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Influence of rainy season and land use on drinking water quality in a karst landscape, State of Yucatán, Mexico

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ABSTRACT

To understand the impacts of dry and wet seasons and land use on water quality in a karst system, twenty-one deep municipal wells were sampled synoptically across the State of Yucatán. Surrounding land uses comprised urban, crop, and livestock as defined by the National Institute of Statistics and Geography of Mexico. Measurements included pH, temperature, specific conductance, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, alkalinity, NO_3^{-}, and fecal coliforms. Data were reduced using various geochemical, statistical, and spatial analytical methods and compared to a similar study on cenotes (sinkhole). Results show that 1) groundwater is diluted during the rainy season, but not for all parameters; 2) the geochemical structure of the water is obscured during the wet season; 3) the change in values for most parameters differs from that in the cenotes, however for both, fecal coliforms are higher in the wet season; 4) the relationship of land use to water quantity is unclear, however some influence of agriculture and urban were observed, and 5) water quality is at risk in both dry (NO_3^{-}) and wet (fecal coliforms) seasons. It is hypothesized that these results may be explained by changes in dominant flow paths between dry (matrix, fracture flow) and wet (conduit flow) seasons. In addition, results suggest that rock-water interactions, hydrology, and land cover maybe more important in understanding the influence on water quality than land use. Clearly, understanding the impact of both land use and season on groundwater quality in any karst environment is challenging. Further work should include using different methods for defining land use need to be explored and a more diverse set of water quality measurements need to be made.

1. Introduction

Karst terrains comprise limestone bedrock that has typically weathered to a state allowing for channelized flow of groundwater and a collapsing of the land surface, forming sinkholes (*cenote* in Spanish) (Cvijić, 1893; Schmitter-Soto et al., 2002). Karst aquifers occupy 12–25% of the Earth's surface with an estimated 25% of the world's population relying on water from such formations now (Brahana, 2007a; b), and the potential for significant increased use in the future (Guo and Jiang, 2009). Regardless of uncertainty in these estimates, there is a compelling need to bolster the current dearth of knowledge on water quality influences in karst aquifers.

Most geologic and hydrogeologic research in karst environments (e.g., Brahana, 2007a; b; Hollingsworth et al., 2008) has been aimed at understanding processes and rates of limestone dissolution (Butscher et al., 2011), especially those related to global warming (Moore et al., 2010; Ford and Williams, 2007; Guo et al., 2005) and optimization of non-Darcian flow models (Rehrl et al., 2008). While there is a significant body of knowledge on karst hydrogeology, a process-level understanding of water quality influences that may be relevant to human health, is severely lacking.

In karst settings, the presence of microbes from human waste has

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been widely reported (e.g. Meusburger et al., 2006; Stambuk-Giljanovic, 2006; Alcocer et al., 1998; Tranter et al., 1997). Chemical contaminants from human activities have also been found, including estrogen (Wicks et al., 2004), soap and bleach (Smith and Ley, 2009), agricultural fertilizers (Guo and Jiang, 2009), mining (Hg-Deng et al., 2011 and Cr-Yolcubal and Alyol, 2007), pesticides (Polanco-Rodríguez et al., 2015) and petroleum products (Fels, 1999). Contaminant transport in karst is fundamentally different from the traditional Darcian processes that occur in porous media. For example, particle transport is significant (Schwarz et al., 2011), filtration is limited (Domenico and Schwartz, 1990), and rapid flushing occurs following precipitation events, which has been believed to dilute contaminants. However, increased microbial levels have been observed after heavy rainfall and flood events (Dura et al., 2010; Boyer and Kuczynska, 2003). Chemical contaminants could also be introduced into the aquifers from such events since filtration is limited. Furthermore, flow pathways and the timing of sampling have been shown to both increase and decrease solutes during storm events (Huebsch et al., 2014). Due to the lack of knowledge and the complexity of karst systems, in this study, we examined potential influences on water quality by season and land uses in the karst aquifer of the State of Yucatán, Mexico.

2. Background and hypotheses

The study area comprised sites proximate to Mérida in the State of Yucatán, Mexico (Fig. 1; area ~40,000 km^2), whose bedrock is mainly Eocene and Pliocene with coastal Holocene sediments (Gondwe et al., 2011). Dolomite and evaporites occur locally as well as gypsum and anhydrite ejecta from the Chicxulub impact (Perry et al., 2009). The climate is tropical with a wet season (typically June–October) which is influenced by strong storms and hurricanes (Few et al., 2008; Farfán et al., 2014). The State of Yucatán contains a vast groundwater reserve, which is subject to limestone and dolomite dissolution and salt-water intrusion (e.g., Back and Hanshaw, 1970; Back et al., 1986). Recent studies have also identified human-related contaminants in the groundwater, including NO_3^-, fecal coliforms and metals (Rocha et al., 2015; Sanchez et al., 2015; Arcega-Cabrera et al., 2014, 2017; Derrien et al., 2014; Arcega-Cabrera and Fargher, 2016).

The aquifer is an unconfined flat-lying karst landscape with abundant cenotes, and little surface drainage (Escolero et al., 2000; Graniel et al., 1999; Lesser and Weidie, 1988). The topographic high is in the southwest (water Table 5-10 m above sea level) and slopes downward toward the coast (Bauer-Gottwein et al., 2011). This dominant flow path is locally influenced by conduits formed by dissolution, especially along the Ring of Cenotes and the Ticul fault (Bauer-Gottwein et al., 2011; Perry et al., 2002) (Fig. 1). As a result, groundwater chemistry does not appear to change or evolve along a particular flow path, but instead appears to be largely controlled by water-rock reactions (Back and Hanshaw, 1970; Perry et al., 2002) and influenced by local factors. The thin soils of the State of Yucatán are *terra rossa*-like consisting of mainly Leptosols, Cambisols, Luvisols, and Vertisols (Bautista et al., 2011, 2015; Krasilnikov et al., 2013). Thus, the aquifer can be easily contaminated.

The State of Yucatán includes 106 municipalities, and the largest urban area is the city of Mérida (greater metropolitan population ~1 million). Landuse/landcover is characterized mainly the intermix of agricultural activities and undeveloped areas (INFOFLR, 2016; Delgado et al., 2010). Animal farming tends to be concentrated regionally, with pig farming in the center of the state and cattle farming in the north (INFOFLR, 2016; Delgado et al., 2010, 2011). A longitudinal study (1970–1991) showed that wells in Mérida were highly contaminated by human waste (Graniel et al., 1999). Other research identified other water quality issues related to pesticides, fertilizers, NO_3^-, fecal coliforms, metals and untreated wastewater (Rocha et al., 2015; Sanchez et al., 2015; Arcega-Cabrera et al., 2014, 2017; Arcega-Cabrera and Fargher, 2016; Gonzalez-Herrera et al., 2014; Pacheco et al., 2000; Escolero et al., 2002; Li et al., 2010). In Mérida, contamination from the effects of urbanization such as untreated sewage, industrial effluent, and landfill leachate, have led to the upper 20 m of the aquifer being deemed unfit for human consumption (Graniel et al., 1999; Escolero et al., 2002).

Several studies on the influence of the wet season on water quality in the State of Yucatán help set the stage for this study. Pacheco et al. (2001) focused on the role of agriculture on groundwater quality. They measured NO_3^-, K^+, and Cl^- concentrations monthly in 12 municipal wells over the period April 1992 to March 1993. Municipal wells are pumped to supply water to local villages and are typically deeper (e.g., 30 m) than cenotes and differ in that they are not directly open to the atmosphere. These authors concluded that the source for both elevated NO_3^- and K^+ was from agricultural activities. Our study on municipal wells includes five sampling sites of Pacheco et al. (2001). Castro et al. (2018) studied the influence of wet season on karst water quality in the

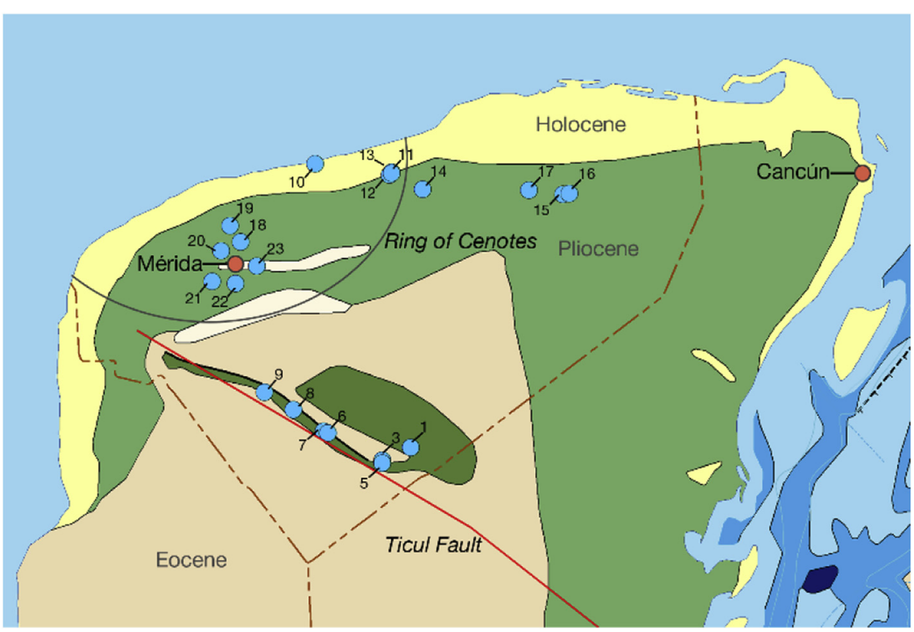

Fig. 1. Geologic map (Gondwe et al., 2011) of the state of Yucatan showing the sampling localities. See Table 1 for more information on the sampling sites.