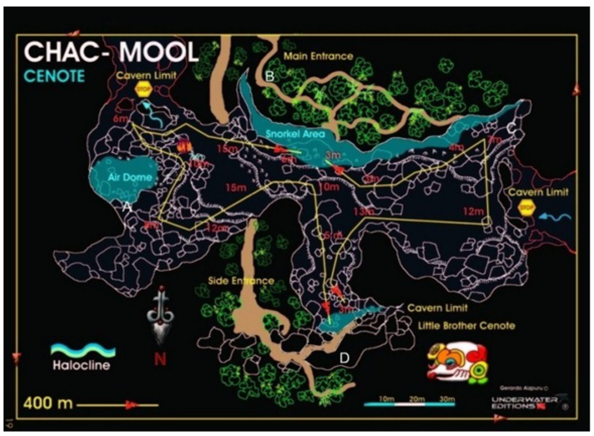
Reviewer 1 answers:

To improve manuscript. Authors indicate that there are previous woks in the area carried out by the Speleological Survey; It should be interesting to be able to compare the obtained data from geophysics and the available data from direct study.

We added some lines in the manuscript saying that The (x, y) locations was obtained from the scuba divers map. The depth (z) is inferred from our 3D resistivity model. We sign the inferred cave section as a rectangle, because we cannot see details. Where dot is red is because is not reported by the scuba divers map, but we see a similar pattern where a river crosses. This location is inferred.
The scuba diver map is for tourists and it was difficult to extract the information we needed, as you can see.



It should be of interest to include a geological map in order to evaluate the geological characteristics from the area, its context but also, if available, hidrogeological information at the regional-local scale previous to the geophysical analysis.

We added some words in the Study Area Chapter to say that limestones are everywhere and terrain is very flat.

Moreover it can be also of interest to include a geomorphological map about the surficial indicators of karst activity and some photographs from the study area. This photographs will permit the evaluation of the survey conditions but also the karst characteristics from the study area.

There is not surface manifestation about fractures or subduction. As you can see in the pictures. The profiles were taken over the clear way and we did not see any surface subduction.

There are not units in the representation from figure 4 (color scale), at figure 5 the scale color requires an inset (log 10 (r) means, r at logarithmic scale but it lacks units and the figure caption requires to be rewritten as I am not sure that I am able to understand what is described.

We corrected this, putting units on the plots.

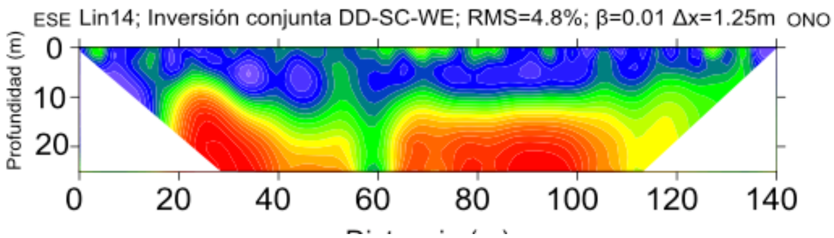
Information related to the referenced small sink- holes from the area (2.1 chapter) requires to be included in the geological preliminary map but also in the geophysical models to be compared with the geophysical data.

Profiles data were taken over flat paths on the jungle as you can see in the pictures. There were not small features over the ways to suspect about a sinking (we added a line in the manuscript about this). We also added some lines to the manuscript to emphasize that Geology is cretaceous limestones everywhere.

Also at chapter 2.1 there is not an evaluation of the expected values for bedrock and the way to choose or discuss the origin of obtained values. If the analyzed units are rocks it can be difficult that they are complete saturated, that it is the explanation for such data. This requires to be more detailed interpreted and discussed.

Here we show you a resistivity section very close to the chac-mool area. This was obtained by DC resistivity inversion of Dipolo-dipole, Schlumberger and Wenner data sets joint inversion in order to get a single resistivity model. Here we used a source-receiver separation of 5m. With this separation was possible to see the dry limestones close to the surface that we call it as *roof*. In x=60m there is a small sinking, meaning that a subterranean river is close and that collapse is possible. However, you cannot distinguish the resistivity change between the subterranean river and the bedrock. Even that here, we used a shorter source-receiver separation. We only see a green color disruption on the dry limestones and a disruption on the red color long body. We can not explain this since the geophysical point of view. Only salt water and shales can low the resistivity in the bedrock. That is why, we think that bedrock is in some way saturated of salty water that lows the resistivity. We have no other explanation. If you have one explanation, we will be very grateful.

In the EM inversion we do not recover the roof thickness sharply because the shortest source-receiver separation (10 m) was to large. The EM34 equipment has only separations of 10, 20 and 40 m.



At 2.1 authors describe how they interpret the presence of sinkholes in the area, however there is not reference to surficial-geomorphological data to be compare with or about the presence of sinkholes in the area to be compared with the geophysical data.

As you can see in the pictures, there are no surface evidences of sinking.

What criteria has been used to select the 160 ohm/m for the separation of units in the geophysical model? Do authors indicate that the "bottom topography of the lime- stone roof" but what they are referencing is "the topography of the limestone roof"?

We changed this in the manuscript to do not confuse. We explain that blue iso-surface represente the bottom of the dry limestones (700 to 1000 ohms-m). Red iso-surface represents the resistivity contact between fresh and salty water (could be the Halocline). This is valid just where data was taken (under the profiles locations). We can extrapolate or interpolate a little bid outside the profiles locations.

About the interpretation and description, roof cannot be thick, this is a contact, then it is needed to correct "the roof appears to be very thick", or "the roof is very thin". After in the same paragraph authors indicate that the, what I interpret, the thickness of the level is thick,

Yes, we agree. We did some modifications on the manuscript .

then the susceptibility to collapse is lower, does author have information about the fracturation nets from the unit? Not necessarily from the local area, but the state of the massive can be evaluated in a regional scale to know if stability can be related to the fracturation state of the unit if authors want to evaluate collapse susceptibility or hazard.

We have no surface evidences of sinking in the Chac-Mool area, but in the cross-section shown before, there is an area close to Chac-Mool where a small sinking is evident on surface.

At Figure 6. I suppose that this is a 3d view of the topography of the contact, but it is not clear to see it, Can authors include the isolines of topography, or two maps with the topography and by the other hand of the resistivity values?. In this sense, as previously pointed out, the selection of the resistivity values requires to be discussed in order to define if other values can be better to evaluate the 3D under- ground structure.

Surface topography is very flat and we emphasized that on the manuscript. Dry limestones should be very resistive (1000 ohms-m or more; blue color). Salty water should be very low-resistive (1 to 5 ohms-m; red color). Fresh water around 50 to 80 ohms-m (green color). There are not shales in this area. Only water content can justify the resistivity values.

In order to evaluate data from the area, where the water level is expected to be? are there any change related to the water salinity in the geophysical data?.

The water table was measured at 7 m depth where the sinkhole is open. This value is present in the manuscript.

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

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Abstract. In the Yucatan Peninsula (YP), southern Mexico, cities and towns are settled on a platform of calcareous sedimentary sequence, where karst processes have formed numerous sinkholes, underground rivers, and caverns. Anthropogenic activities there threaten the only source of freshwater supply, which is in a regional unconfined aquifer; there are no lakes or rivers on the surface. For the sustainable management ~~use~~ of this~~ese~~ resource~~s~~ ~~at~~in the YP, mathematical tools ~~to help the~~are needed in order to model groundwater ~~modeling~~. ~~In order to~~ To determine the geometry of the aquifer, ~~as~~for example –the positions of caves, sinkholes, and underground rivers, we ~~have~~ developed a software to invert three-dimensional electromagnetic low-induction number~~s~~ (3D EM-LIN) data for a set of profiles at arbitrary angles. In this ~~work~~ study we ~~have explored with the aid of~~used the EM-LIN geophysical method~~,~~ to explore the Chac-Mool sinkhole system ~~at~~ in 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~~yields– models that ~~allow~~ enable us to correlate the path of the underground rivers with the subsurface electrical resistivity. In this work we show 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 Yucatan Peninsula is a regional unconfined karst~~ic~~ aquifer that is constituted by sedimentary limestones (Bauer-Gottwein et al., 2011). Karst~~ic~~ aquifers are extremely vulnerable to contaminants ~~due~~ because of their high permeability and ~~because of~~ the peculiar turbulent groundwater flow ~~in turbulence~~ passing through karst conduits and caves (Worthington et al., 2001; Parise et al., 2015). The rapid~~ly~~ population growth ~~of the population~~ in the state of Quintana Roo and coastal ~~touristic activities~~tourism threaten the only source of fresh–water supply in the peninsula.

In order to guarantee the sustainable use of ~~these~~this groundwater resource~~s~~ ~~it is necessary to have~~ knowledge ~~of~~ on the hydrogeological characteristics, such as geometry and position~~s,~~ of caverns and sinkholes ~~as well as~~and the depth of the freshwater~~-~~/salt-water mixing zone (halocline) is needed.

Con formato: Resaltar

Con formato: Inglés (Estados Unid

Comentario [MDJH1]: Ambigüedad no es claro a qué recursos se refieren.

Con formato: Inglés (Estados Unidos), Sin Resaltar

Comentario [MDJH-22]: La segund sugerencia que indico entre comillas aba se desvía un poco de la redacción origina pero creo que en esencia "sustainable management" encaja mejor en el context de la oración y con lo que mencionan en texto general. Además, la segunda sugerencia incluye un orden secuencial d la idea general. Marco en verde "these resources" porque esta frase de la oració aún queda ambigua (ver comentario anterior sobre esta frase).

Segunda sugerencia: "Mathematical tool are needed to model groundwater for the sustainable management of these resources."

Comentario [MDJH-23]: No se vue a utilizar esta abreviatura en el resumen.

Con formato: Resaltar

Comentario [MDJH-24]: Sugiero eliminar "peculiar".

Comentario [MDJH5]: Esta parte de oración puede prestarse a confusión. Si se refieren a las actividades turísticas Quintana Roo, entonces mejor colocar la frase "in the state of Quintana Roo" después de "activities" como sigue: "Rapid population growth and coastal tourism in the state of Quintana Roo threaten…"

Pero si se refieren a actividades turística otro lado que no es Quintana Roo, enton sería conveniente aclarar en qué lugar suceden las actividades turísticas costera por ejemplo, si se refieren a las actividad turísticas en la península de Yucatán,

Comentario [MDJH6]: Los párrafos una sola oración generalmente son desaconsejados. Recomiendo unir esta oración con el párrafo anterior. Esta unió

Comentario [MDJH7]: El plural aqu implica más de un tipo de recurso subterráneo, pero en el párrafo anterior s han mencionado uno.

Sinkholes are natural~~ly~~ geological features ~~that~~ connecting the land surface ~~of the Earth~~ with ~~the~~ underground ~~of~~ karst~~ic~~ terrains, and they are formed when rain-water dissolves limestone, creating underground voids (Coskun, 2012). Two main groups of sinkholes have been ~~reported under~~ identified in the genetic classification (Williams, 2004; Gutierrez et al., 2014). The first ~~one corresponds to~~group comprises solution sinkholes, ~~generated~~ which are formed by differential corrosion, lowering the ground surface where karst rocks are exposed. The second group ~~can be designated as~~comprises subsidence sinkholes, which results from both subsurface dissolution and downward gravitational movement.

~~Many~~ In Quintana Roo many ~~of~~ sinkholes, caverns and underground rivers~~these features~~ have been reported ~~before~~ by scuba divers, and the Quintana Roo Speleological Survey has ~~performed~~ produced an underground map of the Riviera Maya ~~with a~~ for touris~~tic~~m purposes~~ in the Riviera Maya~~. However, geophysical techniques have rarely been ~~barely~~ applied as non-invasive ~~methods for exploration over~~ approaches to explore this area (~~Gondwe et al. 2010;~~ Estrada-Medina et al. 2010; Gondwe et al., 2010; Beauer-Gottwein et al., 2011). ~~It is well known that e~~Electrical resistivity tomography has ~~shown good results to explore karst~~ proven effective for exploring karst areas (Ahmed ~~y~~and Carpenter 2003, Chalikakis et al. 2011)~~,~~; however, in the Quintana Roo~~this~~ region the lack of soil on ~~this~~ the hard limestone ~~ground~~ terrain ~~difficult the electrodes placing which results in a complicated and time consuming problem, making even more expensive the~~ has made placing electrodes a complicated and time-consuming task, raising expenses for data collection. New approaches ~~in~~to geophysical and coastal karst prospecting are therefore ~~required in order to protect and develop future~~ needed to develop and maintain sustainability plans in the ~~YP~~Y~~ucatan Peninsula~~.

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

We did not find references ~~for EM-LIN methods applied~~on the use of EM-LIN in karst systems, but we found that the Direct Current DC and aero Time Domain Electromagnetic Method (TDEM) ~~method~~ was ~~applied in~~ used for the Sian-Kan natural reserve ~~(~~ by Supper et al. (2009). ~~They also~~These authors ~~took~~ performed EM-34 measurements~~,~~ but they ~~they did~~did ~~made~~ no further processing, like perform a geophysical inversion.

1.1 Study area

2 This research was ~~done~~ carried out in the Yucatan Peninsula (YP), which is the emerged ~~part~~portion ~~of the great,~~ largely karst~~,~~ Yucatan ~~p~~Platform ~~largely karstified~~ (Bauer-Gottwein et al., 2011). From the geological point of view, the YP ~~is a platform~~ is constituted by a sequence of calcareous sediments (Bonet and Butterlin, 1962) and is characterized by ~~being~~ its flat ~~with~~ landform (no topography) and ~~no~~the absence of surface rivers. A review of the YP karst aquifer is well

Comentario [MDJH-28]: Agregué "the Earth" para dejar explícita qué superficie. Otra posible sugerencia pued ser "the land surface" en lugar de "the surface of the Earth".

Comentario [MDJH-29]: ¿"cover-subsidence sinkholes"?

Comentario [MDJH-210]: ¿Reemp ar "movement" por "force"?

Comentario [MDJH-211]: Porque el párrafo anterior es un relato de conocimiento general, agregué "in Quint Roo" aquí para dar a entender que esta

Comentario [MDJH-212]: La frase "these features" en la parte resaltada de

Comentario [MDJH-213]: OBSER CIÓN: En casos como este, donde coinc

Comentario [MDJH-214]: Sugiero especificar la palabra "this"–por ejemplo

Comentario [MDJH-215]: Eliminé palabra "future" porque ya queda implíc

Comentario [MDJH-216]: Las sigl YP las definen hasta la siguiente sección

Comentario [MDJH-217]: Por favo cambiar a "applying" si la aplicación del

Comentario [MDJH-218]: Por favo verificar que no haya cambiado el mensa

Comentario [MDJH-219]: "DC" y "TDEM" no fueron definidas previamen

Comentario [MDJH-220]: Por favo rechazar este cambio y dejar "did".

Con formato: Color de fuente: Tex 1

Con formato: Color de fuente: Tex 1

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Con formato: Color de fuente: Amarillo

Con formato: Color de fuente: Tex 1

Con formato: Color de fuente: Tex 1

Con formato: Color de fuente: Tex 1

Con formato: Resaltar

Comentario [MDJH-221]:

Comentario [MDJH-222]: ¿OK?

described by Bauer-Gottwein et al. (2011), and an extended description of coastal cave development is given by Smart et al. (2006).

~~We took a~~Our study area ~~that~~ covers the Chac-Mool sinkhole, which is located 20 km ~~southward~~ south of Playa del Carmen in the state of ~~QR~~ Quintana Roo ~~state at~~ (approximately 20º-30'-46.37" N and 87º-14'-49.32" W) (Fig. 1). The area ~~covers an extension of~~ extends to 1 km^2 and ~~it~~ is fully covered by dense vegetation. The ground presents ~~a large~~ high secondary porosity. ~~The QR state receives~~ Annual precipitation there is around 1,200 mm ~~of annual precipitation~~ and topography is a flat surface with a slope of 9 m ~~over~~ above ~~the~~ sea level within 20 km ~~since~~ from the shore-line (CNA, 2016). The hydraulic gradient in the southern part of Playa del Carmen was estimated ~~in~~ at 58-130 mm/km (Beddows, 2004). Due to its proximity to the coast (2 km), the study area is penetrated by ~~the~~ sea-water. ~~Such an~~Water intrusion ~~oscillates depending~~is dependent on tides and ~~rain recharge~~rainfall (Beddows, 2004). Chac~~k~~-Mool is a sinkhole~~s~~ complex where ~~it is assumed that~~ two underground rivers presumably connect the Little-Brother sinkhole and the Air-Dome sinkhole. The underground river ~~paths~~pathways ~~are known~~ in some ~~parts~~ sections ~~by~~ have been documented on maps made by scuba div~~er~~ers~~ing maps~~ (Quintana Roo Speleological Survey ~~QRSS~~) but other ~~parts~~ sections and vertical components remain unknown ~~as well as the vertical components~~. ~~It is possible that the~~The entire rock matrix is possibly saturated ~~of~~ with fresh~~/~~ and brackish water ~~through~~ in ~~the~~ ~~porosity~~ pores and small conduits. The apparent conductivity is ~~large~~ high because it averages the matrix conductivity (low value) with the sea-water conductivity (high value).

Comentario [MDJH-223]: El texto original da a entender que el cenote Cha Mool se ubica a 20 km al sur de playa de Carmen y que las coordenadas geográfic que dan entre paréntesis son para el cenc Chac Mool.

Si lo que quieren decir es que el área de estudio está a 20 km de playa del Carme que las coordenadas que se dan entre paréntesis son para el área de estudio, entonces, por favor reemplazar "which i por "and is".

Comentario [MDJH-224]: No se ha definido "QR" para el texto general.

Comentario [MDJH-225]: Hace fa el sujeto de la oración. ¿Está bien "the study area"?

Comentario [MDJH-226]: Almend habiendo aclarado esto por teléfono, sug el siguiente cambio para la para que resa el comentario: "on maps made by scuba divers"

Con formato: Resaltar

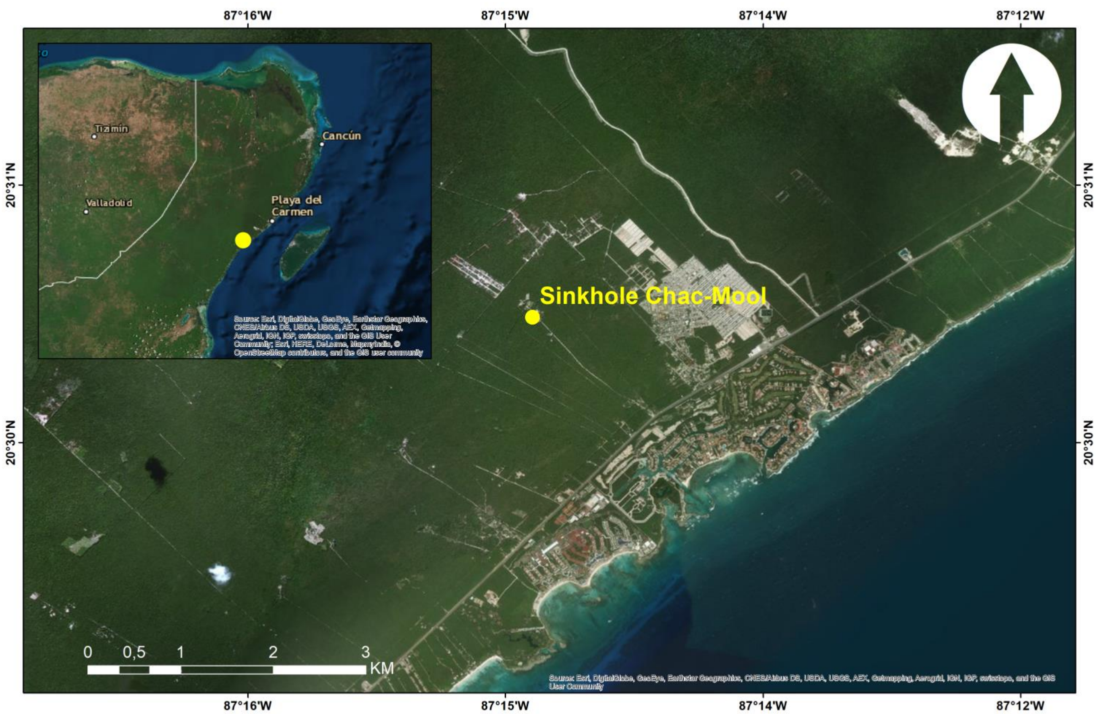

Figure 1. Study area: Chac~~k~~-Mool sinkhole in the state of Quintana Roo~~ state~~, Mexico.

1.2 Electromagnetic survey

In September 2015, we carried out a field ~~trip~~survey over the study area. We ~~took ~~obtained seven profiles with the EM-34 (Geonics) instrument that operates ~~under ~~within the LIN domain as described in McNeill (1980). The main reason ~~we are~~for using the EM-34 is ~~because it is easy and fast to take data~~that it can accurately obtain data in a more easy and faster way in terrains with ~~lack of~~no soil~~ without loss of accuracy~~, ~~making faster the~~expediting field-work in hard, ~~r~~tough terrains.

The basic principle consists in the transmission of an alternating current of constant frequency, *f*, through a coil (transmitter), which ~~will ~~generates 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~~A secondary electromagnetic field in the ground ($\boldsymbol{H_s}$) is ~~created due ~~then generated by these conductive bodies. These two fields ~~will ~~differ in amplitude and phase, and they ~~will be~~are detected by a coil (receiver) that is 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~~LIN (*N*<1) the imaginary part of

Comentario [MDJH-227]: Dentro de la figura, considerar cambiar la etiqueta "Sinkhole Chac-Mool" por "Chac-Mool sinkhole".

Con formato: Resaltar

Comentario [MDJH-228]: La parte resaltada implica, indirectamente, que además del instrumento EM-34 que opera dentro del dominio LIN, existe otro tipo de instrumento EM-34 que no opera dentro de ese dominio.

Si existe solo un instrumento EM-34 que opera dentro del dominio LIN, entonces sería necesario cambiar parte resaltada por la sugerencia entre comillas:
"with the EM-34 instrument, which operates within the LIN domain,"

[Por favor, noten la coma después de "domain". Esta coma implica que los 7 perfiles, y no el dominio LIN, se obtuvieron de acuerdo con lo descrito por McNeill (1980). **Pero**, si la frase "as described in McNeill (1980)" hace referencia al dominio LIN y no a la obtención de los 7 perfiles, por favor, no incluyan la coma y eliminen la palabra "as" después de "domain"]

Con formato: Resaltar

Con formato: Resaltar

Comentario [MDJH-229]: ¿Quieren decir "rough" o "hard"?

"rough terrain" = terreno duro, irregular, rugoso
"hard terrain" = terreno duro

Comentario [MDJH-230]: Agregué "basic". ¿Es correcto?

Comentario [MDJH-231]: Aquí hace falta un verbo, frase o sustantivo que se complemente con la frase "through". Para enmendar, he insertado la frase "the transmission of", pero sería necesario verificar si la frase "the transmission of" es atinada.

Con formato: Fuente: Cursiva

Con formato: Fuente: Cursiva

H_s/H_p is a straight line ~~whose~~ for which the slope is the conductivity of a homogeneous half-space. Because ~~of~~ the ~~real~~ ground is not homogenous, we ~~refer to~~say we get an apparent conductivity: $\sigma_a = (4/\omega\mu_0 S^2)(H_s/H_p)$.

~~It is usual to use b~~Both loops (source and receiver) are commonly used in a coplanar way. We have two possible arrays, one when both loops are parallel to the earth's surface (vertical magnetic dipoles, V~~H~~MD) and ~~another~~ the other when both loops are perpendicular to the earth's surface (horizontal magnetic dipoles, HMD). ~~For both arrays we can extend the~~The separation between loops ~~from~~ can be extended to 10 m, 20 m, and 40 m in both arrays. ~~In~~ For this ~~research the~~ study, measurements were made along 6 lines (Fig. 2), and the observation points were spaced every 5 m. ~~Due~~ Because ~~the dense~~ vegetation ~~of~~ in the jungle was dense, ~~it was not possible~~ we were unable to locate profiles anywhere, ~~instead~~ and so we took the ~~available~~ paths around the ~~sinkholes~~ Chack-Mool, Little Brother, and Air Dome sinkholes. ~~Then, we~~We then tried to follow straight lines ~~thinking in doing~~so we could perform 2D inversion modeling ~~for~~ on every data profile, but ~~then~~ we realized that six of the profile~~s~~ distributions were more or less covering a rectangular area. Therefore, we performed a 3D inversion, in addition to the 2D model profiles (not presented here). For the 3D inverse modeling we followed the method by Perez-Flores et al. (2012 but the algorithm they used was designed for profiles that were measured in parallel or perpendicular positions with respect to the other profiles~~) method, but that the algorithm they used was designed to parallel or perpendicular data profiles between them~~. Later~~,~~ on we ~~will~~ show how we modified the equations for arbitrary angle profiles. The length of the six profiles (1 to 6) ~~length~~ varies between 50 m and 140 m (Fig. 2).

Comentario [MDJH-232]: Sugiero eliminar esta palabra.

Comentario [MDJH-233]: No entiendo qué quieren decir aquí.

¿Quizás "on the same plane" [en el mism plano]?
¿O quizás quieren decir, modificando to la oración, "Both loops are usually coplanar"?

Comentario [MDJH-234]: Estas si no han sido definidas, y son las mismas se utilizan en la siguiente línea para "horizontal magnetic dipole".
¿Quizás aquí debería ser "VMD"?

Con formato: Fuente: (Predeterminado) Times New Roman Color de fuente: Texto 1, Inglés (Estados Unidos)

Con formato: Fuente de párrafo predeter., Fuente: Color de fuente: Automático, Inglés (Reino Unido)

Comentario [MDJH-235]: Mientra que la palabra "parallel" sí se puede utili como verbo, la palabra "perpendicular" Aquí, ambas palabras están siendo usada como verbos. Además, no es claro a qué hace referencia el pronombre "them". Po tanto es difícil captar el significado intencionado aquí.
Puedo sugerir la siguiente redacción, ma sería necesario verificar si la sugerencia atinada y no modifica el mensaje intencionado:

"the algorithm they used was designed t obtain data profiles with parallel and perpendicular orientations"

Quizás esta frase la podemos resolver en reunión.

Con formato: Fuente de párrafo predeter., Color de fuente: Texto 1, Inglés (Estados Unidos)

Figure 2. EM survey on the Chac-Mool sinkhole. The ~~N~~numbered profiles cross~~ing~~ the hidden rivers. White lines mark the sinkholes.

1.3 Inverse modeling

~~We assume the~~ EM data (apparent conductivity, σ_a) ~~as a~~were assumed to be the weigh~~t~~ed average of the subsurface electrical conductivity distribution, as described by Pérez-Flores et al. (2004). ~~—~~We ~~relate~~ associated the apparent conductivity (σ_a) with the true subsurface conductivity (σ) ~~through~~ by means of 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):

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

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

For the inversion we ~~have~~had to consider how the magnetic dipoles ~~are~~ were used~~,~~. ~~we~~We ~~have~~ obtained the ~~V~~vertical and horizontal magnetic dipole~~s~~ (VMD and HMD, respectively) arrays as describe~~r~~d ~~in~~by Pérez-Flores et al. (2012). The integral equation for ~~the vertical magnetic dipoles (~~VMD~~)~~ is~~,~~

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

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

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

~~And~~ HMD in the x direction is given by:

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

The expressions 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~~ at any angle (Eq. 2), but HMD profiles run~~s~~ only in either the y (90°; Eq. 3) or x (0°; Eq. 4) direction~~s~~. ~~A problem is when we have a~~Arbitrary direction profiles ~~as it happened~~like those observed around the Chac-Mool sinkhole (Fig. 3) constituted a problem. So, we had to modify Eq. (4 and 5) in order to accept the arbitrary angle profiles.

Comentario [MDJH-236]: Por favo[r] eliminar la "t".
Aunque el autocorrector lo indica como error, la palabra correcta es "weighed".

Comentario [MDJH-237]: ¿O quiz[á] quieren decir "the point of the electric source"?

Con formato: Resaltar

Con formato: Resaltar

Con formato: Resaltar

Comentario [MDJH-238]: ¿O quiz[á] quieren decir "the point of the magnetic source"?

Con formato: Resaltar

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

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

~~Similarly, along~~and the x direction~~,~~ is

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

When we rotate Eq. (3) ~~in~~ 90^0, ~~this~~ it 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 an 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~~equation,

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

For ~~T~~terms ~~(~~*a*, *b*, *c*, *d*, *e*, and *f*~~)~~ ~~can be obtained from~~see 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~~ as the source-–receiver separations for VMD and ~~the same separations for~~ HMD in every profile. We pooled all data sets and performed a joint inversion to obtain a single 3D conductivity model.~~We inverted together the whole sets of data in order to get~~ ~~to obtain 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~~ was constant, however unknown. Eq. (2) and (8) can be written as a linear equation~~s~~ system~~,~~ and in a matrix ~~way,~~fashion:

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

~~W~~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 used quadratic programing to minimize the ~~next~~ following objective function, $\boldsymbol{U}$:

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

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

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Comentario [MDJH39]: ¿"collectiv inverted all sets of data"?

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Con formato: Resaltar

Comentario [MDJH40]: Usar "following" en lugar de "next" si se refi a la "siguiente ecuación", es decir a la ecuación 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~~ was low, we ~~got~~ obtained a rough 3D model. ~~First~~ The first term ~~is to~~ fits the apparent conductivity data taken at the field. The ~~S~~second term in Eq. (10) ~~has~~ contains the spatial derivatives of the conductivity in (x, y, z) direction. The ~~S~~smoothness parameter controls the ~~second term~~ magnitude of the second term. If zero, ~~we just fit the data~~only the data was fit and the model use to be very rough~~,~~; if very large, the model converge~~s~~d into a homogenous half-space. We use to transform the Hessian in order to be unity in diagonal. This way~~,~~ the smoothness parameter ~~can vary~~varies in a very narrow window. We ~~use to try (~~tested the values 0.1, 0.01, and 0.001~~)~~. ~~Value~~ The 0.1 value yield~~give~~s a smooth model and the 0.001 value a rough model. We began with a smooth value that ~~gives~~ gave the simplest but the most probable model (according to the Occam's Razor principle), and we lowered the parameter ~~in order~~ to recover ~~-~~more structure ~~but we will see that~~; however, after ~~some~~ a certain point the structure turn~~s~~ed unreal ~~since~~ from the geological point of view. The idea ~~is~~was to recover ~~the more~~ most of the structure ~~and at the same time~~while keeping the simplest and ~~the more~~most probable model.

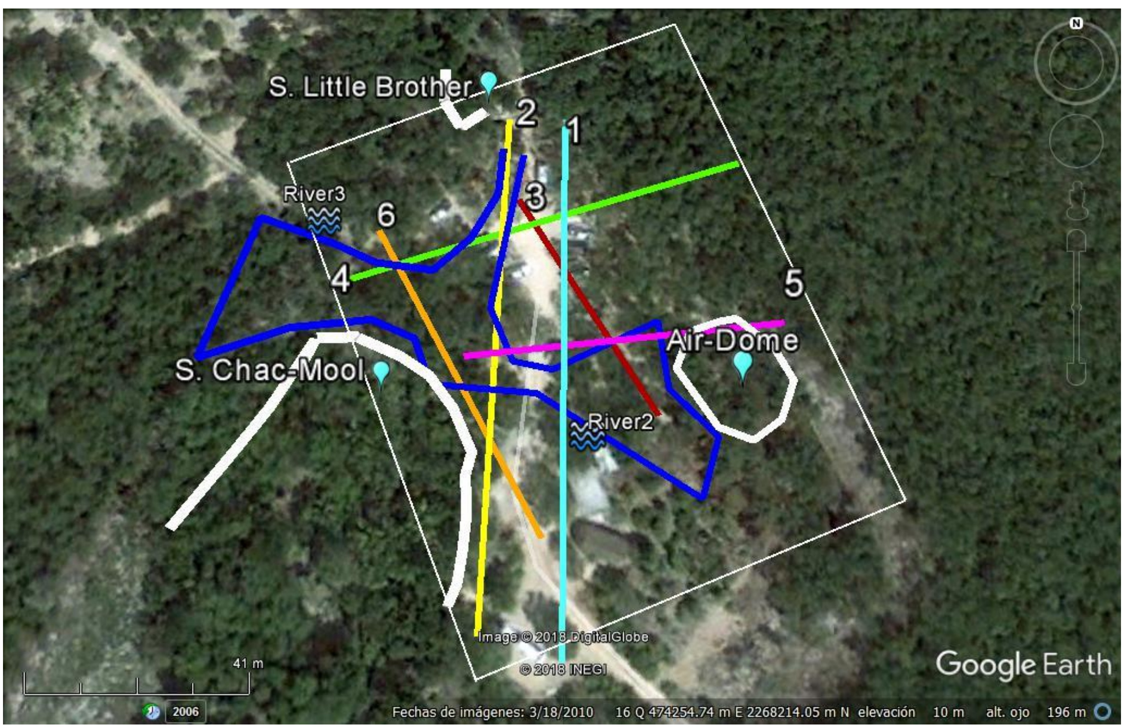

Figure 3. Profiles crossing underground rivers ~~on~~in the sinkhole area (numbered lines). The white rectangle is the 3D model~~ing~~ed area.
White lines mark the sinkhole boundaries. Dark blue lines are the suggested rivers paths.

Comentario [MDJH41]: ¿"was"?

Comentario [MDJH42]: No es clara expresión intencionada aquí. ¿Quizás "We transformed the Hessian to achieve diagonal unity"

[NOTA: Gramaticalmente, la sugerencia tiene sentido, mas no sé si matemáticamente tenga sentido]?

Con formato: Resaltar

Con formato: Resaltar

Con formato: Resaltar

Comentario [MDJH43]: No estoy segura de lo que quisieron expresar aquí. Por favor, verificar que el mensaje intencionado no haya sido cambiado.

Con formato: Resaltar

Con formato: Resaltar

Comentario [MDJH44]: Usar "yielded" (pasado) si se trata de sus resultados, pero "yields" (presente) si se trata de una generalidad.

Con formato: Izquierda, Interlineado sencillo, No ajustar espacio entre texto latino y asiático, No ajustar espacio entre texto asiático y números

2. Resistivity cross-sections ~~over~~ on the 3D model.

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

Conductivity is the unknown, but we prefer to show the ~~results in~~ resistivity (the inverse of conductivity ~~inverse~~) results. In Fig~~.~~ure 4 we present the 3D resistivity model after the inversion ~~process~~ of ~~the~~ whole sets of data. In ~~this~~ that figure we present the interpolated resistivity cross-sections under the six profiles. Blue ~~are~~ indicates resistiv~~e~~ity areas and red low resistiv~~e~~ity. There are spaces between profiles ~~that have~~with no data. ~~In those areas the~~The 3D model for those areas is not ~~very confident~~so reliable. Therefore, as a first approach, we ~~better~~ show the model ~~where the data are as a first approach~~for the areas for which we had data. There is ~~a~~ very good coherence where the model crosses. ~~In this figure are shown the~~Figure 4 shows irregular paths ~~of~~ for the two rivers, according to the ~~diver's~~ map from the divers (x, y, z) ~~map~~. Water table depth in the open sinkholes 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 been mapped by the divers. ~~It is i~~Interestingly, ~~that~~ some paths were marked below ~~the~~ resistiv~~e~~ity areas. ~~Probably the~~The upper water level ~~top~~ of subterranean rivers ~~are~~ is probably far from the surface, making the roof more ~~stable~~ structurally stable, or maybe there are air-filled caves over the water table. ~~We assume as~~By *roof* ~~as~~ we refer to the limestone~~s~~ rock between the surface and the upper water level ~~top~~ of the subterranean river. We can idealize a typical cave in this area (near the coast), vertically consisting of a limestone roof and/or an empty space, ~~then~~followed by fresh water (lower resistivity), the halocline (mixing of 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~~ obtained with the 3D resistivity model. Cross-section (a) corresponds to the profile~~-~~1 model, cross-section (b) to the profile~~-~~2 model, and so on. Every profile is ~~signed~~ indicated with a white ~~dot~~circle, which pinpoint the interpolated (x, y, z) hidden-rivers. The (x, y, z) locations were obtained from the ~~scuba diver's map~~mapping made by scuba divers. We ~~sign~~ delineated the inferred cave section ~~as~~ with a rectangle, because we ~~cannot~~ could not see details. We assumed the saturated limestone ~~as~~was bedrock, because dry limestone resistivity ~~is~~was 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 some small ~~spots look~~sections were blue ~~or~~ (1000 ohms-m).

Comentario [MDJH-245]: No me quedó claro porque utilizaban 'top' en e casos y no lo había indicado poruqe no estaba segura si así era la terminología técnica. Pero, me quedé con la duda si querían decir "upper water level".
Este uso lo emplean en más de una ocasi , pero sólo lo he indicado aquí. Si es necesario cambiar algo, sería convenient hacer el cambio en los demás casos.

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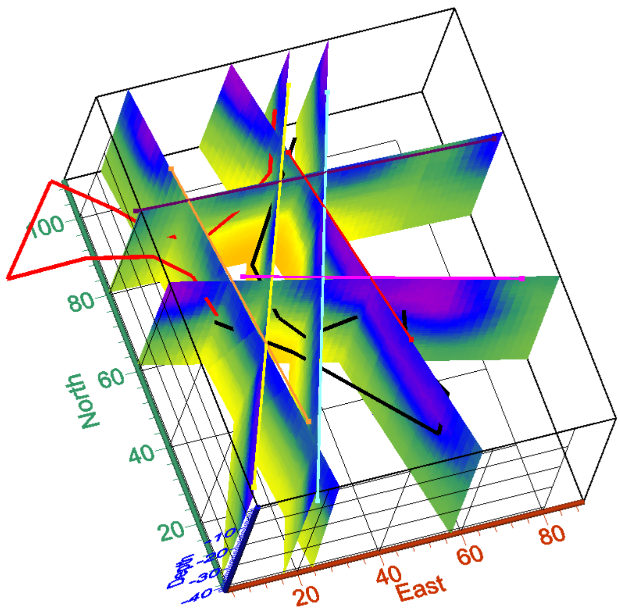

Figure 4. 3D resistivity model for Chac-Mool sinkhole. Here, we ~~only present~~show only the distribution of the cross-sections ~~distribution~~ where the profiles were run. The red and black irregular lines represent the hidden rivers.

~~Looking~~ From the six ~~-~~resistivity cross-sections, we can see that most of the river crossings show a green color over them. ~~Meaning perhaps~~This means that the subterranean rivers are probably close to the surface and ~~therefore~~ the ~~roof~~ thickness of the roof is therefore thin~~ner~~, ~~making~~ meaning roofs in those areas are more ~~sensible for~~vulnerable ~~roof~~ to sinking, ~~even that~~though we did not ~~see surface evidences of~~find evidence of subduction or fracturing on the surface. ~~Profile 1~~The cross-section for profile 1 (Fig. 5a) shows three crosses: one at x=18 m show~~s~~ing a thin~~ner~~ roof~~,~~ and the other~~s~~ two showing a thicker roof. Profile 2 (Fig. 5b) shows a green color, meaning thinner roofs. Profile 3 (Fig. 5c) shows one river crossing that is shallow and another deeper one. ~~-~~We ~~can see that~~clearly detected a shallower subterranean river ~~is well detected~~ (green color) ~~by~~ using the EM-LIN equipment but it is not ~~obvious~~clear ~~when this is deeper~~how much deeper it is. We must remember that the white ~~dots~~ circles are interpolations ~~of~~ taken from the diver's map. ~~In the deeper river cross, this~~The deeper river crossing coincides with the location of a ~~big~~ large resistiv~~e~~ity mass between zero and 20 m~~,~~; this means that divers had to dive bel~~l~~ow this resistiv~~e~~ity mass (1000 ohms-m). ~~In p~~Profile 4 (Fig. 5d) ~~they~~ shows three crossings with green color. Profile 5 (Fig. 5e) shows three crossings, two are deep~~er~~ (between z=20 m and z=30 m) and one is shallow~~er~~ (z=15 m). The deeper crossings are consistent with the reported ~~diver's~~ diving depth ~~reported~~ and the thicker roof ~~obtained by a big~~

Con formato: Izquierda, Interlineado sencillo, No ajustar espacio entre texto latino y asiático, No ajustar espacio entre texto asiático y números shown by the large resistivity mass~~,~~. ~~h~~However, at x=25 m the river seems to be 10 m deeper~~, this could be explained, considering that there is~~, possibly because of the presence of a huge hard rock (very resistive)~~ that could be affecting~~. ~~The last p~~Profile 6 (Fig. 5f) shows a shallow~~er~~ river and a deeper one. Resistivities are consistent with the position of the river.

We know that divers ~~passed~~ swam throughout subterranean rivers. In Fig. 5 ~~we propose a broad suggestion about~~we broadly suggest the location ~~those~~of the river crossings (rectangular polygon). ~~Giving an explanation to the colors~~Given the color descriptions in Fig. 5, we can ~~think~~ say that blue ~~can correspond to~~is an indication of dry limestone roofs or dry limestone ~~plus~~ and air-filled caves at the top of ~~the~~ rivers or close to the surface. ~~Green~~ The green color is so widespread that it surely ~~contains~~ indicates clean water (50 to 70 ohms-m). Also, the resistivity cross-section shows a green color whe~~n~~re the subterranean rivers seem to be shallow~~er~~. ~~Instead, we~~We ~~would~~ expected to see a narrow blue coloration ~~plus~~ and~~a~~ green color over those shallow~~er~~ rivers~~. That is not happen~~, but we did not, because the ~~lowest~~ narrowest source~~-~~–receiver separation at the EM34 ~~is~~ was 10 m (~~it is~~too~~-~~ large to see surface details). In some way the estimated true conductivity ~~estimated continues being~~is still an average. Maybe if we ~~could use a lower~~use a narrower separation, we could ~~resolve~~ see a thinner blue color for the roof and then a green color ~~from~~ for 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 in the rivers ~~is~~ to be stratified~~ inside the rivers~~, with the salty water at the bottom.

We drew the river section ~~with the idea~~ to emphasize that the resolution of the EM34 instrument ~~have not the resolution~~is not good enough to sharply isolate the rivers from the bedrock. ~~An explanation is that~~A possible explanation is that the upper sections of unaltered bedrock (limestone) ~~is~~ are partially saturated ~~of~~with clean water ~~at the shallow depths~~ (because of the 50-70 ohms-m values) and the deeper sections are saturated ~~of~~ with salty water ~~at the deeper parts~~ (because of the 6-10 ohms-m values). So, there are ~~not~~ no large horizontal resistivity ~~changes~~ differences between the river location and the bedrock. It is almost ~~sure~~ certain that the permeability ~~in~~ of the bedrock is as high as the permeability of the limestone~~s~~ ~~on~~ at the surface. When ~~raining~~it rains, ~~the~~ water quickly disappears~~ quite fast~~.
~~With the a~~Aerial-electromagnetics (flying 30 to 50 m over the surface) ~~we will have~~would yield an even ~~a~~ lower resolution, but we ~~could~~ would be able see in a faster way where the subterranean rivers are ~~when~~ in the areas where they are closer to the surface. 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~~ section close to x=70 m (red square). It is possible that there is a shallow subterranean river ~~pass~~ close to the surface ~~and it was not yet~~that has not yet been mapped by the divers.

Comentario [MDJH46]: ¿"fresh water"? No se había utilizado el término "clean water".
NOTA: De aquí en adelante utilizan "clean", pero sólo lo he marcado en esta ocasión porque no sé si el uso fue intencional o si se refieren a "fresh wate

Con formato: Resaltar

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Comentario [MDJH47]: ¿Quizás m "distance"?

Con formato: Resaltar

Comentario [MDJH48]: El texto aq necesita revisión, pero no estoy segura d mensaje intencionado.

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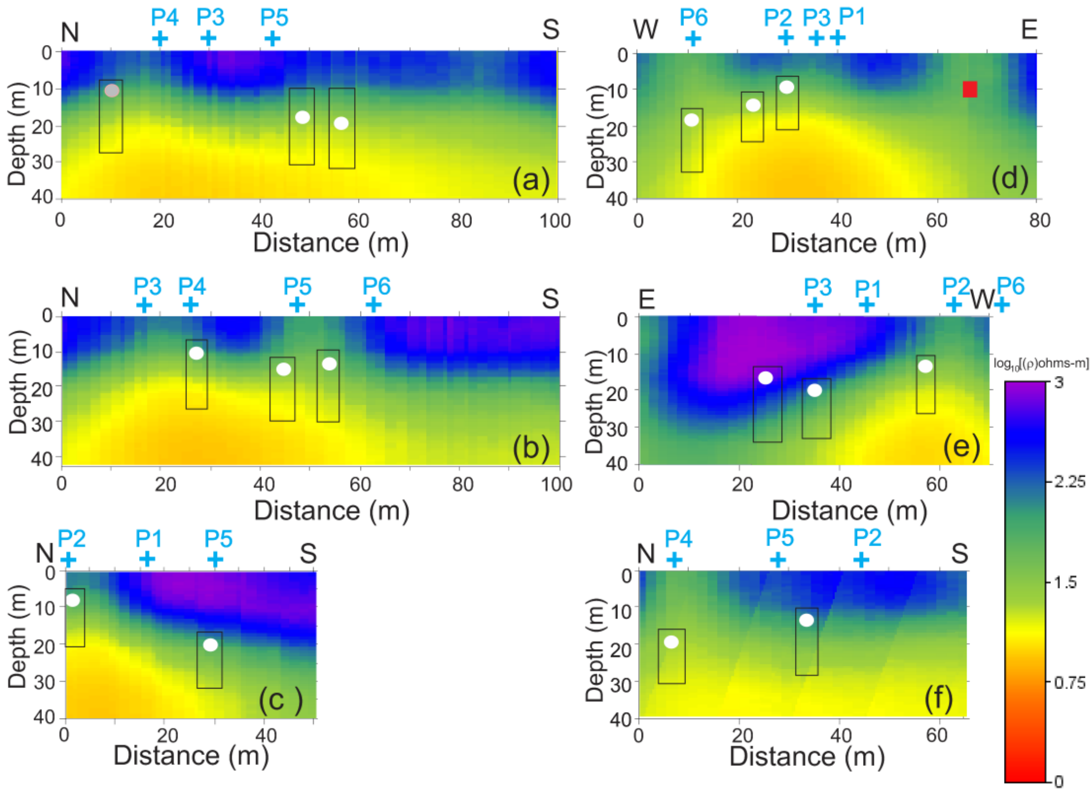

Figure 5. Cross-sections of the 3D resistivity model ~~under~~ for profiles 1 to 6. ~~Units~~ Resistivity units are base 10 logarithm ~~of the resistivity~~. Blue color ~~colors~~ indicates~~are~~ more resistive areas and red ~~colors~~ the least resistive areas. Blue numbers ~~signs~~ indicate the other profile~~s~~ crossings. White ~~dots~~ circles ~~signs shows~~pinpoint the areas where ~~the~~ scuba divers have mapped the underground rivers. Red ~~dot sign~~circles show~~s~~ the position of an underground river inferred from the model. The ~~S~~square polygon is a broad suggestion of the river tunnels.

2.1 Isometrics of the 3D resistivity model.

The Chac-Mool sinkhole system is a complex of three small sinkholes (Air-Dome, Little Brother, and Chac-Mool ~~itself~~). According to divers, there are two underground rivers. Their vertical variations may cause ~~the thinner~~thinning of the limestone roofs and therefore sinking. According to the cross-section in Fig. 6, the EM-LIN equipment cannot sharply diesitinguish between the subterranean river tunnels and the bedrock, maybe because there is not enough change in resitivity ~~change, meaning~~. This means that ~~bedrock~~ limestones bedrocks are partially saturated ~~of~~with water and therefore under ~~the~~a process of chemical disolution~~ process~~. ~~Looking t~~The isometric view of the 3D resistivity model (Fig. 6) ~~we can see~~shows the spatial distribution of the three sinkholes ~~inside~~ in the system. ~~-~~With two kind of blue the two proposed rivers and their paths. ~~We~~ Figure 6 also ~~see~~ shows the location of the five EM-LIN data profiles~~ of EM-LIN data~~.

The blue and green surfaces are equal-resistivity surfaces ~~of~~ in the 3D model (160 ohm-m). The blue ~~one pretends~~surface ~~to show~~portrays the bottom topography of the limestone roof. This resistive layer may contain unaltered limestone ~~plus~~ and air-filled caves. It is very interesting that this layer outcrops areas where underground rivers are very shallow, and those paths ~~are very coincident~~coincide with areas where the rivers are shallow. This surface ~~is not shown~~ does not show where the sinkholes are~~, due to lack of data~~, because data is lacking. We did not manipulate the 3D model to ~~obligate the model to~~force outcrops ~~where~~of areas with sinkholes~~ are~~, but we ~~can~~ could do so ~~by mean of~~with quadratic programing in the minimization process of equation (10).

~~It is also~~Also ~~interesting that in~~worth noting is the middle part of the study area, where ~~there is~~ a resistive massif (MR letters)~~, where~~ indicates that the roof ~~appears to~~could be higher than 20 m in thickness~~deepness~~. ~~That~~ This means that ~~that~~ the zone is the least hazardous area for roofs to collapse because there are no voids or caverns that may collapse (Gutierrez et al., 2014).

The green surface should be the surface ~~where the~~ indicting clean water ~~is located~~ (80 ohm-m). Nevertheless, it is also present where there are blue surface outcrops~~. This occurred maybe~~, probably because the EM-LIN source~~-~~receiver separation was too large (10 m) and we are probably seeing a ~~kind~~ sort of resistivity average between the roof (resistive) and the clean water (less resistive). But this happens ~~just~~ only where the roof is~~-~~ thin. ~~We must be careful~~Caution should be taken with this model ~~where no data exist~~in areas for which there were no data.

Con formato: Resaltar

Comentario [MDJH49]: Esta es una oración incompleta porque carece de suj y verbo. No estoy segura cómo interpretarla.

Con formato: Resaltar

Comentario [MDJH-250]: Aquí fal un espacio.

Comentario [MDJH51]: Ok?

Comentario [MDJH52]: Frase confusa/contradictoria: el techo puede te una **altura** de más de 20 m en **profundidad**.

¿Quizás "be higher than 20 m from the bedrock"?
¿o quizás "be located at more than 20 m from the land surface"?

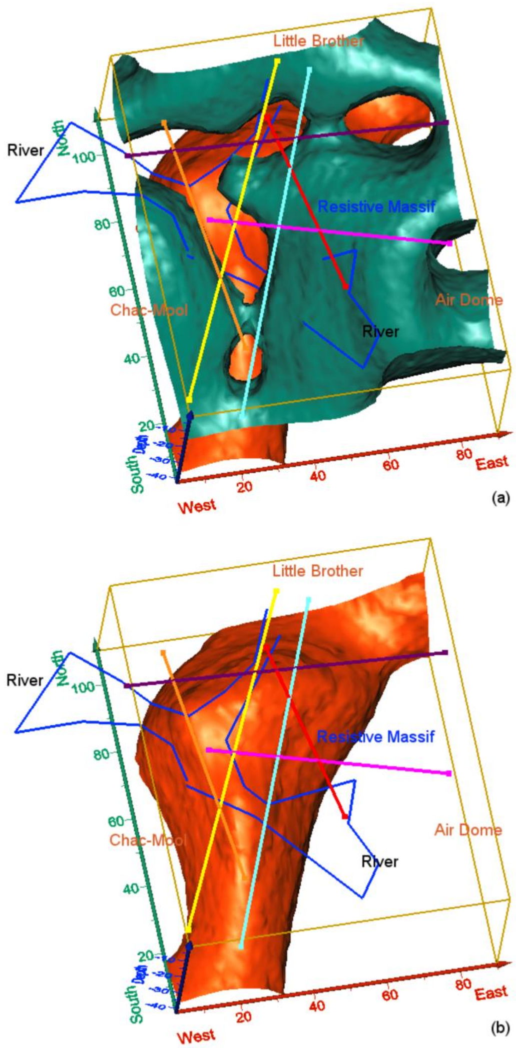

Figure 6. Isometric representation of the 3D resistivity model. Straight lines ~~are~~ represent the EM profiles~~ done~~. (a) Blue iso~~-~~surface represent~~s~~ing the bottom topography of the dry limestones. (b) Red iso~~-~~surface represent~~s~~ing the ~~contact between~~area where fresh and salty waters meet.

3. Conclusions

In this research we studied~~investigated~~ the Chac-Mool sinkhole complex by ~~means of electromagnetic~~EM methods ~~operating~~ at ~~low induction numbers (EM-~~LIN~~)~~. These methods consist of a source loop and a receive~~d~~r loop operat~~work~~ing coplanar ~~to the Earth's surface~~ (VMD) and perpendicular (HMD) the Earth's surface. These two polarizations ~~look~~ view the land surface~~Earth~~ in a different way. ~~That is why; we~~We used both arrays ~~in order~~ to ~~do~~ perform a joint inversion and to obtain a single three-dimensional (3D) resistivity model. ~~Those e~~Equations ~~were~~ had already been 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~~man-made paths~~, that however, were~~; however, these paths were located at arbitrary angles. We ~~had to modify~~modified the existing equations~~, arriving to~~ and obtained a more general set of equations.

~~We did~~ The 3D inversion of both VDM and HDM arrays ~~arriving~~led to a single 3D resistivity model. The cross-sections of this 3D model show the points where the underground rivers cross. ~~Where~~ The areas where the underground rivers ~~approach~~ are close to the surface~~, they may create~~could represent ~~a~~ hazard zones because of the possibility of roofs collaps~~e~~ing. We also ~~see~~observed the distribution of ~~the clean~~ fresh and salty waters ~~distribution and their contact or~~and the areas where they meet or the transition surface (halocline). ~~We see~~ Our observations indicate that rivers ~~must~~ might run along tunnels, but the resistivity of those tunnels does not ~~sharply~~ differ sharply from the resistivity of the bedrock, meaning that ~~they~~ tunnels are ~~also~~ saturated ~~of~~ with water (clean and salty depending ~~the~~on depth). The isometric view shows that the resistiv~~e~~ity iso-surface corresponds with the bottom topography of the underground roof. At the center of the area of study this roof seems to be very thick, ~~making~~ indicating this area is save from~~very stable for~~ sinking hazard. This isometric view also shows that the areas where the blue iso-resistivity surface outcrops ~~is~~are the areas where the underground rivers are close to the surface.

~~This~~ The EM-LIN technique is~~ very efficient,~~ a fast, efficient, and ~~cheap~~ inexpensive procedure for ~~exploring~~explorations over hard~~-~~rock sinkhole areas. ~~We can get~~It allows us to obtain the geometry of the underground rivers and the distribution ~~between~~ of clean and salty water.

Acknowledgements

Many thanks go to ~~Conacyt~~ CONACYT and Gemex for providing funds. ~~Thanks to~~We thank CICESE for allowing us to use the geophysical equipment~~. Thanks to~~ and CICY for enabling the facilities to run the research.

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.

Comentario [MDJH-253]: Opino q "explored" o "studied" podrían encajar mejor en el contexto de esta oración (incluso en el título).

Comentario [MDJH54]: ¿?

Con formato: Sin Resaltar

Comentario [MDJH-255]: Mayúsc "E" si se trata del planeta tierra. Minúscula "e" si se trata del término tier en general

Comentario [MDJH56]: Es mejor especificar a qué hace referencia el pronombre "they". ¿Es acertado el sustantivo "tunnels"?

Comentario [MDJH57]: ¿"or"?

Comentario [MDJH58]: ¿"the area study?

Comentario [MDJH59]: La frase es contradictoria. ¿Quizás quieren decir "safe from sinking hazards"?

¿O, por el contrario, quizás "vulnerable sinking hazards"

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.

Coskun, 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.

Gutierrez F., Parise M., De Waele J. and Jourde H.: A review on natural and human-induced geohazards and impacts in karst. Earth Science Reviews, 138, 61-88, 2014.

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

Parise M., Ravbar N., Živanovic V., Mikszewski A., Kresic N., Mádl-Szo˝nyi J. and Kukuric N.: Hazards in Karst and Managing Water Resources Quality. Chapter 17 in: Z. Stevanovic (ed.), Karst Aquifers – Characterization and Engineering. Professional Practice in Earth Sciences, 601-687, 2015.

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.

Williams, 2004.

Worthington S.R.H., Ford D.C. and Beddows P.A.: Characteristics of porosity and permeability enhancement in unconfined carbonate aquifers due to the development of dissolutional channel systems. In: Gunay G., Ford D.C., Williams P.W and Johnson K. (Eds.), Present state and future trends of karst studies. Unesco, 13-29, 2001.