Author response to Referee #1

We would like to thank the referee for taking the time to review our manuscript and for providing thoughtful and substantial feedback, which we are sure will help us to substantially improve the manuscript.

In the following, reviewer comments are typeset in black, authors' answers (A) in blue, and planned modifications (M) in green.

Anonymous Referee #1

1 General comments

The present manuscript is a solid compilation of results of geophysical measurements of two karst lakes in Mexico. The paper is well structured and the reader gets detailed insights into the extensive measurements with different geophysical methods. However, the paper strongly reminds of a project report. In my opinion a scientific paper in SE should go beyond a case study (maybe even with a more interesting title?). First, I would like to know more about the authors' motivation why this kind of lakes should be studied. In the introduction it is mentioned that it could be about choosing a suitable drilling location. This is not further discussed in the paper. I lack the approach how these results can be transferred to other locations / problems. On the other hand, the fact that these karst lakes are falling dry is an extremely interesting point. Finally, this offers the geophysicists the possibility to repeat the measurements with a "covered" layer and to verify the results. This could be emphasized much more in the paper. The topic has much more potential to serve not only as a method comparison or case study.

A: Motivation to study this kind of lakes

We agree with the reviewer that besides the mere possibility to test a multi-methodological survey approach for the geophysical investigation of lakes, our motivation to study this kind of lakes remains unclear.

In general, the adaptation of geophysical techniques for the investigation of karst lakes is of relevance, given that ground and surface water in karst areas may react very sensible to even smaller variations of climatic conditions (e.g., precipitation, temperature, etc.). About 10% of the world's continental area is covered by karst and up to one quarter of the earth`s population at least partly depends on drinking water from karst aquifer systems (e.g., Hartmann et al., 2014). Thus, karst water management will be important in the future and require reliable geological information. Where geological drillings are not available to obtain this information directly, geophysical methods have been used successfully to explore the subsurface of karst systems (Bechtel et al., 2007). Karst lakes are often in direct contact with the aquifer via karst conduits, which results in an increased vulnerability of both water bodies. This motivates the search for new, complementary geophysical exploration methods, which can be applied on land and on the water.

At the same time, paleoenvironmental studies, e.g. based on the analysis of lake sediments, can help to better understand the impact of a changing climate on karst systems. By extracting information on past variations from the sedimentary record of lakes, these studies shed light on the local links between climate and availability and quality of water of karst lakes and the connected karst aquifer. In order to obtain a continuous paleoenvironmental record, which goes as far back into the past as possible, the drilling sites for the extraction of lakes sediments have to be carefully selected.

Detailed information on the sedimentary infill of the lakes, in particular on thickness, composition, and possible perturbations, helps to find a suitable location. Thus, a geophysical survey, which is able to provide such information, can greatly contribute to the success of the paleoenvironmental approach.

Field-observations and paleoenvironmental studies from the study area indicate that large seasonal lake-level variations are part of the nature of the lakes and even “catastrophic” events such as the one observed in 2019 might be recurrent (with a period >50 years). Thus, urgent questions in the study area are whether the sudden drainage of 2019 could be linked to recent climate change and whether it is possible that such events will occur more frequently in the future. Besides the ongoing paleoenvironmental investigation, a comprehensive geological picture of the lakes´ geological substructure is essential to discuss possible draining mechanisms and their triggers.

Based on these considerations, the present geophysical study has three main objectives: (1) Determine suitable drilling locations to obtain complete, undisturbed, and far-reaching sedimentary sequences for paleoenvironmental studies, (2) provide basic knowledge on the geological substructure of the lakes (distribution and thickness of sediment cover, distribution of bare limestone rock with possible connectivity with the karst aquifer, etc.), and (3) adapt and test a multi-methodological geophysical approach to achieve the first two objectives.

M: We will include this extended motivation into the revised version of the introduction of our manuscript and clearly state the three main objectives of the survey.

A: Further discuss search for drilling location

After having broadened the scope of the manuscript as sketched above, we will also discuss the selection of drilling sites as well as the geological information provided by the geophysical survey and its implications in more detail.

Based the results discussed so far, the thick (5-6 m according to the SBP image) and apparently undisturbed fine-grained lacustrine sediments along Profile 1 (between 450 and 550 m, as well as between 600 and 700 m) lend themselves for a successful paleolimnological perforation. A perforation at these sites would also have the potential to shed light on the real nature of the second layer and either verify or falsify our interpretation as debris-sediment mixture.

With a thickness of >50 m according to our electrical imaging results, the sedimentary cover along Profile 5 of Lake Tzibaná is thicker than the sediments of Lake Metzabok. However, our results also show that much of these sediments rather correspond to fluvial deposits of the river delta. In this depositional regime, we expect much higher rates of sedimentation, such that the mere sediment thickness does not necessarily imply an older record. In addition, a river delta is a much more complex system, in which sediments can be deposited, eroded, and redeposited repeatedly, which decreases the probability to obtain undistorted sediment records as encountered further offshore.

Or field observations and geophysical results also have implications for the general understanding of the geological setting of the two studied lakes. Obviously, large areas of Lake Metzabok are covered by a layer of fine-grained (clayey) sediments, which – in these areas – is sufficiently thick to act as a hydrological barrier between the lake and the surrounding and underlying karst. However, the remaining heavily fractured and uncovered limestone outcrops effectively connect the lake with the karst system. This conclusion is underscored by the velocity at which the two lakes drained practically simultaneously between February and July 2019. During this time, the water loss amounted to 28,000 m³/day or 0.3 m³/s on average (Matti Altmann, personal communicatioin), which corresponds to the discharge of a large creek (e.g., McManamay and DeRolph, 2018).

While the interconnectivity between surface water and karst aquifer is well documented by field observations and further underpinned by our geophysical results, the actual mechanism as well as the cause of the sudden drainage remain unrevealed. The suddenness of the drainage (onset of discharge in the first days of February derived from satellite-image time series, Altmann, personal communication), indicates that one or more previously clogged karst conduits were unplugged around these dates. Planned time-series analyses of hydrological (e.g., lake water levels from satellite data) and meteorological data (precipitation, temperature, etc.) in combination with paleoenvironmental studies on sediment cores will possibly provide more hints on the mechanism and its triggers, and thus shed light on the question whether the drainage is influenced by climate variations.

M: We will include (and possibly further extend) this discussion in the revised version of our manuscript.

A: Transfer of results to other locations and problems

We consider the discussion of the combined application and interpretation of various geophysical methods on the two karst lakes itself a relevant reference for similar surveys at other locations. However, we agree with the reviewer in so far as the general importance of our findings can be developed in more detail.

M: Reviewer 2 suggested to provide a table that summarizes the used methods, as well as their advantages and limitations. Based on this table and the following key points we will extended our discussion of the general lessons learned for the geophysical investigation of lakes:

- TDIP on lakes: Based on the extended discussion of the IP response of lake sediments encourages by both reviewers, we will discuss further potential applications of this method – in particular for shallow lakes with only a few meters of water column.
- TEM on lakes: In comparison to other floating TEM systems, the one used in this study is extremely light weight, cost-efficient, and quick to assemble. However, in terms of measurement noise and depth of investigation it provides comparable results as obtained using more sophisticated systems (e.g., Yogeshwar et al., 2020). We will compare the characteristics of our system in more detail with those of others in order to underpin this conclusion.
- Combination with seismics: The joint interpretation of electrical and seismic methods showed that combining "standard" seismic methods with electrical data greatly improves the scope of the geophysical investigation. While seismic methods are still the "standard" for the investigation of the sedimentary infill of lakes, our study shows that electrical methods perfectly complement the obtained information by providing hints to the actual composition and hydrological characteristics of seismic units.

A: Emphasize more the fact that lakes fall dry and the positive implications for geophysics

M: As suggested, in the revised version of the manuscript, we will put more emphasis on the positive implications of the drainage for our geophysical investigations. The occurrence of this event has really provided us with a unique opportunity to "repeat" measurements without a removed cover layer of up to 20 m water.

A: Not only method comparison or case study

We agree that study and topic have more potential, which will take advantage of by extending the scope of the manuscript as sketched above.

2 Specific comments

• Chapter 3 deals in great detail with data acquisition and processing. All measurements of the applied wave and potential methods are clearly explained. In this as well as in the chapters 4 and 5 the insufficient signal-to-noise ratio is pointed out for some configurations. However, when evaluating the results, the reader is left in the dark when it comes to quantifying the error influences. This is an issue that urgently needs to be addressed - how much data could be included into the inversion process compared to the amount of measured data. How can the errors of the obtained models be estimated? (Example in line 182 - mean picking percents is ...)

M: We will describe the determination of the measurement error for the TEM, TDIP, and SRT data and include exemplary data and error visualizations in a new appendix. Data quality and its general implications for the depth of investigation will also be discussed in the main text. The model misfit of the final inverted models will be included into the figures showing the imaging results.

TEM. The determination and assessment of the measurement error for the TEM-soundings is discussed in more detail in the answers to the comments of Reviewer 2.

TDIP. As described in the main text of the manuscript, the TDIP data is filtered based on the apparent resistivity and phase data. In a first step, erroneous measurements with apparent resistivity values ≤ 0 Ωm and/or apparent phase values ≤ 0 mrad are removed. Based on the visual assessment of the raw data pseudo sections (see Figure R1.1 for an example), in a second filtering step, measurements with apparent phase values > 8 mrad are removed as further outliers. The selection of the upper limit of 8 mrad for the apparent phase values is based on the observation of a narrow distribution of “physically meaningful” phase values in the apparent-phase histograms (see Figure R1.1). In the case of the second part of the roll-along profile 1 of Lake Metzabok, this filtering results in a reduction of the TDIP data set to 57% of the original data set. This loss of data is related to a relatively poor data quality of the phase measurements along this long line (470 m length, 10 m electrode spacing) and is expected to significantly reduce the depth of investigation of the phase images. Data sets of shorter profiles with a reduced electrode spacing (5 m in the case of profiles 2-5) are less affected by phase noise, which results in a higher percentage of useful data (up to ~88% in the case of Profile 3 of Lake Metzabok.

In the revised version of our manuscript, we will include an exemplary TDIP data set (in the new appendix) and provide information on the percentage of useful data as well as the individual model misfits (in terms of the RMS error) of all resistivity and phase images. In the main text, we will briefly discuss the effect of individual data quality on the depth of investigation of each image.

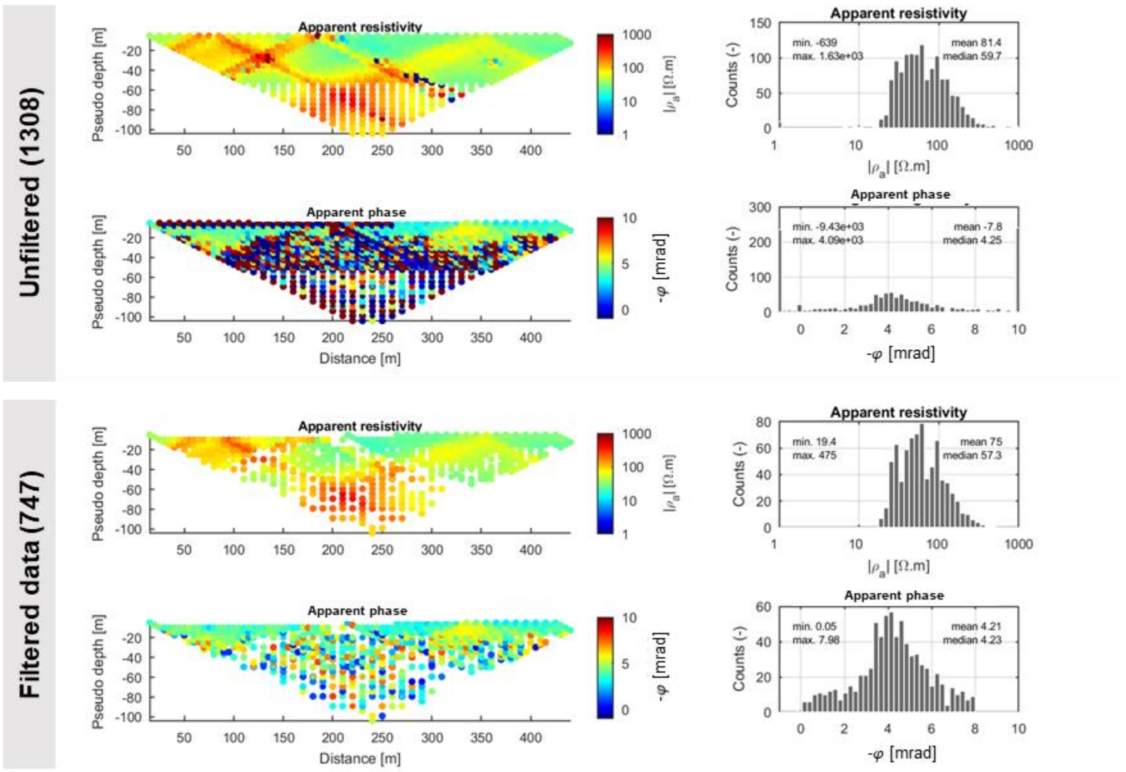

Figure R1.1. *Apparent resistivity and apparent phase pseudo sections (left column) and histograms (right column). The first two lines show unfiltered raw data set consisting of 1308 measurements, the last two lines show the remaining data after the application of the filters described in the main text (747 measurements).*

SRT. In order to provide more detail on the data quality of the SRT measurements, in the new appendix, we will provide exemplary visualizations of first-arrival picks for one relatively clean and one relatively noisy measurement. Collected with 24 geophones and 25 shot positions, each tomographic data set consists of a total of 600 seismic traces. The picking percentage reflects the number of traces, for which a first arrival can be identified, and serves as a measure for data quality. Figure R1.2a shows data and travel time curves for Profile 2 and Profile 4 of Lake Metzabok. A low data quality of Profile 2 data results in a low picking percentage (341 out of a total of 600 traces) and mainly affects long-offset data reducing the expected depth of investigation. In comparison, the SRT data collected along Profile 4 is much cleaner (552 out of 600 traces), which results in a larger depth of exploration.

In the revised version of out manuscript, we will include exemplary SRT data and travel-time curves (in the new appendix) and provide information on picking percentages for all SRT profiles. We will also provide information on the individual model misfits (in terms of the RMS error) of the inverted velocity images. In the main text, we will link the depth of investigation of the individual images to the data quality (i.e., the picking percentage).

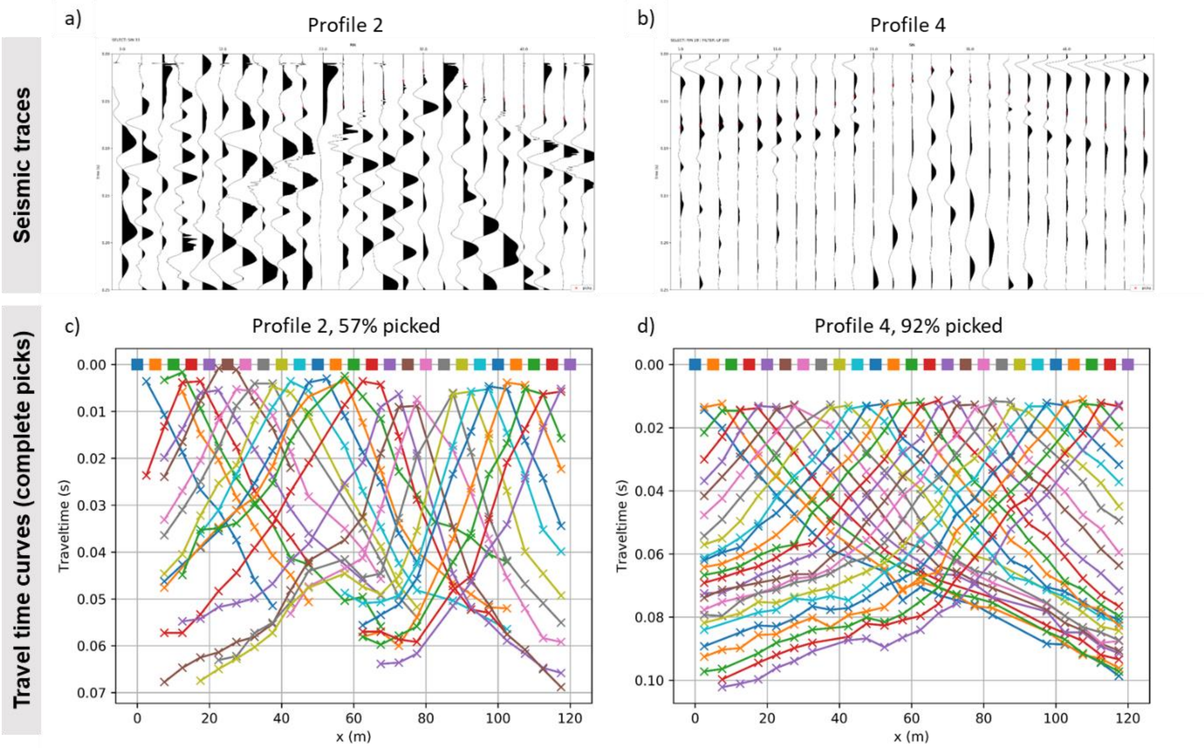

Figure R1.2. *Exemplary SRT data from (a) the noisy Profile 2 and (b) the relatively clean Profile 4. As a result of data quality, the (c) travel-time curves of Profile 2 (picking percentage of 57%) are much less populated than those of (d) Profile 4 (92% picked). Also note the different scaling of the vertical axes (0.07 s in the left panel and >0.1 s in the right panel).*

• Is it possible that sample TSI19-A is influenced by higher limestone content? This would support the latter interpretation of field measurement results.

A: A more detailed laboratory analysis of the sediment samples is still underway. Thus, we have not yet been able to understand the obvious deviation of the TDIP response of sample TSI19-A.

Preliminary results do not indicate a different mineralogical composition of sample TSI19-A compared to the rest of the samples. X-ray powder diffraction analyses show similar concentrations of dolomite (calcium magnesium carbonate) and calcite (calcium carbonate) in all six samples. However, the geochemical analysis does show a significantly increased total organic carbon (TOC) and carbon-to-nitrogen ratio (C/N) of the sample TSI19-A compared to the other five samples. Together, the high levels of these two parameters point to a larger fraction of organic matter from terrestrial sources (i.e., land-based plants), while the smaller amount of organic matter of the other five samples probably stems from algal plants.

Both samples TSI19-A and TSI19-B were collected on the exposed delta of the Nahá river. However, the location TSI19-A seems to have received more fluvial deposits due to its position closer to the estuary of the river, while location TSI19-B corresponds to a residual body water (i.e., in a predominantly aquatic environment) situated within the delta. In fact, in Figure 9, we can see that TSI19-A is located on the northernmost extension of the unit labelled as fluvial deposits, while TSI19-B is located in a (partly water-filled) depression underlain by the fine-grained (clayey) lake sediments. Thus the deviation of the TDIP response of sample TSI19-A is rather linked to the source of the sediment (fluvial vs. lacustrine) than to its mineralogical composition (e.g., limestone content) as might be assumed based in the TDIP field survey, where particularly higher phase responses can be related to the limestone bedrock.

M: We will include a brief summary of this discussion into the revised manuscript in order to make clear that the higher phase and resistivity values of the sample TSI19-A are rather related to the depositional regime than the limestone content.

• In Line 214 ff. you mentioned underlain collapsed blocks - did you see some hints after the lakes are fallen dry?

A: The following pictures of the (few) uncovered limestone outcrops show both highly fractured limestone as well as limestone debris. However, the presence of limestone debris below the (thick) sediment cover has not been validated independently in the field.

Figure R.1. Photographs of the limestone outcrops of Lake Metzabok. a) Debris-covered limestone outcrop, b) close-up of limestone debris, and c) highly fractured limestone outcrop.

Thus, the underlying collapsed bedrock is clearly an interpretation, which is solely based on (i) a reasonable conceptual model of the evolution of the lakes from collapsed bedrock and (ii) the layered resistivity structure below the flat sediment-filled parts of lake Metzabok (pure sediments, sediment-debris mixture, bedrock).

M: We will include an additional Figure (similar to Figure R.1) showing superficial expressions of the interpreted geological units, in particular the limestone debris and the fractured limestone, in section "4.2.5 Geological interpretation of the geophysical survey on Lake Metzabok".

• Line 229 and Fig. 4f: you do not interpret phase values for depth gt 50 m (due to insufficient data quality, ok - see first comment in list!), but than you should avoid to show this part of inversion model - it is more than the half of the picture!

M: We will reduce the maximum depth of these images (Figures 4f and 4g) to about 70 m.

• I am amazed by the variety of methods and the integrative approach for this survey. Only the complementary methods produce a comprehensive geological model. I would not use chapter 5.3 as a confrontation of methods (title: seismic vs electrical methods) but rather promote these complementary techniques as a great advantage, the usage of the methods depends on the given situation and problem!

M: We will reformulate the main points of chapter 5.3 in this sense and, as suggested by the reviewer, include a discussion of the advantage of using complementary methods and data.

• Chapter conclusion should pick up some information from the introduction and give a broader (more general) summary at the end - how about the drilling, what is the take home message?

M: As suggested, we will give a broader and more general summary in the conclusions section of the revised manuscript. In particular, we will include conclusive statements regarding the findings with respect to a more general geological interpretation connecting the two studied lakes (also suggested by the second reviewer), the selection of drilling locations for paleoenvironmental studies, and the implications of our results for other locations and problems.

3 Technical Corrections

The pictures are generally of very good quality. Sometimes it is a bit confusing to recognize the correct position of the subprofiles (There are also different names for one and the same profile - to much information: example profile 1 aka L4NS aka MET19-1 MET19-2). Especially in Figure 5 it would help to use the same coordinates as in figure 4 (even if the profiles have an 10 m offset in EW direction). In Figure 4 the TDEM is slightly shifted in comparison to SBP.

M: We will reduce the names indicated in the figures to the profile names (i.e., Profile 1 through 5) and remove the labels referring to the IDs of the data set published along with the manuscript (e.g., L4NS, MET19-1, etc.).

In the revised version of the manuscript, in Figure 5, we will use the same coordinates as in Figure 4.

The TDIP images in Figures 4f and 4g have an offset of about 25 m with respect to the SBP profile in Figure 4e. We will add a dotted rectangle into Figure 4e (and a brief explanation in the caption) in order to indicate the position of the TDIP profile with respect to the SBP image.

Additional references

Bechtel, T., Bosch, F., & Gurk, M. (2007), Geophysical methods in karst hydrogeology, in: Methods in Karst Hydrogeology, edited by N. Goldscheider and D. Drew, pp. 171–199, Taylor and Francis/Balkema, London, U. K.

Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., & Weiler, M. (2014). Karst water resources in a changing world: Review of hydrological modeling approaches. Reviews of Geophysics, 52(3), 218-242.

McManamay, R. A., & DeRolph, C. R. (2019). A stream classification system for the conterminous United States. Scientific data, 6, 190017.