3D Inverse modeling of EM-LIN data to investigate coastal sinkholes in Quintana Roo Mexico

Luis E. Ochoa-Tinajero[1], Marco A. Perez-Flores[2], Almendra Villela y Mendoza[3]

[1]Posgrado en Ciencias de la Tierra, CICESE
[2]Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE)
[3]Universidad Autónoma de Baja California (UABC)

Correspondence to: Marco Pérez-Flores (mperez@cicese.mx)

Abstract. In southern Mexico at the Yucatan Peninsula (YP), cities and towns are settled on a platform of calcareous sedimentary sequence which has originated a wide formation of sinkholes, underground rivers and caverns due of karst process. The anthropogenic activities threat the only source of fresh water supply which is located in a regional unconfined aquifer; there are not lakes and rivers. For sustainable use of these resources at the YP, it is required to develop mathematical tools to help the groundwater modeling. In order to determine the geometry of the aquifer as the positions of caves, sinkholes and underground rivers, we have developed software to invert three-dimensional electromagnetic low-induction numbers (3D EM-LIN) data for a set of profiles at arbitrary angle. In this work we have explored with the aid of EM-LIN geophysical method, the Chac-Mool sinkhole system at the state of Quintana Roo (QR), Mexico. We have performed inverse modeling in 3D using the EM-34 instrument for vertical and horizontal magnetic dipoles. The 3D inversion process gives us models that allow us to correlate the path of the underground rivers with the subsurface electrical resistivity. In this work we have shown that inverse modeling of EM-LIN data is necessary to explore and understand coastal karst systems.

1 Introduction

The main source of fresh water in the YP is a regional unconfined karstic aquifer constituted by sedimentary limestones (Bauer-Gottwein et al., 2011). Karstic aquifers are extremely vulnerable to contaminants due their high permeability; the rapidly growth of the population in Quintana Roo and coastal touristic activities threat the only source of fresh water supply (e.g. Richards and Richards, 2007).

In order to guarantee the sustainable use of these groundwater resources it is necessary to have knowledge of the hydrogeological characteristics such as geometry and positions of caverns and sinkholes as well as the depth of the fresh /salt water mixing zone (halocline).

Sinkholes are naturally geological features that connect the surface with the underground of karstic terrains and are formed when rain water dissolve limestone creating underground voids (Coskun, 2012).

Many of these features have been reported before by scuba divers and the Quintana Roo Speleological Survey has performed an underground map with a touristic purpose in the Riviera Maya. However, geophysical techniques have been barely applied as non-invasive methods for exploration over this area (Beauer-Gottwein et al. 2011; Gondwe et al. 2010; Estrada-Medina et al. 2010). It is well known that electrical resistive tomography has shown good results to explore karst e.g (Chalikakis et al 2011; Ahmed y Carpenter 2003), however in this region the lack of soil on this hard-limestone ground difficult the electrodes placing which results in a complicate and time consuming problem, making even more expensive the data collection. New approaches in geophysical and coastal karst prospecting are therefore required in order to protect and develop future sustainability plans in the YP.

In this study we aim to investigate the application of a novel approach by using electromagnetic methods in the low-induction numbers limit (EM-LIN) and apply 3D geophysical inverse modeling (Perez-Flores et al., 2012) with the goal of set up a conceptual model of a sinkhole system and to get a wide knowledge of the site geomorphology. Moreover, the methodology and results will also help as tool of management in the coastal zones of Quintana Roo due these is important for touristic activities which demands accurate knowledge for prospect plans of future development.

We did not find references for EM-LIN methods for karst systems, but we found DC and aero TDEM method applied in the Sian-Kan natural reserve (Supper et al. 2009). They also took EM-34 measurements, but they did not do any further processing or inverse modeling interpretation.

1.1 Study area

2 This research was done in the Yucatan Peninsula (YP), which is the emerged part of great Yucatan platform and 150,000 km^2 of 300,000 km^2 are largely karstified (Bauer-Gottwein et al., 2011). From the geological point of view, the YP is a platform constituted by a sequence of calcareous sediments from cretaceous everywhere (Bonet y Butterlin, 1962) and characterized by the mountains and surface rivers absence. It is a very flat terrain. A review of the YP karst aquifer is well described by Bauer-Gottwein et al. (2011) and an extend description of coastal cave development by Smart et al. (2006).

3 We took a study area that covers the Chac-Mool sinkhole and it is located 20 km southward Playa del Carmen in QR state at approximately 20^{o} 30' 46.37" N and 87^{o} 14' 49.32" W (Fig. 1). The area covers an extension of 1 km^2 and it is full covered by dense vegetation. The QR state receives around 1,200 mm of annual precipitation and topography is a flat surface with a slope of 9 m over the sea level in 20 km since the shore line (CNA, 2016). The hydraulic gradient in southern Playa del Carmen was estimated in 58-130 mm/km (Beddows, 2004). This site is lack of soil and it is constituted by hard limestone rocks. Due to its proximity to the coast (2 km) is penetrated by the sea water. Such an intrusion oscillates depending on ties and rain recharge (Beddows, 2004). Chack-Mool is a sinkholes complex where it is assumed that two underground rivers connect the Little-Brother sinkhole and the Air-Dome sinkhole. The (x, y) river trajectories are known in some parts by scuba diver maps (Quintana Roo Speleological Survey QRSS) but other parts remain unknown as well as the vertical components. It is possible that the entire rock matrix is saturated of fresh/brackish water through the porosity and small conduits. The apparent conductivity is large because it averages the matrix conductivity (low value) with the sea water conductivity (high value).

1.2 Electromagnetic survey

In September 2015, we carried out a field trip over the study area. We took seven profiles with the EM34 (Geonics) instrument that operate under the LIN domain as described in McNeill (1980). The main reason we are using EM-34 is because it is easy and fast to take data in terrains with lack of soil without loss of accuracy, making faster the field-work in tough terrains.

The principle consist in to pass an alternating current of constant frequency *f* through a coil (transmitter) which will generate a primary electromagnetic field ($\boldsymbol{H_p}$) that induces electrical currents in the conductive bodies embedded in the subsoil (following Faraday's Law). Then a secondary electromagnetic field in the subsoil ($\boldsymbol{H_s}$) is created due these conductive bodies inside a half-space media. These two fields will differ in amplitude and phase and they will be detected by a coil (receiver) separated by a distance *s*(m) from the transmitter. The induction number N is defined as the quotient between *s*(m) and the skin depth δ(m) as $N = s(m)/\delta(m)$. At low-induction numbers N<1 the imaginary part of $\boldsymbol{H_s}/\boldsymbol{H_p}$ is a straight line whose slope is the conductivity of a homogeneous half-space. Because of the real ground is not homogenous, we speak of an apparent conductivity $\sigma_a = (4/\omega\mu_0 S^2)(H_s/H_p)$.

It is usual to use both loops (source and receiver) in a coplanar way. We have two possible arrays, when both loops are parallel to the earth surface (vertical magnetic dipoles, HMD) and another when both loops are perpendicular to the earth surface (horizontal magnetic dipole, HMD). For both arrays we can extend the separation between loops from 10 m, 20 m and 40 m. In this research the measurements were taking along 6 lines (Fig. 2) and every 5 m. Due the dense vegetation of the jungle it was not possible to locate profiles anywhere, instead we took the available paths around the sinkholes Chack-Mool, Little Brother and Air Dome. Then, we tried to follow straight lines thinking in doing 2D inversion for every data profile, but then we realized that six of the profiles distributions were more or less covering a rectangular area. Therefore, we performed a 3D inversion in addition of the 2D model profiles (not presented here). For the 3D inverse modeling we followed Perez-Flores et al. (2012) method, but this algorithm was designed to parallel or perpendicular data profiles between them. They do not run for arbitrary angles like these profiles (Fig. 2). Later, we will show how we modified the equations for arbitrary angle data profiles. The six profiles (1 to 6) length varies between 50 m and 140 m (Fig. 2).

1.3 Inverse modeling

We assume the EM data (apparent conductivity σ_a) as a weighted average of the subsurface electrical conductivity distribution, as described by Pérez-Flores et al. (2004). We relate the apparent conductivity (σ_a) with the true subsurface conductivity (σ) thought a weighting function (that is the Green function and electric field product) by using the approximate integral equation formulated by Pérez-Flores et al. (2001):

$$\sigma_a(\boldsymbol{r_2},\boldsymbol{r_1}) \cong -\frac{16\pi s}{\omega\mu_0 m}\int_v \boldsymbol{G}(\boldsymbol{r_2},\boldsymbol{r})\cdot\boldsymbol{E}(\boldsymbol{r},\boldsymbol{r}_1)\sigma(\boldsymbol{r})dv \tag{1}$$

Where $\boldsymbol{r_1}$ and $\boldsymbol{r_2}$ are the source and the receiver positions, $\boldsymbol{G}$ is the Green function for a homogeneous media due to a point electric source in $\boldsymbol{r}$ and measured in the magnetic receiver and $\boldsymbol{E}$ is the electric field for a homogeneous media due to the point magnetic source. Equation (1) is an approximation for low conductivity contrasts and it is very useful for inversion, where $\boldsymbol{G}$, $\boldsymbol{E}$ and σ_a are known, remaining $\sigma(\boldsymbol{r})$ as the unknown.

For inversion we have to considerer how the magnetic dipoles are used, we have the Vertical and horizontal magnetic dipoles (VMD and HMD respectively) arrays as describer in Pérez-Flores et al. (2012). The integral equation for the vertical magnetic dipoles (VMD) is,

$$\sigma_{a,z}(\boldsymbol{r}_1,\boldsymbol{r}_2) \cong -\frac{16\pi s}{\omega\mu_0 m_z}\int_v \boldsymbol{G}_{H_z}(\boldsymbol{r},\boldsymbol{r}_2)\bullet\boldsymbol{E}_{H_z}(\boldsymbol{r},\boldsymbol{r}_1)\sigma(\boldsymbol{r})dv \tag{2}$$

For HMD the integral equation in y direction is given by:

$$\sigma_{a,y}(\boldsymbol{r}_1,\boldsymbol{r}_2) \cong -\frac{16\pi s}{\omega\mu_0 m_y}\int_v \boldsymbol{G}_{H_y}(\boldsymbol{r},\boldsymbol{r}_2).\boldsymbol{E}_{H_y}(\boldsymbol{r},\boldsymbol{r}_1)\sigma(\boldsymbol{r})dv \tag{3}$$

And HMD in x direction is given by:

$$\sigma_{a,x}(\boldsymbol{r}_1,\boldsymbol{r}_2) \cong -\frac{16\pi s}{\omega\mu_0 m_x}\int_v \boldsymbol{G}_{H_x}(\boldsymbol{r},\boldsymbol{r}_2).\boldsymbol{E}_{H_x}(\boldsymbol{r},\boldsymbol{r}_1)\sigma(\boldsymbol{r})dv \tag{4}$$

The expression for $\boldsymbol{G}_{H_z}$, $\boldsymbol{E}_{H_z}$, $\boldsymbol{G}_{H_y}$, $\boldsymbol{E}_{H_y}$, $\boldsymbol{G}_{H_x}$ and $\boldsymbol{E}_{H_x}$ can be consulted in Perez-Flores et al. (2012). VMD profiles can run for any angle (Eq. 2), but HMD runs only in y (90^0; Eq. 3) or x (0^0; Eq. 4) directions. A problem is when we have arbitrary direction profiles as it happened around the Chac-Mool sinkhole (Fig. 3). So, we had to modify Eq. (4 and 5) in order to accept arbitrary angle profiles.

Using a simply notation for $\boldsymbol{E}$ and $\boldsymbol{G}$ in terms of their vector components, we have for y direction HMD,

$$G_{H_y}(\boldsymbol{r},\boldsymbol{r}_2) = d\hat{\imath} + e\hat{\jmath}\,, E_{H_y}(\boldsymbol{r},\boldsymbol{r}_1) = a\hat{\imath} + b\hat{\jmath} \tag{5}$$

Similarly, along the x direction,

$$G_{H_x}(\boldsymbol{r},\boldsymbol{r}_2) = e\hat{\imath} + f\hat{\jmath}\,, E_{H_x}(\boldsymbol{r},\boldsymbol{r}_1) = b\hat{\imath} + c\hat{\jmath} \tag{6}$$

When we rotate Eq. (3) in 90^0, this becomes Eq. (4). So, we can find $\boldsymbol{E}$ and $\boldsymbol{G}$ in terms of their rotated components.

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} cos\theta & sen\theta & 0 \\ 0 & cos\theta & sen\theta \end{pmatrix}\begin{pmatrix} a \\ b \\ c \end{pmatrix},$$

$$\begin{pmatrix} G_x \\ G_y \end{pmatrix} = \begin{pmatrix} cos\theta & sen\theta & 0 \\ 0 & cos\theta & sen\theta \end{pmatrix} \begin{pmatrix} d \\ e \\ f \end{pmatrix} \tag{7}$$

If a HMD profile runs at 0^0, $(E_x,\ E_y)$ becomes $\boldsymbol{E}_{H_y}$ from Eq. (3). If the profile runs at 90^0, $(E_x,\ E_y)$ becomes $\boldsymbol{E}_{H_x}$ from Eq. (4). Thus, for an arbitrary angle profile, Eq. (3 and 4) become a single one,

$$\sigma_a(\boldsymbol{r}_1, \boldsymbol{r}_2) = -\frac{16\pi s}{\omega\mu_0 m} \int [G_x(\boldsymbol{r}, \boldsymbol{r}_2) E_x(\boldsymbol{r}, \boldsymbol{r}_1) + G_y(\boldsymbol{r}, \boldsymbol{r}_2) E_y(\boldsymbol{r}, \boldsymbol{r}_1)] \sigma(\boldsymbol{r}) dv \tag{8}$$

Terms *(a, b, c, d, e, f)* can be obtained from Perez-Flores et al. (2012).

For the 3D inversion, we used Eq. (8) for the HMD profiles and Eq. (2) for the VMD profiles. We used 10, 20 and 40 m for the source-receiver separations for VMD and the same separations for HMD in every profile. We inverted together the whole sets of data in order to get a single 3D conductivity model. We simulated the heterogeneous half-space as a conglomerate of rectangular prisms. We assumed that conductivity is constant in every single prism but unknown. Eq. (2) and (8) can be written as a linear equations system, and in a matrix way,

$$\boldsymbol{\sigma}_a = \boldsymbol{W\sigma} \tag{9}$$

Where $\boldsymbol{\sigma}_a$ represents the column vector of apparent conductivities, matrix $\boldsymbol{W}$ contains the weights or products of the Green function and electric field and it is partitioned for VMD and HMD and $\boldsymbol{\sigma}$ represents the column vector of the real conductivities (unknowns). We use quadratic programing to minimize the next objective function $\boldsymbol{U}$

$$\boldsymbol{U}(\boldsymbol{\sigma}) = \frac{1}{2}\left\|\boldsymbol{\sigma}_a - \mathbf{W}\boldsymbol{\sigma}\right\|^2 + \frac{1}{2}\beta\left\|\mathbf{D}\boldsymbol{\sigma}\right\|^2$$

$$\boldsymbol{\sigma}_{lower} < \boldsymbol{\sigma} < \boldsymbol{\sigma}_{upper} \tag{10}$$

Matrix $\boldsymbol{D}$ represents the first order spatial derivatives of the contiguous prism conductivities. Parameter β controls the smoothness of the 3D conductivity model; when it is low, we got a rough 3D model. First term is to fit the apparent conductivity data taken at field. Second term in Eq. (10) has the spatial derivatives of the conductivity in (x, y, z) direction. Smoothness parameter controls the second term magnitude. If zero, we just fit the data and the model use to be very rough, if very large the model converges to a homogenous half-space. We use to transform the Hessian in order to be unity in diagonal. This way, the smoothness parameter can vary in a very narrow window. We use to try (0.1, 0.01, 0.001). Value 0.1 gives a smooth model and 0.001 a rough model. We began with smooth value that gives the simplest but the most probable model (according the Occam's Razor principle) and we lower the parameter in order to recover more structure but we will see that after some point the structure turns unreal since the geological point of view. The idea is to recover the more structure and at the same time keeping the simplest and the more probable model.

2 Resistivity cross-sections over the 3D model.

For the 3D inverse modeling we used a *(x, y, z)* grid of prisms, assuming constant conductivity in every one. We performed the inverse modeling choosing $\Delta x=\Delta y=2.5$ m in the *(x, y)*-directions due the EM measurement was taken every 5 m; a variable discretization of Δz was chosen as (0, 2, 5, 8, 12, 18, 25, 35 and 50 m) and β=0.01 as the smoothness factor.

Conductivity is the unknown, but we prefer to show results in resistivity (conductivity inverse). In Fig. 4 we present the 3D resistivity model after the inversion process of the whole sets of data. In this figure we present the interpolated resistivity cross-sections under the six profiles. Blue are resistive areas and red low resistive. There are spaces between profiles that have no data. In those areas the 3D model is not very confident. Therefore, we better show the model where the data are as a first approach. There is a very good coherence where the model crosses. In this figure are shown the irregular paths of the two rivers, according to the divers (x, y, z) map. Water table depth is 7 m measured in the open sinkholes. Rivers follow very intricate paths. We think that there are narrower river branches that have not yet mapped by the divers. It is interesting that some paths were marked bellow the resistive areas. Meaning that maybe the top of subterranean rivers are far enough from surface, making the roof more stable structurally or maybe there are air-filled caves over the water table. We assume as *roof* as the limestones rock between the surface and the top of the subterranean river. We can idealize a typical cave in this area (near the coast) consisting of a limestone roof and/or an empty space then fresh water (lower resistivity), the halocline (fresh and salty water mix), and at the bottom, salty water (the lowest resistivity) and surrounded by saturated limestones as bedrock. In Fig. 5 we show the six cross-sections done to the 3D resistivity model. Cross-section (a) correspond to the profile 1 model, cross-section (b) to profile 2 and so on. Every profile is signed with a white dot, the interpolated (x, y, z) hidden-rivers. The (x, y, z) locations were obtained from the scuba divers map. We sign the inferred cave section as a rectangle, because we cannot see details. We assume saturated limestone as bedrock, because dry limestone resistivity is larger than 1000 ohms-m. In the 3D model cross-sections, the bedrock looks green everywhere and that correspond to 160-170 ohms-m. Only small spots look blue or 1000 ohms-m.

Looking the six-resistivity cross-sections, we can see that most of the river's crosses show a green color over them. Meaning perhaps that the subterranean river is close to the surface and therefore the roof thickness is thinner, making those areas more sensible for roof sinking, even that we did not see surface evidences of subduction or fracturing. Profile 1 cross-section (Fig. 5a) shows three crosses: at x=18 m shows a thinner roof, the others a thicker roof. Profile 2 (Fig. 5b) shows a green color, meaning thinner roofs. Profile 3 (Fig. 5c) show one river crossing shallow and another deeper. We can see that a shallower subterranean river is well detected (green color) by the EM-LIN equipment but it is not obvious when this is deeper. We must remember that white dots are interpolations of the diver's map. In the deeper river cross, this coincide with the location of a big resistive mass between zero and 20 m, this means that divers had to dive bellow this resistive mass (1000 ohms-m). In profile 4 (Fig. 5d) they show three crossings with green color. Profile 5 (Fig. 5e) shows three crossings, two deeper (between z=20 m and z=30 m) and one shallower (z=15 m). The deeper are consistent with the diver's depth reported and the thicker roof obtained by a big resistivity mass, however at x=25 m the river seems to be 10 m deeper, this could be explained, considering that there is a huge hard rock (very resistive) that could be affecting. The last profile 6 (Fig. 5f) shows a shallower river and a deeper one. Resistivities are consistent with the position of the river.

We know that divers pass throughout subterranean rivers. In Fig. 5 we propose a broad suggestion about those river crossings (rectangular polygon). Giving an explanation to the colors in Fig. 5, we can think that blue can correspond to dry limestone roofs or dry limestone plus air-filled caves at the top of the river or close to the surface. Green color is so spread that surely contains clean water (50 to 70 ohms-m). Also, the resistivity cross-section shows green when the subterranean rivers seem to be shallower. Instead, we would expect a narrow blue color plus a green color over those shallower rivers. That is not happen, because the lowest source-receiver separation at the EM34 is 10 m (it is too large to see surface details). In some way the true conductivity estimated continues being an average. Maybe if we could use a lower separation, we could resolve a thinner blue color roof and then a green color from the clean water. The transition from green to red (yellow) could be the transition from clean water to salty water. We expect that clean water is stratified inside the rivers with the salty water at the bottom.

We drew the river section with the idea to emphasize that EM34 have not the resolution to sharply isolate the rivers from the bedrock. An explanation is that unaltered bedrock (limestone) is partially saturated of clean water at the shallow depths (because of the 50-70 ohms-m values) and saturated of salty water at the deeper parts (because of the 6-10 ohms-m values). So, there are not a large horizontal resistivity changes between the river location and the bedrock. It is almost sure that permeability in the bedrock is high as the permeability of the limestones on surface. When raining, the water disappears quite fast.

With the aerial-electromagnetics (flying 30 to 50 m over the surface) we will have even a lower resolution, but we could see in a faster way where the subterranean rivers are when they are closer to the surface in a horizontal map. However, a non-quantitative roof thickness images and not a better resolution in depth would be expected (Supper et al. 2009).

In profile 4 (Fig. 5d) there is a green color sector close to x=70 m (red square). It is possible that a shallow subterranean river pass close to the surface and it was not yet mapped by divers.

2.1 Isometric of the 3D resistivity model.

Chac-Mool sinkhole is a complex of three small sinkholes (Air-Dome, Little Brother and Chac-Mool itself). According to divers, there are two underground rivers whose position in (x, y, z) varies. Their vertical variation may cause the thinner of the limestone roof and therefore sinking. According to the cross-section in Fig. 6, the EM-LIN equipment can not sharply desitinguish between the subterranean river tunnels and the bedrock, maybe because there is not enough resitivity change, meaning that bedrock limestones are partially saturated of water and therefore under the chemical disolution process. Looking the isometric of the 3D resistivity model (Fig. 6) we can see the spatial distribution of the three sinkholes inside the complex. With two kind of blue the two proposed rivers and treir paths. We also see the location of the five profiles of EM-LIN data.

The blue and green surfaces are equal-resistivity surfaces of the 3D model (160 ohm-m). The blue one pretends to show the bottom topography of the limestone roof. This resistive layer may contain unaltered limestone plus air-filled caves. It is very interesting that this layer outcrops where underground rivers are very shallow, and those paths are very coincident where the rivers are shallow. This surface does not outcrop where the sinkholes are, because there are not data there. They were gaps where it was impossible to take data. We did not want to manipulate the 3D model to obligate the model to outcrops where sinkholes are, but we can by mean of quadratic programing in the minimization process of equation (10). But we rather want to see a non-manipulated result.

It is also interesting that in the middle of the study, there is a resistive massif (MR letters), where the roof appears to be very thick. That means that that zone is the least hazard area for roof collapse.

The green surface pretends to be the surface where the clean water is located (80 ohm-m). But this surface also outcrops where blue surface outcrops. Maybe because the EM-LIN source-receiver separation was too large (10 m) and we are looking a kind of resistivity average between the roof (resistive) and the clean water (less resistive). But this happens just where the roof is very thin. We must be careful with this model where no data exist.

3. Conclusions

In this research we are exploring the Chac-Mool sinkhole complex by mean of electromagnetic methods operating at low-induction numbers (EM-LIN). These methods consist of a source loop and a received loop working coplanar to the Earth surface (VMD) and perpendicular (HMD). These two polarizations look the Earth in a different way. That is why; we used both arrays in order to do joint inversion and to obtain a single three-dimensional (3D) resistivity model. Those equations were already published for a mesh of perpendicular and parallel profiles, but not for arbitrary angle profiles. In this research the profiles were taken inside the jungle and we took the advantage of already made walk paths, but these were in arbitrary angles. We had to modify the existing equations, arriving to a more general set of equations.

We did 3D inversion of both VDM and HDM arrays arriving to a single 3D resistivity model. The cross-sections of this 3D model show where the underground rivers cross. Where the underground rivers approach the surface may create a hazard of roof collapse. We also see the distribution of the clean and salty water distribution and their contact or the transition surface (halocline). We see that rivers must run along tunnels but resistivity of those tunnels do not sharply differ from resistivity of the bedrock, meaning that they are also saturated of water (clean and salty depending the depth). The isometric shows that resistive iso-surface corresponds with the bottom topography of the underground roof. At the center of the area this roof seems very thick making this area very stable for sinking hazard. This isometric also shows that where the blue iso-resistivity surface outcrops is where underground rivers close to surface.

This EM-LIN technique is very efficient, fast and cheap for exploring over hard rock sinkhole areas. We can get the geometry of the underground rivers and the distribution between clean and salty water.

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References

Ahmed, S. and Carpenter, P. J.: Geophysical response of filled sinkholes, soil pipes and associated bedrock fractures in thinly mantled karst, east-central Illinois, Environmental Geology, 44, 705-716, 2003.

Bauer-Gottwein, P. Gondwe, B.R. Charvet G., Marin, L.E. Robellodo-Vieyra, M. and Meresiz-Alonso, G.: Review: The Yucatan Peninsula karst aquifer, Mexico, Hidrogeology Journal, 19, 507-524, 2011.

Beddows, P. A.: Groundwater hydrology of a coastal conduit carbonate aquifer: Caribbean coast of the Yucatán Peninsula, México, PhD thesis, University of Bristol, 2004.

Bonet, F. Butterlin, J.: Stratigraphy of the northern part of the Yucatan Peninsula, Field trip to Peninsula of Yucatan guide book, New Orleans Geological Society, New Orleans, LA, 1962.

Chalikakis, K. Plagnes, V. Guerin, R. Valois, R. and Bosch, F. P.: Contribution of geophysical methods to karst-system exploration: an overview, Hydrogeology Journal, 19, 1169-1180, 2011.

Comisión Nacional del Agua (CNA).: Resumen Técnico de las Condiciones Geohidrológicas del Estado de Quintana Roo, Comisión Nacional del Agua, Subgerencia Técnica, Gerencia Regional del Sureste, Mérida, Yucatán, México 2016.

COŞKUN, N.: The effectiveness of electrical resistivity imaging in sinkhole investigations. International Journal of Physical Sciences, *7*(15), 2012.

Estrada-Medina, H. Tuttle, W. Graham, R.C. Allen, M.F. and Jiménez-Osornio, J.J.: Identification of underground karst features using ground-penetrating radar in Northern Yucatán, México, Vadose Zone Journal, 9, 653-661, 2010.

Gómez-Treviño, E.: Nonlinear integral equations for electromagnetic inverse problems, Geophysics, 52, 1297–1302, 1987.

Gondwe, B.R. Lerer, S. Stisen, S. Marín, L. Rebolledo-Vieyra, M. Merediz-Alonso, G. and Bauer-Gottwein, P.: Hydrogeology of the south-eastern Yucatan Peninsula: new insights from water level measurements, geochemistry, geophysics and remote sensing, Journal of Hydrology, 389, 1-17. 2010.

McNeill, J.D.: Electromagnetic terrain conductivity measurement at low induction numbers, Technical Note TN-6, Geonics Limited, 1980.

Pérez-Flores, M.A. Antonio-Carpio, R.G. Gómez-Treviño, E. Ferguson, I. and Méndez-Delgado, S.: Imaging of 3D electromagnetic data at low-induction numbers, Geophysics, 77, WB47-WB57, 2012.

Pérez-Flores, M.A. Méndez-Delgado, S. and Gómez-Treviño, E.: Imaging low-frequency and dc electromagnetic fields using a simple linear approximation, Geophysics, 66, 1067-1081, 2001.

Richards, D. and Richards, S.: Overview of the geology and hydrology of coastal Quintana Roo, AMCS Activ Newsl 30, 104–109, 2007.

Smart, P. L. Beddows, P. A. Coke, J. Doerr, S. Smith, S. and Whitaker, F. F.: Cave development on the Caribbean coast of the Yucatan Peninsula, Quintana Roo, Mexico, Geological Society of America Special Papers, 404, 105-128, 2006.
Supper, R., Motschka, K., Ahl, A., Bauer-Gottwein, P., Gondwe, B., Alonso, G. M., & Kinzelbach, W.: Spatial mapping of submerged cave systems by means of airborne electromagnetics: an emerging technology to support protection of endangered karst aquifers, Near Surface Geophysics, *7*, 613-627, 2009.