Responsible Development in Tulum, Mexico: Considering Water Quality and Subaqueous Cave Locations

by

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Abstract

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Development is rapidly occurring along the Mayan Riviera in the Yucatan Peninsula, Mexico with little regard to environmental regulations or wellbeing. In particular, fresh water must be considered when planning for future development. The sole source of fresh water in the Yucatan is from a karstic aquifer that is characterized by an extensive network of subaqueous caves, a system that is particularly sensitive to contamination. This master's project focuses on the current and future water supply for the town of Tulum since the town's future development will have long term repercussions on the surrounding environment. Two methods were used to determine how and where Tulum should or should not develop with regard to the protection of future water quality. Water samples collected around Tulum in the summer of 2008 were analyzed to determine the current water quality of wells and cenotes (sinkholes). Cave survey data that was collected by cave divers and the Quintana Roo Speleological Survey was used to create a map of the known cave systems. Satellite imagery was classified to determine the current land use/ land cover of the area and the extent of future development was estimated according to the Urban Development Plan (UDP) of Tulum.

Water quality results show that nitrate contamination is within acceptable limits according to Mexican water standards. These results would likely be very different if the samples had been taken during a different time of year (the dry season) when nitrate contamination is more concentrated. Chloride and sodium concentrations are well above Mexican water standards; the water supply that the city of Tulum relies upon is already experiencing salinization. It is likely that higher future withdrawals from this water source will be increasingly more saline, which may necessitate a different freshwater source for the city. Mapping of the known subaqueous caves shows that the vast majority of the network (81%) is overlaid by forest and is therefore less likely to be contaminated from the surface. Future development according to the UDP of Tulum will occur above a substantial area of subterranean caves. To protect water quality, the UDP should be altered to take cave locations into consideration. High impact development should be resituated and land above the cave systems should be zoned for limited, if any, development.

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Introduction:

The eastern coast of the Yucatan Peninsula, also known as the Mayan Riviera, has experienced enormous tourism and population growth in the past 20 years. The tourism industry in this region began in the mid-1970s when Cancun was targeted as a center for tourism development. It grew rapidly as the Mexican government assisted with this plan by investing in necessary infrastructure such as roads and airports. Within a decade, the tourism industry began to spread south of Cancun, to the Mayan Riviera, greatly changing the nature of the small coastal towns in this region.

The city of Tulum is the focus for this Master's project because it is in the midst of planning for further expansion and development and is located near an environmentally sensitive underground water system and a major World Heritage biosphere reserve. Tulum is poised to experience the same rapid growth as other towns further north, such as Playa del Carmen. It already has a significant tourism industry due to the Mayan ruins near the town, its beautiful white beaches and its proximity to the Sian Ka'an Biosphere Reserve. Since there are many other towns that are in the same situation as Tulum, on the verge of rapid development, hopefully the city of Tulum can provide a positive example of thoughtful and deliberate developmental planning. The city government released an urban

Figure 1: The Yucatan Peninsula

development plan (UDP) to the public in late 2006 (Tampieri, 2006). This plan was opposed by several groups, including governmental bodies, citizens and local organizations. The plan was withdrawn for further revision, in part to address concerns over future freshwater resources in the area.

How the town of Tulum chooses to grow will have long-term consequences on the surrounding environment, especially the availability and quality of freshwater resources. Of particular interest is the potential impact of development pressures on the underground water conduit system, the primary source of fresh water in the area. This delicate system needs to be more fully understood and mapped so that it can properly be taken into consideration when planning for Tulum's future growth. A variety of biodiversity and ecosystems rely on the quality of this aquifer including the Sian Ka'an Biosphere Reserve, an important, World Heritage conservation area.

This master's project has two separate components that will be useful in determining how and where Tulum should or should not expand its tourism industry. Water quality measurements and geospatial analysis will complement each other and allow for a more complete analysis. Water samples in the area surrounding Tulum were taken in July of 2008. These samples have been analyzed for contaminants and trace metals in order to better understand the current quality of the available fresh water. The geospatial part of the analysis involves characterizing the extent of current and future development around Tulum and identifying areas where the underground "rivers" exist in the area. This aspect of the project could not have been accomplished without the trust and support of the cave divers who allowed me access to their invaluable data. Using the water quality data and the maps, I will identify areas where the town should avoid or restrict further development.

I. Background:

This section will provide an introduction to the different aspects of Tulum's environment and its development so that the results from this report can be put into a wider context. Background sections include the following topics: hydrogeology, the subterranean cave system, the Sian Ka'an Biosphere Reserve, Mesoamerican Great Barrier reef, tourism development, population growth and water quality issues facing the region.

A. Hydrogeology:

The Yucatan peninsula is made of calcium carbonate bedrock that has developed into a mature karst system with extensive fissures, fractures and cave structures. It covers an area of approximately 75,000 km^2 and rises to about 15 m above sea level (Beddows, 2002). Because the rocks are porous and the overlying soil very thin, precipitation quickly filters into the aquifer, usually not more than 30 meters below the surface (Escolero Fuentes, 2007). The aquifer is an unconfined coastal aquifer with the recharge area covering its entire area. Since transistivity of the aquifer is very high, the hydraulic gradient is low, ranging from 7-10mm/km through most of the peninsula (Gonzalez-Herrera, 2002).

The conceptual Ghyben-Herzberg model (Figure 2) describes a typical coastal aquifer's fresh and saltwater interface (Domenico and Schwartz, 1998). In the case of the Yucatan, it appears that the cave conduits in this aquifer make this model less applicable. The conduits may essentially reduce the freshwater lens thickness that the Ghyben-Herzberg model predicts (Beddows, 2002). Another aspect that sets this aquifer apart from other coastal aquifers is the that cones of depression, from pumping of freshwater, are limited in size and the aquifer stabilizes almost immediately after pumping (Gonzalez-Herrera, 2002). This indicates that the aquifer is quick to respond to changes in water level and precipitation.

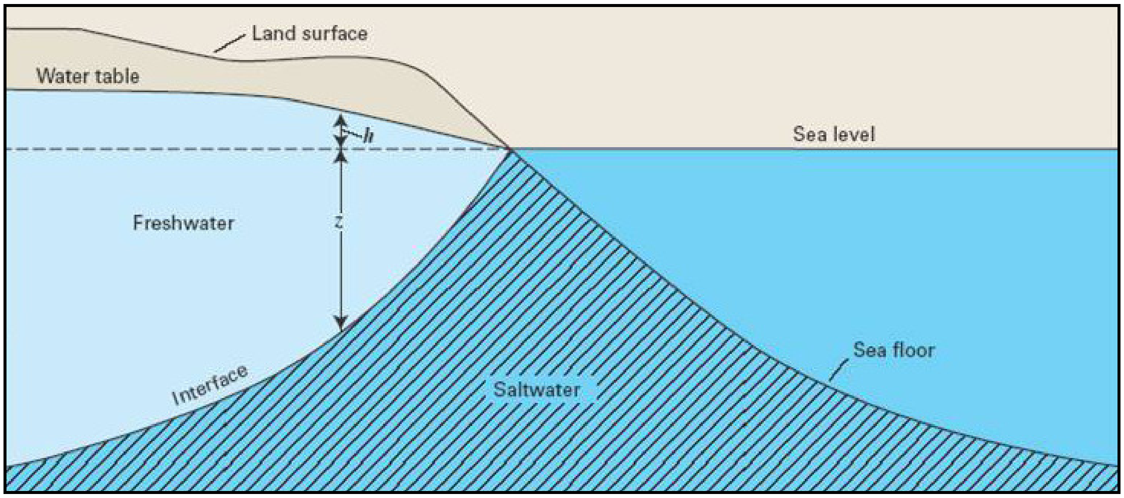


Figure 2: Fresh and saltwater interface for theoretical coastal aquifer

The aquifer is primarily saline with a thin lens (45-60 m) of freshwater that floats above the salt water (Escolero et al., 2000). The presence of saline water has been measured 110 km from the coast (Marin, 2007) and it has been determined that the origin of salt water is both from salt water intrusion near the coast and dissolution of evaporates (Perry, 1995). The freshwater lens is the only source of freshwater on the peninsula (Alcocer et al., 1998, Gonzalez-Herrera, 2002). The freshwater lens flows toward the coast but it appears that the saline water beneath changes flow direction seasonally and may be controlled by the ocean cycles (Beddows, 2003). Hydrologists have measured flow of saltwater at a distance of five km inland (Meacham, 2007) and detected salinity in the aquifer 110 km inland (Steinich and Marin, 1996). If the saline water flows inland there is the possibility that contamination may actually be reintroduced inland (Beddows, 2003) and could ultimately be much harder to control.

When precipitation falls, fractures in the rock become channels through which water flows. The Holbox Fracture System is a series of fractures running NNE-SSW from Cabo Catoche to Playa del Carmen (Beddows, 2003, Frausto, 2008). The length of the fracture system is about 100 km and about 50 km wide running parallel to the coast (Frausto, 2008). This fracture system extends to the Sian Ka'an Biosphere Reserve (Lutz, 2000). The water flow slowly causes further dissolution of the limestone, thereby continuing to widen the conduits. Many refer to these conduits as "underground rivers." This is not technically accurate but provides a good reference to understand how this water flows.

The majority of the freshwater (97%) is stored in the aquifer matrix (Beddows, 2002). Water flows through this matrix, the young carbonate rock, at the rate of cm's per year but flow rate increases dramatically when the water enters a conduit. Flow can increase up to 0.5 – 2 km per day (Beddows, 1999). Despite most of the water being stored in the aquifer matrix, more than 99% of the freshwater flow occurs in the conduits or cave system (Beddows, 2002). For this reason, the karstic cave systems are the most dominant hydrological feature of the aquifer (Gonzalez-Herrera, 2002). Virtually all water, and contaminants in the water, will eventually enter the cave systems and move rapidly through the network to be deposited in the ocean.

The porosity of the rock and the thin to nonexistent soil layer means that there are no surface rivers on the Yucatan peninsula. Fresh water is accessible by wells or sinkholes (cenotes). Cenotes (derived from the Mayan word d'zonot) are formed naturally when the ground above a dissolved conduit collapses, allowing direct access to the water in the cave. They were critical for the survival of the Mayans, Spaniards and current population living on the Yucatan Peninsula as they provided access to a year-round water source in a land that has an annual six-month dry season (LaMoreaux, 1999). Cenotes have long had cultural and religious significance to the indigenous Mayans as is demonstrated by the discovery of pottery shards, carvings and human remains within the cenotes (Beddows, 2003a). Currently cenotes are used by many people in the area as their primary source of fresh water for drinking, household and agricultural use as well as to dispose of waste water. In addition, they are valuable for recreation as tourist will pay to swim and/or dive in them.

The state of Quintana Roo receives approximately 1250 mm/year in precipitation (Semarnat, 2009). This is highly concentrated in the months of June through October when almost 70% of the rainfall occurs (Semarnat, 2009). Much of this precipitation comes during extreme weather events such as cyclones, hurricanes and tropical storms. These extreme weather events flush surface pollutants into the aquifer (Escolero, 2007). The peninsula also experiences a high level of evapotranspiration, between 70 - 90% of the precipitation that falls on the peninsula (Gonzalez-Herrera, 2002). But despite these losses, the large quantities of precipitation means that fresh water resources in the Yucatan are abundant.

***B. The Subterranean Cave Systems*:**

The extent of the subterranean cave system is extensive and yet not fully understood. Most of the caves are subaqueous though there are subaerial cave systems that have also been explored. A portion of the underground conduits have been mapped by volunteer members of the Quintana Roo Speleological Survey (QRSS) but many systems still need further exploration and systematic mapping. Over 774 km of submerged caves located within 179 distinct cave systems (both single-entrance and multi-entrance) have been explored so far (Coke, 2009), including the two longest underwater cave systems in the world: Sac Actun and Ox Bel Ha (Meacham, 2007, Gulden, 2009). There are many more kilometers of caves that have not yet been explored and many conduits that are too narrow for human exploration or in remote areas. The conduits can be very large, up to 5 meters in height and 20-30 meters in width (Meacham, 2007, Coke, 2009). The large size alone suggests that contaminant transport may be unusually fast, on the order of kilometers per day. Currently it is thought that these caves systems extend 8-12 km inland (Smart *et al*., 2006). Cave depth and the water table level varies by location but generally increases from the coast (sea level) inland (up to 30 m. depth) (Beddows, 2006).

Divers and hydrologists have discovered that there are two layers of underwater caves or conduits (Beddows, 2003a). The upper conduits occur between 0 and 20 meters of depth and generally carry freshwater seawards. This freshwater flow also entrains the top layer of saline water. These systems empty into coastal wetlands, mangroves and even directly onto the coastal reef. The deeper conduit system extends to 120 m below the surface, in one

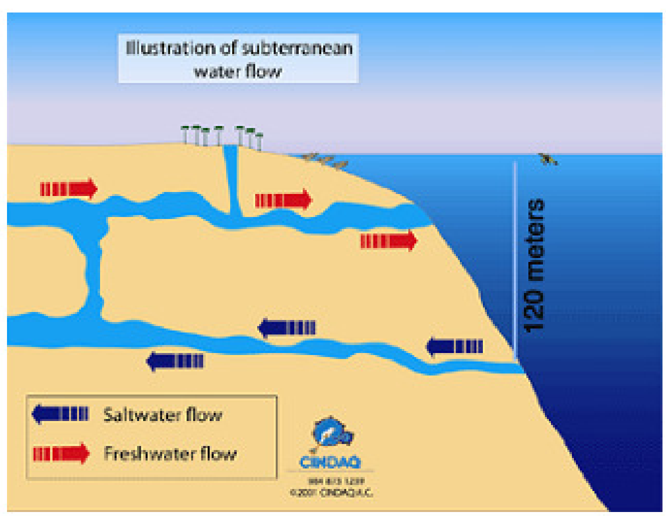


Figure 3: Two-layer conduit system **Cindaq, 2007**

explored cave, and it primarily carries saline water inland (Meacham, 2007). This flow of saline water compensates for the entrained saline water flowing towards the ocean (Beddows, 2003a).

The Ox Bel Ha cave system is still being explored but over 177 km has already been surveyed (Coke, 2009). It is recognized as the eighth longest cave system on earth (Gulden, 2009) and it travels through every major ecological zone in the area, emptying onto the reefs around Tulum. In this cave system it is possible to enter a cenote nine kilometers from the coast and travel through the underground caves to the reef without resurfacing. In fact, 13 of the longest 20 underwater caves in the world are located in Quintana Roo near Tulum (Gulden, 2009). Each cenote within the system has a variety of freshwater fish species, reptiles, amphibians, plant life, mammals and birds, some of which are endemic to the area.

It is exceedingly important to understand these conduit systems and to know how the caves are connected in order to model water flows and identify potential movement of contamination within the freshwater resource of the area.

C. The Sian Ka'an Biosphere Reserve:

The Sian Ka'an Biosphere Reserve (SKBR) is internationally recognized for being rich in biodiversity and cultural history. The reserve was declared a national park in 1986 and a UNESCO World Heritage site in 1987. It encompasses 528,000 hectares on the Eastern coast of the Yucatan Peninsula and is approximately 1/3 tropical forests, 1/3 marshes and mangroves, and 1/3 coastal lagoons, bays and marine habitats. The rainforests are part of the Gran Selva Maya, which is the world's largest continuous rainforest area north of the Amazon Basin. Over 550 terrestrial and 843 aquatic invertebrate species, 859 vascular plants, 103 species of mammals and 339 bird species (UNEP-WCMC, 2008) have been found within the reserve, as well as 40 Mayan archeological sites (UNEP, 2007). Approximately 800 people of Mayan descent live within the reserve and depend upon fishing and agriculture for subsistence (UNEP-WCMC, 2008).

Current threats to Sian Ka'an primarily involve the rapid growth of tourism along the eastern coast of the Yucatan. Mega-resorts and major highways are bringing increasingly more people to the area. This development reduces habitat, increases local demand for water and natural resources, increases effluent and pollutants, potentially alters the hydrology of the area and generally increases the number and impact of tourists to the Sian Ka'an Biosphere Reserve. Freshwater resources within the reserve may be impacted by contamination and/or salinization due to excessive water withdrawal (UNEP, 2007). Tulum is the town through which most tourists travel to see Sian Ka'an because of its proximity (see Figure 1).

D. Mesoamerican Barrier Reef System:

The Mesoamerican Barrier Reef System is the second largest reef system in the world after the Great Barrier Reef in Australia. It extends for over 1000 km along the Yucatan Peninsula, Belize, Guatemala and Honduras. This extensive system hosts a diverse array of flora and fauna as well as critical nursing and feeding grounds for a variety of marine species. The Mesoamerican Barrier Reef is recognized as one of the World Wildlife Fund's Global Priority eco-regions, which are areas of outstanding biodiversity whose protection is vital for the conservation of the world's biodiversity.

(WWF, 2002) Water from cave systems around Tulum enters directly onto the reef and is a potential source of contamination of the marine ecosystem (ArandaCirerol, 2006).

E. Tourism Development:

Tourism is an important part of the Mexican development strategy that began in the 1970s with the development of Cancun's infrastructure. The federal government's investment soon paid off as Cancun became the largest tourist destination in Latin America. The national tourism sector topped 6 billion USD in 2004 which contributed approximately 30% of the total foreign currency generated from tourism activities in Mexico (Lutz et al, 2000). Recently, the Mayan Riviera has exhibited faster growth in new tourism ventures than Cancun. Approximately 76,000 hotel rooms (nearly 20% of the hotel infrastructure in the entire country of Mexico) have been built in the state of Quintana Roo and growth is only continuing to increase. Hotel rooms along the Mayan Riviera have taken only 7 years to reach the same capacity as it took Cancun 25 years to build (Meacham, 2007).

Tourism in Quintana Roo accounts for 90.2% of the Gross State Income (INEGI, 2002). Given that it is such an important part of the state's economy, it is not surprising that growth has been encouraged by the federal, state and local governments. Specifically, the state has just finished paving the road from Cancun to Tulum which allows for easier transportation to this region by visitors. The state is also considering building a new airport near Tulum that will allow direct access to the region. The benefits of increased tourism revenues and employment must be balanced with the need to protect the natural resources that are ubiquitous in the Yucatan.

F. Population Growth:

Population in the state of Quintana Roo has grown tremendously in the past few decades, primarily to support the growing tourism industry. It is estimated that the population of the entire state has increased 994% since 1970 (INEGI, 2002). Figure 4 shows the population for the state of Quintana Roo between 1910 and 2005. Jobs in the tourism industry are created by the thousands and quality of life in the state remains relatively high (Quintana Roo has the 6th highest HDI[1] of all Mexican states, UNDP, 2004). Because of these factors, immigration into the state is rapid at 5.23%, the highest immigration rate of all Mexican states (Rodriguez-Oreggia, 2002).

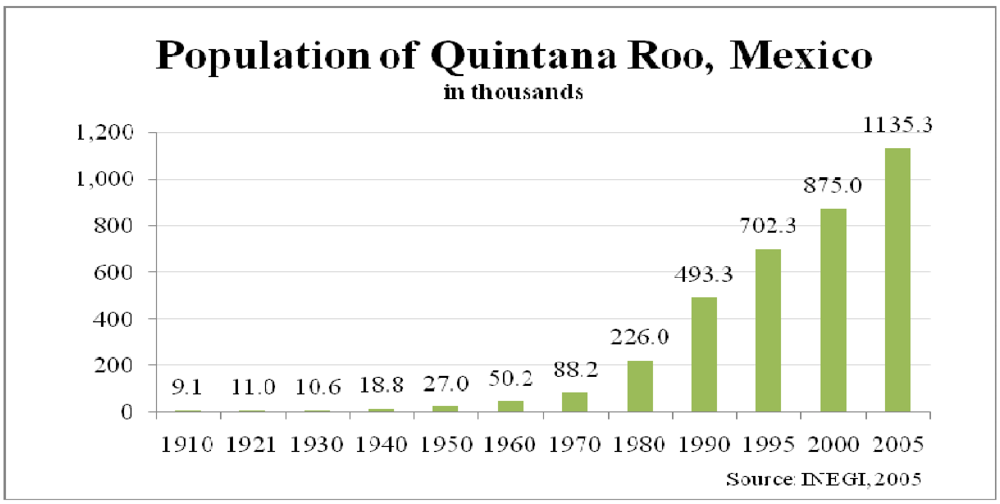
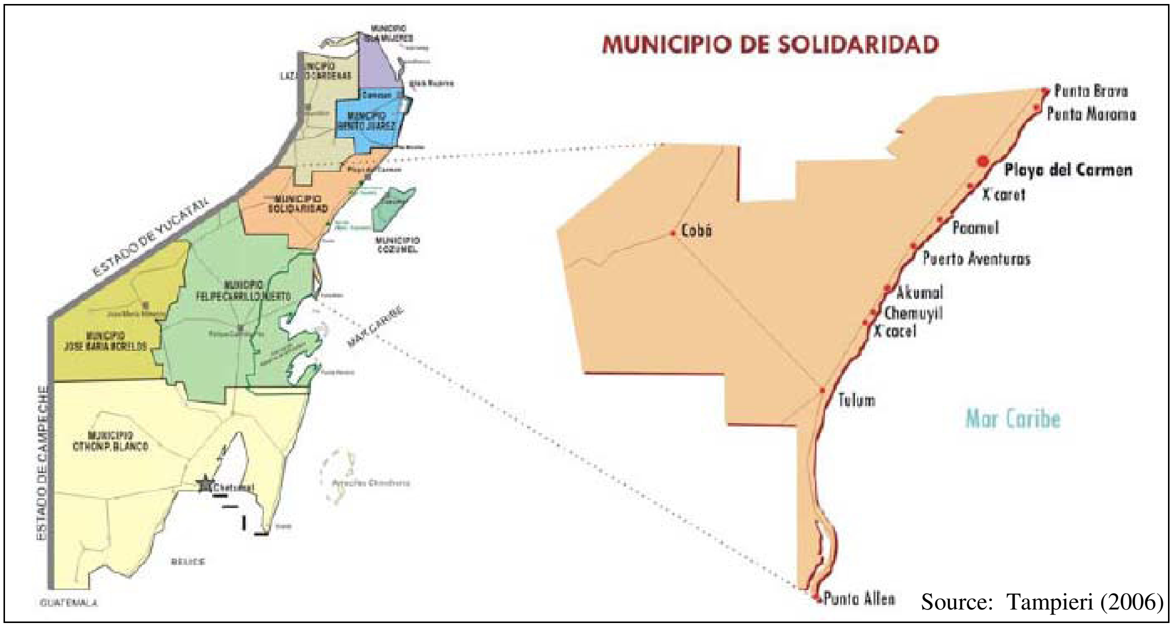


Figure 4: Population of Quintana Roo, Mexico from 1910-2005

In 2008, Tulum ceded from the Municipality of Solidaridad and formed the new Municipality of Tulum. There is, therefore, no historical statistics for the municipality of Tulum and data from Solidaridad will be used for previous population and growth statistics. The municipality of Solidaridad (shown in Figure 5, below) has undergone massive changes in the past 25 years, especially recently, growing from 28,784 in 1995 to

[1] The Human Development Index (HDI) uses variables such as life expectancy, literacy, educational attainment and GDP per capita to provide a standardized means of measuring human development.

135,512 in 2005 (INEGI, 2006). The rate of population growth for many towns in the municipality of Solidaridad is over 20% per year (INEGI, 2006) due, in large part, to tourism development along the coast. Approximately 73% of the municipality's population is employed in the services sector (Tampieri, 2006).



Source: Tampieri (2006)

Figure 5: Map of the State of Quintana Roo and the Municipality of Solidaridad

A good example of the growth of towns in the Riviera Maya is Playa del Carmen which lies 65 km north of Tulum. Twenty-five years ago, the city of Playa del Carmen was just the little town from which tourists could catch the ferry to the island of Cozumel, an important tourism island. In the 1980's the population of Playa del Carmen was 1500 which grew to 10,000 in the early 1990's and exploded to nearly 120,000 by 2007 (Meacham, 2007).

Tulum has also experienced substantial growth though it is still much smaller than other towns like Playa del Carmen. Barely ten years ago, Tulum was a small, sleepy town of a few thousand people. As of 2005, its population was over 15,000 (Meacham, 2007) and the annual average rate of population growth is 15.9% (Tampieri, 2006).

Currently Tulum is home to many Mexicans who commute to work at the large resorts along the coast (Tampieri, 2006). However, as hotels continue to develop locally, job opportunities in the service sector will attract increasing numbers of internal immigrants (and their families), creating additional pressures on resources and services.

It is estimated that between 10-18 support staff is needed per hotel room (Marin, 2007). This includes direct hotel staff plus indirect support staff (restaurant, transportation, maintenance, etc.) in the community. Given that as of December 2008 there were 76,305 hotel rooms in Quintana Roo (SEDETUR, 2009), it is easy to see the reasons behind the rapid population growth in this region. It is the local population, not the tourists, who pose the greatest threat to the freshwater system along the Riviera Maya (Marin, 2007).

G. *Water Quality Threats:*

There are several threats to the quality of freshwater in the region around Tulum, ranging from natural to anthropogenic contamination. Natural contamination could be further salinization of the aquifer due to over withdrawal of fresh water. Anthropogenic contamination includes nitrate, pesticide, herbicide and trace metal contamination caused by human activities.

The phenomenal growth in tourism and population in Quintana Roo is occurring with little regard for the natural environment, especially the quality of the freshwater resources. Hotels are required to have waste water treatment facilities and the treated wastewater is supposed to be injected into the bedrock at a depth of between 50 and 100 m (Tampieri, 2006). Deep injection can potentially further mix and contaminate the aquifer below as the less-dense waste water is pumped below the denser saline water causing the waste water to move back up towards the halocline, mixing the water layers (Beddows et al, 2005). Figure 6, below, shows the potential for contaminants from sewage disposal to circulate throughout the freshwater system and potentially impact water that is drawn up through wells (Beddows and Hendrickson, 2007). Eventually all of these contaminants will ultimately end up in the Mesoamerican Coastal Barrier Reef (Beddows, 2002). Most large hotels treat the water for their guests with reverse osmosis or desalinization (Tampieri, 2006) to ensure suitable water, so future water quality degradation of the natural fresh water will likely not affect tourists in the area.

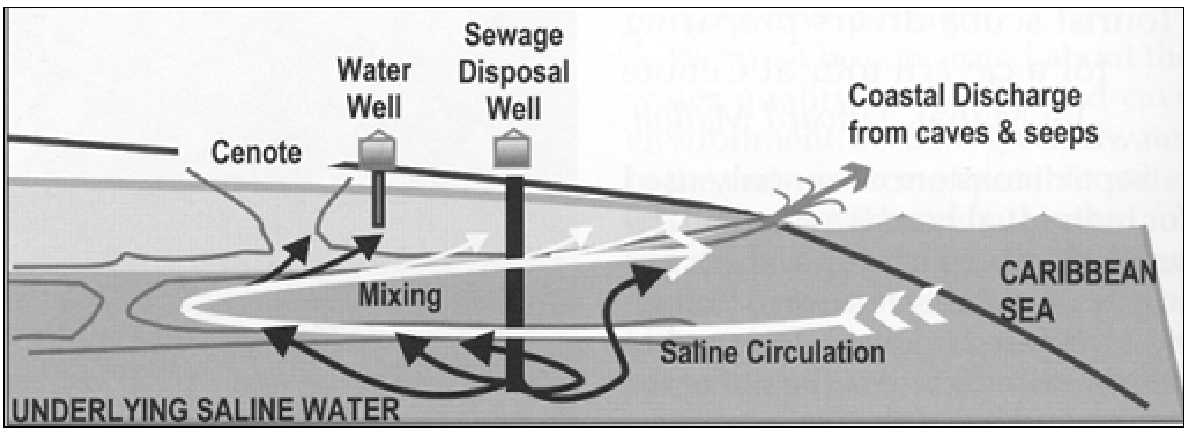


Figure 6: Potential for sewage circulation from disposal wells **(Beddows and Hendrickson, 2007)**

Waste-water injection has the potential to further distribute contaminants through the aquifer but direct contamination from cesspools and ineffective septic tanks also poses a threat to water quality. While hotels are supposed to have waste water treatment plants for their facilities, these facilities are not available to the local population. It has been demonstrated that there is a link between urban growth, disposal of untreated wastewater and nutrients pollution (Pacheco et al., 2001). The settlements of support staff that usually develop around hotel infrastructure do not have basic waste water services (Marin, 2007). "Invisible infrastructure," such as waste water treatment plants and storm sewers, has not been able to keep pace with the rate of growth along the corridor, leaving large areas with ineffective septic systems or cesspools or no waste facilities at all (Marin, 2003, Beddows, 2002). With the thin soil layer and karstic geology, it is recognized that many septic systems are inadequate as the rock does not filter out nutrients and that untreated waste is filtering directly into the aquifer (Marin, 2003, Beddows, 2002). Septic tanks should normally be emptied of solid material on a regular basis. Many homeowners in Quintana Roo are proud that they have never had to empty their septic tank (Beddows, 2002, Tampieri, 2006). This suggests that the septic systems are likely contaminating the aquifer.

Nitrates from fertilizer use are also a source of potential contamination. A study in the southern part of Yucatan State has shown nitrate levels over 200 ppm, greatly exceeding the Mexican standard of 50 ppm (Pacheco et al., 2001). It was determined that the source of the nitrates in this study was primarily from fertilizer input, not untreated sewage. This suggests that land use practices may have important consequences for groundwater quality. Additional tourist attractions, such as golf courses, are also contributing to nitrate contamination of the water supply.

Solid waste poses an additional threat to the water quality of the aquifer in the Yucatan. It has been estimated that approximately 200 tons of garbage per day is generated in the Municipality of Solidaridad (Meacham, 2007). This garbage is stored in unlined pits where it is buried or later burned. Leachates can easily travel through the limestone to the water table below. There is no water quality testing of wells located near current landfills.

Mistreatment of the aquifer can lead to serious contamination problems, as has been seen in the city of Merida in the Northwestern area of the Yucatan peninsula. Marin and Perry (1994) have concluded that the first 20 m of the 60 m thick freshwater lens in this area has been contaminated by human waste and therefore has high nitrate levels that it make it no longer fit for consumption. Land zoning for residential and waste disposal sites is a crucial key to maintaining the quality of the aquifer.

Aquifer salinization is also a big threat to future use of the fresh water resource. Salinization can easily occur when more water is being withdrawn from the aquifer than is being recharged through precipitation. With the large amount of freshwater input each year, this is less likely to happen in the Yucatan aquifer. Up-coning of saline water at well sites is another problem that usually occurs in coastal aquifers where withdrawals occur faster than water flow through the matrix allows. However, this needs to be studied further in the Yucatan. Gonzalez-Herrera (2002) found that the large conduit systems may help this aquifer stabilize more quickly than is typical and therefore up-coning of saline water may not pose the same problem as it does in other coastal aquifers.

II. Methodology:

In order to assess the threat of development on the water quality and subaqueous cave locations, I conducted two different methods of study. I analyzed water quality samples that were collected in July, 2008 to assess current water quality in wells and cenotes near Tulum. I also utilized Geospatial Analysis to characterize the current level of development and the location of known subterranean rivers in the area. The future development plan of Tulum will also be compared with the cave locations to identify areas of potential contamination in the future.

A. *Water Quality Testing:*

Samples were collected between July 20-22, 2008 from 13 cenotes and 7 wells. Locations were determined based on ability to access, distance from the ocean, distance from development, and proximity of wells and cenotes to each other. Samples from cenotes were collected within 6 inches of the surface. Wells that were pumped were determined to be in use (not stagnant) before they were sampled. Some samples were collected with buckets from the open well, some had been freshly pumped and some had been stored in storage containers that had been filled within the previous two days. Specific sampling methods are described in Appendix 1 which also includes sample name, sample date and time and description of sample location and circumstances. At the time the sample was taken, geographic coordinates were also measured with a GPS Garmin 60 using WAAS to determine location within 5 meters.

Water was filtered at the time of sampling with 0.45 µm syringe tip Millipore filters. A new syringe and filter was used at each site. Samples were stored in new high-density polyethylene (HDPE) bottles. Bottles used for trace metals were acid washed using a three-step procedure of trace metal-grade acid as follows: rinsed with 1 normal HCl then rinsed with 1 N HNO_3 and finally with 1 N HCl. Bottles were then rinsed three times with deionized water with resistivity >17.5 MΩ-cm and dried in a laminar-flow hood. Samples for anions and alkalinity were also filtered and stored in new HDPE bottles. Samples for cations were filtered directly into HDPE bottles containing 100 microliters of high-purity nitric acid preservative because samples were not going to be analyzed immediately.

To determine alkalinity (as bicarbonate concentration), samples were titrated to pH 4.5 with 0.02 N HCl after instrument had been calibrated with 7.0 and 4.0 buffers.

Trace metals (Li, Be, Mg, Ca, V, Cr, Mn, Co, Ni, Cu, Zn, As, Rb, Sr, Mo, Cd, Sb, Ba, Tl, Pb, Th, U) were determined by ICP-MS (Inductively Coupled Plasma- Mass Spectrometry) that had been calibrated with the certified trace metal solution, NIST 1643. Major cations (Ca, Mg, Na, Sr, Ba, Fe, and Mn) were analyzed with direct current plasma spectrometer, and K was measured by atomic absorption spectrometry. Certified water standard NIST 1643e was analyzed as check standard. Anion concentrations (chloride, bromide, nitrate, and sulfate) were measured using ion chromatography. When duplicates were run, the results presented in Table 1 were an average of the two.

B. Geospatial Analysis:

Geospatial analysis involved analysis of several existing data sets (including population centers, road networks and development plans for Tulum) provided by Amigos de Sian Ka'an, a Mexican NGO that works in the area. Road and population center data came from data from the Mexican government and the Urban Development Plan for Tulum came from the municipality of Tulum, Mexico. The underwater cave system survey data has been collected by many cave divers and coordinated and stored by Jim Coke of the Quintana Roo Speleological Survey. After gaining permission from each diver I was able to access a line map of the underwater cave system that has been collected by various divers over many decades.

To protect the specific location of each cave and to estimate an accurate area in which conduits exist, the cave system line data was buffered by 50 meters on each side. This buffer accommodates for the width of the cave and potential side conduits that may be too small for humans to pass through but are still important hydrologic features (Coke, 2009). This buffer also helps protect the exact location of the caves from unscrupulous

Figure 7: Excavation of a cenote courtesy of Jim Coke

landowners or developers who would like to develop a cenote on their land. Areas containing cenotes are significantly more valuable than land without them because cenotes can be a source of considerable income, relative to other financial opportunities in the area. With minor improvements and amenities, tourists can be charged a fee for swimming or diving in the fresh water. This source of potential income as led some developers to excavate the land with the purpose of "creating" a cenote (as seen in Figure 7). This opens the cave system to increased threats of direct contamination. To ensure that this practice does not take place due to my research, all caves have been buffered by 50 meters and maps are not zoomed in to high enough resolution to identify particular cave locations.

A reliable land use/land cover map is not available for the area so one aspect of this project involved the classification of land cover from a satellite image. Free, recent and reasonable spatial resolution satellite images are needed for this project. Unfortunately, only Landsat 7 images currently fulfill these requirements. The scan-line corrector (SLC) is a small device on the Landsat 7 satellite that allows for continuous data acquisition despite the forward movement of the satellite (USGS, 2003). In 2003 the SLC malfunctioned and currently collects images that are only complete in the center of the image but slices of information (up to 14 pixels or 1320 m. wide) are missing from the edges (Zhang et al, 2007). Approximately 22% of each image contains no data. Image 1 shows an example of the missing data in SLC-off ETM images. The left side of the image is the center of the frame where no data is missing and the right side of the image shows the progressively large gaps that occur.

Figure 8: Segment of SLC-off ETM+ image. Path 19, row 46 Acquisition date: 11/5/08

In order to create a seamless classification cover it was necessary to fill in the data gaps with another image of the area. As Quintana Roo is notoriously cloudy, finding relatively cloud-free images proved to be quite a challenge. The two images that best suited the projects needs were taken in December 5, 2007 (0.18% cloud cover) and November 5, 2008 (2.25% cloud cover). These dates are nearly one year apart which is not ideal but each image was corrected so that they could be used together. Radiometric adjustments account for the different sun angles. They were also atmospherically corrected with the Dark Object Subtraction method (Song, 2001) so that their values could be directly compared before classification as well as afterwards. The best method for seamless classification was deemed to be classifying each image separately and replacing the no-data lines from the original image with the classified wedges from the second image.

After the images were merged, a filter was used to smooth out speckle that is common after classification, especially for cloud edges. It was not possible to do an accuracy assessment for the classified land cover map as no reference data is available for the region. When reference data is not available it is usually the practice to utilize a resource like Google Earth to spot check accuracy. This is not an option for my study area because the satellite images used in Google Earth at the time of this analysis ranged in dates from 2002 to 2007. This time discrepancy is unacceptable as land use easily may have changed since 2002 considering the rapid changes that the region is experiencing.

The final data set used was the location of the water samples that were taken July, 2008. This includes the 20 sample locations as well as reference points that could be compared to other data sets. All data that was used was georectified to ensure that information overlapped correctly for the spatial analysis that was done next. In particular the Tulum UDP needed to be corrected by "rubbersheeting" the data to known ground points, such as roads and an airstrip.

Areas of current contamination threat were determined by locations where underground conduits were located beneath the land cover class "development" and "cleared land" as both of these classifications imply human impact on the land cover. Areas of high future threat of contamination were determined by overlaying current and future development (as projected by the municipality of Tulum) with known underground conduits. Some types of future development are considered more of a contamination threat, such as residential and commercial areas. The above ground features that are on top of the underground conduits were also analyzed to determine how much of each class was above the cave systems.

Points where water quality was sampled was overlaid with the land cover classification to determine if areas of higher contamination are within a specific land cover types.

III. Results:

A. Water Quality Testing:

Samples from the 13 cenotes and 7 wells were tested for alkalinity, anions, cations and trace metals. Table 1 below shows the results of these tests as well as seawater and Mexican water standards, for comparison. Also shown are the calculations of ion balances, or charge balance errors.

Table 1: Water samples testing results

Table 1: Water sample testing results ppm

sample	description	Ca	Mg	Na	Fe	Si	K	Cl	Br	NO_3 (as NO_3)	SO_4	$CaCO_3$	HCO_3	error (%)	Na/Cl	Ca/Na	Br/Cl
C10	Cenote - used by family for water	141.30	43.02	177.57	0.64	8.23	10.08	343.07	BDL	14.31	49.97	370.17	452	-0.12	0.80	0.46	BDL
C11	Cenote - open to public, swim	198.93	220.92	1635.77	0.75	0.00	65.10	3305.90	11.48	9.79	432.34	335.22	410	-4.74	0.76	0.07	0.0015
C12	Cenote - private, swimming	153.13	76.50	461.70	0.69	15.56	12.53	891.40	3.29	10.74	128.62	351.54	429	-1.46	0.80	0.19	0.0016
C13	Cenote - private, swimming	164.29	92.77	590.22	0.85	0.00	16.75	1127.52	4.03	11.23	156.61	351.85	430	-0.95	0.81	0.16	0.0016
C14	Cenote - private, being developed	129.09	64.31	365.07	0.00	0.00	14.06	715.17	2.55	5.03	96.94	313.83	383	-1.67	0.79	0.20	0.0016
C15	Cenote- private, in forest, not used	132.51	49.86	250.70	0.35	0.67	11.11	513.08	1.80	7.93	73.07	329.72	402	-2.47	0.75	0.30	0.0016
C16	Cenote - Ejido owned, swimming	201.24	205.64	1503.54	0.98	0.00	57.44	3088.93	9.74	11.06	406.54	338.74	414	-5.23	0.75	0.08	0.0014
C17	Cenote - in forest, not being used	106.56	27.29	201.28	0.07	0.00	10.21	357.95	BDL	BDL	50.03	265.72	324	-0.40	0.87	0.30	BDL
C18	Cenote - private, swimming	159.61	75.29	448.04	1.02	0.00	16.11	841.13	2.99	11.63	121.56	368.33	450	-0.26	0.82	0.20	0.0016
C19	Cenote - private, family uses water	85.90	8.57	58.75	0.01	1.04	1.62	116.09	0.30	0.51	6.03	205.15	250	-0.27	0.78	0.84	0.0011
C20	Cenote- Ejido, swimming, drink	137.03	49.28	250.00	0.00	1.00	9.82	476.95	1.97	10.09	71.81	338.32	413	-0.27	0.81	0.31	0.0018
C21	Cenote- restricted for protection	196.49	197.14	1408.42	1.85	0.00	55.46	2961.23	10.57	10.59	390.91	355.53	434	-6.27	0.73	0.08	0.0016
C22	Cenote- park, swimming	144.01	79.68	493.95	0.36	0.00	16.01	1011.20	3.62	9.64	143.18	332.31	406	-4.20	0.75	0.17	0.0016
W10	Well- private, several families	126.05	42.53	174.65	0.00	2.32	6.61	349.54	1.33	47.80	48.72	341.09	416	-3.01	0.77	0.41	0.0017
W11	Well- Federal Tulum well (bucket)	129.94	52.91	322.90	0.54	13.41	14.73	628.10	2.39	4.11	92.26	318.09	388	-2.32	0.79	0.23	0.0017
W12	Well- private family (rotoplus)	124.60	31.01	139.62	0.00	2.12	5.46	271.95	1.02	18.04	43.05	315.50	385	-1.09	0.79	0.51	0.0017
W13	Well- police station, bathroom tap	121.49	38.34	135.70	0.08	1.39	4.71	279.16	0.93	8.83	37.92	352.33	430	-2.38	0.75	0.51	0.0015
W14	Well- Tulum water from hotel	146.21	63.17	346.24	0.48	1.57	10.36	665.77	2.43	10.18	91.30	361.30	441	-0.94	0.80	0.24	0.0016
W15	Well-near highway, (bucket)	164.63	49.13	321.94	0.39	4.55	23.20	628.07	2.07	55.57	101.06	302.80	370	-0.98	0.79	0.29	0.0015
W16	Well- abandoned property (bucket)	120.60	49.16	382.32	1.12	2.30	17.91	714.69	2.30	11.38	103.85	266.75	326	-2.12	0.82	0.18	0.0014
Seawater		410	1350	10500				390	19000	67		2700	116		0.8522	0.0224	0.00156
Mexican Water Standards				200	0.3			250		50	400	400.00					

ppb

sample	description	Li	B	Al	Mn	Cu	Zn	As	Rb	Sr	Cd	Ba	Pb	Th	U
C10	Cenote - used by family for water	3.2	77.9	9.4	1.9	8.3	48.0	1.5	3.6	1345.3	0.1	25.0	0.5	0.0	3.1
C11	Cenote - open to public, swim	27.6	654.0	45.9	11.7	8.3	54.4	5.3	18.2	2288.9	0.0	23.2	2.7	0.0	3.1
C12	Cenote - private, swimming	8.7	194.3	172.6	4.1	19.0	62.6	2.6	5.3	1440.4	0.1	21.2	1.1	0.0	2.9
C13	Cenote - private, swimming	10.1	233.3	15.4	3.8	2.0	55.3	3.1	6.5	1510.0	0.2	21.4	0.8	0.0	3.0
C14	Cenote - private, being developed	6.2	139.2	2.7	3.7	0.0	50.7	2.4	5.1	1322.4	0.3	19.9	0.3	0.0	3.4
C15	Cenote- private, in forest, not used	4.2	106.9	34.6	3.0	3.6	58.1	1.6	3.4	1361.7	0.1	23.3	0.6	0.0	2.9
C16	Cenote - Ejido owned, swimming	26.0	645.9	6.0	7.0	1.2	59.0	5.9	17.4	2197.3	0.0	21.1	2.2	0.0	2.9
C17	Cenote - in forest, not being used	2.5	132.6	0.0	69.6	0.0	30.6	4.9	3.8	2772.1	0.1	17.0	0.2	0.0	0.8
C18	Cenote - private, swimming	7.7	176.5	0.0	3.3	1.1	52.3	2.3	5.1	1511.7	0.1	22.4	1.3	0.0	3.2
C19	Cenote - private, family uses water	0.6	39.0	0.0	14.3	0.0	50.7	0.5	1.7	514.4	0.3	10.0	0.2	0.0	0.2
C20	Cenote- Ejido, swimming, drink	6.0	134.1	61.0	5.6	5.0	55.3	3.3	3.7	1385.8	0.2	36.4	1.0	0.0	4.3
C21	Cenote- restricted for protection	27.6	678.0	35.5	10.2	4.8	55.6	6.8	18.6	2426.1	0.2	33.7	2.8	0.0	4.5
C22	Cenote- park, swimming	10.0	238.5	430.1	7.3	39.1	72.4	3.9	6.5	1330.1	0.5	33.1	2.7	0.0	3.8
W10	Well- private, several families	3.9	89.7	82.8	3.2	5.0	60.7	2.4	2.4	1181.6	0.3	28.7	0.8	0.0	3.3
W11	Well- Federal Tulum well (bucket)	6.3	167.7	75.7	41.5	3.9	45.2	4.6	6.7	2798.9	0.2	24.8	1.0	0.0	5.1
W12	Well- private family (rotoplus)	1.7	79.0	38.3	6.8	4394.2	52.6	1.0	2.5	1145.3	0.3	45.8	0.5	0.0	2.6
W13	Well- police station, bathroom tap	3.1	68.3	30.1	2.2	28.4	60.6	1.6	2.1	1284.6	0.1	24.7	1.9	0.0	3.1
W14	Well- Tulum water from hotel	5.7	131.6	93.2	2.0	82.0	103.6	1.6	3.8	1384.2	0.0	18.5	8.0	0.0	3.2
W15	Well-near highway, (bucket)	10.5	146.7	38.4	7.0	3.4	91.2	1.1	27.2	2698.8	0.0	29.0	0.4	0.0	2.1
W16	Well- abandoned property (bucket)	4.3	165.0	35.0	77.6	0.8	56.8	1.5	10.2	1883.5	0.1	25.7	0.4	0.0	1.2
Mexican Water Standards			300*	200	150	2000	5000	50			5	300*	25		1400*

*** indicates WHO standards**

Charge balance error calculation is a simple method to verify reliability of the lab analysis. Typically, an acceptable charge balance error is below 5% but that low ionic strength samples may have charge balance errors higher than 10% (Fritz, 1994). 18 of the 20 samples were below 5% and the highest charge balance error was -6.27%. These results are therefore acceptable given the levels of dilution that was necessary in order to avoid harming the equipment.

Figures 9 and 10 show the location of well and cenote samples and the concentration of the contaminants nitrate and chloride, respectively.

Nitrate ppm for Wells and Cenotes around Tulum, Mexico

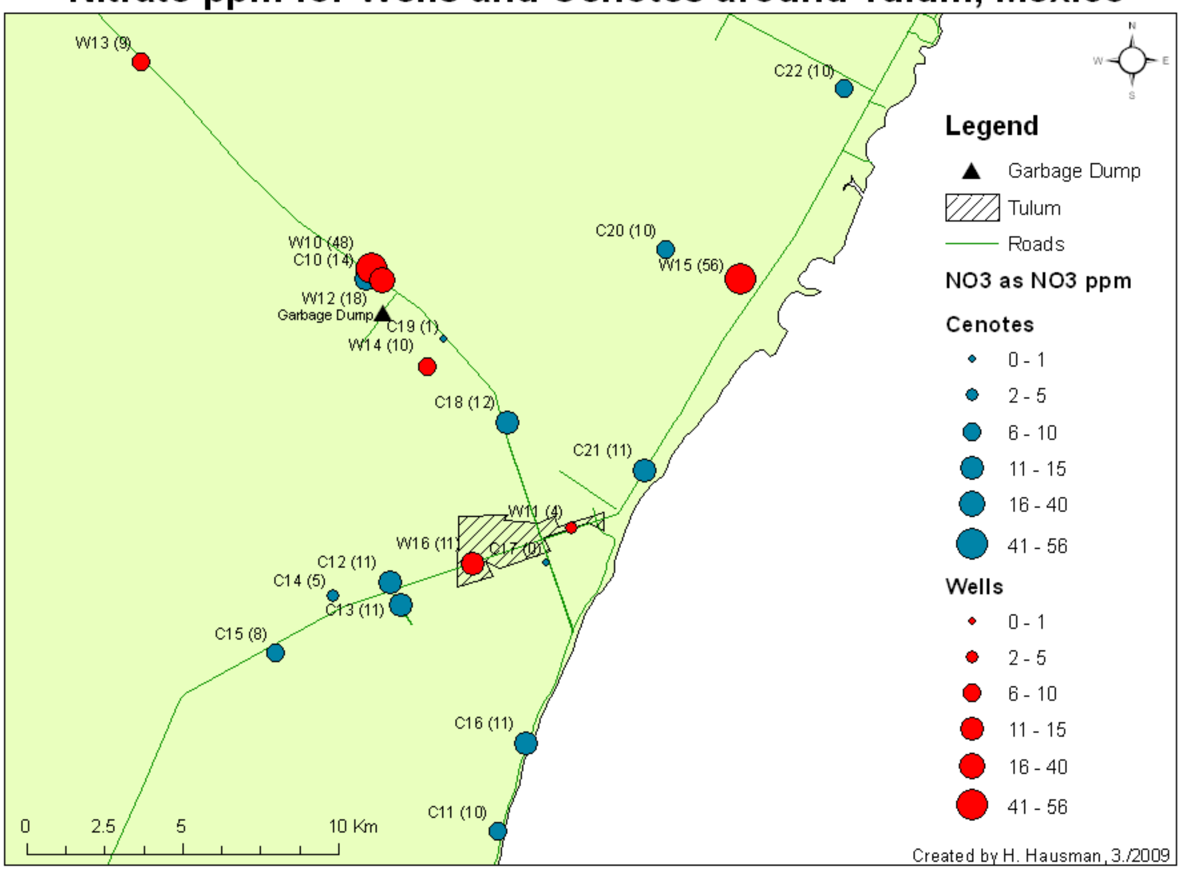


Figure 9: Nitrate ppm of sampled wells and cenotes

We can see from the map of nitrate ppm concentrations that there is a general concentration difference between wells and cenotes with only wells showing nitrate levels higher than 14 mg/L. High nitrate concentrations tend to be centralized in areas where direct contamination from above ground is likely. The highest three samples (W10, W12 and W15) are all located near agriculture or animals. For instance, after testing sample W10 the 12 year-old who was helping me walked 20 meters to feed the pigs. It is highly probable that these sources of nitrates are localized.

Figure 10 shows the concentration of chloride ppm in the samples that were taken around Tulum. These samples vary considerably between very brackish water in the coastal cenotes, to very low chloride concentrations further from the ocean.

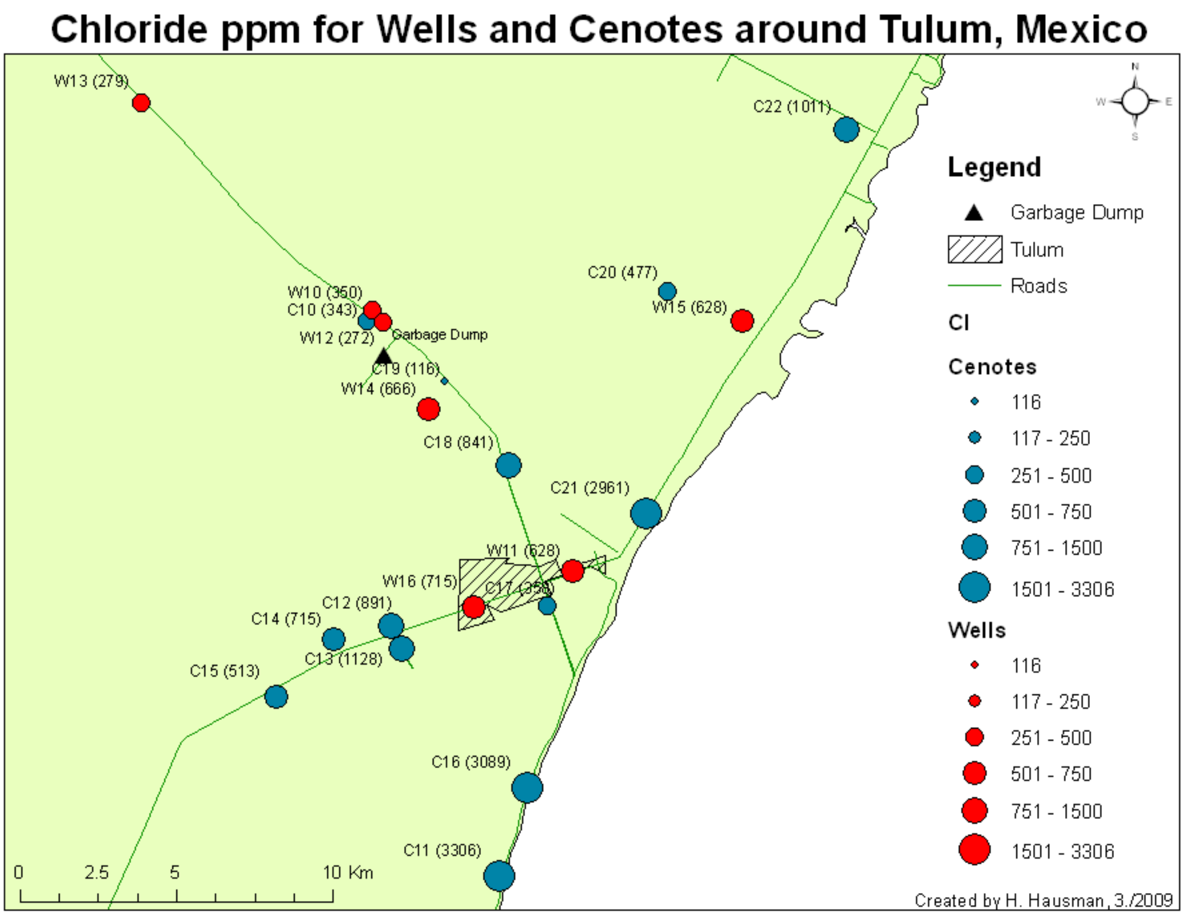


Figure 10: Chloride ppm for sampled wells and cenotes

One visible trend is the general contamination differences between cenotes and wells. As seen in Figure 11 below, most samples look very similar in terms of NO_3/Cl ratio.

Outliers for high nitrate or high chloride are only of one type of sample. For instance, only wells are higher in nitrates whereas only cenotes are higher in Cl concentrations.

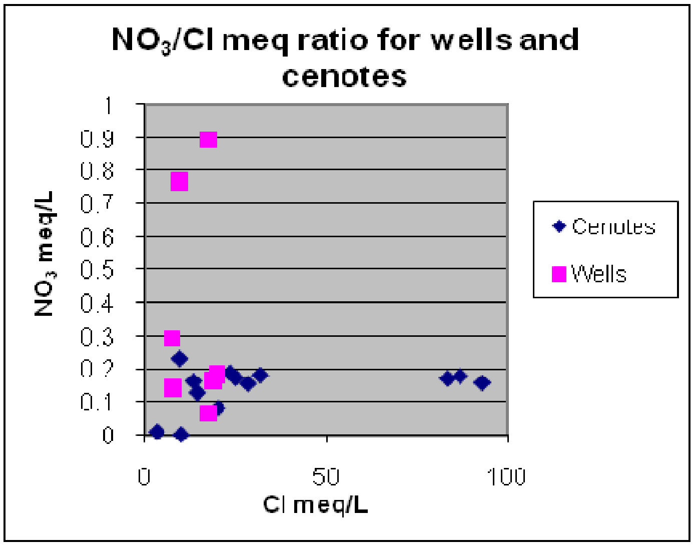


Figure 11: NO_3/Cl ratio for wells and cenotes

Figures 12-15 show the composition of the ion ratio of field samples in comparison with 5x diluted seawater. These graphs demonstrate that the salinity measured in the samples is in fact due to seawater intrusion since the field sample ratios mimic the seawater ratio. Sodium, magnesium and boron all show slightly lower levels than seawater where as Figure 15 (Ca/Cl ratio) shows an enrichment of calcium in comparison to seawater. This is due to the calcium carbonate substrate that is dissolved when freshwater flows through it.

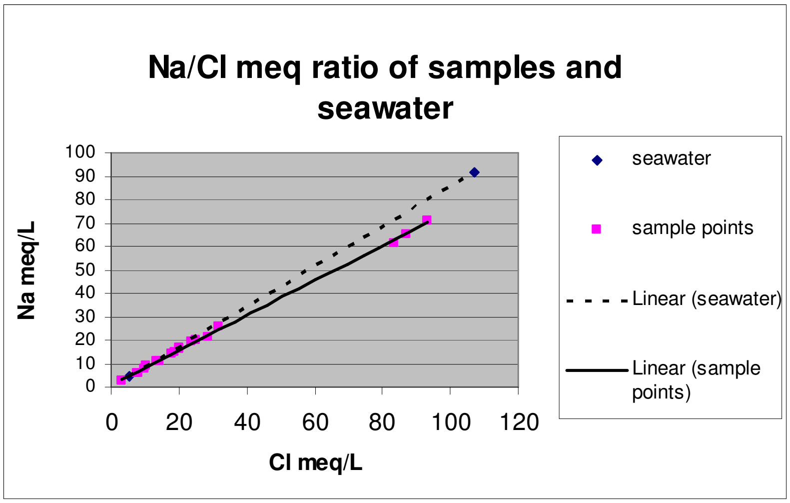


Figure 12: Na/Cl ratio of water samples compared to seawater

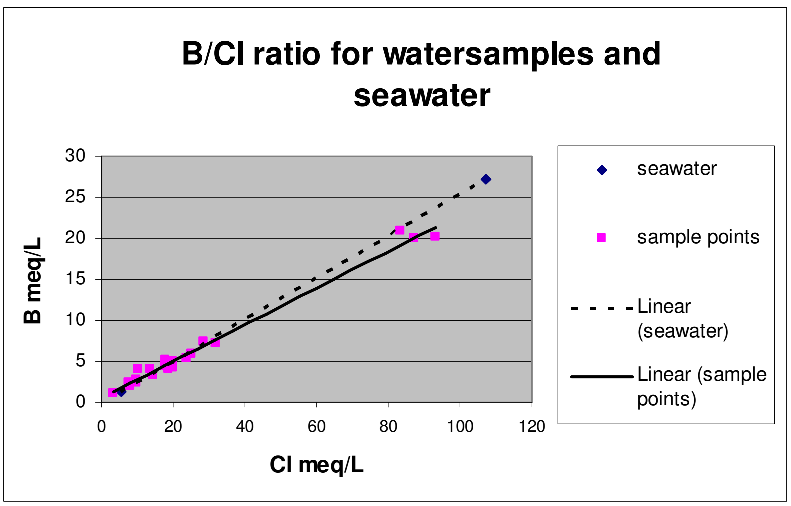


Figure 13: B/Cl ratio for water samples compared to seawater

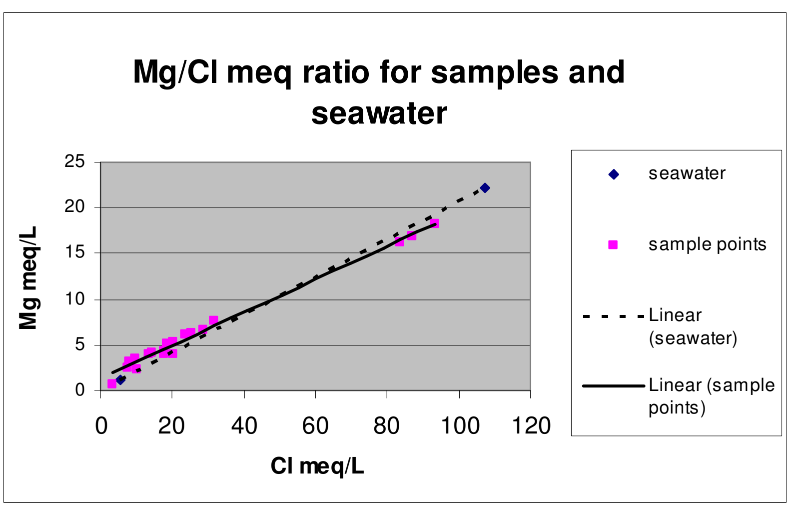


Figure 14: Mg/Cl ratio for water samples compared to seawater

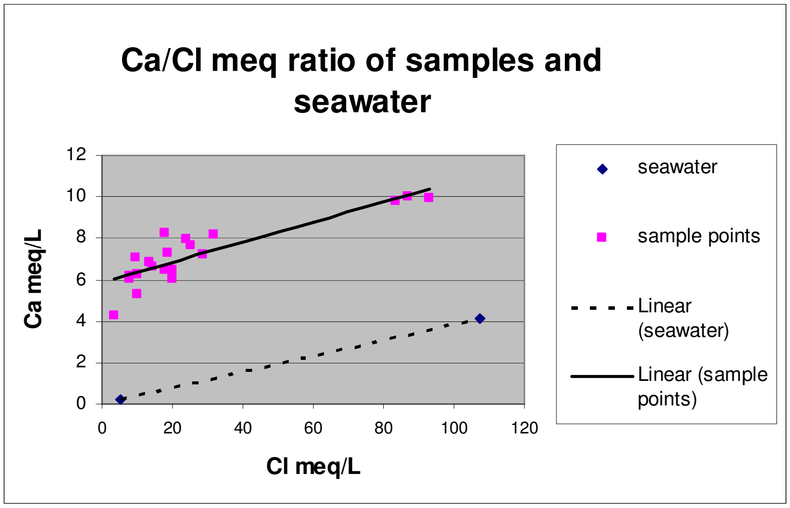


Figure 15: Ca/Cl ratio for samples compared to seawater

B. Geospatial Analysis:

The results of my satellite classification provide a recent land use/land cover map that can be used to determine the current land cover around Tulum. The map (Figure 16) shows the classification of land use/land cover from the Landsat 7 ETM+ imagery. The black lines of unclassified area are due to the merging of two different dates of data and the clouds that were present in one of those images. The primary area of study, located at the cross-section of the reads in the middle of the image, is least affected by this problem of unclassified area.

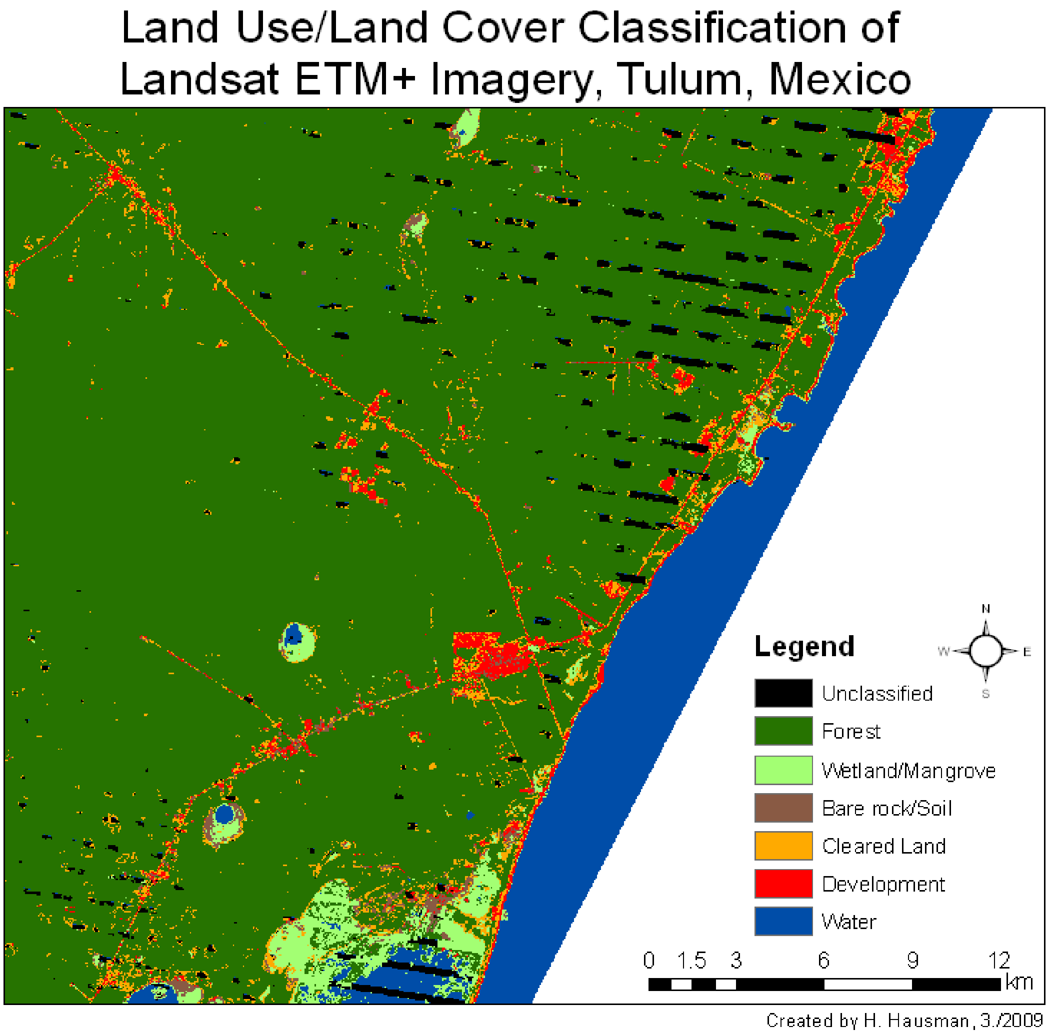


Figure 16: Classification of Land Use/Land Cover in Tulum Mexico

Table 2, below, shows the total area and percent coverage of each land use land cover type. The majority of the terrestrial landscape is forest.

Table 2: Total area and percent coverage of classified map

Land Cover Classification	*Area, ha*	*% cover*
Unclassified	2,044.9	2.47%
Forest	65,458.9	79.20%
Wetland/Mangrove	1,850.4	2.24%
Bare rock/soil	644.3	0.78%
Cleared	2,534.6	3.07%
Development	1,550.3	1.88%
Water	8,569.4	10.37%

The locations of the subaqueous caves that have been surveyed around Tulum by members of the Quintana Roo Speleological Survey are shown in Figure 17. Mapped conduits only represent those large enough for humans to dive through and it is likely that many smaller conduits are also prevalent throughout the area (Coke, 2009). Each cave has been buffered by 50 meters on each side in order to encompass the full extent of the cave and account for the groundcover from which runoff could potentially infiltrate and contaminate the cave system below. The total area of the subaqueous caves, including the 50 meter buffer, is 3,876.9 Ha or 3.9 km^2.

Also visible in Figure 17 are the locations of the sampled wells and cenotes in relation to the underground water conduits, for reference.

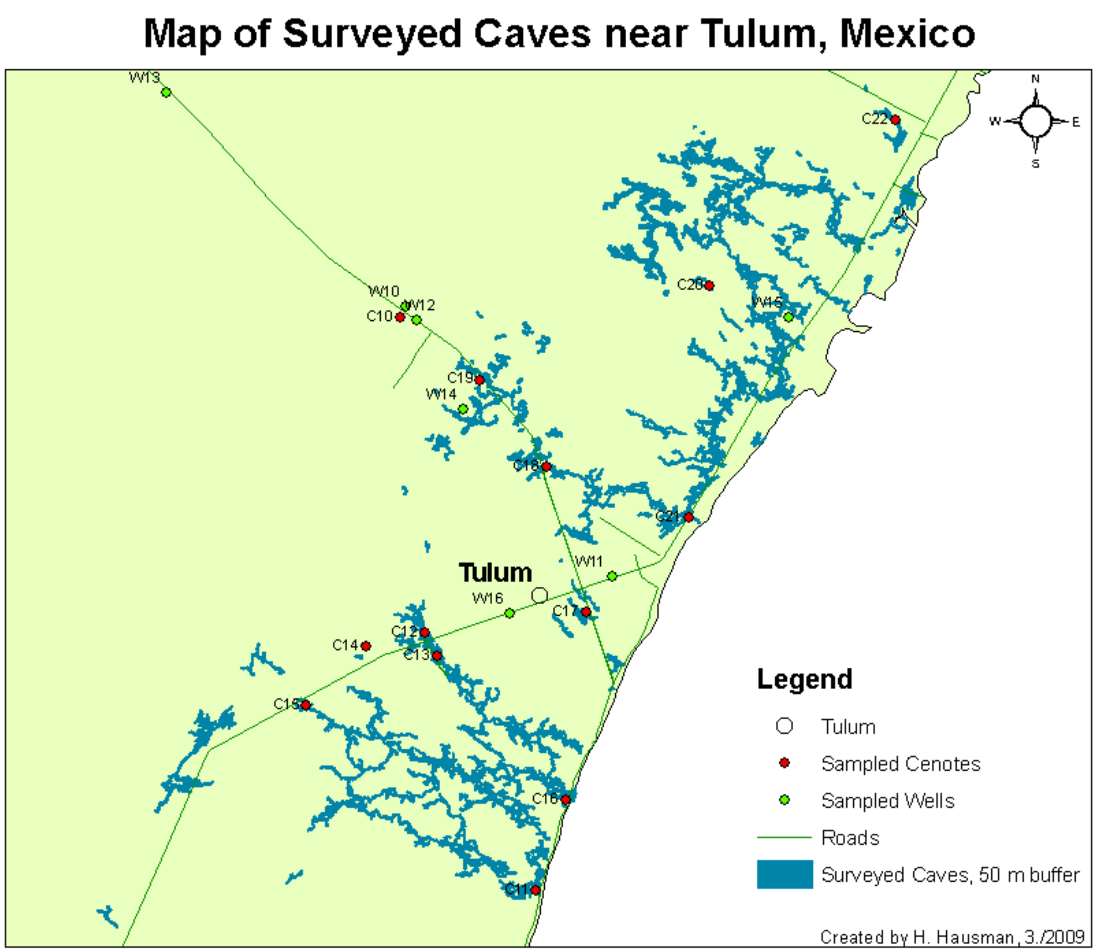


Figure 17: Surveyed caves near Tulum, Mexico and water sample locations

Figures 16 and 17 were combined to determine what type of land cover classification currently overlays the cave locations. Table 3 summarizes these findings and Figure 18 provides an image of this overlay.

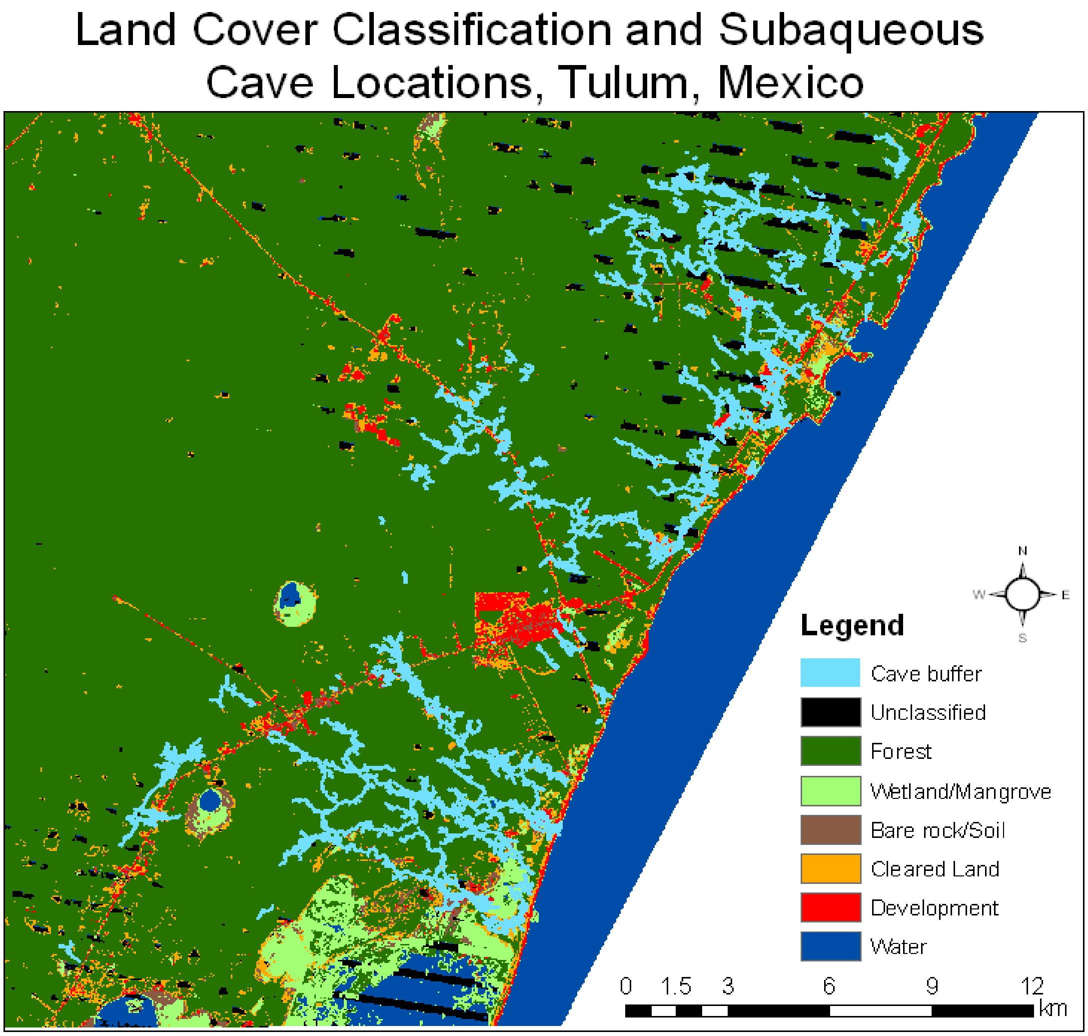


Figure 18: Land Cover Classification and Subaqueous Cave Locations near Tulum, Mexico

Table 3: Land cover classification above subaqueous cave locations

Cave Buffer coverage	*Area, ha*	*% coverage*
Unclassified	150.66	3.9%
Forest	3,170.79	81.8%
Wetland/Mangrove	68.67	1.8%
Bare rock/Soil	62.73	1.6%
Cleared Land	234	6.0%
Development	169.38	4.4%
Water	20.7	0.5%

The previous maps and tables represent the land cover that currently exists over the area of greater Tulum. For the next analyses, the recently released Urban Development Plan (UDP) for Tulum was used to estimate what future land cover would exist over the subterranean cave systems. Figure 19 shows the UDP and the underlying subterranean cave systems around Tulum. Table 4 summarizes the extent of the different UDP zones and the total area over which they extend above cave systems.

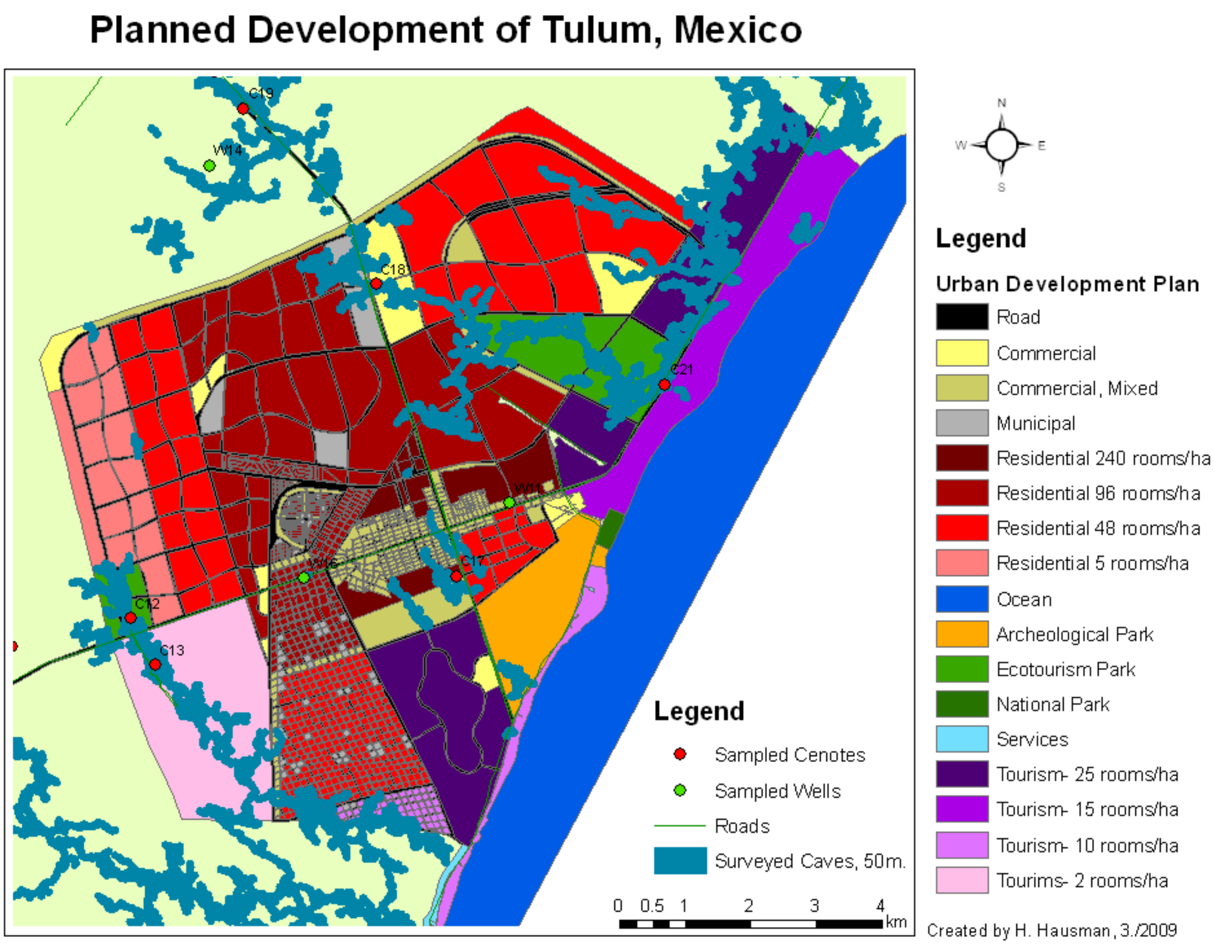


Figure 19: Urban Development Plan for Tulum and cave system locations

It is clear from Figure 19 that there are several areas where the development of Tulum will overlap with underlying cave systems. Some zones have the potential to cause more contamination of the underground water than others. For instance, residential zones currently do not have an adequate sewage systems so increased septic tanks (which are inappropriate technology considering the karstic substrate) and effluent are likely to impact water quality below. Commercial zones are also likely to have negative impacts on water quality due to the amount of people and vehicles that will be active in the area. Table 4 quantifies different zones of the UDP and the area of caves that they overlay.

Table 4: Future zoning of Tulum with cave extent area

Future Zoning of Tulum	*Area, ha*	*Area, ha (with caves)*
Road	934.3	157.6
Commercial	269.6	43.5
Commercial, mixed	451.2	43.9
Municipal	160.3	28.5
Services	66.9	17.5
Residential - 240 rooms/ha	227.4	15.7
Residential - 96 rooms/ha	1,389.5	81.3
Residential - 48 rooms/ha	1,583.2	102.1
Residential - 5 rooms/ha	382.0	9.1
Ocean	5,832.8	1.0
Archeological Park	265.7	15.7
Ecotourism Park	374.9	159.3
National Park	15.6	0
Tourism/Hotel - 25 rooms/ha	830.1	156.1
Tourism/Hotel - 15 rooms/ha	413.0	34.9
Tourism/Hotel - 10 rooms/ha	213.4	28.3
Tourism/Hotel - 2 rooms/ha	596.1	133.7
Unclassified	9.7	0
Total:	14,015.7	1,028.3

Lastly, I compared the cave systems that exist within the UDP limits. The current land cover of these caves is compared with the future land cover or zoning (according to the UDP.) The current land cover, summarized in Table 5, shows that 80% of the caves are currently covered in forest and that 14% have human impacted land cover ("cleared land" or "development") above them. This is a marked difference from Table 4, the future zoning of the land above the caves. If the UDP is implemented, over 83% of the caves will be covered in some sort of development and only 17% will be "protected" by less intense development (archeological and ecotourism parks).

Table 5: Current land cover of caves within UDP

Land Cover	*Area, ha*	*% cover*
Unclassified	33.3	3.5%
Forest	771	80.8%
Mangrove/ Wetland	3.4	0.4%
Bare Soil	6.1	0.6%
Cleared Land	70.7	7.4%
Development	64	6.7%
Water	5	0.5%

Figure 20 shows the difference between current land cover of the cave systems within the UDP limits and the land cover that would be expected with the implemented UDP.

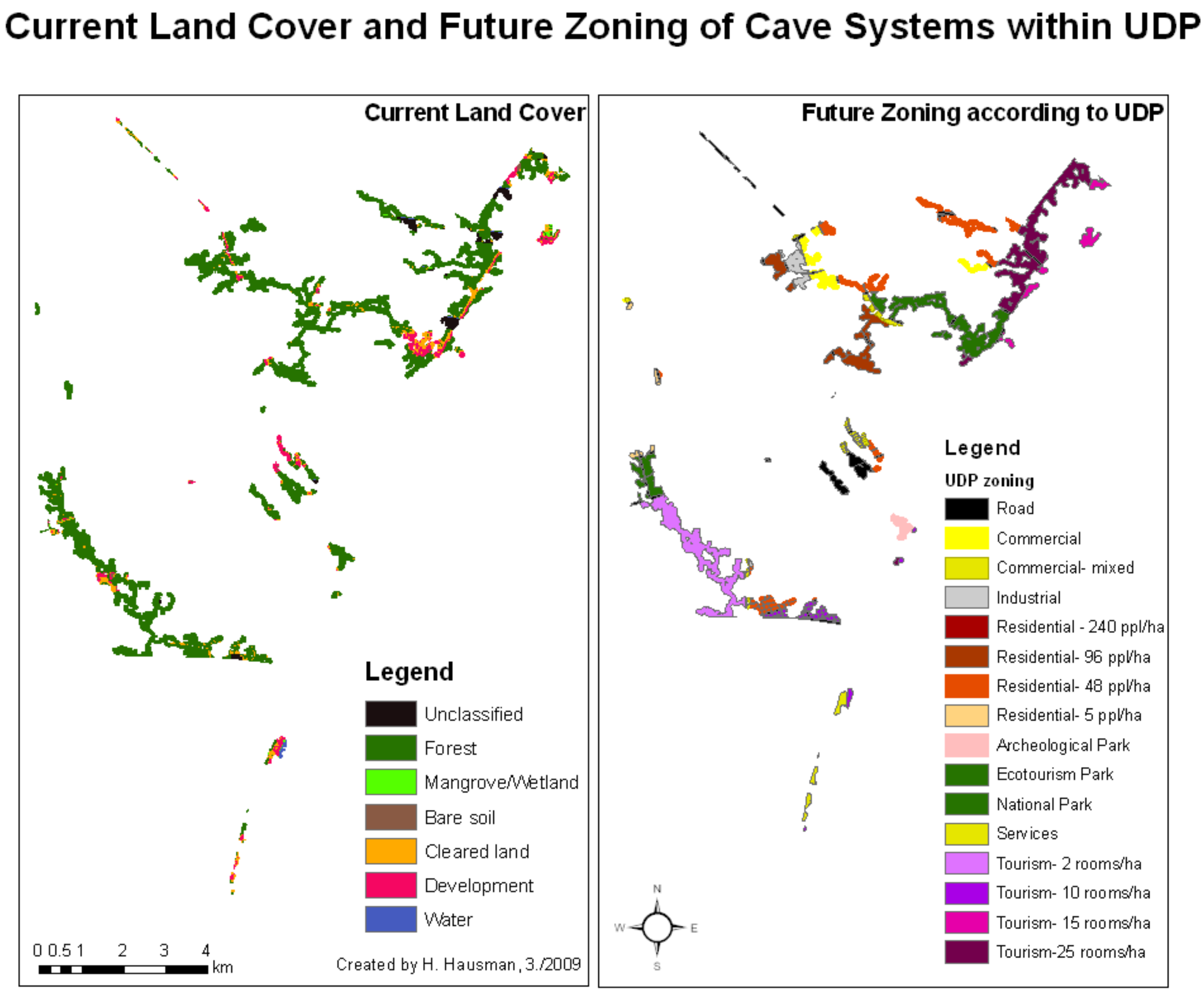


Figure 20: Current and Future Land Cover of Cave Systems within UDP

IV. Discussion:

A. Water Quality Testing:

It is clear that there are general differences between the well and cenote water samples. Table 5 shows each sample, a description of the sample site, the land cover according to the satellite image classification and concentrations of chloride and nitrates. Sample sites that are located within areas classified as "development" are shaded orange and sites classified as "forest" are shaded in green. This table shows that the highest values of chloride concentration are located in cenotes, most of which are within the “forest” class. High values of nitrate concentration are only in wells and areas that are classified as

Table 6: Sample site land cover, nitrate and choride concentration

Site ID	*Sample site description*	*Land cover*	*Cl ppm*	*NO_3 ppm (as NO_3)*
C10	Cenote - used by family for water	development	343.1	14.3
C11	Cenote - open to public, swim	Forest	3,305.9	9.8
C12	Cenote - private, swimming	Forest	891.4	10.7
C13	Cenote - private, swimming	Forest	1,127.5	11.2
C14	Cenote - private, being developed	bare rock/soil	715.2	5.0
C15	Cenote - private, in forest, not used	Forest	513.1	7.9
C16	Cenote - Ejido owned, swimming	cleared	3,088.9	11.1
C17	Cenote - in forest, not being used	Forest	357.9	BDL
C18	Cenote - private, swimming	cleared	841.1	11.6
C19	Cenote - private, family uses water	Forest	116.1	0.5
C20	Cenote - Ejido, swimming, drink	Forest	476.9	10.1
C21	Cenote - restricted for protection	Forest	2,961.2	10.6
C22	Cenote - park, swimming	Forest	1,011.2	9.6
W10	Well - private, several families	development	349.5	47.8
W11	Well - Federal Tulum well (bucket)	development	628.1	4.1
W12	Well - private family (rotoplus)	development	272.0	18.0
W13	Well - police station, bathroom tap	development	279.2	8.8
W14	Well - Tulum water from hotel	Forest	665.8	10.2
W15	Well -near highway, (bucket)	development	628.1	55.6
W16	Well - abandoned property (bucket)	development	714.7	11.4

“developed.” The correlation between wells and developed land cover is not surprising as all wells exist to serve local populations and generally would be close to “development.” The one exception to this statement is W14 which is the municipal well that is located far outside of the city (within the “forest” land cover) but whose water supplies the entire town.

Unfortunately, except for one instance, I was unable to find wells and cenotes that were near each other. Interestingly, this one set of points that are near each other have similar chloride levels but considerably different nitrate levels. These samples (W10, W12 and C10) exhibited fairly consistent chloride concentrations, at 350, 272 and 343 ppm, respectively. For nitrates, however, their concentrations (ppm) were 48, 18, and 14, respectively, with the cenote (C10) having the lowest concentration. It would be interesting to sample more pairs of wells and cenotes to see if this situation is common.

The nitrate concentrations that were measured from samples taken in July 2008 were low, mostly within the 50 ppm limit that the Mexican government has set. It is likely that these concentrations would have been substantially higher were the samples collected during the dry season. According to a study by Pacheco et al. (2001), nitrate levels declined during the rainy season from early June to November as nutrients in the water were diluted by large amounts of precipitation. It is therefore safe to assume that nitrate levels are higher in other parts of the year and some areas may certainly see nitrate concentrations well above the Mexican limit during the dry season. My sampling suggests that there is no overall trend in nitrate contamination (Figure 9), unlike the obvious trend in chloride concentration. Areas of highest nitrate concentration appear to be localized in areas where the above ground land use is likely to affect the groundwater. The wells with the highest nitrate levels (W10 and W15) were characterized by nearby animals and agriculture.

There is a clear and expected trend in chloride concentrations with respect to distance from the ocean as seen in Figure 10. Cenotes that are closest to the shore have the highest amount of salinity; chloride levels decrease further inland. This, and the results from Figures 12-15, indicates that the chloride present in the samples is due to salt water intrusion as opposed to another source of salinity. Figures 12-15 show that the ratio of ions in field samples and diluted seawater were clearly aligned. The field samples were slightly less concentrated in sodium, magnesium and boron and more enriched in calcium than seawater. This is to be expected from the dissolution of calcium into the water from the rock substrate of the aquifer.

One significant finding is that W14, the municipal well for Tulum, was measured to have chloride concentrations of 665.8 mg/L, well above the 250 mg/L limit set by the Mexican government and World Health Organization. In fact, 19 of the 20 samples tested were higher than the official Mexican limit of 250mg/L Cl (as can be seen in Table 1) and 15 of the 20 samples had more sodium than the official Mexican standard of 200 mg/L Na including the municipal well that measured 346.2 mg/L Na.

Water that the city of Tulum is currently relying upon is already more saline than federal limits allow. It is likely that increasing withdrawals to support a larger population in the future may worsen the salinity problem. Unfortunately, without access to previous records of chloride concentrations from this well, it is not possible to judge if the salinity problem is changing or if it is relatively static. This is a serious problem for the residents of Tulum who rely on municipal water, especially those who are not financially able to purchase safe drinking water. This is not an issue that tourists will have to contend with since most hotels have reverse osmosis facilities. Furthermore, if salinization of the drinking water supply worsens the municipality will have to look for other sources of high quality fresh water or consider costly alternatives such as desalinization plants for its citizens.

B. *Geospatial Analysis:*

The classification of the satellite image indicates that the vast majority of the current land cover above the underground cave systems is forest (81.8%). Just over 10% of the caves are covered by human impacted land cover ("development" and "cleared land”). Overall, this is a positive situation for the quality of the water in the cave systems as most of the area directly above the caves is undeveloped and it is therefore less likely that pollutants will infiltrate directly into the water system.

The future of the caves within the area of Tulum’s UDP will change dramatically if the UDP is eventually carried out as planned. Instead of the current situation where the majority of the land cover above caves is forest (80%) only 17% of the caves will not be developed (zoned for “archeological park” or “ecotourism park”). The current 14% of the caves that is impacted by above ground human development will increase to over 83% of the above ground cave area. This is a significant amount of change for these caves and the potential for anthropogenic contamination percolating into the water conduits will likely increase dramatically.

A fact that is perhaps more important than how much of the cave system is covered by human development is the location of the development relative to the “upstream” and “downstream” sections of the caves. Some of the cave systems shown below in Figure 21 (zoom 1) appear to only cross human development near the coast. This means that even if the human development is causing contamination, this contamination is occurring further “downstream” and thus affecting less terrestrial area (this does not, however, avoid contamination of the marine ecosystem, an equally important problem). In comparison, the cave systems in Figure 21, zooms 2 and 3, cross the road and human development further “upstream.” This means that potential contamination from human activities (from sewage as well as pollutants such as oil or gasoline from the highway) may enter the system earlier and have a larger terrestrial impact. In particular, zoom 2 shows a system that passes through much residential and commercial area before flowing into the ecotourism park. If water is contaminated by sewage infiltration, the ecopark may no longer be attractive to tourists or visitors. Protecting the "upstream" cave systems is just as important to the quality of water as the actual ecotourism park area.

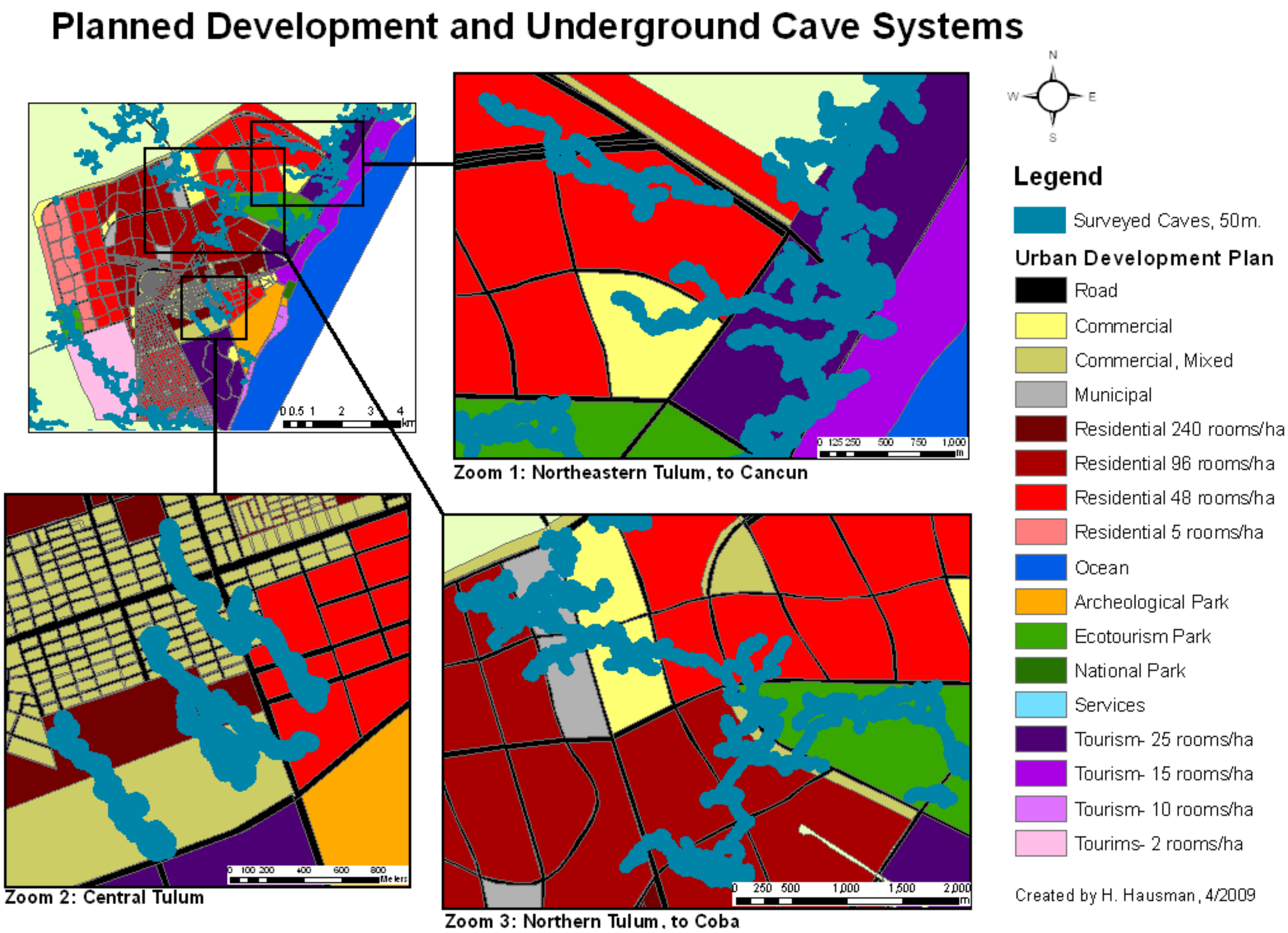


Figure 21: Planned development and underground cave systems

In general, there are some types of high impact zones that are likely to have an increased impact on the water quality located below ground. Specifically residential zones and commercial zones may have higher water quality impact. Because Tulum lacks a proper waste water treatment facility, septic systems are likely to continue being used. Over 200 hectares of residential area (zoned to different densities) in Tulum's UDP lies above cave systems. Commercial areas (85 hectares) and roads (150 ha) which cover subterranean caves may also be a large source of contamination due to the high density of development and the constant presence of human activity in the area. Furthermore, roads typically have nearby gasoline stations that may leak small amounts of hydrocarbons into the water.

In order to protect future water quality, the municipality must rezone the UDP so that the zoning takes into account the location of the cave systems. Ensuring that the areas above cave systems are zoned for appropriate use (with minimal human activity) will help reduce the potential threat of development on water quality in the future. In particular, residential areas, commercial areas and roads need to be resituated, when possible, so they are not above cave systems.

It is hopeful to see that the UDP includes an ecotourism park that covers a large area (150 ha) of caves. This area should be minimally affected by development. It appears that if the municipal government is aware of the cave locations, perhaps they will expand the "ecotourism" zone to include more areas with known caves. However, to protect the water quality in those caves the entire cave system must be protected, otherwise contaminants can enter the caves further inland or "upstream" and affect water quality in the ecotourism park.

Without question, Tulum needs a municipal waste water treatment facility so that citizens no longer use ineffective septic systems, cesspools or cenotes to dispose of their sewage. This system should not be deep-well injection of waste water as that is likely to facilitate the spreading of contaminants throughout the aquifer. A waste water facility will be a large investment but it will be well worth the avoided pollution, the terrestrial and marine ecosystem degradation and the possible loss of future tourism income if contamination becomes severe enough.

V. Conclusions:

My analysis has found that chloride and sodium concentrations in the Tulum municipal water supply currently exceed Mexican water standards. Due to the lack of previous data on chloride concentrations it is unclear if this situation is stable or worsening. Increased water withdrawals, as would be necessary to support a larger population, may exacerbate the current salinity problem.

Despite the fact that nitrate concentration levels were found to be within acceptable limits, anthropogenic contamination of the aquifer remains a threat. The results from my sampling should be considered the low end of potential concentration levels that may occur during the year. Due to the very nature of the karstic substrate and the lack of sewage treatment, contamination is a huge potential problem in the area. Tulum must learn from the example of Merida where lack of proper sewage treatment and solid waste disposal has contaminated the top 20 meters of their freshwater source (Escolero et al, 2000). Sewage treatment facilities must be a priority as must proper siting and lining of future solid waste disposal facilities.

Tulum's development is almost inevitable given the eagerness of the state and local government to create additional employment opportunities and the substantial number of investors ready to build additional tourism facilities. Before Tulum continues down its current path of growth, however, city officials need to weigh the effects that development might have on the freshwater resources in the area. It is not enough to set strict rules to regulate the environmental impact of hotels. The impact of the hotel support staff and their families must also be taken into consideration. The municipality's principle concern should be to ensure appropriate sewage facilities for everyone. Given that major development has not yet occurred, this is the ideal time to set strict zoning rules that minimize avoidable damage to the freshwater ecosystem. This can be done by ensuring that, to the greatest extent possible, land above the cave systems are minimally, if at all, developed.

Tulum may do well to follow the example of Belize and Costa Rica where the focus on ecotourism is widespread. Tourists and hotels alike value the environment while still allowing for development. With Tulum's pristine beaches, the nearby Biosphere Reserve and extraordinary underwater caves, it has natural resources that will attract visitors far into the future. By valuing these resources and resisting uncontrolled growth it could set itself apart from neighboring cities, like Playa del Carmen and Cancun. Tulum needs to protect the freshwater resource that feeds its people and the natural environment on which it relies.

Lastly, in order to be fully informed before growth continues, it would be useful if the decision makers of Tulum visit other communities in the region that are considering water quality protection in their development plans. Much can be learned from cities like Merida where human contamination of the aquifer has forced the city to invest in maintaining the quality of their freshwater supply as it never before had to. Tulum could also learn about other techniques to handle wastewater, such as the example of constructed wetlands in nearby Akumal (Whitney et al, 2003). Instead of proceeding with rapid growth at the potential expense of water quality, Tulum can be a leader to other communities by responsibly planning for growth that will not harm the water resources that sustain humans and ecosystems alike.

VI. Recommendations for Further Study:

I recommend that further research is needed to determine the extent of salinization of the current water supply for the city of Tulum. Water testing needs to occur directly from the municipal pumps during multiple times throughout the year to see if there is temporal variation. If water testing has happened in the past, these results need to be compared with current concentration levels to determine if there is a trend in chloride levels that may imply the salinization situation is worsening or stable.

Most importantly, a thorough and systematic mapping of caves needs to be performed and available to decision makers in Tulum. We cannot expect the municipality, individuals and local NGOs to effectively take the cave systems into consideration for future planning if their locations are not known. The amazing natural phenomenon of subaqueous caves needs to be protected into the future and in order to accomplish this, the extent and location of caves needs to be known and available.

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Appendix 1: Samples collection details

Sample Name	Date/Time acquired	Description/Notes
C10	7/20/08 12:58pm	"Santa Liberata" cenote. Manuel and his family use this cenote for drinking, cooking and bathing.
C11	7/20/08 2:46 pm	Cenote at entrance of Sian Ka'an Biosphere Reserve toll area. Took sample off of dock, people swimming
C12	7/21/08 11:56am	Cenote Cristal. Private "park" with paid entrance. Fish in cenote. No other visitors.
C13	7/21/08 12:15pm	Cenote Escondido. Large private cenote with many visitors. Took sample from bottom of wooden stairs.
C14	7/21/08 12:54pm	Cenote "Hatz Act" behind Rancho Sta Elena. Smaller cenote, milky blue color. In midst of being developed. Hard to filter water.
C15	7/21/08 1:38pm	Cenote in forest. Two men led me to this cenote in the forest. Small in diameter (5 m) but deep and clear with fish.
C16	7/21/08 2:38pm	Cenote belonging to Ejido on coast. Very close to sea, no visitors present
C17	7/21/08 3:41pm	Cenote across the street from fire station. Down path and to the left. Cave with large overhang along path
C18	7/21/08 5:00pm	Grand Cenote. Large private/paid cenote with many people swimming and lots of amenities
C19	7/21/08 5:26pm	Cenote behind house on main road to Coba. Man uses this water to shower. Significant algae growth
C20	7/22/08 2:20pm	Cenote Caracol. Community cenote open to paying public and villagers. All community use this water for drinking. Reading taken outside of cave
C21	7/22/08 3:23pm	Cenote Abjeas. Area is closed by Tulum Government to protect water. Guard said water was less clear due to rain previous night
C22	7/22/08 5:16pm	Cenote Xunaan Ha. Developed as park. Collected sample from wooden ladder
W10	7/20/08 12:05pm	Well serves several families. Drilled two years ago. Near agriculture and animals. Behind pink house on Road to Coba. Fresh sample taken directly from pump
W11	7/21/08 10:05am	Federal Property. Tulum well next to police station. Sample taken from bucket.
W12	7/21/08 5:43pm	Well at Rancho Dos Hermanos. House well that had been drilled. Water stored in Rotoplus container less than two days.
W13	7/21/08 6:13pm	Macario Gomez Well. Sample taken from tap in police station. Water stored in Rotoplus container on roof, recently filled.
W14	7/21/08 7:46pm	Tulum Municipal Water. Sample taken from hotel but town water is pumped from different location. Location on map has been moved to show location where water is extracted.
W15	7/22/08 2:58pm	Well from house near highway. Sample taken with bucket. Owner says water is not as clear today because of rain.
W16	7/22/08 3:54pm	Well from abandoned property. Likely cenote (could see bottom). Used plastic bucket to collect sample.