Dear reviewers, editor,

Thank you again for the given opportunity to further improve our manuscript. Previous replies to each comment are in red; in blue we mentioned their location in the modified manuscript.

Yours sincerely,

The authors

Content

Rev#1

Although this paper has the potential to be a very interesting contribution to Hydrology and Earth System Sciences, I think that the following major issue of concern exists.

Since the geomorphological context (fluvial paleo-channel) of the survey area and the proximity of the present-day Seine river, it should be expected the presence of the water table hosted in the near-surface porous sediments investigated by the geophysical survey. Actually, this aspect is hardly discussed at all and, since the presence at depth of water hosted in sediments affect the bulk electrical resistivity, it is crucial in for the interpretation of the electrostratigraphic units from ERI in terms of lithology and/or sedimentary facies association and, thus, for the three-layer model adopted all over the site to represent the studied area Considering that the results obtained are very intriguing, I suggest the Author to add a more focused discussion regarding the presence of the water table (or its absence), it its depth below ground surface and the chemistry of groundwater (i.e., the electrical conductivity). Alternatively, I suggest the Authors to explicit if this data were available to them (or not) and, if so, how they were considered in the discussion of results. I think that this discussion will greatly improve the scientific value of the results because can help geologist/geophysicist that have to face a similar problem.

The water table was measured in the last series of auger soundings done in June 2015 (PTA02 to PTA04 and PTA11 to PTA13) during a low water period. The clay infilling is always saturated. The upper topsoil/loam unit is never dry, but its degree of saturation could probably vary from 50% to 100% (which is most likely the case during high water periods).

Because the resistivity of the clays is close to 10-20 Ohm.m, and the water conductivity (measured from a piezometer located 1km apart from the site, is about 640 µS/cm ~15 Ohm.m) the change of the saturation of the topsoil/loam formation (~ 80 Ohm.m from the half meter spaced ERI) is not sufficient to lower the resistivity down to the level of the clays.

A qualitative XRD (X-ray Diffraction) experiment has been carried out on an old recovered sample of the clayey infilling, which gives the following results for a geological formation that can be described as a marl: ~60% carbonate, ~20% quartz, ~20% illite/montmorillonite and traces of kaolinite. Even fully saturated, the first decimeters (up to 1 m thickness in the southwestern part of the survey) of the topsoil/loam could not reasonably reach the conductivity level of the clayey formation, and its electromagnetic signature is almost undetectable (considering the configuration of the CMD explorer device) for thicknesses lower than 30 cm.

We agree: an extended discussion on that aspect should help, and will be proposed in the revised version of the manuscript. See new § Discussion

SPECIFIC COMMENTS Minor issues of concern are listed in the following.

1) *When describing ERI Measurement setup, considering the use of 48 channel georesistivity meter and 0.5 and 1 m electrode spacing it is not clear how the procedure of rollalong of resistivity data for subsequent transects was accomplished.*

We did not use a classical roll-along sequence. Because each pseudo section was measured in less than 15mn (multi-channel Syscal Pro from Iris Instrument), we performed successive pseudo sections with overlaps (half the ERI profile length=24m). Text will be annotated accordingly. L183

2) *Apparently, no motivation for defining the topsoil as "resistive" (line 272) is furnished. A motivation for this could be that the soil is plowed (as it can be seen form aerial view in Fig)?*

The resistivity/conductivity value for the topsoil is inferred from the half meter spaced ERI, southwestern part or ERI section in Figure 5. The surface is covered with grass and the logs clearly indicate the topsoil-loam cover.

Text will be annotated to specify that the site was a grassy meadow during the survey and the weather conditions will be described (sunny weather during all the survey). L106, L160

TECHNICAL CORRECTIONS

1) Fig. 3: the location of hand auger drilling are notdisplayed. It can be useful for the reader in order to facilitate the comparison between data. Done.

2) Fig. 5: The SW-NE orientation of the ERI transect is not displayed. It can be useful for the reader in order to facilitate the comparison between data. Done.

3) Fig. 5bis: it could be useful to represent in the ERI model the location at depth where the auger soundings achieved by a refusal. Done.

Rev#2

REVIEW COMMENTS

0- OVERALL

I would like to address your approach towards apparent conductivities and electrical conductivity in general. First of all, as both properties are repeated quite often, I would suggest using the abbreviations EC (true) and ECa (apparent). Second, the difference between both is often unclear in the presented work. It can't be stressed enough that apparent electrical conductivity (ECa; as defined by McNeill (REFERENCE); 'apparent') shouldn't be compared to electrical conductivity (EC; a value of the half-space model; 'true'; retrieved after inversion of EMI data) of the subsurface (see also Figure 5).

Also, the symbols used within the paper should elucidate this difference. At present, you use σ for both EC and ECa. I suggest using σ and σa, respectively, to avoid confusion and enhance the distinction between both.

EC and EC_a used in the modified version of the manuscript.

Be consistent when using abbreviations, and stick to these once defined. You use the abbreviation EMI at the beginning, though later on use the full notation (e.g., L156, L162). Done.

Some obvious questions arise during reading:

(1) why use a reference line to calibrate the data where no sampling overlap exists between the two survey modes?

To be honest, the current ERI/EMI calibration process (Lavoué et al. approach) was not planned; it has been decided afterwards during the processing of the data. A planned reference common line is clearly the best solution, but it is also interesting to illustrate what can be obtained if just crossing lines are available.

(2) Why use a 3 layered inversion model for the EMI data when the ERI shows 2 layers?

Throughout the entire "blue" zone (Thickness 1 < 10-20 cm) Fig 8, a two-layer model should have been ok (similar SRMR -standardized root-mean squared residual- values). The 1-meter spaced ERI is mostly located in this blue zone which corresponds to thickness 1 less than 20 cm.
Nevertheless, we kept a three-layer model because:
1- the logs clearly showed a distinct layer over the clay infilling (without presuming of their respective contrast of resistivity).
2- of the specificity of the southwestern part illustrated by the results of the half meter spaced ERI (Figure 5), where the thickness of the resistive top layer above the clay infilling exceeds 1 m.
We must admit that the question of mixing 2 and 3 layered model over the site was discussed a lot, but not kept (essentially because of 1-, and thanks to 2-). It is clear that the "blue" areas of Figure 8 for Thickness 1 correspond to zones where the top resistive layer can be considered as inexistent (from a geophysical point of view, considering the resolutions of the method used).
The text have been modified L299 § 3.3

(3) Why is there no comparison of the inverted ERI data to the inverted EMI data?

The comparison is implicit as the ERI results have been set as the reference for the depth of the clay infilling – substratum interface. EMI results have been scaled and shifted to fit ERI interpretation. It is the purpose of Fig 5 which actually shows the inverted EMI data with the estimated bottom depth of the clay infilling (as resistivities were fixed during EMI inversion with the help of the ERI interpretation).

(additionally: you could include an isosurface indicating the shape of the river? This is ultimately the goal of the presented work, i.e. retrieve the shape/morphology of the river.)

The clay infilling (the conductive formation) is without doubt, associated with the presence "at a moment" of the river. However, the past evolution of the meanders is very complicate with multiple crossing and overlapping over time. It is only possible to delineate the clay infilling, and difficult to retrieve the river shape at a given time from the measurements of the electrical conductivity only. It would require linking the information obtained from geochemical measurements with geophysical data, which is far from being straightforward from EMI data only. Consequently, in the present paper, we prefer not to draw the isosurface, and rather let Thickness #2 as the lone paleoriver geometrical information. Text will be annotated accordingly. Cf. new § Discussion

1- INTRODUCTION

L49-51: EMI devices are increasingly used for a large number of near-surface geophysical applications, as a consequence of their ability to produce 2D images of the apparent electrical conductivity, σ, over a large surface.

This is an example of my previous overall comment. 2D images of ECa (σa) are actually spatially lateral maps of the ECa; apparent. 2D cross-sections (inverted) of the EC (σ) are what is of interest in this article. I would suggest to rephrase this sentence, based on what you exactly mean with this.

"2D images" has been replaced by "mapping". Done

The focus of this study is to evaluate the reliability of EMI at meso-scale to image globally in 3D, even if it is interpreted in 1D locally. ERI is not meant for providing 3D image of such "large object". ERI and logs are highly recommended as "the best geophysical/direct observations" calibration support for EMI in this context. Text will be modified accordingly. L59-69.

L60-63: "This shift can be conveniently represented by a complex number, comprising quadrature and in-phase (respectively, real and imaginary) components, which can be inverted and then interpreted in terms of an apparent conductivity and an apparent depth of investigation (DOI)."

Should be: (respectively, imaginary and real). The quadrature (or imaginary) and in-phase (or real) components. Done.

After inversion it is the EC (not ECa; example of overall comment) I'm not really sure what you exactly mean with apparent DOI (I now only know that it is opposed to the real, L72). So I assume a specific DOI which you attribute to a certain setup independent of the soil model?

Indeed, "inverted" is misleading in the present context. It will be removed. Here, it's all about apparent property and its corresponding DOI. Done

L67-70: "This interpretation relies on the fact that, for a given soil model, one specific apparent DOI is defined by three device setup parameters: (1) the offset between the transmitter and receiver magnetic dipole, (2) the orientation of the dipole pair, and (3) the frequency of the transmitter current oscillations. "

I think the fourth setup parameter: (4) instrument elevation or instrument operation height is of great importance and worth noting as well. Agree. Text modified. L87

L78: The word 'typical' should be specified more. E.g., low, non-Ferro… Done. L94

L80-84: "In a resistive or highly conductive environment, such as that presented in the present study, the McNeill equation is no longer valid, and EMI recordings, in particular their in-phase component, must be interpreted within the specific measurement context, taking all of the physical properties of the local environment into account."

I suggest to list the physical properties (i.e., EC, mag. susc., diel. perm.) instead of mentioning 'all'. Done. L101-102

2- DESCRIPTION OF THE STUDY AREA

What were the weather conditions when the measurements took place? Maybe worth to note, as they could have their influence as well (influence of watertable, moister content). In how many days or during which period was the survey conducted? This could have its influence on the results later on (see 2-layered vs 3-layered model).

Details concerning the site conditions will be added, as well as a new discussion concerning the influence of the water table and the hydro-modeling perspective. L106, L160 + new § Discussion

An EMI survey is fast compared to an ERI survey and can be used to determine the location of the ERI survey. Was the EMI survey used to determine the location of the ERI survey to incorporate more lateral variations. If not, why not? In case of calibrating your signal, it is very important to cover as much as possible of the present variation.

It is a wise and usual strategy of prospection to map "quickly" and "roughly" with EMI, before doing ERI to characterize depth and lateral variations accurately: we totally agree. In the present case, little time was available for a wide area to be investigated before setting up the ERI section.

We define the strategy of prospection from the LiDAR map and the old hand-auger soundings (done one year before the survey). Actually, we must admit that the EMI/ERI calibration procedure was not planned, but decided afterwards during the inversion process.

L138: this □ these these Done.

3- METHODOLOGY

Include instrument survey height here as well. Done.

L154: …a reference transect of almost… Done

L166-167: Three different offsets were used between the centers of the Tx and the Rx coils, namely: 1.48m, 2.82 m and 4.49 m, each corresponding to a distinct DOI.

I suppose you mean a distinct apparent DOI in this case? Based on each coil separation, without further knowledge of the soil model. Indeed. ”apparent” will be added. Done.

L170: The word attempting makes this sentence sound like you just tried something. Assuming this was done deliberately, I would use another word. “Attempting” will be removed. Done.

L195-199: “When compared to the analysis achieved using auger soundings, the electrical properties of the topsoil/loam formation appear to be merged with the clayey formation, with the exception of the western portion of the cross-section, which has significant sand and gravel content. This outcome could also be due to the finer spatial resolution of the ERI measurements (electrode spacing of 0.5 m).”

Based on the fact that later on a 3-layer model was used, I assume that the finer spatial resolution is given as the reason why there are only 2 distinct layers in the ERI profile? Maybe add a little information about the sensitivity distribution of the used ERI array setup?

The array used is a mixed Wenner-Schlumberger (reciprocal configuration in order to allow a strong multi-channel parallelization). Theoretically this configuration has enough sensitivity (Furman et al., 2003; Dahlin and Zhou, 2004). With hindsight, a gradient or multiple gradient array should have probably be more efficient to discriminate the first decimeters with a 1m-spacing.

Text will be modified accordingly. Done L204

Is it justifiable to calibrate an assumed 3-layer profile with a 2-layered inverted ERI model?

See previous response to a similar comment of Rev#1 (L100-112 of this reply).

The inversion of ERI data is also an inversion with parameters and uncertainties. It is unfair to say that this model is ‘true’. ‘True’ will be replaced by ‘interpreted’. Done.

What were the weather conditions when the measurements took place? Maybe worth to note, as they could have their influence as well? Dry and sunny weather all the time during the 3 days campaign. L106, L160 A discussion about the water table impact will be added. Cf. new § Discussion.

L205-208: I would suggest to rephrase in a more comprehensive way. Done L225-228.

L227-232: “During the field data acquisition we faced several difficulties that prevent us to do a CMD profile exactly on the reference profile. Actually, the EMI data used for the calibration have been taken from the mapped data closest to the reference profile. This has led to several positioning and alignment errors : 1) the EMI data do not exactly cross the reference profile, 2) the EMI data are irregularly spaced along the ERI profile, and 3) the orientation of the CMD device was not exactly the same, for each measurement retained for the calibration.”

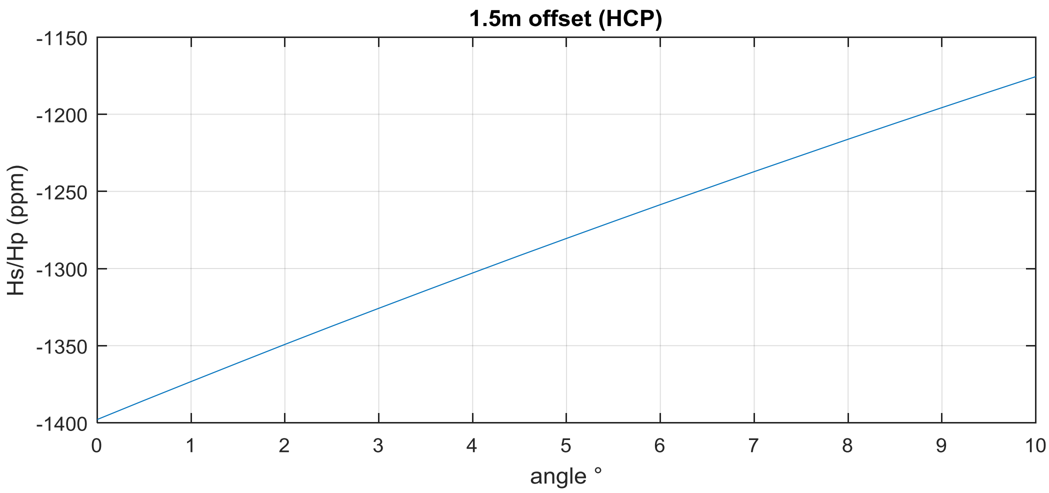
I don’t really get why you draw a reference profile on a location where you can’t perform a CMD survey. This is the core of the calibration process. Because the present EMI/ERI calibration as developed here, was not planned. (L95-98 of this reply)

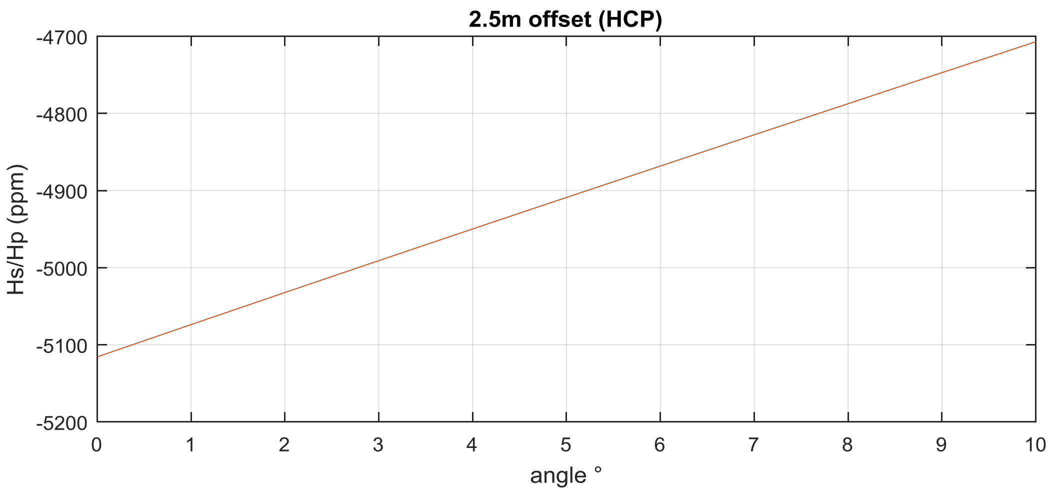
Also add the fact that (4) the height above the surface is changing constantly (as you are wearingthe instrument?) for each measurement. Done L87.

The changing orientation has a great impact on the calibration as other sensitivity distributions are constantly used to attain the results.

You are naming these errors that are included in the process but do not really assess how to contribute to the results. What is their impact, is this not too big?

It is difficult to assess quantitatively from *in situ* measurements. There are different for each offset. Apparent conductivities measured are a little bit noisier for the smallest offset, nothing abnormal. During the campaign, the carriers encountered difficulties to cover the area because of the presence of dense vegetation; the pitch angle was oscillating of a few degrees at least. Below, two plots show the theoretical variation of the quadrature part in function of the pitch angle (< 10°) for the 1.5 and 2.5 meter offsets. For example, for the CMD configuration, a pitch variation of 2° (which corresponds to a height variation of 7 cm for the Tx coil, 3 cm for Rx 1.5 meter offset, and <1cm for the Rx 2.5m meter offset) shows 4% and 2% changes, for the 1.5 meter and 2.5 meter offsets respectively (16% and 8% for 10°). This is not 0% but can be considered as usual field errors. Moreover, the pitch is generally changing smoothly from sounding to sounding.





L244: Once calibration is done… Done.

L252-265: “Step (3) does not guarantee that estimated interfaces will match the ERT interfaces 1) if the fixed/chosen resistivities are not correct, or 2) if EMI does not integrate the ground in the same way as the ERI in case of strong anisotropy, which seems not to be the case here, since a good match is obtained.”

The correlation coefficients are comprised between 0.5 and 0.7. Such values can be explained by several sources of errors in the estimation of the EMI apparent conductivities along the reference profile: 1) the differences in the location between the EMI measurements used for the calibration and the ERI profile, 2) the fact that the one dimensional model used for the EMI modeling is extracted from the inversed 2D resistivity section, 3) the difference of sensitivity between the ERI and EMI data. The regressions indicate the need of a stronger correction for the VCP configuration than for the HCP configuration. The scaling correction decreases as a function of offset, particularly for the HCP, which can be explained by the fact that small offsets are more sensitive to positioning and orientation errors, as well as natural near-surface variabilities.

Based on the correlation coefficients it is hard to say that a good match is obtained. The correlation isn’t that high (i.e. it does indicate anisotropy). This is also visible in the VCP configuration, which is more influenced (compared to the HCP conf.) by the anisotropy (also due to the 1 m instrument operation height). The VCP configuration has a highly concentrated sensitivity close to the instrument compared to the HCP which reaches this high sensitivity (in 1D) at a lower point (more spread compared to the VCP). This results in an increasing correlation for bigger coil separations (due to a smaller relative impact on the response of the present anisotropy).

We agree it is a coarse match. The primary reason is that the EMI performed on the reference profile have been extracted from perpendicular cross lines: the idea of calibration from ERI, has come afterwards.

But comparing to Lavoué’s *et al.* (2010) data, where an EMI profile has been specifically acquired for the calibration, the dispersion is of **the same order** (unfortunately no correlation coefficients provided). It is not perfect, and linear correlation is, as expected, more difficult to obtain for the smallest offsets for which exactitude of the measurement locations of the 2 methods is more critical (and the different integrated ground volumes by the 2 methods are more sensitive to small scale changes). But despite this, Figure 5 shows that the interface from the EMI inversion better matches the ERI all along the profile after calibration, especially for VCP, while calibration has a minor effect on the HCP results.

L271-273: Consequently, a three-layer model seems reasonably justified all over the site during the inversion process to represent the studied area: a resistive topsoil, a conductive clayey filling, and a resistive sand/gravel layer.

Is it justifiable to use a 3-layered model for the inversion after you calibrated the EMI data using a ‘2-layered’ model, i.e. the inverted ERI results?

See response to Rev#2 lines95-107 of this reply.

Shouldn't the ERI spacing be adjusted such that the small top layer can be detected? (Like in the western part). Yes. Next time, it would be clearly an asset to do some additional small-offset ERI to evaluate the very near surface resistivity.

Maybe discuss the characteristics of the sensitivity distribution of the ERI array setup? Text annotated, and reference added L203-205

L844-286: Maybe use the abbreviation SRMR (or SRSR?) to indicate the standardized root-meansquared residual and then also in the formula (L286): SRMR = … Done.

4- EMI INVERSION RESULTS AND DISCUSSION

Overall, I think there should be an increased focus on explaining why something is occurring and on the validation of the inversion.

I think it would be an asset to show the 2D slices of the inverted EMI data on the location of the reference ERI profile. This could provide a means of comparing the inversion results of both techniques. Actually, it is the case in Figure 5, where the position of the clay-substratum interface from the EMI inversion before and after calibration is shown. Showing a full 2D slice for the EMI inversion results is not pertinent as the resistivities are fixed during the inversion, and the thicknesses of the first two layers inverted only.

"L333-335: The combined HCP&VCP data inversion naturally leads to the occurrence of higher values of data residual, than in the case of the individual HCP or VCP inversions."

Why is this the case? Because, at least theoretically, you add extra information into the inversion process.

The data residual is a quantitative assessment on how the model "explains" mathematically the data. Theoretically, comparison between data-residuals should be done for a single dataset. In the present case: a) the two measurements in HCP and VCP modes have been carried out in 2 times => not perfectly identical positions, heights and orientations a bit different for both data sets, b) HCP and VCP modes do not integrate the ground in the same way. If the ground within the footprint of the system is a bit far from a tabular model, then the interpretation with local 1D models can be more difficult with both data sets inverted jointly than with one of the two sets only.

New § 3.4.2 annotated L354-370

Is this the best approach? Should they be inverted together? Or both separately and use them in a complementary way?

It depends on the characteristic size of the anomalies and variations that need to be mapped; using HCP, VCP or both brings specific information. Using both is a mean to mix information from both setup, but with a weighting depending of their respective sensitivity (i.e. DOI). Figure 8 illustrates the results of inverting HCP and VCP alone, and both at the same time. Two conclusions expected: 1) the near surface variability is inferred more accurately by VCP, 2) the low frequency variability is almost the same for all configurations.

New § 3.4.2 annotated L347-353

5- CONCLUSION

Overall, the limitations of the presented technique can be stressed more, as they are obviously present.

L343-345: "In order to correct the sensitivity issues arising from EMI measurements, a calibration procedure was implemented, based on the use of a linear correction with ERI inversion results and auger soundings."

These aren't sensitivity issues, but drift and factory calibration issues. Text will be modified accordingly. *L360-362: This is unnecessary to mention, it is more a future practical goal based on specific information regarding the institutional framework of the research. Research programs have to be mentioned in acknowledgements, not in the body of the paper.* Removed.

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Rev#3

Dear Authors and Editor,

This paper presents a case study for testing the utility of multiconfiguration EMI surveys to characterize the interanl structure of a representative paleochannel in an alluvial plain setting of the river Seine, France. There is a growing interest in using near-surface EMI techniques for mapping relict geologic features, such as; paleochannels, towards improving our understanding of how these features influence groundwater dynamics as well as how they control the development and evolution of the modern landscape. The results from this study show an interesting application of EMI, ERI, and auger soundings to map the internal structure of a paleochannel. However, I think there are several key pieces that are missing regarding the link between methods and the "bigger picture" attempting to understand the long-term hydrological processes. Thus, it is my opinion that the paper is incomplete in its present form, but could improve if there is more emphasis on the main considerations I have outlined below. I have made comments and questions throughout the manuscript, roughly following the order of the paper, which should be considered as suggestions for helping to improve the paper.

Main considerations:

1) *In the abstract, the authors state that "A detailed knowledge of the internal heterogeneities of such paleomeanders can thus lead to a comprehensive understanding of its long-term hydrogeological processes." Similar statements are made in Lines 44-48, however, the findings of this study are not described within a framework of how EMI, when calibrated with ERI and auger soudings, contributes to a better understanding of the hydrological processes of the river Seine alluvial plain "La Bassée." I realize that the main focus of this paper is to map the internal geometry of the paleochannel, but I am left wondering why the authors make the above statements without any discussion throughout the paper? The authors end (Lines 358-362) by stating that their technique "could significantly improve the accuracy of hydrological modeling…" but this will be debated later (it is unclear whether this is another phase of the project, conference?). It is my opinion that this is a critical piece that is missing from the paper. Without this important discussion, the paper is missing a key aspect of how EMI methods provide an innovative way of characterizing the geological controls on hydrologic processes, and as a result, falls short of satisfying the aims and scopes of the journal* http://www.hydrology-and-earth-system-sciences.net/about/aims_and_scope.html.

Ok.

A discussion will be added concerning the impact on the EMI results of the water table in the present context. In a near-surface "clayey" context, resistivity methods are less sensitive to pore water content. In addition, when the upper formation is quite thin (less than half the ERI electrode spacing) and because the clayey infilling is always saturated, the influence of the water table on the loam/topsoil resistivity is hardly detectable.

Hydrogeological modeling is not proposed here, but planned by our colleague hydrogeologist. It will be limited by our (geophysicist) capability to set a relationship between the electrical properties and in the present case the water, clay and salinity contents (even mineralogy proportion). Text will be annoted accordingly. Cf. new § Discussion.

Why didn't the survey go beyond the expected boundaries of the channel, visible in the LiDAR data? In otherwords, the surveys were only performed within the channel, making it difficult to fully characterize the variations in lithology/hydrology inside and outside the channel. Although vegetation cover (treeline) seems to be one limiting factor for the survey design, based on the LiDAR map, it seems feasible that the survey could have extended further to better capture the transition between outside and inside the paleochannel.

Not only treeline but also: 1- cultivated area, 2- unauthorized access to private fields, 3- ERI / EMI survey to manage sequentially and just 3 days to perform all the campaign.

The structure of the paper in the Methods and Results/Discussion sections is confusing. There is a mixing of methods and results in the Methods section, and nearly all of the results and figures are presented in the Methods section, with no figures presented in the Results/Discussion section, which is only two pages long? If the authors can 1) restructure the Methods, and Results/Discussion sections, 2) incorporate a more in-depth discussion of the hydrologic influences on the EMI measurements, water table information, weather conditions, and survey design, and 3) relate the results of the EMI surveys to how the "estimation of the geometry of the Seine river can provide valuable insight into its paleo-hydrology…" then they will have a paper that is beneficial for geologists, geophysicsts, and hydrologists interested in these complex problems.

Ok. The structure of the paper will be modified and better balanced with a discussion focused on the theoretical impact of the water content as well as the hydro-modeling perspective as suggested. Water table values in some of the hand auger soundings as well as the water conductivity (recorded in a nearby piezometer) will be discussed.

Concerning the point 3), it will be first reminded that without a clear link between geophysical and dating data, it will be difficult to propose an accurate "past and future hydro-scenarios".

Below, the updated table of content:

Specific comments/suggestions:
Abstract:

- Lines 23-25: As stated above, there is no discussion about this later in the paper and how the methods used in the present study can help address this important problem. Cf. new § Discussion.

Introduction:

- In general, the Introduction is not referenced enough (e.g., Lines 34-37; 54-63; 64-72). There are several other studies that have looked at very similar problems that the current paper is trying to address, and should be cited. For example, please refer to Fitterman et al. (1991); Maillet et al. (2005); De Smedt et al. (2011), which also used similar procedures to investigate paleochannel geometry, thickness, etc. Ok. The literature concerning EMI in general, even for the lone paleo environment mapping is huge. De Smedt, Fitterman, Delefortrie, and Huang added. No EMI mentioned in Maillet at al.

- Line 39: I suggest defining electrical conductivity as: σ, and apparent conductivity as: σa, and use this notation consistently throughout the manuscript. In fact, apparent electrical conductivity (Lines 50-51) is mislabeled (not σ as stated) and should be σa. Text modified with EC , EC_a

- Line 40: Fine sediments do not necessarily correspond to conductive, and coarse sediments to resistive materials. Fine and coarse sediments that consist of the same mineralogy (e.g., quartz) should in principle have similar resistivities. What is missing here is that the mineralogy, quartz, clay, etc. is also an important property. In addition, the porosity and fluids within the pore space, whether freshwater or saline water, also have an important influence on σ. This needs to be clarified. Elements of mineralogy have been added in the discussion.

- Lines 44-48: Similar to my above comment for the Abstract. The idea that EMI can be used to provide valuable insight into the paleo-hydrology and as the author's state, climatic fluctuations, does not come out later in the discussion of the paper. Cf. upgraded § discussion.

- Line 51: "over a large surface," or is it that EMI methods are capable of covering large areas/distances over relatively short periods of time? Text annotated. L59-67

- Lines 54-63: There are no references in this paragraph, and citations are needed as this information regarding the background EM physics is probably not general knowledge to the reader. Done, Nabighian ….

- Line 61: This should be "respectively, imaginary and real" Done.

- Line 63: I haven't seen this term used before in the literature: "apparent depth of investigation," and have only seen it reported as the depth of investigation (DOI), see Huang, (2005), and references therein. Corrected.

- Lines 67-70: I think a fourth point to add is that the DOI is also a function of the height of the instrument above the ground. Done.

- Line 78: What are "typical conductive properties"? Perhaps give a few examples here. Done.

Description of the study area:

- What is missing from this section is a description of any information on the depth of the water table, as this is important for data processing and interpretation. Information provided in the introduction. Cf. new § Discussion.

- Lines 105-107: This is already stated in lines 47-48, and could either be removed or combined with the earlier statement in the Introduction. Text modified accordingly.

- Line 116: What kind of soundings? Borehole soundings from a hand auger? Mechanical not hand borehole soundings reaching between 6 and 10m depth. Text will be modified accordingly.

- Line 138: Please change "this" to "these" Done.

- Line 144: This sentence should be referenced Done.

- Lines 145-149: This last paragraph seems a bit out of place in the Study Area section. The objectives of the study should be listed in the last paragraph of the Introduction. Agree. § removed. Objectives already defined in the introduction.

Methodology, Measurement setup:

- Overall, I am surprised to see that most of the results and nearly all of the figures are discussed in the Methods section and not the Results section? It is confusing to the reader and I am left wondering why the authors chose to structure the paper in this way? I think the clarity of the paper could be improved if the basic background of the methods is described in the Methods subsections, and the results be left for the Results/Discussion section. In fact the Results/Discussion section is only 2 pages long, compared to 6 pages of Methods! Structure of the paper will be modified as suggested. See the new outlines L395-406 of the present reply. We changed the paper outline, hopefully clarity is improved.

- Line 153: Please provide the details of where you got the LiDAR map, i.e., what database, the dates of data collection, how it was produced, etc. Also include a citation. The LiDAR map was provided by the Seine Grands Lacs public organism (http://seinegrandslacs.fr/) to the PhD thesis of B. Deleplancque referenced in the current paper.

- Lines 155-157: This sentence is repeated in Line 162, and is Line 158 intended to be a separate paragraph, or part of the same paragraph? Indeed. Text modified

- Lines 162-164: Electromagnetic induction (EMI) is already spelled-out before, and I don't think it is necessary to write ElectroMagnetic (EMI); Horizontal CoPlanar – HPC, and Vertical CoPlanar – VCP, like this. In other words, I don't think it is necessary to capitalize the beginning of each abbreviation as this is already common knowledge in the literature, i.e., electromagnetic induction (EMI), not ElectroMagnetic Induction. Done.

- Line 167: What is the approximate DOI for each offset? It would be useful to include this instead of just saying "a distinct DOI." Ok. Approximate values of DOI will be mentioned. *Additionally, it would be helpful to mention what the instrument height above the ground was, as well as what the step-size was (e.g., 0.5 m), what was the acquisition mode (stationary/fixed spacing, continuous mode, random walk). In other words, what were the specific survey details used in this study? Also, what is missing here is a description of the weather conditions, and how long the surveys were performed, when they were performed, as these are also important for the reader to understand what the conditions were during data acquisition.* Done. Introduction modified accordingly.

- Line 168: Why were "slightly different sampling intervals used"? This needs to be explained. Shouldn't the sampling intervals be the same if the intention is to compare different dipole configurations at the same acquisition point? Acquisition was made with the continuous mode (0.6 s

time step, walking at approximately 2-3m/s). 1) In continuous acquisition the instrument can be used for a single orientation at a time, 2) the survey was performed with GPS, 3) we faced GPS reception issues. Consequently the walking paths are not the same for each orientation (Fig 3). Text clarified in § 3.2.

- Line 170: Please change "attempting to merge" to "merging" as attempting to do something implies that you were not able to do it. Done.

Auger sounding results:

- Much of this section is results and not methods. Is it possible to briefly summarize the methods that you used for the auger sounding here and present the results in the Results section? This also follows for the other subsections in the Methods section, which are a mix of methods and results. Ok. Structure of the paper will be modified. See the new outlines L 391-402 of the present reply.

- Line 183: Missing PTA 06, as this also contains a peat layer according to Figure 4. Ok.

ERI results:

- Again, much of this section is mixing methods with results.

EMI calibration from ERI:

- Have the authors performed any other site-specific calibrations such as; instrument drift, temperature effects, topographic effects? These have been shown to be important for data processing (see Sudduth et al., 2001; Delefortrie et al., 2014) and is not discussed in the current study. No additional calibration has been done. But concerning the quadrature part, the CMD instrument drift due to temperature is not significant with this instrument for usual daily variations (+ or – 10°C). This not the case for the in-phase part, not presented here.

- Line 207: "near surface" should be hyphenated "near-surface" Done.

- Lines 217-222: This is a similar to what was already described in the Auger sounding results section and can either be removed, or combined with Lines 175-183. Text removed.

- Line 241: Please change "developed in Schamper et al" to "developed by Schamper et al" Done.

- Line 244: Please change "once the calibration done" to "once the calibration is done" Done.

- Line 246: Please remove "Actually" at the beginning of the sentence, and start with "Despite" Done.

- Lines 250-251: "All those non-straightforward steps…" I would suggest rewording the start of this sentence and remove "non-straightforward" Done.

Inversion parameters:

- Line 270: Please remove the word "clearly" Done.

- Lines 280-281: As mentioned above, the instrument height should be mentioned earlier in the paper. Done. L207

- Lines 284-286: An equation sign is missing, e.g., RMSE = …., also there is no equation number assigned to this equation (1) on the right-hand side of the margin. Please check the journal formatting for equations. Done.

- Lines 289-290: Is this sentence meant to be a standalone paragraph? This information is also listed in the Figure 8 caption (Lines 480-482). Text has been reformatted.

EMI inversion results and discussion, General trend:

- Lines 294-295: The introductory sentence is a standalone paragraph? Is this a formatting error when Line 296 should be a continuation of the same paragraph? Also, same comment for Lines 307-308. Text has been reformatted.

Conclusion:

- Lines 341-342: Please delete "(CMD explorer from GF instruments," as this is already mentioned earlier in the paper. Done.

Figures:

- Figure 1, Line 441: In the bottom panel, is the study area highlighted by the small red star on the figure? It would be helpful to either enlarge location start, or show a boxed area where the surveys were performed to help the reader easily locate the study site. Additionally, for the figure caption there is a typo: "maps" should be uppercase "Maps," and add the word "bottom" after "plain" to denote the top vs. bottom panels. Done.

- Figure 2, Line 443: Please change "studied area" to "study area". Done.

- Figure 3: It would be helpful to show where the locations of the auger soundings were performed with respect to the geophysical surveys Done.

- Figure 4, Line 454: Please change "log" to uppercase "Log" to begin the sentence. Done.

- Figure 5, Line 460: Please remove the word "clearly" Done.

- Figure 7, Line 473: Please change "histogram" to uppercase "Histogram" Done.

Bibliography completed.

Multiconfiguration electromagnetic induction survey for paleochannel internal structure imaging: a case study in the alluvial plain of the river Seine, France.

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Running title: Geophysical Investigations of a Paleochannel

Abstract

The La Bassée floodplain area is a large groundwater reservoir controlling most of the water exchanged between local aquifers and hydrographic networks within the Seine River Basin (France). Preferential flows depend essentially on ~~sediment fills~~the heterogeneity of alluvial plain infilling, whose characteristics are strongly influenced by the presence of mud plugs (paleomeander ~~heterogeneities.~~clayey infilling). These mud plugs strongly contrast with the coarse sand material that composes most of the alluvial plain, and can create permeability barriers to groundwater flows. A detailed knowledge of the global and internal ~~heterogeneities~~geometry of such paleomeanders can thus lead to a comprehensive understanding of ~~its~~the long-term hydrogeological processes~~.~~ of the alluvial plain. A geophysical survey based on the use of electromagnetic induction was performed on a ~~representative~~wide paleomeander, situated close to the city of Nogent-sur-Seine in France. In the present study we assess the advantages of combining several spatial offsets, together with both vertical and horizontal dipole orientations (6 apparent conductivities), thereby mapping not only the spatial distribution of the paleomeander derived from LIDAR data, but also its vertical extent and internal variability.

1. ~~1~~ Introduction

Dipolar source electromagnetic induction (EMI) techniques are frequently used for critical zone mapping, which can be applied to the delineation of shallow heterogeneities, thereby improving conceptual models used to explain the processes affecting a wide range of sedimentary environments. This mapping technique is very effective for environments in

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which the spatial structure has strongly contrasted electromagnetic (EM) properties~~,~~ especially that of interpreted electrical conductivity~~.~~ (EC).

Since the seminal work of Rhoades (Rhoades et al., 1976) much research has been conducted to link the petrophysical and hydrodynamic soil properties to the apparent electrical conductivity (EC_a). EC_a is affected by numerous parameters (Friedman, 2005) whose major ones can be separated into three categories: (1) the bulk soil properties (porosity, water content, structure); (2) the type of solid particle (geometry, distribution and cation exchange capacity) mainly related to the clay content; and, (3) environmental factors (EC of water, temperature,…). The clay infilling of paleochannels, and the deposition of alternate layers of ~~fine (~~conductive (clayey) and ~~coarse (resistant~~resistive (sandy) material in alluvial plain systems, are examples of natural geophysical processes having contrasted EM properties.

EMI measurements have previously been applied to the imaging of conductive fine-grained paleomeander infilling, produced by meander neck cutoff or river avulsion, which can form permeability barriers with complex geometries (e.g. Miall, 1988; Fitterman et al., 1991; Jordan and Prior, 1992; De Smedt at al., 2011). In addition to providing detailed local information on alluvial plain heterogeneities, which can be applied to the study of aquifer-river exchanges~~,~~ (Flipo et al. 2014), the estimation of the geometry of the Seine river paleochannels can provide valuable insight into its paleo-hydrology, as well as physical transformations resulting from climatic fluctuations during the Late Quaternary.

EMI devices are increasingly used for a large number of near-surface geophysical applications, as a consequence of their ability to produce ~~2D images of the apparent electrical conductivity, σ, over a large surface. A very large body of scientific literature has been~~

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~~dedicated to~~mapping of EC_a over extended areas and at different depths. The main issue of EMI concerns the quantitative mapping of the vertical variations of EC, obtained after multilayer inversion of EC_a, because of the limited number of measurements at different depths (i.e. source-receiver offsets). Despite the spreading use of multiple-frequency and multiple-coil EMI instruments compared to the classic twin coils configuration, a way to overcome this issue is, at least to constrain, and at best to calibrate multilayer inversion of EMI measurements against ERI (electrical resistivity imagery) profiling. A very large body of scientific literature has been published on the study and use of near-surface electromagnetic geophysics, especially in the frequency domain, as described by Everett (2012).

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By design, an EMI system energizes a transmitter coil with a monochromatic oscillating current, and the oscillating magnetic field produced by this current induces an oscillating voltage response in the receiver coil. The voltage response measured in the absence of any conductive structure is used as a standard reference. However, the magnetic field oscillations are distorted by the presence of nearby conductive structures, such that the voltage signal induced in the receiver coil experiences a shift in amplitude and phase with respect to that observed in the standard reference. This shift can be conveniently represented by a complex number, comprising quadrature (or imaginary) and in-phase (~~respectively,~~or real~~ and imaginary~~) components, which can be ~~inverted and then~~ interpreted in terms of ~~an apparent conductivity and an apparent~~ EC_a (from the quadrature or out-of-phase part) and depth of investigation (DOI~~).~~) (Huang, 2005). A comprehensive and more detailed description of the EMI principles can be found in (Nabighian, 1988a, 1988b).

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Although EMI systems were initially used as mapping tools, and were designed to measure the lateral variability of σ associated with a single ~~apparent~~ DOI, the measurements they provide are now generally interpreted to provide information as a function of depth,

Mis en forme : Couleur de police : Automatique albeit down to only relatively shallow depths ~~only~~. This interpretation relies on the fact that, for a given soil model, one specific ~~apparent~~ DOI is defined by ~~three~~four device setup parameters: (1) the offset between the transmitter and receiver magnetic dipole~~,~~; (2) the orientation of the dipole pair~~, and~~; (3) the frequency of the transmitter current oscillations; and, (4) the instrument height above the ground. An EMI survey during which at least one of these parameters is varied can thus be used to resolve depth-related variations of ~~conductivity. The real (as opposed to the apparent) DOI is determined from the computed distribution of the ground's electrical properties.~~EC. This distribution can be retrieved by solving an inverse problem, which is derived from a large number of applications (e.g. Tabbagh, 1986; Spies, 1989; Nabighian, ~~1988~~1988b; Schamper et al., 2012).

The physical model used in the inversion procedure must be suitably adapted to the electromagnetic properties of the surveyed ground. In the case of a medium characterized by typical conductive properties~~,~~ (e.g. low, non-ferromagnetic materials), at a low induction number the quadrature response is interpreted in terms of the apparent ground resistivity, which to a first order approximation varies linearly with the quadrature response (McNeill, 1980). In a resistive (EM effects other than induction become non negligible) or highly conductive (low-induction number assumption is no more valid) environment, such as that ~~presented~~mapped in the present study, the McNeill equation is no longer valid, and EMI recordings, in particular their in-phase component, must be interpreted within the specific measurement context~~, taking all of~~. One must then take into account, in addition to the ~~physical properties~~EC, the magnetic susceptibility and viscosity, as well as the dielectric permittivity of the local environment ~~into account~~, especially if this one is resistive (e.g. Simon et al., 2015, Benech et al., 2016).

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The present study focuses on the La Bassée alluvial plain ~~of La Bassée~~, a zone located in the southern part of the Seine basin, 2 km to the west of Nogent-sur-Seine (France). The geophysical campaign has been performed during 3 days of good weather in June during a low water period. The use of geophysical exploration for this investigation is of significant importance, since it should pave the way for the paleo-hydrological reconstruction of the Seine River (estimation of its transversal geometry and paleo-discharge).

The aim of this study is to delineate the geometry of a paleochannel (i.e. its thickness and width), using a state-of-the-art 1D inversion routine applied to EMI ~~apparent conductivity~~EC_a measurements. The inverted data ~~consists~~consist in a set of EMI measurements implemented with (1) three different offsets, and, (2) for two dipole configurations: horizontal (HCP) and vertical (VCP).

Following a description of the study area, we present the technique used to calibrate the EMI measurements, which relies on reference ERI (Electrical Resistivity Imaging) measurements and an auger sounding profile. The EMI inversion is then constrained to limit the solution space to images that are consistent with the observations provided by the ERI and auger soundings. To this end, a local three-layer model is derived with fixed conductivities, and is then introduced into the inversion routine for each position of the surveyed area. The thicknesses of the soil and conductive filling, corresponding to the presumed paleochannel, are determined through the use of an inversion algorithm.

2. ~~2~~ Description of the study area

The study site is located within a portion of the Seine ~~river~~River alluvial plain (locally named "~~La~~ Bassée"), approximately one hundred kilometers upstream of Paris (France), between the confluence of the Seine and Aube rivers to the North-East, and the confluence of the Seine

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and Yonne rivers to the South-West (Figure 1). This 60 kilometer-long, 4 kilometer-wide alluvial plain constitutes a heterogeneous sedimentary environment, resulting from the development of the Seine River during the Middle and Late Quaternary. ~~It is important to fully characterize a river's alluvial plain geometry, in order to understand the fluvial system's response to climatic fluctuations. More practical issues related to water resource management require an accurate understanding of the exchanges that took place between the regional aquifer and the superficial hydrosystem (Flipo et al. 2014).~~

Cartographic studies of this area have been carried out in the past, using geomorphological and sedimentological techniques (Mégnien, 1965; Caillol et al., 1977; Mordant, 1992; Berger et al., 1995; Deleplancque, 2016), thus allowing the broad-scale distribution and chronology of the location of the main Middle and Late Quaternary alluvial sheets to be estimated.

In addition, the French Geological Survey (BRGM) has compiled a database of more than 500 soundings, which are uniformly distributed over the Bassée alluvial plain, and most of which reached the ~~cretaceous~~Cretaceous chalky substrate. A detailed analysis and interpretation of this database has allowed the substratum morphology to be reconstructed, the alluvial infilling thickness to be evaluated, and a preliminary quantitative analysis of the sedimentary facies distribution to be determined (Deleplancque, 2016). The maximum thickness of the alluvial infilling is thus known to lie between 6 and 8 m.

Geophysical investigations of gravel pits (after removal of the conductive topsoil) were carried out using ground-penetrating radar (Deleplancque, 2016), and have contributed to the characterization of the sedimentary contrast of the sand bar architecture, between the Weichselian and Holocene deposits. The Weichselian deposits are typical of braided fluvial

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systems, with fluvial bars of moderate extent (< 50 m) truncated by large erosional surfaces. The thickness of the preserved braid-bars rarely exceeds 1.5 m. The Holocene architecture is associated mainly with single-channel meandering fluvial systems, characterized by thick point-bar deposits (> 4 m) with a lateral extent of several hundred meters, sometimes interrupted by clayey paleochannel infillings. Traces of small sinuous channels, probably using the paths of former Weichseilian braided channels, are also identified at the edge of the alluvial plain.

Aerial photography and a LIDAR (laser detection and ranging) topographic survey (Figure 2) have been used to characterize the paleochannel plan-view morphologies (style, width, meander wavelength), of the most recent (Holocene) meandering alluvial sheets in this area (Deleplancque, 2016). These measurements were complemented by auger soundings and ^{14}C dating of organic debris or bulk sediment (peat), in order to determine a time-frame for the development of the Seine meanders~~,~~, and to allow ~~this~~these changes to be compared with other regional studies (e.g. Antoine et al. 2003; Pastre et al., 2003). The paleochannel investigated in this study is located 2 km to the South-West of Nogent-sur-Seine~~,~~ (covered by a grassy meadow) and is characterized by larger dimensions than the present-day Seine ~~river~~River. Its width is estimated to lie between 150 and ~~200~~300 m, with a meander wavelength between 2 and 3~~-~~ km. According to the alluvial sheet analysis and the dating of organic material in the mud-plug of the abandoned meander, it is very likely that this paleochannel was active between the Late Glacial and Preboreal periods~~.~~ (Deleplancque, 2016).

~~The main objective of the present study is to refine the lateral extent, and to determine the depth of this paleochannel. The use of geophysical exploration for this investigation is of significant importance, since it should pave the way towards paleo-hydrological~~

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~~reconstruction of the Seine river (estimation of its cross-sectional geometry and paleo-discharge).~~

~~**3 - Methodology**~~

~~*3.1 Measurement setup*~~

3. Field survey and measurement setup

The survey coordinates were determined through the use of a LIDAR map~~,~~, (Deleplancque, 2016), combined with the analysis of a series of auger soundings made along a reference transect of almost 400 m in length (Figure 2~~,~~ and Figure 3). The lateral extent of the meander was delineated using an ~~electromagnetic induction~~EMI system (CMD explorer) produced by GF instruments s.r.o., with non-regular gridding and non-perfect overlapping inside the same area.

~~The identification of Holocene clay infilling along this reference profile was confirmed by measuring several electrical resistivity profiles (ERI), along the reference transect.~~ 3.1 ERI and hand auger soundings~~For this, a Wenner-Schlumberger array was selected, with 48 electrodes positioned at a 1 m spacing for the first 340 m, and a 0.5 m spacing thereafter.~~

~~ElectroMagnetic Induction (EMI) surveys were carried out using a CMD explorer (GF instruments), with vertical (Horizontal CoPlanar - HCP) and horizontal (Vertical CoPlanar - VCP) magnetic dipole configurations. The CMD explorer operates at 10 kHz, and allows simultaneous measurements to be made with three pairs of Tx-Rx coils, using a single~~

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~~orientation (T-mode). Three different offsets were used between the centers of the Tx and the Rx coils, namely: 1.48 m, 2.82 m and 4.49 m, each corresponding to a distinct DOI. As the VCP and HCP surveys were made separately, slightly different sampling intervals were used. In addition, GPS reception difficulties led to several gaps in the VCP and HCP surveys. It was thus important to carefully evaluate these shortcomings, before attempting to merge the HCP and VCP measurements during the inversion. As the CMD allows the user to export raw out-of-phase data (including the factory calibration only), no pre-processing is needed to obtain the value of the ratio between the secondary and primary magnetic field amplitude.~~

~~*3.2 Auger sounding*~~ results

A total of 13 hand auger soundings down to a maximum depth of 2.4 m (Figure 4), were made along the reference profile. Some of these soundings did not reach the base of the paleomeander mud-plug (clay / gravel transition), suggesting that the maximum depth of the paleomeander is greater than 2.4 m. The auger soundings revealed the presence of two main units. The uppermost unit is comprised of topsoil, which overlies a layer of loam containing a significant proportion of gravel and sand in the eastern part of the reference profile~~portion of the paleochannel.~~. A clayey layer, the bottom of which was not reached in the deepest portion of the paleochannel, is situated below this unit. In some soundings, the clayey facies contains layers of peat (PTA, 04, 05, 06, 08, and 09, in Figure 4).

~~*3.3 ERI results*~~

The identification of the Holocene clay infilling along this reference profile was confirmed by measuring several and overlapping ERI profiles (24 m common), along the reference transect. For this, a Wenner-Schlumberger array was selected, with 48 electrodes positioned at a 1 m spacing for the first 340 m, and a 0.5 m spacing thereafter.

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The ERI cross-section (Figure 5) is produced using a dataset of more than 5000 measurements. ~~In order to estimate the true~~A Wenner-Schlumberger reciprocal array was used, which provides a good compromise between lateral and depth sensitivities (Furman et al, 2003; Dahlin and Zhou, 2004). In order to estimate the interpreted resistivity distribution, the resulting apparent resistivity sections were processed by means of inverse numerical modeling~~,~~ using the Res2dinv software (Loke et al., 2003) with its default damping parameters, and the robust (L1-norm) method. Following a total of 7 iterations, the resulting ERI profiles had an rms error of 0.48% and 0.93%, for the case of the 1 m and 0.5 m electrode spacings, respectively.

The resistivity cross-section reveals two main units: an uppermost conductive unit with a resistivity below 20 Ωm, corresponding to a clayey matrix, and a second, more resistive unit with a resistivity greater than 60 Ωm, associated with a medium/coarse-grained silty horizon. The auger soundings are always achieved by a refusal, which is most likely due to the fact that they had reached the resistive second unit. When compared to the analysis achieved using auger soundings, the electrical properties of the topsoil/loam formation appear to be merged with the clayey formation, with the exception of the western portion of the cross-section, which has significant sand and gravel content. This outcome could also be due to the finer spatial resolution of the ERI measurements (electrode spacing of 0.5 m). It is worth noting that the current sensitivity issue associated to the topsoil/loam identification could have probably been overcome with a gradient or a multiple gradient array, without significant loss in DOI (Dahlin and Zhou, 2006).

3.2 ~~*3.4*~~ EMI surveys and calibration ~~*from ERI*~~

EMI surveys were carried out using a CMD explorer (GF instruments), at 1-meter height above the ground, with vertical (HCP, horizontal co-planar) and horizontal (VCP, vertical co-

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Mis en forme : Retrait : Première ligne : 0 cm planar) magnetic dipole configurations. The CMD explorer operates at 10 kHz, and allows simultaneous measurements to be made with three pairs of Tx-Rx coils (unique Tx coil), using a single orientation (T-mode). Three different offsets were used between the centers of the Tx and the Rx coils, namely, 1.48 m, 2.82 m and 4.49 m, each corresponding to a distinct DOI (approximately 2.2 m, 4.2m, 6.7 m for HCP respectively, and 1.1 m, 2.1 m, 3.3 m for VCP respectively). As the VCP and HCP surveys were made separately in continuous mode (0.6 s time step), slightly different sampling intervals were used. In addition, GPS reception difficulties led to several gaps in the VCP and HCP surveys. It was thus important to carefully evaluate these shortcomings, before merging the HCP and VCP datasets prior to the inversion. As the CMD allows the user to export raw out-of-phase data (including the factory calibration only), no pre-processing is needed to obtain the value of the ratio between the secondary and primary magnetic field amplitude.

Apparent electrical conductivities measured using EMI are particularly sensitive to the orientation of the device, the height above the ground at which the EMI system is ~~installed~~setup during the survey, and the 3D variability of the ~~conductivity~~EC. In addition, for the interpretation of the measurements, the ground is assumed to be horizontally layered at any given location, even for the smallest dipole offset. ~~Although~~It is worth noting that even if the orientation (vertical or horizontal) and height of the dipole are initialized at the beginning of each survey, ~~the noise associated with the measurements is related to the near surface variability and in a certain way to~~ variations ~~in~~of orientation and height of the EMI device ~~during acquisitions~~inevitably occurs and add noise to the measurements.

In order to improve absolute (not relative) evaluation of EMI data, in situ calibration of EMI data is important. Ideally, calibration must be performed for several heights and over a perfectly known half space of which electromagnetic properties ~~spanned~~span over a

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representative range of ~~conductivity~~EC_a values. For the CMD instrument, calibration factors are provided by the manufacturer for 0 (laid on ground) and 1 m heights. However those factors are valid for a given ~~conductivity~~EC_a range and are dependent on the prospection height (which is never exactly 1 m). This height effect, as mentioned above, has a relative stronger influence on the shortest offsets; consequently, to improve the absolute estimation of ~~the apparent conductivity~~EC_a, it is important to have a reference zone where the ground is very well constrained. ~~A series of hand-made auger soundings were used to obtain reliable direct observations down to a depth of 2 m. It shows that the interface between the silty clay and the gravel corresponds to the conductive filling; this was observed at some of the auger sounding locations, namely soundings numbered: 01, 02, 03, 10, 11, 12, and 13, which barely attained a depth of 2 m.~~ In order to obtain deeper information than obtained with the hand-made auger soundings, an ERI prospection has been carried out; the inversed~~-~~ ERI section provides reference and absolute values of the local resistivities and can be used in the calibration process as described in Lavoué et al. (2010). It is worth noting that other in situ ways of calibration could be performed~~,~~ (e.g. Delefortrie et al., 2014), particularly, using the theoretical response of a metallic and non-magnetic sphere (Thiesson et al., 2014).

During the field data acquisition we faced several difficulties that prevent us to do a CMD profile exactly on the reference profile. Actually, the EMI data used for the calibration have been taken from the mapped data closest to the reference profile. This has led to several positioning and alignment errors ~~:~~ because: (1) the EMI data do not exactly cross the reference profile~~, ~~; (2) the EMI data are irregularly spaced along the ERI profile~~, and ~~; (3) the orientation of the CMD device was not exactly the same, for each measurement retained for the calibration~~.~~; and, (4) the height above the surface is changing constantly during the acquisition (less than 10-20 cm).

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In order to compute the ~~apparent conductivity~~EC_a of a layered ground, based on measurements made using a horizontal or vertical magnetic dipole configuration, we used the well-known electromagnetic analytical solution for cylindrical model symmetry, given by (Wannamaker et al., 1984; Ward and Hohmann, 1988; Xiong, 1989). However, in the case of thin layers or high frequency content, convergence problems can be encountered in the numerical integration of the corresponding oscillating Bessel functions. At frequencies below 100 kHz, as in the case of the present study, the numerical filters developed by Guptarsarma and Singh (1997) were found to provide an efficient solution to this problem. The inversion scheme developed ~~in~~by Schamper et al. (2012) was used to invert the EMI measurements. For each offset and dipole orientation, a linear relationship (shifting and scaling) is determined between each measured ~~apparent conductivity~~EC_a and the ~~apparent conductivity~~EC_a estimated from the resistivity models (derived from the ERI panel, Figure 6). Once the calibration is done,~~-~~ the new EMI inversion matches the ERI used for the calibration which illustrates the validity of the procedure. ~~Actually, despite~~Despite the~~-~~ linear relationship assessed between the EMI and ERI resistivities, several non-linear operations are applied: (1) ERI local 1D models along the profile are used to simulate EMI measurements~~,~~; (2) EMI field data are then fitted (linearly) to those simulations using a non-linear optimization procedure to estimate calibration factors~~,~~; (3) finally the calibrated/shifted data are inverted with a non-linear forward modeling. ~~All those non-straightforward steps imply that~~Each of the previous operations implies a ~~check is~~ necessary check to ensure that the calibration process has been correctly applied. Step (3) does not guarantee that estimated interfaces will match the ERT interfaces (1) if the fixed/chosen resistivities are not correct, or (2) if EMI does not integrate the ground in the same way as the ERI in case of strong anisotropy, which seems not to be the case here, since a good match is obtained.

The correlation coefficients are comprised between 0.5 and 0.7. Such values can be explained by several sources of errors in the estimation of the EMI apparent conductivities along the reference profile: (1) the differences in the location between the EMI measurements used for the calibration and the ERI profile~~,~~; (2) the fact that the one dimensional model used for the EMI modeling is extracted from the inversed 2D resistivity section~~,~~; and, (3) the difference of sensitivity between the ERI and EMI data. The regressions indicate the need of a stronger correction for the VCP configuration than for the HCP configuration. The scaling correction decreases as a function of offset, particularly for the HCP, which can be explained by the fact that small offsets are more sensitive to positioning and orientation errors, as well as to natural near-surface variabilities.

3.~~*5 Inversion*~~3 EMI inversion parameters

Once the calibration process is completed, the corrected, apparent HCP and VCP conductivities are inverted, following their interpolation (by kriging) onto the same regular grid. The ERI results indicate a two-layer model (but do not highlight the topsoil), while the auger sounding show ~~clearly~~ a topsoil layer of a few decimeters thickness above the conductive formation. Consequently, a three-layer model seems reasonably justified all over the site during the inversion process to represent the studied area: a resistive topsoil, a conductive clayey filling, and a resistive sand/gravel layer. The resistivity of each layer corresponds to the peak values of the bimodal histograms of the reference 1-meter-spaced ERI profile, as shown in Figure 7. The topsoil ~~conductivity~~EC derived from the half-meter-spaced ERI profile in the ~~eastern~~western portion is found to be very similar to the ~~conductivity~~EC of the resistive layer inferred from the 1m-spaced ERI profile~~;~~: thus, the first and third layer ~~conductivities~~EC are ~~thus~~ considered to be equal. This leads to the following model for the mean ~~conductivity~~EC of the three layers: σ_1 = 13 mS/m; σ_2 = 72 mS/m; σ_3 = 13 mS/m. It

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should be noted that the CMD explorer is operated at a single frequency (10 kHz). The sounding height was taken to be ~~1m~~1 m for all the field measurements.

It is worth noting that the 3-layer model chosen instead of a 2-layer model, all over the site, could be questionable. Letting the inversion process decide between a 3 or 2-layer model could have been an option. In the present case, the difference between a 2-layer or 3-layer model is clearly negligible where the interpreted thickness of the topsoil (for the 3- layer model) is less than a few decimeters. For such low thicknesses the topsoil can be considered as non-existent considering the acquisition geometry and settings of the CMD explorer.

Figure 8 shows the inverted thicknesses of the first and second layers, and the data residual for the HCP (3 offsets), the VCP (3 offsets), and the combined HCP and VCP conductivities (6 apparent values). The standardized root-mean-squared residual (SRMR) for N independent measurements is given by:

$$\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{d\_(i)-d_{meas}(i)}{std(i)}\right)^{2}}{N}}$$

$$SRMR = \sqrt{\frac{\sum_{i=1}^{N}\left(\frac{d(i)-d_{meas}(i)}{std(i)}\right)^{2}}{N}} \quad (1)$$

Where N is the number of data points, d is the forward response of the estimated model at the end of the inversion, d_{meas} contains the data, and *std* is the ~~stand~~standard deviation of the data.

The standard deviation *std* was estimated from repeated measurements at several locations, as 1 mS/m (with a minimum error of 5%).

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3.4~~-~~ EMI ~~inversion~~ results ~~and discussion~~

3.4~~-~~.1 General trend

The layer thickness inversion was performed using three different datasets: (1) the HCP dataset, (2) the VCP dataset, and (3) the combined HCP and VCP dataset (Figure 8).

Whatever the dataset used for the inversion, the thickness computed for the topsoil formation (indicated by *"Thickness 1"* in Figure 8) is globally very small (blue), whereas that computed for the conductive infilling (indicated by *"Thickness 2"*) has a significantly higher value (red), and *vice versa*. Although it varies in thickness, the conductive layer formation spans most of the survey area, whereas the resistive topsoil formation varies mainly in two distinct locations: (1) the south-western limit of the surveyed area, where it reaches a depth of 2 m; and, (2) the mid-northern portion of the surveyed area, where its thickness never exceeds 0.6 m. In addition, very small scale topsoil formations are scattered over the surveyed area. In all places where the estimated thickness of the first layer is less than 20 cm, the topsoil can be considered as inexistent and a 2-layered model is enough to explain EMI data. Nevertheless, all of the observed topsoil formations appear to be correlated with a local increase in data residual. The thickness of the conductive infilling lying below the topsoil formation~~,~~ ranges between 0 m, in the south-western portion of the studied zone, and its maximum value of almost 2 m at the center of the map.

The VCP mode increases the measured thickness of the shallowest portions of the topsoil layer, whereas the HCP mode tends to negate this layer over most of the surveyed area (central part), where it is not extremely thick. This tendency appears to be correlated with a slight increase in the thickness of the second conductive layer.

The inversion of all data, in the form of a single dataset, appears to lead to a mixture of the properties inherent to each of the constituent datasets. This outcome is particularly

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noticeable in the case of the topsoil formation, where certain structures retrieved by both datasets are emphasized with respect to structures that are present in only one or the other of these.

3.~~4~~.2 Internal variability

In addition to strong meander wavelength variations, each dipole orientation reveals different level of heterogeneities in the material present in the conductive ~~fill~~infilling, as well as the topsoil. Concerning the material close to the surface (< 2 m), this variability is clearly illustrated by the auger soundings, whereas the conductive unit identified by the ERI section is considerably more complex. In simple terms, the thickness of the conductive material tends to decrease, wherever the silty and sandy material reaches the surface.

It should be noted that the inversions observed for each dipole orientation are not systematically preserved in the inversion produced by combining the data from both dipole orientations. This result indicates that in the present context, each orientation is complementary, and contributes a specific set of information. This is particularly relevant in the northern portion of the studied area, where the thickness of the first resistive layer is more variable when it is measured with the horizontal dipole configuration (VCP), than with the HCP configuration.

The data residual has numerous peaks in the south-western portion of the study zone. In this zone, the resistive topsoil reaches a thickness of 1 m, leading to EMI measurements with a lower sensitivity (and thus lower signal to noise ratio - SNR). The combined HCP&VCP data inversion naturally leads to the occurrence of higher values of data residual~~,~~ ~~than in the case of the individual HCP or VCP inversions.~~ than in the case of the individual HCP or VCP inversions. Indeed, it is difficult to compare the data residual maps between the three proposed datasets (i.e. HCP alone, VCP alone and both) as the physical contribution

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associated to each dataset inversion results is related to the couple dataset & model used for the inversion. HCP and VCP modes do not integrate the ground in the same way exactly. If the ground within the footprint of the EMI system is a bit far from a tabular model, then the interpretation with local 1D models can be more difficult with both data sets combined than with only one of the two sets analyzed. The difficulty to invert the HCP and VCP datasets jointly also arises from the fact that: (1) the locations of the soundings between the two surveys are not exactly the same as the modes cannot be acquired at the same time; (2) the heights varies differently; and (3) the pitch and roll are not constant. For those last two points one could imagine the monitoring of these “flight” parameters to correct the data, which is routinely done for airborne electromagnetic surveys. But this feature does not exist at the present time for ground based EMI devices.

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~~**5- Conclusion**~~

4. Discussion

In the present study, the outcomes of ERI and EMI surveys integrate quite satisfactorily the lithological information provided by the auger soundings, but have not yet been checked with exhaustive hydrological information. During the presented geophysical campaign (low water period), the water level measured from PTA02 to PTA04 and from PTA11 to PTA13 locations indicate a groundwater situated at 1 m depth, roughly at the interface between the clay infilling and the upper geological unit (Figure 4). In the survey area the water table could rise close to the surface at high water periods, which implies that the conductivity of the topsoil/loam formation should increase. In the closest piezometer located 1 km west from the

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prospected site, the water table was situated at 70 cm below the surface. The EC measured in the same piezometer in 2011 was 640 µS/cm (12Ωm) and showed a seasonal variation of the water table of approximately 60 cm (Voies Naviguables de France (VNF) tech. report, 2011).

The clay infilling is then always saturated while the topsoil/loam upper unit is almost never dry. Even significant changes in the degree of saturation of the topsoil/loam formation would hardly allow the value of its resistivity to lower down to the resistivity of the clay infilling (~10-20 Ω.m) estimated thanks to the histogram (Figure 7). Consequently, if the thickness of the topsoil/loam formation is significantly larger than a few decimeters, the presence of the water table at the surface does not challenge the three layer model assumption based on the lithological boundaries.

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From a hydrogeological modeling perspective, one of the most important issues is the assessment of the constitutive relationship that links EMI/ERI electrical conductivity/resistivity to hydrodynamic properties (i.e. the permeability) because of the difficulty to discriminate the bulk conduction from the surface conduction mechanism. In the present case, a sample located at PTA12 and at a depth between 140 and 160 cm, show major peaks of calcite and quartz, significant peaks of illite-montmorillonite, and small peaks of kaolinite. The clayey infilling corresponds to a saturated marl sediment containing 20-30% of clay and 50-60% carbonate. The high amount of carbonate originates from the weathering of the chalky cretaceous limestones that outcrop on the borders of the alluvial plain. As the salinity is low and the clay content significant, the electrical conductivity of the clayey infilling is essentially driven far more by the surface conductivity than by the pore water conductivity. As it is not the case for the first decimeter of topsoil/loam, it could be another argument that reinforces the pertinence of the three layer model assumption for the inversion process.

From a more general perspective, EMI calibrated with ERI and auger soundings contributed to a better characterization of the geometry and variability of this paleomeander. The results reveal a complex cross-sectional geometry of the conductive clayey layer, featuring from the south-west to the north-east: (1) a sharp contact to the south-west with a resistive sand and gravel layer; (2) a roughly constant thickness of 2 meters of the conductive layer, extending over more than 200 m; (3) a decrease of the thickness of the conductive layer (~ 0.5 m) related to the raising of the gravely substrate, over a length of ~ 100 m; and, (4) an increase of the conductive layer to the north-east. Unfortunately, the contact of the conductive layer with the resistive layer to the north-east was not captured due to the limited extent of the surveyed area. It is thus difficult to conclude if the paleomeander is restricted between PTA03 and PTA10, with a mean depth of 2 m and a width of 250 m, or if the former channel was wider (> 350 m) with shallower part associated to sand/gravel bars. It is also not excluded that several (2 or 3) small channels were active during low water stages within a larger “bankfull channel”, producing local incision of the bed. Nevertheless, and compared to the modern Seine river (~ 50 m wide, up to 5 m deep), this paleochannel attributed to the Late Glacial/Preboreal period shows a larger width, and a significantly larger width-to-depth ratio. These differences are attributed to different paleohydrological and paleoclimatic conditions, with larger water discharges, larger and coarser solid fluxes, and less cohesive soils in the absence of developed vegetation.

From a hydrogeological perspective, the paleo-meanders of the Late Glacial/Preboreal period are filled with large but relatively thin (2 m) mudplugs compared to the alluvial plain thickness (6 to 8 m), which should produce little impact on the groundwater flow. However, this should be confirmed by numerical modeling. The study should be extended to paleomeanders attributed to different climatic periods of the Holocene, which present different morphologies and aspect ratios.

5. Conclusion

We presented the results of the geophysical investigations of a paleochannel in the ~~alluvial plain of La~~ Bassée alluvial plain (Seine ~~basin~~Basin, France). The location of this paleochannel and its ~~internal variability~~geometry, suggested by a LIDAR campaign, have been accurately mapped using a multi-configuration (various offsets and orientations) electromagnetic induction device ~~(CMD explorer from GF instruments).~~ .

In order to correct the ~~sensitivity~~drift and factory calibration issues arising from EMI measurements, a calibration procedure was implemented, based on the use of a linear correction with ERI inversion results and auger soundings. The shifting and scaling of EMI HCP and VCP measurements was made for the three available offsets (1.~~48m~~48, 2.~~82m~~82 and 4.~~49m~~49 m), at a frequency of 10 kHz. Six apparent conductivities allowed the inversion of a reliable three-layer model, comprising a conductive filling with ~~a conductivity~~an EC equal to 72 mS/m below the topsoil, and a resistive substratum having ~~a conductivity~~an EC equal to 13 mS/m. The conductivities of the three-layer model were adjusted using the bimodal histogram distribution of the reference ERI profile.

~~In conclusion, the~~The inverted thicknesses are characterized by a significant internal variability in the conductive filling and the topsoil, associated with the paleochannel geometry.

The joint inversion of multi-offset HCP and VCP configurations leads to a very interesting result, in which the internal variability description is considerably enhanced. We

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believe that multiconfigurationmulti-configuration EMI geophysical survey carried out at an intermediate scale, should provide a great complement to TDR (Time Domain Reflectometry) for a quantitative and physical calibration of remote sensing soil properties and moisture content. Combined multi offset VCP and HCP prospections could significantly improve the accuracy of hydrogeological modeling by potentially providing a hydrogeological picture of the first meters sedimentary setting in terms of lithological distribution; but it would also lead to a substantial increase in survey costs with the instruments currently available on the market.

Although the generalization of combined VCP and HCP prospection could significantly improve the accuracy of hydrogeological modeling, it would also lead to a substantial increase in survey costs. This option thus remains to be debated during the 7th phase (WP 1: Sedimentary, Morphological, Hydrogeological and Thermal properties of Hydro-ecological Corridors) of the PIREN Seine research program (2015-2019).

6- Data availability

In order to access the data, we kindly ask researchers to contact the corresponding author.

7- Acknowledgement

This research was supported by the PIREN Seine research program. (2015-2019). We extend our warm thanks to Christelle Sanchez for her participation in the geophysical survey. and to Laurence LeCallonnec for carrying out the XRD experiment.

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Figures

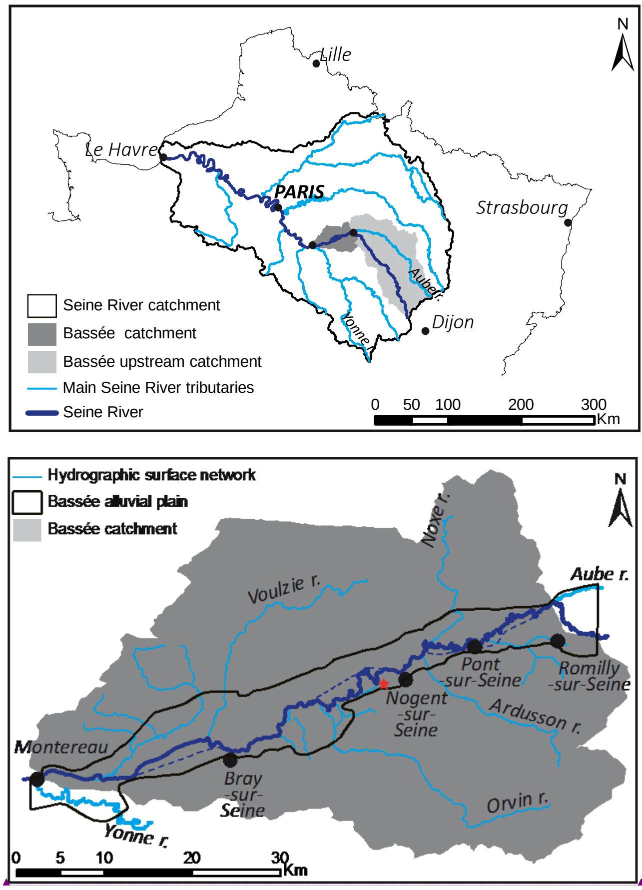

Figure 1: ~~maps~~Maps of the Seine catchment (top) and the Bassée alluvial plain~~.~~ (bottom).

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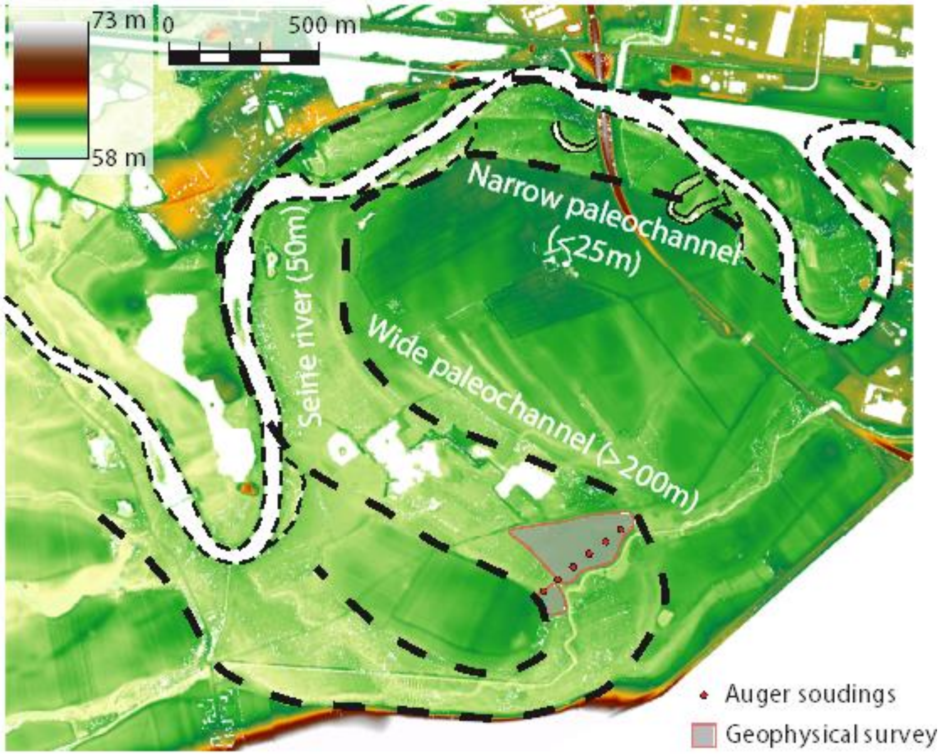

Figure 2 : LIDAR map of the ~~studied~~study area, showing the contemporary location of the Seine ~~river~~River, together with the narrow and wide paleochannel interpretations.

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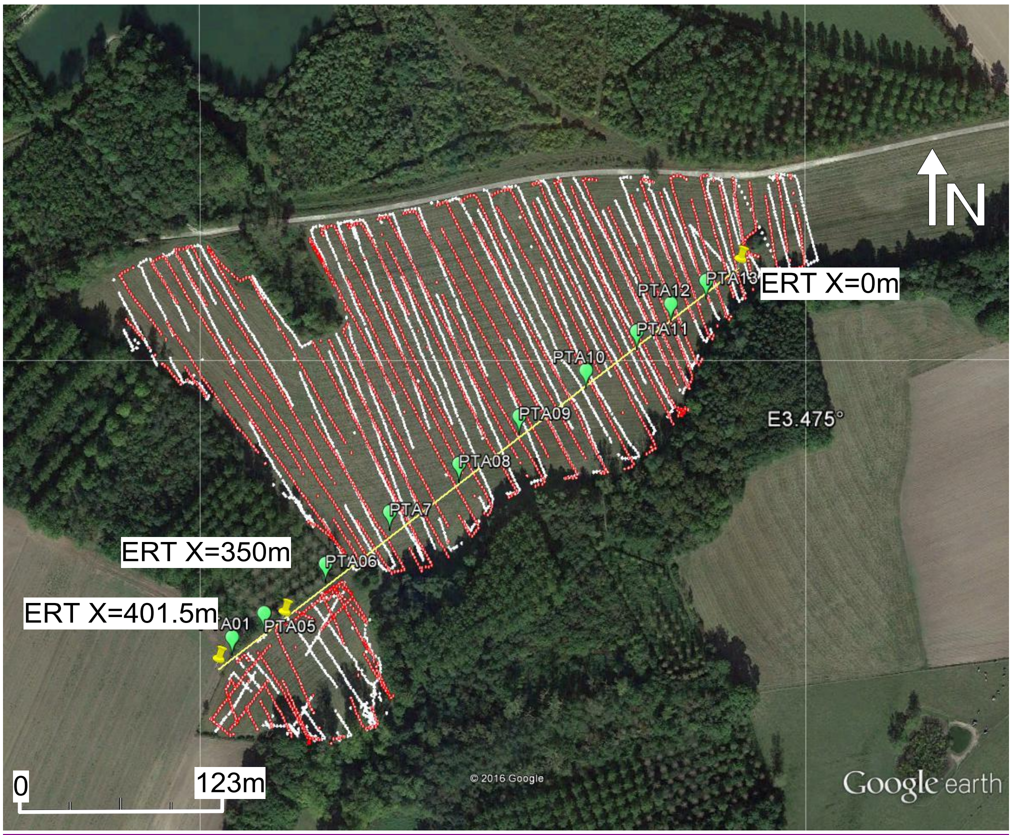

Figure 3: Map of the surveyed area, showing the ~~loci~~locations of the VCP (red) and HCP (white) measurements~~.~~ (GPS issues explain the holes within the lines). The reference (ERI) profile, recorded with a Wenner-Schlumberger configuration using 1 m electrode spacing between 0 and 350 m, and a 0.5 m electrode spacing between 350 m and 401.5 m, is indicated by the yellow line. As green dots, the locations of the hand auger drillings.

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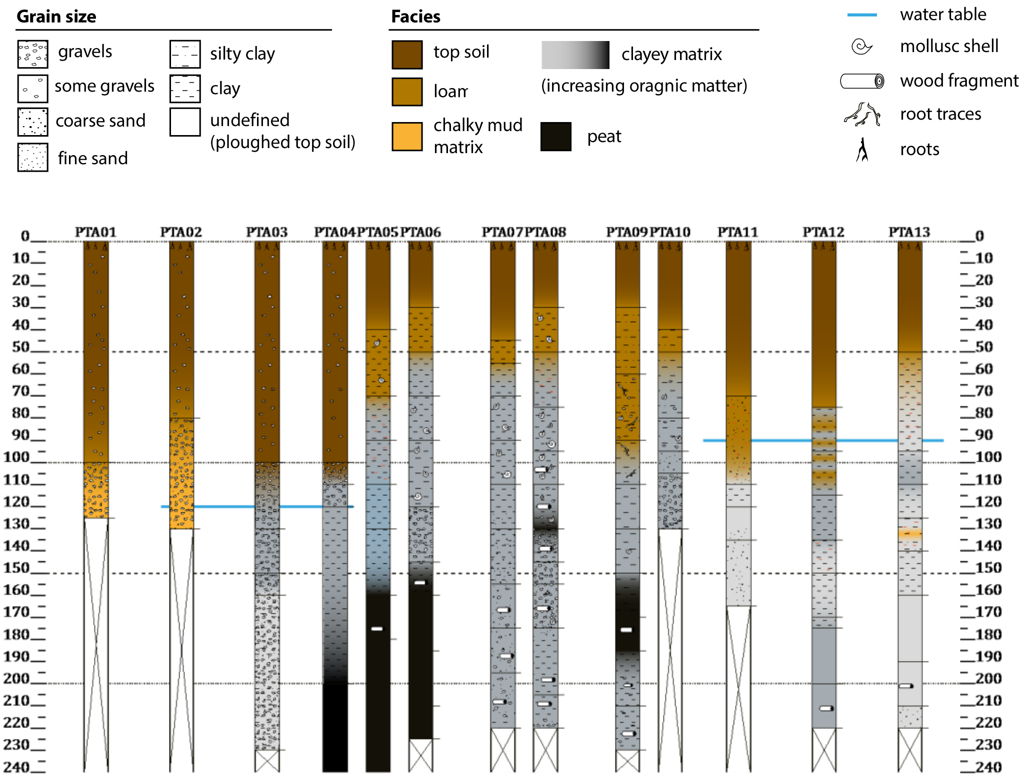

Figure 4: ~~log~~Log of hand auger soundings performed along the reference profile. The position of each sounding along the ERI profile is shown in Figure 5.

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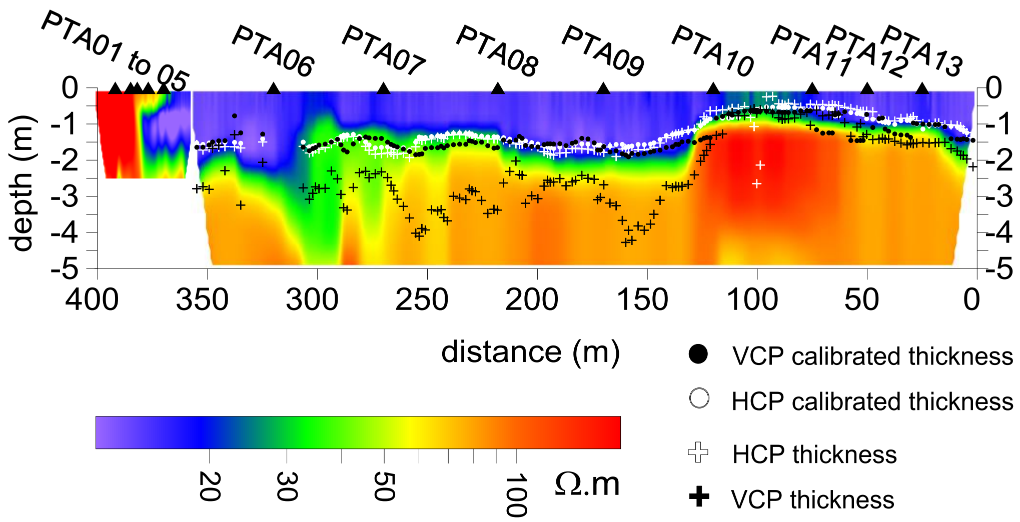

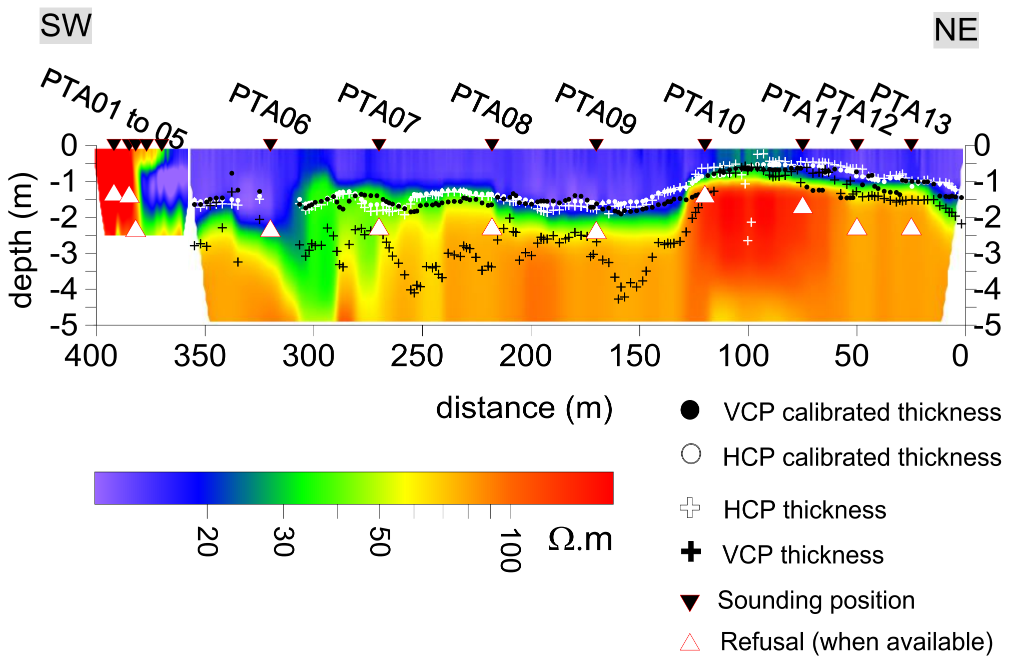

Figure 5: Results from the electrical resistivity tomography (ERI) inversion, computed along the reference profile. This ~~map clearly~~section reveals the two main (conductive and resistive)

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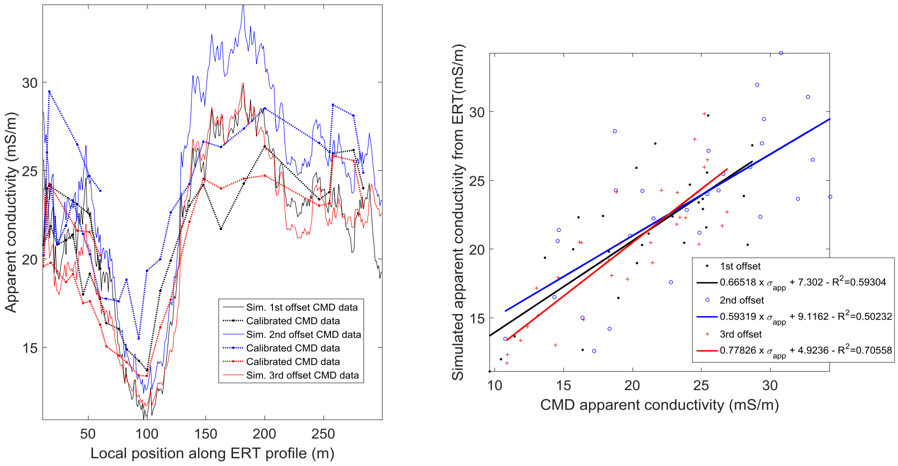
geological units. The markers correspond to the inverted ~~loci~~location of the interface (from EMI measurements) between the conductive unit and the substratum, before and after linear calibration (Figure 6). This figure shows that calibration of the raw VCP measurements leads to significant corrections in inverted depth, when compared to the calibration of the HCP measurements.



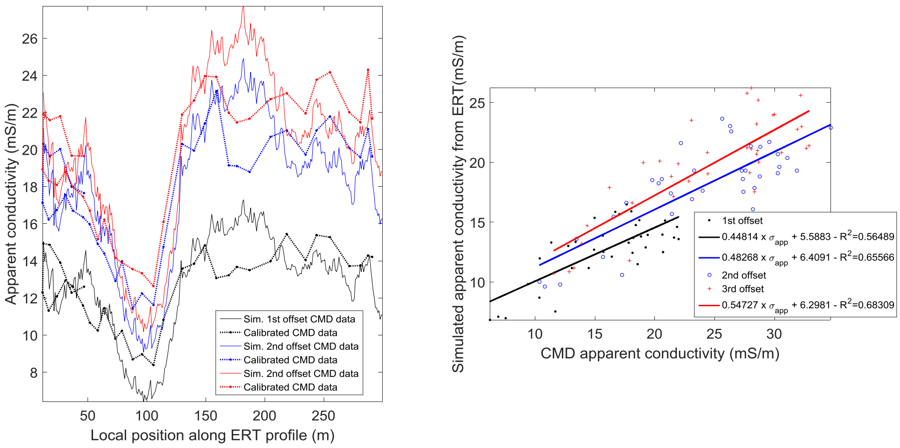


Figure 6: HCP (top) and VCP (bottom) calibration results obtained along the reference profile. Left: the simulated apparent CMD conductivities based on the ERI inversion

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compared to the calibrated EMI measurements. Right: scatter ~~plot~~plots of the measured *vs.* simulated apparent conductivities. The solid lines indicate the corresponding linear regressions.

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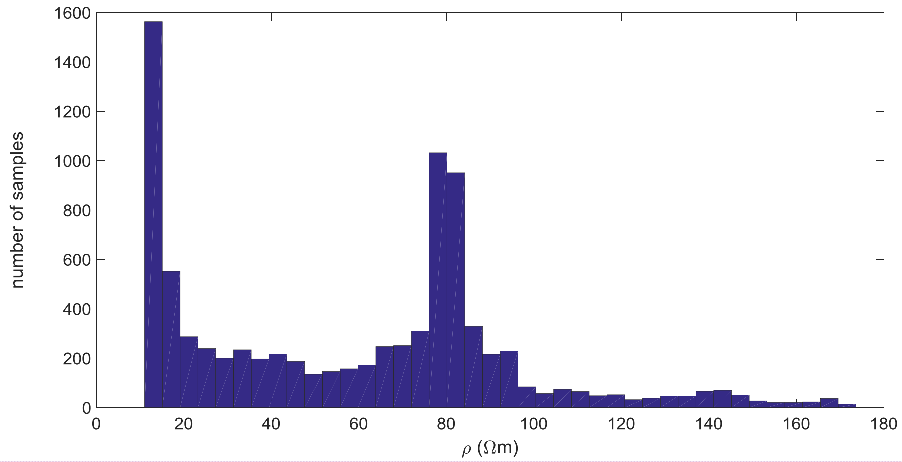

Figure 7: ~~histogram~~Histogram of the electrical resistivity values determined for the ~~tomographic cross~~ERI section shown in Figure 5.

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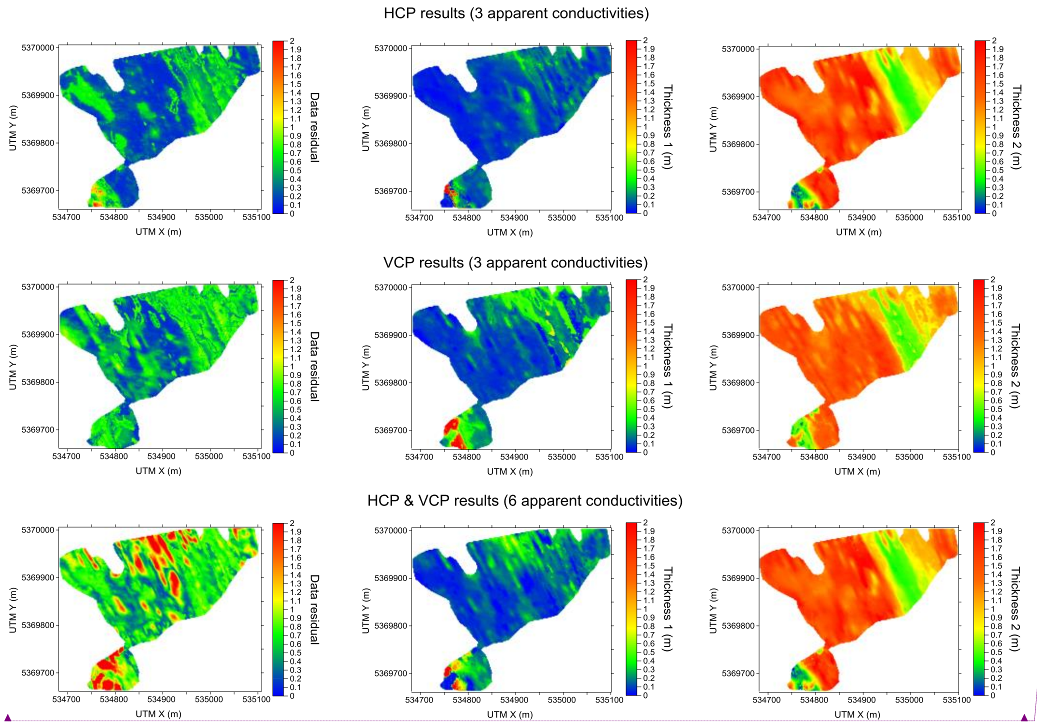

Figure 8: Results of the CMD inversion, including the data residual (left column), for a three-layer model (1: topsoil, 2: conductive filling, and 3: resistive substratum). The thicknesses 1 and 2 correspond to the topsoil and conductive filling, respectively. The prospection height is 1 m. The conductivities are set to σ_1 = 13 mS/m, σ_2 = 72 mS/m and σ_3 = 13 mS/m. A noise level of 1 mS/m on the apparent conductivities was assumed, with a minimum relative error of 5%.

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