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Regional response of the coastal aquifer to Hurricane Ingrid and sedimentation flux in the Yax Chen cave system (Ox Bel Ha) Yucatan, Mexico

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ABSTRACT

Coastal karst aquifers are an important source of potable water which can be affected by external forcing on various temporal and spatial scales (e.g. sea-level) but there is a lack of long-term data to understand their response. Sediment cores and their proxy records have been used in lakes and oceans to assess past environmental change, but haven't been extensively applied to anchialine caves where there is less known about the physical, biological and chemical processes affecting sedimentation. Over fifty sediment traps were placed in Yax Chen which is part of the Ox Bel Ha cave system near Tulum, Mexico and four water level sensors were placed in two additional cave systems (Ponderosa, Sac Actun) for comparative water table fluctuations. Data collected over the past three years (2011–2013) captured seasonal and spatial sediment flux including the effect of an intense rainfall associated with Hurricane Ingrid (September 18, 2013). The data indicates that sediment deposition was controlled by cenote size and the presence of mangrove. Areas upstream of Cenote Gemini had negligible sediment accumulation as there were few cenotes and the terrain is dominated by lowland tropical forest, while areas downstream from Cenote Gemini were dominated by mangrove forests and larger cenotes which resulted in higher sediment accumulation rates (0.014 vs. 0.22 mg/cm^2/day). Bi-annual sedimentation rates in 2013–2014 were higher in the months after the rainy season (0.2 vs. 0.5 mg/cm^2/day) indicating that cenote productivity was likely controlling sedimentation. Mangrove areas with their peat accumulations occlude the porous karst causing funneling of nutrient rich rainwater into the sunlit cenotes enhancing primary productivity and sedimentation in downstream areas. Hurricane Ingrid had little effect on the yearly sediment rate even though water table fluctuations were high (0.7 m) compared to the yearly values (0.3 m). This likely is due to water bypassing the cenotes with little residence time to enhance productivity and sedimentation in downstream areas.

1. Introduction

The Yucatan Peninsula has a coastal anchialine aquifer and has been used as a potable water source since the first Paleoamericans migrated to the area in the Late Pleistocene/Early Holocene (Veni, 1984; Back, 1995; Rissolo, 2001; González et al., 2008). As in other anchialine settings, freshwater sits on top of a denser saline water mass. Coastal communities around the world rely on this freshwater resource but there is little long-term information on how groundwater masses respond to sea-level or climate change. Most of our understanding comes from short-term instrumental monitoring as there are no developed proxies to examine long-term changes. Preservation and protection of freshwater reserves requires comprehensive environmental regulations, continued karst landform research, along with a long-term hydrological monitoring program (Bauer-Gottwein et al., 2011).

Sediment cores from lakes and oceans have been used extensively in the past to understand spatial and temporal trends in climate and oceanography and could be applied to cave sediments to examine long-term paleohydrology (e.g. van Hengstum et al., 2015). However, to take advantage of the information recorded by these proxies, a clear understanding of the sedimentation processes must be established, which currently does not exist.

Cave passages in the Yucatan often have karst windows or cenotes (collapsed caverns) which funnel allochthonous organic matter (OM) sediment into the cave, OM is either generated through primary productivity in the sunlit cenotes or transported from surrounding land areas via meteoric waters, but no primary OM productivity occurs in the dark cave (Pohlman et al., 1997; Benavente et al., 2001; van

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Hengstum et al., 2010). The input of OM sediment and associated nutrients defines much of the benthic life in the cave and there is little clastic sediment (e.g. aeolian dust, oxides; Gabriel et al., 2009; Steinich and Marin, 1997; van Hengstum et al., 2010). Initial paleohydrological research in Actun Ha (Gabriel et al., 2009; van Hengstum et al., 2010) had uncertainties regarding the process of sedimentation (e.g. sources, sedimentation rates, microfossil transport). In this study from Yax Chen cave system (part of Ox Bel Ha cave system), we have mapped the cave passage (bottom, ceiling and sidewall), instrumented the cave (water depth sensors) and deployed sediment traps ($n = 51$) along the length of the cave (2.5 km). For comparative purposes we also instrumented three other cave systems (Xtabay–Ponderosa cave system, Temple of Doom–Sac Actun cave system, Mayan Blue–Ox Bel Ha). The experiment was monitored for three years documenting sources and rates of sediment accumulation, but also the effects of Hurricane Ingrid (Sept 2013; Beven, 2014). The results show the effect of overlying vegetation (i.e. forest vs. mangrove type) and cenote size on sediment accumulation in the cave but also the regional water level response to Hurricane Ingrid. The results provide important background information for further paleoenvironmental studies in Yax Chen but also for cave studies worldwide, as it establishes comparative data for assessing sediment accumulation and information on the paleohydrology of the aquifer.

1.1. Geologic/hydrologic setting

The Yucatan Peninsula (Fig. 1) platform is over 350,000 km^2 of Cenozoic limestone and hosts a largely unconfined coastal aquifer (Weidie, 1985) with low hydraulic gradients of 1–10 cm/km (Marin, 1990; Moore et al., 1992; Beddows, 2004; Gondwe et al., 2010). The area is tectonically stable with stratigraphy that is largely sub-horizontal (Coke, 1991; Beddows, 2004). The limestone has high porosity combined with large cave passages that vary in dimension but often are tens of meters in size (Smart et al., 2006). This high net porosity (14–51%) allows immediate penetration of rainwater through the vadose zone to the water table resulting in few lakes or rivers in the Yucatan (Stoessell, 1995; Beddows et al., 2007). Permeability in the subsurface is increased due to mixing zone dissolution and enlargement of fractures, bedding planes and joints (Smart et al., 2006). Repeated glacio-eustatic sea-level cycles have been the primary mechanism for dissolution enlargement of the caves in the Yucatan aquifer (Back, 1995; Smart et al., 2006). There are over 1000 km of subaqueous caves currently documented in the Yucatan Region, but this value increases every year with continued exploration (Kambesis and Coke, 2013). Cavern ceiling collapse forms cenotes providing surficial access and allows the inputs of sediment to the cave passages through these karst windows (Finch, 1965; Chatters et al., 2014).

The Yucatan groundwater is density stratified with an upper meteoric lens (ML) which is positioned on top of a Marine Water Mass (MWM; Bauer-Gottwein et al., 2011; Steinich and Marin, 1997). The ML has low salinity (1–7 PSU vs 35 PSU, MWM) and a stable temperature (25.0 ± 0.2 °C vs 25.50–28.0 °C, MWM) with a thickness ranging from 56 m at the center of the peninsula to 10 m closer to the coast (6 km; Stoessell, 1995; Stoessell and Coke, 2006). The halocline or Mixing Zone (MZ) between the ML and MWM also varies with distance from the coast, becoming deeper and thinner (Smart et al., 2006; Werner, 2007). ML flow increases towards the coast and is ~1 cm/s at ~10 km inland but rises to ~12 cm/s at the coastline and is due to decreasing thickness of the ML (Moore et al., 1992).

Numerous environmental factors influence the flow dynamics in the unconfined aquifer. Regional variables such as sea-level fluctuations and differences in hydraulic head driven by climate can alter the circulation patterns in the MWM which can also affect the MZ and ML (Whitaker and Smart, 1990; Beddows et al., 2007). The response of

Fig. 1. The location of Cenotes Yax Chen, Mayan Blue, Temple of Doom and Xtabay on the Yucatan Peninsula, Mexico.