cave (Adriana's Room) where the temperature is slightly cooler. However the distinctness of this water is clearly discriminated by looking at the SpC, which is significantly lower than elsewhere in the cave with a value of ~2750 µS/cm (minimum 2900 µS/cm). A second type of water is discriminated by looking at Profiles 2, 3, and 4 from the inland northwest and central portion of the cave around Cenote Luke's Hope. Here the waters are all 25.31-25.32 °C, but with generally higher SpC of ~3000 µS/cm. Profile 5 data is a compilation from along the whole of the passage inland from Cenote Car Wash and approaching, but not reaching, Cenote Luke's Hope. Here the water is of intermediate SpC with values of 2900 µS/cm.

In the inland section of this cave system, the common idea amongst cave divers is that the water flows simply from the northwest and northeast segments, along the large trunk passage measuring 30 x 10 m, around and through Cenote Car Wash, and then on into the coastward sections of the cave. However, the physico-chemical data from temperature and SpC clearly show three distinct water masses, and these cannot be explained by the hypothesized hydrology. There is no likely process for the water in the northeast branch (Profile 1) to be cooled before merging into the water flowing into

Cenote Car Wash. Equally there is no likely process for the removal of solutes and salts from the second water mass in the northwest segment and near Luke's Hope, such that it arrives more dilute should it flow coastward directly through Cenote Car Wash.

Dye Tracing to Test for Hydraulic Connectivity

Fluorescent dye tracing was used to test the hydrological connectivity between the different zones of the cave identified to have different water masses by physico-chemical profiles (Figure 2c). A single sampling location in Cenote Car Wash was used with water samples pumped manually from ~11 m water depth through a tube anchored in the middle of the NW inland side of the debris-collapse pile within Cenote Car Wash (Figure 3a, 3b). On April 19, 2007, water soluble and food/domestic product grade dyes were released within the flooded cave by cave divers with Rhodamine WT released in the NE inland segment (FL on Figure 3b), and Uranine (sodium Fluorescein) released immediately downstream of Cenote Luke's Hope. Background water samples were collected before dye release, and then at intervals of 1/10th the time elapsed since the first dye release rounded to the closest 10 minutes. The internal volume of the sample tubing was calculated, and voided into a bucket before each sample. No adjustments to the time series have been made to account for the 2–5 minutes spent voiding the tube volume. Water samples were analyzed for relative fluorescent intensity at the University of Western Ontario using a PTI QM-1 spectrofluorometer with a xenon arc source. Both emission and excitation variations were accounted for with real-time corrections. Synchronous-scan spectra were produced at delta lambda = 20 from excitation range 250 to 600 nm and emission of 270-600 nm.

The breakthrough of Uranine dye was rapidly observed in the water samples from Cenote Car Wash with a recession curve spanning 13 hours, and returned to near background levels afterwards, although a possible secondary pulse is evident through the last sample taken 21.5 hours after initial appearance (Figure 4). In contrast, the fluorescent intensity at 578 nm for Rhodamine WT showed little variation over the course of sampling, which may simply result from natural variations in

Figure 3.(a) Cave divers handling two lengths of the sample tubing at the cenote surface.

Figure 3(b) Pre-dive briefing on the dye-release protocol showing the two heat-sealed, impermeable cloth pouches containing masses of dye. These are cut open with utility shears underwater.

the background fluorescence, such as from organic acids, or may indicate some minor dye leakage beginning at 1:00 on April 20. Cave divers provided additional visual observations of the dye distribution in the system. A "vivid green algae colour" along the ceiling in NW section was observed three months after injection (E. Reinhardt, pers. com.). Previous experience of the principal author in that section of the cave suggests that this likely was dye, as water discoloration has never been previously observed there. Furthermore, the only locations regionally with vivid green coloration are those with open water pools experiencing algal blooms, and there are no exposed water surfaces in that section of the cave. In the NE section, observation by

Figure 3(c) *Manual pumping of water samples from a fixed point in the water-filled cave. The internal volume of the tubing is voided into the bucket before each sample.*

the primary author the day after the dye release indicated a significant red color consistent with the RhWT dye that had been released there, with no obvious displacement of the water. A further unsolicited report arrived three weeks later, reporting that red discoloration remained in the NE section of the cave (B. Phillips, pers. com.).

Conclusions and Implications

Physico-chemical profiles of temperature and specific electrical conductivity have effectively identified three distinct water masses in the inland portion of Sistema Aktun Ha. A dual dye release indicated that water in the inland NE section of the cave (Adriana's Room) is near stagnant over weeks and months, with little, if any, water flowing coastward via the large diameter (30x10 m) flooded

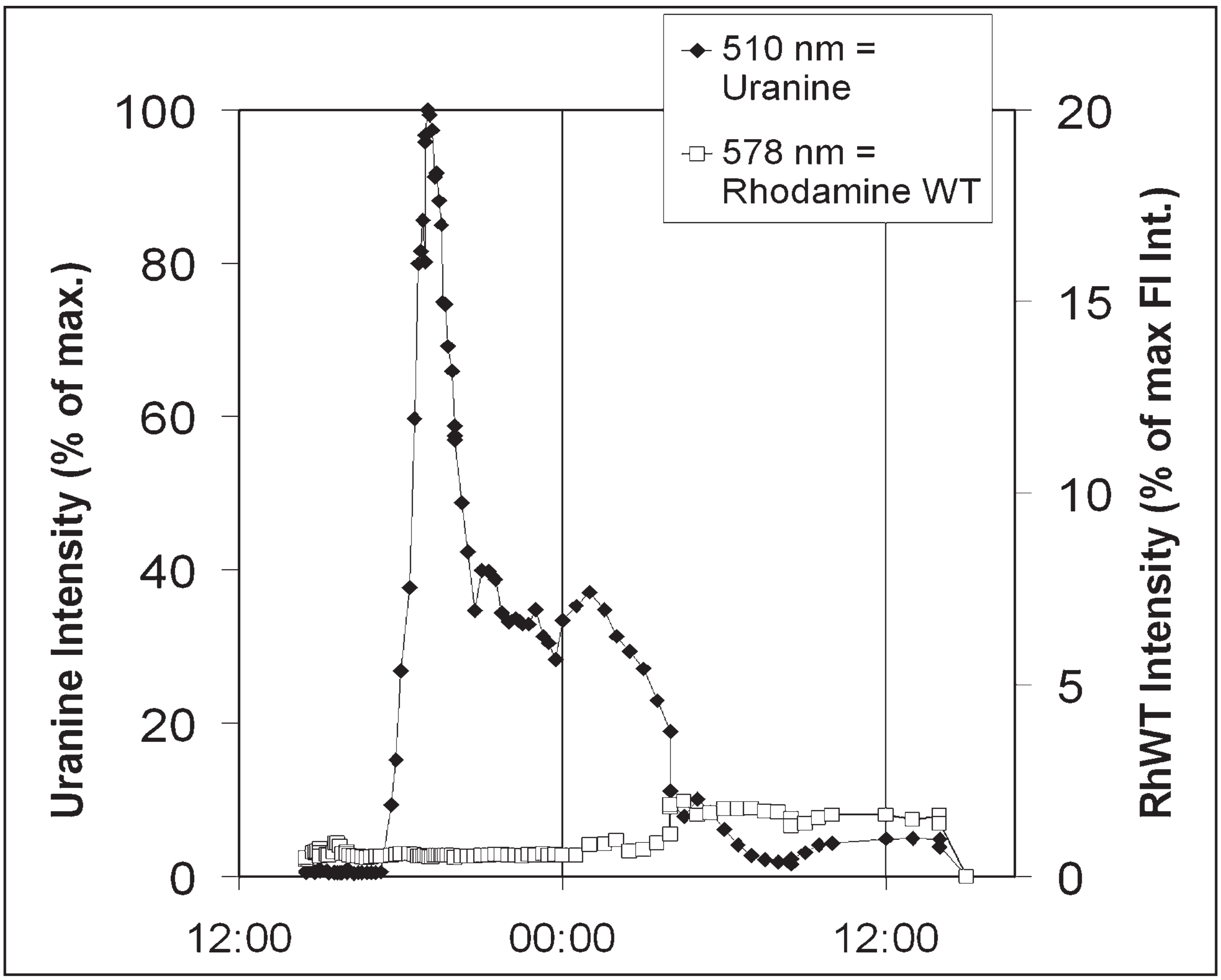

Figure 4(a) *Relative intensity (three-point moving average) of fluorescence at 510 nm for Uranine (Sodium Fluorescein) and at 578 nm for Rhodamine WT in water samples pumped from ~11 m water depth on the inland NW side of Cenote Car Wash, Sistema Aktun Ha.*

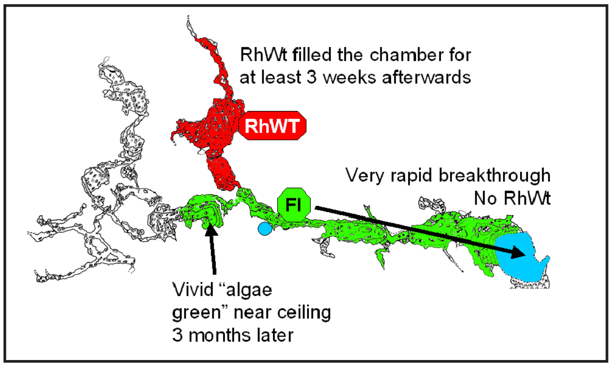

Figure 4(b) Schematic showing the regions of the inland cave affected by the two dyes released based on dye-tracing and divers' observations.

cave towards Cenote Car Wash. The water within this large passage inland of Cenote Car Wash has a dominant rapid flow coastward but with a relatively extended flushing time spanning more than 12 hours over this relatively short distance of ~220 m. Furthermore, some inland flow of water from this principal trunk passage into the NW section of the cave is indicated by divers' observations of water discoloration three months after dye release, while residence time in the NE section is very long.

The complex flow paths within Sistema Aktun observed here are inconsistent with the simple model of coastward flow of water through the largest available and continuous cave passage. Furthermore, the source of the water flowing through the principal trunk passage immediately inland of Cenote Car Wash cannot be either the NE or NW sections of the cave, posing the challenge of locating the inflow of such large volumes of water, which then flows through Cenote Car Wash. Close examination of the NE wall at and just coastward of Cenote Luke's Hope is warranted.

The complex flow paths of water through Sistema Aktun Ha demonstrated here suggest that contaminants from the municipal garbage dump may follow equally complex flow paths through the aquifer, and therefore may not traverse this particular cave even though the cave is located nearby and coastward of the site. Similarly complex flow paths on the coastward side of the explored cave may further mediate the direct arrival of contaminants from the dump to the municipal water supply wells. Conversely, other point and diffuse sources of contamination in the broader area may instead pose a more direct threat to the municipal well field of Tulum and the cave system, but it would be very difficult to identify such sources since they are not necessarily located along obvious inland-coastward locations.

Using multi-parameter probes while cave diving may be a cost-effective and efficient means of identifying distinct water masses. Characterizing physico-chemical properties of cave waters throughout the Yucatán Peninsula could elucidate the locations of complex, obscure flow paths. Where the observed physico-chemical properties of the water throughout the cave are inconsistent with the simplest hypothesized flow path, the actual hydrology through the cave system may be revealed using well-constrained (one-day, <500 m) dye traces.

Acknowledgments

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