Author response to Referee #2 (Pritam Yogeshwar, University of Cologne)

Thank you, Pritam, for taking your time to review our manuscript and for your detailed and constructive feedback – especially on the TEM method – which we will surely help us to improve the manuscript a lot!

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

Pritam Yogeshwar (Referee)

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1. General Comments

I have carefully and interestingly read and reviewed the manuscript (MS). The authors present an interesting multi-method case study on two lakes in Mexico using water borne geophysics. Especially the sudden lake water level drop as well as the application of multiple methods are highlights of this study. The results are very well prepared and technically on a high level. Besides my positive impression, there are a few points to be addressed.

The authors present studies on two lakes - Metzabok and Tzibana. If feasible, I suggest to incorporate some more general discussion on how these lakes are connected. Are there any general conclusions/interpretations that apply to both lakes or is it even possible to connect the subsurface structure? For example, there is no clay interpreted in lake Metzabok whereas major parts of the subsurface in lake Tzibana is related to clay rich sediments.

A: We agree. Resulting from the very limited information provided on Lake Tzibaná, it does not become clear, how the two neighboring lakes are connected. Figure R2.1 shows the result of one long SBP transect crossing Lake Tzibaná and the delta of the Nahá river from North to South. From this line, it becomes clear that outside the delta with it sandy sediments, the deeper part of Lake Tzibaná shows a similar geology as Lake Metzabok (flat sediment-covered lake bottom). However, the flat parts of Lake Tzibaná, which are expected to be more comparable with Metzabok, are much deeper than Metzabok and were also not accessible (still water covered) during the second field season, such that no additional data could be collected directly on the lake bottom.

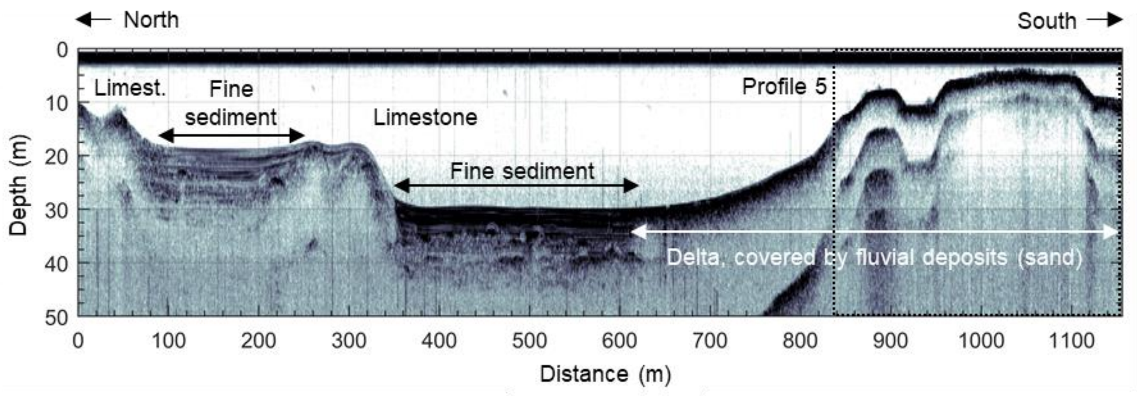

Figure R2.1. *Long SBP profile crossing Lake Tzibaná from North to South. The last ~400 m roughly coincide with the position of Profile 5 (indicated by dotted rectangle). Below the sandy delta* *sediments, no further reflectors can be observed. As in the case of Lake Metzabok, also the flat zones of Lake Tzibaná are covered by an at least 5 m thick layer of (fine-grained) lake sediment.*

M: We will include this SBP profile in the revised version of the manuscript and provide a more complete discussion of the common features and differences between the two studied lakes.

It is not easy to find a red line in the MS. This is partly due to the fact that all profiles on lake Metzabok are discussed one by one. And, subsequently the results for lake Tzibana are shown. I suggest to strengthen the explicit motivation why both studies were performed. Possibly a road-map can be formulated indicating why which method was used and how the survey was designed to address the scientific questions. As I understand the study aims at few aspects (1) detect depth to bedrock (2) understand sudden lake level drop and related subsurface conditions such as Karst collapse and (3) combined interpretation of various methods (especially TD-IP phase data evaluation for the first time in sedimentary studies).

A: We agree. The focus of the manuscript in its current form is the comparison of methods, which is developed and discussed step by step along the profiles. Both received reviews demand for a broadening of the scope by improving the description of the more general scientific motivation and the inclusion of a more rigorous geological/hydrogeological contextualization. In our response to reviewer 1, we develop concrete idea of how to respond to this suggestion, which also includes a "road-map", which is similar to the one suggested here.

I suggest to elaborate more on the benefit of using TD-IP and evaluating the phase data for the two lake studies, since this is not very common. If feasible elaborate more in detail how the phase data relates to subsurface physical properties in general.

A: We also see the benefit of discussing the IP response of lake sediments in more detail.

M: Motivated by the question of Reviewer 1, whether the sample TSI19-A might contain a larger fraction of limestone, we will extend our discussion of the IP response of lake sediments in the results and interpretation section and possibly include selected geochemical laboratory data for this purpose. Based on this discussion, we will also be able to draw some (preliminary) conclusions regarding the possible contribution of IP data for the study of lakes and lake sediments.

2. Specific comments

• I understand that the focus is on the geoscientific interpretation using a multidisciplinary approach. However, I do miss some technical aspects of the study with respect to method and inversion. For example, some typical survey parameters (e.g. anchored or continuous TEM system; typical measurement errors).

A: We recognize that we might have overshot the target of providing very brief descriptions of the various methods used in this multi-method survey. In the following, we provide some additional information on the TEM measurement setup and the inversion approach.

During the survey, the TEM system was towed from station to station. The electromotor of the rubber boat was only used for navigation between sounding locations and remained turned off during the measurements themselves. Because we did not use any anchors, depending on the wind conditions at the sounding sites, the loop slowly drifted during the measurements resulting in maximum estimated displacements of 1 – 2 times the loop diameter (i.e., ~40 m).

For the transient length of 1024 µs used for our measurements, the TEM-FAST48 records 64 transients, which are analogously averaged by the hardware. For one sounding measurement, this basic measuring cycle is repeated $n \times 13$ times. For $n = 4$ (our measurements), this results in 52 repetitions of the basic cycle (and a total of 3328 effective stacks), which are used to compute the impulse response by digital averaging and to determine the measurement error as the standard error of the mean (SEM). As the exemplary data in Figure R2.2 shows, for the latest time gates used for the inversion (around 200 µs), the SEM is $\lesssim 2 \cdot 10^{-6}$ V/A (or $\lesssim 5 \cdot 10^{-9}$ V/Am²).

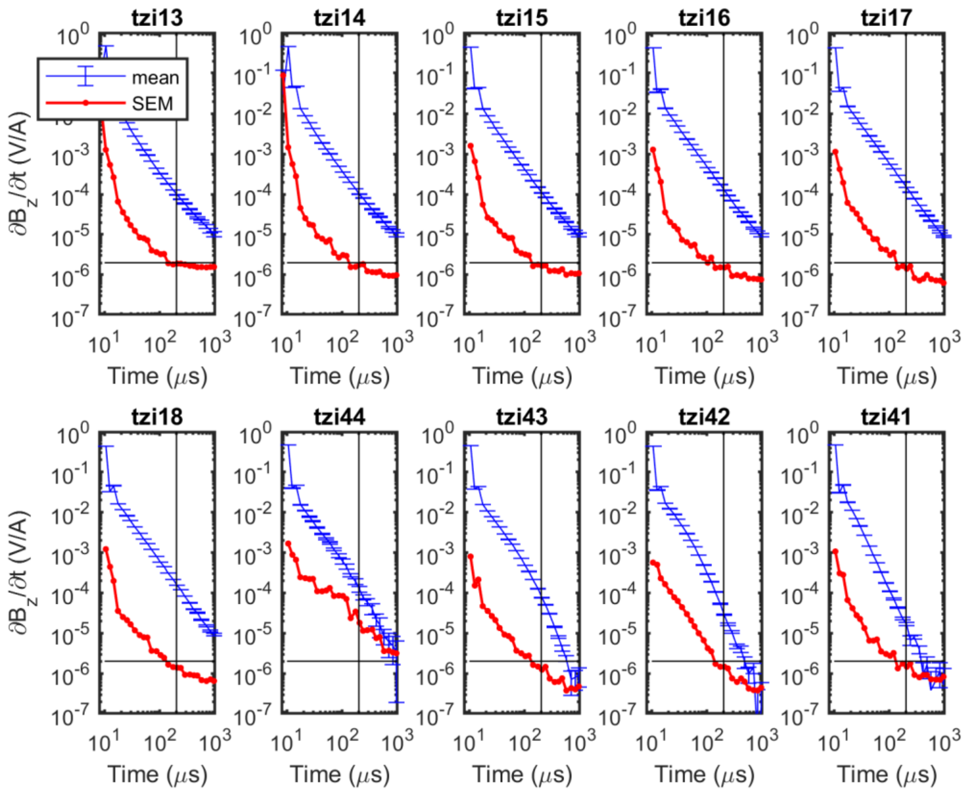

Figure R2.2. *Exemplary TEM transient impulse response data of the TEM soundings along Profile 5 of Lake Tzibaná. The mean values of the stacked signal per time gate are shown in blue, the standard error of the mean is given in terms of error bars of the blue curves and separately in terms of the red curves. Black lines indicate the relatively constant late-time error level of* $2 \cdot 10^{-6}$ *V/A (horizontal line) at 200 µs (vertical line).*

We use the conventional 1D smoothness-constraint inversion approach implemented in the software ZondTEM1d (Kaminsky, personal communication) to interpret the TEM soundings. The software supports arbitrary shaped loops, the vertices of which can be defined independently for transmitter and receiver. This warrants a correct interpretation of our coincident loop transient data. While our measurements were carried out with a circular loop (transmitter and receiver) of 22.9 m diameter (area 412 m²), we use a square loop of equal area (20.4 m x 20.4 m) in the inversion.

M: We will add (at least) the above listed details on the TEM data and inversion to the methods sections and an additional appendix, which is to be included in the revised manuscript.

Moreover, there is currently no data visualized (Only the TD-IP lab data). I suggest to include a section with data, and possibly also with inversion model response (If feasible, for example in an appendix). Of course this should not distract from the study itself.

A: We see the importance of including visualizations of exemplary data and inversion model responses (as an appendix) in order to allow the interested reader to quickly gain an impression of data quality and inversion model fits. Besides this new appendix, all data, inverted models and computed responses will still be available from the open data repository and can be revised there in detail.

M: We will add an appendix to show exemplary data and inversion model responses for TEM, TDIP, and SRT measurements.

• From my experience, the TEMfast device sometimes shows significant distortions using small loop configurations. Did you observe any data distortions especially since a very small configurations was used? And, did you for example compare some land based soundings using a larger transmitter to validate that the very small layout gives correct transient data? In this respect, I also suggest to show at least some data.

A: Figure R2.3 shows measured and calculated apparent resistivity curves of the 10 soundings along TEM profile 5 of Lake Tzibaná (smooth resistivity models shown in Figure 9 of the manuscript). The measured curves are well recovered by the inverted models and do not show any conspicuous features, which would point to a distortion (e.g., due to the small loop configuration).

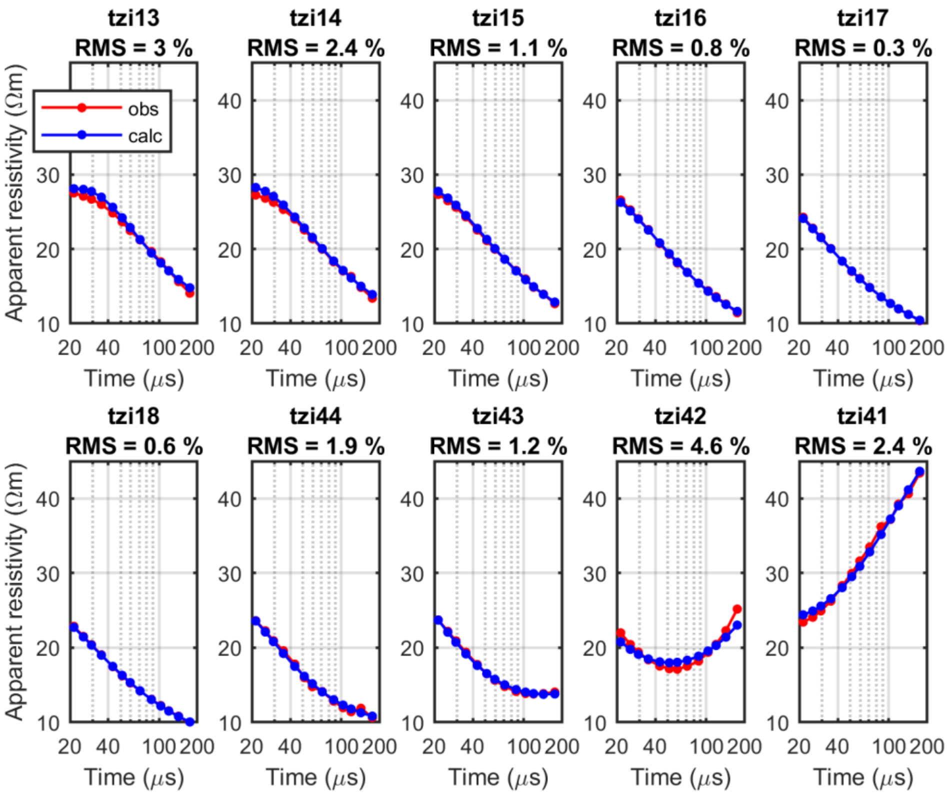

Figure R2.3. *Observed (red) and calculated (blue) apparent resistivity curves of the TEM soundings of Profile 5 of Lake Tzibaná. The corresponding root-mean-square errors of the model fit are indicated, too. The inverted models (smooth models with 20 layers) are visualized in Figure 9 of the manuscript.*

We have not carried out test measurements with different loop sizes during the field work in Mexico. But we do have some test measurements at different locations in Europe: Figure R2.4 shows the impulse responses for single-loop measurements with 4 different sizes of the square loop (6, 12, 25, and 50 m). For times >10 µs, all loop sizes result in consistent transients without conspicuous distortions. In particular, the same applied for the uniform time window between 20 and 200 µs, to which our transients from the Mexican lakes were truncated. It is worth mentioning that the average resistivity of the test location (approx. 120 Ωm across the first 50 m) is slightly larger than the average resistivity in the lake environment (20-30 Ωm). However, from our own practical experience, distortions due to small loop sizes rather decrease when the ground is more conductive.

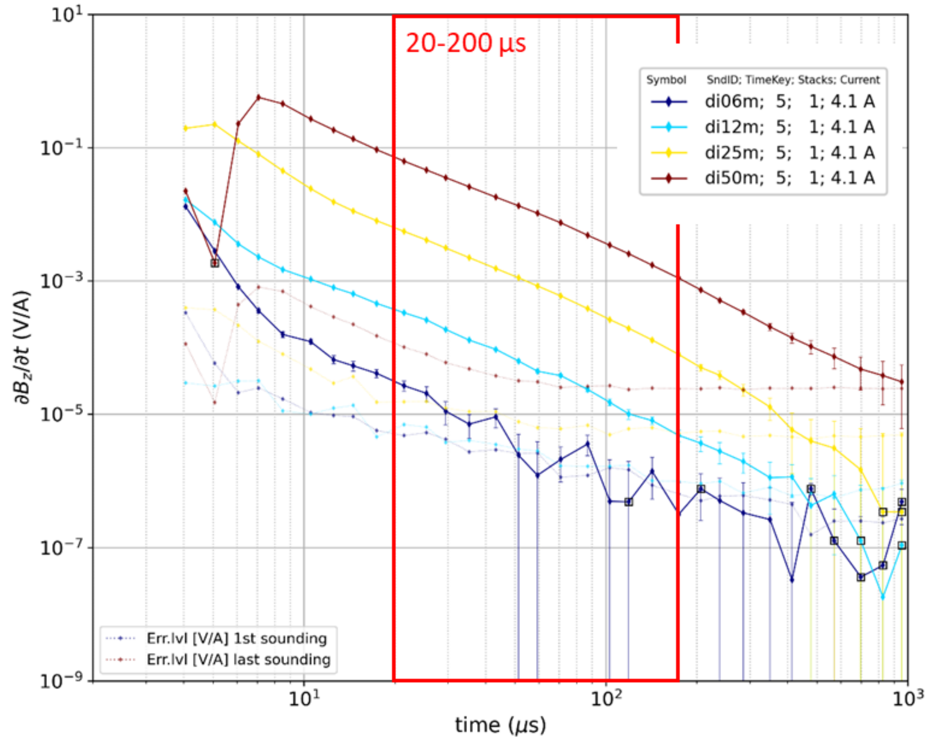

Figure R2.4. *Impulse response of a single-loop configuration using a TEMfast device at a side with an average resistivity of 120 Ωm across the uppermost 50 m (Donau Island, Vienna, Austria). The solid lines show the impulse responses for square loops with side lengths of 6 m (dark blue), 12 m (light blue), 25 m (yellow), and 50 m (brown). The dotted lines show the corresponding error levels (determined as the standard deviations of the repeated measurements). The red rectangle highlights the time window between 20 – 200 µs, to which the transients of our study at the Mexican lakes were truncated uniformly.*

M: We will add a short comment on possible distortions due to small loop configurations and shortly discuss the (probable) absence of such adverse effects in our data set. As announced above, we will add an appendix to show exemplary data and inversion model responses for TEM measurement. This will allow the reader to follow this discussion and to visually assess the data quality.

We are not planning to include the above test measurements with different loop sizes in order to avoid overloading the manuscript.

• A conductor is indicated below the limestone towards the east in Fig. 7a. Please discuss this feature if it can be related to any geology such as fracture zones or if this is an artifact (probably related to distorted late time transient data). A slightly similar feature is also seen in Fig. 9 towards the south.

A: Unfortunately, both conducting features (Figures 7a and 9a) are located at the very ends of the TEM lines, which are not covered by the collocated TDIP profiles. In addition, geological reference data, such as detailed maps or even drillings, is not available for these depths. Thus, we do not have any control on the nature of these features, i.e., we cannot decide whether they reflect a geological feature (e.g., a fracture zone or a more conductive claystone unit) or arise from distorted late time data.

M: We will include a discussion of this issue into the revised version of the manuscript.

• Does the ZOND software actually invert for coincident loop or for a central loop receiver? For very early times the central loop transients differ from coincident loop data.

A: In order to be sure, we have checked this detail with the author of the code (Alex Kaminsky, zondgeo@gmail.com). His response can be summarized as follows: The software ZondTEM1d supports any arbitrary shaped loops, the vertices of which can be defined independently. The response is calculated as the integral along the transmitter loop path, i.e., the transmitter loop is implemented as a set of directed electrical dipoles. The same applied to the receiver loop, where the response (Bz) is integrated over the exact area of the receiver area.

M: We will briefly mention this detail in the methods section.

• The TEM data might be effected by 2D effects especially considering rather steep slope angles towards the edges. possibly include some discussion such as “multidimensional effects in TEM data were not considered as the TEM survey lines were not along strong bathymetry or steep slopes”.

A: We are aware of the possible problems of multidimensionality can cause in the 1D interpretation of TEM soundings on lakes with steep bathymetry gradients (see, e.g., the extensive discussion of this issue provided by Mollidor et al., 2013). As you mention, the variation of the bathymetry along the lines shown here is relatively slight, which implies that this type of problem will probably not be of great relevance here. The assumption of onedimensionality might be more problematic at sounding sites located close to the lake shore.

M: We will include a corresponding discussion in the methods section and come back to this topic in the discussion of the two profiles with TEM results to confirm that the bathymetry varies softly along both lines and the assumption of onedimensionality is suitable, here.

• P315 - Obviously the p-wave velocity is less than expected. Can you elaborate why a lower vp < 2000 m/s was observed in the SRT measurements.

A: Possibly a misunderstanding? The depth of investigation of this SRT line (approx. 40 m below the water table of March 2018) is less than the depth of the surface of the limestone bedrock inferred from the TDIP resistivity section (> 40 m). Thus, the p-wave velocity at the lower limit of the SRT image is not lower than expected but lower than the typical p-wave velocity in the limestone unit.

M: We substitute the formulation “expected for limestone bedrock” by “typical for the limestone bedrock” to prevent this misunderstanding to happen.

• P350 - I suggest to include a table that summarizes the specifications of each method such as resolved physical parameter, DOI, pro/con of each method. Such a table would also summarize the used methods a bit and emphasize the integrative approach.

M: We like this idea very much and will include such a table to summarize the scope and limitation of all 4 field methods, i.e. SBP, TEM, TDIP, SRT.

• P-365 - For TEM a water-depth of 20 m depending on the water conductivity is not necessarily a limitation. Please correct this statement.

A: We fully agree: Due to the maximum water level reduction of about 20 m (from March 2018 to October 2019), we were only able to collect additional data on the dry lake floor at locations with less than 20 m of water column during our water-borne measurement campaign. This is the water depth down to which we were able to have a direct comparison of water-borne TEM data and terrestrial TDIP data. Of course, this does not imply that the system does not also work in deeper water.

M: We will add the following sentence to prevent possible misunderstandings: "Furthermore, there is no reason to assume that the system should not work as well in even deeper (>20 m) water depending on the water conductivity."

• For all interpretation a smoothness constraint inversion is used. Do you expect a smooth transition from the sedimentary layers to the limestone. In this respect, is a smoothness constraint inversion appropriate to image the geological situation here?

A: Actually, we have been thinking about including seismic contacts (from SBP images) as a-priori information (geometric constraints) into the TDIP and SRT inversion process. However, we decided not to further pursue this approach as we consider it more conclusive to have various methods confirming similar structures without "forcing" geometries to coincide by using constraints in the inversions.

While we do not see any real alternative to a smooth inversion of our 2D data sets (i.e., TDIP and SRT), we do agree that it is not as straight forward to only discuss the results of a smoothness constrained approach for the TEM inversion. Here, the decision to only show the smooth models was motivated by facilitating the intended comparison with the (smooth) TDIP resistivity images.

In addition, there is no simple answer to the question whether we expect a sharp resistivity contrasts between the main lithological units, i.e.., sediment cover and limestone, or not. As our interpretation of the Metzabok data suggests, within the mixed layer (sediment and limestone debris/heavily fractured limestone) there might well be a rather smooth transition as a result of a continuously increasing volume content of limestone with depth. The same is true for the contacts between the different sedimentary units (fine-grained lake sediments/sandy delta deposits), which we expect to be rather gradual, too.

M: We will include some layered models in the new appendix and provide a more detailed discussion of the selection of the inversion approach in the revised version of our manuscript.

• As water-borne TEM studies are still quite rare, I miss some references to recent water borne TEM studies. For example, we recently applied boat-towed TEM to image a hydrothermal target on the Azores. In this study we gathered around 600 soundings using the TEM system (initially developed by Mollidor et al.) in a continuous mode. There are also other very recent studies. These can be included as references, if the authors find them suitable:

- Yogeshwar, P., Küpper, M., Tezkan, B., Rath, V., Kiyan, D., Byrdina, S., ... & Viveiros, F. (2020). Innovative boat-towed transient electromagnetics Investigation of the Furnas volcanic lake hydrothermal system, Azores. Geophysics, 85(2), E41-E56.

- Lane Jr, J. W., Briggs, M. A., Maurya, P. K., White, E. A., Pedersen, J. B., Auken, E., ... & Adams, R. (2020). Characterizing the diverse hydrogeology underlying rivers and estuaries using new floating transient electromagnetic methodology. Science of The Total Environment, 140074.

A: Thanks a lot for the hint! We missed these very recent studies. They are more than relevant.

M: We will update the state-of-the-art part on boat-towed TEM devices in the introduction by including these additional references.

3. Technical corrections

The MS is very well written and the language is very good. All figures are well prepared with well readable fonts. Therefore, I only have a few technical corrections:

• P70 - the term reference data is misleading. I do not see that the data is actually used as reference data. Better - “additional/complementary data for comparison with the water borne data”

M: We will replace the term “reference data” by “additional data”.

• Please check that all abbreviations are defined, e.g. ERT etc.

A: We have checked the abbreviations. Besides the undefined abbreviation ERT (line 77 and in the caption of Figure 6), we have not found any additional problems with undefined abbreviations.

M: We will replace the term “ERT results” in line 77 by “TDIP resistivity results” and the term “ERT/IP data” in the caption of Figure 6 by “TDIP resistivity and phase data”.

• P140 - explain or remove the skip parameters (skip-1 skip-2 etc.)

M: We will remove the skip parameters specified between the brackets.