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Composition and fluxes of submarine groundwater along the Caribbean coast of the Yucatan Peninsula

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ABSTRACT

Submarine groundwater discharge (SGD) to the coastal environment along the eastern Yucatan Peninsula, Quintana Roo, Mexico was investigated using a combination of tracer mass balances and analytical solutions. Two distinct submarine groundwater sources including water from the unconfined surficial aquifer discharging at the beach face and water from a deeper aquifer discharging nearshore through submarine springs (ojos) were identified. The groundwater of nearshore ojos was saline and significantly enriched in short-lived radium isotopes (^{223}Ra, ^{224}Ra) relative to the unconfined aquifer beach face groundwater. We estimated SGD from ojos using ^{223}Ra and used a salinity mass balance to estimate the freshwater discharge at the beach face. Analytical calculations were also used to estimate wave set-up and tidally driven saline seepage into the surf zone and were compared to the salinity-based freshwater discharge estimates. Results suggest that average SGD from ojos along the Yucatan Peninsula Caribbean coast is on the order of 308 $m^3 d^{-1} m^{-1}$ and varies between sampling regions. Higher discharge was observed in the southern regions (568 $m^3 d^{-1} m^{-1}$) compared to the north (48 $m^3 d^{-1} m^{-1}$). Discharge at the beach face was in the range of 3.3–8.5 $m^3 d^{-1} m^{-1}$ for freshwater and 2.7 $m^3 d^{-1} m^{-1}$ for saline water based on the salinity mass balance and wave- and tidally-driven discharge, respectively. Although discharge from the ojos was larger in volume than discharge from the unconfined aquifer at the beach face, dissolved inorganic nitrogen (DIN) was significantly higher in beach groundwater; thus, discharge of this unconfined beach aquifer groundwater contributed significantly to total DIN loading to the coast. DIN fluxes were up to 9.9 mol $d^{-1} m^{-1}$ from ojos and 2.1 mol $d^{-1} m^{-1}$ from beach discharge and varied regionally along the 500 km coastline sampled. These results demonstrate the importance of considering the beach zone as a significant nutrient source to coastal waters for future management strategies regarding nutrient loading to reef environments and coastal development. This study also identifies the importance of understanding the connectivity of submarine spring discharge to the nearshore coastal environment and the impact of inland anthropogenic activities may have on coastal health.

1. Introduction

Submarine groundwater discharge (SGD), the discharge of subterranean fresh water and recirculated seawater to the coastal zone, occurs throughout the world's coastlines and has been identified as an important source of nutrients to many coastal ecosystems (e.g. Corbett et al., 1999; de Sieyes et al., 2008; Knee et al., 2010; Paytan et al., 2006; Slomp and Van Cappellen, 2004). Many studies have documented the impact of SGD in different environments (Burnett et al., 2003; Moore, 2010; Taniguchi et al., 2006), however SGD in karst environments may be particularly important due to rapid recharge and channelized flow pathways through fractures and cave systems. Specifically two types of flows may be present in karst systems: (1) focused fracture flow (conduits), and (2) diffuse flow through porous medium (Fleury et al., 2007; Moore et al., 1993; Perry et al., 2002). Conduit flow from deeper aquifers may discharge as submarine springs offshore. Along the Yucatan Peninsula submarine springs (locally known as ojos) are natural features of carbonate dissolution and are linked to extensive underground cavern systems (Beddows et al., 2002, 2007). Diffuse flow from SGD is also evident in the surf zone and includes freshwater from meteoric sources and recirculated seawater from tidal pumping and wave set-up.

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Submarine spring discharge in coastal karst systems can be fresh or saline depending on the geology, hydraulic head, rainfall, and extent of subsurface mixing with intruded seawater (Bonacci and Roje-Bonacci, 1997; Fleury et al., 2007). High infiltration rates and rapid flow make aquifers and coastal ecosystems in karst environments vulnerable to anthropogenic pollution including agricultural fertilizers, urban runoff, and untreated sewage from leaking septic systems and/or a lack of wastewater treatment facilities (ArandaCirerol et al., 2011). Volume and constituent loading from submarine springs to nearshore marine environments are difficult to quantify because karst connectivity can be an intrinsic system of open conduits with focused discharge points that vary greatly in space, magnitude, and quantity within one region (Fleury et al., 2007). There is a need to better understand how anthropogenic activity and groundwater delivery in areas with karst geology are linked to land use and pollutant transport that impact local coastal ecosystems.

Groundwater flow and discharge to the Yucatan Peninsula coast has been estimated using regional water balance considerations for the Peninsula as a whole (Hanshaw and Back, 1980), for the north coast (Smith et al., 1999), and for the east coast (Beddows et al., 2002) and the potential impact of associated nutrient loads was recognized (Herrera-Silveira, 1998). Nitrogen (N) is often the limiting nutrient in coastal marine environments although phosphorus (P) discharge to nearshore environments in karst regions is extremely low because of interactions with calcium carbonate (Fourqurean et al., 1993), thus P may also be of interest in these systems. Specifically, nutrient ratios of the discharging water may affect productivity and species abundance and distribution in coastal ecosystems in karst settings. Furthermore, human impact may alter the natural nutrient ratios through agriculture and development both along the coastline and inland at the recharge areas.

Anthropogenic activities that increase nutrient delivery to coastal waters are responsible for shifts in phytoplankton community structure and degradation in the health of coral reefs and seagrass beds throughout the world (Chérubin et al., 2008; Haynes et al., 2007; Paytan et al., 2006). In the Yucatan Peninsula, rapid population growth and development, tourism, and agricultural practices with intensive fertilizers have increased pressures on coastal resources and have raised concerns about groundwater pollution and overall coastal ecosystem health (Metcalfe et al., 2011). The objectives of this study are to quantify SGD contributions from both the beach face and ojos along the eastern coast of the Yucatan Peninsula and to estimate the nutrient fluxes to the nearshore coastal reef environments associated with SGD. Four sites located in different geomorphological regions and with different land-use practices were selected to determine regional and site specific fluxes and relate them to human activities near the coast.

2. Methods

2.1. Study region

Four sites (Cancun, Puerto Morelos, Sian Ka'an, and Xcalak) located in the state of Quintana Roo that borders the Caribbean Sea on the eastern coast of the Yucatan Peninsula were sampled (Fig. 1). The Yucatan Peninsula is a low-relief limestone platform. The south central area has the highest elevation, up to 250 m above sea level. The rainy season in the region is between June and October and precipitation ranges from 900 to 1500 mm yr^{-1} (Chavez-Guillen, 1986; Perry et al., 2002). The area is characterized by minimal surface runoff due to high infiltration rates but a lag of several months may exist before peak discharge of groundwater to the coast occurs (Michael et al., 2005; Perry et al., 1989).

The Yucatan Peninsula can be divided into six regions based on hydrogeochemical and physiographic characteristics (Perry et al., 2002). The hydrogeochemical zonation of the Peninsula is based on differences in tectonic history, rainfall, rock type, and erosion (Perry et al., 1995). Cancun, Puerto Morelos (PM), and Sian Ka'an are located in the Holbox Fracture Zone/Xel Ha Zone, whereas Xcalak is located in the “Evaporite Region” (Perry et al., 2002). Recent studies suggest that Sian Ka'an is located in the Rio Hondo

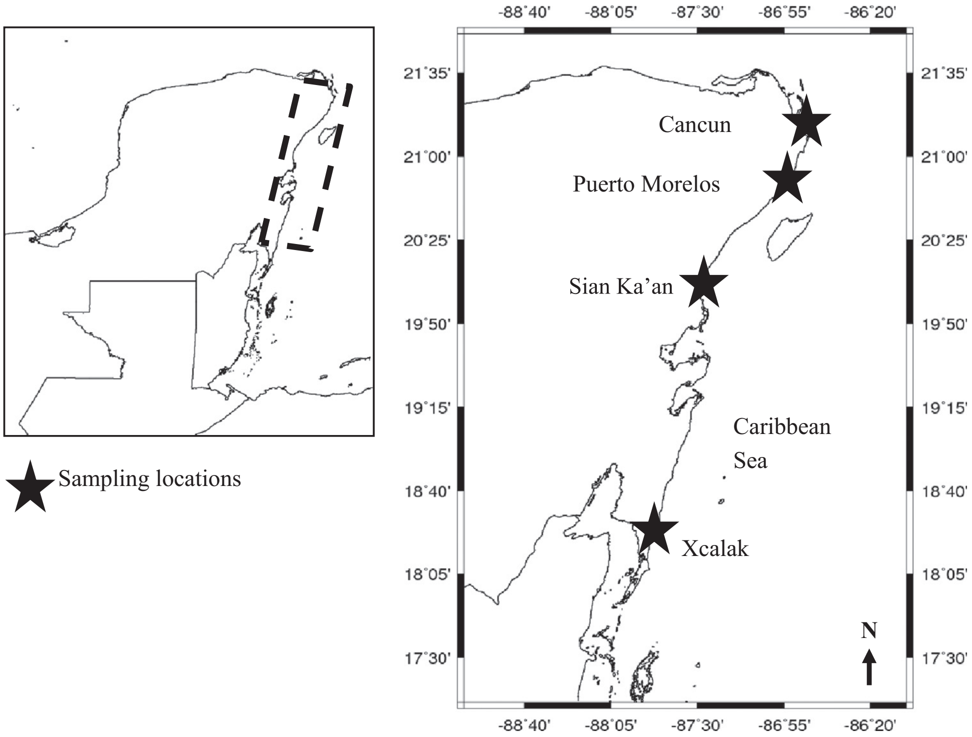

Fig. 1. Map of the four sampling sites (Cancun, Puerto Morelos, Sian Ka'an, and Xcalak) located along the eastern Yucatan Peninsula, Mexico bordering the Caribbean Sea.