DENSITY STRATIFIED GROUNDWATER CIRCULATION ON THE CARIBBEAN COAST OF THE YUCATAN PENINSULA, MEXICO

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Introduction

The Dupuit-Ghyben-Herzberg (DGH) model provides a simple description of the steady state balance between fresh and saline water in density stratified coastal aquifers. However, the dynamic circulation of fresh water towards the coast is thought to induce entrainment of the underlying saline water (Cooper, 1959) and results in a mixing zone between the fresh and saline water such that coastal discharges are often brackish. A compensatory inflow of saline water must occur at depth.

In coastal karst aquifers, dissolutional porosity develops preferentially in the mixing zone and thus increases the overall aquifer permeability. This leads to the development of horizontally extensive cave systems that significantly increase groundwater circulation in depth zones related to present and palaeo sea-levels, and may effectively reduce lens thickness from that predicted by the DGH model. The challenge is to understand the behaviour of density stratified groundwater circulation in highly karstified systems, such as that developed on the Yucatan Peninsula, Mexico, that are known to competently drain the large inland catchment area via point discharges at coastal springs. In this study we have used cave diving to access groundwaters within the caves, and to install instrumentation for long term monitoring. Here we report preliminary results of a multi-seasonal regional study of coastal carbonate aquifer hydrodynamics.

Study Area

The Yucatan Peninsula is an extensive (75 000 km^2) low lying carbonate platform situated between the Gulf of Mexico and the Caribbean Sea. The limestone ranges in age from Palaeocene in the interior to Quaternary on the coastal margins (Lesser & Weidie, 1988). Cave diving exploration along the Caribbean coast has identified at least 74 horizontally extensive submerged cave systems with a combined length greater than 400 km and an average maximum depth of −16 m (QRSS, 2001). The abundant vadose speleothem deposits indicate that the large passages (often > 10 m wide) have formed during previous sea level high stands, and have been reoccupied by the present fresh water lens. The mixing zone which is visible to the eye as a defined interface, lies in the middle of much of the shallow explored passage supporting the hypothesis that mixing zone corrosion is the dominant control on speleogenesis in this aquifer.

Quantitative dye tracing conducted over 5 km in Sistema Nohoch Nah Chich shows that 99.7% of the fresh water flow occurs in the cave conduits (Worthington et al., 2000), which link to coastal springs that are often located at the headward end of inlets known as caletas. Significant saline circulation is demonstrated by the brackish nature of the spring discharge, as well as an increasing number of points with hydrological connection to deeper voids (The Pit, Sistema Dos Ojos, -119 m; Blue Abyss, Sistema Nohoch Nah Chich, -74 m). The focus of the present study is Sistema Ponderosa (Figure 1) as it provided good access across the mixing zone into saline water over almost 1 km of passage, and the site demonstrated significant fresh water flows.

Spatial Variation In Thermal And Salinity Gradients

Regional thermal and salinity gradients are examined here using a data set of specific electrical conductance and temperature values from surface water bodies and hand dug wells as determined with a WTW temperature-conductivity probe. In-cave values are drawn from the isohaline and isothermal zones of profiles obtained with a YSI 6000XL multi-parameter probe during controlled descents through the water column (Figure 2). Data are not included in this study for open cenotes.

The inland fresh groundwater (from 10 km inland to 50 km inland) has an average conductivity of 1.2 ± 0.3 mS/cm (n=11) and temperature of 25.0 ± 0.2 (n=8), reflecting the

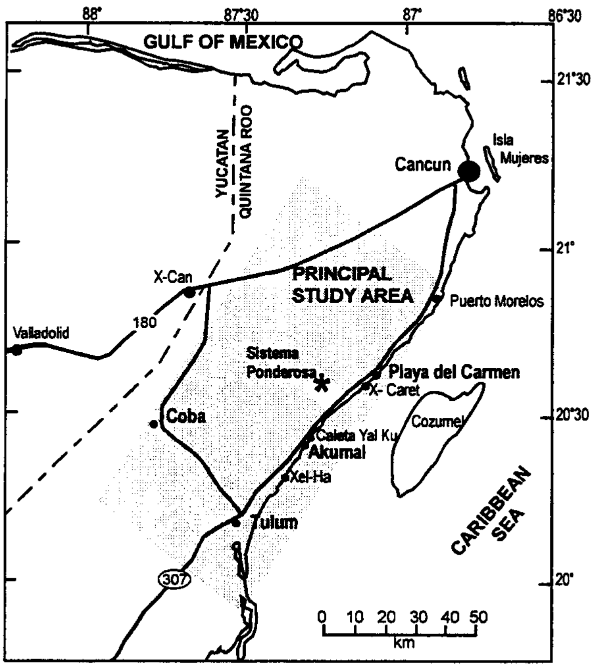

Figure 1: Principal study area on the Caribbean Coast of the Yucatan Peninsula, México.

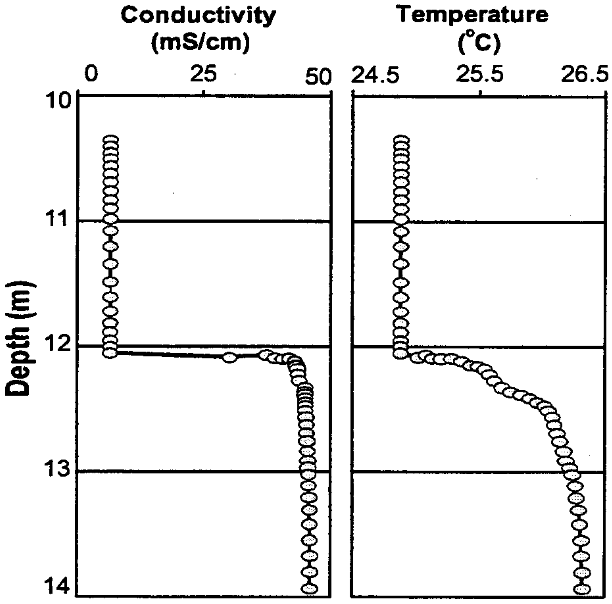

Figure 2: Specific electrical conductivity (mS/cm) and temperature (°C) depth profiles through the mixing zone in the River Run Passage, Sistema Ponderosa near Cenote Eden. The halocline at this site is particularly sharp, while the thermocline extends over a wider depth range.

distributed recharge by pure, cool meteoric water (0.3 mS/cm & 24.1 °C for limited sample size of n =2), and the absence of any significant point sources of thermal energy affecting this water mass.

The fresh water lens between 1 and 10 km from the coast, is typically slightly brackish (2.8 ± 1.5 mS/cm , n=34) but still cool (25.1 ± 0.2 °C, n=33) relative to the mean air temperature of 26.8 °C as observed from Jan. 1998 to Oct. 2001, at 7 Yucatan Peninsula weather stations (Figure 3). The fresh water conductivity increases at a low rate with proximity to the coast in this intermediate distance zone. Long-term records from 2 km inland show that the sharp gradients of the fresh/saline interface fluctuate in depth semi-diurnally by only 2-6 cm in response to the coastal tide. Although major perturbations such as hurricanes do thicken the interface, the sharp gradients are generally reestablished within a few tidal cycles. The fresh/saline interface is very stable in the conduits, and forms an effective barrier to mechanical mixing except in the near coast zone (<1 km). Thus, slow double-diffuse convection is the dominant transport mechanisms of heat and solute across the interface over much of the aquifer.

In the near coast zone (< 1 km), the fresh water lens is significantly brackish and warm with some coastal springs discharging water near three-quarters marine salinity and of similar temperature to the Caribbean Sea (Figure 3). Despite the micro-tidal regime, where maximum coastal amplitude is ~30 cm, the extensive karstification of this aquifer allows transmission of 84% of the coastal amplitude to open cenotes at 1 km inland (Beddows, 1999). The temperature and conductivity suggest an enhanced rate of warm saline water incorporation into the fresh water lens in response to tidally induced oscillations in the near coast zone.

The electrical conductance of saline groundwater (49.9 ± 4.0 mS/cm, n=23) is comparable to offshore ocean water (51.0 ± 1.6 mS/cm, n = 7). Three outlier sites suggest potential increased conductivity by a point source such as dissolution of evaporite deposits that are present at depth within the carbonate platform (currently the focus of chemical and isotopic analysis).

Saline groundwater temperatures decrease exponentially with distance from the coast, coastal saline groundwater being ~1.9 °C warmer than the fresh water and similar to Caribbean Sea temperatures. This warm saline water at the coast suggests a very active circulation of marine water from the warm shallow Caribbean Sea into the aquifer at the peninsular margin. Thermal equilibration between the water masses at ~ 9 km may result from thermal diffusion from the saline groundwater to the aquifer matrix due to a longer residence time of inflowing saline water, and/or from reduced saline circulation inland at this distance.

Our evidence of warm ocean water influx to a distance of > 9 km inland may be explained by the conventional circulation

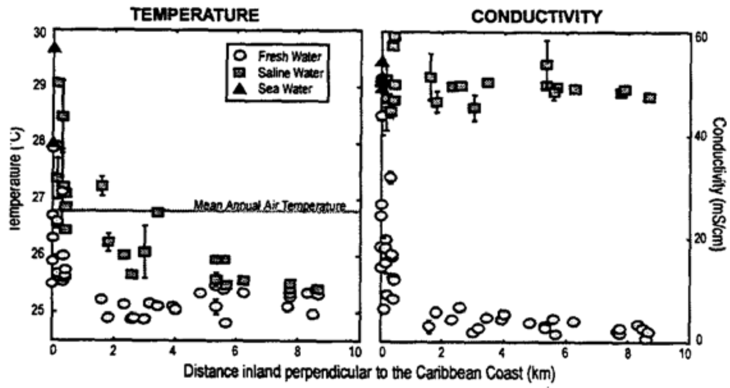

Figure 3: Temperature and conductivity of the fresh and saline water with respect to linear distance from the Caribbean coast of the Yucatan Peninsula. The vertical bars on some data points represent ± 1 standard deviation when multiple observations have been made at one site.

model, if the coastward flow of fresh water is very effective at inducing entrainment in the saline water, rapidly driving the shallow saline water back to the coast so the circuit may continue with saline influx at depth at the coastal margin. The saline water is always warmer than the fresh even at the most inland sites, suggesting that geothermal equilibration is not complete, or that there is a geothermal drive contributing to the saline groundwater circulation. The later is supported by the profiles observed at two deep sites where temperature and conductivity increase with depth, however maximum values are within the range observed for shallower saline groundwater. Our current data set does not provide conclusive evidence of geothermal heating driving saline circulation as we do not observe a distributed diffuse heating from rising heated water through the carbonate matrix and fracture systems, nor the occurrence of 'hot-spots' from rapidly rising heated water through large collapse features known to reach ~100 m depth. Notwithstanding, the deep tier of saline passages formed at palaeo sea-levels may provide important pathways for rapid saline flux from the coastal margin to a distance inland.

Groundwater Flow Rates And Direction

In order to determine the rate of entrainment of saline waters, point measurements of velocity were made in the fresh and saline water bodies in River Run passage (Sistema Ponderosa) using a customized submersible OTT Nautilus current meter. There was an average coastward fresh water flow of 6.2 ± 6.2 cm/s (n = 9), with the saline velocity averaging 0.9 ± 0.8 cm/s (n = 8) coastward between the hours of 14:00 and 19:00 on July 9, 2001. These observations support the suggestion of rapid fresh water flows entraining a significant but more subdued movement of the underlying saline groundwater. This was further investigated by a paired release of Fluorescein in the fresh water and Rhodamine WT in the saline water 528 m inland from Cenote Eden at 15:25 on July 12, 2001. Water samples drawn from tubes in the fresh and saline water at Cenote Eden show a relatively rapid transmission of tracer in the fresh water lens (peak velocity 1.8 cm/s), however no Rhodamine WT was yet recovered by mid-day July 14 (Figure 4).

An observation dive was undertaken on July 14 to observe the progress of the Rhodamine WT dye cloud. No fluorescence above background levels was noted in saline (or fresh) water samples collected from Cenote Eden to the dye injection site. A second observation dive on July 15 targeted the passage around and inland from the injection site. A faint red haze only visible at the halocline was noted and both saline and mixing zone samples were positive for Rhodamine WT (Figure 4) indicating inland flow of the saline water despite coastward flow of fresh water above the density interface.

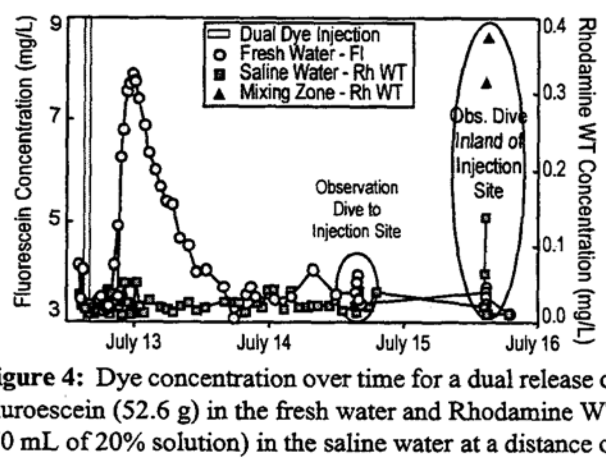

Figure 4: Dye concentration over time for a dual release of Fluroescein (52.6 g) in the fresh water and Rhodamine WT (50 mL of 20% solution) in the saline water at a distance of 528 m upstream from Cenote Eden in the River Run passage of Sistema Ponderosa.

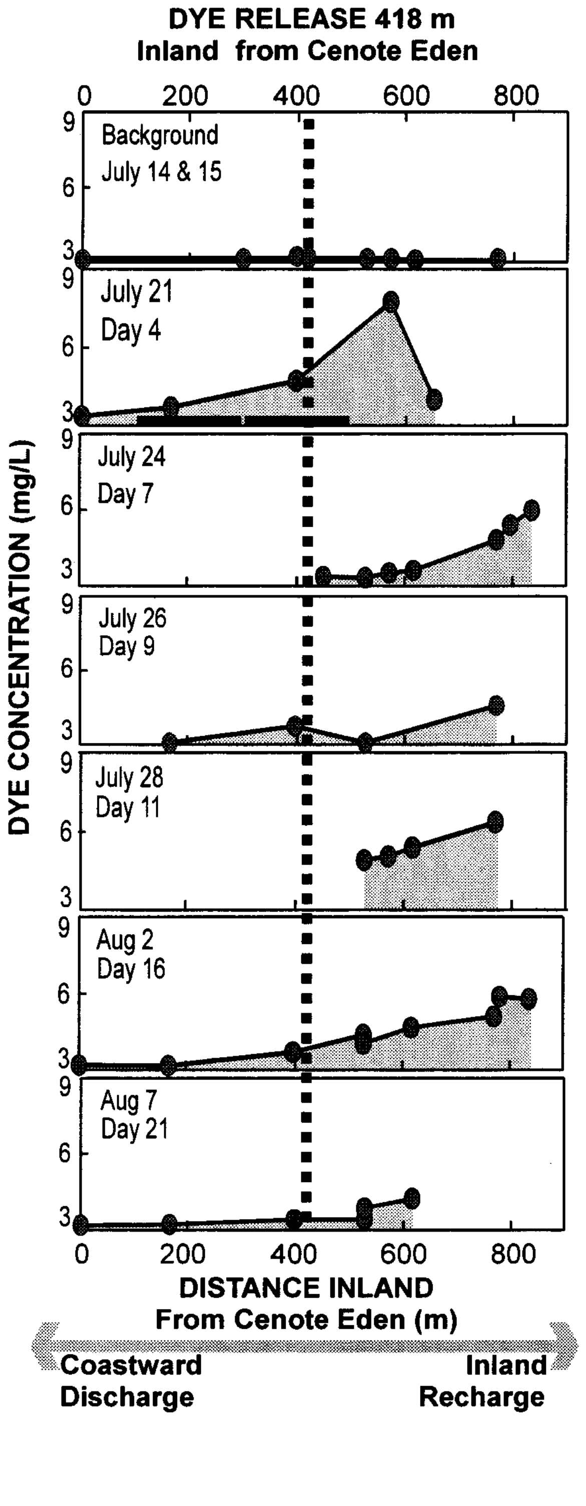

Figure 5: Fluorescein dye concentration in the saline water along the length of the River Run passage, Sistema Ponderosa. Fluorescein (228.6 g) was released 418 m inland from Cenote Eden, such that positive samples located at distances greater than 418 m represent inland flow of the saline water, and positive sample at distances less than 418 m indicate coastward flow.

A second dye trace in the saline water was initiated 418 m inland from Cenote Eden on July 18, 2001 at 10:50 (Day 1) to confirm this inland flow. Although an amount of dye had moved coastward (Figure 5), this second dye trace confirmed the net inland flow of saline water, with peak dye concentration having moved ~150 m inland of the dye injection site 4 days after release. By Day 7, the dye peak traveled inland beyond the limits of accessible passage where it apparently remains through to our last sampling on Day 21. Coastward moving dye is apparent on Day 9 with increased concentration at the dye injection site, and substantiated by positive samples coastward on Day 16 although dye concentration of the coastward moving dye trail is declining again by Day 21. This experiment which spans more than the 14 day spring-neap tidal cycle indicates that net direction of saline groundwater circulation immediately below the interface in Sistema Ponderosa at this time was inland, however periods exist that are competent are shuttling secondary amounts coastward.

Decoupled Flow Across The Halocline

High resolution (15 minute) records of saline groundwater flow were acquired at the initial dye trace injection site (528 m inland of Cenote Eden) from the 21st to 27th July using an electromagnetic Inter-Ocean S4 current meter. This revealed that net inland flow in the saline zone shown by dye tracing, is a product of alternating periods of significant recharge (inland flow) at high tide stages, and discharge (coastward flow) at low tide stages. Maximum velocities in both directions approach 2 cm/s (Figure 6A & 6C). The coastward flow of fresh water has been argued to induce a parallel entrainment of the underlying saline. However these dye tracing and current meter records indicate that the saline water shuttles back and forth within the density stratified conduits, such that there is complete decoupling of flow direction across the halocline. Thus, entrainment is clearly not the dominant mechanism driving saline flow in the cave systems of the Yucatan aquifer.

The first dye trace (July 12 2001) where no tracer was recovered coastward of the injection site, was initiated during an extended period of rising sea levels which resulted in the net inland migration of the dye. Sea levels continued to rise from July 21 - 24, 2001 (Figure 6C) during the first portion of the instrumental record. From midday July 24, falling sea levels correspond to tidal cycles with substantial net discharge of saline water (Figure 6B) and similarly to observed increased tracer concentration near the injection site within River Run cave passage, indicating movement of tracer from inland to coastward of the injection site (Day 9 & 16, Figure 5).

The net velocity per cycle is consistently positive indicating saline influx as the tide stage rises and tidal phases are of equal amplitude. However the velocity per cycle changes after 24 July reflecting a shift in tidal regime, alternating between significant saline discharge during Low-Low tides, and a small saline influx during High-Low tides as overall tidal stage falls. These subtle shifts in the character of the saline flow regime imply a direct and causal relationship between tidal stage and saline influx phases, despite the micro-tidal regime on this coast.

Analysis of the long term trend in mean coastal water level, as observed by the Centro Ecologico Akumal in a near coast (~100 m) observation well, show an annual cycle of rising sea levels from July through to November (2000 & 2001), falling sea levels from November to February (2000 & 2001 to date), and a variable period at generally low stages from February to June (2000 & 2001). The dye tracing and the instrumental observations from July & August 2001 were undertaken during a period of net rising mean sea level. To observe the influence of net falling sea levels, the S4 current meter was deployed again at the same site from December 1 – 6, 2001. The record indicated a tidally modulated net saline flow towards the coast of 1.1 cm/s (0 - 4 cm/s range). Saline discharge may therefore be continuous during overall falling mean sea level, further supporting the role of mean sea level as a dominant control on saline circulation.

Conclusions And Implications

Our observations of saline groundwater temperature suggest that warm ocean water derived from the Caribbean Sea circulates to > 9 km inland. Incorporation of saline groundwater in the overlying fresh water occurs progressively seawards at a relatively slow rate, but within 1 km of the coast there is a much more rapid incorporation within the discharging fresh waters. These observations accord well with the conventional circulation model for density stratified coastal aquifers in which discharge of fresh water entrains underlying saline water, although our field evidence suggests that some of the saline inflow takes place through underlying cave passages. However, detailed *in situ* monitoring of groundwater velocities and dye tracing strongly suggest an alternative model, in which at least some of the saline groundwater is recharging via inland flow beneath the saline/fresh water interface in the caves. This occurs during periods of rising net ocean level, with discharge occurring when ocean levels fall. Fresh groundwater discharges at all times, the two flows being decoupled rather than the fresh water simply entraining saline groundwater flow.

This research demonstrates that *in situ* observations in density stratified conduit flow aquifers are very useful in improving our conceptual understanding of the groundwater flow system. The study also has important practical implications as it demonstrates that at some times sustained inland flow of saline groundwater can occur. The government mandated practice for sewage effluent disposal is deep well injection into the saline zone, the supposition being that contaminants will be filtered as they move diffusely through the matrix towards eventual discharge at the coast. However it is clear that both movement of saline groundwater in

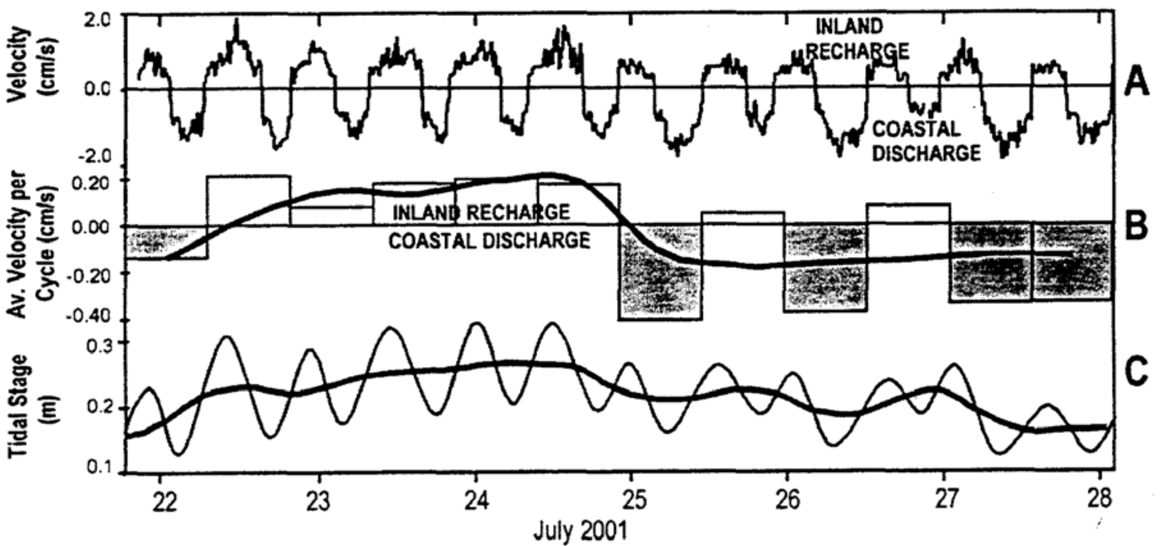

Figure 6:
A. Saline groundwater velocity at 1 m depth below mixing zone in the River Run Section of the Ponderosa System, 2.4 km from the coast. Positive velocity indicates inland flow of saline water, while negative velocity indicates coastward flow.
B. Average saline groundwater velocity per paired flow cycle, with two-point moving average line.
C. Coastal water level observed at the Centro Ecologico Akumal with two-point moving average line.

conduits is rapid, and that it can occur inland, with subsequent mixing leading to potential contamination of the freshwater lens, coastal outlets, and the barrier reef systems, all of which are essential resources for the rapidly expanding local population and tourism industry on this coast.

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