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Hydrogeochemical Characterization and Speleogenesis of Sistema Huautla in Oaxaca, Mexico

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HYDROGEOCHEMICAL CHARACTERIZATION AND SPELEOGENESIS OF SISTEMA HUAUTLA IN OAXACA, MEXICO

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HYDROGEOCHEMICAL CHARACTERIZATION AND SPELEOGENESIS OF SISTEMA HUAUTLA IN OAXACA, MEXICO

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Sierra Mazateca, Mexico is home to Sistema Huautla, the deepest cave in the Western hemisphere with 1,560 meters of depth and 90 kilometers of passage, including 26 entrances distributed in a high-relief, karstified terrain, within the Sistema Huautla Karst Groundwater Basin. Exploration of the cave has generated research questions about its evolution and geomorphology given the different vadose and phreatic zones impacted by tectonic and incision processes. Dye traces during this study of Cueva de La Peña Colorada confirmed it is a fossil resurgence of the cave system. An additional cave, Cueva Elysium, was connected hydrologically in 2019, expanding the basin and recharge area for the cave system. Four springs were monitored at high-resolution along the Rio Santo Doming for water level, temperature, and specific conductivity in 2019. The dye trace results indicate connection between the springs and that primary dissolution likely occurs at the water table and phreatic zone, due to the extreme verticality of the cave system, while flood responses are rapid and short-lived, despite seasonal storms. Results from this study also help aid in understanding and managing water resources in the region, further exploration of the cave system and potential connections, and the future evolution of Sistema Huautla under a changing climate as exploration continues.

Chapter 1: Introduction

During the last century, cave exploration has prompted considerable attention to high mountanious karst systems in successive efforts to discover the deepest caves in the world, and in recent years ongoing changes in climate and population growth have bestowed increasing importance on the understanding of high mountainous karst aquifers (Bates et al. 2008; Lauber and Goldscheider 2014). Well-developed karst landscapes supply water to 20-25% of the world's population (Palmer 2007). Approximately one quarter of the Earth's mountainous areas are karstic and highly vulnerable to contaminants (Meybeck 2001; Viviroli et al 2007; Hilberg 2015). Human dependence on this karstic mountain hydrology has prompted studies in Switzerland, Spain, Croatia, France, Georgia, and Canada (Ford 1983; Hauselmann 1999; Kutha et al. 2001; Klimchouk et al. 2006; Vigna 2015), but regional examinations in the high karst areas in southern Mexico are minimal despite their importantance to essential water supplies.

This study focused on the complex Sistema Huautla Karst Aquifer (SHKA), which is located in a high Cretaceous limestone plateau called the Sierra Mazateca, in Oaxaca, Mexico. This karst region is home to the Sistema Huautla cave system, which attracts the attention of speleologists from all around the world due to its vertical extent. Currently, the entire cave system measures 1,560 meters in depth (Caverbob 2020) and includes approximately 90 km of explored passage as of the most recent expedition conducted in April 2019. The water recharging Sistema Huautla Karst Aquifer and, subsequently, the cave system has been dye traced in a previous study to a single outlet called Huautla Resurgence spring, located at approximately 345 meters of elevation in the Santo Domingo River (Smith 2002), and using high-resolution logger data, geochemical sampling, and more dye traces this study deepened the understanding of the cave and groundwater systems.

Karstic high mountains present a unique hydrology derived from both high fracture porosity and high rock solubility, which typically create networks of conduits within the rock called karst aquifers. In addition to sinking and gaining streams and springs, sinkholes and caves are typical of landscapes associated with dissolutional proceses in karst aquifers. Surface and groundwater flows are highly interconnected in karst regions and function as single, dynamic flow systems that can be traced from the point of water recharge to spring outflows (White 1993). Karst aquifers tend to be complex with highly heterogeneous hydraulic properties (Ford and Williams 2007) that are mainly attributed to karst conduits that develop in the subsurface; nevertheless, fracture and matrix porosity also play an important role in the movement of water in certain lithologies.

High relief karst aquifers are characterized by pronounced differences in elevation between inputs and outputs, which may extend for thousands of meters. High relief karst aquifers may reside in carbonate rocks that have been structurally deformed during mountain building. This results in complex internal structures consisiting of folds, faults, and fractures that produce large scale fracture patterns that control groundwater movement. These characteristics, along with the inaccessibility of some high elevation karst regions, make accurate delineations of surface and subsurface watersheds complicated to perform; nonetheless accurate delineation is of critical importance to understand hydrologic function of the aquifer, vulnerability to contamination, source of water, and climatic influence (Kambesis 2007).

Previous studies by Smith (1994) of the Huautla System include proposed speleogenesis models based on geomorphological observations and dye-trace studies of both the surface and subsurface terrain. Smith (1994) hypothesized multilevel phase development, controlled by regional tectonics, as the overlying siliclastic caprock receded and exposed the underlying carbonates through dissolution. Measuring geochemical parameters, such as dissolved ions and trace elements, as well as physical parameters, such as hydrochemical analyses and flow pathways delineation by dye tracing, helped produce contemporary quantitative data to supplement Smith's speleogenesis model (Smart 1980; Quinlan 1990). These data also helped determine catchment and infiltration areas, its hydrogeological characteristics, and processes of speleogenesis during the system's continuing evolution.

This study employed a combination of quantitative methods to assess the geochemical evolution of groundwater in SHKA to advance understanding of the function and structure of the regional aquifer and its influence in cave development. Geochemical sampling aided in illustrating ongoing karstification throughout the system and, through a series of dye traces, the study better delineated the boundary of SHKA and other potential inflows and outflows.

1.1 Research Questions

Using these methods, this study answered the following research questions:

- What are the main recharge sources and outputs for the SHKA and what are the boundaries of the hydrological basin?
- What temporal and spatial patterns can be observed with respect to hydrogeochemical variation in SHKA hydrological basin and what do such patterns indicate regarding karstification and speleogenesis?

This study improves the understanding of aquifer dynamics in high relief karst terrains. Examining geochemical and physical parameters of SHKA yielded more information about the karstification process, including how conduits develope, discharge fluctuates, rates of dissolution, and groundwater mixing contribute to speleogenesis at depth. The use of dye trace data helped to identify differences in groundwater flowpaths and hydrological divides, despite changing seasonal water levels (Baena et al. 2009). This information lends itself not only to a more robust explanation of speleogenesis in deep cave systems, but also provides the Mazatec region and similar communities in karst mountainous regions throughout the world, with a deepened understanding of their water resources in these extreme environments.

Chapter 2: Literature Review

2.1 Karst Landscapes

Ford and Williams (2007, 1) define karst as "comprising terrain with distinctive hydrogeology and landforms that arise from contributions of high rock solubility and well developed secondary (fracture) porosity." Karst landscapes contain caves, closed depressions, sinking streams, rock outcrops, springs, and extensive underground water systems that are developed in soluble rocks, such as limestone, marble, dolomite, and gypsum (Dreybodt 1988; Goldscheider 2007; Ford and Williams 2007; Palmer 2007). Karst landscapes are capable of being modified by dissolution processes, while other processes, such as mechanical erosion and gravity, only play a secondary role (Dreybrodt 1988; Palmer 2007).

2.2 Karst Development

Karst landscapes are influenced by a number of factors that can alter how they change over time; these include the type of rock, the fluid that creates dissolution, structure of the rock, the hydraulic gradient of groundwater, and changes in climate over geologic time (Palmer 1991; Palmer 2007). The changes in karst landscapes are dependent upon the capacity of the subsurface to accept water through bedding planes, joints and other fractures, which facilitate water movement through the rock (White 1988; Dreybrodt and Gabrovsek 2002).

Karst is divided into three zones of development, as mentioned by Palmer (2007), which are positioned vertically and relate to the proximity of the water table. The epikarst zone is the top layer in the karstic system. This layer is the first in contact with meteoric water and soil, which carry high concentrations of carbon dioxide (Palmer 2007; White 2007). The epikarst is highly porous and nearly all initial openings are enlarged at comparable rates by highly under-saturated water (Palmer 2007). In the vadose zone, water moves by gravity towards the water table or is held by capillarity. Water does not fill all of the openings. Last is the phreatic zone, where all openings are filled with water and the beginning of the layer is the top of the water table (Palmer 2007). The epiphreatic, or floodwater, zone is commonly mentioned in karst hydrology and, this layer is the area in the vadose zone that gets filled with water during flood events. This area is of extreme importance in karstic models, because a large amount of dissolution occurs here, due to undersaturated floodwater (Prelovsek 2009).

2.3 Flow of Water and Conduit Formation in Karst Aquifers

Due to the complexity of underground pathways, water flow in karst aquifers is not homogeneous. At the turn of the century, Grund (1903) proposed a model for subterranean flow in karst systems using Darcy's Law. This model envisioned the movement of water through an aquifer that was isotropic and homogeneous, which is not optimal for karst aquifers. Models based on Darcy's equations produce uncertainties on flow dynamics and are not representative of the actual system (Freeze and Cherry (1979). Karst aquifers are more complex than those represented in initial studies because they display anisotropic flow as function of differing porosity and permeability, which is concentrated along enlarged fractures, conduits and openings (Palmer 2007). One of the major advances in understanding these complex systems is the influence of turbulent flow on conduit development. The flow changes from laminar to turbulent flow, due to flow velocity, fissure width, and water temperature, but only commonly occurs when the opening gets wider than 0.5 to one cm (Palmer 2007).

In comparison with non-karstic systems, secondary porosity is the dominant control in the system development of karst. Secondary porosity is represented by openings larger than primary porosity, which include joints, fractures, and bedding planes in which water preferentially flows (White 1988; Ford and Williams 2007; Palmer 2007). The secondary porosity causes the flow on the underground system to become highly anisotropic (Vacher 2002). Tertiary porosity refers to conduit flow, which is one of the pillars of what White (2003) defines as “triple porosity” of karst aquifers, where granular porosity and conduit porosity both contribute to recharge and transmissivity (Fig. 2.1).

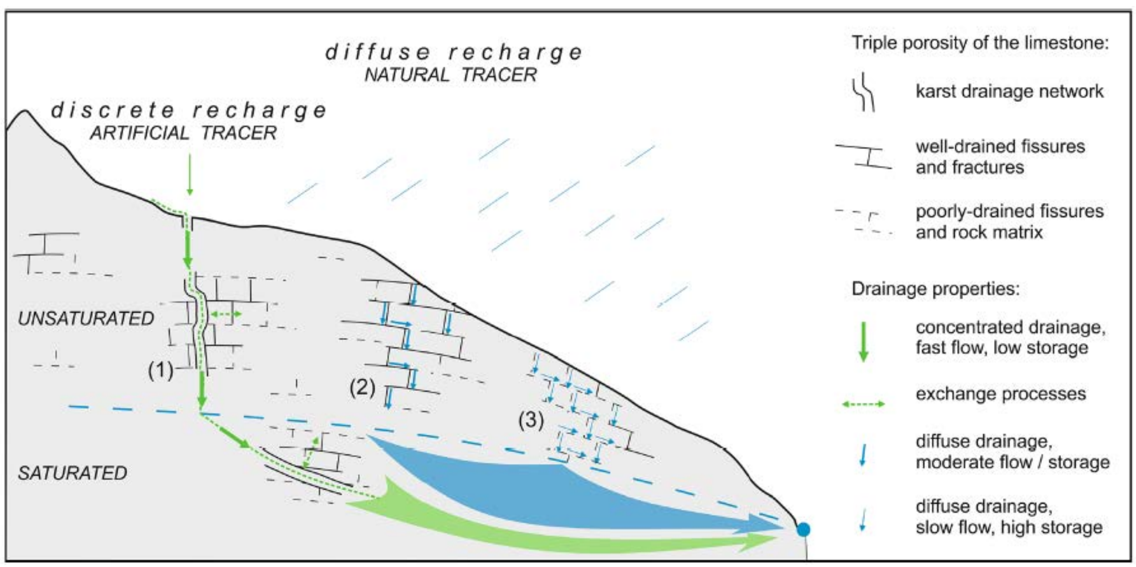


Fig. 2.1. Conceptual model of drainage in alpine karst systems in the Wetterstein Mountains, Germany (Source: Lauber and Goldscheider 2014).

2.4 Telogenetic and Eogenetic Karst

Karst systems can be divided into telogenetic or eogenetic depending on their depositional and burial stages and amount of induration (Vacher and Mylroie 2002). Eogenetic refers to primary deposition and early exposure, having undergone little diagenesis. In contrast, telogenetic karst typically refers to post-burial exposure and advanced induration and mature diagenesis. Based on diagenetic stage, it is assumed that eogenetic limestones are younger and less mature than telogenetic karst. Telogenetic limestone has been buried and further compacted, typically giving it a massive structure. The structure and, by association, the age of the limestone highly influences the matrix permeability. Before this subdivision was more strongly used, karst aquifers were assumed to have minimal matrix porosity and more porosity associated with fractures and conduits. Mylroie and Vachner (2002) compared eogenetic karst in Florida and Bahamas (millions of years old) to studies done by Worthington (2000) in Mammoth Cave of (hundreds of millions of years old, Mississippian-age) in south-central Kentucky. The study found that the matrix porosity was much higher in eogenetic karst than on telogenetic karst. Martin and Dean (2001) further expanded this idea with geochemical studies in the Santa Fe River and found that most of the flow in the aquifer was provided by matrix flow during low-flow conditions. These examples have provided a great incentive for scientists to approach the study of karst aquifers through different lenses depending a system's structure and age.

Florea and Vacher (2006) demonstrated that telogenetic karst exhibits fast response to rain events and a prompt return to baseflow conditions due to the absence of matrix porosity by analyzing 38 different springs from eogenetic and telogenetic karst.

Their study also demonstrated that a high flood incidence in teleogenetict karst and a change in climatic events could affect discharge more. Baena et al. (2009) found that high variation in spring discharge in telogenetic karst landscapes due to seasonal and storm precipitation variation is equivalent to high variations in groundwater temperature and electrical conductivity; thus, showing the importance of analyzing individual storm events and seasonal variability to understand telogenetic karst dynamics (Lawhon 2014).

2.5 Geochemistry of Karst Aquifers

Aquifers can be recharged by meteoric water that flows into points of input, such as swallets, streams, and solutionally enlarged features. Meteoric water and soil microbial activity capture CO_2 into the water before infiltration, and drop the pH of the water as low as four (Palmer 2007). Low pH values in the water flowing through carbonate systems leads to dissolution process that form the characteristic features in karst.

The main process for carbonate karstification can be summarized in the following series of formulas (White 2002; Palmer 2007):

1. Precipitation captures CO_2 from the atmosphere and microbial activity on the soil to form carbonic acid:

   $CO_2\ (g) + H_2O_{(aq)} \leftrightarrow H_2CO_{3\ (aq)}$

2. Carbonic acid dissociates to create bicarbonate:

   $H_2CO_3 \leftrightarrow HCO_3^- + H^+$

3. As water has contact with carbonate rock, ions dissociate:

   $CaCO^3\ _{(s)} + H_2O_{(aq)} \leftrightarrow Ca^{2+} + CO_2 + H_2O$

4. The carbonate ion associated with H^+ to create another bicarbonate:

$CO_2 + H^+ \leftrightarrow HCO_3^-$

In summary, water and carbonic acid interact with carbonate rock to produce dissociated calcium, bicarbonate, and excess carbon dioxide:

$2H_2O + CO_2 + CaCO_3 \leftrightarrow H_2O + Ca^{2+} + 2HCO_3^-$

In the case of dolomite, the equation varies slightly with respect to Mg:

$2H_2O + CO_2 + CaMg(CO_3) \leftrightarrow H_2O + Ca^+ + 2HCO_3^-$

Chemical composition of groundwater in karst environments is influenced by composition of the rock, the water-rock contact time, landuse and climatic conditions in the region. The use of water samples from springs, caves, surface streams, well water, and soil within the karst aquifer can help identify the origin and path of water, rate of karstification, temporal hydrological regimes, and mixing processes (Lakey and Krothe 1996; Sanchez 2005; Palmer 2007).

According to Glyn and Plummer (2005), physiological and chemical tracers have been used to study aquifer dynamics extensively during the last century. Baena et al. (2009) used temperature and electrical conductivity variations in mountain aquifers to better understand the elevation of the source water, water and rock interactions, and flowpaths in Sierra de las Nieves karst aquifer in Spain. The electrical conductivity in karst groundwater is influenced by the amount of dissolution in the karst system due to the amount of dissolved ions (primarily Ca and Mg) produced during the weathering process, which makes it a representative parameter to study the evolution of karst landscapes (Hillberg 2016). Laudon and Slaymake (1997) studied variations in conductivity in the Coast Mountains in British Columbia and found that electrical conductivity is a good indicator of the temporal sources of flow in the springs based on their response to storm events.

Hydrogeochemical analysis techniques can help understand the acquisition of mineralization in the water and, therefore, allow the use of dissolved minerals much like tracers to intepret the origins of the water as it moves through the karst landscape (Sanchez 2005). Dissolved inorganic carbon (DIC) in underground karst waters is composed of mainly bicarbonate (HCO_3), carbonate (CO_3), and dissolved carbon dioxide ($CO_2 + H_2CO_3$). These elements are the product of a karstification process that introduces the DICs through weathering of carbonate rocks and microbial activity in the soil (Jarvie et al. 1997; Palmer 2007).

Steinich et al. (1996) established groundwater divides in the Yucatan Peninsula by conducting a geochemical analysis of groundwater. This mineral characterization was pivotal in identifying different groundwater flow paths as indicated by sulfates present in the system due to rock and water interaction. In a similar way, Lauber and Goldscheider (2014) used a combined methodology of mineral characterization (using calcium, magnesium, sodium, potassium, chloride, bicarbonate, sulfate, and nitrate), carbon isotopes and dye tracers to obtain information about different flow paths in the Wetterstein Mountains in Germany. The study found two different flowpaths, a deep-slow and shallow-fast flow that had distinct mineral composition.

2.6 Spatial and Temporal Influences on Karst Development

Sanchez et al. (2015) found that greater hydrochemical variability of springs during a hydrological year in the carbonate aquifers of south of Spain are indicative of higher development of karstification. Recharge can be of two types: allogenic or autogenic. Allogenic recharge comes from flow of a neighboring or overlying non-karst rock into a karstic system. Usually, this water is undersaturated with calcium and saturated with carbon dioxide. This characteristic makes the water very aggressive and produces extensive caves (Ford 2003; Ford and Williams 2007; Palmer 2007). An ideal example of allogenic recharge is Cueva Cheve in Oaxaca, Mexico (Smith 1994). The hydrologic input of this cave comes from carbonate outcrops that are adjacent to metamorphic rock. The streams that flow from the insoluble rock sink into the cave at the contact between the limestone and metamorphic rock (Hose 1995). In contrast, autogenic recharge refers to rainfall or snowmelt that falls directly into the karst terrain. Recharge functions through internal drainage and collects water from all parts of the terrain, tending to produce a more diffuse recharge, due to multiple paths of input.

2.7 Influences on Conduit Formation

Differences in flow capacity in karst aquifers result from flow modes that range from conduit (turbulent) to matrix (diffuse) (Martin 2001). The aquifer can be conduit flow dominated, in which water travels through large conduits in the aquifer with little attenuation. For example, the study by Goldscheider (2014) in the Holloch system presented rapid transport though conduits that are highly dominated by advective transport, wherein water moves rapidly through major conduits. Travel times tend to be short from the input to the discharge source in karst systems. The water has a high fluctuation in electrical conductivity after a rain event, due to the short travel time in the aquifer and slow accumulation of ions. In contrast, diffuse recharge is through highly permeable karst with low secondary porosity. Travel times tend to be longer and water has slow response to rain events. Typically, karst systems present a combination of both flow mechanisms (Martin 2001; White 2002; Palmer 2007; Ford and Williams 2007; Anaya 2014).

2.8 Dye Tracing to Study Recharge Sources and Outflows

Dye tracing is a fundamental tool that hydrogeologists employ to study and protect karst systems (Aley 2008). It is a point-to-point method that is highly dependent on the site of introduction of the dye and the area of recovery (Benson 2016). This method enables hydrologists to delineate the boundaries of a system, groundwater velocities, characterization of conduit networks, pollution transportation, and aquifer capacity (Ford and Williams 2007). Non-toxic tracers have commonly been used to trace groundwater flow from areas of recharge to areas of discharge such as springs (Field 1995). The most commonly used dyes are fluorescein, eosine, Sulforhodamine B, and rhodamine WT (Aley 2008). The selection of the dye must be adequate for the site and background studies must precede dye tracing to avoid inaccurate results or false positives if background dye persists in the aquifer. Smith (2002) used a comprehensive dye trace study to locate the major outflows of SHKA and trace some of the underground flow paths through the cave system associated with it. Smith found that most of the dye associated with fast flow of the system, was delivered to a single conduit spring at the bottom of the Santo Domingo Canyon.

2.9 High Elevation and Deep Karst Studies

While several deep caves exist and have been studied and documented for decades around the world, there lacks intensive study of the geochemical and hydrologic processes that form them. Due to the technical difficulty of accessing remote study areas in deep karst aquifers, scientific advances have developed to where new techniques exist to conduct detailed studies of the recharge regimes, dissolution processes, and hydrologic pathways in these systems using higher-resolution data in combination with advanced mapping and dye tracing work. This study will contribute one of the first high-resolution, multi-proxy methods of studying one of the deepest caves in the world to enhance knowledge about its formation, evolution, and hydrologic function with respect to water resources and geomorphology.

Chapter 3: Study Area

The Sistema Huautla karst groundwater basin is located in the Sierra Mazateca, in the northeastern part of the state of Oaxaca in Mexico (Fig. 3.4). It is named after the indigenous Mazatec community which has long called this region home. The Sierra Mazateca is considered part of the Sierra Madre Sur which in part is a section of the Sierra Madre Oriental. The Sierra Mazateca can have altitudes from 640 to 2,750 m of elevation (Munn-Estrada 2017). The study site has an approximately elevation of 1,500 m reaching its highest elevation in Cerro Ocote with 2,200 m above sea level. The Sierra Mazateca is delineated to the north by the Rio Petalpa, which separates it from the Sierra Zongolica in the nearby state of Puebla and Veracruz. The south end of the Sierra Mazateca is the Santo Domingo Canyon that separates it from the Sierra Cuicateca, which harbors more deep cave systems. The region is characterized by a rugged terrain with numerous huge dolines, sinking streams and high walled valleys that drain water to the major rivers, like Rio Santo Domingo and Rio Petalpa. The regional capital is the city of Huautla de Jimenez, with a population of approximately 36,000 habitants. Beneath the surface of the mountain, the limestone contains a vast network of passages formed by solutional process that stretch from the plateau south to the Santo Domingo Canyon ten kilometers away. This mountain region serves as a divide between the tropical lowlands and the high arid regions of the Tehuacan Basin. (Hapka and Rouvinez 1996). The region is divided by the local inhabitants into Mazateca Alta or Tierra Fria (1,000-1,600 m) and Mazateca Baja or Tierra Caliente (400-1,000 m).

3.1 Climate

The Sierra Mazateca receives a huge amount of orographic precipitation from the Gulf of Mexico, due to its proximity to the sea without any other features to stop precipitation. As the area of the Sierra Mazateca captures most of the rainfall from the Gulf, the west side has an arid region that starts at the foot of the mountain near the area of Tehuacan. The precipitation of the region decreases from the east to the west. The mean annual precipitation in Huautla de Jimenez reported by the Servicio Meteorológico Nacional de Mexico is 2,535.4 mm/year, which is situated on the western edge of the study site. To the east of the study site, in a lower elevation, the city of Tenango reports a mean annual rainfall total of 5,224.5 mm/yr. The Sistema Huautla karst groundwater basin is situated in the middle of the two stations in the cities of Huautla and Tenango. By averaging the two stations, the study site precipitation is approximately 3,500 mm/yr. This region is one of the areas with the highest precipitation amounts in the Mexico, due to its proximity to the Gulf of Mexico (INEGI 1983; Servicio Metereologico Nacional 2017). The rainy season extends from the month of June to October, with August being the wettest month on average. The dry season is from November to the month of May.

The average temperature on the area of Huautla de Jimenez is 17.4 °C. The temperatures reach a maximum average of 23 °C and low of 11.8 °C. In general, the average temperature of the highlands where part of the recharge for the hydrological basin occurs varies from 16 °C to 22 °C on a yearly basis. As observed by speleologists exploring the Huautla cave system, the start of the wet season has been highly variable over the years. In April 2018, there were heavy rains that were not expected resulting in regional flooding. Flooding in the caves prevented collecting data. Subsequently, in 2019, during the months of March, April and May there was hardly any rain at all. The region suffers from strong droughts, which are reflected in the availability of water for the community. The monitoring of precipitation and other climatic conditions was discontinued in the year 2010 by Servicio Metereologico for reasons unknown.

3.2 Vegetation and Soils

The Sierra Mazateca contains a high variation and diversity of habitats that include thorn scrub, tropical semi-deciduous, pine-oak forest, oak forest and cloud forest (Rzedowski 1983). The lower levels in the Sierra Mazateca are characterized by arid to semi-arid vegetation that can vary from thorn scrub to tropical deciduous forest that reaches an elevation of up to 1,600 m. At this elevation, tropical rainforest dominated the area until reaching an elevation of 1,800 m. Boege (1988) reports on the distinctive vegetation found in different forest habitats. The tropical forest present in the Sierra is very thick composed of *Brossium alicastrum*, *Quercus corrugata* and *Ulmus mexicana*. Tropical forest transitions to semi-deciduous forest consisting of *Quercus salicifolia*, *Trophis mexicana*, and *Coccolaba grandifolia*. The temperate forest that is found in the highest elevations can have vegetation like *Pinus patula*, *Pinus ayacahuite*, and *Pinus tenuifolia*.

At the 1,800 m to 2,300 m the vegetation gives ways to pine, oak and cypress forest. In the highest elevation range, there is cloud forest up to 2,600 m in areas of the Cerro Rabon (Sanchez-Cordero 2001). The area is characterized by different types of soils throughout the region, which include umbrisoils, luvisoils, cambisoils, acrisoils, regosols, and phaeze (INEGI 2007), due to the heterogenous geology, weathering processes, and climate.

3.3 Geology and Geomorphology

The lithology and geological structure determine the characteristic features of the karst region of the Sierra Mazateca, which include sinkholes, karren, caves, swallets, springs, and shafts. The SHKA is developed in carbonate rocks of the Jurassic and Cretaceous age. Marine transgression in the Cretaceous period gave the conditions ideal for carbonate deposition, thus creating the extensive Cordoba Platform, of which the Sierra Mazateca is part (Gonzalez 1976; Smith 2002). The Cordoba Platform consists of reef limestone of over 5,000 m of thickness of the Orizaba, Guzmantla and Atoyac formations. It is part of a major tectonic unit in the region and is directly overthrusted by the outliers of the Orizaba Platform in the northeast area of the study site (Ortuno-Arzate 2003).

The geological area around the SHKA consists of an allochthon called the the Orizaba-Cerro Rabon, which is formed on upper Cretaceous carbonates from the detached section of the Orizaba Platform (Ortuno-Arzate 2003). The Xonamaca Formation is on the base of the platform, sequence normally is situated under the Jurassic sandstones and red conglomerates of the Todos Los Santos Formation (Nieto-Samanego et al. 2006; Rosales et al. 2013).

In the Sierra Mazateca, the following strata of the Mesozoic are of interest to the study site and are illustrated in Figure 3.1. On top of the Tepexilotla Formation, lies the black limestone of the Tuxpanguillo and the Capolucan formations (Toriz 1983; Smith 1994; Rosales et al. 2013).

From Aptian to Cenomian age, the layer is called the Orizaba Formation. This rock formation from the Middle Cretaceous consists of light gray limestones, with massively stratified beds, with 50 to 80 cm layers of dolomite, wackestones, and boundstones (Smith 2002; Guiterrez 2009). The formation has a range from 200 to 400 meters to up to 840 meters thick (Ramos 1983). Most likely the karstic aquifer is situated in this layer and overlying units.

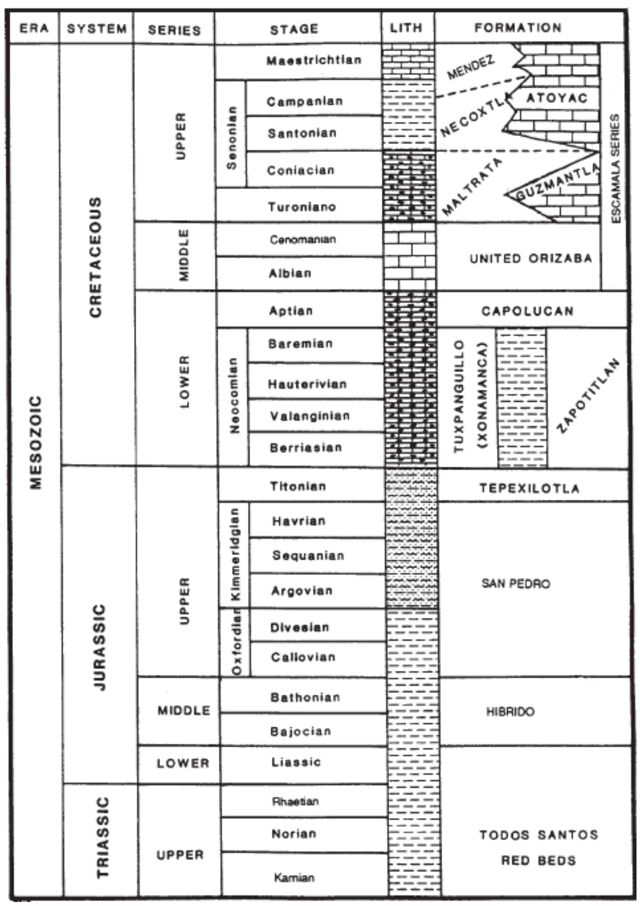


Fig. 3.1. Lithostratigraphy of the Sierra Cuicateca. Compiled by Smith (2002) from Echanove (1963), Viniegra (1965), Moreno (1980), and Ramos (1983).

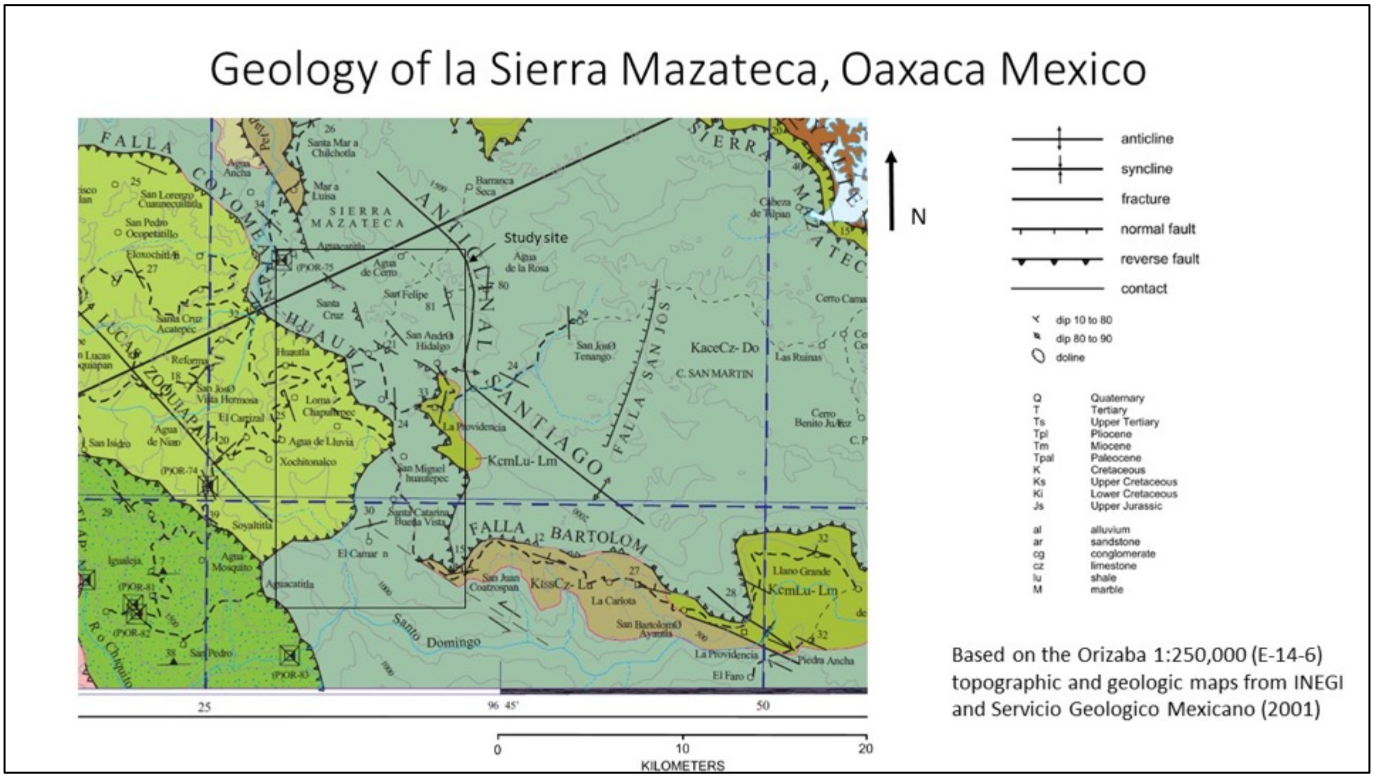


Fig. 3.2. Geology of the Sierra Mazateca, Oaxaca Mexico (Source: SGM 2001).

In the literature, the Sierra Mazateca is defined as part of Sierra De Juarez Geological Subprovince (Fig. 3.2). This mountain range was formed during the Laramide Orogeny, which occurred during the Late Cretaceous to Paleocene. The Sierra Cuicateca, located in the same nearby region, began its uplift sequence around the Middle Miocene (Centeno-Garcia 2004). Rocks affected by the Laramide Orogeny can also be found throughout the study site, as thrust faults and folds are very common in the region.

The most common and largest structures along the Sierra Mazateca consist of thrust-faults that position older rocks on top of younger rocks (Fig. 3.3). The Coyomeapan-Huautla Reverse Fault is one of the most important major faults concerning Sistema Huautla, because it caused the non-carbonate Jurassic rocks to overlay the

Cretaceous limestone, providing a source of allogenic recharge from the clastic aquifer above. The aggressive water that recharges the limestone contributes to the development of dolines and caves (Moreno 1980; Smith 2002).

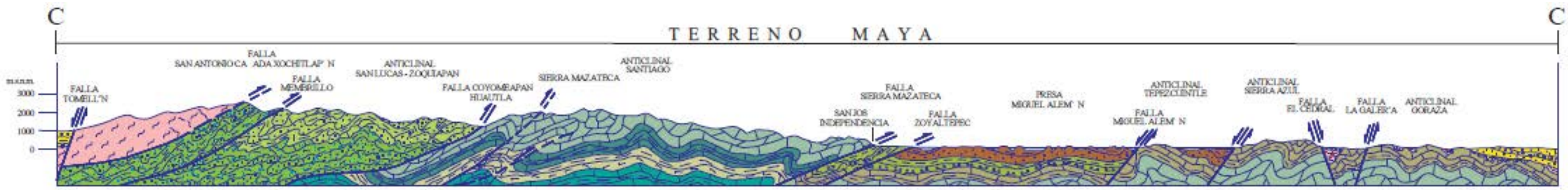


Fig. 3.3. Geological Crossection of the Terreno Maya. Green = Tepexilota Formation non-karstic rock. Light blue = Orizaba Formation karstic limestone. (Source: SGM 2001).

3.4 Hydrology

The Sierra Mazateca is situated near the border of the states of Oaxaca, Veracruz, and Puebla. This mountainous region is bordered by the Veracruz Basin to the east and the intermountain basin of the Cañada de Oaxaqueña to the west. This valley is drained to the east by the Rio Tomellin and Rio Salado, which eventually formed to join the Rio Santo Domingo. The Rio Santo Domingo delineates the Mazatec Region to the north, separating the Sierra Mazateca with the Sierra de Juárez and the Cuicatlan Region. This river cuts across the Sierra Madre Oriental del Sur and eventually joins the Rio Papaloapan to ultimately be part of the Papaloapan hydrological basin, which discharges into the Gulf of Mexico. The Papaloapan basin is one of the most important fluvial systems in Mexico due to its high usage and streamflow (Pereyra-Diaz et al. 2010; CONAGUA 2016; Munn-Estrada 2017).

The Santo Domingo River (Rio Santo Domingo) is the only river that manages to cross the Sierra Madre del Sur, due to the process of karstification along joints and fractures (Fig. 3.4). The proposed hypothesis is that water has percolated through dolines creating underground rivers and extensive caves, which later collapsed to expose the River (Ortiz et al. 2004). This is similar to the observations that Smith (1994) made in the Peña Colorada Canyon, which feeds into the Santo Domingo River, and in which the walls of the canyon show features that would be presented inside caves. Observations by the Author indicate that some of the conglomerate units visible in the canyon are related to rock units inside the caves based on visual comparison and basic petrology. Discussions with Smith (1994), along with these observations, indicate a more complex process may have occurred. Due to the size of the Rio Santo Domingo and its discharge, downcutting of the river may have been more from bedload scouring from the transport of a significant sediment from the Canada de Oaxaquena delivered by two rivers draining a huge area. Karst processes were likely at work, but the primary cutting mechanism for canyon development was likely through corrasion and corrosion from large flows in the river moving bedload during steady uplift of the mountain range. There is not much evidence of any significant remnants of major cave passages in the canyon walls indicating that the Rio Santo Domingo was always underground. The Canyon does narrow downstream and has 150 m high walls cutting through the strata, with few caves observed along most of it above the water level. Rio Santo Domingo drainage to the Papaloapan was present when the Laramide Orogeny began and the Sierra Madre began its steady uplift, which continues to present. In contrast, Pena Colorado is more likely a remnant feature formed phreatically, and as the canyon down cut and lowered to form the regional water table, the phreatic tubes were evacuated by stream incision. Canyon development then followed the structure and heterogeneities induced by karst development, which continues today.

Fig. 3.4. Study area in Mexico and Papaloapan river basin (Source: Kmusser 2008).

The Petlapa River is important to mention due to its proximity and influence in the Sistema Huautla region. Petlapa River is located in the northern part of the sierra and flows into the Miguel Aleman dam in the lowlands. The recharge of the region is achieved by infiltration of numerous sinking perennial and intermittent streams that are distributed through the entire karstic region. The discharge of the Sistema Huautla Karst Groundwater Basin has been identified at just one outlet located in the Rio Santo Domingo by Smith (1994).

Delineation of flow in the SHKA was achieved by Smith in (1994) and, by connecting Sistema Huautla to the river via baseflow spring, Sistema Huautla Resurgence (SHR), more analysis is needed to determine the boundaries of the system. The basin groundwater divide is hypothesized to be delineated to the north somewhere around Cerro Ocote in relation to the Agua de Cerro Fault (Fig. 3.2).

3.5 Caves

The region gained international notoriety because of the extensive network of deep caves, which later came to be known as Sistema Huautla (Figures 3.5, 3.6, and 3.7). Sistema Huautla is perhaps the most complex of the world's deepest caves, with 26 entrances and numerous independent deep routes, reaching a total depth of 1,560 meters (Smith 2012, Smith 2018). It has approximately 85 kilometers of passage, making it the longest cave system of the ten deepest caves on the world and is formed in the Cordoba Limestone massif. This area is home to many other caves and karst features that play an important hydrological role in the whole groundwater basin.

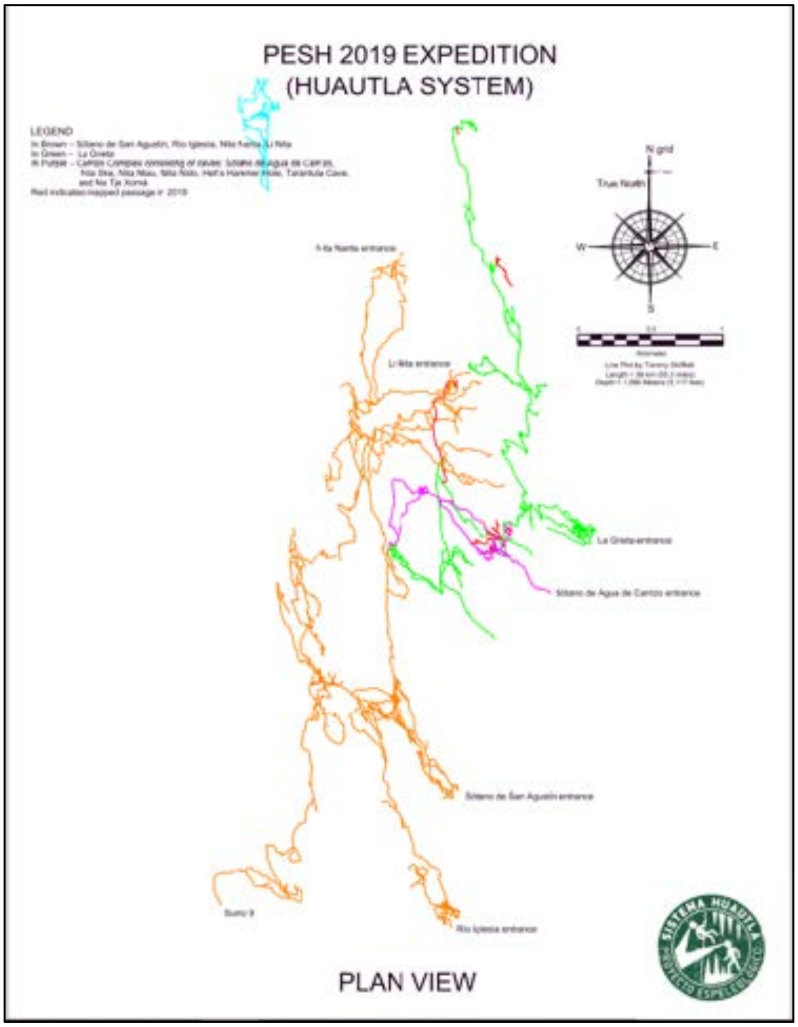


Fig. 3.5. Plan view of Sistema Huautla Cave Map from 2019 (Source: PESH 2019).

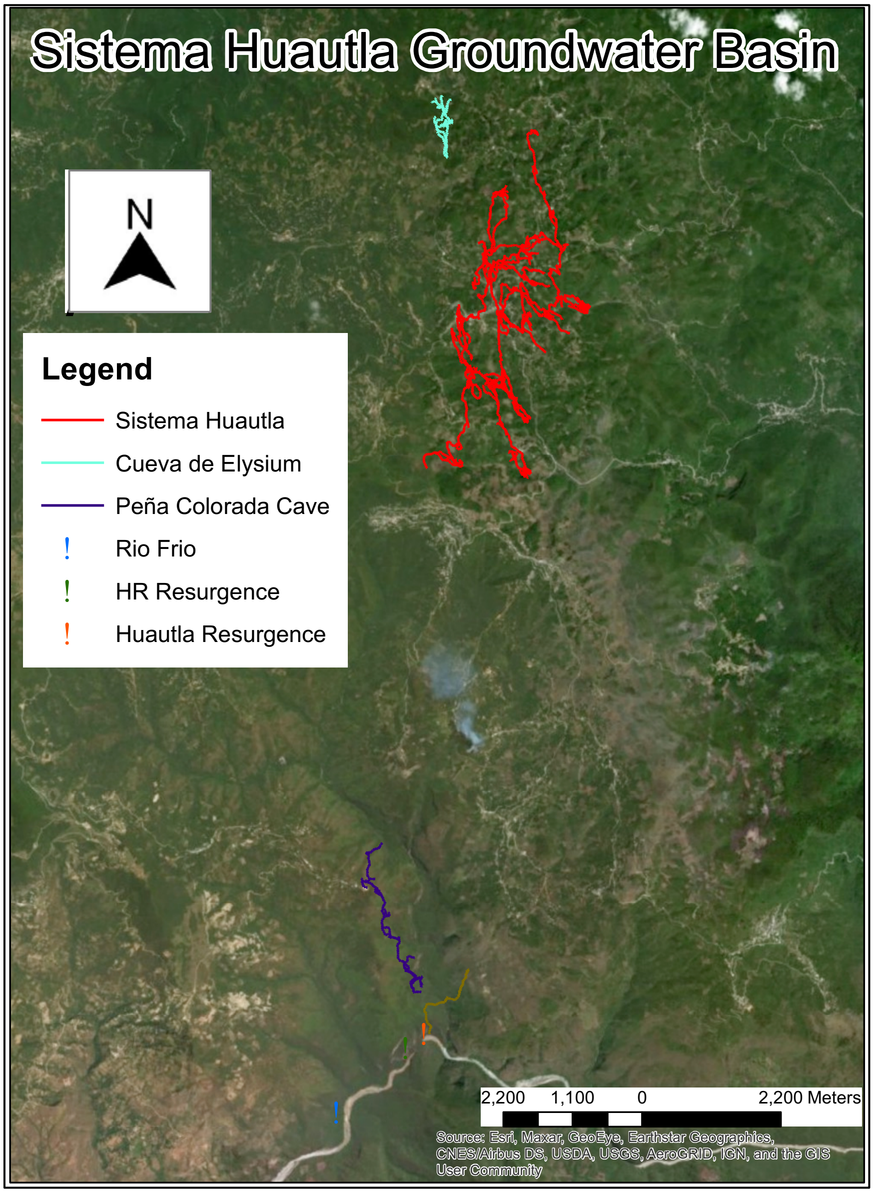


Fig. 3.6. Map of the Known Extent of Sistema Huautla and relation with springs, Oaxaca, Mexico (Source: Author).

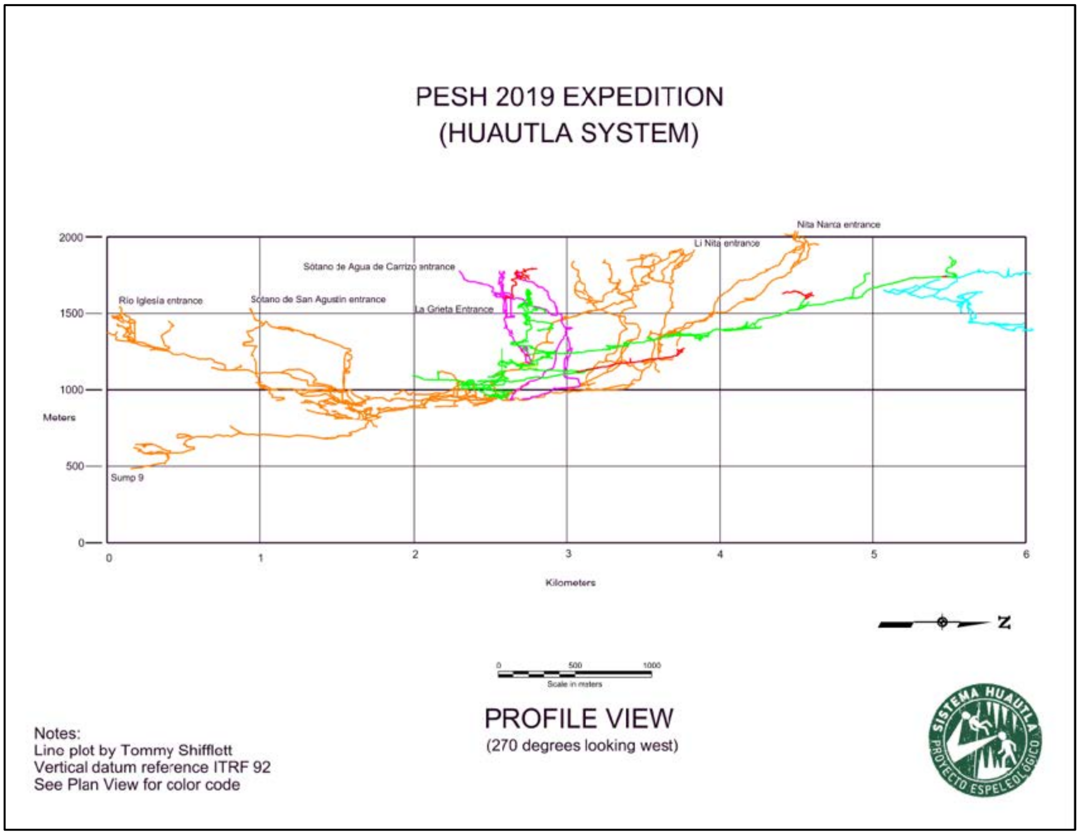


Fig. 3.7. Profile view of Sistema Huautla in 2019. Orange = Sistema Huautla. Green= La Grieta Entrance. Pink = Carrizo entrance. Blue = Cueva Elysium. (Source: PESH 2019).

The main passages of the cave dip steeply to the southwest at about 30-40 degrees and are cut by several major faults that intersect the system perpendicularly trending NW-SE (Smith 2002; Palmer 2007). The Huautla system penetrates deep beneath the surface because of the extent of faulting and the thickness of soluble carbonates (Palmer 2007). On the other side of the canyon, the Sierra Juarez contains the second deepest cave in the Western Hemisphere, after Sistema Huautla; which is Sistema Cuicateco; also known as Cheve. The region around Cheve has many solutional features most likely associated with the system. The area is characterized by a series of large dolines adjacent to noncarbonate rocks from which surface streams flow and disappear into sinks and caves. Groundwater flows to the north toward the Rio Santo Domingo, opposite to the groundwater flow from Sistema Huautla.

3.6 Springs and Caves

3.6.1 Cueva de la Peña Colorada

The Cueva de la Peña Colorada (Fig. 3.8) is a resurgence cave located in the eastern border of the municipality of Mazatlan Villa de Flores in the Mazatec region. The entrance to the cave lies on the east facing cliff side in the Peña Colorada Canyon, which gets its name because of the orange stained walls that adorn the cliffs. The canyon subsequently drains into the Santo Domingo Canyon. The Sistema Huautla Resurgence is about 50 meters upstream of the confluence of the Peña Colorado. To access the cave, one has to descend 700 vertical meters from the nearest town, called Loma Grande. Multiple sumps in the cave have been explored during different expeditions, with the first time being in 1984 by the United States Deep Cave Team, and most recently in 2018 when they reached the furthest sump, Sump 7.

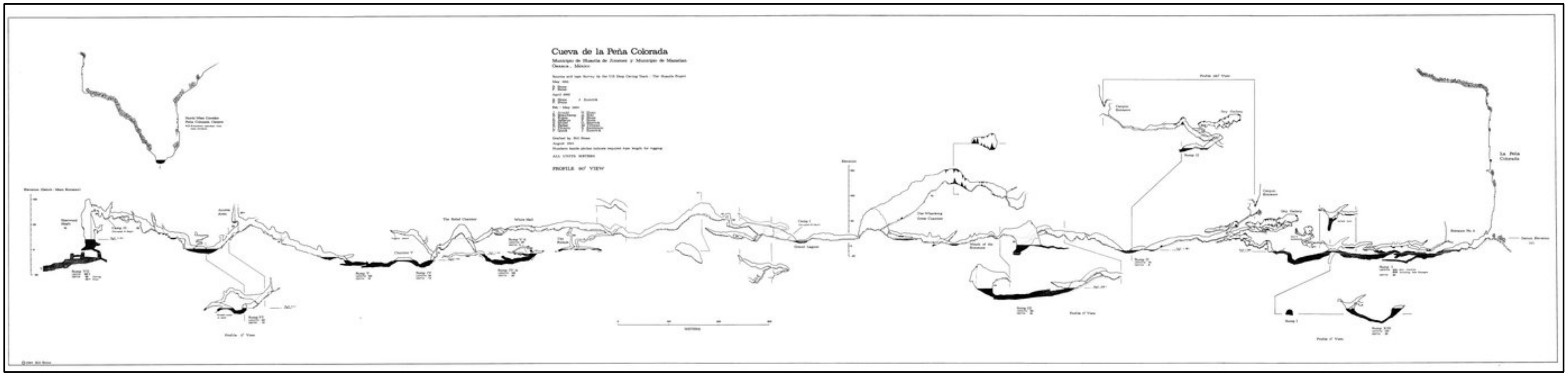


Fig. 3.8 Cueva de la Peña Colorada Map (Source: AMCS)

Local villagers have reported seeing the cave become a river in the rainy season, but there have not been visual reports of this event by explorers. Many geological features on the cave walls and floor include scallops and sediment deposition suggesting a great amount of water has been sculpting the canyons. The dimensions of the cave and the very well-developed network of phreatic conduits suggest that this could possibly be the old resurgence for the Sistema Huautla Groundwater Basin. The cave contains several phreatic loops.

Some of the observations done by cave divers in 2017 suggest that there are several pathways that feed the sumps. During a major rain event in the region, the sumps rose rapidly from water that seem to be fed from underneath passages. Supporting the idea that Peña Colorada is an overflow path of the Huautla system.

Smith (2002) conducted a dye trace for his studies by placing receptors in the first sump of the cave, as well as along the Peña Colorada Canyon to observe leakage of water from the overflow channel to the main resurgence. The dye trace was negative and inconclusive because the water in Sump 1 was not flowing. Observations from explorers determine that the only flowing stream they observed was located in Sump 7. The Cueva de la Peña Colorada entrance is approximately one kilometer from Sistema Huautla Resurgence (SHR) and around 92 meters higher (Smith 1994).

3.6.2 HR Resurgence

HR Resurgence was found during the Santo Domingo Canyon exploration. The main entrance of the spring cave is located in the north wall of the Santo Domingo Canyon and is 20 meters from the river before entering "The Narrows" section of the canyon. Ten meters higher than the main entrance, there is another entrance that intersects as skylight into the first room of the cave. The cave was formed in the phreatic zone, which is suggested by the horizontal passage shown in the explored section of the cave. The first room contains a high amount of debris related to riparian plants species that suggests that the Santo Domingo River intrudes into the cave mouth during the monsoon season. The main active section of the cave stream comes out from a boulder pile below the main entrance below the base of the Rio Santo Domingo. In the first 20 meters of the cave there is a massive gour coming from a passage on the ceiling with a parallel direction to the active stream of the room suggesting a fossil phreatic passage. Currently, the room is full of bats, which produce a lot of guano noticeable on the walls of the room. At the end of the room, there are visible shards of pottery suggesting that the section of the room remains dry even in the monsoon season.

The next section intersected the active stream of the cave. The room where these two intersected was the only section that contain active formations on the wall with a couple of stalactites and columns. The meandering passage had a five-meter tall mud bank on each side of the stream. The dimension of the passage was consistently six meters wide by 13 meters tall. The ceiling of the meandering passage had a parallel fossil passage guided by a big joint on the ceiling of it. After 300 meters of cave, the stream sumps into a sandy bottom with no visible passage. Divers attempted to explore the sump with diving gear only to find a sand bank that proved to be impassable.

3.6.3 Rio Frio

Nacimiento Agua Fria, or Rio Frio (Fig. 3.9), is the most upstream and most western known resurgence cave in the Santo Domingo River in the north wall. Initially, it was explored in 1995 during the Rio Tuerto expedition. The cave has 1.5 km of horizontal development and 70 meters of depth. The cave has four sumps, none of which were fully explored due to the limitations of the diving equipment available. The sumps seem to be part of an active stream that moves water to the outside spring. The entrance is in an upper level dry passage, which currently has speleothems and big chambers that seem to stay dry during the rainy season. The direction of the cave trends slightly northeast heading toward Cueva de la Peña Colorada.

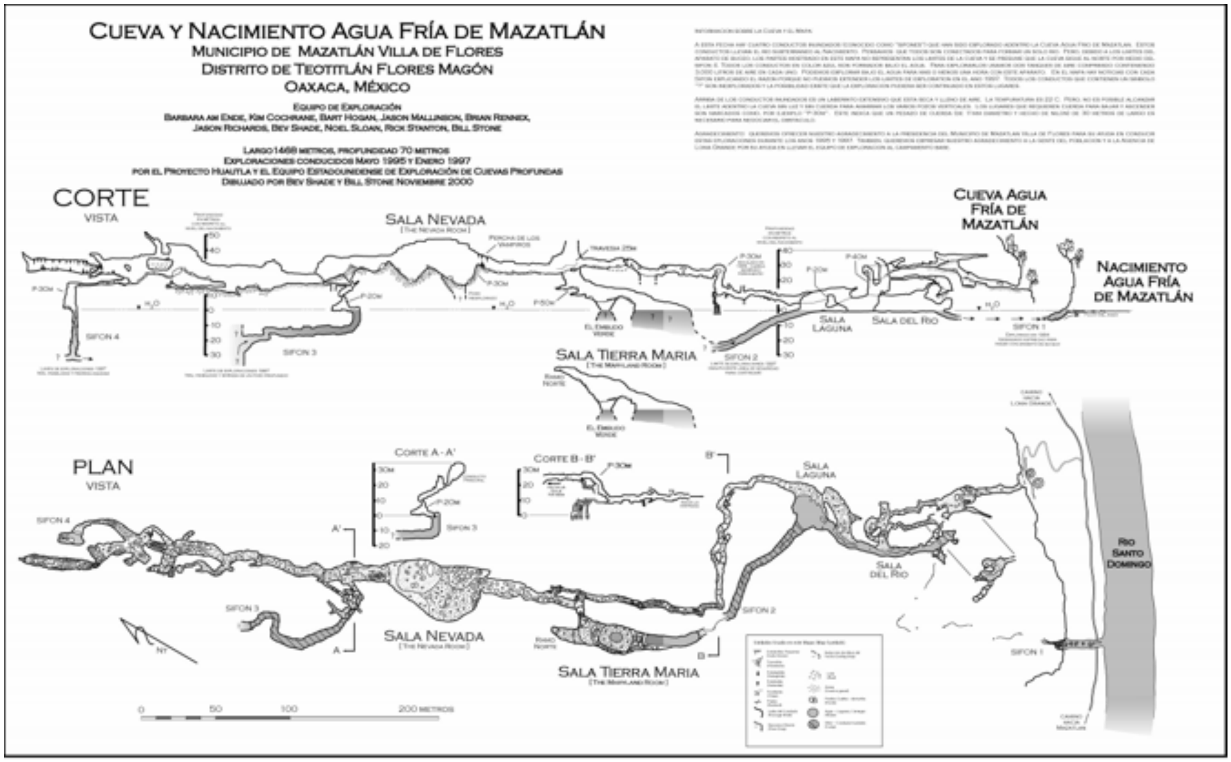


Fig. 3.9 Rio Frio map (Source: AMCS 2002).

3.6.4 Cueva Elysium

Cueva Elysium was found during the expedition of 2019 with Proyecto Espeleologico Sistema Huautla. The cave was found during ridge walking in the area of Plan de Escoba, the most northern explored region of the Sistema Huautla Karst Groundwater Basin. Many caves and features were found during the recon of the area, but Cueva Elysium was the most extensive one. The cave is located in a deep sinkhole, is canyon-like (30 meters long and five meters wide), and descends down a steep slope to a vertical shaft with a depth of six meters. The first section of the cave consists of a south-trending borehole eight meters wide and up to 20 meters high in some areas. The cave is heavily decorated with formations ranging from anthodites, soda straws, flowstone, and helictites, to name a few. The borehole intersects a series of big rooms, until reaching the largest chamber known as Camp Bertha. This room is approximately 40 meters tall and 150 meters wide. The room also has a waterfall in the side of the room with a river passage trending south towards Sistema Huautla. After the big room, a fossil trunk passage ended at a vertical shaft that led to two different routes to a lower section of the cave that ended in an enormous room full of boulders. The water seems to be heading somewhere below the boulder choke. The cave has a depth of approximately 408 meters.

3.7 Community

Sierra Mazateca is home to the Mazetec indigenous group. The Mazatec population is approximately 164,673 Mazatec persons distributed throughout the region. According to INEGI reports (2010), the Mazatec are the ninth largest indigenous group in Mexico. Nevertheless, there are also Nahuatl and Mixteca groups distributed in the area, mostly in the lowlands.

The Mazatec language is the third most widely spoken language in the state of Oaxaca (INEGI 2010, Munn-Estrada 2017). The language is tonal in nature, a characteristic that has gained linguistic notoriety because it enables speakers to communicate through whistling. The head (Presidencia) of the region is located in the Municipio de Huautla de Jimenez in which the main government buildings are situated. Urban centers like Huautla de Jimenez, San Jose Tenango, and San Andres amongst others have access to many services that are brought from the lowlands and enjoy local urban services too, including internet access. Nevertheless, some of the communities in the outskirts of the Huautla de Jimenez still rely on their own subsistence through the production of crops like corn, beans, gourds, greens, plantain, sugar cane, and coffee.

Another, local source of food raised by farmers are livestock which includes turkeys, chickens, pigs, and goats (Munn-Estrada 2017). The Tierra Fria, or highlands, is known to cultivate coffee; meanwhile, in the lowlands, farmers grow sugarcane on plantations (Demanget 2008).

Around 20,000 Mazatecs were displaced from the lowlands when the Mexican government embarked in an ambitious plan to build a dam in the Rio Santo Domingo in 1947. The Presa Miguel Aleman was constructed and the lowlands became a lake that completely inundated a Mazatec town. This created a reorganization of the Mazatec population distribution by situating people from the lower Mazateca Baja into the high areas of the Sierra Mazateca. According to a demographic report from the Secretaria de Desarrollo Social (SEDESOL), the population in 2010 was 30,004. The region has experienced a decrease in population from 2005 to 2010 due to the lack of job opportunities for young people. Populations tends to migrate to larger metropolitan areas like Oaxaca City, Puebla, or Mexico City.

From an administrative point of view, the Sistema Huautla Karst Aquifer falls into the jurisdiction of the Municipio of Huautla de Jimenez. The big entrances to the system, including Sotano de San Agustin and Rio Iglesias, are under the jurisdiction of a further regional division of San Andres, which presides over the smaller entity of San Agustin. Sistema Huautla has multiple entrances that are located throughout the system. Some of the known entrances are located on the towns of Plan Carlota, La Providencia, Plan de Basura, Agua de Tierra, Plan de Arena, Plan de Escoba. The north boundary of the groundwater basin has not yet been defined, but it is predicted that is situated along Cerro Ocote, Agua de Cerro, and Poza Rica. Near Plan de Escoba, the mountains descend to the Rio Petlapa and may represent a surface water divide. Access to this area has proven difficult because of the local communities, but further research in this area is necessary to understand the system better.

The Huautla Resurgence Spring (HRS), Cueva de la Peña Colorada, and Vine Cave fall under the jurisdiction of the municipal head of Mazatlán de Villa de Flores. The Cueva de la Peña Colorada and HRS are accessed through the towns of Loma Grande or El Camaron. The area in between the Sistema Huautla and the Resurgence where Sotano del Cangrejo is located is part of municipal head of San Miguel Huatepec.

3.8 Karst Areas of Mexico

On a larger scale, SHKA fits into the overall karst landscape of Mexico, which occupies 20% of the country (Espinaza-Pereña 2007). Mexico has an impressive number of caves with up to 10,000 caves and more being added each year (Lazcano 2018). The karst is classified into different provinces, which include Yucatan Peninsula, Mountain system of Chiapas, Sierra Madre del Sur, and Sierra Madre Oriental. (Gutierrez 2008). The ages of the carbonate rocks in Mexico extend from Paleozoic to Cenozoic in the Yucatan Peninsula. The Mesozoic carbonate rocks are the main component of the Sierra Madre Oriental, Sierra Madre del Sur, Sierra de Chiapas, and Sierra Juarez (Hernandez, 2009). The Sierra Madre Oriental and Sur karst belt extends from the states of Tamaulipas to Chiapas. The Sierra Madre is dissected by the Neovolcanic Transverse Range in the center of Mexico (Fig. 3.10).

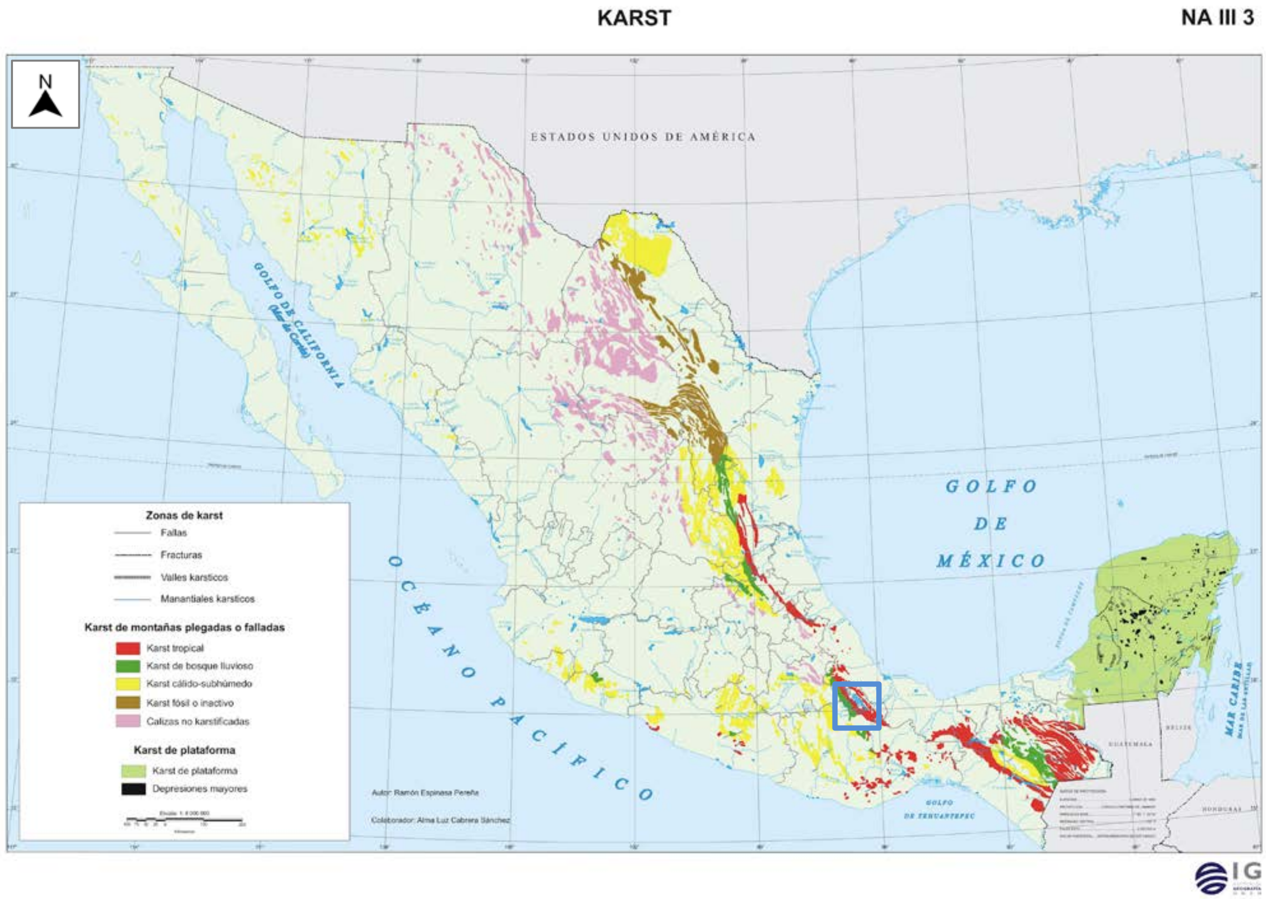


Fig. 3.10 Map of karst zones in Mexico. Blue box = Sierra Mazateca (Source: Espinasa-Ramón 2007).

Chapter 4: Methodology

This project includes several hydrogeochemical investigation methods, including the use of dye tracing, geochemical sampling, and discharge measurements carried out during field seasons in 2018 and 2019. The statistical and laboratory analyses employed include investigation and comparison of cations, specific conductivity, temperature, and pH of samples from spring outflows and possible inputs. Conducting this dye-trace and geochemical study helped to explain the water's origin and flowpath, providing essential information about its time of travel and contributing to an understanding of the geochemical evolution of the water as it moves through the system, as well as its contact with the bedrock and the geomorphological processes driving the cave system's formation.

4.1 Site Selection

Sistema Huautla's hydrological basin covers a large estimated area and it studying its entirety was not within the scope of this study; therefore, site selection was based on accessibility and importance of the area for the objective of the project, as well as available support from the participants in Proyecto Espeleologico Sistema Huautla (PESH) expedition. The sites selected for the project followed a certain criterion to be included as part of the study. Different selections were considered for dye tracing, and geochemical analysis throughout the seasons. There are important limitations to mention regarding site selections. Primarily, the political environment that dominates at the Sierra Mazateca is very volatile. The study sites selected were within the accessible and safe areas of the mountain range.

4.2 Dye tracing

4.2.1 Hydrological Basin Delineation

Two rounds of dye tracing were conducted to determine the hydrological basin dynamics and delineate the boundaries of Sistema Huautla. The first dye trace was performed in April 11, 2018, to determine the relationship of Cueva de la Peña Colorada to the springs in the Santo Domingo River. The second dye trace was performed to confirm connection between the Plan de Escoba area and Sistema Huautla on April 23, 2019. The hydrological conditions in both dye traces was starkly different. In April 2018, there was an anomalous precipitation event, and in April 2019 there was an extended drought event which made the study difficult.

The fluorescent dye used for the groundwater tracing in this area was non-toxic fluorescein (Smart 1984; Field et al. 1995). The dye was introduced directly in cave streams on both occasions. The remoteness of the area and lack of availability of large quantities of water made flushing difficult to accelerate the travel of the dye.

To delineate the northern boundary of the groundwater basin and the connections between the different springs dye injections were made directly in mapped cave streams. Monitoring sites were selected from Smith's (1994) previous work in the area, Pena Colorada 1984 expedition data, Huautla Resurgence Project data, and a karst hydrological reconnaissance trip conducted in April 2018. In the second round of dye tracing in 2019, cave stream locations inside Sistema Huautla were used as monitoring sites where PESH expedition members had reliable access and are discussed further below in this section.

The sites were equipped with charcoal packet receptors made of fiberglass screen mesh filled with approximately three grams of activated coconut charcoal inside. The receptors were placed in the cave stream and in springs, subsequently secured with a variation of non-fluorescent line, weights (especially if flood events are predicted), or aluminum wire for sites that may harbor rats or other wildlife tempted to gnaw on a tethering line. Background samples were collected the weeks prior to dye injection to ensure no presence of the dye prior to the trace.

Collected charcoal packets were placed in a labeled plastic Ziploc bag and stored in a dark container to avoid post-collection deterioration of the dyes caused by sunlight (UV) exposure. Double gloves were used during each exchange and packets were not touched directly. The time of placement, area, and additional observations were recorded in a field notebook. The packets and water samples were stored in a refrigerator in the field house until their transport to the United States in coolers and quantitative analysis in the Crawford Hydrology Laboratory (CHL). In the laboratory, the packets were thoroughly cleaned, weighed out, and eluted with solution with N-Propyl 5 alcohol, deionized water, and NH_4OH. The analysis was done with a Shimadzu RF 5301-PC spectrofluorometer. Interpretation and confirmation of charcoal receptors that presented a positive trace were made upon the comparison of the wavelengths of dye presented in the eluted sample and the previously obtained background levels of dye in the system. The methodology was in accordance with the research procedures presented on the Crawford Hydrology Laboratory website (https://dyetracing.com/documents/). Duplicate samples were not collected due to logistics and funding, but all samples were processed using the highest level of safe handling, lab processing, and detection limits indicated in the CHL standard operating procedures to confirm positives.

4.2.2 Peña Colorada Dye Trace

Groundwater tracing with fluorescent dye was used to determine the hydrologic flowpath of Cueva de la Peña Colorada and to attempt to confirm hydrological connections of Rio Frio Spring, HR Resurgence, and Sistema Huautla Resurgence (SHR) outlets (Fig. 4.1). The PC had not been previously connected to the spring in the Sistema Huautla Karst Groundwater Basin, but was speculated to intersect the system based on previous studies by Smith (2002).

On March 17, 2018, background receptors were installed in the chosen monitoring sites in the canyon in order to collect dye that may be present in the water from the populated communities in the springshed. The monitoring sites for this part of the project were selected using the observations of Smith (1994), Peña Colorada project in 1984, Huautla Resurgence Team observations, and a karst hydrological inventory performed in March 2018. The sites chosen for this round of dye trace are mention on Table 4.1, along with the result of the background analysis.

Table. 4.1 Background result of Peña Colorada dye trace (Source: Created by Author).

Name	Feature Type	Placement Date	Retrieval Date	Result
Huautla Resurgence	Spring	03/17/2018	04/02/2018	Nondetect
Agua Fria Spring	Spring	03/17/2018	Not retrieved	Inconclusive
HR Resurgence	Spring	03/17/2018	04/02/2018	Negative
PC Spring	Spring	03/17/2018	04/02/2018	Negative

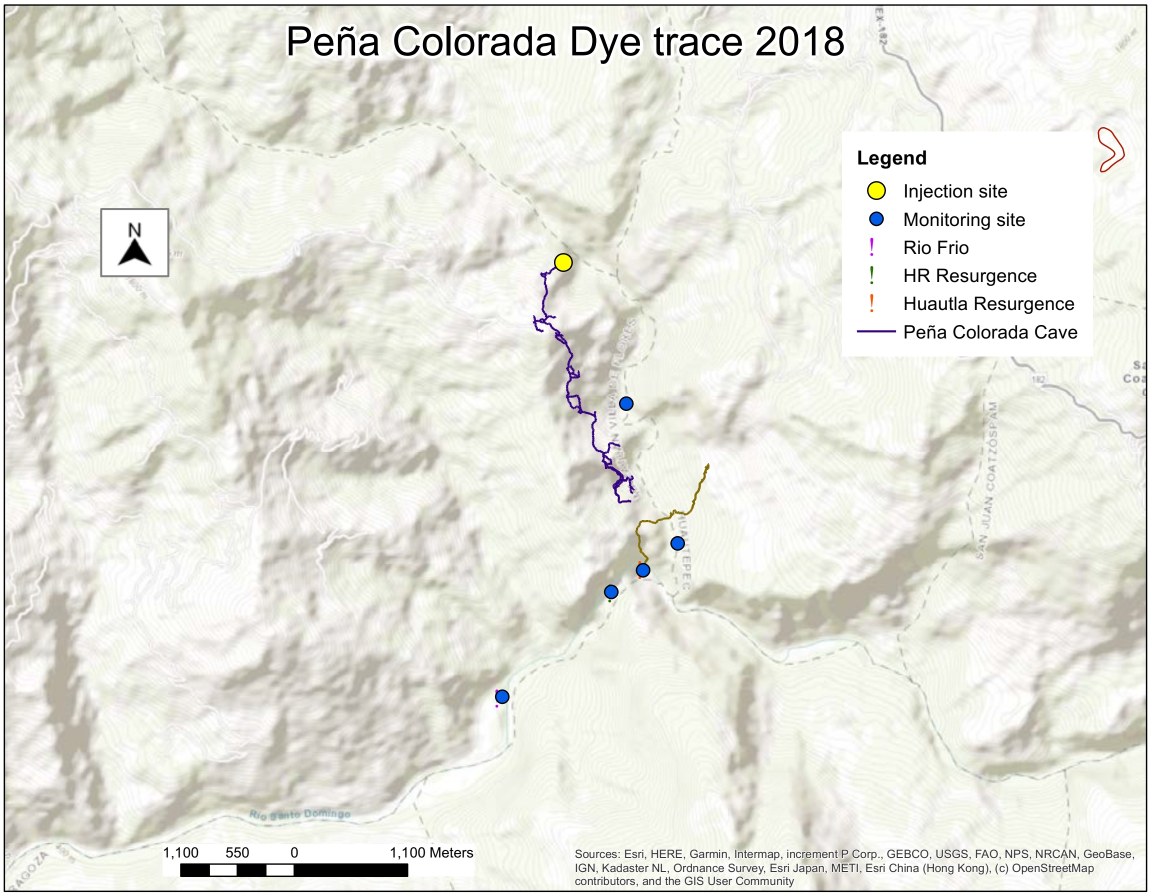


Fig. 4.1 Peña Colorada Dye trace (Map made by author).

On April 7, 2018 three pounds (~1.4 kg) of fluorescein dye were introduced by a team of experienced divers from Peña Colorada Dive Team into Sump 7 of Cueva de la Peña Colorada. The injection site was chosen due to the limited time the diving expedition had to assist with the trace and the long residence time the dye could possibly take traveling from Sistema Huautla to the springs and Peña Colorada in the dry season. The final stations selected for the monitoring of the dye trace were in the Peña Colorada Canyon upstream, Peña Colorada Canyon spring, Peña Colorada Canyon downstream, Sistema Huautla Resurgence, HR Resurgence, and Agua Fria Resurgence (Table 4.2). There were attempts to find other major springs in the area without success. The packages changeout was done once for the collection of the background receptor and once after the injection of the dye. Additional changeouts were not possible due to the diving expedition ending early. After collection, packets were stored in dark containers until transportation to the Crawford Hydrology Lab for analysis.

Table 4.2 Monitoring sites for Peña Colorada Dye trace (Source: Created by Author).

ID#	Site Name	Feature Type	Elev. (m)
001	Sistema Huautla Resurgence	Spring	345
002	HR Resurgence	Spring	320
003	Agua Fria Spring	Spring	380
004	Peña Colorada Canyon Upstream	Surface Stream	560
005	Peña Colorada Canyon Spring	Spring	540
006	Peña Colorada Downstream	Surface Stream	400

4.2.3 Plan de Escoba Dye trace

The focus of this dye trace was to delineate the norther boundaries of Sistema Huautla Karst Groundwater basin. The Plan de Escoba area showed prominent sinkholes in the topographic map and proximity to the speculated surface divide of the Sistema Huautla Groundwater Basin to the suspected hydrological drainage of Rio Petlapa. Upon inspection, there were no visible surface streams found in the area that could be used for an injection. Two major streams of water were found during the exploration of the Cueva Elysium by the PESH team; therefore, the injection was performed inside Elysium Cave in the stream near Camp Berta (Fig. 4.2), where the first stream was encountered trending south towards Sistema Huautla. The stream flowed for an approximately 300 feet (91 m) SW, until it disappeared in a sump that was inaccessible through exploration. The condition of the study was done under very dry conditions due to the lack of precipitation in the region. On April 24, 2019, sixteen pounds (7.25 kg) of powder fluorescein dye was introduced into the stream in Cueva Elysium outside the Camp Berta room area.

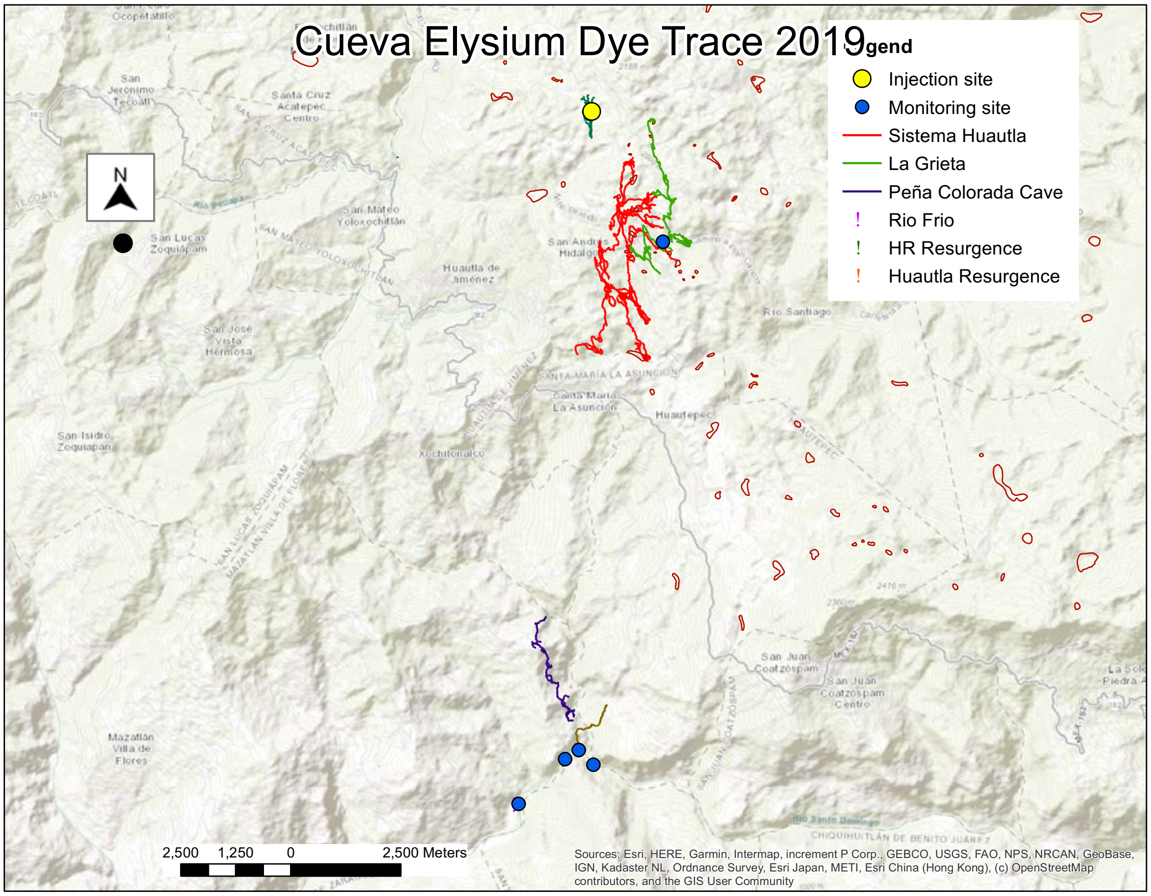


Fig. 4.2 Plan de Escoba Dye Trace (Source: Created by Author).

The sites chosen for monitoring and background (Tables 4.3, 4.4) were the same used in the previous year with the addition of the Puente de Fierro River site and Camp 4 inside La Grieta section of Sistema Huautla. The background receptors were placed between March 29 and April 4, 2019 (Figure 4.3). The receptor in the Elbow section/Camp 4 of La Grieta was collected on April 30, 2019, during the last trip to that section of the cave. The receptors were replaced on the May 7th and then collected again on May 23rd, 2019.

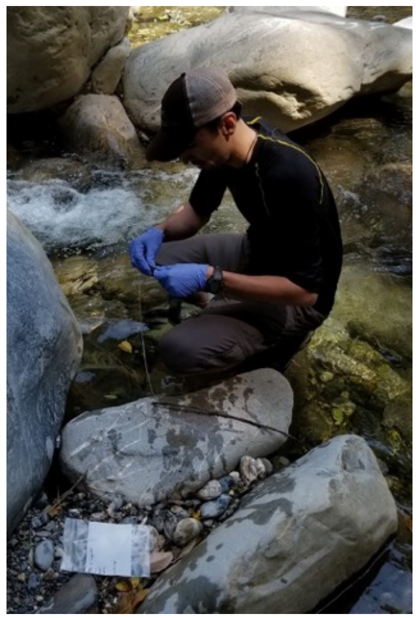


Fig. 4.3 Setting up charcoal packets in the Peña Colorado Canyon (Source: Author).

Table 4.3 Dye Injections in Sistema Huautla (Source: Created by Author).

Round of Injection	Date	Location Description	Coordinates	Elev. (m)
1:1	June 2018	Cueva de la Peña Colorada	W96.81682 N18.04385°	ND
1:2	April 2019	Plan de Escoba	W96.805122 N18.183581	1880

ND = not determined.

Table 4.4 Charcoal receptor monitoring sites (Source: Created by Author).

ID#	Site Name	Feature Type	Round	Elev. (m)
001	Huautla Resurgence	Spring	18/19	345
003	HR Resurgence	Spring	18/19	320
004	Agua Fria Spring	Spring	18/19	380
005	Rio Santo Domingo Upstream	Surface stream	2019	325
006	Rio Santo Domingo Downstream	Surface Stream	2019	320
007	Rio Santo Domingo Narrows	Surface Stream	2019	325
008	Peña Colorada Canyon	Surface Stream	2018	400
010	Camp 4 In-feeder	In-Cave Stream	2019	-

4.3. Rain Gauges

Two Texas Electronics TR525-USW (https://texaselectronics.com/products/rain-gauges/8-collector-rain-gauge.html) tipping-bucket rain gauges with Onset HOBO US-003-64 Pendant Event (https://www.onsetcomp.com/products/data-loggers/ua-003-64/) loggers were deployed in two areas of the Sistema Huautla Karst Basin to record precipitation (mm/10-min). The rain gauges were situated in the two extreme possible boundaries of the speculated groundwater system to obtain an average of the precipitation and temperature for different areas of the region (Fig. 4.4).

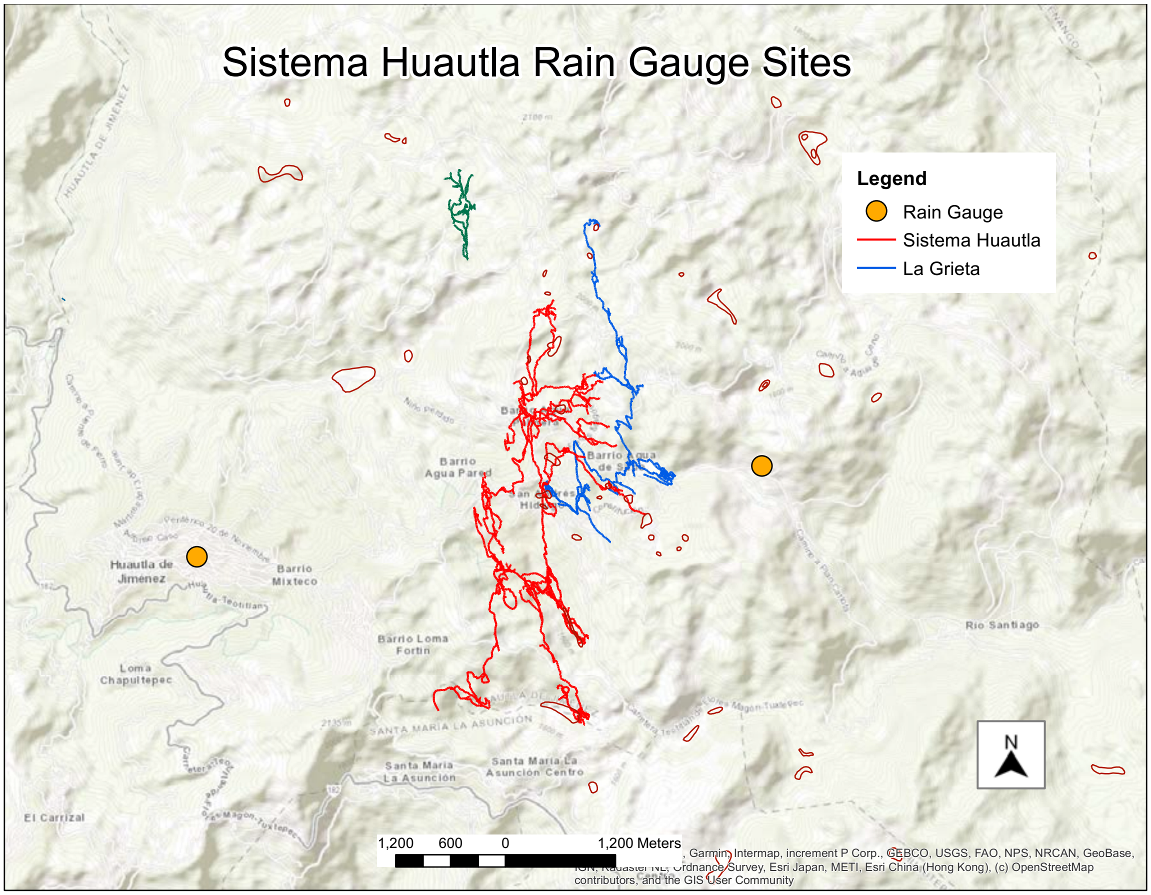


Fig. 4.4 Rain Gauges location in Sistema Huautla (Source: Created by Author).

The city of Huautla Rain Gauge #1 was situated on the roof top in the downtown area of the town. The building was the tallest building in its vicinity and no other building obstruct the precipitation from reaching the collector. The Plan Carlota Rain Gauge #2 (Fig. 4.5) was situated on the roof of a house in the town of Plan Carlota, very close to the speculated east boundary of the Huautla groundwater basin. It was also close to the entrance of La Grieta portion of the Huautla system, which was used in the study. The rain gauges were deployed for the months of February to May 2019.

Fig. 4.5 Rain gauge at Plan Carlota in the roof of the PESH basecamp (Source: Photo by Author).

4.4 Water Level and Specific Conductivity Monitoring

Onset HOBO U24-0011 conductivity data loggers (https://www.onsetcomp.com/products/data-loggers/u24-001/) were used to collect various physical and chemical parameters from spring outlets and in-cave streams at Huautla Resurgence, HR Resurgence Agua Fria, as well as in the La Grieta Cave stream (Table 4.5). Each data logger was anchored to the site inside a PVC stilling well bolted to the wall with multiple holes to allow water circulation. The PVC was installed to the bottom of the stream to provide accurate measurements of the water pressure. A cap was placed on the PVC and locked with a metal pin to secure the data logger to prevent flood pulses from detaching the data loggers.

In the first phase of the project in April 2018, two Onset HOBO UL20 pressure transducer measuring temperature (˚C) and barometric pressure (millibar, mbar) were deployed in La Grieta section of Sistema Huautla with the purpose of measuring the fluctuation of the water levels through the rainy season. Logger #1 was setup up near Camp 2 at 509 meters of depth. Logger #2 was setup on the upstream section of The

Refresher at 410 meters of depth. The loggers collected data points at 10-minute intervals until September 7, 2018. The pressure transducers captured the flood pulses from the rain events that happened in the northeast part of the system.

The location of the upstream logger was in the upper part of The Refresher in La Grieta section of Sistema Huautla, just before the Formation Room (Fig. 4.6, 4.7). It is a canyon passage with a pool of water with visible flow. On the walls there is evidence of sediment in higher areas, which means the passage has periodic fluctuations in the water levels from floods. The downstream logger location was in the lower part of the La Grieta section of the system before Mazateca Shores and the L-Room. It is a canyon passage with a sizable pool of water with visible flow.

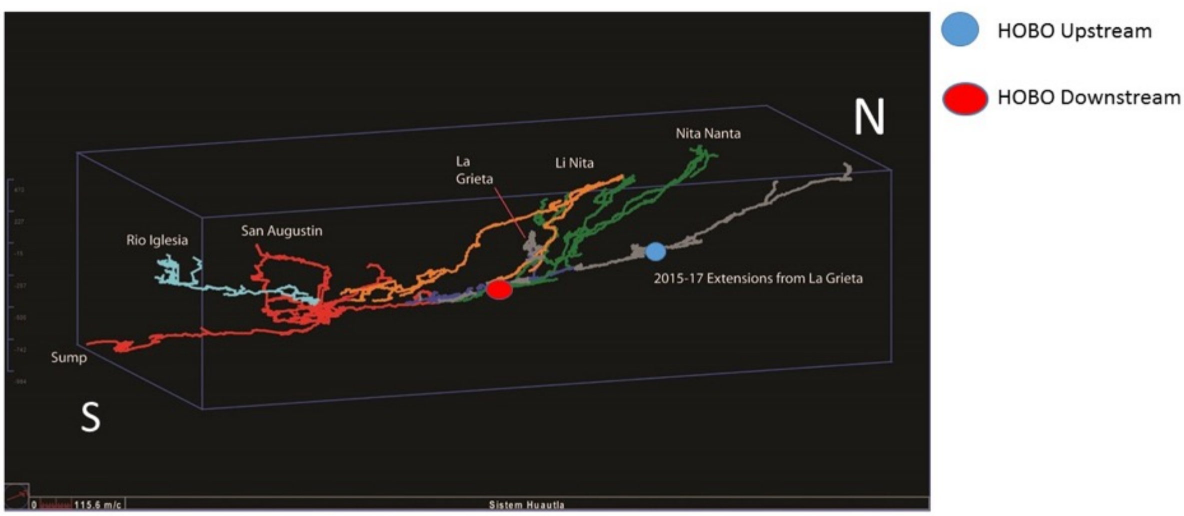


Fig. 4.6. HOBO UL20 Temperature/Pressure Placement in La Grieta, Profile View. (Modified map from Kambesis using COMPASS).

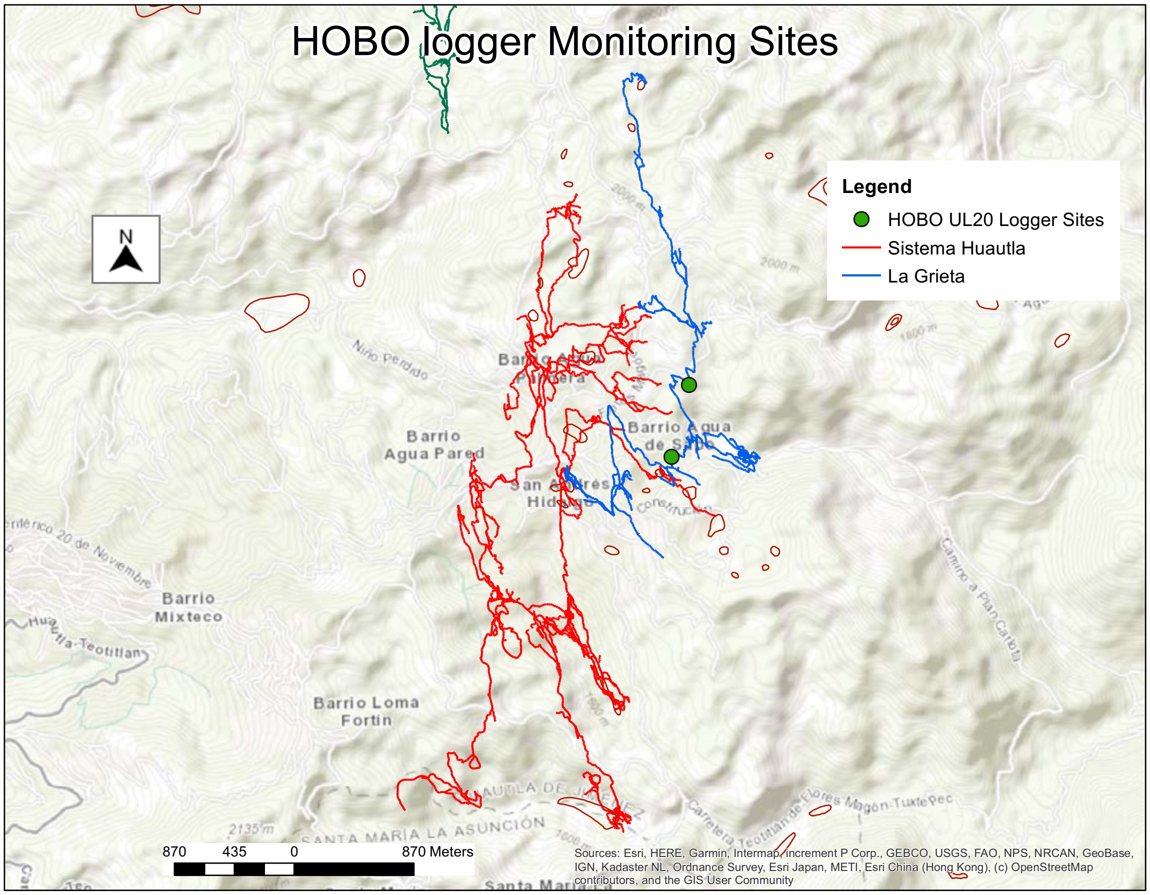


Fig. 4.7. HOBO UL20 temperature/pressure logger placement in La Grieta, Plan View. (Source: Created by Author).

The second phase of the study used four HOBO loggers that measured specific conductivity (SpC) in micro Siemens per centimeter (µS/cm), and three Onset HOBO UL20 pressure transducers in addition to the ones used on Phase 1. Three HOBO loggers measuring SpC were deployed at the three sites in springs that included Sistema Huautla Resurgence, Rio Frio Spring, and HR Resurgence (Table 4.5, Fig. 4.8, 4.9). A fourth logger that measured specific conductivity (SpC, µs/cm) was deployed in the downstream section of La Grieta from April 9 through April 29, 2019. The two HOBO UL20 loggers from 2018 study in La Grieta were downloaded and restarted through the duration of the expedition.

A HOBO UL20 pressure transducer was recording data from the dry entrance of HR Resurgence with the purpose of recording local environmental barometric pressure. The logger was placed in a hole in the wall next to the entrance of the cave.

Table 4.5 Location of monitoring sites for SpC/Pressure loggers (Source: Created by Author).

Name	Feature Type	Elevation (m)	Coordinates
Sistema Huautla Resurgence	Spring	295	W -96.814870 N 18.034510
Rio Frio Spring	Spring	314	W -96.827954 N 18.022208
HR Resurgence	Spring	306	W -96.82810 N 18.02395
Downstream Section La Grieta	Cave Stream	N/A	N/A

N/A= not available.

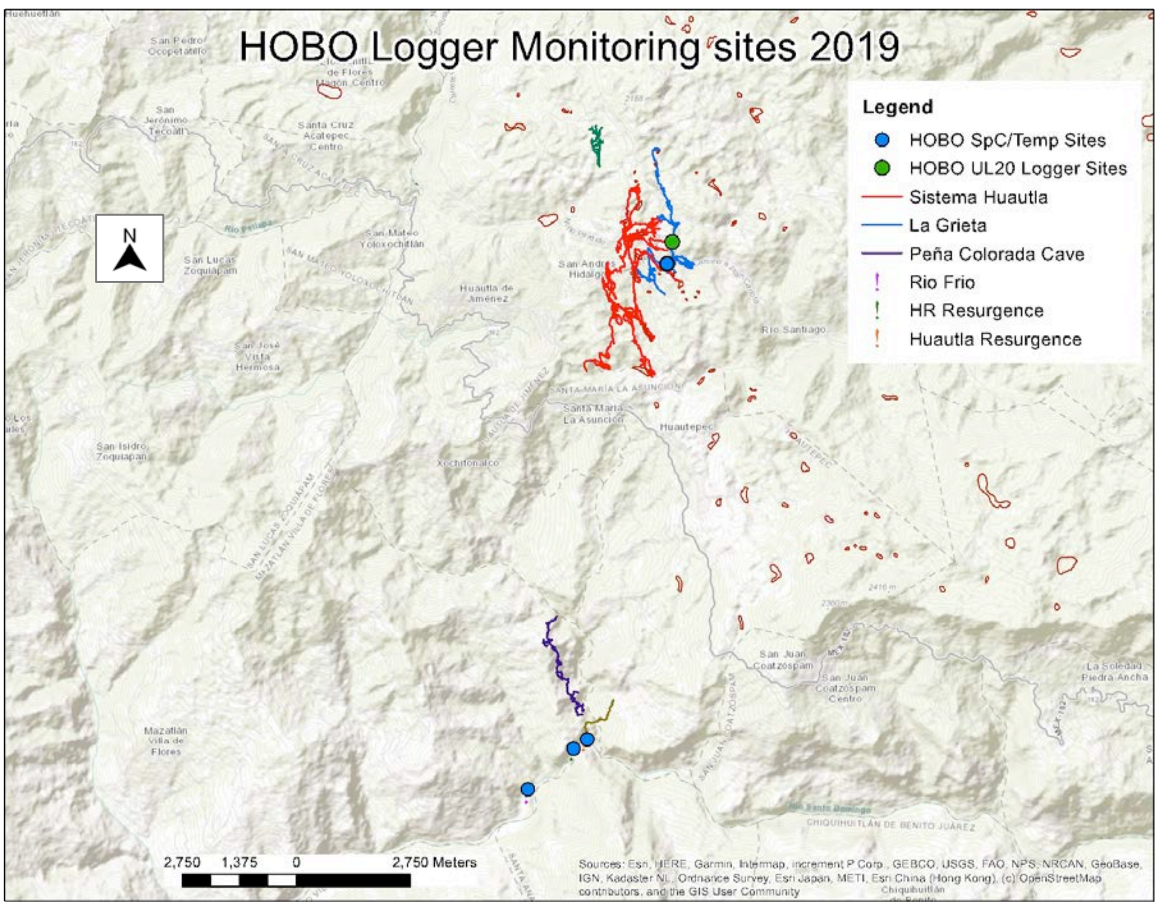


Fig. 4.8. HOBO logger Temp/Spc/pressure selected sites (Source: Created by Author).

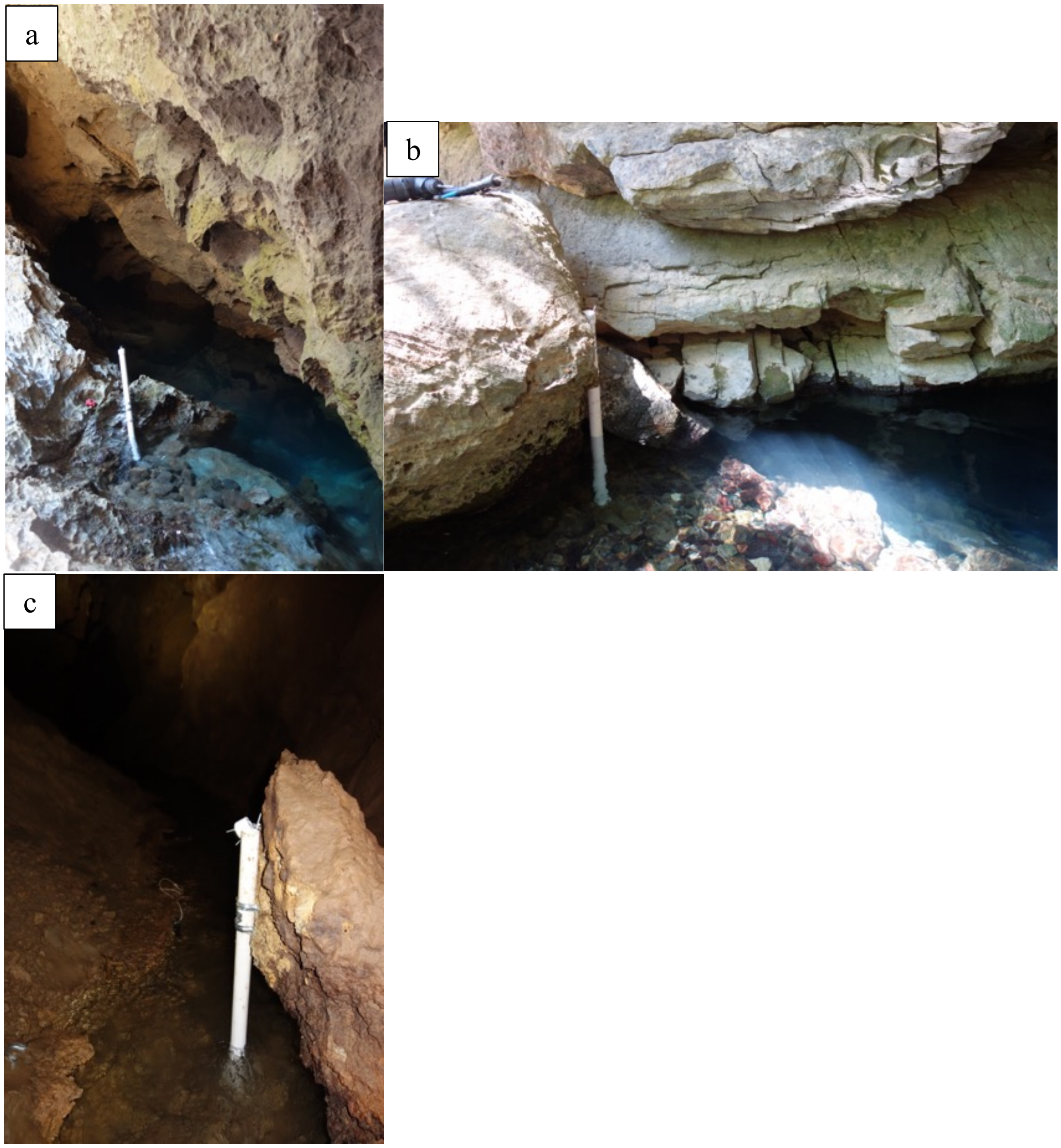


Fig. 4.9 a) Sistema Huautla Resurgence monitoring site; b) Rio Frio Spring monitoring site; and c) HR Resurgence monitoring site (Photos by Author).

4.5 Water Geochemistry

Water grab samples were collected from the springs approximately every two weeks from March to May 2019 and two rounds of in-cave sample collection occurred in April 2019 to be analyzed for cations (Mg, Ca). In-cave samples were collected on April 30, 2019, approximately uniformly from upstream to downstream during a single 24-hour period. The second collection was limited to only half the sites due to equipment malfunction.

The samples were collected in plastic 250 mL bottles in the field at each monitoring site. After collection, bottles were placed in coolers for transportation to the laboratory. Temperature (°C), specific conductivity (SpC, µs/cm), and pH measurements were taken with an Oakton PCTSTestr 35™ handheld device at the time of every grab sample collection and recorded in a field notebook at every site. The handheld device was calibrated before every field day using Oakton pH buffers of 4, 7, and 10 and the Oakton's internal autocalibrate function. All samples were collected following guidelines from the USGS National Field Manual for the Collection of Water-Quality Data (Wilde et al. 2015). The in-cave sites were distributed through the main stream passage of La Grieta cave to obtain a spatial characterization of the water, as displayed in Table 4.6 and Figure 4.10.

Table 4.6 Geochemical Sampling sites (Source: Created by Author).

Name	Feature Type	Coordinates
Sistema Huautla Resurgence	Spring	-96.814870 18.034510
HR Resurgence	Spring	-96.827954 18.022208
Rio Frio	Spring	-96.82810 18.02395°
La Grieta Upstream	In-Cave Stream	N/A
La Grieta Downstream	In-Cave stream	N/A

NA = not available (due to flooding).

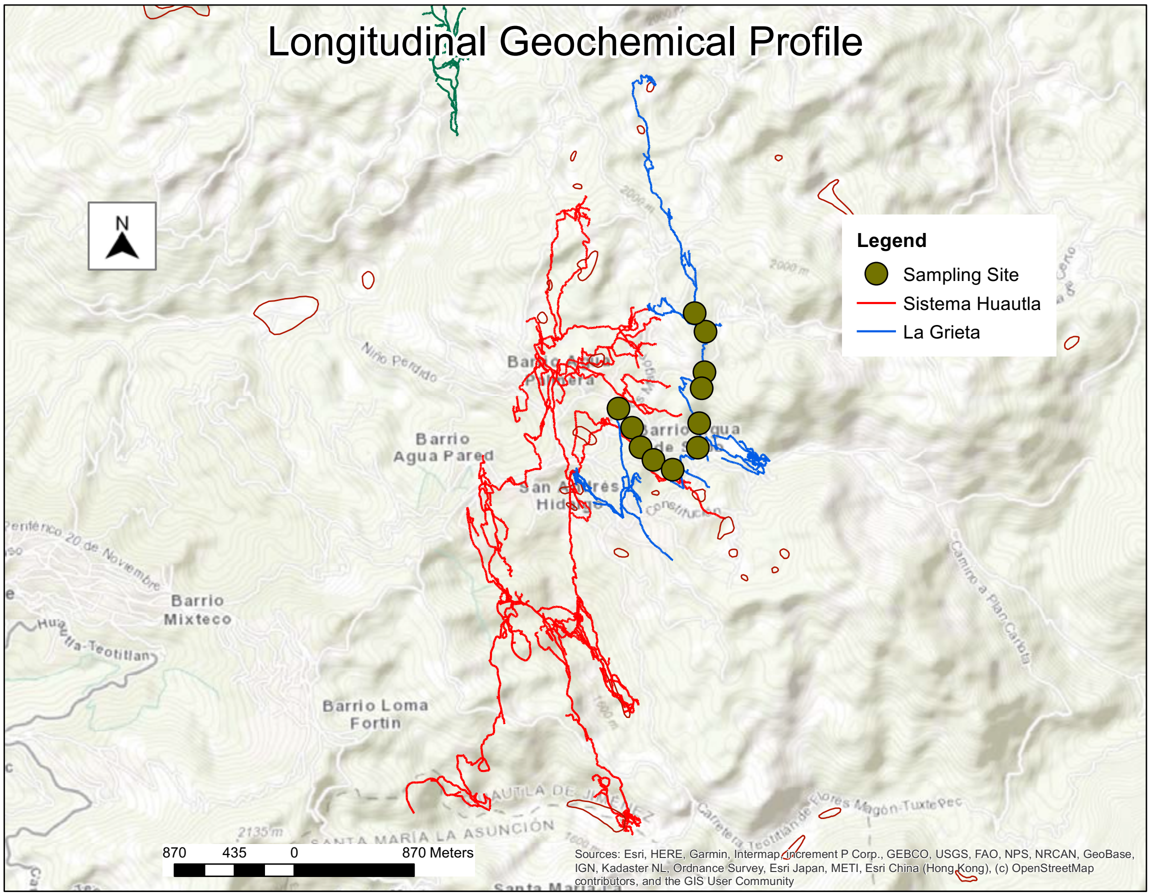


Fig. 4.10. Geochemical sampling selected sites (Map created by author).

Water samples were analyzed at the HydroAnalytical Lab at Western Kentucky University (WKU). Cation concentrations of magnesium (Mg^{2+}) and Ca ($^{2+}$) were determined using inductively coupled plasma emission spectroscopy (ICP-OES) following EPA Method 200.7 revision 4.4 using a Thermo Scientific ICAP 6500 ICP-OES). This instrument provided concentrations in parts per million (ppm) and results were reported equivalently as mg/L.

4.6 Data Analysis

All collected logger and grab sample data were organized and underwent quality control to remove erroneous points and ensure consistency in presentation. Origin Lab's Origin Pro software was used to create time-series graphs of the logger data and grab sample geochemical data plotted against time. Dye trace data were plotted in ArcGIS to determine potential flowpaths and connections. Final data analysis included visual and quantitative comparisons between sites for hydrogeochemical similarities and differences based on the graphed parameters and table values.

Chapter 5: Results and Discussion

Over two years of field seasons in 2018 and 2019, in coordination with cave exploration and survey expeditions, fieldwork was conducted to complete two dye traces, water level and geochemistry monitoring, and geochemical water sampling both at input and output sites and longitudinally along the newest vertical extent of Huautla in order to improve understanding of the flowpaths, geochemical evolution of recharge, and processes related to cave formation in the SHKA. Each of the methods produced results that built upon existing knowledge of the recharge area, connectivity, flowpaths, and geochemical evolution of the water within Sistema Huautla toward better understanding of its geomorphic evolution and speleogenesis.

5.1 Water Level Monitoring and Dye Tracing 2018

5.1.1 Cueva de la Pena Colorada Dye trace

The dye tracing in the first round done in April of 2018 was focused on establishing a connection between Cueva de la Peña Colorada and the springs along the north wall of the Rio Santo Domingo, which include Rio Frio, HR Resurgence, and Sistema Huautla Resurgence. The trace was conducted to understand the relationship between the old phreatic cave passaged in higher elevation canyons and walls in Santo Domingo canyon to the current baselevel of the groundwater. Fluorescein was injected in the Cueva de la Peña Colorada's Sump 7, which was observed to have active flow during the 1984 Peña Colorada expedition. In the previous studies done by Smith (1994), Sistema Huautla was connected to Sistema Huautla Resurgence, but the traces conducted in the other springs, including Cueva de la Peña Colorada, were negative (Table 5.1). The receptors were collected 20 days after injection with just one swap of receptors after the injection due to political and logistical issues. The heavy rainfall that occurred during, and prior to, the trace helped flush the dye through the cave.

Table 5.1. Results for Peña Colorada Dye trace (Source: Created by Author).

ID#	Site Name	Feature Type	Result	Distance from injection
001	Sistema Huautla Resurgence	Spring	Positive	3.3 km
002	HR Resurgence	Spring	Positive	3.5 km
003	Agua Fria Spring	Spring	Positive	4.2 km
004	Peña Colorada Canyon Upstream	Surface Stream	Mild Positive	300 m
005	Peña Colorada Canyon Spring	Spring	Negative	200 m
006	Peña Colorada Downstream	Surface Stream	Positive	400 m

The dye trace results (Table 5.1) support the hypothesis proposed by Smith (1994) that suggested Peña Colorada cave was hydrologically connected with Sistema Huautla's hydrologic flowpath somewhere along Sump 7. The connection also creates a stronger case to support the theory of Smith (1994) that Cueva de la Peña Colorada and Vine cave are part of the older water table of Sistema Huautla, which was abandoned as base level lowered due to the uplift of the Sierra Madre Oriental. The dye trace connection of Cueva de la Peña Colorada and the Sistema Huautla Resurgence is likely tied to the formation of the Peña Colorada Canyon in a major reverse thrust fault, as observed by Smith (1994) in aerial photos and geologic interpretation.

The dye trace connected the hydrologic pathway to two other major springs in the north wall of Rio Santo Domingo; Rio Frio and HR Resurgence, as well as the stream in Peña Colorada Canyon. Rio Frio and HR Resurgence lay west and upstream of the Sistema Huautla Resurgence. Rio Frio is 1.5 km to the southwest coming from the center of an anticlinal fold, which is associated with the nearby Armadillo canyon (Smith 1994).

HR Resurgence is 0.5 km up on the narrow and steep walled section of Rio Santo Domingo, just west the old fossil cave of The Narrows. The springs both have been explored by cavers and divers. The sumped section of Rio Frio was not explored because of low visibility, but all the sumps trend deeper into cave as observed during exploration. Smith (1994) theorized a possible lower level of cave development from the active hydrological flow, due to some of the speleothems that were found in some caves at deeper level. The change in baselevel is likely associated with neotectonics and river aggradation, which might have brought the river level back up and offset slow incision. Further dives and exploration in Rio Frio would be essential to understand the possibility of deeper levels, along with seepage runs in the Santo Domingo River to identify additional inputs. HR Resurgence was not mapped during the study, but it was visited during the dye tracing. The cave showed two distinct levels of development, but the flow of the water was minor. Inspection of the sump indicates the water comes from a sand bank, which makes further exploration impossible. The sand bank might be indicative that the cave does not react very much to rain events, or was deposited during a major flooding, or backflooding, event and has remained for some period of time.

Smith (1994) proposed the western boundary of the system in the lower area of the springs to be somewhere along a thrust fault located 1.5 km to the west of Peña Colorada and to the east of Rio Frio. According to the recent dye trace performed in this study, this extends the hydrological basin towards Rio Frio (Fig. 5.1).

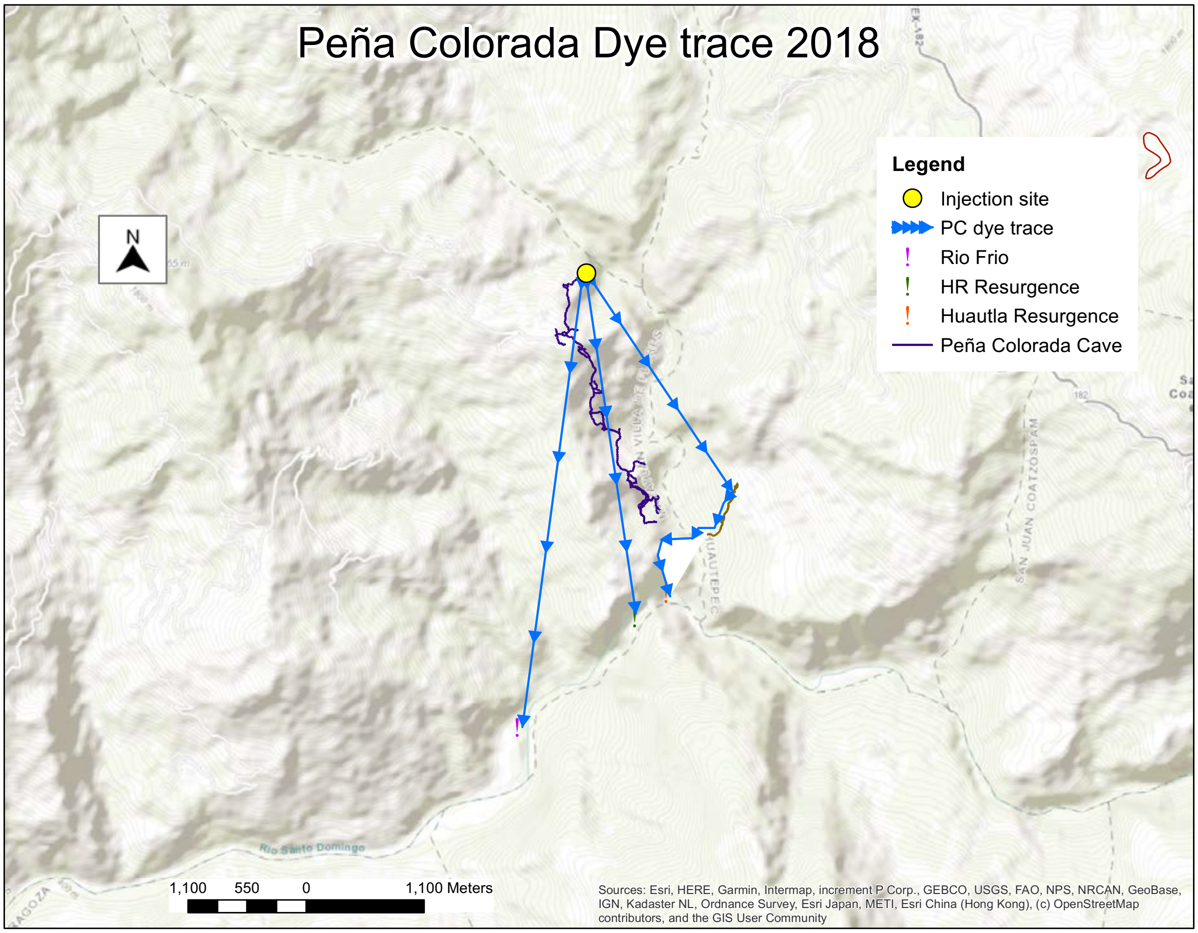


Fig. 5.1 Hydrological pathways observed during the dye tracing of Cueva de la Peña Colorada (Source: Created by Author).

The connection of Pena Colorada to the upstream portion of Sistema Huautla supports the idea of a complex spring system related to the phreatic part of the aquifer. The connection was done under heavy precipitation events, which likely promoted water table rise and overflow into interconnecting conduits with other springs. Dye detection from multiple springs indicates discharge is through a distributary conduit system instead of a single conduit. The fossil water table most likely had more karst development and interconnectedness between the springs presented in the vicinity of Sistema Huautla Resurgence in the north wall of Rio Santo Domingo. As baselevel lowered to the current elevation, the basin likely subdivided into smaller drainage areas. The divided basins most likely drain different elevations of the Sierra Mazateca to outlet springs, and from differing water sources during low flow, as indicated by the different temperatures and varying SpC values between them as discussed below. As rain events bring flood pulses, there is presumably internal drainage flowing through overflow passages providing more aggressive water to nearby springs based on the dye trace connections.

The lowering of the water table was hypothesized by Smith (1994) to be caused by the denudation of the caprock covering the recharge zone, changing the hydraulic gradient of the recharge zone. The hydraulic gradient, in combination with soluble rock at the base of the aquifer, as observed in Cueva de la Peña Colorada, and a series of faults, likely led to the lowering of the water table. In the process of lowering the water table, the water followed distinct faults, including the one present in Peña Colorada Canyon and the one mentioned by Smith (1994) to be 1.5 km to the east of PC Canyon, which could be associated with HR Resurgence and the one forming Rio Frio (Fig. 5.1). Still, there is the question of the origin of the water for Rio Frio and HR Resurgence during baseflow, which is discussed later.

5.1.2 Flood Response

During the dye trace in 2018, an unusual precipitation event occur that changed the hydrologic conditions in the cave drastically. The water rose dramatically in the Cueva de la Peña Colorada and in Sistema Huautla. Cave divers in Cueva de la Peña Colorada involved in the exploration observed the water rise unexpectedly in a matter of hours, as they became trapped in the cave for 69 hours (Peña Colorada Report 2019). The estimated elevation of the water table was from 10 – 15 meters from the normal baselevel. The cavers were transporting equipment through the sumps, when water unexpectedly rose, trapping them in the Whacking Chamber (Fig. 5.2). A lot of the equipment that they had disappeared in the flooding event and was not found on their dives on the sumps (Peña Colorada Report 2019).

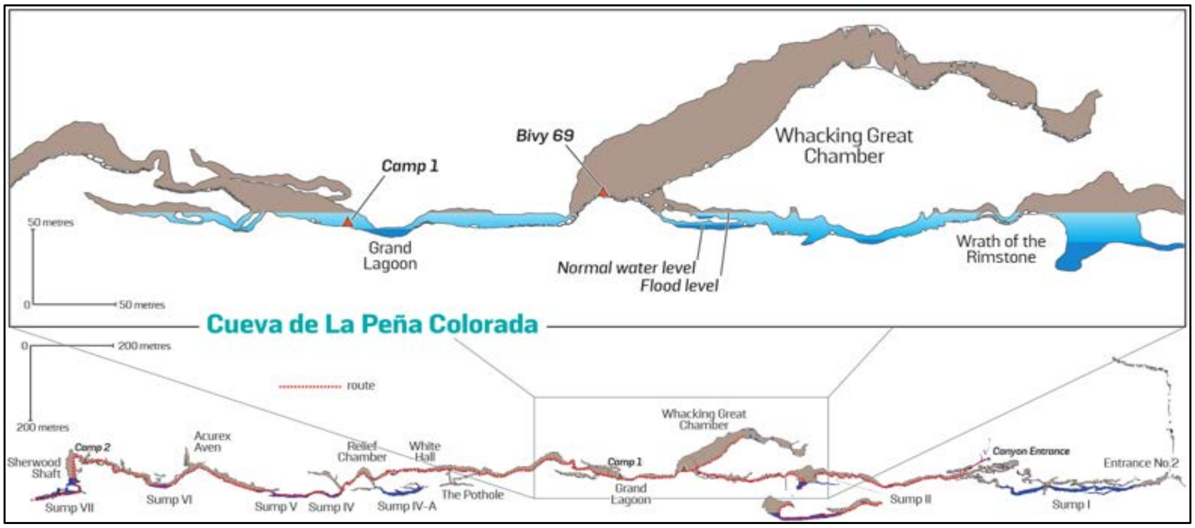


Fig. 5.2 Location of sumps and flooded area during 2018 expedition (Peña Colorada Report 2018).

Flooding events play an important role in speleogenesis by introducing aggressive water into the system that promotes dissolution (Palmer 2001). Even though big rain events only represent a small part of the hydrologic year, they can produce most of the dissolution occurring in caves (Groves and Meiman 2005). It is important to understand how many of these major events occur in a yearly basis on the system and how long the water remains in the system to better characterize the geomorphological processes caused by aggressive allogenic water. Highly vertical cave systems, such as Huautla, differ than lower relief systems, due to the velocity at which the water can move through the system, thus affecting its dissolution potential to be less because of shorter rock-water contact time (Palmer 2007).

To understand the fluctuations associated with heavy precipitation, the HOBO loggers were placed in two sections of La Grieta in the upstream area of the cave to record water level information from April 12, 2018 to September 7, 2018 (JD 100) (Fig. 5.3).

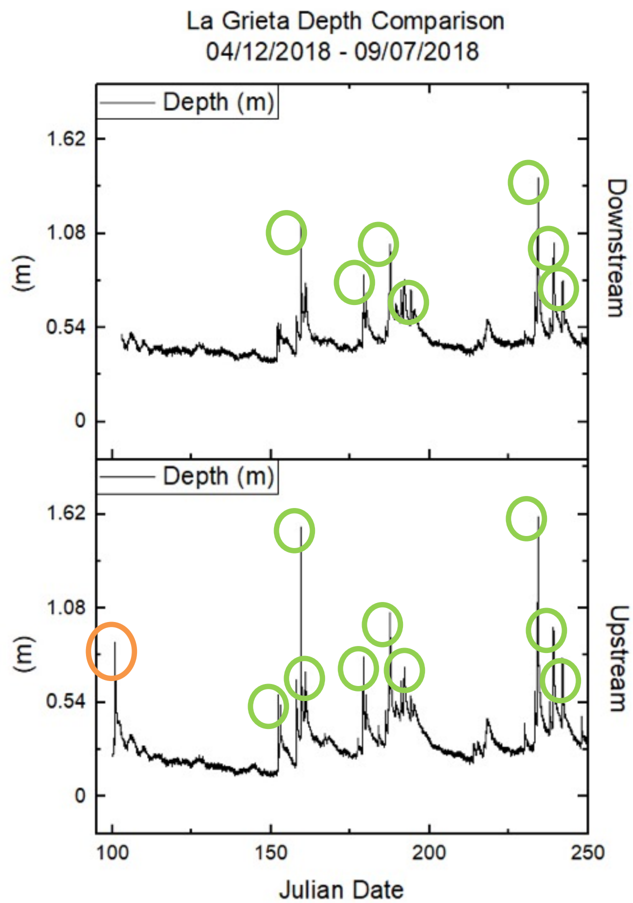


Fig. 5.3 La Grieta water level for the rainy season. In orange is the event observed by the divers, green circles denote other major events (Source: Created by Author).

There were ten large, measurable storm events during the installation of the HOBO during the month of April to early September. The month with most precipitation in the study was June to mid-July. The stations show a mirrored effect with Upstream having a higher magnitude in the height of the water. The event in orange in Figure 5.3

correlated with the precipitation event that was experienced in-cave by the divers. The downstream graph does not show the event, because the cave had to be evacuated due to flooding after the installation of the first logger so it the downstream logger was not yet collecting data at the time of the flooding.

The system presents rapid movement of water through the vadose zone. The flood pulses last approximately three to five days, during which water rises up to a meter in just hours in some events. The time the flood water resides in the system for most of the events is similar to the amount of time that water resided in the Cueva de la Peña Colorada. The similar responses to the rain from La Grieta passages in Sistema Huautla and Cueva de la Peña Colorada adds to the dye tracing results indicating the connection of both caves. The flow of Sistema Huautla Resurgence and Rio Frio was also observed to be very high during the dye receptor exchange, even five days after the rain event.

The rapid recession curves of the system (Fig. 5.4) indicated that water is moving very fast through the system and pulses do not reside long in the vadose section of the cave. This likely indicates less temporal dissolution in the higher elevation passages compared to the baselevel, phreatic portions due to residence time. Nevertheless, during June – July the water seems to accumulate due to the high amount of precipitation and the water level does not return to its original baseflow. This presents the time of possibly the most dissolution on the vadose section on the system as new aggressive water is being introduced constantly to the system and the residence time is increased. Nevertheless, overall, in the system dissolution might be occurring most prominently at baseflow, because the residence time of the water increases at that elevation, with a steady input from the highly vertical vadose zone above, giving it more time to dissolve bedrock and influence cave development.

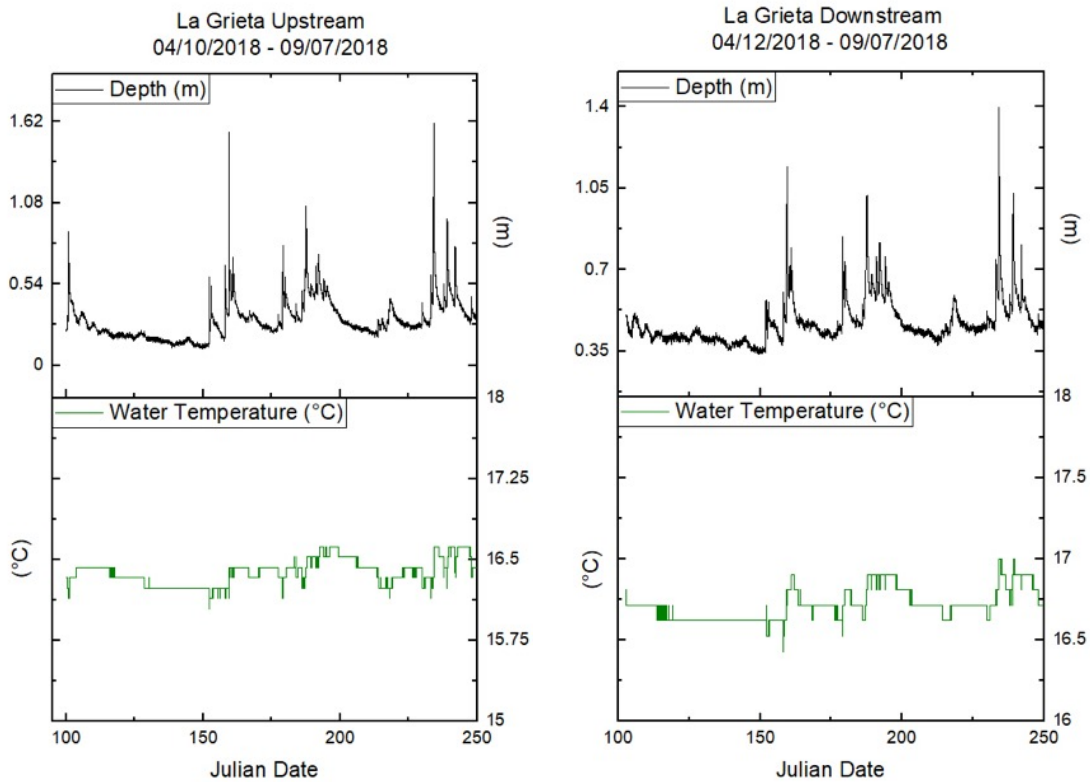


Fig. 5.4 Hydrographs of La Grieta storm pulses from 04/10/2018 – 09/07/2018 on downstream and upstream sites (Source: Created by Author).

5.2 Water Level Monitoring and Geochemistry 2019

During the second phase of the project, HOBO loggers were used to obtain geochemical data and grab samples were collected for cations for the springs that were connected to Sistema Huautla in the dye trace from Cueva de la Peña Colorada and longitudinally from sites in the La Grieta section of Sistema Huautla. The meteorological conditions were different than in 2018, as it proved to be a very dry year. The main part of this phase of the study was performed between April and June 2019, during a period that experienced very little cumulative rain.

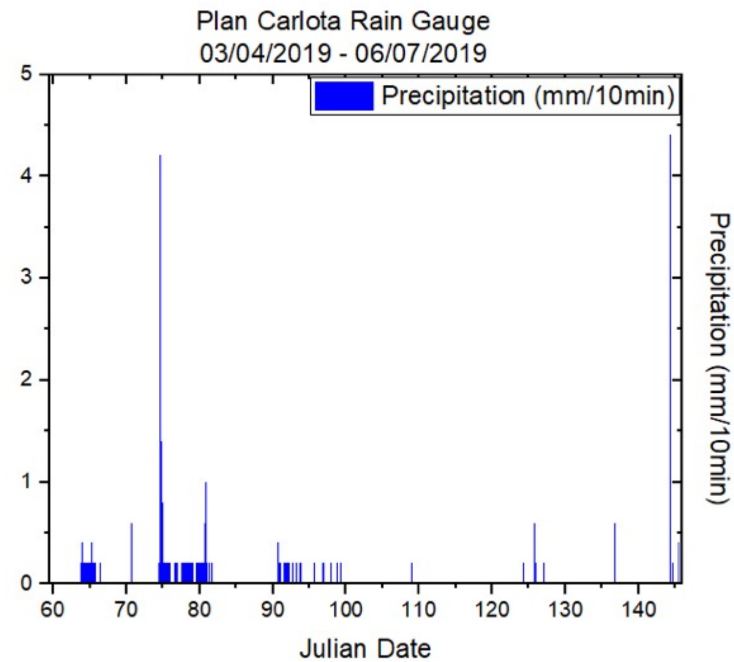


Fig. 5.5 Precipitation in recharge zone of Sistema Huautla Karst Groundwater Basin (Source: Created by Author).

5.2.1 Sistema Huautla Resurgence

In Figure 5.6, the SpC slowly increases as water level is declining due to the longer contact time with rock, therefore suggesting increased dissolution. Pulses occur during rain events, with SpC increases likely indicating storage water being pushed out of the system, or alternatively highly saturated water from aggressive dissolution as the water flowed through the vadose zone. The increase in temperaature could indicate the latter is more likely. Ten days prior to the installation of the logger, there were significant rain events in the recharge zone. The rain gauge marks events of up to 12.7 cm of rain over the course of five days. The decreasing trend of depth alongside the increasing SpC might be due to the system trending back slowly into baseflow. The pH of the spring was measured during grab sampling and was consistently measured around 7.76.

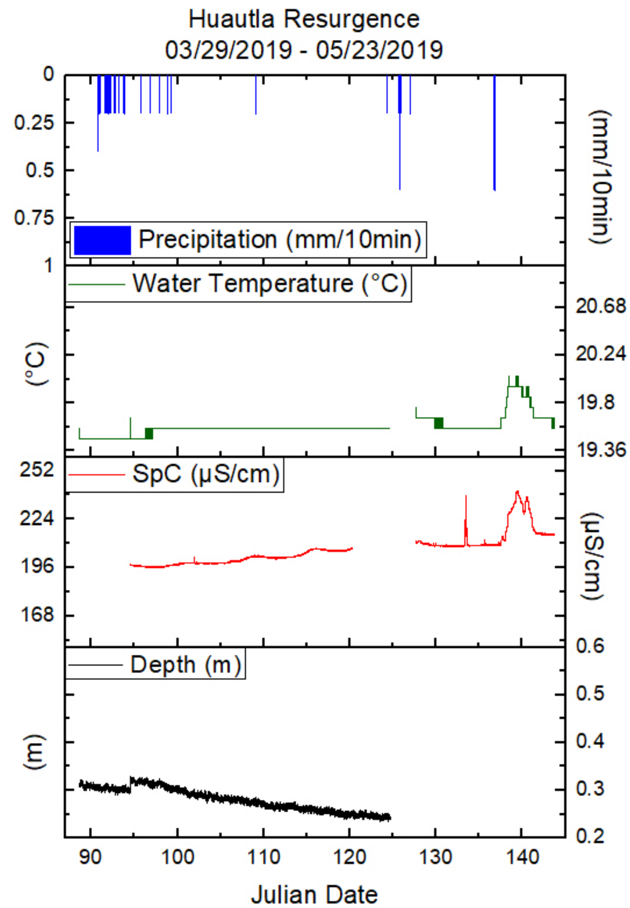


Fig. 5.6 Sistema Huautla Resurgence geochemistry data and water level obtained using HOBO loggers (water level data collection ended prematurely on JD 125 due to equipment access issues) (Source: Created by Author).

On May 16 (JD 137, Fig. 5.6), there was a substantial rain event that created a spike in SpC and temperature. Most likely the rain event pushed some of the storage water that resided in the system for longer periods and created a piston effect, where higher SpC value water was pushed out of the system ahead of meteoric water. Overall, the SpC values are low and consistent through the months of monitoring (Table 5.2), which means the responses on the system are only during significant recharge events.

Table 5.2 Sistema Huautla Resurgence grab sample data (Source: Created by Author).

Sistema Huautla Resurgence Grab Samples						
Date	**Time**	**pH**	**Temp (deg C)**	**SpC (µS/cm)**	**Calcium (mg/L)**	**Magnesium (mg/L)**
3/29/2019	1:05 PM	7.75	19.4	195	36.46	2.675
4/4/2019	1:10 AM	7.76	19.9	206	ND	ND
5/7/2019	1:45 PM	7.77	19.5	197	37.04	3.009
5/14/2019	3:00 PM	7.7	20.8	215	41.98	3.378
5/23/2019	1:47 PM	7.68	20.9	220	40.08	3.146

ND = no data due to no sample collected

5.2.2 HR Resurgence

HR Resurgence showed little variability in any of the parameters and only minor responses to any of the rain events presented in the month of May 2019 (Fig. 5.7). The low variability of temperature and SpC of the spring might suggest that recharge is influenced by high fracturing and poor karstification, causing a more diffuse flow behavior (Baena et al. 2009) and primary conduits being the main flowpaths. Alternatively, it could mean that the system is locally recharged during baseflow conditions and not as responsive to rainfall events outside the primary basin. Having a lower gradient and recharge area would account for the higher SpC and temperature values and lower flow during storm events that are not directly in the basin. As observed in the Sierra de las Nieves karst aquifers, springs with high variation in flow present high variation in hydrological parameters, which is not the case here compated to Sistema Huautla Resurgence. This comparative understanding provides insight into the regular behavior of HR Resurgence during most of the season.

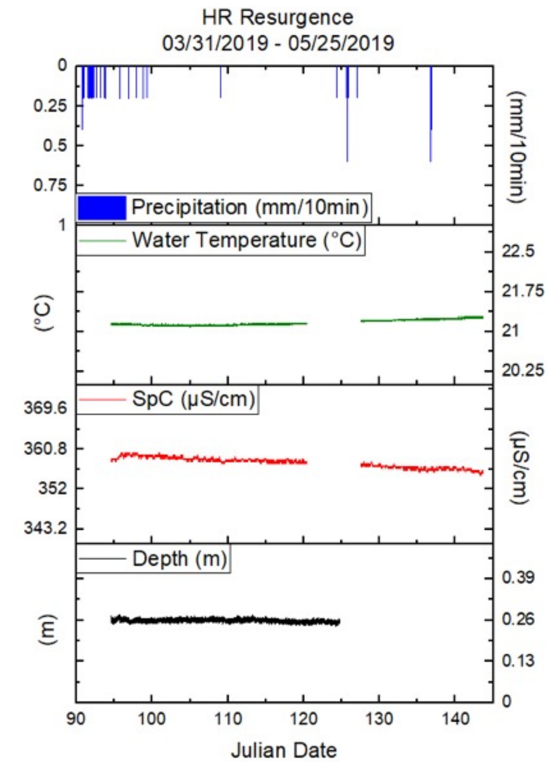


Fig. 5.7 HR Resurgence geochemistry data and water level obtain with HOBO loggers (Source: Created by Author).

HR Resurgence's temperature is the highest of the three springs (Fig. 5.7), meaning the source is likely different in elevation than HR Resurgence, or the water reaches thermal equilibrium at that elevation due to longer residence time. Table 5.3 indicates stable geochemical parameters during grab sampling and a much higher SpC than most sites, with a large amount of dissolved Ca, further supporting the suggestion of this being baselevel storage water moving more slowly in the system at lower gradients and elevations.

Table 5.3 HR Resurgence grab sample data (Source: Created by Author).

HR Resurgence Grab Samples						
Date	**Time**	**pH**	**Temp (deg C)**	**SpC (µS/cm)**	**Calcium (mg/L)**	**Magnesium(mg/L)**
3/27/2019	12:45 PM	7.4	22.2	380	67.62	5.693
3/29/2019	10:00 AM	7.35	22.2	392	63.94	5.548
4/4/2019	4:00 PM	7.35	21.6	390	62.56	5.289
5/14/2019	2:35 PM	7.34	22.6	371	61.57	5.233
5/23/2019	11:23 PM	7.27	22.3	377	64.43	5.419

5.2.3 Rio Frio Spring

The Rio Frio spring is the most western spring connected to the Sistema Huautla Groundwater Basin. The site was vandalized during the study, so little information was able to be obtained from the loggers, which were stolen. Rio Frio presented a stable temperature and depth during the six days that the logger was active (Fig. 5.8). The temperature in the spring is higher than HR Resurgence and lower than Sistema Huautla Resurgence Huautla. The SpC obtained during grab sampling is similar to HR Resurgence (Table 5.3), suggesting a higher rock and water contact time and similar baseflow source and behavior.

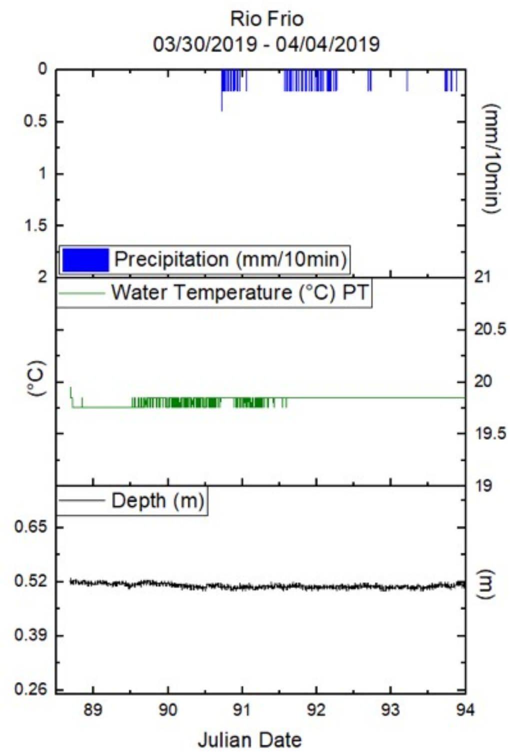


Fig. 5.8 HR Rio Frio geochemistry data and water level obtain with HOBO loggers (only five days of data available) (Source: Created by Author).

Most of the dissolution occurring in this cave is likely happening during overflow connections and backflooding in big precipitation events, where fast moving, allogenic water from the Sistema Huautla drainage is introduced into the basin of the slow-moving springs. The high karstic development presented in the caves could not be explained by the low hydrologic flow, especially by the slow and non-aggressive water present in the springs during most of the year. Fernandez and Pedrabuena (2012) observed similar karstic evolution in Picos de Europa caves. They observed a similar scenario, in which a retreating non-karstic caprock concentrated the hydrological recharge to certain flowpaths. As the caprock retreated completely, many of the old phreatic pathways were abandoned as smaller basins formed as the landscape became more mature. The separation of the hydrologic paths of Rio Frio and HR Resurgence and Sistema Huautla might be associated with the change in water table as the caprock retreated and exposed the karstic rock in the drainage basin.

Table 5.4 Rio Frio grab samples (Source: Created by Author).

Rio Frio Grab Samples						
Date	**Time**	**pH**	**Temp (deg C)**	**SpC (µS/cm)**	**Calcium (mg/L)**	**Magnesium (mg/L)**
3/29/2019	4:20 PM	7.56	21.4	337	45.12	6.587
4/4/2019	3:30 PM	7.53	20.8	342	51.21	7.487
5/7/2019	12:20 PM	7.56	22.8	379	49.37	8.206
5/14/2019	11:25 AM	7.65	21.3	397	49.77	7.7
5/23/2019	10:26 AM	7.6	22	327	50.71	7.579

The data compiled from the HOBO loggers and grab samples (Table 5.4) also suggest that the Huautla Resurgence has very similar characteristics to de in-cave sites, while Rio Frio and HR Resurgence show very different characteristics. The Huautla Resurgence is likely directly fed by the cave site through vadose recharge. The spring reacts constantly with any of the fluctuations shown in the cave by rain events. In comparison, Rio Frio and HR Resurgence do not show any of this characteristic, suggesting the source of the springs at baseflow is more localized and not coming directly from the main cave system. The morphology of the springs represents that of a phreatic loop passage, which is represented by low fissure frequency and low geochemical variability (Palmer 2007). When rain events happen, water homogenizes and the flowpath of the springs comes from the same source (Huautla), creating a distributary spring system with multiple outlets on the Santo Domingo.

Without a study during the rainy season, is difficult to corroborate that hypothesis, but it is likely that during wet seasons there is high increase in daily intense rainfalls. During this stage, water in the springs will likely have lower Ca and Mg values, higher velocity as piston flows, as seen in the hydrographs presented from the wet season months (Fig. 5.4), which would increase the amount of flow in the springs.

Comparison of the SpC data from the three outlets (Fig. 5.9) clearly indicates the similarities between La Grieta and HR Resurgence, which provides further proof of the primary source of discharge in Huautla Resurgence being the modern flow of Huautla, while the higher SpC values found at HR Resurgence and Rio Frio indicate longer residence time flowing at lower gradient that have dissolved more bedrock and are only connected as overflow/interflow outlets during extreme flooding events. Temperature profiles behave in a similar fashion and support the interpretation of the SpC data in indicating that Huautla Resurgence and Sistema Huautla (La Grieta) are connected hydrologically and with fairly fast flowpaths given the values of SpC and similarities between them, despite the distance the water travels.

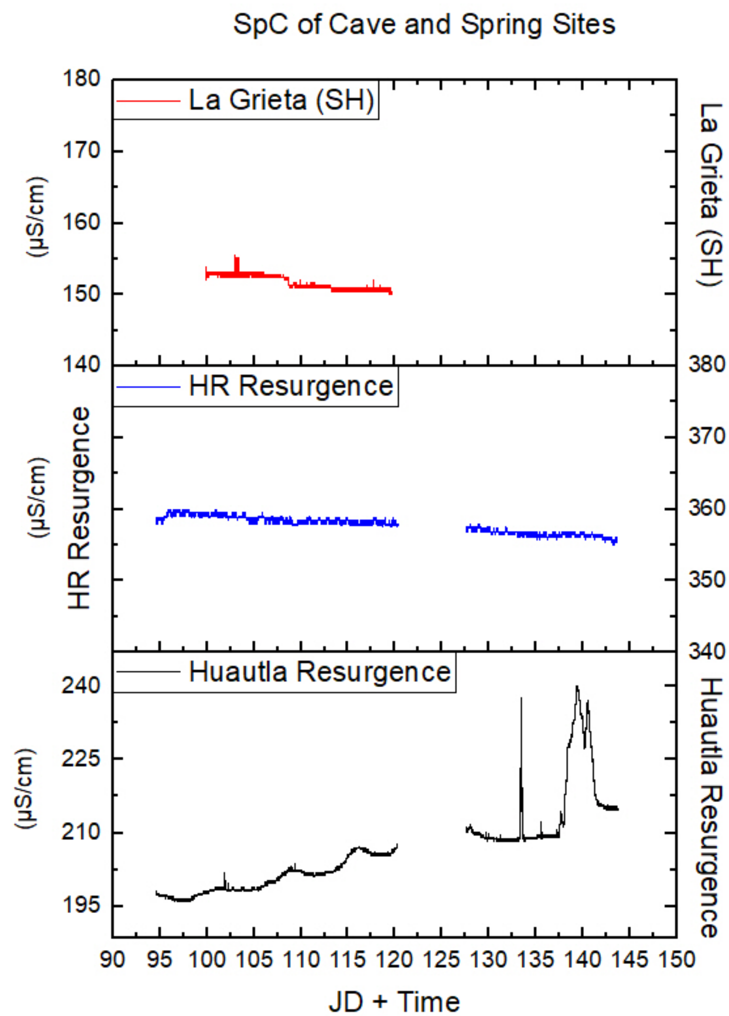


Fig. 5.9 Stacked graph of SpC at monitoring sites (Source: Created by Author).

5.2.4 La Grieta (in cave)

Figure 5.10 indicates the La Grieta Downstream site had low SpC values in the range of 152-153 uS/cm with a maximum spike of 156. These numbers indicate that not much dissolution is occurring, likely because water still is moving fast through the system even during low flow, but the potential for dissolution is high. The low stage properties are due to the high relief of the system, which likely also influence the low

SpC values. This suggests that the system is dominated more by turbulent flow, rather than slower vadose flow like in less vertical systems, such as Mammoth Cave, for example (Palmer 2007). The turbulent nature of the flow keeps the water moving through the cave and aggressive, which can create more cave development at depth as velocity slows down when reaching lower elevation passages and increases contact time with the rock. Most of the development at baseflow is likely occurring at the vadose and phreatic contact zone based on the SpC values (Fig. 5.6, 5.7, 5.8, 5.9).

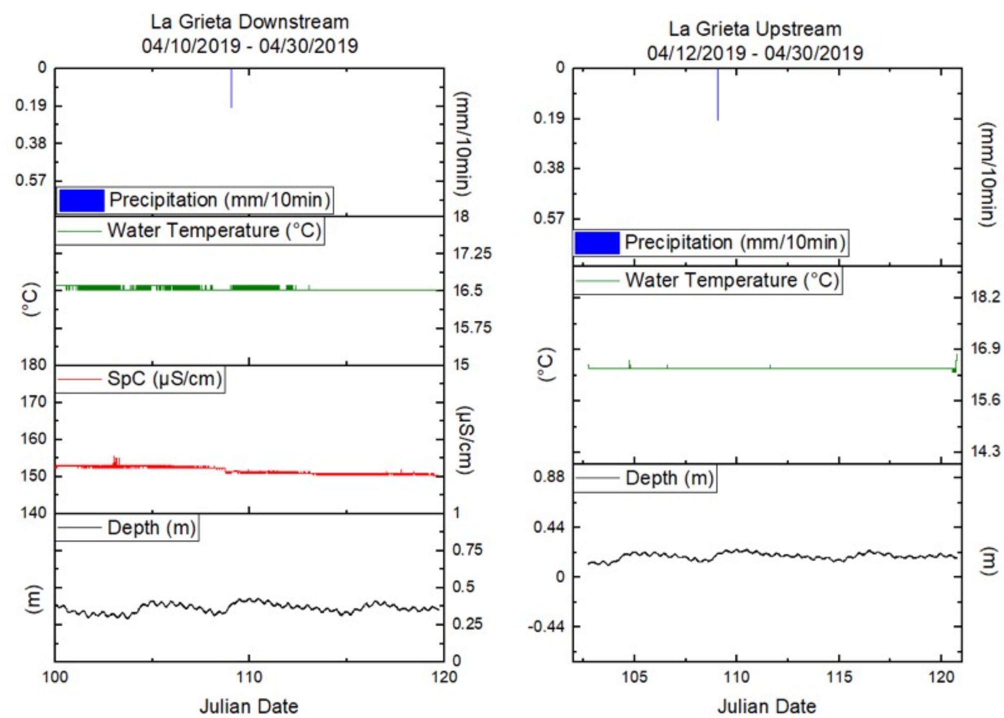


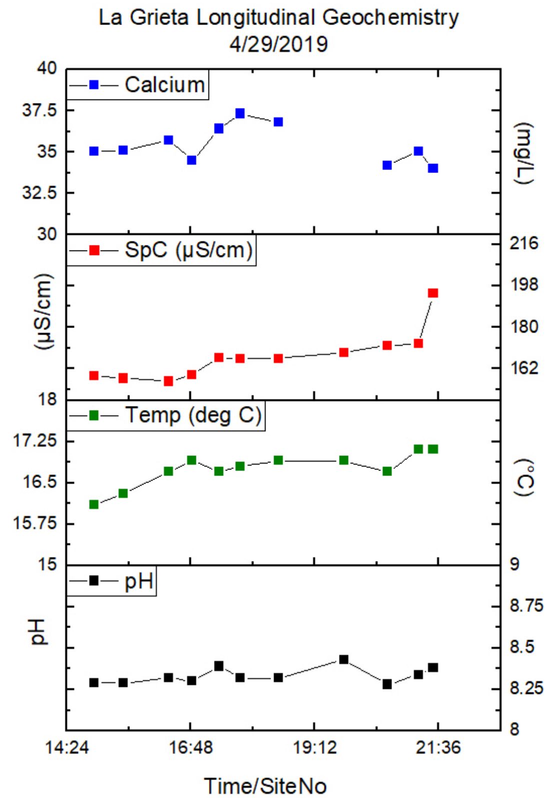
Fig. 5.10 La Grieta geochemistry data and water level obtain with HOBO loggers; left- Downstream, right- Upstream (Source: Created by Author).

Another element to consider is the interconnecting pathways of the system. The mixing of water from different sources due to convergence points can account for more aggressiveness of water represented by lower SpC values. The mixing of different water sources could also contribute to the lower values in the upstream portions of the cave, given the highly developed vadose zone (Palmer 2007). The dye trace that connected Plan de Escoba area with La Grieta represents an example of areas of mixing water from completely different sources, indicating possibly localized input to the other springs on the Santo Domingo outside of the primary Huautla flowpaths.

The temperature presented in the in-cave site correlates with Huautla Resurgence water. Water temperature in La Grieta starts at ~16 ºC and warms to ~19 ºC by the time it reaches Huautla Resurgence (Fig. 5.6, 5.10), which is a rate of about one deg/300 m, the typical atmospheric temperature lapse rate. The vadose flow from the cave to the Huautla Resurgence play an important role in the formation of the system.

5.3 Longitudinal Geochemical Profile In-Cave

The longitudinal data (Fig. 5.11) were obtained in a one continuous one day period in La Grieta section of Sistema Huautla starting from the lowest site being Elbow Canyon to the highest elevation site being Camp 3 (4.10). Eleven samples were taken during the day-long sampling event. The trends in SpC and pH shown in this study demonstrate that water becomes less aggressive as it moves downward on the cave and has longer contact with the rock. Nevertheless, the SpC values are still low overall, which indicates minimal dissolution has happened in the system at the time, which could be associated with the steepness of the gradient in the system or lack of time to dissolve much bedrock.



Time	Site Name
14:56	Camp 3
15:30	Beyond Lunch Room
16:23	Lunch Room
16:50	Formation Room
17:21	CJunction Room
17:46	Mazatec Shores Log
18:30	Camp 2
19:46	Pato Mojado
20:37	Skeleton Canyon
21:13	Scimitar Canyon
21:30	Elbow Canyon/ Camp4

Fig. 5.11 La Grieta longitudinal geochemistry profile data obtained during collection of water samples. Data plotted by time from upstream to downstream sites (Source: Created by Author).

Temperature increases slowly as the water travels to lower elevations in the cave. The warmer temperatures are likely due to warmer inputs at lower elevations and friction of the turbulent water as it moves downward, though these differences are minor in comparison to the those observed at the outlet springs discussed previously. The pH values remain fairly stable and are high, despite low Ca content and, thus, dissolved carbonate, and are more likely a function of the input water pH at this location than of the dissolution process taking place given the velocity of the water.

5.4 Dye Trace of Plan de Escoba 2019

A second dye injection was completed in 2019 after the discovery and exploration of the Cueva Elysium cave in the northern area of the proposed Sistema Huautla groundwater drainage basin. The exploration of this cave was an important discovery for understanding of Sistema Huautla, and dye tracing injections were modified due to this discovery. The cave extended as fossil passage for approximately three kilometers, until reaching a room with a massive fault in the ceiling. A prominent river trends to the south and another passage trends to the north. The river trending south could not be followed by exploration due to a sump, so a dye trace was proposed. The dye injection was performed in the south trending river on April 24, 2019. It was hypothesized that the dye trace was going to reach the cave through the Red Ball Canyon in San Agustin section of Sistema Huautla. This was hypothesized due to the position of the Cueva Elysium in relationship with the section of Sistema Huautla. During the time of exploration of Red Ball Canyon, there was an infeeder coming from higher elevation that was not explored. No access to this section of the cave was possible during the study, so the in-cave receptor was placed at the lowest section of La Grieta section of the cave in the Elbow canyon, as well as all the corresponding springs discussed previously.

The dye packet was recovered on May 2, 2019. The previous packet change was a negative result on April 28, 2019, thus the tracer arrived between April 28 and May 2, 2019. The travel time was between four to eight days over a distance of 1.3 kilometers from injection point to the monitoring site. All the charcoal receptors in the spring area were negative, which was expected due to the low precipitation and time of the trace. The results show that even during very dry conditions, in the vadose part of the aquifer there is still a substantial fast flow pathway. The data indicate the rapid transmission of the water in the vadose part of the system with high vertical relief, supporting the geochemical data presented above. This supports ideas from the Smith (1994) study suggesting the northern boundary of the system lays along Plan de Escoba and Agua de Cerro.

Table 5.5 Results for Cueva Elysium Dye Trace (Source: Created by Author).

ID#	Site Name	Feature Type	Result	Dye concentration in ppm	Distance from injection
001	Sistema Huautla Resurgence	Spring	Negative	0.012	14.4 km
002	HR Resurgence	Spring	Negative	0.009	14.8 km
003	Agua Fria Spring	Spring	Negative	0.010	415.8 km
008-02	Elbow Canyon (La Grieta)	In - Cave	Positive	0.158	2.9 km
009	Rio Santo Domingo Downstream of springs	Surface Stream	Negative	0.037	14.6 km

The tracing results (Table 5.5), combined with the geochemical data, suggest that the water flowing from Cueva Elysium goes to the same vadose vertical shaft system that characterizes the rest of the system (Figs. 5.12, 5.13). This contrasts with the lower part of the system in the base of the aquifer, where the water slows down considerably, and where it is assumed that the horizontal phreatic passages that characterize the springs persist for a considerable amount of time during fluctuating tectonic and incision periods over time. The phreatic section of the system slows down considerably the water flow present in the system at baseflow. The same characteristic was observed by Fernandez and Piedrabuena (2012) during the dye tracing in Comion caves in Picos de Europa. They observed a rapid transmission in the vadose conduits and a slow flow in the phreatic circulation associated to the steepness of the groundwater basin.

The geochemistry in the system compared to the data from the upper section suggest there could also be mixing in the system from other water sources. Hunkeler and Mudry (2007) mention that waters in karst drainage can be considered a mixture of diverse flowpaths due to the variability of connections of passages in karst.

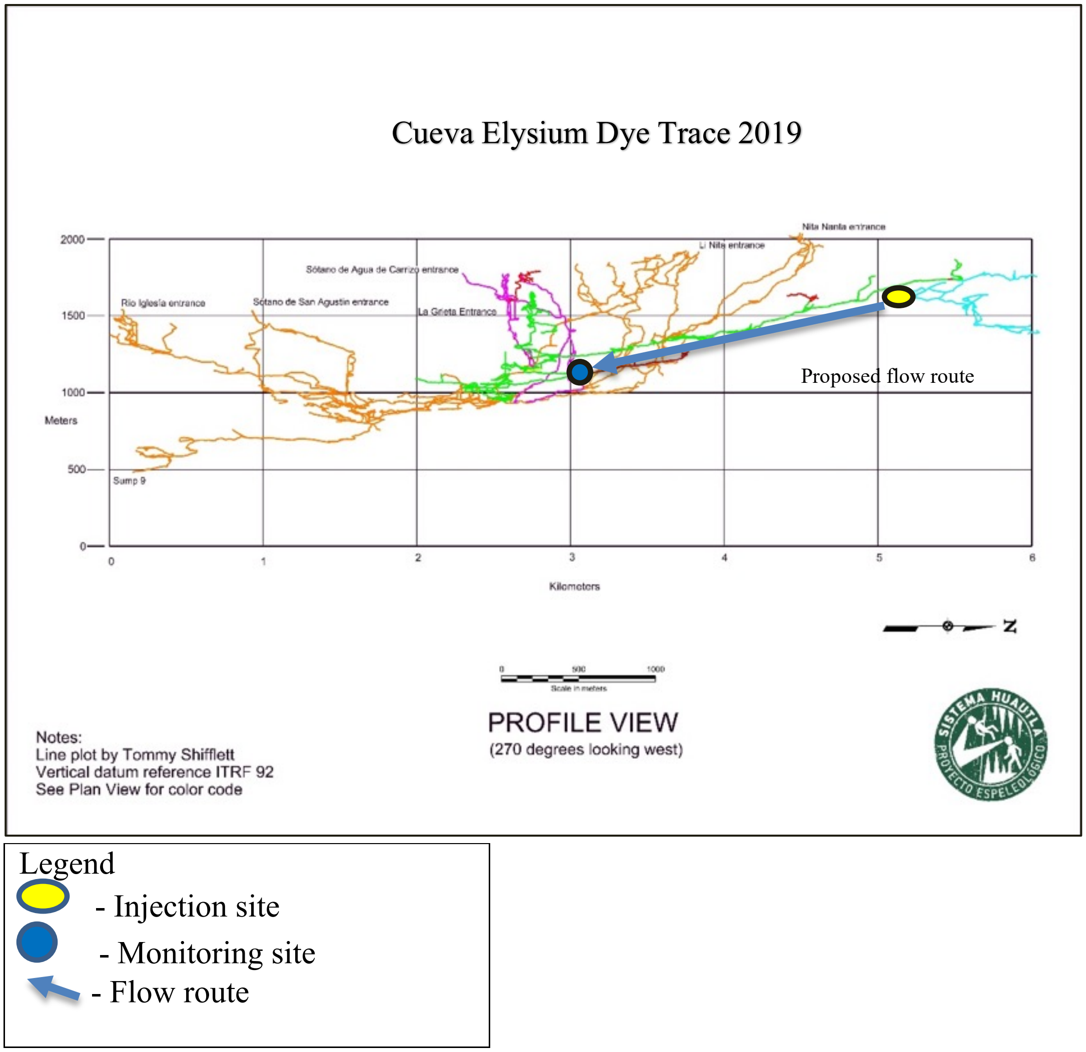


Fig. 5.12 Profile view of the hydrologic path proposed by Cueva Elysium Dye trace (Modified from Shifflet 2019).

The watershed of the lower part of Sistema Huautla has few spring outlets and likely had more connections in between the passages during the evolution of the cave. As the lowering of the water level in the springs occurs, the watersheds start subdividing into

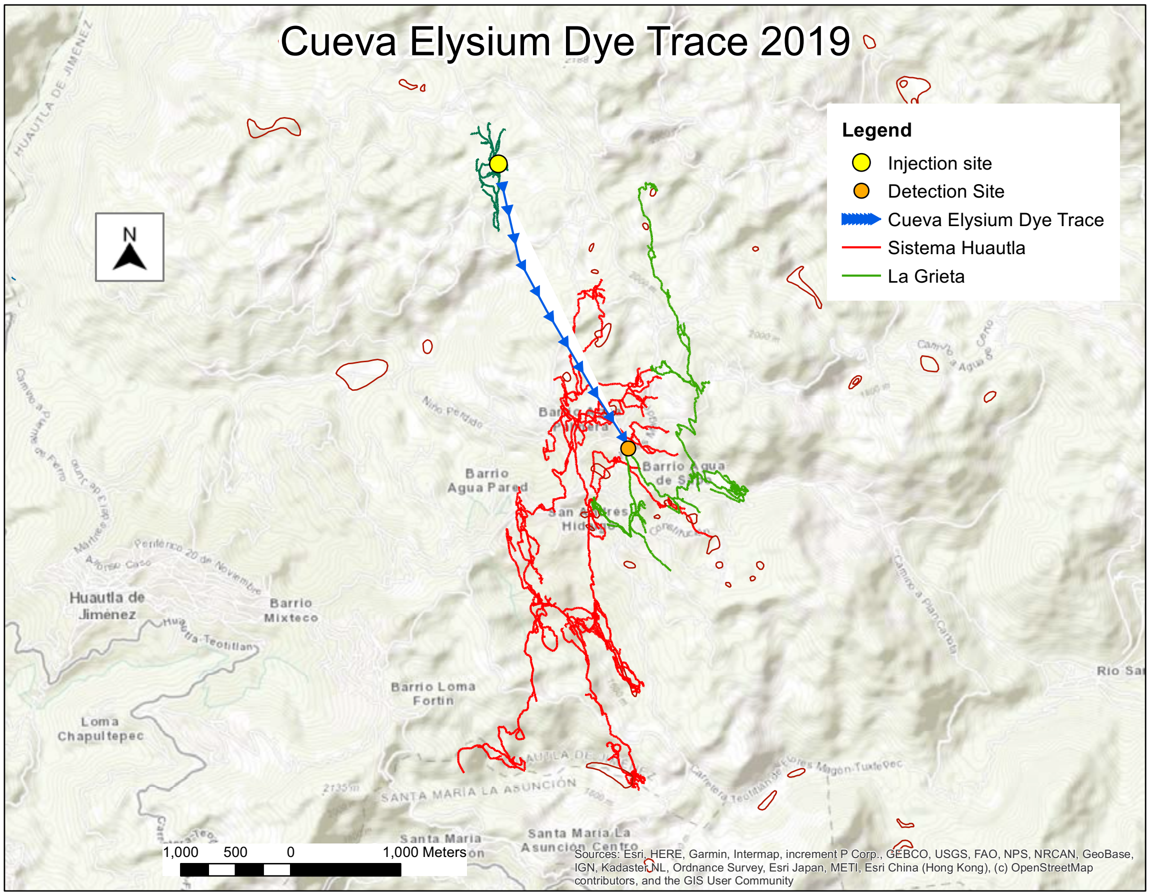


Fig. 5.13 Plan view of hydrologic path proposed by the Cueva Elysium dye trace (Map created by author).

different smaller watershed that receive their source from different area in the system; hence, the differing geochemistry between the springs. The springs tend to be connected during high flow events, which generated conditions that resemble the old fossil watershed and also likely is a result of interbasin transfer and water table rise, wherein the basin size increases to encompass other input sources.

5.5 Geomorphology and Evolution of Sistema Huautla

Cave level development in the phreatic zone of Sistema Huautla, as evidenced by newly discovered passages and dye traced connections in this study, is likely an indicator of persistent baseflow conditions at certain elevations driven by tectonics and river aggradation and incision as a baselevel control. This is expressed by the formation of multiple outlet springs along Rio Santo Domingo including fossil passages at higher elevation and the differences in geochemistry and water level response between the in-cave sites and the springs. Sistema Huautla is a good example of how highly vertical, vadose passages can form quickly from aggressive water to serve as rapid inputs, while larger, more horizontal passages likely form over longer periods and during flood and high flow events that concentrate aggressive water at those levels over more tectonically stable periods to allow for enhanced dissolution and larger, more extensive passage development along structural weaknesses.

5.5.1 Hydrologic and Climatic Influences

The results presented here indicate complex basin morphology, which is expected given the highly faulted and vertical nature of the system (Ballesteros et al. 2011). During the wet season, it is likely that basin boundaries change in size and contribute large amounts of aggressive water to the system that pool rapidly at the lower levels, in combination with likely backflooding in sections of the system (as evidenced by the Peña La Colorada connection), both of which will enhance cave development at the water table. Mature, distributary spring outlets likely caused by the geologically-rapid tectonic uplift, and correspondingly slower incision of the baselevel river, as well as the geologic heterogeneity (such as the caprock theory proposed by Smith (1994)) and structural controls, all combine to create a complex system of inputs and outputs that are more clearly identified through the results presented here. Collectively, the outcomes presented here indicate cave formation and evolution tied to processes common to more horizontally developed systems, such as Mammoth Cave, which are dependent on structural control and rock-water contact dynamics; however, Sistema Huautla's location and stratigraphic variability confound understanding these processes without the types of data collected herein to verify the dissolution dynamics and storm response nature of the system. This suggests the Cave's current evolution is primarily occurring within the phreatic passages and at the water table and are affected most prominently by season, antecedent moisture, and gradient as primary drivers in the formation of the cave.

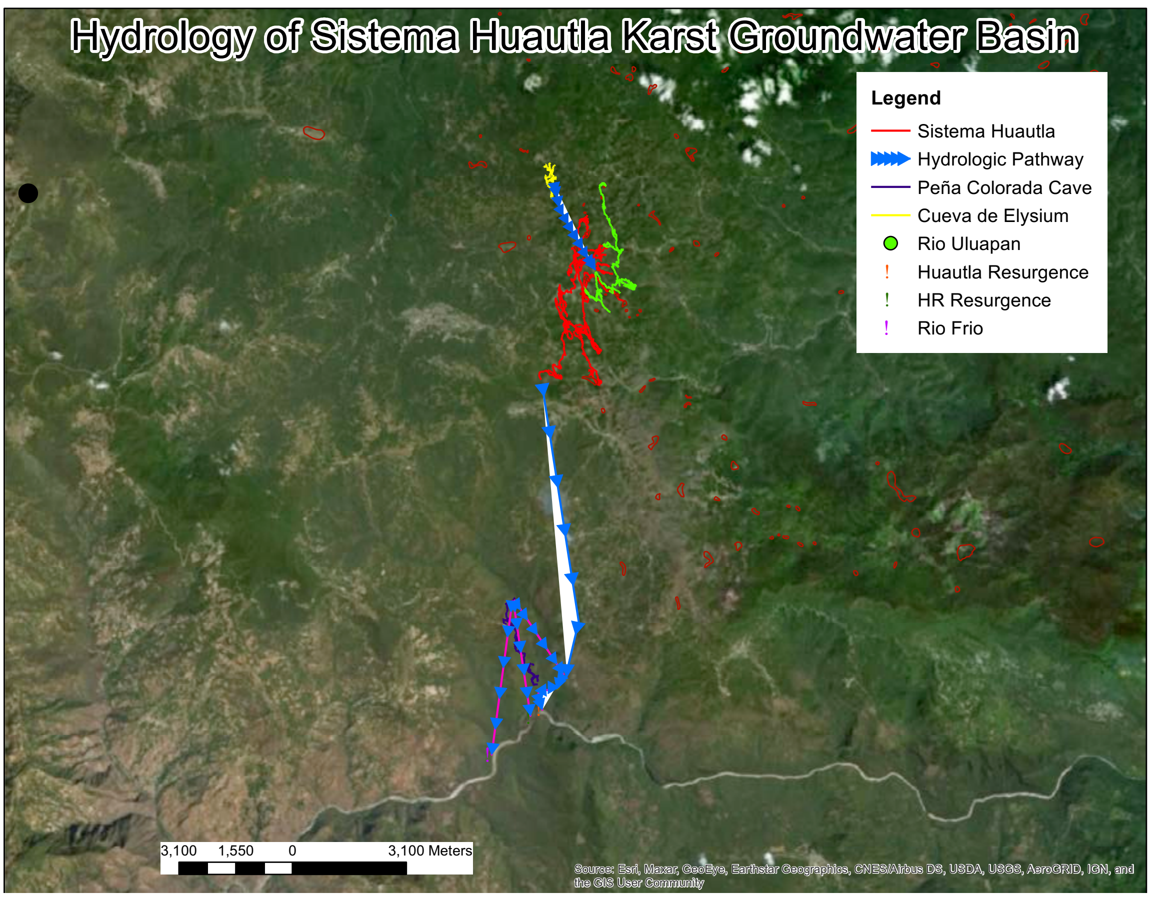


Fig. 5.14 Hydrology of Sistema Huautla (Map created by Author).

Cueva Santa Cruz was aimed to be part of the study in 2019, but conditions did not facilitate its use. It was visited in two different occasions in the dates of March 22, 2019 and April 15, 2019. In both occasions, the cave had stagnant flow in the first pool in the first 150 m of the main passage. Due to the amount of guano present in the pool it was unreasonable to pass through it. Nevertheless, the cave has high importance in the delineation of the groundwater basin, because it is the most western known cave possibly associated with the system. The cave trends southeast, which correlates to the trend of the syncline and is possibly draining toward the main route in San Agustin and Rio Iglesias area. This cave also creates an interest in the structural information about the system, because it is in very close proximity with the Huautla-Coyomeapan fault. This fault runs discordantly through the eastern edge of the city of Huautla, located directly South of the Cueva de Santa Cruz. It is not known if water associated with the springs in Santo Domingo river flows in karst pathways under the city of Huautla by the Fault.

5.5.2 Geologic and Structural Influences

Faulting likely plays an integral role in the formation of Huautla by causing initial vadose development along these structural weaknesses (Smith 1994), which concentrate recharge water to allow it to aggressively dissolve deeper into the bedrock and achieve breakthrough. Upon achieving breakthrough, passage formation and the integration of baseflow springs into the regional hydrology begin to dominate the dissolution and hydrologic dynamics of the system. Mechanical weathering of the caprock and other non-carbonate layers also likely contribute to the dissected landscape and complex basin divides. It is plausible that the existence of a caprock also created discrete inputs as it weathered away, forming the localized basins that continue to flow at outlets lie Rio Frio and HR Resurgence. This may have been intermittent due to tectonic activity and faulting, which could have helped integrated discrete inputs to contribute heavily to the formation of longer flowpaths developed at lower levels by becoming distributary outlets due to breakdown, sedimentation from low gradient, and phreatic loop developement below the water table requiring higher head gradient to allow for discharge to occur in the springs. This would have also been enhanced because the overlying limestone bedrock was protected from complete dissolution and collapse by the caprock, thereby preventing vadose dominance of the system's flow. In turn, the development of many smaller, vadose in feeders created a branching input system, eventually creating the long, vertically extensive network of passages that efficiently drain the area and form Sistema Huautla. Evidence of this exaggerated branchwork is also suggested by the distributary spring system presented herein, which appears to indicate the baselevel springs are similar and may have functioned as vadose passages in the past during lower baselevel periods, or prior to recent tectonic activity stabilizing the water table above the modern, phreatic portions of the cave system. The vertical relief of the system contributes greatly to the influence of gradient controls on the hydrology, which affects the rock-water contact time and dissolution potential. Inputs of allogenic and autogenic water combine with this influence to allow for extensive vertical development and efficient drainage of the system to lower level, more established passages that serve as the primary outlets for drainage, but that are also connected to the rest of the system to allow for efficient drainage during high water events as well.

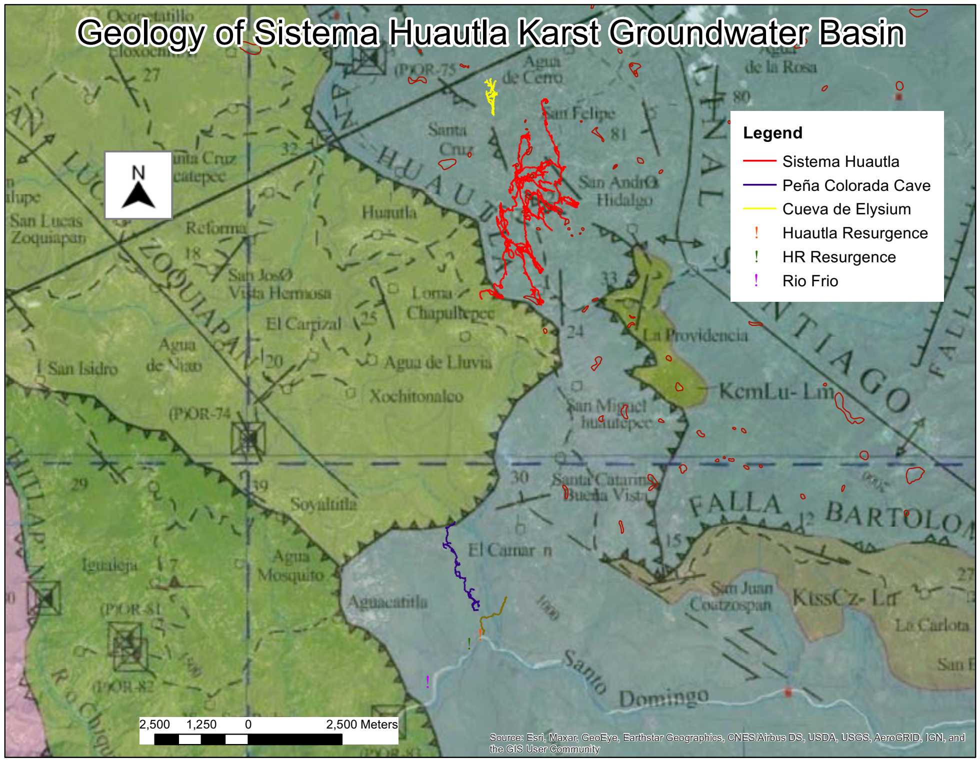


Fig. 5.15 Geologic Map of Sistema Huautla (Map created by author)

In Figure 5.15, important geologic features are present that likely influenced the formation of Sistema Huautla and its distributary outlets. The two major anticlines in the region, to the east anticline Santiago and to the west anticline Lucas Zoquiapian, present the regional delineation for the groundwater basin. Sistema Huautla formed toward the synclinal axis between these two structures. The thrust faults displaced the non-karstic rock of the Tuxpanguillo Formation on top of the Cretaceous limestones of the Orizaba Formation. The non-karstic metamorphic rock presented a source of allogenic recharge into the cave, allowing for rapid formation of vadose infeeders until they reached more laterally continuous bedding planes and folds that create low gradient passages trending toward the modern water table. The thrust fault most likely limited the formation of big conduits after Sump 9, due to the faults at the edge of the thrust fault. Exploration past

Sump 9 in Sistema Huautla, and past Sump 7 in Cueva de la Pena Colorada, have proven unsuccessful possibly due to collapse and sedimentation of passages close to the main fault along which they formed.

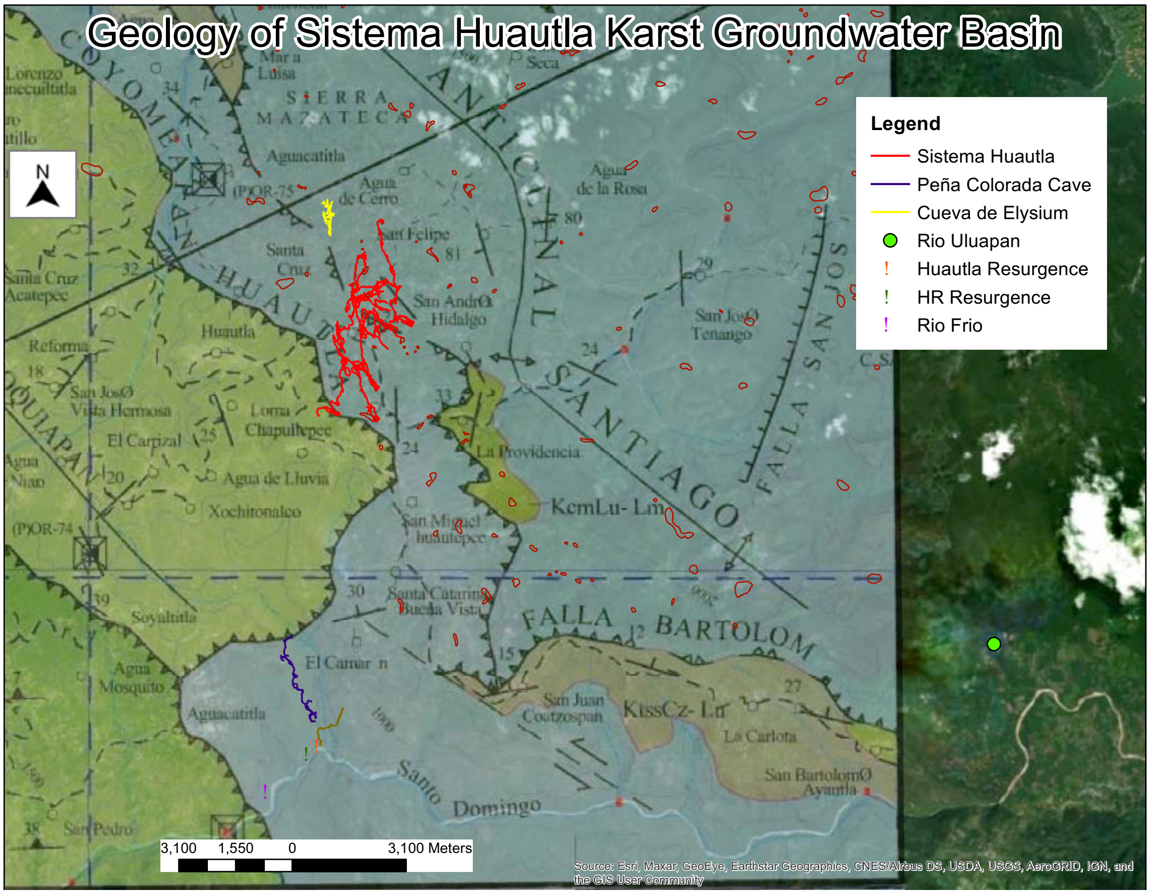


Fig. 5.16 Geology of Sistema Huautla and broader regional extension potentials (Source: Created by Author).

The current hydrologic flow might be trending more towards the San Miguel Huautepec area, which has a vast quantity of well-developed sinkholes. The area would be a major source of autogenic recharge during large flood events, while also providing localized recharge during smaller events. The San Miguel Hautepec area is constricted by another thrust fault to the east. The thrust faults is most likely the eastern boundary of the Sistema Huautla Karst Groundwater Basin to the east. As observed in Figure 5.16, the

Rio Uluapan is the next distinct spring to the east of Huautla Resurgence. The major feature dividing the hydrological drainage of Huautla System and Rio Uluapan drainage is the Santiago Anticline. Future basin delineation work should focus on these areas and proceed under the assumption of faulting and local versus regional dip based on prominent folds being the main structural controls of passage formation connected to the main system, while smaller, localized branches may exist due to the dissected nature of the geology and the hydrologic evolution over time to integrate these into the system under different baselevel conditions in the geologic past.

Chapter 6: Conclusions

Sistema Huautla is a highly vertical cave with extensive relief and multiple entrances, having undergone complex speleogenetic evolution. The recharge of the cave travels fast through the upper section of the system in the vadose zone until it reaches the baselevel, where the flow slows down, and phreatic passage development likely dominates. The study highlights the relationship of the multiple springs associated with the north wall of Rio Santo Domingo near the Huautla Resurgence. During initial analysis at baseflow, the springs seem to have very different water origins Huautla Resurgence similarity with the in-cave site suggested that the flow is associated with a vadose flow and hydrological connection during base flow. The Rio Frio and HR Resurgence present similar geochemical characteristics, which denote a different water source and longer water contact time with rock. Both springs are likely fed by deep phreatic loops that were primary water table passages formed during prior baselevels preceding tectonic uplift and river incision. The morphology of these springs is similar to the Cueva de la Peña Colorada morphology, which has loops of up to 170 vertical meters of extent. As the system becomes active during the rainy season, or during flooding events, the hydrologic dynamics and the springs indicate interbasin water transfer and the system becomes more homogenized with respect to source and flowpaths. During the same conditions, the distributary branching development of the phreatic zone was identified by the dye tracing associated to Cueva de la Peña Colorada.

The spring system has two different types of recharge that play a role in its speleogenesis. The recharge coming from the non-karstic Jurassic metamorphic rock is regionally influence by the anticlines and directed towards the cretaceous limestone. The allogenic recharge presents a constant flow of aggressive water in the system, enhancing the formation of conduits along the edge of the thrust fault. The recharge occurring in the carbonate rocks plays an important role during rainy season or big flood events. The water recharges autogenic in the dolines and flows through the system in pulses. The fast flow of water delivers aggressive water through the system and is the main mechanism of speleogenesis in the vadose area of the cave, while phreatic development occurs at the water table, due to the large drainage basin providing continuous flow to the low gradient passages from an environment with ample sources of acidity and fast enough flow to allow for continued dissolution even after water has traveled long distances in the system.

The faulting and folding in the region formed an efficient distributary system during flood events and the rainy season. As Cueva de la Peña Colorada and the hydrologic pathway of Sistema Huautla floods, the conduits get full and the water backs up; thus, creating the distribution of the flow in between the three springs and homogenizing the water response to the food events. This creates a distributary model that includes HR Resurgence and Rio Frio, in which they receive water from the main hydrologic path of Huautla system, as well as deep seated water, and surface recharge from the nearby area, depending on the amount of flow in the system.

This study provides more clues about the evolution of the whole basin and the likelihood it has evolved through a complex interaction between tectonic uplift, river incision, and vadose infeeder development. The evolution includes both local and regional influences from both the geology and hydrology. These would have been enhanced through caprock retreat and dissolution along preferential faults allowing for rapid cave formation and major passage development horizontally during stable geologic and climatic periods.

To summarize, the research questions that were addressed included:

- What are the main recharge sources and outputs for the SHKA and what are the boundaries of the hydrological basin?

The study expanded the recharge zone to the northern area of Plan de Escoba by connecting to Sistema Huautla in the La Grieta section. This area is most likely the northwest boundary to the Huautla Karst Groundwater Basin and deserves more exploration.

The spring section of Sistema Huautla showed a complex output of the system with mainly discharges from one spring at baseflow, but major storm events activate major springs to the west and act as overflow pathways, including paleo-passages that likely evolved during previous tectonically stable periods of baseflow.

- What temporal and spatial patterns can be observed with respect to hydrogeochemical variation in SHKA hydrological basin and what do such patterns indicate regarding karstification and speleogenesis?

The hydrogeochemistry data from this study indicates the water in the vadose zone flows at a very fast rate with low dissolution happening in the upper part of the system, while most of the dissolution most likely happens at the contact with the phreatic zone below the water table as defined by major springs. Water slows down and promotes rock to water interaction, which is reflected on the spring geochemistry and, thus, baselevel fluctuation is a primary control on the development of the system. Major rain events likely play an important role in Huautla's speleogenesis, with vadose development occurring during major floods and backflooding from the HR Resurgence and Rio Frio. This also indicates that much of the Cave's development could have been in the recent geologic past, despite the older bedrock and tectonic activity, given the implication of climatic factors that would affect the baselevel of the Santa Domingo River and seasonal monsoons driving dissolution through recharge events.

The investigation and exploration of Sistema Huautla shows a lot of promise for new discoveries and future exploration with a high incidence of sinkholes and features in the north boundary. Cueva Elysium showed a very fast and direct hydrological connection to Sistema Huautla and it is most likely other caves around the area will follow the same pattern of development and hydrologic connection.

Furthermore, studies in complex vertical and alpine-like karst areas like Sistema Huautla provide important information to understand the hydrological characteristic of these types of large basins. The people in the highland areas of the Sierra Mazateca have problems with water quantity in the dry season, jeopardizing crops and hygiene. While this study does not offer a solution to the problem, it adds data to further comprehend the area's water resources and produce a comprehensive plan to address future water problems under a changing climate.

6.1 Future Studies

Many more questions are raised from the competition of this study, both from the data collected and those not obtained due to instrument malfunction, to develop more ideas of what studies could be done in Sistema Huautla in the future. There is still more dye tracing to be done with gaps to address based on Smith (1994, 2002) and this study, including dye tracing gaps in these areas:

- Cueva Santa Cruz should be dye traced Sistema Huautla to further consolidate the northwest boundary along the Plan de Escoba trace.
- Agua de Cueva or Agua Verde area should trace to determine NE boundary of the ground water basin.
- Rio Santiago should be dye traced to determine with security the division between Rio Uluapan Basin and Sistema Huautla Ground Water Basin.
- Dye trace the big sinkhole in San Miguel Huatepec near Agua Evangelista. The water from that sink might be connection to Sistema Huautla through a series of faults.

Additionally, a more robust set of geochemical data from the three springs might prove essential to identify water sources of Rio Frio and HR Resurgence during base flow. Water sampling and high-resolution data at Plan de Escoba, Huautla Systems, and springs might be very helpful to understand dissolution in the system and improve speculation on an approximate age of the system.

The use of isotopes to identify source water may be more reliable than dye tracing, due to the slow movement of water, to identify mixing and source water inputs on a broader scale. Also, high-resolution data on spring geochemistry during big rain events or the flooding season over a period of a year would be useful to identify seasonal trends and better determine the recharge-discharge relationships between the inputs and springs within the theorized drainage area.

Lastly, a seepage run on Rio Santo Domingo could identify the presence of springs in a lower level than the current one, with water moving through the alluvium, as well as a better documentation of the flow of most of the springs in the area and its relationship to the true extent of the drainage basin.

Overall, this study has highlighted several new aspects of the geomorphologic and hydrogeological characteristics of Sistema Huautla, including as a proxy for other deep, high-relief, vertical cave systems, providing an improved understanding of their evolution. Specifically, the outcomes indicate further exploration potential for Sistema Huautla based on the connection of new passages and identification of preferential groundwater flowpaths and storms responses, which suggest the cave likely has a much larger drainage area than currently estimated and will continue to develop in response to baselevel changes and seasonal rainfall variability. Future expeditions should take into consideration the potential for large, fossil passages that have been abandoned during the cave's evolution, as well as the threat potential for rapid, severe flooding in lower levels due to a highly developed and efficient vertical vadose drainage system. Future deep cave studies may draw upon these conclusions to assist in exploration and scientific studies by focusing on key monitoring sites and high-resolution data collection to capture the flashy nature of these vertically extensive karst groundwater systems.

Chapter 7: References

Anaya, A. A., Padilla, I., Macchiavelli, R., Vesper, D. J., Meeker, J. D., Alshawabkeh, A. N., 2014. Estimating preferential flow in karstic aquifers using statistical mixed models. *Groundwater 52*(4), 584-596.

Baena, C. L., Andreo, B., Mudry, J., & Cantos, F. C., 2009. Groundwater temperature and electrical conductivity as tools to characterize flow patterns in carbonate aquifers: The Sierra de las Nieves karst aquifer, southern Spain. *Hydrogeology Journal* 17(4), 843-853.

Bates B.C., Kundzewicz Z., Wu S., Palutikof J., 2008. Climate change and water. IPCC technical paper VI. IPCC Secretariat, Geneva, 210 pp.

CONAGUA (Comisión Nacional del Agua), 2016. Atlas del Agua en Mexico. Available online at: https://www.gob.mx/ conagua/documentos/publicaciones-estadisticas-ygeograficas

Dreybrodt, W., 2012. Processes in karst system: physics, chemistry and geology. Vol. 4. Springer Science & Business Media

Espinasa-Pereña, R., 2007, El Karst de México. Mapa NA III 3, en Coll-Hurtado, A. *Nuevo Atlas Nacional de México: Instituto de Geografía, Universidad Nacional Autónoma de México*.

Field, M., R. Wilhelm, J. Quinlan, and T. J. Aley, 1995. An assessment of the potential adverse properties of fluorescent tracer dyes used for groundwater tracing. *Environmental Monitoring Assessment* 38, 75–96.

Florea, L.J., Vacher, H. L., 2006. Springflow hydrographs: eogenetic vs. telogenetic karst. *Groundwater* 44(3), 352-361

Ford, D., 2003. Perspectives in karst hydrogeology and cavern genesis. *Karst Waters Institute, Inc., Charlottesville, Virginia*, 17-29.

Ford, D. and Williams, P., 2007. *Karst hydrogeology and Geomorphology*. England: John Wiley & Sons, 576 pp.

Freeze, R. and Cherry, J., 1979. *Groundwater*. Prentice Hall: New Jersey, 604 pp.

Goldscheider, N., Drew, D., 2007. *Methods in Karst Hydrogeology: IAH: International Contributions to Hydrogeology, 26*. CRC Press

Gonzalez-Alvarado, J., 1976. Resultados obtenidos en la exploración de la Plataforma de Córdoba y principales campos productores. *Boletín de la Sociedad Geológica Mexicana 37*, 53-59.

Grund, A., 1903. Die karsthydrographie: Studien aus Westbosnien. Geog. Abh. Heraus. Von A. Penck, v.7, pp. 103-200

Hilberg, S., 2016. Natural tracers in fractured hard-rock aquifers in the Austrian part of the Eastern Alps—previous approaches and future perspectives for hydrogeology in mountain regions. *Hydrogeology Journal* 24(5), 1091-1105.

Hose, L. D., 1995. World's deepest karst hydrologic system documented in Sierra Juárez, Oaxaca. *Revista Mexicana de Ciencias Geológicas 12*(1), 108-111.

Glynn, P. D. and Plummer, L. N., 2005. Geochemistry and the understanding of ground-water systems. *Hydrogeology Journal* 13(1), 263-287.

Groves, C., Meiman, J., 2005: Weathering, geomorphic work, and karst landscape evolution in the Cave City groundwater basin, Mammoth Cave, Kentucky. *Geomorphology* 67, 115-126.

Iguzquiza, E., Duran, J., Espinar, J., Ardila, P., Rosillo, S., Albert, C., Pedrera, A., 2014. Karst massif susceptibility from rock matrix, fracture, and conduit porosities: a case study of the Sierra de kas Nieves (Malaga, Spain). *Environmental Earth Sciencies* 74(12), 7583-7592.

INEGI, 1983. Map Orizaba E14-16, scale 1:250,000. Carta Hidrol´ogica de Aguas Superficiales. Instituto Nacional de Estadistica, Geografia e Informatica, Aguascalientes, Mexico.

INEGI, 2015. Conjunto de datos vectoriales de informaci on topografica E14B87 (Huautla de
Jimenez), escala 1:50000 Serie III. Instituto Nacional de Estadıstica y Geografıa, Mexico.

Jarvie, H. P., Neal, C., Leach, D. V., Ryland, G. P., House, W. A., Robson, A. J., 1997. Major ion concentrations and the inorganic carbon chemistry of the Humber rivers. *Science of the Total Environment 194*, 285-302.

Jarvie, H. P., King, S. M., Neal, C., 2017. Inorganic carbon dominates total dissolved carbon concentrations and fluxes in British rivers: Application of the THINCARB model–Thermodynamic modelling of inorganic carbon in freshwaters. *Science of the Total Environment*,*575*, 496-512.

Kambesis, P., 2007. Agricultural contaminant source and transport in a karst groundwater basin. MS thesis, Western Kentucky University, Kentucky.

Klimchouk, A., Bayari, S., Nazik, L., and Tork, K., 2006. Glacial destruction of cave systems in high mountains, with a special reference to the Aladaglar massif, Central Taurus, Turkey. *Acta Carsologica* 35(2), 111-121.

Klimchouk, A. 2012. Krubera (Voronja) Cave. In Culver, D. and White, W., (eds.), *Encyclopedia of Caves (Second Edition).* Cambridge, MA: Academic Press, 443-450.

Lauber, U., Goldscheider, N. 2014. Use of artificial and natural tracers to assess groundwater transit-time distribution and flow systems in a high-alpine karst system (Wetterstein Mountains, Germany). *Hydrogeology Journal 22*(8), 1807-1824.

Lazcano, C., 2017. Las Cavernas de la Sierra Gorda. 1era edicion. Universidad de Queretaro. Queretaro, Mexico.

Lakey, B., and N.C. Krothe. 1996. Stable isotopic variation of storm discharge from a perennial karst spring. *Water Resources Research* 32, 721–731.

Lawhon, N., 2014. Investigating telogenetic karst aquifer processes and evolutionin South-Central Kentucky, US using high-resolution storm hydrology and geochemistry monitoring. M.S. Geoscience thesis, Department of Geograpy and Geology, Western Kentucky University, Bowling Green, KY

Martin, J. B., Dean, R. W., 2001. Exchange of water between conduits and matrix in the Floridan aquifer. *Chemical Geology 179*(1), 145-165.

Meybeck, M., Green, P., Vörösmarty, C. 2001. A new typology for mountains and other relief classes: an application to global continental water resources and population distribution. *Mountain Research and Development 21*(1), 34-45.

Moreno, G., 1980, Geologia del area de Huautla de Jimenez, Oaxaca. Tesis Profesional, E. S. I. A., I. P. N., 35 p.

Munn-Estrada, D. X., 2017. Contribution to the Floristic Knowledge of the Sierra Mazateca of Oaxaca, Mexico. *Lundellia* 20(1), 25-59.

Neal, C., House, W. A., Down, K., 1998. An assessment of excess carbon dioxide partial pressures in natural waters based on pH and alkalinity measurements. *Science of the Total Environment 210*, 173-185.

Ortuño-Arzate, S., Ferket, H., Cacas, M.C., Swennen, R., and Roure, F., 2003. Late Cretaceous carbonate reservoirs in the Cordoba platform and Veracruz Basin, eastern Mexico. In Bartolini, C., Buffler, R.T., Blickwede, J., eds., *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics: American Association of Petroleum Geologists Memoir* 79, 476–514.

Palmer, A. N., 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin 103*(1), 1-21.

Palmer, A. N., 2001. Dynamics of cave development by allogenic water. *Acta Carsologica 30*(2), 13-32.

Palmer, A., 2007. *Cave Geology*. Dayton: Cave Books. 454 pp.

PESH (Proyecto Espeleologico Sistema Huautla), 2017. Proyecto Espeleologico Sistema Huautla maps. Drafted by Tommy Shifflet and Derek Bristol.

Pérez-Gutiérrez, R., Solari, L. A., Gómez-Tuena, A., & Valencia, V. A., 2009. El terreno Cuicateco:¿ cuenca oceánica con influencia de subducción del Cretácico Superior en el sur de México? Nuevos datos estructurales, geoquímicos y geocronológicos. *Revista Mexicana de Ciencias Geológicas 26*(1), 222-242.

Pereyra, D., Pérez, J. A., and Salas, M., 2010. Hidrología en Atlas del patrimonio natural, histórico y cultural de Veracruz. Patrimonio natural. Comisión Estatal de los Bicentenarios. Gobierno del Estado de Veracruz y Universidad Veracruzana, 85-122.

Quinlan, J.F., 1990, Special problems of ground-water monitoring in karst terranes. In: Nielson, D.M., and Johnson, A.L., (eds), *Ground water and vadose zone monitoring*.
American Society for Testing and Materials, STP 1053, Philadelphia, PN, 275-304.

Ruiz Fernández, J., Poblete Piedrabuena, M. Á., & García Hernández, C. (2014). Características morfoclimáticas y procesos y formas periglaciares actuales en el Macizo Occidental de los Picos de Europa (Cordillera Cantábrica). *Publicacions i Edicions de la Universitat de Barcelona*.

Smart, P. L., 1984, A review of the toxicity of twelve fluorescent dyes used for water tracing. *NSS Bulletin* 46, 21–33.

Smith, J., 1994. Hydrogeology of the Sistema Huautla Karst Groundwater Basin. Sierra Mazateca, Oaxaca. MS thesis, Western Kentucky University, Kentucky.

Smith, J. H. 2002. Hydrogeology of the Sistema Huautla Karst Groundwater Basin. Sierra Mazateca, Oaxaca. *Association of Mexican Cave Studies Bulletin* 9, 12–141.

Steele, C. W., Smith, J. H. 2012. Sistema Huautla, Mexico. In Culver, D. and White, W., (eds.), *Encyclopedia of Caves (Second Edition).* Cambridge, MA: Academic Press, 712-718.

Steinich, B., Olimán, G. V., Marin, L. E., and Perry, E., 2012. Determination of the ground water divide in the karst aquifer of Yucatan, Mexico, combining geochemical and hydrogeological data. *Geofísica Internacional*, *35*(2).

Toriz, G. J., 1983. Informe geológico de actualización geológica del Prospecto Chapulco-Atzompa.

Vacher, H. and Mylroie, J., 2002. Eogenetic karst from the perspective of an equivalent porous medium. *Carbonates and Evaporites* 17(2), 182-96

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., Weingartner, R., 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research 43*(7), 1-13.

White, W. B., 1988. *Geomorphology and Hydrology of Karst Terrains*. Oxford: Oxford University Press, 464 pp.

White, W.B., 1993, Analysis of karst aquifers. In Alley, W.M. (ed.), *Regional ground-water quality:* New York: Van Nostrand Reinhold, 471–489.

White, W. B. and White, E. L., 1995. Correlation of contemporary karst landforms with paleokarst landforms: The problem of scale. *Carbonates and Evaporites* 10(2), 131-137.

White, W. B., 2002. Conceptual models for karstic aquifers. *Speleogenesis* and Evolution of Karst Aquifers 1(1), 2.

Wilde, F.D., Sandstrom, M.W., and Skrobialowski, S.C. 2015. *National field manual for the collection of water-quality data*. Reston, VA: U.S. Geological Survey, Techniques of Water-Resources Investigations, Book.

Vigna, B. and Banzato, C., 2015. The hydrogeology of high-mountain carbonate areas: an example of some Alpine systems in southern Piedmont (Italy). *Environmental Earth Sciences* 74(1), 267-280.

Worthington, S. R. H., Ford, D. C., and Beddows, P.A., 2000. Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution. In *Speleogenesis: Evolution of Karst Aquifers*. (eds) Klimchouk, A.V., Ford, D.C., Palmer, A.N., Dreybolt, W. National Speleological Society of America, Huntsville, Alabama, USA, 220-223.