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Decoupled fresh–saline groundwater circulation of a coastal carbonate aquifer: Spatial patterns of temperature and specific electrical conductivity

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Summary The coastal carbonate aquifer of the eastern Yucatan Peninsula discharges groundwaters to the Caribbean Sea. Temperature and specific electrical conductance (SEC) are used as natural tracers to gain new insight into the fresh and saline groundwater circulation along an 80 km section of the Caribbean coastline. The aquifer is density stratified, with a cooler freshwater lens overlying a warmer saline water zone. Non-conduit sites generally have lower temperatures and SEC in the freshwater lens than conduit sites. In conduits <1 km from the coast, there is a very rapid increase in both fresh water temperature and SEC indicating very active mixing with the underlying warm saline water. Further inland, the rates of change of SEC and temperature are lower, and conduit morphology and network geometry are important controls on salinisation along the conduit flow paths. Turbulent mixing is enhanced by flow around obstacles where the conduit spans the mixing zone (sites 1–4 km inland), but mixing is limited where the conduit is entirely filled with fresh water (sites >4 km inland). Within the shallow saline water zone, temperature decreases exponentially with distance from the coast, with near equilibrium with the fresh waters reached at ~10 km inland, a distance coincident with the known limit of conduit development. This pattern is indicative of the progressive cooling of warm seawater moving inland from the coast, a flow direction opposite to that of both the conventional freshwater flow entrainment and geothermal convection models of coastal aquifer circulation.

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Introduction

There is an increasing recognition that groundwater discharge to the oceans from the continents is of large magnitude (Moore, 1996, 1999; Bokuniewicz, 2001; Bokuniewicz et al., 2003). New results using geochemical tracers show that previous estimates using seepage meters and diffusion gradient models have significantly underestimated the net contribution. For example, Moore (1996) showed that groundwater discharge was 40% that of river discharge along a segment of the South Carolinian coast. Subsequent studies have shown that this apparent volume of submarine groundwater discharge is in part due to local recirculation of saline water at shallow depth but that nonetheless is of great significance to the redistribution and discharge of nutrients and other solutes to the near-coast waters (Shaw et al., 1998; Burnett et al., 2003). The term ''submarine estuary'' has been coined by Moore (1999) in recognition of the magnitude and geochemical importance of submarine groundwater discharge to land—ocean subterranean exchange and recirculation along diverse coastlines of the world. Along carbonate coastlines, there is commonly a paucity and even absence of surface river discharge (Bokuniewicz, 2001; Bokuniewicz et al., 2003). Thus groundwater discharges and the behaviour of the ''submarine estuary'' are of even greater significance than in non-carbonate terrains.

Unconfined coastal aquifers are density stratified, with a fresh water lens (FWL) overlying a saline water zone (SWZ). The two water bodies are separated by a mixing zone (MZ). The conventional model for groundwater circulation in coastal aquifers indicates that the more rapid coastward flow of the FWL entrains a parallel but slower coastward flow of the shallow SWZ, with a compensatory inflow of saline water at some depth (Henry, 1964). The progressive entrainment of saline water into the FWL along the flow path results in a gradual salinisation of the FWL towards the coast (Fig. 1).

Early development of this model for coupled fresh—saline groundwater circulation in coastal aquifers was undertaken by Hubbert (1940), Cooper (1959) and Henry (1964). Subsequent studies particularly by Kohout (1965) in Florida demonstrated that in thick carbonate aquifers, the circulation of the saline groundwater might be augmented by geothermal heating of cold seawater inflowing at depth from the adjacent oceans. Others have considered the possibility that saline circulation will be augmented by increases in the density of the saline fluids, for instance due to evaporative concentration (Adams and Rhodes, 1960; Jones et al., 2002). In addition, differences in sea surface height from high to low temporal frequencies (tidal to seasonal) may drive shallow saline circulation simply through elevation head (Dillon et al., 1999; Chanton et al., 2003).

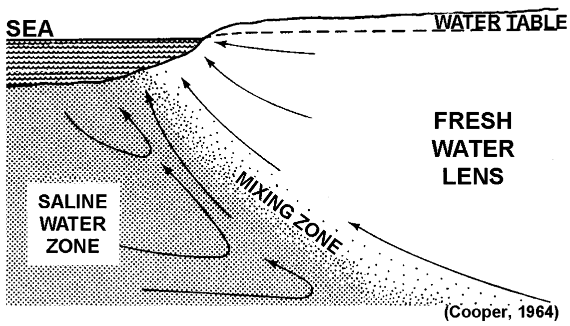

Figure 1 Conventional model of density stratified groundwater circulation in an unconfined coastal aquifer (modified from Henry, 1964).

Groundwater flow modelling has broadly supported the role of these head and density dependent drives in enhancing saline circulation. However these models generally only consider homogeneous aquifers or aquifers with equivalent porous medium conditions (Sanford and Konikow, 1989a,b; Jones et al., 2000; Wilson, 2005) whereas carbonates aquifers are typically highly heterogeneous with porosity features from intergranular pores to large caves spanning five or more orders of magnitude in size scale (Quinlan et al., 1996; Worthington et al., 2000), and resulting in a strong scale dependence of hydraulic conductivity (Whitaker and Smart, 1997). Wilson (1989) drew attention to the large discrepancy in the predicted thickness of FWL in the homogeneous coupled reactive transport groundwater flow model of Sanford and Konikow (1989a,b) compared to his field observations in the Yucatan Peninsula. He ascribed the difference in the calculated depth of the MZ to the presence of cave systems. Such flooded cave systems comprise turbulent flow conduits within which complex density dependent flow structures similar to those in open channel flow in surface estuaries can be set up. Continuous large magnitude flows of seawater through conduits traversing the island of Cephalonia (Greece) in the Mediterranean have been well documented, with several sites being historically developed as ''sea-mills'' (Stringfield and LeGrand, 1969; Drogue and Soulios, 1988; Drogue, 1989). In Florida, complex fresh (brackish)—saline groundwater flows occur in a number of coastal conduits, including Jewfish Sink, Horseshoe Crab Sink, and Crystal Beach Springs, all located on the Gulf coast (Garman and Garey, 2005). However the saline influx in these sites may in part be induced by over-exploitation of the terrestrial fresh groundwaters, altering the relative land—ocean hydraulic gradients. Drogue and Bidaux (1986) report on the tidal inflow of saline water while the overlying fresh water continuously discharges from a coastal conduit in a karst aquifer on the Mediterranean coast of France. On the east coast of Andros Is., flow meters deployed in flooded conduits showed flow direction reversals in response to semi-diurnal tides (Whitaker and Smart, 1990, 1993). As in surface estuaries, the circulation of fresh and saline groundwater in such coastal conduit networks developed near sea level can be highly responsive to changing boundary conditions, and present complex and non-steady state patterns with semi-diurnal flow reversal. This may also affect interactions between fresh and saline groundwaters, limiting entrainment of saline water by the FWL where flow is concentrated within coastal conduit systems.

In this study we focus on the behaviour of groundwater circulation in the Yucatan carbonate coastal aquifer. The flooded caves explored along the Caribbean coast are a particular focus as they account for 99% or more of the fresh water flux to the ocean in this area (Worthington et al., 2000). This spatial concentration of flow within discrete features draining to point discharge along the coast