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Research papers

Hurricane Ingrid and Tropical Storm Hanna's effects on the salinity of the coastal aquifer, Quintana Roo, Mexico

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ABSTRACT

There is a lack of information on aquifer dynamics in anchialine systems, especially in the Yucatán Peninsula of Mexico. Most of our knowledge is based on "spot" measurements of the aquifer with no long-term temporal monitoring. In this study spanning four years (2012–2016), sensors (water depth and conductivity (salinity)) were deployed and positioned (−9 and −10 m) in the meteoric Water Mass (WM) close to the transition with the marine WM (halocline) in 2 monitoring sites within the Yax Chen cave system to investigate precipitation effects on the salinity of the coastal aquifer. The results show variation in salinity (<1 ppt) of the freshwater over seasonal cycles of wet and dry (approx. 6.5–7.25 ppt), depending on the position of the halocline. The aquifer response to larger precipitation events (>95 mm) such as Hurricane Ingrid (2013) and Tropical Storm Hanna (2014) shows meteoric water mass salinity rapidly increasing (approx. 6.39 to >8.6 ppt), but these perturbations have a shorter duration (weeks and days). Wavelet analysis of the salinity record indicates seasonal mixing effects in agreement with the wet and dry periods, but also seasonal effects of tidal mixing (meteoric and marine water masses) occurring on shorter time scales (diurnal and semi-diurnal). These results demonstrate that the salinity of the freshwater lens is influenced by precipitation and turbulent mixing with the marine WM. The salinity response is scaled with precipitation; larger more intense rainfall events (>95 mm) create a larger response in terms of the magnitude and duration of the salinity perturbation (>1 ppt). The balance of precipitation and its intensity controls the temporal and spatial patterning of meteoric WM salinity.

1. Introduction

The regional geology of the Yucatán Peninsula of Mexico consists of biogenic limestone that accumulated during the Cenozoic era (Ward et al., 1985). This limestone has high permeability and porosity (Bauer-Gottwein et al., 2011). The landscape has been extensively karstified by the interaction of mixing-zone hydrology, littoral processes, and glacioeustacy (Smart et al., 2006). As a result, precipitation (i.e. rainwater) percolates though the porous substrate into the underlying unconfined coastal aquifer, where this meteoric water forms a distinct Water Mass (WM) positioned on top of the intruding marine WM from the coast. Due to density differences the WMs are separated by a halocline (or pycnocline) which is a sharp transition zone between the water bodies (anchialine; Kambesis and Coke, 2013; Perry et al., 2003). Due to the nature of the subterranean drainage as well as the low-lying topography, surface water bodies and streams are absent or very limited in the region (Metcalfe et al., 2000). For this reason, the main source of freshwater for human consumption in addition to industrial and agricultural usage is supplied from groundwater (Escolero et al., 2002).

Groundwater is sensitive and susceptible to contamination (Ford and Williams, 2013; Vesper et al., 2001), including both anthropogenic (Metcalfe et al., 2011) and saltwater contamination (Marin and Perry, 1994). Recent water quality data has shown the effects of urbanization, with groundwater contaminated with fecal coliform and nitrates near towns and developments which are often near or exceed the Mexican Drinking Water Standards (Alcocer et al., 1998; Metcalfe et al., 2011; Pacheco et al., 2001).

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This is of increasing concern, as development and planned expansion of tourism projects is projected to increase ten-fold over the next two decades (Municipalidad de Solidaridad, 2005). Increased groundwater usage with urban development and agriculture may contribute to marine intrusion and salinization of groundwater (Alcocer et al., 1998; Back and Hanshaw, 1970; Delgado et al., 2010).

Despite these increased anthropogenic pressures on groundwater in the Yucatan, there remains a lack of information on how the meteoric WM and marine WM interact over seasonal cycles or large scale weather events (i.e. hurricanes), and there is no long-term monitoring data on which to base predictions. Here we present 4-years of monitoring data (salinity, water level and precipitation) showing seasonal forcing of the aquifer but also the effects of large rainfall events (hurricanes and tropical storms). This study is important, as it is the longest record available for testing numerical modeling results (Coutino et al., 2017), but also for interpreting paleo-environmental records of groundwater response to climate change (i.e. van Hengstum et al., 2010). The paleo-records can provide long-term perspective on groundwater condition, spanning millennia of wet/dry periods but also the effects of sea-level change and periods of more intense hurricane activity (van Hengstum et al., 2016, 2013). Atlantic hurricane frequency is projected to increase with a warmer climate due to greenhouse gas emissions (Sobel et al., 2016) and it is important to understand how the coastal aquifer will respond, so that informed management strategies, and preventative measures can be developed for the Mexican Caribbean (Manuel-Navarrete et al., 2011). An integrated approach using monitoring, modeling and long-term paleo data can provide that understanding, however, there is a lack of available research to base predictions upon.

2. Study area

2.1. Regional geology and hydrologic setting

The Yucatán Peninsula is situated south of the Gulf of Mexico and West of the Caribbean Sea (Fig. 1). Regional topography is characterized by low lying limestone with high net permeability, allowing for precipitation to infiltrate through the vadose zone and into the underlying unconfined aquifer (Beddows et al., 2007; Coke, 1991; Stoessell, 1995). The coastal phreatic caves are considered as hydrologically open-systems as the flow of the groundwater predominately flows towards the ocean (Smart et al., 2006), with hydraulic gradients (considered as low) on the scale of 1–10 cm/km (Beddows, 2004; Gondwe et al., 2010; Moore et al., 1992). The aquifer is stratified, containing the meteoric WM that floats above the denser marine WM that penetrates inland from the coast (Back and Hanshaw, 1970; Perry et al., 1989). The geochemistry of the two WMs is distinct, the meteoric WM has a salinity of 1–7 parts per thousand (ppt) and average temperature of ~25.0 °C, while the marine WM has a 95% full marine salinity (35 ppt) and mean temperatures of ~27 °C (Stoessell, 1995; Stoessell and Coke, 2006). External forcing mechanisms influencing the flow dynamics on a regional scale have been ascribed to fluctuations in sea-level and hydraulic head differences (Smart et al., 2006; Whitaker and Smart, 1990). Circulation of the WMs (meteoric and marine) are unique, as the meteoric WM flows coastward (one dominant direction) whereas the underlying marine WM flows in a landward direction (Whitaker and Smart, 1990). A halocline, or transition zone, separates the meteoric and marine WM and the depth of the halocline increases with distance inland from the coast (Smart et al., 2006; Werner, 2007). For the zone that is 0–0.4 km from the coast, Beddows (2004) documented that due to low conductivity (restricted size of the conduits) the salinity gradient is steep (referred to as mixing zone; Beddows, 2004). Whereas, the zone that encompasses >0.4–10 km (and in areas of high conduit density), the gradient is less extreme and the halocline position was found to be lower than the predicted Ghyben-Herzberg principle (Beddows, 2004). A mixed layer below the freshwater lens may also be present close to the coast (<10 km) due to tidal mixing between the meteoric and marine watermasses (Beddows, 2004; Beddows et al., 2007).

2.2. Climate

Based on the Köppen-Geiger climate classification (Kottek et al., 2006), the Yucatán climate is tropical with cooler dry and warmer wet seasons, influenced by the position of the Intertropical Convergence Zone (ITCZ; Hastenrath and Greischar, 1993; Hughen et al., 1996). The ITCZ is the zonal belt of low pressure near the equator that encompasses subtropical high-pressure convergence of high-pressure belts from the Northern and Southern Hemisphere, consequently driving large scale precipitation patterns experienced within the tropics (Hastenrath, 2012; Peterson et al., 1991). The cool/dry climatic season (December to April) is a result of the ITCZ position being further south (~10 deg N latitude, i.e. below Central America; Ref. Fig. 1, Haug et al., 2003) and precipitation accumulation during this time is typically low (avg. < 100 mm per month; Negreros-Castillo et al., 2003), and often associated with effects of mid-latitude frontal systems (Stahle et al., 2016). This is in contrast to the wet season (May to November), where the ITCZ moves northward during the equatorial summer and the Yucatán Peninsula experiences increased precipitation (avg. 1000–1500 mm during the season; Hodell et al., 2007; Metcalfe et al., 2015).

2.2.1. Hurricane Ingrid – 2013

The synoptic history of Hurricane Manuel and Ingrid is unusual in that two hurricanes made landfall on opposite sides of Mexico within 24 h, a phenomenon not experienced since 1958 (Appendini et al., 2014). Manuel originated on September 12th 2013 from a strong low pressure area south of Acapulco and intensified into a tropical storm that migrated northward and received category 1 hurricane status shortly after September 18th 2013, and made landfall at peak intensity on September 19th 2013 just west of Culiacán. The storm reached wind speeds near 100 km/hr (Table 2: Pasch and Zelinsky, 2014), numerous locations recorded excessive amounts of precipitation >250 mm (1110 mm recorded in Guerrero), which had a devastating economic impact exceeding $4.2 billion USD.

On the coast of the Gulf of Mexico, Ingrid originated from a tropical depression east-northeast of Veracruz, Mexico (September 12th 2013) and became a tropical storm September 13th 2013 which moved west-southwest ward before attaining category 1 hurricane status September 14th 2013 over Northeastern Mexico (Beven, 2014). The intense precipitation caused widespread flooding, (peak areas recorded excess of 500 mm of precipitation, Tuxpan, Veracruz), attaining peak wind speeds of 140 km/hr and estimated damages at $1.5 billion USD. Appendini et al. (2014) documented that the precipitation (~1000 mm) was the largest over the previous decade (1999–2013; Appendini et al., 2014). Collins et al. (2015a) documented flooding events in several cave systems in the area from Tulum to Puerto Aventuras and the effects of the hurricane on sedimentation in the Yax Chen cave system.

2.2.2. Tropical Storm Hanna – 2014

Tropical Storm Hanna originated (remnants of eastern Pacific Tropical Storm Trudy) as a tropical depression October 22nd 2014 over the bay of Campeche, moved eastward to east-southward toward the Yucatán Peninsula, making landfall in the proximity of the eastern/southern portion of Yucatán Peninsula