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Interactive comment on "Combining cross-hole geophysical and vadose zone monitoring systems for vadose zone characterization at industrial contaminated sites" *by* N. Fernández de Vera et al.

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Dear Anonymous referees 1 and 2,

First of all I would like to thank you for the time that you have taken in reviewing our document. Your comments are really valuable and essential to improve the outcome of our work. Responses are shown one by one to the questions that you proposed. Upon decision of the editor, a revised manuscript will be prepared with an improved version of the document.

Previous to responding to each of your comments individually, some clarifications must be made to both referees. After having a careful read to both of your comments, it

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was observed that some of your questions and comments were relatively coincident. Therefore, a general explanation of the aims and purposes of the study must be made in order to clarify such issues. Table 1 summarizes the comments that you have both pointed out, followed by a response to them which is explained with further details below. In addition, improvements that will be made in the manuscript following these comments are pointed out.

The motivation of the study is initiated from the technical challenges that arise when characterizing the vadose zone of industrial sites with in-situ field instrumentation. The VMS has been successfully implemented in a variety of conditions and climates (e.g., Dahan et al, 2009; Rimon et al., 2011; Turkeltaub et al., 2015). However, such system has never been tested at industrial contaminated environments containing disturbed underground with possible fractured systems and in such climatic conditions. Therefore, the main topic of the manuscript is based on VMS studies. In order to support and improve the spatial heterogeneity in which the VMS system is installed, images from cross-hole ERT methods are considered. Cross-hole ERT methods are not the main topic of the manuscript. As pointed out by reviewer 1, the title might suggest that the study is mainly focused on ERT monitoring, and this might be misleading. Therefore, the title will be modified as follows: “Improved characterization of industrial sites with the Vadose Zone Monitoring System (VMS)”.

In order to test the VMS and cross-hole concept, an industrial contaminated site was chosen for installation. At this site, water infiltration mechanisms and contaminant transport across the vadose zone are not well understood, as the subsoil has been disturbed and no in-situ information of the vadose zone is available. The installation of both VMS and borehole geophysics was implemented in such site in order to improve the lack of information of the subsurface as it is. Therefore, this manuscript presents the results from initial monitoring studies from the VMS under natural recharge conditions. Specifically, the main objectives of the monitoring studies are to identify rainfall infiltration mechanisms and to characterize the chemistry of infiltrated waters as well

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as contaminants leaching across the vadose zone. In addition, cross-hole ERT images are used to identify structural features of the subsurface. These initial studies are intended to demonstrate that general interpretations can be made already thanks to a more complete set of data provided by the VZES, with minimum amount of indirect estimations and modelling required. Initial interpretations from monitoring studies constitute the foundation of further experiments. This is the case of tracer experiments carried out on site after the initial monitoring period, where time lapse measurements with cross-hole geophysical methods were carried out. However this is out of the scope of the initial monitoring phase proposed in this study, and such experiments are not presented in this manuscript (a subsequent paper is in preparation to present these tracer experiments). An improved explanation of the objectives of the study will be presented in the introduction.

Even though time lapse measurements are not included in this study, ERT images provide value for the following reasons. Although the main lithologies of the subsurface at the study were identified in previous drilling campaigns, their thicknesses and lateral distribution were not known as a consequence of extensive soil disturbance and the presence of artificial materials. The borehole material was only recovered partially, as technical problems occurred during the drilling procedure and logging could not be completed Therefore, geophysical imaging was necessary. Multidirectional imaging allowed to identify not only the lateral extent of backfill layers, but to understand which flow mechanisms are likely to be dominant in different directions as a consequence of structural heterogeneities.

As pointed out correctly by both reviewers 1 or 2, this manuscript does not show a combination of both VMS and geophysics to characterize the vadose zone. Instead, each component of the VZES is providing information to obtain a more complete characterization of the vadose zone of the study site. Therefore, it is an integration of techniques for the purpose of characterization, rather than a combination of discussion and methods. This point will be clarified in the study objectives. Regarding the limitations of

VMS sensors, previous studies have pointed out that water content measurement by flexible time domain reflectometry sensors (FTDR) on the VMS could overestimate water contents under dynamic conditions of vertical water percolation (Hinnell and Ferré, 2008). Dahan et al. (2009) calculated an overestimation of 1% at low water contents and up to 3% at maximum measured percolation velocities. In this study, water content measurements are used to assess water flow mechanisms on the basis of FTDR sensor reaction to rainwater infiltration. Accordingly, potential overestimation of water content should not affect the general results and conclusions.

Cross-hole ERT techniques are limited by resolution and borehole inversion effects. As pointed out already in the introduction, geophysical information is mostly used in a qualitative manner, but is valuable when combined with hydrological information (Slater et al., 2002). According to Nimmer et al. (2008), borehole inversion effects are not significant in small diameter boreholes ($\leq$0.1m) when the fill resistivity contrast is one order of magnitude or less. In this case the external diameter of the boreholes built for geophysical purposes is 4 inches (0.1016m) and the mixture of the filling was designed so it would not have a big contrast with background resistivities. In addition to cross-hole methods, surface ERT measurements were carried out during preliminary investigations. The results from surface profiles are consistent with those from cross-hole measurements, which confirm that the artifact effects do not affect large areas of ERT data, allowing interpretation from images. The resolution of the images is enough for the purpose of identification of structures.

To conclude, it is hoped that these clarifications together with individual responses and listed potential changes in the manuscript will contribute to improve the overall understanding and aims of our work.

Individual responses

Anonymous Referee 1

Article: The authors present a Vadose Zone Monitoring Setup at an industrial con-

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taminated site motivated by the need to better understand hydrological and chemical processes. The monitoring system consists of four deep borehole ERT arrays and a TDR and suction cup array in a slanted borehole. In addition seven piezometers are reported. Based on one ERT tomography and the borehole logs the Subsurface is characterized. Continuous monitoring of soil water content and sampled water analyses for dissolved ions and heavy metals are used for process interpretation.

1 General comments The overall study appears to be an excellent example of shallow geophysics for hydrological applications in combination with water chemistry and soil water dynamics. The authors also approach subsurface flow in matrix and macropores. As such the study is highly relevant and fits the scope of HESS. Unfortunately, the manuscript (MS) is not yet in a shape that really pinpoints the strengths and limitations of the approaches and corroborates the findings with data. I hence suggest the MS to be strongly revised along the following lines prior to publication in HESS. I hope the authors find these comments as constructive contribution to improve the presentation of their work.

1.1 Title and structure of the MS From the title I have expected much more application of the installed ERT arrays as main part of the proposed vadose zone monitoring system. This mismatch of expectation and presentation somewhat remained through the MS. On the one hand, this is due to a lack of structure. On the other hand, the used terms and explanations deserve more precision. What is the experiment in contrast to the monitoring?

This question is clarified in the general explanation.

Why do you distinguish between VZES and VMS?

The difference between the VZES and the VMS is that the VZES includes both the VMS and borehole geophysics. The term VZES was established to group both techniques (VMS and geophysics). However, this term will be eliminated if it leads to confusion.

What is the theoretical concept of your study, what hypotheses do you approach and how does the setup contribute to the identified shortcomings?

As clarified already in the general explanation, the study arises from a technical challenge, rather than a theoretical concept. At this point our hypothesis was based on the idea of improving in-situ vadose zone data quality and accessibility by integrating the VMS and geophysical techniques. The implementation of the setup has provided complete sets of data containing hydraulic, chemical and spatial information of the subsurface. Such initial results obtained from in situ monitoring of rainfall infiltration have allowed making interpretations of water flow mechanisms and solute chemistry with minimum amount of indirect estimations. Based on such successful outcome, the implementation of VZES at industrial contaminated sites could be used as a tool to improve the development of site conceptual models.

By what means are analyses done?

In this study, FTDR methods are used to monitor water content changes as a response to rainfall infiltration episodes. From such variations water flow mechanisms are inferred. Water samples from VSP are analysed to characterize the chemistry of infiltrated water and contaminants and its evolution over time and space. Results from analyses are used with multiple purposes. The impact of the setup installation on the chemistry of pore water samples is assessed by monitoring the evolution in time and depth of certain ions in water. Subsequently, the chemical signature of infiltrated waters across the vadose zone is identified by representing the proportion of anions and cations in Piper diagrams (Piper, 1953). Finally, contaminants are analysed in sampled waters and the evolution of their concentrations at multiple depths is monitored. Geophysical images are used to identify the structure and lateral extent of the subsurface. The ultimate goal of these analyses is to have a better understanding of hydraulic and chemical processes of water and contaminants infiltrating across the vadose zone system of the study site.

What error margins have to be considered for the respective techniques?

As described in the general explanation, overestimation of water contents from FTDR sensors of 1% at low water contents and up to 3% at maximum measured water contents. Errors from water samples retrieved with Vadose Sampling Ports (VSP) materials might arise from the limited capability in the measurement of in-situ parameters as a consequence of low quantities of water available for sampling. As for geophysical images, direct and reciprocal measurements were carried out in order to assess the quality of the ERT data, as the smoothness of the image depends on the data set error level (LaBrecque et al., 1996). For this study, a linear error model was used to quantify the error parameters for the inversion. This method, which was used by Slater et al., (2000) and Singa and Gorelick (2005) among others, follows the following formula: $|e|=a+b|R|$ (1)

Where a defines the minimum error, and b is the increase in e with R. R is the measured resistance. Parameters a and b were measured by removing outliners after the trend line that fitted all measurements was found. Parameter a is 0.02 Ohms and b is 5%.

[...] In general the MS is not well structured. A thorough clarification of the research questions and a precise methods section could help understanding a lot and would leave more room for results and a more detailed discussion.

As discussed in the general explanation, it is hoped that the clarifications will contribute to a better understanding of the manuscript.

1.2 ERT system and analysis

For my understanding this is intended as main focus of the manuscript. However, in the current version ERT is only used once for six cross-borehole profiles in order to characterize the already well-known lithology of the subsurface. I do not understand why there is no repeated or time-lapse data shown. Nor do I agree that the six profiles are already a tomography.

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This point is clarified in the general explanation.

Is the setup not suitable for much more electrode pairs than simple pairwise measurements?

The resources for carrying out geophysical measurements at the study site were quite limited. There was no access to electricity, so the power supply was limited. The equipment could not be left on site, limiting the number and time of measurements. The device used for carrying out geophysical measurements (Terrameter LS) is equipped with two connectors for electrode cables. The configuration of the geophysical setup was developed for pairwise measurements, given the limited resources. To clarify, we performed 1749 measurements (bipole-bipole) per imaging plane using two pairs of injection electrodes and two pairs of measurements.

I also miss an interpretation of the data beyond the imaging of electrical resistivity. How does borehole-based ERT add precision and information in comparison to surface-based ERT?

Although surface ERT is usually used to monitor more extensive regions than cross-hole ERT, its resolution decreases rapidly with depth, in particular in highly conductive environments. The presence of electrodes in boreholes solves the problems of signal attenuation with depths, improving vertical resolution.

Using ERT as part of a vadose zone monitoring would also require clarifying the possible resolution in time and space and whether or not this is sufficient for the processes under study.

This point has been clarified in the general explanation.

1.3 Soil moisture dynamics One very interesting finding of the study is the quick reaction of soil moisture to events also in greater depth (mainly comprised in Figure 4). However, without a more detailed analysis of single events (e.g. concerning water balances, breakthrough timing, recessions) I find it very vaguely argued how this can step beyond a first formulation of process hypotheses. Especially as I do not see that the authors draw any connection beyond the process hypotheses between the used methods I find it a missed opportunity of the study.

As clarified in the general explanation, this initial study is intended to demonstrate that general interpretations can be made already thanks to a more complete set of data provided by the field setup, without additional indirect estimations. However, data might be used for more detailed analysis in the future, and calculations of water balances, breakthrough timing and recessions might be made in the scope of a different manuscript.

1.4 Water chemistry Water chemical signatures are classified as facies which sounds very interesting but is not described in the methods. From the MS I find it very difficult to bring together the bits and pieces without getting lost in minor details or broader expectations. The MS lacks a combination of soil water dynamics and soil water chemistry. Especially with regard to preferential flow the frequency of sampling may be an issue to give attention to..

As clarified already in the general comments, the results of the study are integrated to provide vadose zone characterization, rather than a combination of methods and discussion from results. It is important to point out that a general interpretation is discussed here. Further experiments will be required in order to obtain further details of soil water dynamics and chemistry. Sampling the vadose zone pore water often results in limited sample volume during dry seasons and low water contents. Suction cups take time to drain water from the subsurface. In addition, the capability to perform some of the chemical analyses that require larger sample volumes is limited. The system does not allow a very dynamic process. Instead, it offers time-averaged water chemistry on a monthly basis.

2 Specific comments

Abstract Streamline the abstract closer to the core findings which are really corroborated by data. In the current form it does not match well and sparks confusion.

In addition to clarifying the objectives of the study in the abstract, an improved description of results will be carried out. This description would include a more direct explanation of core findings.

Introduction. This should be the place to frame the study. Leave technical details to the methods section and make sure to clarify the core questions of the study at hand. Be more precise about scales and language in general.

As pointed out in the general explanation, a clarification of core questions and study objectives will be made. Technical details will be reduced. However, the conceptualization of the methodological concept arises from field technical challenges of depth and data quality, and it is important to point this out in the introduction.

P3L9 what is the experiment?

The experiment is clarified in the general explanation and will be better explained within the objectives of the introduction. In this section, the geology and hydrogeology of the site is explained.

P3L16 what kind of conventional methods? what scales to you consider (time and space)?

The conventional methods for fracture detection during preliminary studies refer to surface geophysical measurements. Preliminary surface ERT profiles were carried out in May and June 2012 at different locations of the study area. Surface profiles were 256m long and the depth of investigation covered 20m depth. The resolution of acquired images was not high enough to allow fracture identification.

Sec2.1 It is very interesting to consider the history of the anthropogenically formed site. However, I cannot really get the overall behaviour from the brief information here. The overall behaviour of the contaminants at the study site is not completely understood.

The study site is part of an industrial megasite, where a variety of industrial activities of different origin were carried out, such as colorant and fertilizer production or elaboration of byproducts from Mn. Such activities lead to a complex contamination problem with multiple unknown sources. Investigations are currently in progress at different scales in order to better understand the the overall behaviour of contaminants.

P4L24 which geophysical method?

The geophysical method is cross- borehole ERT.

Why does it allow for structure detection?

Electrical resistivity values obtained from geophysical measurements are a function of the structural and textural characteristics of the subsurface (Arora and Ahmed, 2011).

What scale?

Geophysical measurements cover a vertical scale of 15m and horizontal distances delineated by the distances between borehole (maximum distance: 6.6m).

What sensitivity?

The sensitivity of tomographic profiles for cross-hole geophysics is high due to the electrodes set-up configuration in the subsurface and the short distance between borehole pairs (ratio between length of borehole versus distance between boreholes is 2.2).Therefore, there is no need to establish a sensitivity threshold.

What error margins?

Error parameters for the inversion, as discussed in the section regarding error margins, were established using a linear error model. Parameter a is 0.02 Ohms and b is 5%.

P4L26 Single campaign? is the borehole material also considered as data? ERT only in addition?

The geophysical images displayed in the document correspond to a single campaign, as it is used for improving spatial resolution of the subsurface. No time resolution is added with these geophysical images. The borehole material was only recovered partially, as technical problems occur during the drilling procedure and logging could not be completed.

P5L10 which CTD sensors?

A total of 3 Mini-Diver, 1 Baro-Diver and 1 CTD diver (Schlumberger) were installed in 4 piezometers with the aim of monitoring groundwater levels.

P5L14 what is meant by "Geophysical images". what data, what methods?

Geophysical images are generated upon inversion of resistivity data. The image shows the spatial distribution of electrical properties of the subsurface, from which identification of structures can be made.

Fig3 I cannot judge the other ER pairs. Revise Figure.

An improved figure is suggested and shown in the figure A for the sake of clarity. In the manuscript, Fig. 3 shows images of the vadose and saturated zones obtained from in-situ measurements at different directions. Images obtained from such geophysical campaign are shown in more detail for vadose zone characterization in Fig. 5. Therefore, merging two figures in to one could provide a better visualization of the images, where all ER pairs are shown.

P5L21 what tomographic model?

The tomographic model refers to the geophysical images obtained from resistivity inversions.

Sec4.1 one would expect that a well-defined artificial deposit can be well-detected by ERT. Where is the interesting part in this - especially since the results are not free from noise and ambiguity?

This point is clarified in the general explanation.

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P6L6 Where can I see fast rises? What is fast? Are these the spikes? What event water balances can be calculated?

Fast rises refer to the spikes that are observed in the figure 4. Fast refers to the abrupt increases of water content subsequent to rainfall infiltration events. Not water balances are considered as it is out of the scope of this document.

Fig4 where are the axes ticks of the magnified plots? what sensors are giving the coloured dots? Label points properly. What are the many spikes in the chalk and silt layer sensors?

An improvement of Fig. 4 by showing a magnified plot of the event scale with the axes ticks is suggested (Fig. B). Ticks of the magnified plots are included in the new figure. The coloured dots represent the VSP sensors. Their position on the lithological log refers to the depth where they are installed. Their location on the central water content graph indicates the time at which water sampling from these sensors was carried out. The many spikes in the chalk and silt layer indicate preferential flow. In the suggested figure, the magnified plots are located on the right.

P6L10 from fig 4 it is very difficult to judge the event-scale.

An improvement of Fig. 4 by showing a magnified plot of the event scale is suggested (Fig. B).

P6L17 where are these profiles? I cannot really follow the argumentation – especially as for the given event I cannot see a strong reaction in greater depth

The profiles refer to the magnified infiltration patterns at the given event. Reaction to infiltration patterns is observed to depths down to 3.62m as a consequence of percolation. No stronger reaction is observer at greater depth.

P7L3 is this matrix flow induced from percolation at the site or externally driven? I cannot distinguish this important point for the site under study.

Matrix flow is produced as a consequence of rainfall infiltration events. No tracer experiments are considered in this document.

P7L8 so far the VMS does record states from which dynamics can be inferred.

Yes, that is correct, water infiltration mechanisms can be inferred from water changes in FTDR sensors.

P7L12 isn't it rather a hypothesis than identification?

Yes, it is a hypothesis.

P7L16 what else flow could it be? I don't get the point.

In the NW-SE and E-W directions the presence of backfill and sandy materials is significant compared to chalk. Therefore it is less likely that preferential flow produced by the presence of fractures will occur.

P7L18 low electrical resistivity. this can have different causes... be more precise.

These causes will be added in a revised manuscript.

Sec4.3 Move to methods section. Expand. It is really hard to guess what is intended from this step. I don't get the intention and the meaning of the data, nor the results from this.

The aims of the data in this section are the following: 1) Identify for how long and into what extent the chemistry of the subsurface was affected by the disturbance of the subsoil provoked by the installation of the setup. 2) Identify the chemical signature of water infiltrating across the vadose zone, as well as its evolution with depth 3) Understanding the influence of water flow mechanisms in the chemistry of infiltrated waters. A clarification of the aims will be added in the method section.

Fig6 this figure is very complex and deserves more guidance.

The main graph of Fig. 6 shows ion evolution in time and depth in order to determine the consequences of soil disturbance by installation of the setup. The Piper diagrams on the right show. the chemical evolution of waters at different depths of the vadose zone and its relation to water flow mechanisms. The figure will be splitted in two for the sake of clarity.

How are the facies of water determined and how is the process inferred?

Major elements from water analyses are used to build Piper diagrams with the software Diagrammes (developed by the University of Avignon in France). Piper diagrams are very classical way of representing hydrochemical data in the field of water chemistry. They allow identifying the chemical signature of water samples by representing the proportions of ions and cations. Both ions are combined as a single point in the diamond shaped area, from which inferences in hydro-geochemical facies can be made as a function of the area where the point is represented (Sadashivaiah et al., 2008).

What is the signal to noise ratio here? is it only based on monthly samples?

As explained in previous sections, water samples are limited by the amount of quantity that is retrieved from the vadose zone, and the sampling procedure is more limited than those from groundwater samples, as in situ physico-chemical parameters are challenging to be obtained. The amount of sample that is retrieved each time is limited and it cannot be predicted.

Is this appropriate to speak about preferential flow with this coarse resolution?

As explained in the general interpretation, the manuscript presents a general initial interpretation. Further studies will need to be made in order to obtain a better resolution. P7L29 Continuous? What intervals? Is the resolution sufficient?

Results from samples taken on a monthly basis show no significant fluctuations in water chemistry over time, with the exception of the initial period after installation. Therefore, resolution is thought to be sufficient for the purposes of this study.

Anonymous Referee 2

The manuscript describes a methodological concept for vadose zone subsurface characterization by combining point measurements and information from cross-hole ERT methods. This setup is tested at an industrial contaminated site in Belgium. In general I think the manuscript has an interesting topic, and promises a nice topic to combine geochemical and geophysical information, which would fit into the scope of HESS. However, in my opinion at the moment, this goal is not reached and major parts of the manuscript have to be clarified substantially before considering it for publication. Additionally, there I have major questions especially concerning the ERT data setup and the structure of the manuscript. Consequently, in its present state the manuscript does not reach substantial conclusions and requires to be resubmitted in a restructured and improved from.

1) The authors claim to combine geophysical and vadose zone monitoring systems, but they do not include a geophysical monitoring. They rather describe the results of classical borehole ERT survey, which is interpreted in terms of structural features.

A clarification has been made in the general explanation.

In my opinion this results are not state of the art, as they do only invert 2D section, where a 3D inversion of the six ERT borehole profiles should be possible.

A 3D inversion of the profiles was not carried out as 2D inversion was thought to be appropriate for the purpose of structure identification. Although possible, the electrode coverage is not ideal for 3D data collection (like a grid of electrode would be). 3D inversion would result in a resolution decrease between the 2D image planes and most likely dominated by the reference model in the inversion. The independent 2D inversions provide consistent results and coherent interpretation with the boreholes and are sufficient in this case for our purpose.

In addition I would expect to see a real geophysical monitoring e.g. by time-lapse ERT measurement as they authors claim to present a geophysical monitoring system. Currently, they show only a structural interpretation of the ERT data, which is not very different to the already known information from the borehole logs (Fig 3). Therefore, it is unclear from the manuscript, which advantage can be generated by using the ERT data.

A clarification of this comment is provided in the general explanation.

2) Major methodological information of the ERT setup and inversion major information are missing or are hidden in the results section (e.g., the electrode configurations, inversion algorithm and parameters). In addition the ERT data in Fig. 3 are not consistent with the colourbar information, while the colourbar in Fig. 5 is missing completely.

Table 2 shows information on ERT acquisition parameters. Data was inverted with CRTomo, we therefore refer to Kemna (2000) for more details (regularization, error model, lambda optimization, stopping criteria) (Parameter a is 0.02 Ohms and b is 5%). Such methodological information will be introduced in the manuscript. An improved version of the geophysical figures is suggested (shown in Fig. A).

3) The data ERT data show obvious artifacts close to the boreholes, which the authors discuss to be ignorable like it can be done in very high resistive environment. I consider it very questionable if this observation can be transferred to the present setting. In addition the used citation (Deiana et al., 2011) is neither from an ISI listed journal, nor openly accessible. Moreover, from my point it seems these artifacts effect large areas of the ERT data, resulting in a questionable interpretation of the ERT data. Taking into account the previous points, it is impossible for me to comment on large parts of the manuscript as substantial technical information are questionable or missing.

Artifacts in ERT data have been discussed in the general explanation. The citation has been removed and changed to another citation from a different author (Perri et al., 2012) from an ISI listed journal (Journal of Applied Geophysics). Borehole artefacts come from the difference of resistivity between the borehole filling and the surrounding rock/soil and are typically very difficult to avoid because of the experiment itself. We tried to minimize the effect as much as possible here. The setup here is a rather large conductivity in the surrounding rock/soil so that the borehole effect should be less than expected (no current channeling in the borehole filling).

4) In the soil moisture data, the authors observe indications of preferential flow in a fracture network, However, such structures are known to be difficult to be observed by potential methods like ERT. Maybe an structural imaging method like GPR can provide better results in such settings. An exemplary study from a similar application is: S. Truss, M. Grasmueck, S. Vega, and D. a. Viggiano, "Imaging rainfall drainage within the Miami oolitic limestone using high-resolution time-lapse ground-penetrating radar," Water Resources Research, vol. 43, no. 3, pp. 1–15, 2007.

GPR methods were initially considered as an option for vadose zone characterization. However results from preliminary geophysical surveys have shown that the subsurface is highly conductive. Sampled waters across the vadose zone were found to have electrical conductivities of up to 1800 μS/cm. GPR methods may be difficult in such conditions, as it limits the penetration of electromagnetic waves and attenuation becomes more relevant (Rinaldi 2006) . In addition, monitoring of the system was of importance and ERT monitoring is easier to set-up than GPR. Given that electrodes were already in place in the boreholes, it would have been difficult to perform GPR measurements in the ERT equipped boreholes, although not impossible according to Giorgio Cassiani (personal communication).

5) Most of the chemical analysis described in chapter 4.3 and 4.4 indicate that Nickel is being transported through the vadose zone which is related with pyrite oxidation at the top, while other heavy metals are not detected. In my opinion, this part not well structured making it difficult to follow the storyline. In addition, it is unclear, why the transport of Ni from the backfilled material is important in the context of preferential flow path and spatial resolved structures. This should be pointed out in more detail in a separate discussion chapter, which clearly discusses the connection of the chemical data with the spatial information and the knowledge of preferential flow behavior.

The aim of section 4.4 is to make an initial identification of which contaminants are leaching across the vadose zone, as a part of an initial characterization process. As you point out correctly, a separate discussion chapter should be made, including the transport of Ni in the context of preferential flow paths and spatial resolved structures.

6) The information in Fig 6 and Fig. 8 is largely identical except for the Ni concentration added to Fig 8. Here it might be possible to condense these plots. Overall I found the plots have to be improved and should be better integrated into the text. Therefore, I suggest more to add more figure references in the text and highlight the areas of interest in the plots.

The vertical scale in the concentration graphs presented in Fig. 6 is uniform, so the disturbance of the VMS by anomalous concentrations at different depths can be observed. The vertical scale of Fig. 8 was changed for a better comparison between Ni and sulfate. If Ni concentrations are integrated in Fig.6, the trend would not be seen at 0.66m, as the scale does not allow observing sulfate fluctuations in detail. Nevertheless, an attempt to integrate such data in Fig. 6 was made. However, reviewer 1 pointed out that Fig. 6 is quite complex. Integrating additional data might add more complexity.

7) In general I miss the combined discussion or methodological combination of the methods as promised in the title and the abstract of the manuscript. Here, I expect a combined interpretation and discussion of the applied methods and their limitations, which should be added to the manuscript.

This point has been discussed in the general explanation.

8) References should be reworked with respect to ISI listed journals and accessibility.

An attempt has been made regarding this point. However, some of the essential information is only displayed in close access and non ISI listed journals.

References Arora, T., and Ahmed, S.: Characterization of recharge through complex

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-79, 2016.

Pointed out by both authors	Response (further details on the text)	Potential improvements in the manuscript
Mismatch between expectation and presentation (section 1.1 reviewer 1, comment 7 reviewer 2)	The VMS is the main topic of the manuscript (geophysics supports the VMS for spatially distributed structural information but not monitoring in this manuscript)	Changing the title to "Improved characterization of industrial sites with the Vadose Zone Monitoring System." Clarifying the objectives in the abstract and introduction
	The manuscript presents initial interpretations from data sets with minimum indirect estimations	
	This study is the foundation of further experiments, out of the scope of the present manuscript	
No geophysical monitoring (section 1.2 reviewer 1, comment 1 reviewer 2)	Cross-hole ERT techniques are used in this study to improve the spatial characterization of VMS.	
	Time-lapse measurements are out of the scope of the manuscript objectives (they were performed in experiments not presented here).	
What is the added value of ERT images if borehole logs are available? (section 1.2 reviewer 1, comment 1 reviewer 2)	To identify the thickness and lateral distribution of layers (and complete subsurface characterization due to problems during drilling operations)	Clarify the added value that ERT images provide in this study
	To assess the influence of subsurface lithologies on flow mechanisms	
No combination of discussion and methods (section 1.4 reviewer 1, comment 7 reviewer 2)	Each individual component of the VZES is providing information to obtain a more complete characterization of the vadose zone of the study site. Therefore, an integration of discussion and methods is made, rather than a combination.	Improving the final discussion of the paper to propose a more integrated view of all the components
Limitations (section 1 reviewer 1, comment 7 reviewer 2)	TDR: overestimation of water contents	Adding the limitations of each technique in section 3 of the manuscript.
	Water samples: limited amount of water at different depths, measurement of in-situ parameters is challenging	
	Geophysics: it only provides a qualitative interpretation, borehole inversion effects are present	
Structure of the manuscript (section 1.1 reviewer 1, general comments, reviewer 2)	It is hoped that the clarifications and modifications in the manuscript makes the structure of the manuscript more clear	

Fig. 1. Table 1: Common issues found by both reviewers, followed by responses and potential improvements in the manuscript.

Cross-hole ERT acquisition parameters	
Depth of investigation	15m
Electrode number	24 per borehole
Electrode spacing (m)	0.6
Array	Bipole-bipole (AM-BN)
Injection	100mA
Acquisition time (s)	0.3
Delay time(s)	0.1
Max. number of stacks	3
Min. number of stacks	2

Fig. 2. Table 2: Cross-hole ERT acquisition parameters.

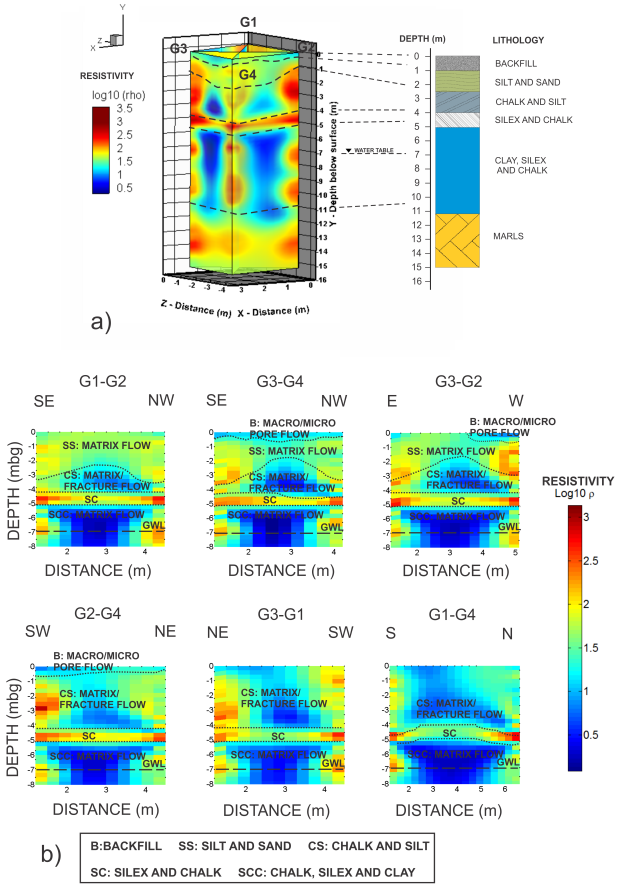

Fig. 3. Figure A: Resistivity images of the vadose and saturated zone obtained at different directions (a) and correlation with the lithologies and flow mechanisms of the vadose zone (b).

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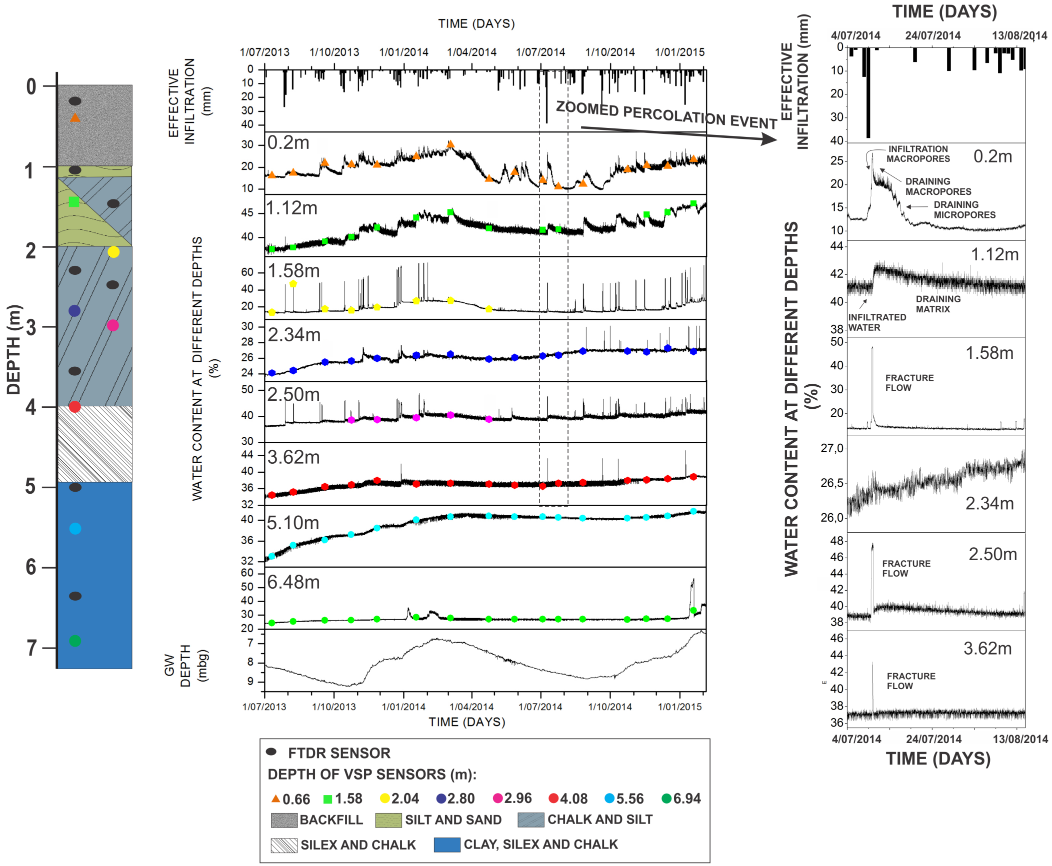

Fig. 4. Figure B: Water contents registered at different depths of the vadose zone with a lithological log on the left and a magnified plot of an infiltration event on the right.

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