# Review: The Yucatán Peninsula karst aquifer, Mexico

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**Abstract** The Yucatán Peninsula karst aquifer is one of the most extensive and spectacular karst aquifer systems on the planet. This transboundary aquifer system extends over an area of approximately 165,000 km$^2$ in México, Guatemala and Belize. The Triassic to Holocene Yucatán limestone platform is located in the vicinity of the North American/Caribbean plate boundary and has been reshaped by a series of tectonic events over its long geologic history. At the end of the Cretaceous period, the Yucatán Peninsula was hit by a large asteroid, which formed the Chicxulub impact crater. The Yucatán Peninsula karst aquifer hosts large amounts of groundwater resources which maintain highly diverse groundwater-dependent ecosystems. Large parts of the aquifer are affected by seawater intrusion. Anthropogenic pollution of the aquifer has been increasing over the past few decades, owing to relentless economic development and population growth on the Peninsula. This review summarizes the state of knowledge on the Yucatán Peninsula karst aquifer and outlines the main challenges for hydrologic research and practical groundwater-resources management on the Peninsula.

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## Introduction

The Yucatán Peninsula (YP) is a vast limestone platform with a surface area of about 165,000 km$^2$, comprising the Mexican federal states of Campeche, Yucatán, Quintana Roo, and parts of Tabasco, as well as the northern parts of Belize and the northern parts of Guatemala's department of El Petén. Population and economic activity on the YP have been growing rapidly in recent years. Economic activity is concentrated in a large service sector which includes an extensive tourism industry along the Caribbean coast of the YP. A major part of the tourism development consists of large all-inclusive resorts. The rapid economic development in the region causes pressure on the available water resources. Apart from human development, the water resources of the YP sustain rich and highly diverse ecosystems, including wetlands, tropical forests and one of the world's largest coral reef systems. The Sian Ka'an Biosphere Reserve (6,510 km$^2$, including the Sian Ka'an Reefs Biosphere Reserve and the Uaymil Wildlife Protection Area), located on the Caribbean coast of the YP is a groundwater-dependent wetland of international importance protected by the Ramsar Convention and declared a UNESCO World Heritage site.

The only available water resource on the YP is groundwater. The Peninsula is flat and due to its geological characteristics, surface-water runoff and drainage are practically non-existent, except in the southern parts of the Peninsula. The southern portions of the YP are drained by the northwestward-flowing Rio Usumacinta and its tributaries (average discharge to the ocean 1,650 m$^3$ s$^{-1}$) and the northeastward-flowing Belize River and its tributaries (average discharge to the ocean 155 m$^3$ s$^{-1}$). In this paper, the southern limits of the YP are defined following Vinson (1962) and Lopez-Ramos (1975): in the southwest, the Rio Usumacinta and its tributary, the Rio San Pedro, form the limit. In the southeast, the Belize River forms the limit. In between, the limit follows the La Libertad fault zone, which has the Lago Petén Itzá in Guatemala as its most notable surface expression (*lago* means lake; Figs. 1 and 2).

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Groundwater storage and flow occur in a regional karst aquifer with major cave systems, where groundwater flow is dominated by turbulent conduit flow. The hydrogeological properties of the subsurface have been modified by the Chicxulub meteorite impact 65 million years ago. Major cavities and conduits are embedded in the karst aquifer, including the world's largest underwater cave systems. Sinkholes (which are locally called *cenotes*) are common throughout the YP but cenote density varies significantly over the YP (Fig. 2). Seawater intrusion into the YP karst aquifer is extensive and reaches tens of kilometers inland. Groundwater use is thus restricted to a relatively thin freshwater lens (<10–100 m thick).

This paper reviews the state of knowledge on the hydrogeology of the Yucatán Peninsula. The practical aspects of groundwater-resources management are emphasized. As in many other places around the world, the key groundwater-management problem on the YP is trading off groundwater for human use against groundwater for ecosystems.

## The geological setting of the Yucatán karst aquifer

The Yucatán Peninsula consists of limestones, dolomites and evaporites reaching thicknesses of >1,500 m (Weidie 1985), which are lying on top of igneous and metamorphic basement rocks. The limestone platform (total area of approx. 300,000 km$^2$) consists of a submerged shelf and an emerged portion which are roughly equal in size. Unconformities in the sediment layer indicate intermittent partial subaerial exposure and erosion of the platform's surface (Lefticariu et al. 2006; Perry et al. 1995; Pope et al. 1996). Early geological reconnaissance work by K. Sapper, F. Bonet, M. Alvarez and J. Butterlin established sequentially younger ages of the carbonate sedimentary rocks towards the northern parts of the YP (Alvarez 1954; Bonet and Butterlin 1965; Butterlin 1958; Sapper 1896). The Pemex drilling program of the 1970s along with regional gravity and magnetic surveys, established the present conceptual geological understanding of the YP (Lopez-Ramos 1975; Ward et al. 1985): sedimentary rocks exposed at the land surface range in age from Upper Cretaceous to Holocene. Sediment strata are generally nearly horizontally layered and off-lapping, with gradually younger carbonates deposited towards the Peninsula margins (Lopez-Ramos 1975; Schönian et al. 2005; SGM 2007). The Cretaceous age of the oldest sedimentary rocks exposed at the ground surface is a recent interpretation (Schönian et al. 2005) but the possibility was already mentioned by Lesser (1976). Kenkmann and Schönian (2006) emphasized that the geology of the southern Peninsula is poorly constrained due to few exposures and difficulties in dating the sedimentary rocks through biostratigraphy.

At the end of the Cretaceous, a large asteroid (about 10 km diameter) hit the YP (Alvarez et al. 1980; Hildebrand et al. 1991; Morgan et al. 1997; Penfield and Camargo 1981; Pope et al. 1991; Sharpton et al. 1992). The center of the ~200 km impact crater, named the Chicxulub impact crater, is located off the present YP Gulf of México coastline, at approximately 21.4˚N/89.52˚W. A

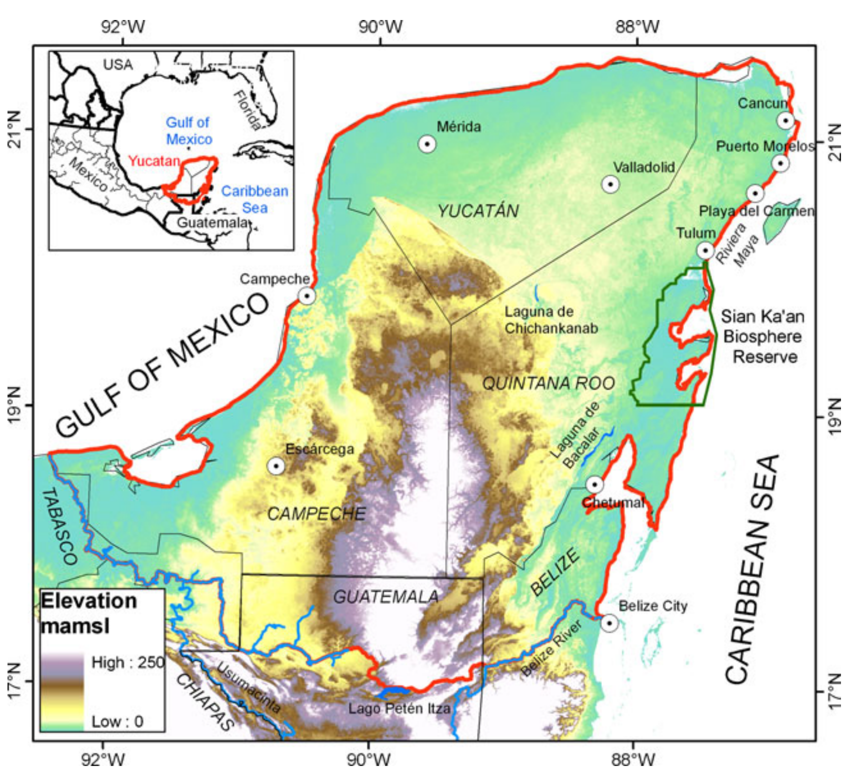


**Fig. 1** Location and base map of the Yucatán Peninsula. Background shading indicates topographic elevation. SRTM, meters above mean sea level (*mamsl*). *Circles* indicate cities


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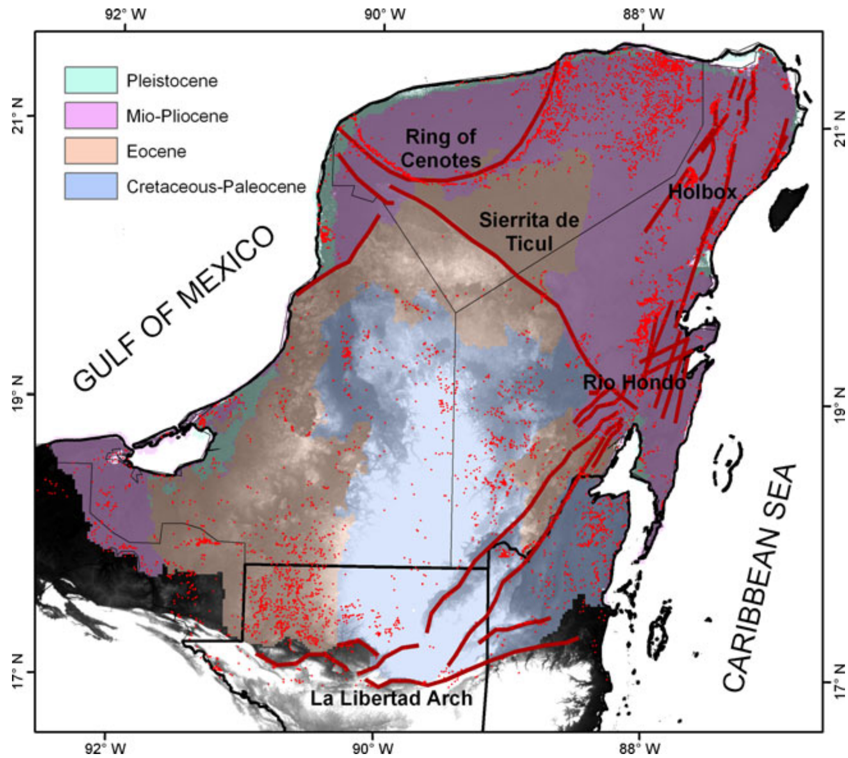


**Fig. 2** Map of regional-scale preferential flow paths (*red lines*) and cenote locations (*red dots*) on the YP. Cenotes were identified visually on high-resolution satellite imagery (CNES-SPOT, and Quickbird, accessed through Google Earth). *Background colors* indicate age of surface geology (SGM 2007). *Background shading* indicates SRTM topography

recent review on the impact and the associated mass extinction was published by Schulte et al. 2010. The outline of the impact crater is marked by a fracture zone with a high density of sinkholes ('Ring of Cenotes', Perry et al. 1995). After the impact, the Chicxulub impact crater became a sedimentary basin. Deposition had completely filled the impact crater by the middle Miocene (Lefticariu et al. 2006). High iridium concentrations indicate that components of the asteroid may be preserved in the crater (Schuraytz et al. 1996). The crater was extensively drilled to maximum depths of about 1,500 m. Layers of impact breccia were encountered in several of the boreholes (Rebolledo-Vieyra et al. 2000; Safanda et al. 2007; Safanda et al. 2009; Urrutia-Fucugauchi et al. 2004; Wohlgemuth et al. 2004).

Ejecta associated with the Chicxulub meterorite impact, at the contact between Cretaceous and Paleogene sediments, have been found at the surface in southern Quintana Roo and neighboring Belize, as far away as ~360 km from the impact crater (Fouke et al. 2002; Kenkmann and Schönian 2006; Ocampo et al. 1996; Pope et al. 1999; Pope et al. 2005; Schönian et al. 2005). Based on geochemical data, Perry et al. 2009 proposed that the ejecta blanket extends south and east of Lake Chichankanab (Fig. 1). It appears that in official geological maps some ejecta deposits in the central hill district may have been misdated to be Quaternary deposits, as some locations correlate with locations mapped by Kenkmann and Schönian (2006) as ejecta (Neuman and Rahbek 2007; Perry et al. 2009). The ejecta is expected to have a low hydraulic permeability, as it is clay-rich, and described to have a sealing or partially sealing effect (Grajales-Nishimura et al. 2000; Mayr et al. 2008; Ocampo et al. 1996; Perry et al. 2009).

## Preferential flow paths in the Yucatán karst aquifer

Preferential flow paths in the Yucatán karst aquifer occur over a range of scales. Here, preferential flow paths are classified into regional-scale fracture zones (~10–100s of kilometers), large dissolution conduits (~1–10s of kilometers) and small-scale fractures and dissolution cavities (~10s of meters). Groundwater flow in the conduit systems is turbulent.

### *Regional-scale fracture zones*

Isphording (1975) divided the emerged part of the YP into five distinct physiographic regions: the coastal zone, the northwestern coastal plain, the northeastern coastal plain, the central hill district and the eastern block fault district. The different regions are characterized by a variable degree of fracturing. The most notable regional-scale fracture zones are the Ring of Cenotes, the Sierrita de Ticul fault line, the Holbox fracture zone, the Rio Hondo block fault zone and the La Libertad fault zone (Fig. 2). The southern portions of the Yucatán Peninsula are located about 200 km north of the present North American/Caribbean plate boundary. Coney (1982) provides a general account of the tectonic history of Central America. The present boundary crops out in eastern Guatemala and forms the E–W trending Polochic and

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Motagua fault systems. These are lateral-moving transform faults caused by the movement of the Caribbean Plate relative to the North American Plate (Burkart 1978; Erdlac and Anderson 1982; Lodolo et al. 2009; Schwartz et al. 1979). The YP forms part of the Maya continental block, located north of the Motagua and Polochic fault systems. The Chortis block, located south of the fault systems, collided with the Maya block in the Late Cretaceous (Giunta et al. 2002; Lodolo et al. 2009), producing complex thrust sheets on the Cretaceous sediment layers, which can be clearly distinguished on the shuttle radar topography mission (SRTM, Rabus et al. 2003) topography map of the southern YP (Fig. 1).

The Ring of Cenotes is a regional-scale structure, which possibly conducts groundwater more effectively than its surroundings, as evidenced by declining water-table elevations towards the ring (Marín 1990), and high temporal variability of hydraulic heads (Steinich and Marín 1997). Geophysical surveys confirmed anisotropic subsurface electrical conductivity distributions which can be interpreted as indications of fracturing (Steinich and Marín 1996). Possible causes of high permeability for groundwater flow are faulting associated with differential lithological compaction within the sedimentary basin, a buried reef complex or impact breccia collapse (Perry et al. 1995). Numerical groundwater modeling of the northwestern Yucatán karstic aquifer provided limited evidence for significantly higher permeability along the Ring of Cenotes (Gonzalez-Herrera et al. 2002; Marín 1990; Marín et al. 2004).

A sharp, NE facing escarpment along the northern edge of the Sierrita de Ticul was interpreted as a normal fault by Weidie (1985). Based on groundwater geochemistry, the Sierrita de Ticul fault line has been interpreted as a zone of high permeability by Perry et al. (2002), while Gonzalez-Herrera et al. (2002), Marín (1990) and Marín et al. (2004) implemented it as a flow barrier in their regional-scale numerical-groundwater-flow model of northwestern Yucatán.

The Holbox fracture zone was first described by Weidie (1982) as a lineament of unknown origin. Surface expressions of the Holbox fracture zone are large, flat-bottomed, elongated swales. Southworth (1985) delineated the Holbox fracture zone in an early application of satellite remote sensing for hydrogeological exploration. Tulaczyk et al. (1993) refined the delineation of the Holbox using LANDSAT satellite imagery and concluded that the fracture zone guided the development of regional dissolution features in the karst aquifer resulting in high permeability and groundwater drainage. Frequency domain airborne electromagnetic mapping was performed over the southern extensions of the Holbox fracture zone in the vicinity of Tulum and higher subsurface electrical conductivity values compared to the surrounding areas were found, indicating increased porosity and permeability (B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010).

Weidie 1985 described the Rio Hondo fault zone as the on-shore continuation of an extensive horst and graben block fault system off the Caribbean coast of the southern YP. Marine-seismic-data interpretation by Dillon and Vedder (1973), Lara (1993), Leroy et al. (1996) and Rosencrantz (1990) indicate a fault system aligned sub-parallel to the southern Caribbean coast of the YP. The fault system extends on-shore in the southern parts of Quintana Roo and Belize (Weidie 1985). The fault system was created by distinct tectonic events over Late Cretaceous to Pliocene times (Lara 1993). Freshwater lakes such as the ~3.1 km$^2$ Laguna de Bacalar occupy some of the larger fault basins (Isphording 1975; Burkart 1994). Based on synthetic aperture radar (SAR) remote-sensing image analysis, Gondwe et al. (2010a) proposed that the Rio Hondo fault system extends northwards and intersects with the Holbox fracture zone in the vicinity of Tulum. This possibility was already discussed by Southworth (1985). Using geochemical data, Perry et al. (2002) showed that the Laguna de Bacalar has no direct hydrological connection to the ocean, which may indicate drainage of the lake towards the north, along the extended Rio Hondo fault system.

Vinson (1962) defines the boundary of the Yucatán platform as the La Libertad fault zone in northern Guatemala. The fault zone is caused by the anticlinal La Libertad arch which extends from the Rio Usumacinta in the west to the Maya mountains in the East (Burkart 1994; Miller 1996; Vinson 1962). The Maya mountains constitute an uplifted block of Paleozoic metasediment. Their northern and southern boundaries are delineated by major faults (Miller 1996). The Cretaceous sedimentary rocks in the La Libertad fault zone are heavily karstified (Miller 1996).

Regional-scale structures in southern Quintana Roo were identified, which are aligned E–W to NE–SW and possibly form part of the Rio Hondo fault zone (B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010). Surface expressions of the structures are topographic depressions, surface-water bodies and anomalous signature in multi-spectral satellite imagery. Selected structures were transected with frequency domain airborne electromagnetic surveys. The structures showed an anomalous geophysical response. However, interpretation of the geophysical response in terms of subsurface porosity and permeability remains ambiguous.

### Large dissolution conduits

Many Yucatecan carbonates are heavily karstified and display large dissolution conduits (~10s of km). They host abundant caves, including the world's longest underwater cave system (Supper et al. 2009; Quintana Roo Speleological Survey 2010). Mapped caves are mainly found on the Riviera Maya, possibly as a result of its vicinity to population centers, rather than lack of cave systems elsewhere (Beddows 2004; Smart et al. 2006). Large dissolution features and cenotes have not been systematically mapped for the entire YP.

Figure 2 shows the distribution of cenotes that could be visually identified on high-resolution satellite imagery (Quickbird and CNES-SPOT, provided through Google Earth). This map confirms earlier qualitative assessments by Isphording (1975) who concluded that cenotes are mainly restricted to the coastal plains and are practically absent in the central hill district. High cenote density in the coastal plains may be caused by more dynamic interaction with the intruding seawater and, thus, faster rates of limestone dissolution (Hanshaw and Back 1980). There are, however, some major caveats: comparatively small cenotes cannot be detected on satellite imagery under dense vegetation; image quality (cloud cover) and resolution are not uniform over the YP; some cenotes in the Cretaceous surface may have been covered and sealed off by the ejecta layer (Kenkmann and Schönian 2006). Miller (1996) reports that large dissolution features and karstification in Belize is confined to rocks of Cretaceous age. Villasuso (2007) presents a map of faults, fractures, cenotes and dolines on the YP. However, data sources and references are not listed in the report. Steinich (1996) mapped more than 7,000 cenotes or aguadas using the Mexican Census and Geography Agency (Instituto Nacional de Estadística y Geografía, INEGI) 1:50,000 topographical maps.

The Riviera Maya karst conduits have been investigated and mapped using scuba diving, dye tracing and geophysical techniques. Beddows (2004) and Smart et al. (2006) give a comprehensive overview of the mapped cave systems on the Riviera Maya, their geometry and in-situ observed flow velocities and water quality. Key characteristics of the Quintana Roo cave systems are listed in Smart et al. (2006): in total, several hundreds of kilometers of cave passage have been explored and this number is continuously increasing; the passage density of the caves ranges from ~6 to ~19 km km$^{-2}$; generally, the cave depth correlates with the position of the halocline because of preferential carbonate dissolution in the mixing zone; cave depths near the coast are thus between 10 and 15 m and increase inland; maximum depths of up to 72 m have been recorded; cave sizes and shapes are variable; conduit diameters of up to >30 m have been observed (Smart et al. 2006). Thomas 1999 reviewed data on flow velocities, cave discharge and groundwater salinity from the Riviera Maya region and performed water balance calculations for this area. Some information on the Nohoch Nah Chich cave system is reported in Beddows (2003). Available estimates of cave flow characteristics were reviewed and compared with numerical model outputs (B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010).

Non-invasive mapping methods have been used with some success for mapping cave systems and their flow characteristics in Quintana Roo. Beddows and Hendrickson (2008) used multiple dye tracing to infer flow characteristics and residence times in the Aktun Ha system, which is located a few kilometers northwest of the town of Tulum. Results showed highly heterogeneous local flow systems with rapid flow in one branch of the cave system and almost stagnant water in an adjacent branch. Schwaiger et al. (1997) used ground penetrating radar to map a known cave system. The results were ambiguous due to weak reflections which only sometimes corresponded to the known cave geometry. Supper et al. (2009) evaluated the performance of ground-based electrical resistivity imaging and airborne electromagnetic imaging for mapping known caves. Both techniques reliably detected known cavities and provided indications of cave geometry and depth. Villasuso (2007) presents successful fracture and cave-mapping applications using time-domain electromagnetic sounding and multi-electrode resistivity imaging for a locality close to Puerto Morelos, northern Quintana Roo.

### *Small-scale fractures*

Small-scale fractures and dissolution cavities are ubiquitous in the sedimentary rocks of the YP. Little specific information on their genesis is available in the published literature. Erosion, seismic activity and dissolution of carbonate rocks by rainwater are important processes for the formation of small-scale fractures. Small-scale fractures enable rainwater to rapidly infiltrate into the carbonate rocks and provide access paths for plant roots (Fig. 3). Due to the presence of small-scale fractures, effective hydraulic conductivities of "inter-conduit" areas on the YP are often significantly larger than hydraulic conductivities of decimeter-scale samples of the carbonate rocks (Table 1).

## The water balance of the Yucatán karst aquifer

Average annual rainfall ranges from 550 to 1,500 mm year$^{-1}$ in the YP—Tropical Rainfall Measuring Mission (TRMM), 3B42 product, 1998–2008, see Huffman et al. (2007) for details on the data product. The spatial distribution of

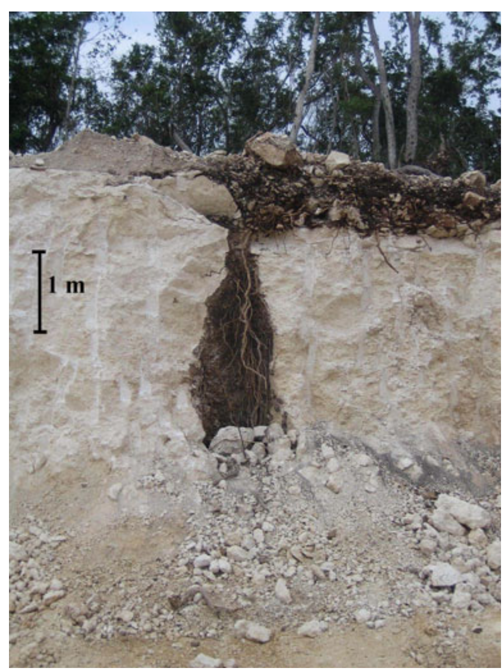


**Fig. 3** Vegetation tapping groundwater sources for phreatic evapotranspiration. Open-pit gravel quarry in the vicinity of Tulum (~20.2955°N, 87.5028°W). The scale is approximate

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Table 1 Summary of published effective hydraulic conductivity estimates for the YP. Aquifer type codes: *U* undifferentiated aquifer; *M* matrix; *HPZ* high permeability zone; *LPZ* low permeability zone

| K (m $s^{-1}$) | Aquifer type | Scale | Method | Location | Source |
|---|---|---|---|---|---|
| 0.0116 | U | 10s of meters | Test pumping | 21.0591 N, 87.0270 W | Aguakan S.A de C.V. (2009) |
| 0.004 | U | 10s of meters | Test pumping | 21.0637 N, 87.0331 W | Aguakan S.A de C.V. (2009) |
| $9{\cdot}10^{-4}$–$1{\cdot}10^{-2}$ | U | 10s of meters | Test pumping | Mérida | Andrade-Briceño (1984) |
| 0.1 | U | 10s of km | Numerical model calibration | Northwest Yucatán state | Marín (1990) |
| 1 | HPZ | 10s of km | Numerical model calibration | Northwest Yucatán state | Marín (1990) |
| 0.55–1.115 | U | 10s of km | Numerical model calibration | Northwest Yucatán state | Gonzalez-Herrera et al. (2002) |
| 6 | HPZ | 10s of km | Numerical model calibration | Northwest Yucatán state | Gonzalez-Herrera et al. (2002) |
| 0.0055 | LPZ | 10s of km | Numerical model calibration | Northwest Yucatán state | Gonzalez-Herrera et al. (2002) |
| 0.064 | U | 10s of km | Numerical model calibration | Mérida | Mendez-Ramos (1991) |
| 0.36–2.59 | U | 100s of km | Numerical model calibration | Southern Quintana Roo | (B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010) |
| 0.26–68.84 | HPZ | 100s of km | Numerical model calibration | Southern Quintana Roo | (B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010) |
| 0.014–2.48 | U | 100s of km | Numerical model calibration | Yucatán Peninsula | Charvet (2009) |
| 7.38–295.8 | HPZ | 100s of km | Numerical model calibration | Yucatán Peninsula | Charvet (2009) |
| 0.19–0.65 | U | 10s of km | Darcy's law | Playa del Carmen | Moore et al. (1992) |
| $10^{-6}$–$5{\cdot}10^{-3}$ | M | 10s of cm | Hydraulic testing of core samples | Mérida | Gonzalez-Herrera (1984) |
| $3{\cdot}10^{-4}$–$5{\cdot}10^{-2}$ | M | 10s of cm | Hydraulic testing of core samples | North of Mérida | Reeve and Perry (1990) |

average rainfall is shown in Fig. 4. Average annual potential evapotranspiration (ET) ranges from 850 to 1,600 mm $year^{-1}$ and displays a weak NW–SE gradient with higher potential evapotranspiration in the NW YP decreasing towards the east coast and the south. Potential ET was computed from the operational surface analysis dataset, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF 2010). Actual evapotranspiration was determined by Gondwe et al. (2010b) for the period from 2004 to 2008 from remote-sensing data. The average annual actual evapotranspiration for the YP varied spatially between 350 and 2,500 mm $year^{-1}$. Actual evapotranspiration has a distinct spatial variability with higher actual evapotranspiration along the coasts and relatively low actual evapotranspiration in the drier and less densely vegetated Yucatán State. The YP is generally characterized by thin soils and, in the coastal plains, by thin (i.e. <10 m) unsaturated zones. Lesser (1976) provided the first estimate of regional-scale groundwater recharge, based on simple water-balance calculations. He gives the recharge as 150 mm $year^{-1}$, or roughly 14% of mean annual precipitation. Back (1985) and Hanshaw and Back (1980) refined the recharge estimate but maintained a similar overall ratio of groundwater recharge to precipitation. Groundwater recharged to the YP karst aquifer ultimately flows to three groundwater sinks: coastal outflow, pumping and phreatic evapotranspiration. Beddows (2004) measured coastal groundwater outflow in major submarine springs over a 80-km stretch of coastline in southern Quintana Roo and computed an average outflow of about 0.73 $m^3$ $s^{-1}$ per km of coastline. Using the recharge estimate by Lesser (1976), the average coastal outflow would be around 0.27 $m^3$ $s^{-1}$ per km of coastline. Based on these results, Beddows (2004) argued that overall average groundwater recharge for her study area near the Caribbean coast may be between 30 and 70% of average precipitation. Gondwe et al. (2010b) calculated the groundwater recharge rate using precipitation data from the TRMM mission (3B42 product, Huffman et al. 2007) and actual evapotranspiration estimates derived with a modified triangle method (Jiang and Islam 1999; Stisen et al. 2008). For their 35,000 $km^2$ study area in southern Quintana Roo, Gondwe et al. (2010b) computed an average groundwater recharge rate equivalent to 17% of the mean annual precipitation, which is in good agreement with the estimate by Lesser (1976). The study also suggested limited average recharge rates at the Caribbean coast. The apparent discrepancy with the Beddows (2004) estimate may be explained by flow of groundwater from distant parts of the YP to Beddows' coastal study area. The different available estimates of coastal outflow were reviewed and compared with regional groundwater modeling results (B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010), and for that study area, coastal outflow was modeled equivalent to ~0.3–0.4 $m^3$ $km^{-1}$ $s^{-1}$, which is in the same range as estimates by Hanshaw and Back (1980) and Thomas (1999) based on field measurements. The magnitudes of groundwater recharge to the YP karst aquifer and coastal outflow from the aquifer to the ocean require further research which should address a range of scales.

The amount of groundwater pumping from the YP karst aquifer is presently not known precisely because of weak monitoring infrastructure. Charvet (2009) gives the present pumped amount for Cancún drinking water supply as 1.9 $m^3$ $s^{-1}$ from a total of 142 wells. The water-supply agency in Quintana Roo (Comisión de Agua Potable y Alcantarillado, CAPA) gives the total pumped amount for the five municipalities of Othón P. Blanco, Felipe Carrillo Puerto, José María Morelos, Solidaridad, and Lázaro

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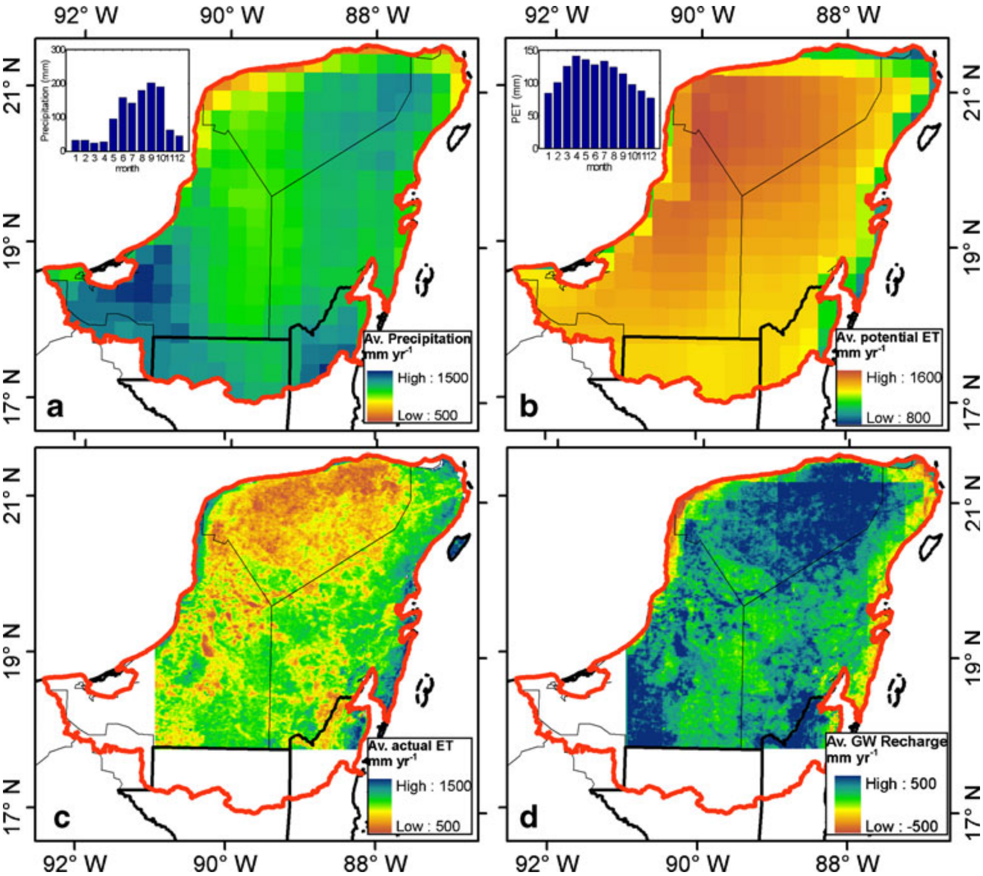


**Fig. 4** Maps of **a** precipitation (TRMM-3B42, average 1998–2008), **b** potential evapotranspiration (PET, ECMWF, average 2000–2008), **c** actual evapotranspiration (average 2004–2008) and **d** groundwater recharge (average 2004–2008) for the Yucatán Peninsula. All quantities are given in mm per year

Cárdenas as 0.81 $m^3\ s^{-1}$. Gonzalez-Herrera et al. (2002) estimated a total amount of pumping for all sectors including agriculture equal to 8.4 $m^3\ s^{-1}$ for the 36,550 $km^2$ area covered by their numerical groundwater model in Yucatán State. Escolero et al. (2000) estimated total groundwater abstraction of the Mérida metropolitan area as 3.8 $m^3\ s^{-1}$. The National Water Commission (Comisión Nacional del Agua; CONAGUA 2010), reports the official abstraction volume for the Mexican part of the YP as 75.1 $m^3\ s^{-1}$ or 1.63 $m^3\ day^{-1}$ per capita in 2008. The total groundwater abstraction on the YP is thus equivalent to 1.4% of the mean annual precipitation. According to CONAGUA, 61% of the total abstraction is used for agriculture, 20% for domestic use and 19% for industrial use. Using the LANDSCAN global population database (Dobson et al. 2000) and the average per capita water use, a groundwater abstraction map for the YP was constructed (Fig. 5). The underlying assumptions are that per capita water use is constant over the entire YP and is equal to the value given by Comisión Nacional del Agua (CONAGUA 2010) for the Mexican part of the YP. The groundwater abstraction map shows good correlation with the locations of groundwater abstraction wells officially registered by CONAGUA (Fig. 5). Figure 5 shows that groundwater abstraction is heterogeneously distributed over the YP, due to very variable population density. Overall however, groundwater abstraction is relatively low compared to the available resource and groundwater scarcity is not a serious problem on the YP.

Water tables in the coastal plains of the YP are fairly shallow (10–20 m below ground in most places). Phreatic evapotranspiration is therefore expected to be a significant term in the water balance of the YP karst aquifer. Field evidence from cave divers and quarries in the YP shows trees growing extensive vertical root systems that may reach the water table (Fig. 3). Phreatic evapotranspiration is hard to directly measure and quantify. Querejeta et al. (2007) report results of a study in northern Yucatán (approximate location 20.8˚N, 89.5˚W) using stable isotopes of water ($^{18}O$) to discriminate between different water sources used by the vegetation. Contrary to their expectation, they found that stem water isotopic signature was different from groundwater isotopic signature and similar to soil water isotopic signature for all times, including the dry season. This finding indicates insignificant groundwater use for the investigated locality and plant species. Actual evapotranspiration determined with remote-sensing techniques were correlated and depths to groundwater for a ~35,000 $km^2$ study area in southern Quintana Roo were simulated (B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010). The results indicate that actual evapotranspiration is close to potential evapotranspiration for water-table depths less than 10 m below surface. The ratio of actual evapotrans-


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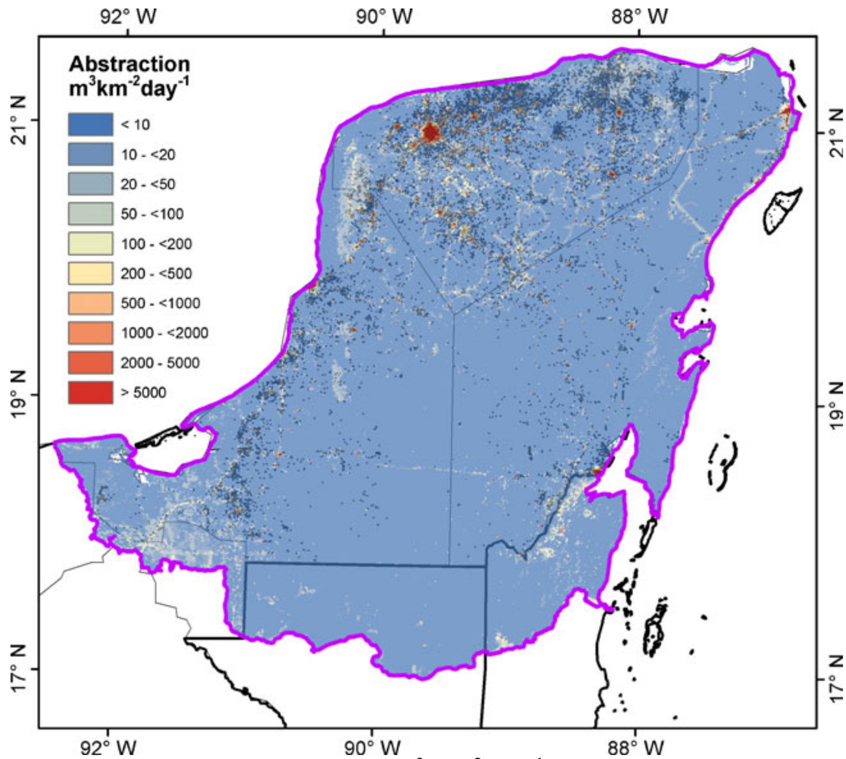


**Fig. 5** Groundwater abstraction map of the Yucatán Peninsula ($m^3\ km^{-2}\ day^{-1}$). The map has been constructed from the LANDSCAN population density map using average per capita withdrawals for the Mexican part of the YP. Note that non-permanent residents (tourists) are not included in the LANDSCAN population density. Water abstraction in the tourism areas may therefore be severely under-estimated. *Grey dots* indicate officially registered wells extracted from the archives of the Mexican National Water Commission (Mexican part of the YP only)

piration to potential evapotranspiration decreases between water-table depths of about 10 to about 30 m and stabilizes for deeper water tables. Vegetation growing in localities where the water table is less than 10 m thus appears to never suffer from water stress, while vegetation can use significant amounts of groundwater down to a groundwater depth of 30 m. These findings are in contradiction to the results reported by Querejeta et al. (2007). Magnitude and dynamics of phreatic evapotranspiration on the YP require further investigation.

## Groundwater flow in the Yucatán karst aquifer

Groundwater flow in the Yucatán karst aquifer is dominated by turbulent conduit flow. At scales much larger than the individual conduit, an "effective" hydraulic conductivity can be defined as the ratio of specific water flux and hydraulic head gradient. Such "effective" hydraulic conductivity values are useful when the aquifer is modeled as an equivalent porous medium. Hydraulic gradients in the Pliocene geology of the coastal plains of the YP are extremely low, typically ranging from 1 to 10 cm $km^{-1}$ (Back and Hanshaw 1970; Beddows 2004; Gondwe et al. 2010b; Marín 1990; Moore et al. 1992). Determination of the phreatic surface and groundwater flow directions therefore requires precise referencing of well measurement points to mean sea level. Large portions of the YP are remote areas with scarce infrastructure. Carrier phase differential GPS is the only feasible option for regional mapping of the phreatic surface (Charvet 2009; Gondwe et al. 2010b; Marín et al. 2008). A potential complication arises from geoid uncertainties on the YP. The global geoid model EGM96 (Lemoine et al. 1998) and the Mexican geoid model GGM05 (INEGI 2005) differ significantly on the YP (B.R. Neuman, Technical University of Denmark, unpublished report, 2007). In the central hill district on Cretaceous geology, measured water-table elevations are highly variable, indicating a discontinuous, possibly perched aquifer system. Figure 6 summarizes the available regional scale water-table elevation data from the YP. The data are based on the studies by Marín (1990); Gondwe et al. (2010b); Charvet (2009) and Fratini (C. Fratini, Technical University of Denmark, unpublished report, 2007). Water-table elevations for large, permanent water bodies have been extracted from the SRTM topographic elevation map. In general, the data confirm concentric flow from the center of the YP towards the margins. While data from the coastal Pliocene geology indicate continuous and consistent aquifers, data from the central Cretaceous geology indicate discontinuous and compartmentalized aquifer systems which are possibly perched. However, Derse et al. (2008) identified, in the Puerto Morelos area (Fig. 1), a nutrient rich, surficial, fresh groundwater aquifer and a Ra-rich lower nutrient source from a deeper aquifer discharging offshore. This finding suggests the presence of distinct aquifer units also in the coastal plains. Seasonal water-table dynamics in the

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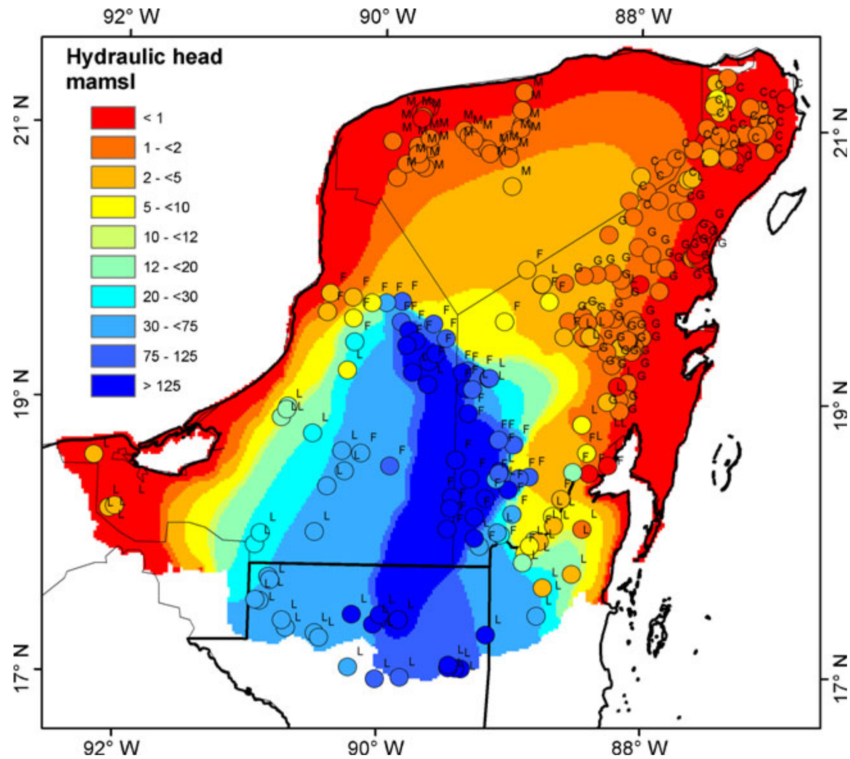


**Fig. 6** Water-table elevations on the YP. *Circles* are measurements. The *labels* refer to the datasets by Marin (1990) (*M*), Gondwe (2010) (*G*), Charvet (2009) (*C*), and Fratini (C. Fratini, Technical University of Denmark, unpublished report, 2007) (*F*). Water tables were measured in different years between April and July. Points labeled with *L* are permanent surface-water bodies with the elevation read from SRTM. The *colored contours* are the steady-state hydraulic heads calculated with a YP groundwater flow model modified after Charvet (2009)

Pliocene coastal plains of the YP are generally less than 0.5 m (Gondwe et al. 2010b; Marín 1990). In the Cretaceous hill district, some boreholes show much more pronounced seasonal fluctuations, confirming localized aquifer systems (Gondwe et al. 2010b).

The effective hydraulic conductivity of the YP karst aquifer is highly scale dependent. According to Worthington and Ford (2009) effective hydraulic conductivity in the Yucatán karst aquifer ranges from $10^{-4}$ $ms^{-1}$ at the 10 cm scale to 1 $ms^{-1}$ at the 100 km scale. Few published data or results of aquifer pump tests can be found in the literature, probably due to the high effective hydraulic conductivity of the aquifer which requires huge abstraction rates for successful test pumping. Effective hydraulic conductivity estimates are either based on small-scale laboratory experiments (Gonzalez-Herrera 1984; Reeve and Perry 1990) or regional-scale groundwater model calibration (Charvet 2009; Gonzalez-Herrera et al. 2002; Marín 1990; Marín et al. 2004; Villasuso 2007; B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010). Laboratory values are generally several orders of magnitude lower than model calibration results.

Several studies have used numerical groundwater modeling to elucidate groundwater flow patterns on the YP and provide groundwater-management decision support. Marín (1990) and Marín et al. (2004) simulated groundwater flow in northwestern Yucatán, around the Ring of Cenotes. Using a two-layer, equivalent porous medium approach, they were able to reproduce the observed hydraulic heads satisfactorily. Gonzalez-Herrera et al. (2002), simulated a similar area of northwestern Yucatán. The model was used to investigate the importance of regional-scale fracture zones and karstification for groundwater flow and to determine the impact of groundwater abstraction for the city of Mérida on the groundwater flow field. Numerical groundwater modeling was used in conjunction with particle tracking and Monte Carlo simulation to outline stochastic capture zones of the Sian Ka'an Biosphere Reserve (B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010); used an equivalent porous medium model with two domains representing regional-scale fracture zones and background "matrix" was used. Substantial conceptual model uncertainty remained after calibration with observed hydraulic heads, which indicates the need for more highly resolved calibration data (both in space and time) and calibration data of different types (flows, flooding patterns, tracer concentrations etc.).

In a workshop organized by Amigos de Sian Ka'an, groundwater experts from the region prepared a consensus map of regional-scale groundwater flow patterns on the YP—Fig. 7; ASK (2003). In order to check this map for physical consistency and in order to synthesize the available data, Charvet (2009) prepared a regional scale groundwater model of the entire YP. Several scenarios were run to investigate the effect of regional-scale high-permeability zones. Figure 6 shows the results of a modified version of the model by Charvet (2009). While the model simulates the observed water tables in the coastal plain successfully, performance in the Cretaceous

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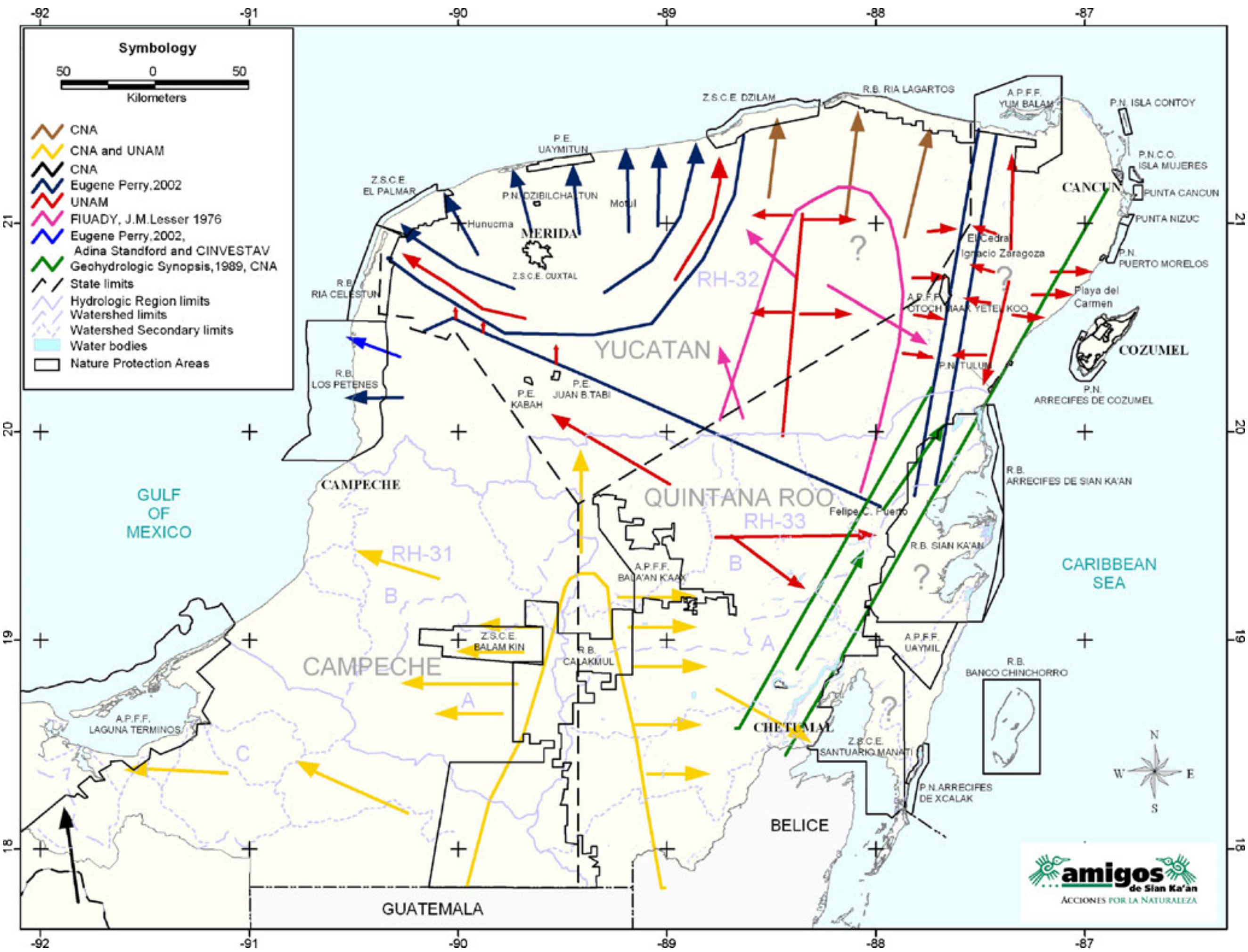


**Fig. 7** Consensus map of regional-scale groundwater flow (ASK 2003, with permission from Amigos de Sian Ka'an). *Arrows* indicate groundwater flow directions according to the respective reference. Details of references: *CNA* Comisión Nacional del Agua, personal communication, 2003; *UNAM* Universidad Nacional Autónoma de México, personal communication, 2003; *Eugene Perry 2002* refers to Perry et al. (2002). *FIUADY* Universidad Autónoma de Yucatán, personal communication, 2003; *J.M. Lesser 1976* refers to Lesser (1976); *Adina Stanford and CINVESTAV* refers to Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional, personal communication, 2003; *Geohydrologic Synopsis, 1989, CNA* refers to Comisión Nacional del Agua, personal communication, 2003

central hill district is worse due to compartmentalized aquifers and lack of data. A detailed model of the Cancún wellfields was subsequently nested into the regional-scale model. The Cancún groundwater abstraction was shown to be too small to significantly alter the regional flow field. Backward particle tracking was used to outline the well catchment zones for the Cancún abstraction wells. This information can guide land use management policies.

## Groundwater quality in the Yucatán karst aquifer

Large parts of the YP are affected by seawater intrusion into the freshwater aquifer. Because of the high effective hydraulic conductivity of the Pliocene coastal plains, freshwater aquifer water-table elevations are low. According to the Ghyben-Herzberg principle (Ghyben 1888; Herzberg 1901; Hubbert 1940), the elevation of the saline interface ($s$) can be computed as $s = -40 \cdot h$, where $h$ is the water level. Both $h$ and $s$ are in m above mean sea level. This formula is valid under the assumptions of a homogeneous geological medium, a sharp interface, and steady-state conditions in both the freshwater and salt-water domain. Low freshwater heads thus allow for intrusion of saline ocean water far inland. Beddows (2004) hypothesized that deep saline groundwater circulation may occur in a continuous salt-water layer from the Caribbean coast to the Gulf of México coast of the YP. The depth of the saline interface on the YP has been measured in situ in cenotes, boreholes and caves, as well as non-invasively, using geophysical techniques. While some authors confirm the validity of the Ghyben-Herzberg principle for the YP karst aquifer, others find significant deviations. Perry et al. (1989) report saline interface observations from northwestern YP and found good agreement with the Ghyben-Herzberg principle. Moore et al. (1992) measured depth to the saline interface in boreholes along a 70-km transect parallel to the northeastern coast of

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the YP. They found that the Ghyben-Herzberg principle generally overestimated the actual thickness of the freshwater lens. Beddows (2004) measured vertical profiles of electrical conductivity in numerous cenotes and cave system in the Riviera Maya along the Caribbean coast of the YP. The measured interfaces varied in shape from sharp to smooth transitions. Marín et al. (2004) report interface depths from northwestern YP and found good agreement between measured values and predictions using the Ghyben-Herzberg principle. Charvet (2009) reports a number of interface observations from the northeastern YP supplied by the Cancún water-supply utility Aguakan. Beddows et al. (2007) report detailed results on the interface configuration within the cavernous zone of the aquifer and found that conduit morphology was the dominant control on the interface configuration within the conduits. Steinich and Marín (1996) used resistivity techniques to determine the depth to the interface in the northwestern YP. Interface depths ranged from 18 to 110 m below ground and showed good correlation with in-situ measurements and predictions using the Ghyben-Herzberg principle. Gondwe et al. (2010b) performed geophysical borehole logging in 17 wells and 21 time domain electromagnetic (TDEM) spot soundings covering a ~35,000 $km^2$ area in southern Quintana Roo. The inferred interface depths confirmed the validity of the Ghyben-Herzberg principle at the regional scale. Supper et al. (2009) used geoelectrical imaging to determine the depth of the halocline in several locations in southern Quintana Roo. Figure 8 synthesizes the present state of knowledge on the YP freshwater–saltwater interface. Interface elevation data are plotted together with a simple one-dimensional Ghyben-Herzberg model of the coastal aquifer (Beddows 2004). Non-stationary, vertically heterogeneous flow fields around conduits violate the assumptions of the Ghyben-Herzberg interface. Deviations from the Ghyben-Herzberg principle are therefore likely due to the presence of conduit systems. In the absence of a reliable conduit map for the YP karst aquifer and of detailed, spatially resolved hydraulic head data, this hypothesis cannot be validated at the present stage.

Few studies have addressed the dynamics of the freshwater–saltwater interface on the YP. Beddows (2004) reports multi-temporal observations from localities on the Riviera Maya and found both stable and dynamic interface configurations. Escolero et al. 2007) report interface observations in the aftermath of hurricane Isidore (22–24 September 2002). They observed cyclic fluctuations in the interface position following this abnormal recharge event.

The groundwater geochemical signature has been used to infer flow paths and recharge mechanisms on the YP. Back and Hanshaw (1970) compared the hydrogeochemistry of the YP and the Florida Peninsula (USA). They characterized the groundwater geochemistry of the YP as being dominated by freshwater–saltwater mixing and the absence of downstream geochemical gradients. More recent results by Perry et al. (2009); (2002) and Gondwe et al. (2010b) show that this is valid for the areas with Pliocene geology but not necessarily for the portions of the YP with older carbonates. Perry et al. (2009) found a distinct geochemical signature of groundwater that has been in contact with the ejecta blanket. This geochemical signature can be used to trace groundwater flows at the regional scale on the YP (Gondwe et al. 2010b; Perry et al. 2009; E. Perry, Northern Illinois University, unpublished data, 2010).

Hanshaw and Back (1980) analyzed the phenomenon of chemical mass-wasting on the northern YP. The mixing of calcite-saturated freshwater and saltwater produces brines, which are under-saturated in calcite. The study concluded that this phenomenon could cause high dissolution rates in the mixing zone between freshwater and

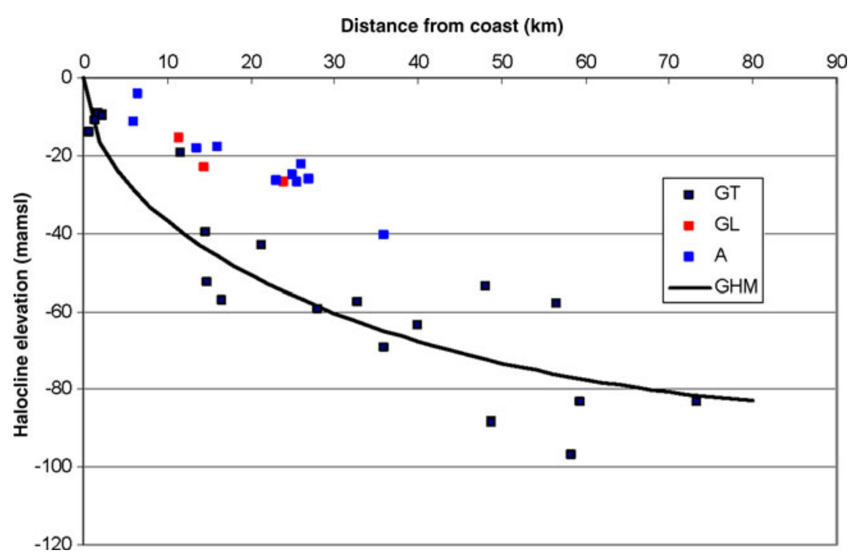


**Fig. 8** Elevation of the halocline as a function of distance to the coast. *Colors* indicate different datasets; *GT* estimates based on TDEM data from southern Quintana Roo collected by Gondwe et al. (2010b); *GL* borehole logging results from southern Quintana Roo by Gondwe et al. (2010b); *A* borehole logging results from northern Quintana Roo by Aguakan S.A de C.V. (2009); *GHM* predictions of the one-dimensional Ghyben-Herzberg model with hydraulic conductivity ($K$)=0.3 m $s^{-1}$ and groundwater recharge equal to 17% of precipitation


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saline water on the YP. The observed correlation between cave depth and depth to the halocline confirms the importance of this process for the geomorphology of the YP. Back et al. (1986) reported similar phenomena from the Xcaret cave system on the Riviera Maya.

Ongoing sedimentation and cementation processes have been reported for parts of the YP. Perry et al. (1989) observed a cemented layer along the northern coast of the YP, which acts as a confining unit for the aquifer. The presence of $^{14}C$ in the cemented layer confirmed that cementation is an ongoing process in this locality. The authors suggested that the cemented layer forms at the interface between the aquifer and a coastal wetland and is triggered by degassing of carbon dioxide from the emerging groundwater. The authors predicted significant changes in the freshwater–saltwater distribution in the coastal aquifer as a consequence of possible breaches in the confining layer due to regional urban development.

## Groundwater management and decision support

Water was a critical constraint for human development on the YP as long ago as Mayan times (2,000 BC to AD 900; Back 1995; Back and Lesser 1981). The Mayans clearly recognized the vulnerability of their water supply and water played a major role in Maya myths and religion. Many of the main Maya cities were associated with cenotes and the Mayans performed considerable engineering works to secure the water supply for their cities (Silverstein et al. 2009) and for agricultural production, for instance in wetland areas (Fedick et al. 2000). The abrupt decline of the classic Maya civilization between AD 750 and 900 has been linked to hydrologic extremes in the region (Hodell et al. 2005; Hodell et al. 2007; Lucero 2002; Webster et al. 2007). The impact of the Maya civilization on forest cover and soil erosion can be tracked in the lake sediment records from Lago Petén Itzá in Northern Guatemala (Curtis et al. 1998).

Modern groundwater-management problems on the YP are dominantly related to water quality. Groundwater recharge on the YP is large and the effective hydraulic conductivity of the coastal aquifer is high. Therefore, groundwater abstractions in the coastal plain are not expected to cause significant quantitative depletion of groundwater resources. In the central hill district, on Cretaceous geology, aquifer yields are lower and dry or low-yielding boreholes have been reported. However (and possibly for this reason), population density and economic development are much lower in these regions. Groundwater quality problems arise predominantly from wastewater discharge. In the absence of rivers, wastewater is mostly re-injected into the aquifer or discharged into cenotes or lakes. Only about one third of the total wastewater is treated prior to disposal (ASK 2003; Beddows 2002; Beddows et al. 2005; Krekeler et al. 2007; Marín et al. 2000). Groundwater quality degradation due to urban development on the YP was studied intensively for the Mérida metropolis (Escolero et al. 2002; Escolero et al. 2000). The main challenges for protecting Mérida's groundwater reserves were (1) the delineation of meaningful wellfield protection zones in the karstic aquifer, (2) the limited vertical extent of the usable freshwater lens, and (3) gradient reversal due to extraction and re-injection of large amounts of groundwater (Marín et al. 2001). The thickness of the freshwater lens is only 60 m underneath Mérida (the capital of Yucatán state). According to the Comisión Nacional del Agua (Mexican Water Commission), the upper 20 m of the freshwater lens are unfit for human consumption due to pollution from septic tanks; thus, currently one third of the potential water supply has been lost. Pacheco and Cabrera (1997) and Pacheco et al. (2001) reported widespread elevated nitrate concentrations in boreholes from different portions of Yucatán State. They related nitrate contamination both to agricultural practices and local wastewater contamination. Drucker and Latacz-Lohmann (2003) and Mazzotti et al. (2005) discuss groundwater contamination due to agricultural practices in southern Quintana Roo. Charvet (2009) evaluated the risk of seawater intrusion into the Cancún water supply wells due to upconing of the freshwater–saltwater interface. Due to the high effective hydraulic conductivity of the aquifer, this risk was evaluated as being of low significance, when the current filter depths are used in the groundwater abstraction wells. This conclusion probably holds for the Pliocene coastal plains in general. However, pollution of the shallow freshwater layer may require deeper screen intervals in the future. Moreover, at the local scale, aquifer hydraulic conductivity can be much lower than the regional-scale effective hydraulic conductivity used in equivalent porous medium models, resulting in higher risks of saltwater upconing.

On the Riviera Maya, a coastal district in Quintana Roo, relentless, large-scale tourism development threatens groundwater resources (Fig. 9). Economic development and associated population growth lead to exponentially increasing amounts of wastewater and solid waste. The region lacks comprehensive regulation of wastewater treatment. Landfills are particularly critical in this high-permeability karstic area. Stress on groundwater resources is thus continuously increasing and threatens both water-supply assets and groundwater-dependent ecosystems. Along with first-rate beaches and the Mayan cultural heritage, ecosystems and nature reserve areas are the main tourist attractions on the YP. Groundwater-dependent ecosystems on the YP include numerous cenotes (which are often used as starting points for scuba-diving exploration), wetlands (the most important is the Sian Ka'an Biosphere Reserve), rainforests and the over 600-km-long coral reef.

In this setting, the principal challenge of groundwater-resources management is land-use zonation and the establishment of groundwater protection areas. High permeability areas represent critical areas, as pollution can spread over large distances without being significantly attenuated. Protected areas can be established based on aquifer vulnerability maps or based on catchment zones


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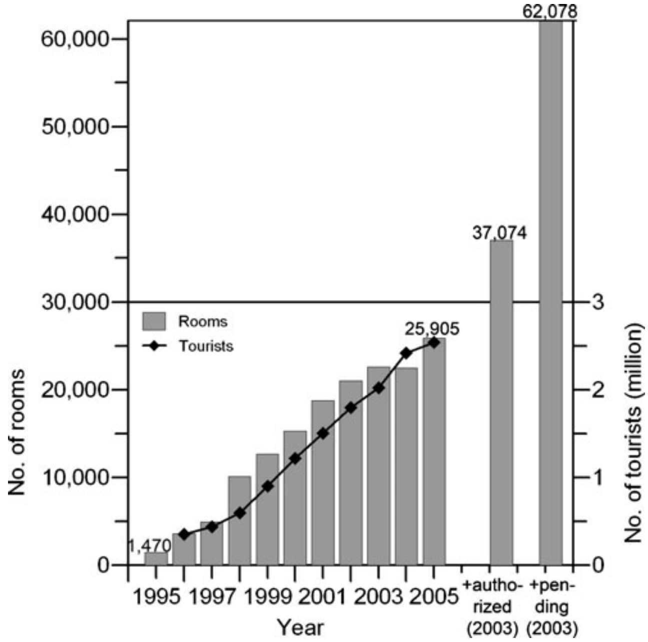


**Fig. 9** Tourism development in Quintana Roo. Sources: Fideicomiso para la Promoción Turística de la Rivera Maya (2006) and SEDUMA (2003)

for significant water supply or ecosystem assets. Both approaches have their merits. The rationale of the vulnerability mapping approach is to confine polluting activities to where the aquifer is least vulnerable. The rationale of the catchment zone approach is to confine polluting activities to where the impact on assets is smallest. Numerous methodologies for karst aquifer vulnerability mapping have been presented in the literature (e.g. Doerfliger et al. 1999; Goldscheider 2005; Vias et al. 2005). Morales-Lopez (2007) used the vulnerability mapping approach for the northern parts of the Sian Ka'an Biosphere Reserve. The catchment zone approach can be useful to determine which areas are critical for the maintenance of a specific ecological or water-supply asset. The catchment zone approach was used to outline the groundwater catchment of the Sian Ka'an Biosphere Reserve (B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010) and Charvet (2009) used the approach to determine the catchment of the Cancún water-supply wells. Figure 10 presents a tentative map of groundwater streamlines on the YP. The map is based on a modified version of the YP groundwater model developed by Charvet (2009). Model input and calibration data are extremely scarce, particularly in the central hill district, Campeche, northern Guatemala and Belize. At the present stage, the model can thus only provide a rough idea of groundwater streamlines and groundwater catchment zones on the YP.

The presence of important high-permeability structures in the YP such as the Holbox fracture zone, influences the underground water flows because they transmit water at higher flow velocities (Gondwe 2010; B.R.N. Gondwe, Technical University of Denmark, unpublished data, 2010; Neuman and Rahbek 2006). For that reason, fractures may also influence the flow of contaminants or facilitate water infiltration to the aquifer. Therefore, wastewater management has to be approached at a regional scale and protection of forests and wetlands linked to fracture areas becomes a priority.

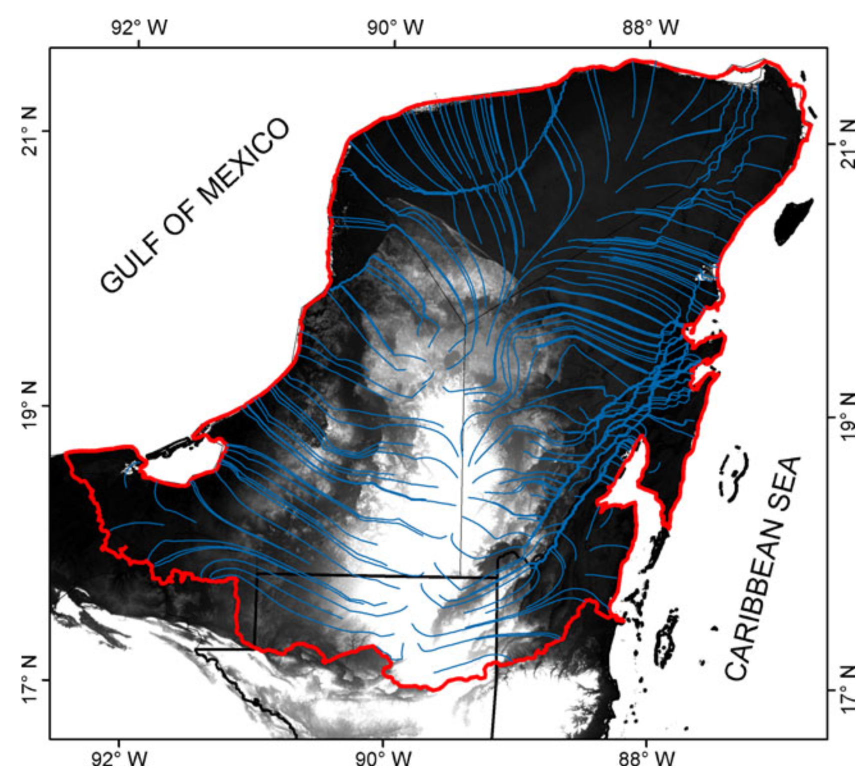


**Fig. 10** Groundwater streamlines based on a modified groundwater model of the YP after Charvet (2009). *Grey background shading* indicates relative topographic elevation (SRTM) – white highest

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The importance and vulnerability of the groundwater resources and the associated management challenges have been increasingly recognized in México. In 2001, the Centro de Investigación Científica de Yucatán (Yucatán Research Center, CICY) established a water-research unit (Centro de Estudios del Agua) in Cancún as a result of the importance of groundwater for this region. In 2007, the Mexican Academy of Sciences held a joint workshop whose title was "Science-Based Decision Making for Sustainable Groundwater Management", focusing specifically on the YP groundwater resources (Holliday et al. 2007).

## Conclusions

The Yucatán Peninsula hosts one of the world's largest and most spectacular karst aquifer systems. Remarkable features include the Chicxulub impact crater, the world's longest underwater cave systems and unique, spring-fed groundwater-dependent ecosystems. Over the last few decades, significant progress in understanding the hydrogeology of the YP has been achieved. However, major challenges for hydrogeological research and practical groundwater management remain. These include

1. Understanding the evolution of permeability over geological time scales
2. Location and properties of regional-scale preferential flow paths on the YP
3. Development of groundwater flow and transport models taking into account turbulent conduit flow and Darcian matrix flow
4. Hydrogeological characterization of the central hill district
5. Role and magnitude of phreatic evapotranspiration
6. Extreme scarcity of hydrogeological monitoring data
7. Relentless economic development and population growth
8. Trade-off between water for human use and water for ecosystems

Challenge 1 is interesting from a research point of view but may also be relevant for practical groundwater management, depending on time scales for conduit network evolution. Past studies have addressed preferential dissolution around the halocline, but the formation of preferential conduit flow paths and how they relate to structural and hydrological controls need further investigation. Challenge 2 is crucial for the development of reliable and robust regional-scale groundwater models for science-based decision support. Recent work has demonstrated that regional-scale preferential flow paths can be mapped using airborne geophysical techniques. Challenge 3 is essential for the development of reliable groundwater flow and transport models at intermediate scales (10s of kilometers). Turbulent conduit flow needs to be simulated in order to reliably predict contaminant transport. At present, data scarcity is the main limitation for the implementation of detailed conduit-matrix models on the YP. Dye tracing techniques can be instrumental to determine conduit network topology at intermediate and small scales. Challenge 4 is crucial for the hydrological understanding of the YP as a whole. Recent work has shown that the hydrogeology in the central hill district is very different from the coastal plains. However, the database for the central hill district is extremely small, even by YP standards. Challenge 5 has important implications for practical groundwater management. Recent results from remote-sensing data analysis show that groundwater-dependent ecosystems are not confined to the coastal wetlands but extend further inland. The natural vegetation thus needs to be recognized as a groundwater user. Challenge 6 is related to the administrative-institutional set-up in the region. At present, long-term operational hydrological monitoring is extremely limited. Given the complexity and vulnerability of the YP karst aquifer, a major effort is required to establish a database that can be used for science-based decision support to groundwater management. Challenges 7 and 8 are related and refer to the main trade-off that groundwater management faces in the region. Water resources are required for economic development (particularly tourism development) and for maintenance of groundwater-dependent ecosystems (which in turn are essential for tourism development). Groundwater management needs to strike a reasonable balance between these often conflicting objectives.

Addressing the aforementioned challenges requires focused and innovative scientific research, an ambitious, spatio-temporally resolved hydrological monitoring program and efficient regional policy making. Ultimately, management should aim at the design of comprehensive strategies to meet the water demands of a growing and developing population, conserve tropical forests, coastal wetlands, and coral reefs, all of them linked by and highly dependent on the regional groundwater resource. The YP karst aquifer is shared between three nations and multiple federal states in México. Management of this transboundary aquifer system requires collaboration and knowledge exchange across federal and national boundaries.

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