Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2019-540-AC2, 2020

Hydrology and Earth System Sciences
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Discussions

Interactive comment on "Combining resistivity and frequency domain electromagnetic methods to investigate submarine groundwater discharge (SGD) in the littoral zone" *by* Marieke Paepen et al.

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Received and published: 30 March 2020

We thank the reviewer for his/her constructive comments. We understand that most of them are related to the interpretation of geophysical data for non-expert. We will try to clarify those as much as possible, but we cannot provide a comprehensive overview of geophysical method within a single paper of limited length. Below, our responses are indicated with "» «".

Abstract

Page 1 lines 18-24: This may be reduced/deleted as it is not really necessary and

lengthens the abstract unnecessarily.

» The fact that we use the robust apparent conductivity obtained by FDEM is a novelty in the research of coastal hydrogeology, it is therefore highlighted it in the abstract. But we will reduce this section. «

Introduction

Page 2 lines 17-34: As for non-geophysicists, it is extremely difficult to comprehend the suitability of each method for SGD detection as neither the method itself nor its potential/limitations are known. Listing them certainly shows that the authors have done a marvellous job in literature research, but it may be more advisable, for the sake of clarity, to spend some words on the methods in a general fashion (vertical resolution, drawbacks, uncertainties in the context of SGD) allowing the reader to better understand.

» Thank you for giving us insight from the perspective of a non-geophysicist. We try to give an overview of the previous uses of geophysics in this context, in order to show how our new methodology fills the gaps. We will try to summarize those studies to better underline their potential and limitations (e.g. resolution). It is however not our intention to provide basic details on the uses of these methods in the introduction as this strongly depends on the design of the system, we let this description to the methodology section. «

Methodology

3.1.3 Processing (electrical resistivity): If I understand correct, the authors did not apply any ground truth data (neither bathymetry, nor any drillings) to invert the raw ERT signals. Instead the three inversions are based on subjective thresholds?

» Bathymetry and seawater conductivity were acquired simultaneously to CRP (page 6 lines 2-3), these are important in the inversion of the marine ERT data because they strongly influence current flow paths in the subsurface. The measured bathymetry is fixed during the inversion while the conductivity of the water layer is introduced as a reference value. The inversion can thus slightly deviate from this reference. It is not advised to fix it, because it can create artifacts in the inverted model. Due to logistical limitation no drillings are available on the beach and at sea (only in the dune). Those are not used for inversion but just for validation. The inversion stops based on convergence criteria typical for ERT applications. «

If so, and all results are based on relative terms, I would urge the authors (I raised a similar request during the results and discussion session), to clearly state (possibly in a separate subsection), which of the results can be stated with certainty given all uncertainties and relative terms/subjectivity.

» The assessment of the quality of a geophysical image is a very important research topic. It is important to understand that the inversion acts as a filter which tends to blur the image, so that the inverted resistivity is only an estimation of the true resistivity. For this reason, it is impossible to link an inverted resistivity value to a specific value of the salinity. However, in this case, we have two well identified extremes (freshwater in the dunes and seawater), together with a petrophysical model (Lebbe, 1978, 1999), so that we can interpret semi-quantitatively the variations of resistivity in terms of salinity classes. To validate the reliability of the inversion models, we show both the DOI and different inversions with/without reference models (figure 8). The DOI is an image appraisal tool used to indicate which portions of the image can be interpreted. If we impose different reference models during inversion, the observed patterns and resistivities in most zones (figure 8, e.g. A1 vs. A2 and A2 vs. A3) remain similar. This indicates that the resistivity structure are driven by the data and yield to low DOI value. Our DOI images show relatively low values everywhere, indicating we can trust the relative resistivity variations which occur in the subsurface. But we are careful in interpreting zones with a higher DOI (higher uncertainty). Both dedicated section of the manuscript will be modified to clarify those important points. «

Page 7 line 9: What does that mean? DOI <0.1 are more reliable than 0.2? Please

add this information and how the readers should interpret figures with DOI.

» The DOI is a widely used image appraisal tool in geophysics, this is why we did not add the corresponding equation. It is calculated as DOI=|log(rho(inv,1))-log(rho(inv,2))| / |log(rho(ref,1))-log(rho(ref,2))|. Where rho(inv) and rho(ref) are the inverted and reference resistivity. The logarithm of resistivity is used because it is the parameter inverted for. The higher the DOI, the more different are the results of two inversions and the less robust the ERT inversion results are. A threshold of 0.1 or 0.2 is commonly used by other authors, but this is subjective. Which is why we are showing both inversion results. More information will be provided on how to calculate the DOI and interpret figure 8. For additional information on the DOI, we also refer to Oldenburg, D.W., and Li, Y. 1999 [Estimating depth of investigation in dc resistivity and IP surveys, Geophysics, 64(2), 403-416, https://doi.org/10.1190/1.1444545] and others.

Page 7 line 25: Later on (pg10 L32) it is mounted on a sled. Please be consistent.

» It is actually mounted on a sled which is towed by a quad, this will be modified. «

Results and discussion

Page 8 lines 10-11: Why is TDS a topic here? It was never before mentioned. I suggest to remove it and to introduce section 4 differently.

» We agree with the reviewer and the result section should start with another sentence. The TDS is relevant because resistivity is only a proxy for the salinity, this section will therefore be transferred to the methodology. In this area, we have a good estimation of the formation factor of Archie's law (Lebbe, 1978), so resistivity can be interpreted as water salinity at the condition that the inversion models are sufficiently accurate. But the influence of inversion does not allow for quantitative interpretation in every zone. We know that some zones of the inverted image are less well resolved (they experience more smoothing, see also our answer below), meaning that some zones in the models indicated as brackish might be more salty or fresher. We will better clarify that the water quality classes deduced from the models only give an estimation of the pore water quality. We will also specify the petrophysical relationship used to derive the classes (Archie's law for our study site). «

Page 8 lines 26-27: The entire text is hard to read and understand others than geophysicists as it is always difficult to interpret resistivity/ conductivity in light of complex and dynamic environments. Nevertheless, I am convinced the geophysics can help shedding light on SGD occurrence on a larger scale and even in the vertical dimension, which other methods cannot. To this end, it would be beneficial, if the authors can add more information to the figures (k1, where is pot. SGD, add a second color bar with likelihood of SGD instead of only resistivity/conductivity) to increase the instantaneous understanding.

» Thanks for this suggestion. Locations of (potential) fresh SGD will be highlighted on the figures. «

Page 9 lines 2-7: I encourage the authors to add all important terms (clay lens, saltwater lens, fresher water, freshwater) into to figure (Fig. 4) to clarify what they are referring to. Without knowing which values belong to which water component it is difficult to understand.

» Thanks for this suggestion. These terms will be added to the ERT and CRP profiles. «

Page 9 lines 20: Again, provided figures do not allow to follow the argumentation. Where is the low water line in Fig. 4 Please consider extensive improvements concerning the naming of terms in the figures to facilitate reading/understanding.

» Thanks for this suggestion. The low water line will be added as a reference point (0m) on the figures with the land and marine cross-sections. «

Page 9 lines 21-22: Why is that? What prove do the authors have to state such a process-based argument from mono-temporal recordings?

» We agree with the reviewer that this statement cannot be made from geophysical data only. We are biased by our overall knowledge of the process occurring here. We will rephrase "but the brackish groundwater is clearly pushed upwards" to "but the brackish groundwater is found relatively close to the seabed". «

Page 9 lines 31-32: This sentence perfectly proves what I stated before. Some of the statements given by the authors are pure assumptions when uncertainties are considered such as the different vertical resolutions and heterogeneities that influence that resolution. I would urge the authors to critically review the results in light of SGD detection. The main questions must be, what are the findings related to SGD that have a definitive certainty? (considering e.g. the multiplicity of methods with "same" result)

» We do not completely agree. These are not pure assumptions but interpretation accounting for the known limitations of inversion. This concept can be illustrated with a simple theoretical case. We start with a simple subsurface model which has four different resistivities, 0.5 (salt water), 5 (clay layer), 50 (fresh groundwater), and 500 Ωm (unsaturated zone in the dunes) mimicking the situation encountered on our site (Figure 1_this_document, bottom). Forward modelling is applied by using RES2DMOD, simulating field data acquisition for this model. We obtain the following apparent resistivity pseudo-section (= data set) (Figure 1_this_document, top). Next, we process and invert the forward model exactly as we do our field data. The following inversion model is obtained (Figure 2_this_document, bottom). Here, you can clearly see that the zone in which there should be freshwater (see theoretical model) is not completely uniform because of smoothing. Since the resistivity is lowest where the saltwater lens is thickest. And this is exactly what was observed on profiles K1 and K0 (Figures 3 and 4_this_document). We will refer to Hermans & Paepen. "Combined inversion of land and marine electrical resistivity tomography for submarine groundwater discharge and saltwater intrusion characterization." Geophysical Research Letters (2020): e2019GL085877 where such a synthetic case is presented for more information. «

Page 10 lines 4-5: This line reads somewhat strange. Please consider a rewording/restructuring of the sentence.

». We'll rephrase it to: "since the groundwater system is least affected by anthropogenic effects in this part of the study area". «

Page 10 line 6: I assume the authors means salty, do they?

» Indeed, it is salty pore water. «

Page 10 line 10: I am afraid, it is not. Above the authors mentioned that all values >20 Om indicate fresh water. The maximum values in Fig 2 are <3. So, maybe I missed something, but it is not clear to me and I cannot follow the line of thought. Please, I strongly encourage the authors to add an axis/scale/bar/arrow to indicate in which part of Fig. 2 the authors see freshwater.

» We understand the confusion of the reviewer. The raw data are presented as apparent resistivity. The apparent resistivity is the value a homogeneous Earth should have to generate the exact same reading. It means that they are not only influenced by the aquifer resistivity but also (and mainly) by the low seawater resistivity. Only after inversion, which accounts for the effect of the low resistive seawater layer (by means of the bathymetry and seawater conductivity), we get an estimation of the true resistivity, you will see that the aquifer is brackish or fresh (Figure 5_this_document, is figure 2, left vs. figure 4). However, from the raw data, we can see an increase of this apparent resistivity. Assuming a constant influence of the seawater (what is true as long as its thickness remains similar), this must correspond to an increase in the aquifer resistivity, and thus a decrease in its salinity. This concept is well-known from geophysicists, allowing to draw qualitative conclusion from the raw data. We will clarify this in the manuscript. And the potential zone of discharge will be highlighted in figure 2. «

Page 10 lines 10-11: Is this so? Please keep in mind that I am a non-geophysicist, but primarily I would assume signals to be constant as long as nothing changes rapidly. The increase the authors show in Fig. 2 are rather smooth, so there is no rapid change.

SGD, in my eyes, would be rather rapid as it occurs at a certain e.g. sediment horizon. As soon as the device passes the horizon, the signal should show a rather rapid change, which I cannnot see in Fig. 2. So how can CRP be used as a rapid exploration technique?

» Similar to the previous question, you have to keep in mind that the raw data is highly influenced by the seawater layer. Its depth slowly decreases to the right of the graph (figure 2, left), leading to a slow increase of apparent resistivity. The increase is enhanced between 150 and 200 m, which is exactly where you find more brackish pore water in the aquifer (figure 4, K0HT). Additionally, you have to keep in mind that an apparent resistivity corresponds to a combination of four electrodes. The distance between those electrodes are 15 m, so that the minimum volume investigated by CRP is at least 60 m long (and gets longer when larger electrode spacing are used, what is necessary to investigate the aquifer). Therefore, the transition in the raw data will always be smoothed as this investigated volume acts as a filter. This is another reason why inversion is needed. This rapid change, as you expect in the signal, is attenuated on the raw data by the influence of the seawater and investigated volume. This will be explained in the manuscript. «

Page 10 lines 12-13: If the authors would scan a line parallel to the beach, but the "leakage" or discharge zone is more offshore, the authors would not see the discharge itself but just the freshwater. So yes, this could be used to see how far freshwater may extend offshore but, a) the scanline should then be very close to the shoreline to not miss SGD close to the shore (which by the way may be difficult due to the a certain depth either the boat or the device may need) and b) to really "see" groundwater discharging, the scanline should be directly above it. If I am mistaken, please correct me, otherwise I suggest to alleviate the very strong statement.

» The reviewer is right about parallel profiles. Perpendicular profiles do not suffer from this limitation. However, we do not claim that CRP can be used to detect fresh SGD everywhere, but it can be used as a quick exploration technique (when you use the raw data) to find zones worth investigating in terms of nutrient/contaminant leakage by SGD. Fresh groundwater discharge does not have to be a discrete outflow, it is often quite diffuse. Making the actual detection of freshwater discharge at the seabed is quite difficult with resistivity measurements. The presence of fresh pore water in the marine aquifer is already proof of fresh groundwater discharging, since it migrates through the sediments towards the seawater due to the buoyancy effect. Also, the upper layer of the marine aquifer is sometimes filled with brackish pore water, making it problematic to see fresh discharge at the seabed surface. «

Page 10 line 16: Please try to avoid any terms that tangent a temporal dimension unless you can prove it. I mentioned it before, the authors record mono-temporal signals which do not allow any statements on temporal dimensions.

» This difference has nothing to do with temporal variation, but with the spatial variation (compared to the groundwater extraction site) and the effect of the saltwater lens thickness on the inversion smoothing (see answer to: Page 9 lines 31-32). We know from modelling studies that in this context, a higher groundwater flux will lead to a thinner saltwater lens, Vandenbohede and Lebbe, 2006a, this will be explained in the manuscript. «

Page 11 line 7: This is likely, but, if I am not mistaken, it can also be due to different methods, a change in heterogeneity due to wave actions/storms etc. Please relativize the authors statement if I am correct.

» Both methods where the same, FDEM. We only used two different devices, with different depths of investigation. Storm and wave action might indeed have an effect on the heterogeneity on the lower beach, but both zones of higher resistivity are related to fresh discharge. This is based on comparison with the (marine) ERT profiles, the zone does not move, only the intensity of the discharge changes. «

Page 11 lines 8-9: This does not support the hypothesis of less discharge (if the signal is really discharge based). The main questions in this context would be, what are the

travel times? What are the groundwater ages? Both would support the statement given by authors but without, it is another assumption and no reasoning.

» We partly disagree with the reviewer. It is true that our interpretation is partly biased by our knowledge of the field. Modelling results in the area show that a decrease in the flux will induce an increase in the salinity of the discharge water, what is confirmed by our geophysical data. We will rephrase the sentence. This statement will be confirmed by planned flux monitoring. «

Conclusions

Page 12 lines 15-16: From my perspective, this statement should be deleted.

» This sentence will be removed. «

Figures

Figure 3: Why does the color bar include values <100 when apparently neither the left nor the right shows these values? As a consequence the reader may see smaller signal variations.

» We choose to use the same colour scale as the resistivity profiles, to help in their correlation. The right image (figure 3) is actually the same as figure 7A, which allows you to see a more detailed conductivity variation. Figures 3 and 7 will be placed in sequence, due to the reorganization of the results section, making this more clear. «

Figure 4: I would suggest to add to features: 1. A scale showing the likeliness of SGD 2. A meter scale beneath all profiles that facilitates the understanding of what the authors talk about (e.g. pg9 L18 // pg10 L7) that includes information on low water line. Besides, are the abs. error statements in the captions needed?

» Zones with (potential) fresh SGD will be highlighted in the profiles and a meter scale will be provided, with the low water line as a reference (0 m). The absolute errors will be provided in the supplements, since it is good practice in geophysics to communicate the final inversion error. «

Figure 8: This figure is overloaded and almost impossible to understand for non-geophysisists. Please rework or/and consider moving it to the auxillary data.

» We will try to better guide the reader through this figure, using a dedicated section in both the methodology and results section. As explained above, this figure is essential to assess the reliability of the inversion and should thus be kept within the main text. «

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-540, 2020.

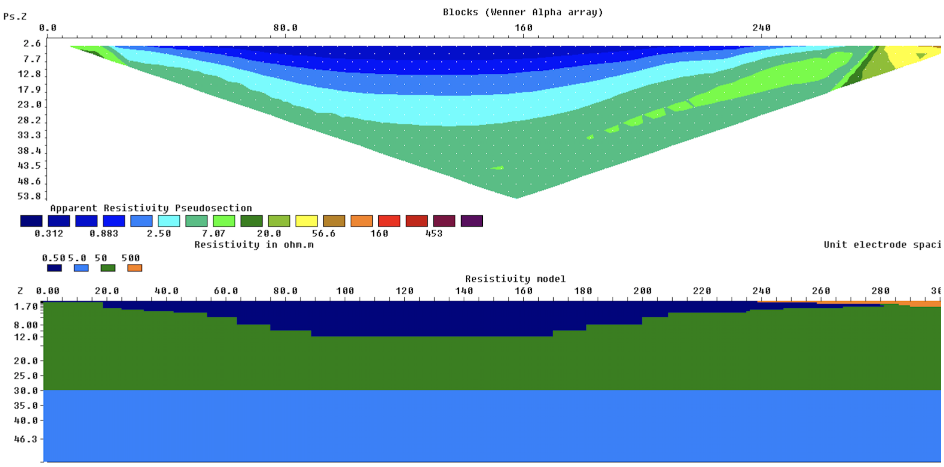


Fig. 1.

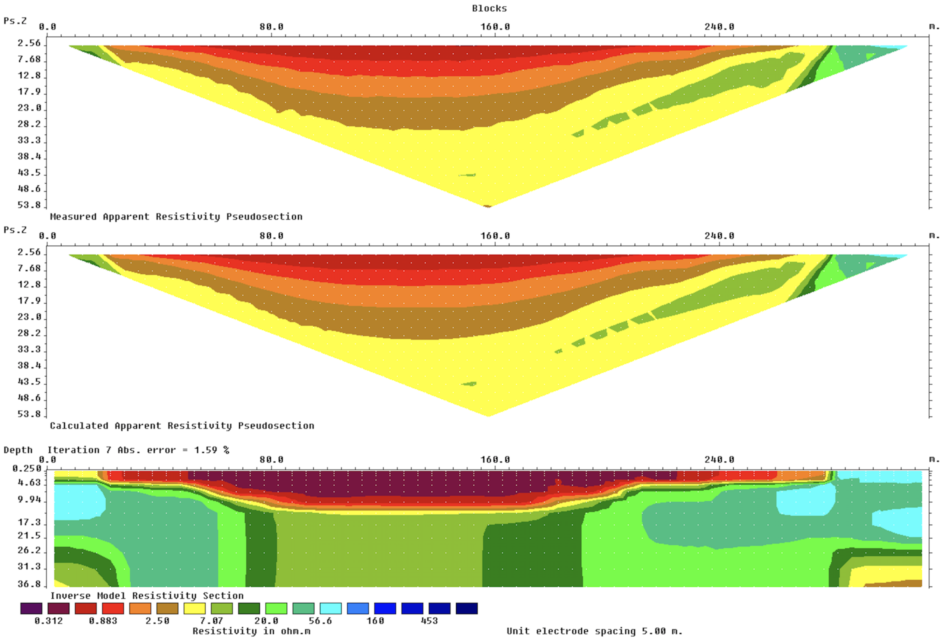

Blocks
Measured Apparent Resistivity Pseudosection
Calculated Apparent Resistivity Pseudosection
Iteration 7 Abs. error = 1.59 %
Inverse Model Resistivity Section
Resistivity in ohm.m
Unit electrode spacing 5.00 m.

Fig. 2.

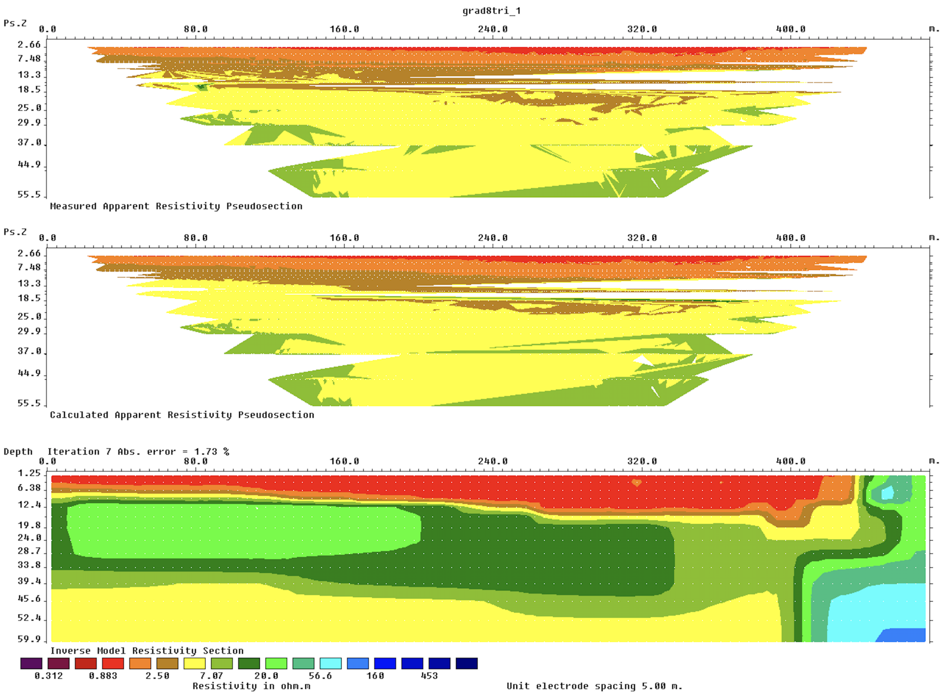
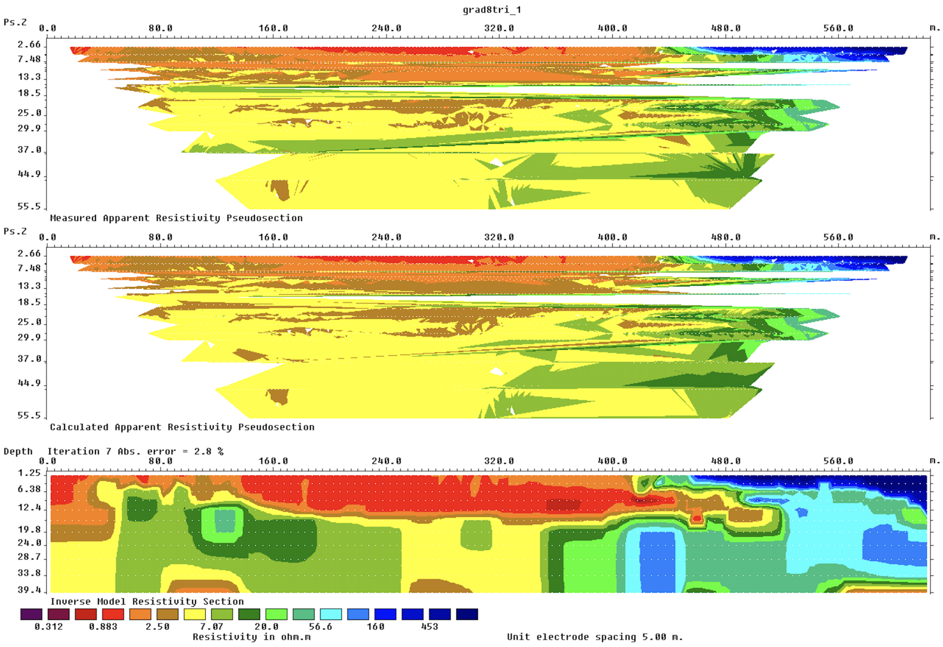

grad8tri_1
Measured Apparent Resistivity Pseudosection
Calculated Apparent Resistivity Pseudosection
Iteration 7 Abs. error = 1.73 %
Inverse Model Resistivity Section
Resistivity in ohm.m
Unit electrode spacing 5.00 m.

Fig. 3.


grad8tri_1
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Calculated Apparent Resistivity Pseudosection
Iteration 7 Abs. error = 2.8 %
Inverse Model Resistivity Section
Resistivity in ohm.m
Unit electrode spacing 5.00 m.

Fig. 4.

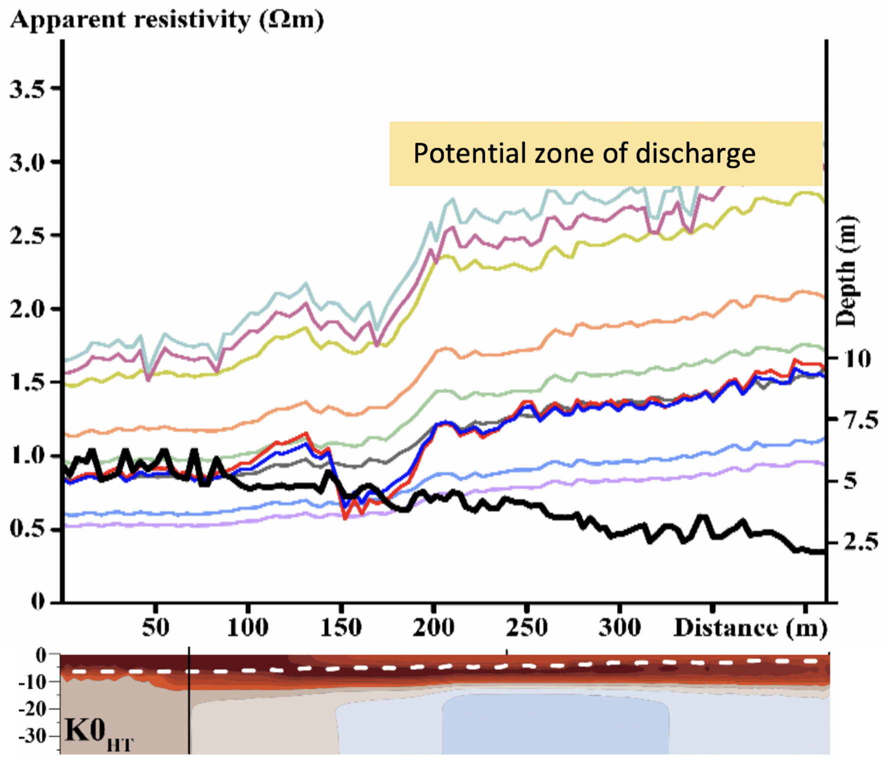
Apparent resistivity (Ωm)
Potential zone of discharge
Depth (m)
Distance (m)
K0HT

Fig. 5.