Journal of Hydrology (2007) **346**, 18–32

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journal homepage: www.elsevier.com/locate/jhydrol

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

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Received 24 September 2006; received in revised form 16 June 2007; accepted 20 August 2007

KEYWORDS
Yucatan;
Carbonate aquifer;
Submarine groundwater discharge;
Saline groundwater;
Density stratified groundwater;
Geothermal convection

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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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2007.08.013

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).

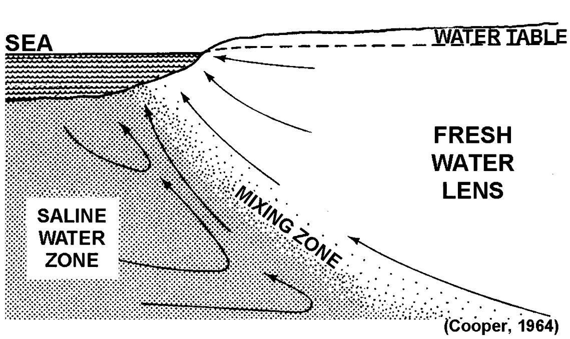

Figure 1 Conventional model of density stratified groundwater circulation in an unconfined coastal aquifer (modified from Henry, 1964).

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 complicates the management of water resources and waste disposal here, and in similar coastal conduit aquifers.

Field area

The Yucatan peninsula is the ~150,000 km^2 emergent portion of the Yucatan Platform which divides the Gulf of Mexico from the Caribbean Sea (Fig. 2). The thickly bedded and highly-permeable limestone extends to a depth of ~1000 m near Merida in the north-west and at least ~150 m some 50 km inland from the Caribbean coast (Ward et al., 1995). Mean annual air temperature was 26.5 °C during the period of the field study (2000–2001) on the Caribbean side of the peninsula (NOAA, 2003). There is a significant east–west precipitation gradient across the peninsula, from >1500 mm/year on the Caribbean coast to <500 mm/year on the north-west coast (Instituto de Geografia, 1973). Insoluble residuum from the limestone is generally much less than 20% and consequently only patchy and thin terra rosa and organic soils are present at the surface (Gmitro, 1986). There are no surface streams and recharge percolates rapidly to the water table.

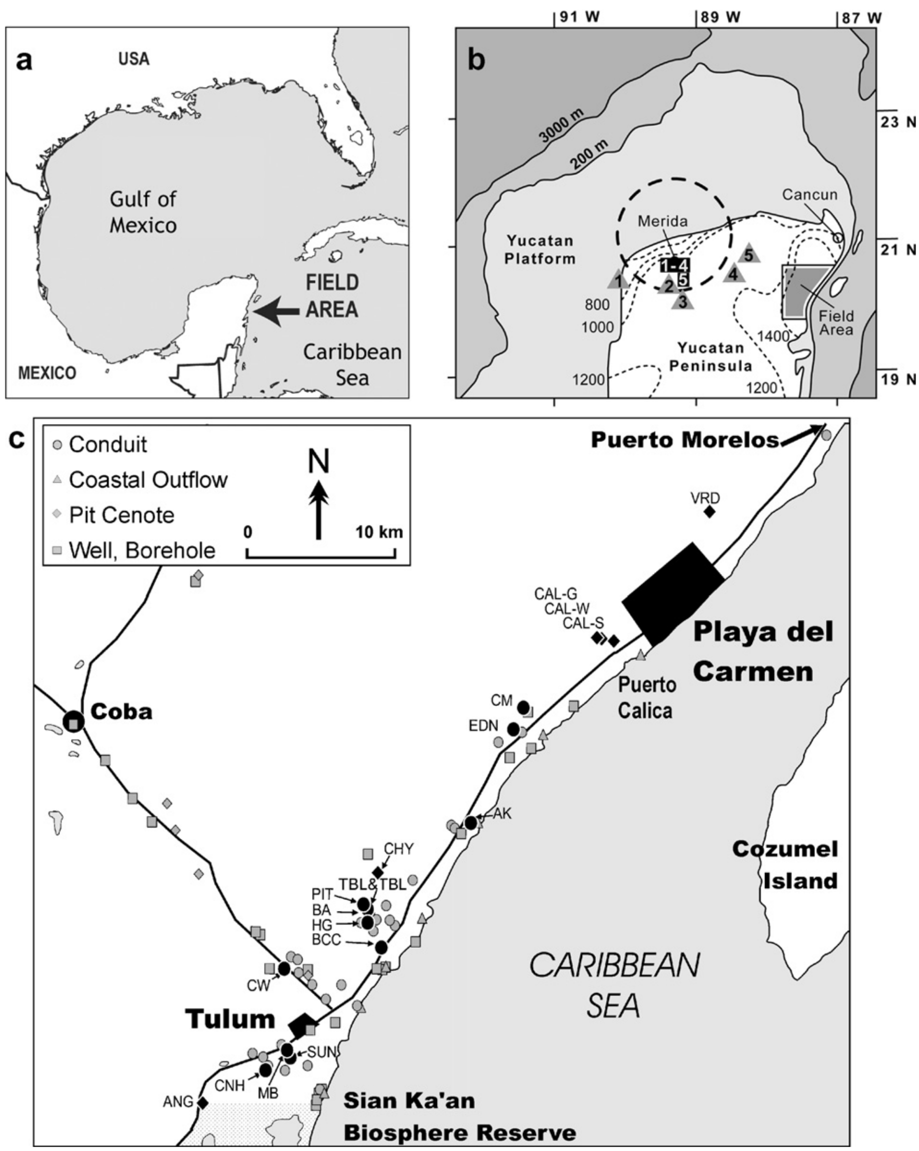

Figure 2 (a) Location of the Yucatan Peninsula. (b) Map of the Yucatan Peninsula showing principle field area on Caribbean coast and north-western sampling sites. Solid lines are bathymetry showing extent of the Yucatan platform. Short dashed lines are precipitation isoyets in mm. Long dashed lines outline the Chicxulub meteorite impact crater, with the portion on land being the associated Ring of Cenotes. Black squares are profiled boreholes, and grey triangles pit cenotes. (c) Detailed map of principal Caribbean coast field area. Black areas are urban centres. Solid lines are major roads. Sites named in the text are labelled with black symbols and other sampling sites in grey. Site name abbreviations: AK, Ak Kimin; ANG, Angelita; BCC, Balam Can Chee; BA, Blue Abyss; CHN, Chan Ha; CHY, Chemuyil; CM, Chac Mol; CAL-G, Calica Grande; CAL-S, Calica Sumergido; CAL-W, Calica ''W'' (these last three also known as Big, Pit, and Little, respectively in Stoessell et al. (2002)); EDN, Eden; MB, Maya Blue; PIT, The Pit; SUN, Cenote of the Sun; TBH, Tak Be Ha; TBL, Tak Be Luum; VRD, Verde.

The aquifer is characterised by three scales of porosity features. The porosity of the aquifer matrix is dominated by primary porosity and the intergranular voids. Average porosity of the Pleistocene deposits along the Caribbean coast is 14–23% (Harris, 1984) while as a result of both localised cementation and dissolution of the limestones, cores from older rocks near Merida in the north-west give a much greater range from 4% to 51% for individual sub-samples (mean 22 ± 10%, $n = 71$; Gonzalez-Herrera, 1984). Fractures, joints, and bedding planes are evident in quarries and in the walls of the flooded conduit networks although these remain poorly characterised. It is clear however, that dissolution enlarges these structural features to dimensions allowing for turbulent flow, thus increasing aquifer permeability. Borehole video logs in the north-west of the peninsula reveal dissolution enlarged turbulent flow conduits measuring 0.01–1 m within which swimming troglobitic fish have been observed (Buckley et al., 1984). Along the Caribbean coast of the Yucatan peninsula, cave divers have explored an extensive cavernous zone which extends some 10–12 km inland from the Caribbean Sea and along an ~80 km length of coast from near the town of Puerto Morelos in the north, to the Sian Ka'an Biosphere Reserve some 10 km south of Tulum (see Fig. 2c). To date, almost 700 km of interlinked anastomosing cave passages measuring 1–100 m in width have been surveyed in this area (QRSS, 2006; Smart et al., 2006). These flooded cave networks function hydrologically as large scale conduit systems linking the inland recharge area to coastal springs.

The connectivity and hydrogeological importance of the small and large scale conduits throughout the peninsula are well documented by their direct exploration notably in the Caribbean cavernous zone, but also through hydrogeological characterisations. The peninsula-wide hydraulic gradient is exceptionally low, being $\sim 5–10 \times 10^{-5}$ in the centre of the peninsula and along the Caribbean coast (Back and Hanshaw, 1970; Marín, 1990; Beddows, 2004) and somewhat lower still at $\leqslant 2 \times 10^{-5}$ on the north-west coast of the peninsula (Reeve and Perry, 2000). The conduits also increase aquifer transmissivity and thus hydrodynamic response to changing boundary conditions, with 84% of the 30 cm amplitude semi-diurnal tidal signal transmitted to free water surfaces in cenotes at 1 km inland, and 39% at cenotes 6 km inland (Beddows, 1999). Typical of heterogeneous carbonate aquifers, the lowest assessed hydraulic conductivity is from smaller test scale core samples which may range from 10^{0} to 10^{-2} m/d (Gonzalez-Herrera, 1984). At the intermediate scale, hydraulic conductivity assessed from pumping tests and fluctuations in piezometers ranges from 10^{1} to 10^{3} m/d (Gonzalez-Herrera, 1984; Marín, 1990; Reeve and Perry, 2000), with a further increase to $10^{4}–10^{5}$ m/d calculated from regional scale numerical modelling focussed on the north-west of the peninsula (Marín, 1990; Gonzalez-Herrera, 1992; Gonzalez-Herrera et al., 2002). This notable scale dependence of hydraulic conductivity underlines the very high permeability and hydrological importance of the turbulent flow conduits, which are only assessed on the largest test scales due to their low spatial density, notably in the interior of the peninsula (Rovey and Cherkauer, 1995; Whitaker and Smart, 1997).

Groundwater access is possible via sinkholes, locally called cenotes. The most common type of cenote in the Caribbean field area is formed by passage roof collapse. These do not necessarily have a directly exposed water surface due to accumulation of collapse debris in the main opening. The second type of cenotes are pit cenotes, which are most common in the north-west lowland plain of the Yucatan peninsula. These are bell-shaped vertical shafts that may extend to ~100 m below the water table, and are typified by the classic cenote of Chichen Itza. A particular alignment and higher spatial concentration of pit cenotes forms the Ring of Cenotes that overlies the Chicxulub impact crater (Perry et al., 1995; Pope et al., 1993). Only a small number of pit cenotes have been found to intersect horizontal conduit, and in all cases these conduits are very short (10–100s of metres; Beddows, 2004). The morphological distinction between pit cenotes and those formed by the collapse of the roof of a relatively shallow conduit suggests that the hydrology of these two cenote types is distinct, with turbulent conduit flow dominating in the horizontally extensive cave systems, whilst circulation through pit cenotes may principally be through matrix porosity and smaller non-penetrable turbulent flow conduits, and thus more limited.

The field area roughly corresponds to the Regional Municipality of Solidaridad and the so-called ''Riviera Maya'' coastal tourism development zone. In this area the population was 63,752 in 2000, of which 75% live in the city of Playa del Carmen. However, the population growth rate of the municipality was 18% per annum over 1990–2000 (INEGI, 2000) principally as a result of tourism developments. As of August 2004, there were also 22,946 registered hotel rooms in the municipality (Municipalidad de Solidaridad, 2005). Water demand and sewage production are thus high. At present liquid effluent is commonly pumped into the saline water below the MZ as per government mandate. Whilst this may be a common practice in coastal aquifers globally, such disposal methods present significant risk in karstified aquifers such as the Yucatan. These risks include direct contamination of the overlying fresh water aquifer, and nutrient loading of the near-coast waters which may lead to eutrophication of the world's second longest barrier reef system (Lapointe et al., 1990; Shinn et al., 1994; Paul et al., 2000, 1995, 1997; Dillon et al., 1999, 2000; Ward-Paige et al., 2005). Further planned expansion of tourist numbers coupled with an intensive government land development plan mean the population is set to increase 10–100 fold in some settlements over the next 20 years (Municipalidad de Solidaridad, 2005).

Methods

The temperature and specific electrical conductance (SEC) of water are used here as natural tracers to characterise the interactions occurring between the FWL, the underlying SWZ, the ocean water and the carbonate aquifer. SEC scales linearly with chloride concentration (salinity) over a wide range, but at values <~4.4 mS/cm there is a greater dependence on the extent of carbonate dissolution (Smith, 2004). Over the majority of the range of SEC considered in this study, the SEC is therefore conservative tracer which demonstrates the extent of mixing between the fresh carbonate groundwaters and saline water. SEC can also be used to discriminate between stratified water masses of different density. In contrast, temperature is a non-conservative natural tracer and is used here to elucidate the direction of groundwater circulation.

Three types of sites are included in this study. Cave sites are horizontally extensive and interconnected water filled *conduits*, including near-coast segments that connect through to coastal and submarine springs. These sites are representative of the rapid flow component of the aquifer where velocities may achieve kilometres per day (Beddows, 1999). Forty-two conduit sites were profiled, all of which are located within 9 km of the Caribbean coast. *Pit cenotes* are water filled vertical shafts which are not necessarily directly connected to the cave systems, and groundwater flows are therefore via intergranular pores, touching vugs, fractures and smaller scale dissolutional conduits (0.01–1 m). Eleven pit cenotes were profiled, of which seven are located 3–12 km from the coast, the remaining four pit cenotes being between 22 and 39 km inland. The third site category is *wells*, which includes both boreholes and hand dug wells. Two boreholes were profiled to maximum depths of 7 and 29 m. Thirty-four hand-dug wells were sampled of which 20 are located <1 km from the coast and the remainder between 1 and 45 km inland. Hand dug wells typically have large areas (>1 m^2) and extend to only ~1 m below the water table. The results are also subdivided by relative location to the coast: near-coast sites are situated within 1 km of the Caribbean coast, cavernous zone sites are situated 1–10 km inland, and sites from 10 to 45 km inland where large scale conduit development is less evident are referred to as from the peninsula interior.

Temperature and SEC data were collected over a 32-month period from February 2000 to September 2002. Pit cenotes, wells and boreholes were profiled from the surface either with a WTW LF90 meter or an YSI 600XLM multiparameter probe, while profiles within flooded caves were obtained during SCUBA dives using the YSI 600XLM probe. All profiles were obtained with a vertical descent velocity of less than 0.2 m/s to allow for thermal equilibration of the probe. The instruments were field calibrated regularly using laboratory prepared SEC standards. All electrical conductivity data have been temperature adjusted to 25 °C to calculate the SEC. Water depths are not corrected for fluid density differences and are reported relative to the water table, which is essentially sea level in our study area. Density profiles are calculated using the UNESCO Equation of State for calculating density of sea water (Fofonoff, 1985).

Fig. 2c shows site locations determined using a Garmin 12XL GPS. These locations were plotted on 1:50,000 topographic maps produced by the Instituto Nacional de Estadística Geografía e Informática (INEGI) and the distance inland perpendicular to the coast was measured to ±50 m for inland sites, and to ±10 m for locations within sightline of the coast. Further details of field methods are provided in Beddows (2004).

Where regression models have been fitted to the data, residuals are calculated. Outlier are identified as points 1.5 and 3 interquartile distance away from the mean and removed from the regression. The identified outliers are plotted and identified in the figures but excluded from the regression calculations. The significance of the difference between the slopes of two regression lines is determined by calculating the t statistic based on the difference between the slopes, divided by the standard error of the difference (Fowler et al., 1998). A 95% confidence interval is used to determined significance of all relationships unless otherwise specified.

Results

Water profile structure and stationarity

The stratified aquifer water column is composed of a cooler FWL overlying a warmer SWZ. In the simplest observed water columns, a thin MZ separates essentially isohaline and isothermal FWL and SWZ (Fig. 3a). However most profiles include secondary features, such as the upwards mixing of saline water into the base of the FWL evident in the conduit site Eden (Fig. 3b). The SWZ was profiled to >1 m below the base of the MZ in 13 conduits, and 4 pit cenotes, others being too shallow to permit deeper access. The profiles from 11 of these 13 conduit sites show that there is a zone of warmer isohaline saline water 1–5 m thick below the MZ. Below this there is an SEC step across which temperature also decreases (Fig. 3b). The SEC step therefore divides the SWZ into two sections, here termed the shallow SWZ for the waters between the base of the MZ and above the SEC step, whilst the deep SWZ refers to the waters below the SEC step. The difference in SEC at the SEC step ($\Delta SEC_{DEEP\ SWZ-SHALLOW\ SWZ}$) is on average 0.59 ± 0.85 mS/cm (n = 17), but this decreases systematically inland from an observed maximum of 3.25 mS/cm in Ak Kimin, 0.15 km inland from the coast (Fig. 4). The largest $\Delta T_{DEEP\ SWZ-SHALLOW\ SWZ}$ is also in Ak Kimin (0.71 °C), the average being much lower (0.16 ± 0.26 °C, n = 8, excluding conduit sites The Pit and the Blue Abyss for reasons explained below). All profiles are density stable with increasing density with depth.

The distinction between the shallow and deep SWZ is more complicated in two of the conduit sites and all four of the sampled pit cenotes. In the pit Cenote Angelita, the SWZ is within instrumental resolution isothermal and isohaline to the maximum depth profiled (10 m below the MZ, limited by depth range of YSI sonde). While in the two conduit sites The Pit, and the Blue Abyss, temperature and SEC increase progressively with depth. In two of the pit cenotes (Grande and Sumergido, also known as Big and Pit, respectively), acute temperature maxima occur within the MZ with temperatures 2–4 °C greater than that of the underlying SWZ. These anomalies, which have been reported on elsewhere (Stoessell et al., 2002; Beddows et al., 2004), are contained within the MZ and do not affect representative temperature values drawn from the isothermal profile segments of the FWL and the SWZ. In the pit cenote Chemuyil, there is no observable SEC step but there is a positive temperature anomaly (0.30 °C) identifiable just below the base of the exceptionally thin MZ in this site. The focus of this study is the shallow SWZ, with the deep SWZ data to be addressed elsewhere. Representative temperature and SEC values characteristic of the FWL and shallow SWZ at each sampling site have been taken from the isothermal and isohaline profile segments 1–5 m below the base of the MZ (see examples Fig. 3) and are used in the following analysis.

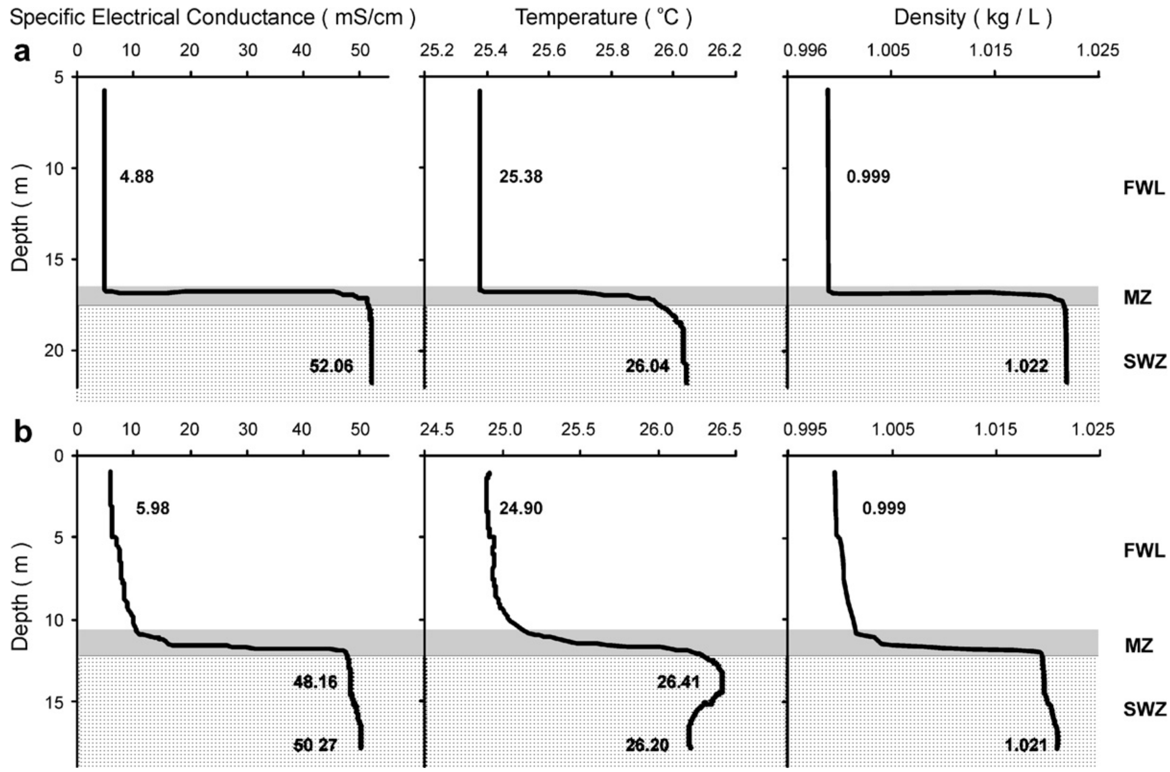

Figure 3 Profiles of specific electrical conductance (SEC), temperature, and density for (a) cave site ''Cenote of the Sun'' (Sistema Naranjal), July 22, 2001, 5.3 km inland; (b) cave site Eden (Sistema Ponderosa), April 8, 2000, 1.8 km inland. Numbers beside profiles are the representative values from the isohaline and isothermal segments. White section is the fresh water lens (FWL). Pale grey is the mixing zone (MZ). The saline water zone (SWZ) is stippled.

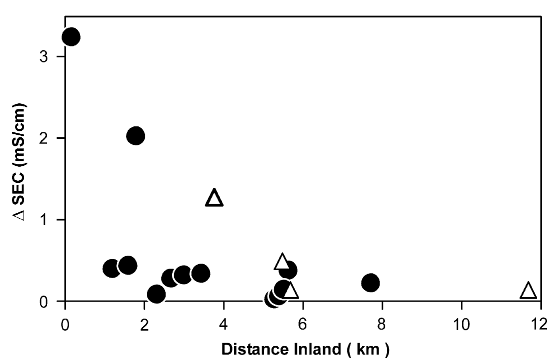

Figure 4 SEC difference (ΔSEC) between the shallow SWZ and the deep SWZ for conduit sites (●) and pit cenotes (△).

Up to 23 repeat profiles were obtained at four sites over the 31-month sampling period (February 2000–September 2002). The variations in temperature and SEC between the repeat profiles at each site were small relative to the intersite range (Table 1). In subsequent analysis, the average value is presented for sites with repeat profiles along with the standard deviation, although the error bars are often smaller than the symbol size.

FWL temperatures

The temperature of the FWL in near-coast conduit sites is quite variable but averages 26.49 ± 0.84 °C ($n = 11$) (Fig. 5a; Table 2). Temperatures decline inland to 25.00 °C at three sites located 1.0–1.2 km from the coast but there is a large scatter, and a regression of temperature with distance inland for the near-coast FWL conduit sites is not significant. In the cavernous zone (1–10 km), there is a small (0.3 °C) but significant increase in FWL temperature at the 99% CI with distance to the furthest inland conduit site sampled at 8.7 km ($T_{FWL} = 0.055x + 24.95$, $n = 31$). Note that three conduit sites, Tak Be Ha and Tak Be Luum both at ~4.7 km inland and Chan Ha at 8.5 km inland, have anomalously low temperatures.

FWL temperatures in near-coast wells have a much larger range (24.20–29.50 °C) but comparable average (26.59 ± 1.74 °C, $n = 18$) relative to the temperatures observed in near-coast conduit sites. For a given SEC, well waters are significantly warmer than conduit waters (Fig. 6). Further inland in the cavernous zone, the FWL temperature in wells have high intersite variability and on average are significantly higher than those observed in conduits (average 26.65 ± 1.10 °C for six wells sampled 1–10 km inland compared with 25.14 ± 0.26 °C for 31 conduit sites 1–10 km inland).

In the pit cenotes located up to 10 km inland (Fig. 5a), there also appears to be a pattern of increasing FWL temperature with distance, although Cenote Verde at 5.5 km inland is a notable outlier with a temperature of only 23.89 °C. The number of pit cenote sites sampled is too limited to be confident in this pattern. Overall (1–45 km inland) there is not a significant relationship between

Table 1 Average, standard deviation (σ) and number of repeated observations of temperature and SEC data for the FWL and the shallow SWZ 1–5 m below the mixing zone for four sites

	FWL			SWZ		
	Mean	σ	Number	Mean	σ	Number
Temperature (°C)						
Chac Mol	24.88	0.06	6	26.18	0.35	6
Balam Can Chee	25.24	0.03	12	27.23	0.15	9
Maya Blue	25.39	0.06	22	25.91	0.08	22
Eden	24.83	0.04	7	26.31	0.30	8
SEC (mS/cm)						
Chac Mol	2.77	0.23	5	47.93	2.54	5
Balam Can Chee	6.67	0.78	12	50.70	1.03	9
Maya Blue	5.13	0.70	23	49.80	1.33	23
Eden	7.48	1.31	8	47.65	1.62	9

observed water temperature and distance inland in pit cenotes. The average FWL temperature in pit cenotes (24.79 ± 0.38 °C, n = 10) is significantly lower than that observed in inland wells over the same distance of 1–45 km inland (25.71 ± 0.92, n = 12). They also have a comparable minimum temperature to that observed in conduits ~1 km from the coast.

The overall pattern of temperature change in the FWL is thus one of rapid decline from elevated temperatures adjacent to the coast to a minimum value of ~25.0 °C at ~1 km inland. Further inland (to ~8 km) there is a gradual increase in temperature best displayed for conduit sites, which generally give lower groundwater temperatures than those observed in wells, but there is considerable variation between individual sample sites.

FWL SEC

The SEC of the FWL in conduit sites (Fig. 5b) decreases exponentially with distance inland ($SEC_{FWL} = 7.26x^{-0.45}$, n = 39, r^2 = 0.88). Here we consider the data in three segments, including the near-coastal zone (0–1 km) followed by sub-division of the cavernous zone into the outer (1–4 km) and inner (4–10 km) zones for reasons that will be provided in the discussion. The SEC of the FWL in the near-coast conduits (<1 km) is elevated and highly variable (18.22 ± 6.62 mS/cm, n = 10), and declines rapidly with distance inland. In the outer cavernous zone between 1 and 4 km from the coast, the SEC of the FWL in the conduit sites decreases more slowly at a rate of ~1.0 mS/cm/km from ~6.6 down to 3.9 mS/cm (based on a linear fit of $SEC_{FWL} = -1.0x + 7.6$, r^2 = 0.35, to the 12 observations over this segment which is significant at the 95% CI). For conduit sites situated from 4 to 10 km inland, the slope of a linear fit is not statistically significant, indicating no further significant decrease of SEC with distance inland; the average SEC here is 3.27 ± 0.91 mS/cm (n = 16).

The SEC of the FWL in wells varies systematically with distance inland in a pattern similar to that seen in conduit sites. The FWL in the near-coast wells is 7.32 ± 0.91 mS/cm (n = 19), which is significantly lower than that observed in the near-coast conduits. The wells located in the cavernous zone have lower SEC (2.19 ± 1.19 mS/cm, n = 7) with a small but not significant further decrease in sites in the peninsula interior (1.13 ± 0.28, n = 8). Inland of the near-coast zone, the SEC of sampled wells is systematically less than that of the conduit sample sites. An exponential fit to all well data from 0 to 45 km inland yields $SEC_{FWL} = 3.14x^{-0.33}$ (r^2 = 0.70; a similar fit is also obtained if only the well data 0–10 km is used).

The SEC of the FWL in pit cenotes follows a highly significant (99% CI) linear decline over the interval 1–45 km inland ($SEC_{FWL} = -0.04x + 2.53$, r^2 = 90, n = 10, 1 outlier Cenote Verde). The average SEC of pit cenotes in the interior is 1.44 ± 0.36 (n = 5), comparable to that determined from wells.

The SEC of the FWL therefore presents a complex pattern. SEC of the FWL in near-coast conduit sites is elevated and highly variable with salinities approaching ~33% of seawater values in some sites. Further inland from 1 to 4 km, there is a significant decrease in SEC of the FWL in the conduits, however the rate of SEC decline is insignificant from 4 to 10 km inland. Conduit sites generally have higher SEC compared to wells and pit cenotes. The SEC of the FWL in pit cenotes and wells in the cavernous zone is significantly higher than in the interior where the average SEC is very low in both non-conduit types of sample site.

SWZ temperatures

The temperature of the SWZ in the near-coast conduit sites is 27.38 ± 0.54 °C (n = 7; Fig. 5e) which is not significantly different from the mean annual near-shore Caribbean sea temperature of 27.9 ± 1.6 °C for 2000–2001 from Puerto Calica (Badan Dangan, A., unpublished data). Temperatures decrease exponentially inland along the function $T_{SWZ} = 26.57x^{-0.017}$, r^2 = 0.74, n = 26), the rate of change being much greater near the coast than further inland.

The temperature of the SWZ in the five pit cenotes located in the cavernous zone (here including Cenote Angelita at 11.7 km inland) lie below the exponential curve fitted to the conduit data. The average temperature is 25.25 ± 0.65 °C which is slightly lower than that in the conduit sites (26.07 ± 0.55 °C, n = 19). However, all SWZ temperatures in pit cenotes plot within the 95% CI bands calculated for the conduit data (not shown), indicating that

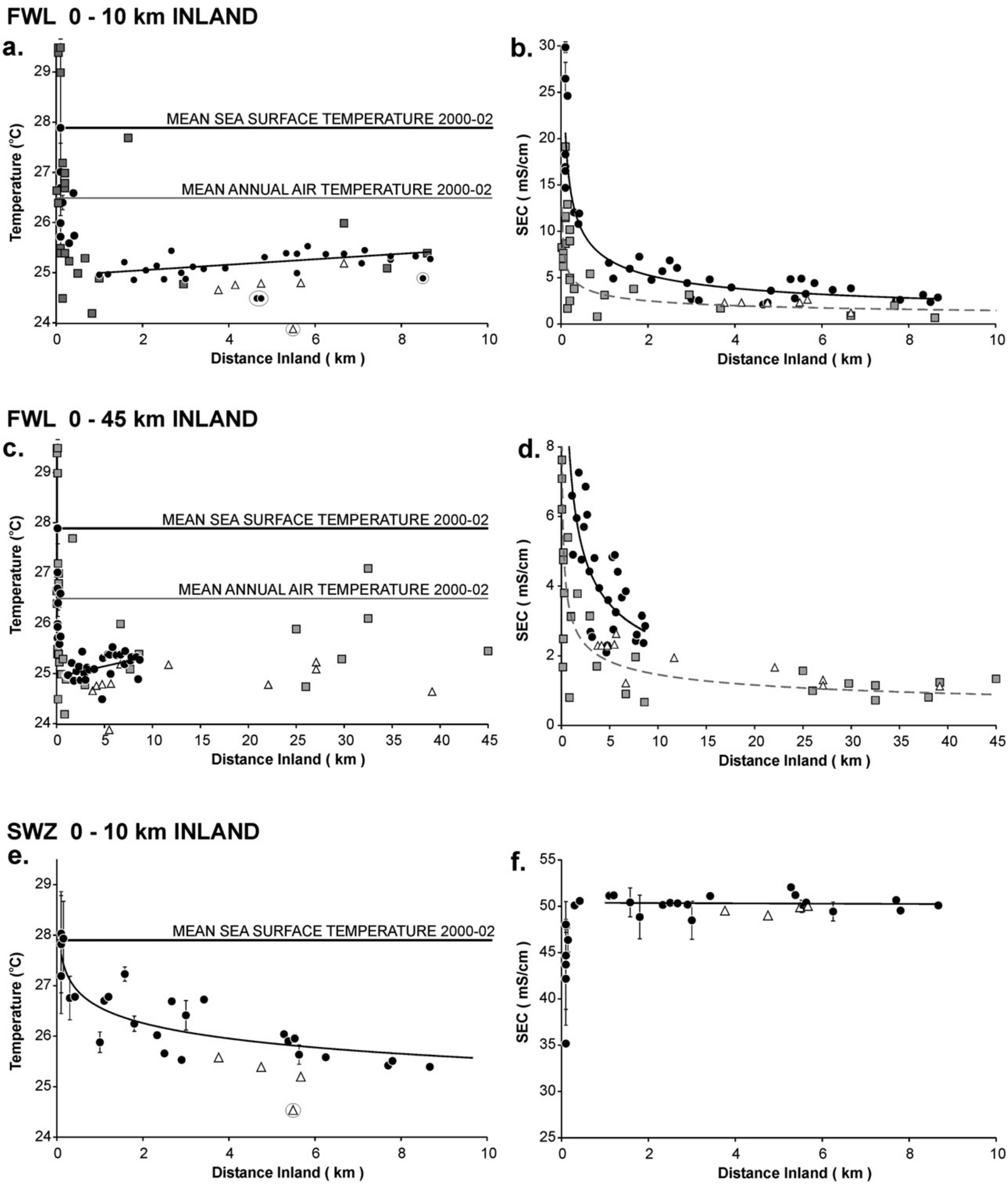

Figure 5 Temperature (left) and SEC (right) of the FWL for near-coast (0—1 km) and cavernous zone (1—10 km) sites (panels a and b), and for the FWL of sites into the peninsula interior (0—45 km inland; panels c and d). Temperature (left) and SEC (right) of the shallow SWZ for sites located between 0 and 10 km inland (panels e and f). All data from sampling sites located along the Caribbean coast: (●) conduit sites; △ pit cenotes; (■) wells and boreholes. Error bars plotted for sites with multiple profiles indicate 1 standard deviation. Outliers are circled and excluded from regressions.

the available data is inadequate to substantiate the significance of this possible difference. Amongst the data, note that Cenote Verde has a particularly cool SWZ (24.58 °C) consistent with its anomalously cool FWL. The data density is inadequate to determine any spatial trends with distance.

The temperature decrease evident with distance inland in the SWZ of conduit sites contrasts with the gentle increase in the corresponding FWL temperatures (Fig. 5e and a). There is thus a systematic reduction in the temperature difference between the SWZ and the FWL ($\Delta T_{SWZ-FWL}$)

Table 2 Summary of the average, standard deviation (σ) and number of sites for SEC and temperature for FWL and shallow SWZ (~1–5 m below the mixing zone)

	FWL				SWZ			
	Distance inland (km)	Average	σ	Number	Distance inland (km)	Average	σ	Number
Temperature (°C)								
Conduit	0–1	26.49	0.84	11	0–1	27.38	0.54	7
	1–10	25.14	0.26	31	1–10	26.07	0.55	19
Pit	1–10	24.59	0.39	5	1–10	25.09	0.62	4
	10–45	24.99	0.26	5	10–45	25.90		1
	1–45	24.79	0.38	10	1–45	25.25	0.65	5
Well	0–1	26.59	1.74	18				
	1–10	26.65	1.10	6				
	10–45	25.77	0.81	6				
	0–45	26.24	1.51	30				
	1–45	25.71	0.92	12				
SEC (mS/cm)								
Conduit	0–1	18.22	6.62	10	0–1	45.10	4.99	8
	1–10	4.13	1.51	28	1–10	50.31	0.88	18
	1–4	5.11	1.48	12				
	4–10	3.27	0.91	16				
Pit	1–10	2.37	0.15	5	1–10	49.62	0.46	4
	10–45	1.44	0.36	5	10–45	49.66		1
	1–45	1.91	0.55	10	1–45	49.63	0.40	5
Well	0–1	7.32	0.91	19				
	1–10	2.19	1.19	7				
	10–45	1.13	0.28	8				
	1–45	1.62	0.97	15				

Data is divided by site type and by distance bands relative to the Caribbean coast of the Yucatan Peninsula: the near-coast (0–1 km), cavernous zone (1–10 km) and peninsula interior (10–45 km). See Fig. 5 for plotted data.

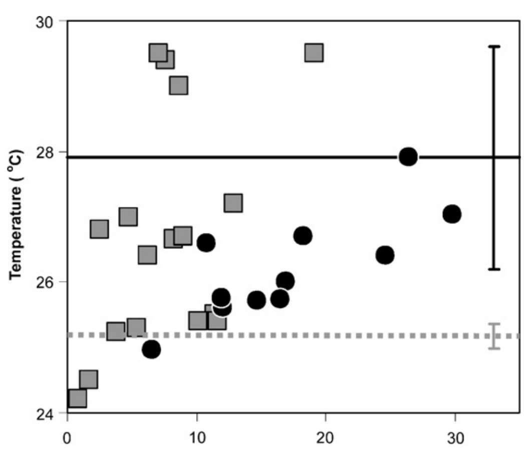

Figure 6 SEC versus temperature for conduits (●) and wells (■) located <1 km inland. Solid line indicates mean annual sea surface temperature (SST) for 2000–2001 (Badan Dangon, A., unpublished data), and dashed line is the mean (±1 standard deviation) of the FWL temperature for conduit sites located >1 km inland (this study).

with distance from the coast, with a $\Delta T_{SWZ-FWL}$ > 1 °C at the coast which decreases to 0.2 °C in three conduit sites more than 7.5 km inland (Fig. 7). The $\Delta T_{SWZ-FWL}$ for four pit cenotes sampled at 3.8–5.7 km inland plot within the trend for the conduit sites (Fig. 7). In the pit Cenote Angelita at 11.7 km inland, the $\Delta T_{SWZ-FWL}$ is somewhat greater (0.7 °C). In the region closer to the north-west coast, the $\Delta T_{SWZ-FWL}$ is 1.3 °C in the pit cenote Sabak Ha located 79.2 km inland, while it is only 0.1 °C in the pit cenote Santa Maria located 14.5 km inland of the Gulf of Mexico (Iliffe, T.M., unpublished data). In this north-western region, additional $\Delta T_{SWZ-FWL}$ values of 0.5 and 1.0 °C are reported in boreholes located respectively 27.6 and 35.3 km inland (Buckley et al., 1984).

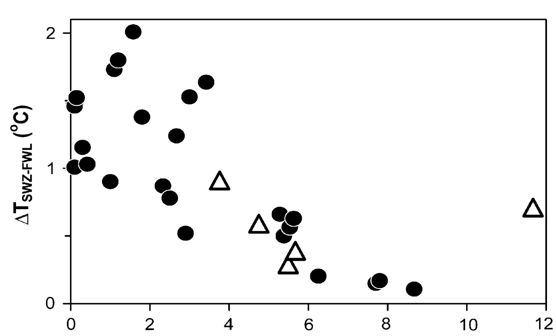

Figure 7 Temperature difference (ΔT) between the SWZ and the FWL in conduits (●) and pit cenotes (△) with distance inland from the Caribbean Sea.

SWZ SEC

In contrast to the marked decline of SWZ temperatures inland, the SEC of the SWZ more than 1 km inland is uniform with an average of 50.31 ± 0.88 mS/cm (n = 18; Fig. 5f). This is very similar to the SEC of SWZ water sampled in pit cenotes (49.63 ± 0.40 mS/cm, n = 5 all located <12 km inland), indicating a water body of relatively constant salinity. Of note, the SEC of this water is not significantly different from that of near-shore seawater collected in the field area (50.56 ± 0.42 mS/cm, n = 5). However, for conduit sites very close to the coast (<200 m), the SEC of SWZ is significantly less than that of seawater (45.10 ± 4.99 mS/cm, n = 8) with a minimum value of 35.17 mS/cm. Flow in the SWZ at these sites is highly turbulent and characterised by flow reversals resulting from tidal fluctuations and storm events (Beddows, 2004). We have not obtained any samples of saline water from the peninsula interior, and are unable to intercalibrate other workers measurements of SEC with our own. Further work is needed.

Interpretation

FWL SEC data

The most notable aspect of the SEC of the FWL sampled in conduit sites is the progressive increase from inland sites at ~9 km where SEC values are similar to, but slightly elevated compared to those in inland wells and cenotes, to the very high SEC values in the coastal zone (Fig. 5b). Extrapolation of this relationship suggests that convergence of the SEC of the FWL for wells and conduit sites would occur at ~10—12 km inland, a distance which marks the known limits of the major accessible and interconnected cave systems. Over the interval 4—9 km inland, the rate of increase of SEC within the freshwater flowing through the conduits is insignificant because the conduits are generally completely filled with fresh water, the MZ lying below the elevation of the conduit floor. Some limited entrainment of saline and brackish water into the FWL remains possible via some connections to underlying cave levels. At distances less than 4 km inland, many conduits have extensive reaches of up to 1 km where the MZ lies within the passage. Within the caves, the MZ itself is often visible as a sharp reflective interface (halocline) separating the fresh and saline water. Turbulent shear is often present at this density interface due to differences in the rate of movement of the over and underlying layers, and is visually manifested in the form of rolling and standing waves. While turbulent shear may be largely responsible for the sharpness of the interface, this may also in part result from double diffuse convection which is driven by the presence of warm density stratified saline water below the interface (Kantha and Clayson, 2000). Our conduit temperature data (Fig. 7) demonstrate precisely such a temperature contrast to be present in the cave conduits, although this difference is smaller inland than at the coast. Larger scale but more localised mixing is also evident where boulder piles, which are ubiquitous because of ongoing collapse in the conduits (Smart et al., 2006), obstruct the density stratified flows. Where the coastward flowing fresh water impinges on the boulders, turbulence can be seen to cause mixing in the underlying saline water giving a shimmering effect. The less sharp interface evident in the SEC profile at Eden compared to that from Cenote of the Sun (Fig. 3) almost certainly arises from such physical mixing caused by the strong freshwater flows and extensive collapse adjacent to the profiling station in Eden.

In the near-coast zone, the rate of incorporation of saline water into the overlying fresh water is much more rapid, such that at many sites the measured SEC indicates that a true FWL is absent. Indeed, SEC of the SWZ is also substantially less than that of normal seawater in the near-coast conduits. This is the true subterranean estuary zone, where both fresh and saline water characteristics have been substantially modified by mixing, but flow remains strongly density stratified. Visual observations within the flooded conduits coupled with instrumental records reveal the occurrence of strong flows of saline and brackish water in the near-coast conduits (Beddows, 2004). These are driven by head differences between the oceans and aquifer associated with the tides, and reverse on a semi-diurnal basis. Rates of mixing will be much higher within the sections of conduit affected by these large tidal flows than in the conduits further inland, in which tidally driven fluxes are much smaller. The minimum FWL temperatures in conduits observed ~1 km inland likely indicates the extent of the main tidally flushed zone although pressure effects may extend much further inland because of the presence of the conduit networks.

The high SEC of the FWL in near-coast conduits is the result of seawater inflows into the conduit networks driven by the aquifer boundary conditions, and this process is distinct from the turbulent sheared mixing between the density stratified flows in conduits located at intermediate distances 1—4 km inland. The data show no evidence for broad scale salinisation of the FWL in inland conduit sites located >4 km inland, and this is ascribed to the physical isolation of these waters from the underlying SWZ. Similarly, rates of salinisation in the non-conduit sites in the cavernous zone and in the interior of the peninsula all maintain low SEC in the FWL despite the exceptional permeability of the aquifer.

FWL temperatures

The temperature of the FWL measured in both pit cenotes and conduits is significantly less than the mean annual air temperature of 26.5 °C by ~1.5 °C (Fig. 5a). The average FWL temperature measured in shallow wells >1 km inland, which are known to be affected by direct insolation, is also significantly less than the mean annual air temperature by ~0.8 °C. However, Perry et al. (2002) reported significantly higher average temperatures for the FWL sampled from pumped and static boreholes and closed cenotes (27.7 ± 0.8 °C, n = 69). For this data, sixty three of the sixty nine sample sites have temperatures greater than the mean annual temperature, and we therefore conclude that these results are biased by surface heating and direct insolation effects in the wells and pump works. Our low FWL temperatures are surprising as the groundwater temperature in carbonate aquifers is generally assumed to be equal to the mean annual temperature (Ford and Williams, 1989) unless distinct geothermal heating effects occur, resulting in more elevated temperatures, for instance at hot springs sourced from deep circulation. In effect, the upper few meters of rocks in the vadose zone thermally damp the short-term seasonal temperature fluctuations. However, transfers of water and water vapour through the vadose zone may have a significant impact on rock temperatures because of the high latent heat and specific heat capacity of water. Soils are largely absent over the 0–10 km study zone along the Caribbean coast, and recharge occurs directly into the porous limestones of the unsaturated zone. Evaporation from the shallow water table may lower rock temperatures because thermal energy is used to supply the latent heat of evaporation. However, such rocks may also draw energy from direct insolation and by downward conduction from the surface. Furthermore, much of the Yucatan is forested with low tropical forest, and most evaporation will not be direct from the surface or the canopy, but rather via transpiration from the vegetation. Energy for evaporation is in this case provided by direct insolation on the leaves, and therefore rock temperatures would not likely be affected. Another possible explanation is that effective recharge of the aquifer occurs principally during convective tropical storms. The very strong uplift that occurs during such storms means that condensation occurs at high elevations where the air is cool, and precipitation temperatures may be significantly less than surface air temperature. We have measured rainfall temperatures less than 20 °C during storms in the study area, suggesting that cooling by infiltration of cold recharge may be significant. Further work is needed to confirm this suggestion.

FWL: Conduit and non-conduit sites

Temperatures measured in large diameter hand dug wells are generally higher than those observed in conduit sites because of the effects of direct solar heating (Fig. 5a). This is particularly evident in the near-coast zone where the water surface is often very close to the ground surface because of the limited depth of the vadose zone, and the wells are often located on exposed beach ridges with no shade (Fig. 6). Furthermore, the two wells in the near-coast zone with relatively high SEC (19.1 and 12.9 mS/cm both <0.5 km inland) are both pumped daily, and may possibly be affected by upconing of brackish and saline water.

In contrast, the FWL SEC of water from hand dug wells in the cavernous zone and the peninsula interior (1–45 km inland) is consistently lower than that from conduit sites (Fig. 5b and d). Some of the near-coast wells have similarly low SEC (1.68, 2.49, and 0.80 mS/cm at 0.15, 0.2, and 0.8 km, respectively), which are values comparable to the average SEC for all wells >1 km from the coast (1.62 ± 0.97 mS/cm, n = 15). The same water is also sampled in pit cenotes located >1 km inland (1.91 ± 0.55 mS/cm, n = 10), and these values are comparable to the 95% CI trimmed average of 1.08 ± 0.36 mS/cm (n = 226) for a large sampling of groundwaters in the peninsula interior by Lesser Illades (1976). The wells and pit cenotes are not directly connected to the network of conduits, and are thus not subject to large scale turbulent mixing processes occurring in the conduits. The low SEC (<4.4 mS/cm) of the FWL waters within non-conduit sites indicates their composition is primarily dominated by limestone dissolution, while the higher SEC of conduit waters suggests mixing of saline waters into the FWL is an important process along turbulent flow paths within conduits. The lower SEC in the non-conduit sites demonstrates the limited role of tidal pumping and the associated transverse dispersion in mixing saline water into the FWL outside of the conduits, despite the highly transmissive conditions of the Caribbean Yucatan aquifer.

The SWZ

The trend of progressive salinisation of the FWL as water moves coastward is in good agreement with the conventional coastal aquifer circulation model. The SEC of the SWZ waters throughout the cavernous zone is essentially that of seawater, and shows no evidence for progressive change in SEC inland. Again this conforms to the conventional model. However, the clear and substantial coastward increase in SWZ temperatures (Fig. 5e) is not consistent with this model.

The conventional model would suggest that Caribbean seawater flows into the peninsula at some depth. However, Caribbean seawater temperature in the upper 50 m is significantly cooler (24.13 ± 2.72 °C, n = 4) than the average SWZ in the conduit systems for significant parts of the year, while at 75 m depth the seawater is perennially cooler (21.44 ± 2.97 °C, n = 4, Fig. 8). Such cool Caribbean seawater inflows would be subject to geothermal heating, decreasing their density by increasing their temperature resulting in a buoyant convective outflow in the upper part of the SWZ completing the ''Kohout'' convection cell. Maximum SWZ temperatures resulting from such a convective circulation are anticipated in the peninsula interior due to progressive warming along the flow path, with a progressive

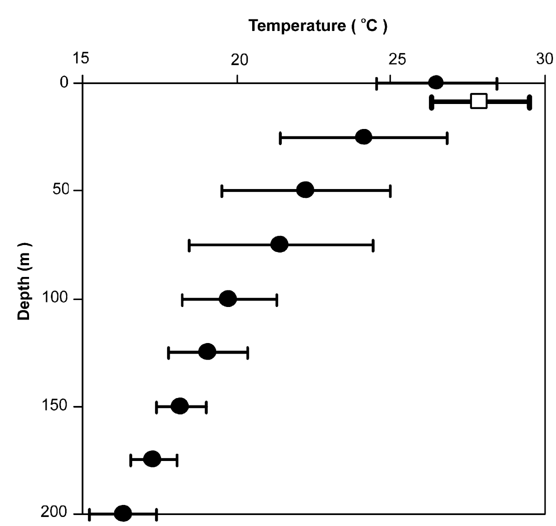

Figure 8 Average temperature with 1 standard deviation (error bars) of Caribbean seawater (●) at a profiling station offshore from Cancun measured in 1984–1986 (modified from Merino, 1997) and mean annual sea temperature measured in Puerto Calica 2000–2001 (□; Badan Dangan, A., unpublished data).

decline in temperatures towards the coasts. Stein (1995) has also suggested a reduced energy flux along platform margins, which would exacerbate this effect. Such a geothermally driven saline circulation has been proposed for the field area by Stoessell et al. (2002) based on positive thermal anomalies observed within the MZ of three of the large diameter pit cenotes located in the cavernous zone (cenotes located at Calica quarry – Grande, ''W'', and Sumergido, aka Big, Little, and The Pit, respectively) which were also sampled for this study. The thermal anomalies reported by Stoessell et al. (2002) may more simply result from the widely observed phenomenon of heliothermic heating by direct insolation in the open cenote (Kohout et al., 1968; Hudec and Sonnenfeld, 1974; Sonnenfeld et al., 1976; Kirkland et al., 1980; Duval and Ludlam, 2001; Labrenz and Hirsch, 2001; Ström and Klaveness, 2003; Beddows et al., 2004), and thus not be a true indication of groundwater conditions. Where direct insolation occurs in a water column stabilised by a significant salinity gradient, the stable stratification impedes convective dissipation of heat in the water column. The water temperature thus becomes elevated in the zone of maximum insolation absorption reaching temperatures that naturally frequently exceed 30 °C, and attaining values in excess of 90 °C in engineering settings (Kirkland et al., 1980). All profiles obtained in this study including those with the positive thermal anomalies are density stable due to step-wise or progressive increases in SEC with depth (e.g., Fig. 3; Beddows, 2004). Thus convective upwelling in the manner suggested by Stoessell et al. (2002) is unlikely to occur. While the clear spatial pattern of declining SWZ temperatures towards the peninsula interior argues against convective circulation driven by geothermal heating as being significant for SWZ circulation, the persistent temperature contrast of 0.05–1 °C observed between the FWL and saline zone in pit cenotes and boreholes in the north-west interior of the peninsula may provide evidence of the presence of some limited effect of geothermal heating on groundwaters (Buckley et al., 1984; Beddows, 2004; Safanda et al., 2005). The SWZ temperature distribution in the Yucatan may also be complicated by anomalies in geothermal heat flow in the vicinity of the Chicxulub crater (Wilhelm et al., 2004; Safanda et al., 2005).

The maximum SWZ temperatures increase from a value close to that of the overlying FWL at the head of the conduit network (∼25.4 °C at ∼9 km inland) to ∼28.0 °C in the near-coast sites. The latter temperature is equal to mean annual near-shore Caribbean sea temperature of 27.9 ± 1.6 °C for 2000–2001 from Puerto Calica (Badan Dangan, A., unpublished data). We propose that a more plausible explanation of the observed SWZ temperature data than the conventional entrainment or geothermally driven circulation systems is that warm near surface Caribbean seawater enters into the aquifer at the coast, and moves inland along the conduit system, a flow directly opposite to that present in the FWL. There is thus a progressive reduction of the temperature of this warm seawater as it equilibrates to the significantly lower temperature of the aquifer. The rate of temperature reduction inland may vary significantly with the discharge and groundwater velocity of individual conduits, explaining the considerable scatter evident in (Fig. 5e). On average, the difference between SZW temperature and FWL temperature reaches a minimum at ∼10 km coincident with the limit of the conduit system and thus the zone of rapid focussed groundwater circulation. This is effectively the inner limit of the conduit subterranean estuary.

The transfer of heat from the shallow saline circulation across the MZ into the cooler FWL might be expected to give a progressive increase in FWL temperatures as waters move coastward. In fact the converse is true, there being a small but significant increase in FWL temperature (∼0.3 °C) towards the interior. At present we have no simple explanation for this trend. Whilst it might be a statistical artefact, the parallel trend evident in the data from pit cenotes suggests that this is unlikely. Another possibility is that there may be significant gradients in precipitation within the coastal zone, and that the enhanced recharge of cold meteoric water (∼20 °C or less) adjacent to the coast compared to in the interior gives a small but significant impact on FWL temperatures (see discussion on FWL and precipitation temperature in Section ''FWL temperatures'').

An implication of the rapid inland flow of Caribbean seawater below the MZ is that the circulation of the FWL and the shallow SWZ must be hydrologically decoupled, with bilateral flows of coastward discharging fresh water overlying inflowing saline water in places within the same conduit. The $\Delta SEC_{SWZ-FWL}$ is generally more than 45 mS/cm, and such a high density interface in excess of 0.02 kg/L (Fig. 2) readily allows for sheared flows, while also effectively damping vertical movements within the water column (Turner, 1973; Kantha and Clayson, 2000). Similarly, the SEC step delimiting the base of the shallow SWZ, although relatively small in comparison to that of the principal MZ, is still substantial in absolute terms (0.59 ± 0.85 mS/cm, ∼0.002 kg/L, n = 17; Fig. 4) and thus similarly represents a shear interface across which the shallow and deep saline circulation may be decoupled. The present data does not allow for clear statistical discrimination between SWZ temperatures and SEC in conduit and non-conduit sites due to the limited number of pit cenotes sampled at less than 12 km inland (n = 5). In general, the temperature of the SWZ in pit cenotes is cooler than the conduit sites. This may indicate that pit cenotes are isolated from the proposed rapid circulation of seawater through the conduit networks. This conjecture is consistent with intergranular and small scale fissure flows that must dominate the hydrological flux through these non-conduit sites. The absence of the SEC step and the associated temperature decrease demarcating the transition from the shallow and deep SWZ in two of the conduit sites (The Pit and the Blue Abyss) suggests that these two sites are not affected by the proposed rapid inland flow of seawater below the MZ, possibly due to the lack of horizontal passages at and below the depth of the MZ which imparts a degree of hydrological isolation. Thus the lower saline groundwater temperatures may arise from isolation of pit cenotes and some of the conduit sites from the proposed rapid inflow of warmer seawater.

Conclusions

Direct study of the spatial distribution of SEC and temperature of groundwaters in the cavernous zone along the Caribbean coast of the Yucatan Peninsula has provided new insights into the groundwater circulation in this density-stratified coastal carbonate aquifer. The FWL immediately adjacent to the coast has elevated SEC due to the dynamic tidally-induced mixing with the underlying saline groundwater. This is most marked in the conduit sites, but also affects non-conduit sites to a variable degree. Inland of a ~1 km wide near-coast zone, the SEC of the FWL decreases progressively in both conduit and non-conduit sites, but generally remains higher in conduit than in non-conduit sites because of their direct interconnection to the ocean.

Conduit morphology is a principal control on the rate of mixing of saline water into the FWL. A high rate of mixing is found in conduit sites 1–4 km inland where shear due to differential movement of the saline and fresh waters occurs, and turbulence is induced by flow through and around obstacles that span the depth of the MZ. Further inland (4–10 km) the MZ generally lies below the floor of the conduits, isolating the FWL in these sites from such direct mixing. The change in conduit morphology and geometry, and thus the potential for in-conduit mixing along the flow path, results in non-linearities in the rate at which SEC of the FWL decreases inland. Inland of the dynamic near-coast zone, the FWL temperatures are generally lower but increase slightly with distance from the coast, possibly due to convective warming from the saline zone. Alternately, the reduction in FWL temperature to a minimum at ~1 km may reflect higher rates of recharge of cold rainwater near to the coast.

The significant exponential decline in the temperature of the shallow SWZ with distance inland can only be explained by the rapid inflow of shallow Caribbean seawater through the conduit system. The temperature data is inconsistent with the conventional circulation model for coastal aquifers in which there is a parallel coastward flow of fresh and saline groundwaters. This finding indicates that the role of entrainment in driving flow in the shallow SWZ is very limited. The field data is drawn from an 80 km segment of coastline with repeat observations in many sites spanning 31 months. The advective circulation of seawater via the conduits is therefore a persistent and spatially extensive feature along the Caribbean coast of the Yucatan Peninsula, demonstrating the cavernous zone which extends to some ~10 km inland to represent a true subterranean estuary. The spatial temperature gradient in the SWZ is opposite to that anticipated from geothermal-driven circulation. However, the elevation of temperatures in the platform interior provides convincing evidence of some limited geothermal convection, and this may maintain the observed temperature offset between the cooler FWL and the underlying SWZ. Thus two thermal inputs to the SWZ are identified; advection of warm seawater through the conduit networks and upward convection of geothermal heat. In a subsequent paper we present flow monitoring and dye tracing data to confirm the persistence and direction of this shallow sub-mixing zone saline flow system.

There is a consistent difference between the SEC and temperature of conduit and non-conduit sites, with the FWL in wells and pit cenotes being slightly cooler and lower SEC than conduit sites at comparable distance inland. This accords with considerably lower flow rates within the aquifer matrix, which dominates storage, and much more rapid circulation within the conduits. The morphology of conduits and geometry of the conduit network are first order controls on the distribution of groundwater temperature and SEC with distance inland in both the FWL and SWZ.

The influx of seawater beneath the FWL has significant implications for carbonate digenesis. Inflow of seawater supersaturated with respect to calcite may result in precipitation of marine phreatic cements which typify the margins of many carbonate platforms (James and Ginsburg, 1979). In addition seawater is rich in magnesium and, subject to kinetic limitations, may result in dolomitisation (Machel, 2004). The circulation pattern reported here is likely to result in a torroidal dolomite body such as reported on the Little Bahama Bank by Vahrenkamp and Swart (1994). Indeed we have previously documented magnesium depletion in saline groundwater in the study area, which is interpreted as indicative of active dolomitisation (Smith et al., 2002; Smith, 2004).

This expansion of our understanding the hydrology of coastal carbonate aquifers has particular implications for water resource protection. The SWZ is commonly used as a receptor of liquid waste along many coastlines of the world, including the Yucatan Peninsula. The prevailing assumption is that contaminated waters will flow offshore after a significant delay of years to decades as predicted by the conventional model for coastal aquifers. Any impact is thus assumed to be limited, and restricted to reefal and other submarine communities. The discovery that shallow saline flows in conduit aquifers can be directed inland from the sea implies that injected waste, particularly buoyant sewage, could potentially contaminate the FWL including wells and cenotes used as potable water supplies some distance from the coast.

Acknowledgements

We greatly appreciate the support of the Universities UK Overseas Research Studentship (PAB), the University of Bristol (University Scholarships to PAB and SLS and Alumni Association Awards to PAB, PLS and SLS), the Royal Society (Dudley Stamp Award to PAB), the Royal Geographical Society (Gilchrist and Ralph Brown Expedition Awards to PLS, and HSBC Grant to FFW), British Cave Research Association (PAB and SLS), the British Sedimentological Research Group (Gill Harwood Award SLS), and Canada Doctoral Study Grants (PAB & SLS). We thank the Centro Ecologico Akumal, Akumal Dive Shop, Hidden Worlds, Akumal Dive Centre, Municipalidad de Solidaridad, Tulum Dive Centre, and Cenote Dive of Tulum for invaluable sponsorship and logistic support, and H. Brown, G. Brown, D. Hodge, M. Jasper, A. Kuecha, E. Mallon, L. Patchell, J. Telling and C. Vizl for dedicated field assistance. We are most grateful for the enthusiasm and camaraderie of the people and cave diving community of Quintana Roo.

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