Authors answer to Referee # 3

Hydrol. Earth Syst. Sci. Discuss., 9, 5261–5294, 2012 - doi:10.5194/hessd-9-5261-2012

"Quantifying freshwater resource in coastal barriers: the joint use of transient electromagnetic and magnetic resonance soundings" by JM Vouillamoz et al.

We thank the reviewer very much for his valuable comments which were useful for improving the manuscript. The comments mainly concern the geophysical part (modelling, inversion and partly the application) which is part of our work: as noticed by Referee#1 and Referre#2, our manuscript is not dealing with geophysics alone but with combining two complementary geophysical tools with hydrological measurements. Consequently, we tried to make the manuscript accessible to both the hydrological and the geophysical communities without giving too much of weight to one specific field. Moreover, our paper is not focussing on the hydraulic properties of coastal aquifers (which we consider as primary parameters) but on the estimate of the groundwater reserve (storage of fresh water), its renewal (recharge) and its vulnerability to possible climate change.

Please find below our answers (denoted A) to all the reviewer questions and comments (denoted C).

C: The presented discussion paper deals with the aim of quantifying hydraulic properties of a barrier island that is possibly threatened by climate change. It is therefore suited for the journal in general and the special issue in particular, although links to the other papers in the latter, with sometimes very similar geophyical methods in fresh-salt water systems, are unfortunately missing.
A -> You are right, we added in the corrected paper links with other papers of the special issue, including the paper which also deals with MRS (Günther and Müller-Petke 2012). We did not include such links before because our manuscript was ready in March 2012 (submitted the 8th of April) when many of the papers of the special issue where not, or were just, submitted yet.

C: The paper starts with the methology of deriving groundwater resource parameters and geophysical methods before explaining the experiments and their results. The method-ology of using a combination of TEM and MRS is goal-oriented since the measured parameters lead to aquifer properties, e.g. water content and resistivity to fluid salin-ity. Moreover, measurements at different times provide some insight into the temporal behaviour of the interface, although the sea-river system is probably far too complex to be understood by a few soundings alone.
A-> Please, note that we did not try to understand the sea-river system with few soundings alone. Geophysics alone can not support the understanding of such system and we used an approach based on both hydrological and geophysical measurements: we monitored groundwater level and EC (Electrical Conductivity) at 65 locations, rainfall at 2 locations, we analysed 5 sand samples at lab, we carried out 32 MRS and 140 TEM including time lapse measurements (Figure 1). This coupled hydro-geophysical approach allowed improving the knowledge of the system and then estimating the fresh water reserve, its recharge and its vulnerability to possible climate change.
Although the coupled hydro-geophysical approach is explained in the text, title of the paper is confusing because it concerns only geophysics. We will modify it (see below).

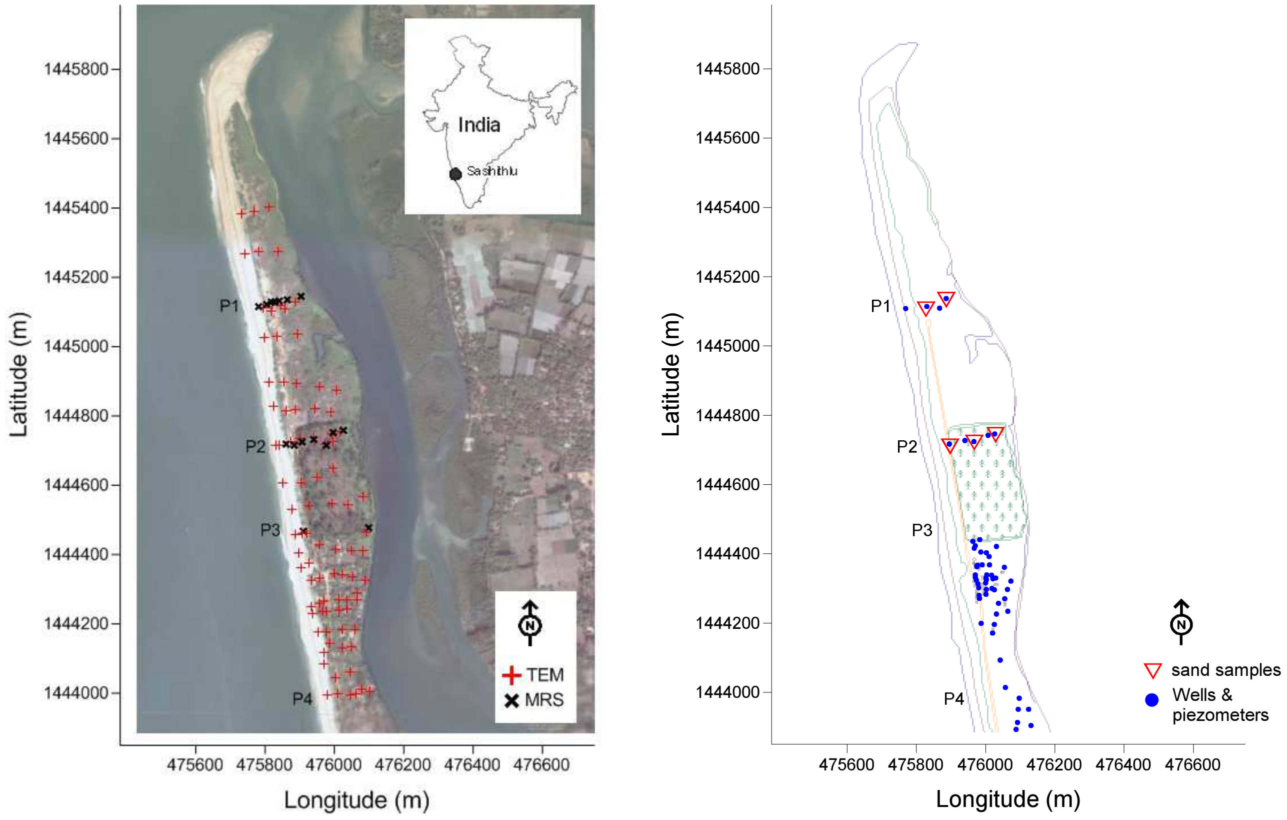

Figure 1: Location of Sasihithlu barrier and measurements.
Left panel=geophysical measurements (including pre and post monsoon time lapse)- Right panel=hydrological measurements

1/ General comments:

C: 1. The title suggests not only freshwater resource but also hydraulic properties.
A -> You are right, we will modify the title according to your remarks: Quantifying aquifer properties and freshwater resource in coastal barriers: an hydrogeophysical approach.

C: 2. Instead of a sequential inversion of the data, a coupled or joint inversion as pre-sented in several papers could further reduce ambiguity in the model and parameter uncertainty. Please make clear statements about existing works and justify why your approach is sufficiently valid.
A -> In the discussion paper, we only referred to the work of Hertrich and Yamaranci (2002) regarding the joint inversion (5267.L24). You are right, references on very recent works are missing but please note that 2 manuscripts have been published after the completion of our discussion paper (Günther and Müller-Petke 2012 & Behroozmand et al. 2012). We will update the statement of the existing works in the corrected manuscript.

Hertrich and Yamaranci (2002) developed a joint inversion algorithm for MRS and VES which results in the differentiation of bound from mobile water. They demonstrated that their algorithm improves the model characterization as compared to the characterization obtained from the inversion of a single method, but their approach is limited in its application by the use of a simplified Archie's law. Vouillamoz et al. (2007) proposed a combined use of MRS and VES in the framework of a hydrogeological approach for quantifying hydraulic properties of a coastal aquifer. They demonstrated that inverting VES with a fixed geometry obtained from MRS significantly improves resistivity uncertainties and thereby the estimate of water EC. Based on numerical modelling, Behroozmand et al. (2012) demonstrated that TEM method is probably the best choice among complementary geophysical method to be used with MRS because of its superior resolution of conductive layers (as compared to DC resistivity). Conductive layers affect the magnetic field values and thereby the MRS response and the authors demonstrated the need for sufficiently deep and accurate resistivity information for MRS inversion. For reducing the error caused by incorrect resistivity values in the calculation of the magnetic field, Günther and Müller-Petke (2012) used an iterative approach for updating the MRS kernel in the framework of a joint MRS and VES inversion scheme. They found that no more than 3 iterations are needed. Behroozmand et al. (2012) developed a fast computation method for calculating the MRS kernel for each resistivity update in a joint MRS/TEM inversion scheme. They found that their joint MRS/TEM inversion scheme improves the determination of aquifer characteristics in conductive environments, and that the use of MRS diminishes the equivalence of the resistivity model. Moreover, they also showed that laterally constrain inversion of joint MRS/TEM results in a reasonable accurate estimation of smooth structures.

In our study, we selected TEM method for complementing MRS measurements, and we used a sequential inversion scheme. In contrast to the common stepwise inversion where the results of one method is used to define the starting model for the non constrained inversion of the other method (Behroozmand et al. 2012), the sequential inversion is an iterative interpretation where the result of one method is used to constrain the inversion of the other one and so on. In our study, the sequential inversion uses the best of each method for constraining the inversion of the other one: the geometry of the salty-water layer obtained from a non-constrained TEM inversion is used to constrain the MRS inversion. Then, the depth to the saturated layer obtained from the MRS is fixed in a new TEM inversion.
Note that the MRS inversion is conducted with a kernel calculated from the first TEM result. As showed by Behroozmand et al. (2012), our sequential inversion introduces some errors in the resulting model because the kernel is not updated as it is done in a joint inversion scheme. For assessing the error introduced by our approach, we compare MRS response calculated with the appropriate kernel with MRS response calculated with kernel computed from the first resistivity model issued from TEM (Table 1). In our case, the resulting error in the MRS results is low because the salty-water layer (which has the greatest impact on the magnetic field) is reasonably defined by the first TEM inversion. We also checked how TEM equivalence problems introduce error in the kernel calculation. As showed by Legchenko et al. (2008) the uncertainty in TEM results has an insignificant effect on MRS (Table1).

	Depth from (m)	depth to (m)	Water content (%)
Model	*2*	*15*	*30*
Inversion with appropriate kernel (4 layers)	2	15.1	29.6
Inversion with kernel obtained form 1st TEM inversion	1.9	15 (fixed from TEM)	28.8
Inversion with kernel calculated from TEM equivalence	1.9-2.1	15 (fixed from TEM)	28.5-29.8

Table 1: error in MRS results caused by errors in resistivity model. Model 4 layers: $\rho 1=1000\Omega$m thickness1=2m; $\rho 2=100\Omega$m thickness2=5m; $\rho 3=0.8\Omega$m thickness3=8m; and $\rho 4=1000\Omega$m. MRS and TEM responses calculated according to our field measurement: loop, pulse moment, frequency, noise….

Finally, we compute the uncertainty of our results based on uncertainties in geophysical inversion (both MRS and TEM). We conclude that our sequential approach allows estimating groundwater reserve with a relative uncertainty of 30 to 50% (Table 2). Sequential inversion leads to acceptable results in favourable cases: low noise level, shallow salty-water and few layers model. However, as showed by Güther and Müller-Petke (2012), uncertainties of sequential inversion are slightly but generally higher than uncertainties of joint inversion.

	Dry season (February-March)		Rainy season (October-November)	
	Average	Uncertainty	Average	Uncertainty
North of the area (uninhabited)	2.2m 500 l/m²	43%	2.9 m 670 l/m²	34%
South of the area (inhabited)	1.8 m 420 l/m²	37%	2.0 m 460 l/m²	51%

Table 2: Thickness of the freshwater lens and corresponding freshwater volume. Relative uncertainties are calculated based on average uncertainties of MRS water content and of the thickness of the fresh water layer obtained from TEM.

C: 2. Main point in your case is the high sensitivity of TEM to the salt-water interface but stating "no equivalence" to the method is not correct.

A -> Yes, stating that there is no equivalence is not correct. However, please note that we did not write "no equivalence" but "about no equivalence". Obviously we will rephrase the sentences for avoiding any misunderstanding, because we perfectly agree that there are equivalences.

In our case study with low noise level, the equivalence on the shallow highly conductive layer (sea-water layer) is low: 15cm on the depth to the layer and less than 0.1 Ωm on its resistivity value for the max depth presented Figure 2. This narrow range of equivalence on the shallow salty-water layer is one of the main interests of using TEM results for calculating magnetic field and constraining MRS inversion.

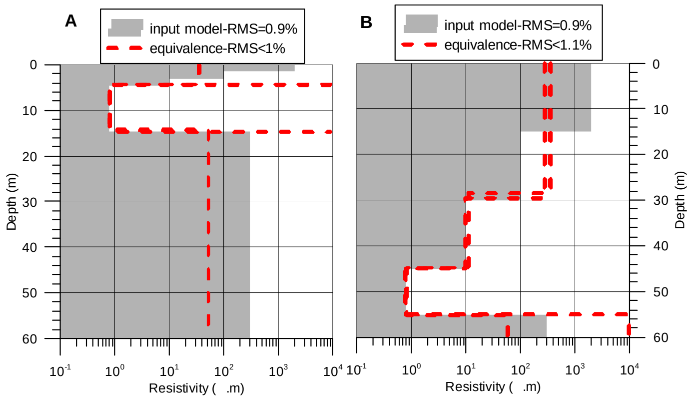

Figure2: Equivalence and suppression of a 5 layers model. Left panel=thin layers resulting in a 3 layers output model. Right panel=thicker top layers resulting in a 4 layers output model. 1% of added noise to the synthetic data.

C: 3. Synthetic modellings (sec. 2.3): Are the synthetic data contaminated with noise as usual and crucial? The resulting RMS is not necessarily a measure of the quality of the inversion result but is expected to represent the added noise.

A -> We computed synthetic data according to our real field case.

Concerning TEM, we computed synthetic data considering the low noise condition of our survey area and considering the measurement capabilities of the TEMFAST 48 (AEMR) (see Figure 3). We used a time range of 5 µS to 1.6ms (shaded zone in Figure 3), with a coincident Tx/Rx square loop of 25 meters side, and we added 1% of noise. For the inversion of the synthetic data, the starting model was a 5 layers model (chosen according to our hydrogeological *a priori*). Then, we reduced the number of layers assessing the impact on the RMS. The smallest number of layers which provides a RMS comparable to the added noise (1%) was selected as the best fit output model.

Concerning MRS, we computed synthetic data considering the low noise conditions of the surveyed area and the capabilities of the used device (Numis+, Iris instrument) (see Figure 4): the loop size (25 meters side, 2 turns) and pulse duration (10 ms) were chosen to fit the shallow target, with a Larmor Frequency of 1720Hz and an inclination of the geomagnetic field of 17°N. 10nV of Gaussian noise was randomly added to compute synthetic data.

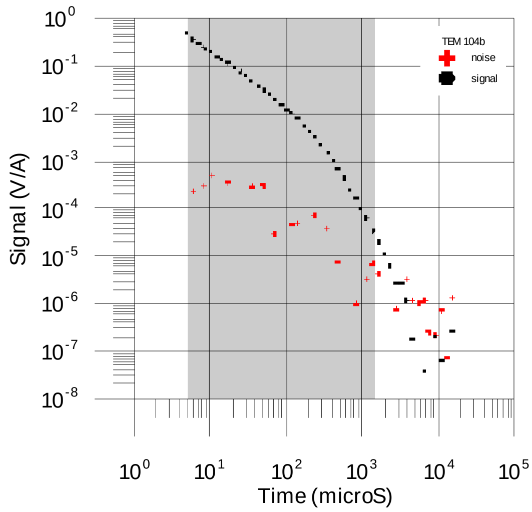

Figure 3: Example of noise and TEM measurements The greyed zone is the time window used for synthetic modelling

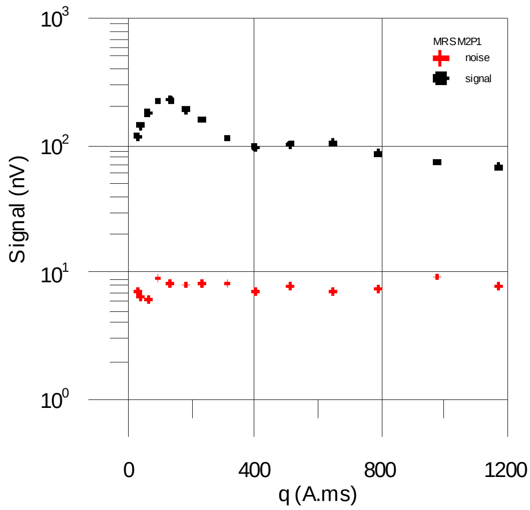

Figure 4: Example of field noise and MRS measurements

C: 3. As there is a known equivalence of resistivity and thickness in TEM, 5269.3-4 is wrong, at least it is better for MRS (line 7) but there is always equivalence so that line 20 is wrong. The actual numbers (lines 19-24) depend on the noise level.
A -> As we mentioned earlier, we perfectly agree that there is equivalence. By "well determined" (5269.3-4) and "about no equivalence" (line 20) we intended "narrow range of equivalence": we will rephrase the sentences to avoid any misunderstanding. This narrow range of equivalence is obtained because of the low noise level. As you suggest, noisy data will generate a large range of equivalence and thereby invalidate our approach.

C: 3. The whole subsection lacks from a technical point of view and would mislead hydrologists. References for the statements will be needed, there are some in MRS literature
A -> In our discussion paper, numerical modelling and sequential inversion are only a subchapter because the paper does not aim at presenting a new inversion process tested on synthetic data and confirmed with field data.
However, the balance between theoretical background (both hydro and geophysics) and results was not an easy task and we agree with your comment: we will give more details and references in the corrected manuscript about this issue.

C: 4. The interpretation of the temporal behaviour of the aquifer is in my opinion rather speculative and can probably not be answered by the presented data alone, e.g. further non-geophysical temporal data would be needed to prove the hypothesis that infiltrated water does not change the salinity interface.
A -> The behaviour of the aquifer is not explained by geophysical data alone: it is both explained by the monitoring of water level and EC at 65 locations (Figure 5) and by 60 TEM monitoring (Figure 1). In the discussion paper we selected some demonstrative results (Figure 7 and 8 in the discussion paper) from the whole data set, but we mentioned all what we did.

We observed that both water table monitoring and MRS time lapse measurements indicate that the water table depth is almost constant at the monsoon time scale. On the other hand, both monitoring of groundwater EC and TEM time lapse measurements indicate a deepening of the salty-water interface after the monsoon, thus indicating infiltration of fresh-water (Figure 5 and Table 2). The amount of rainwater which infiltrates and stays in the aquifer at the monsoon time scale is calculated as about 10% of rainfall, while instantaneous recharge calculated at the event scale is almost 100% of the rainfall.

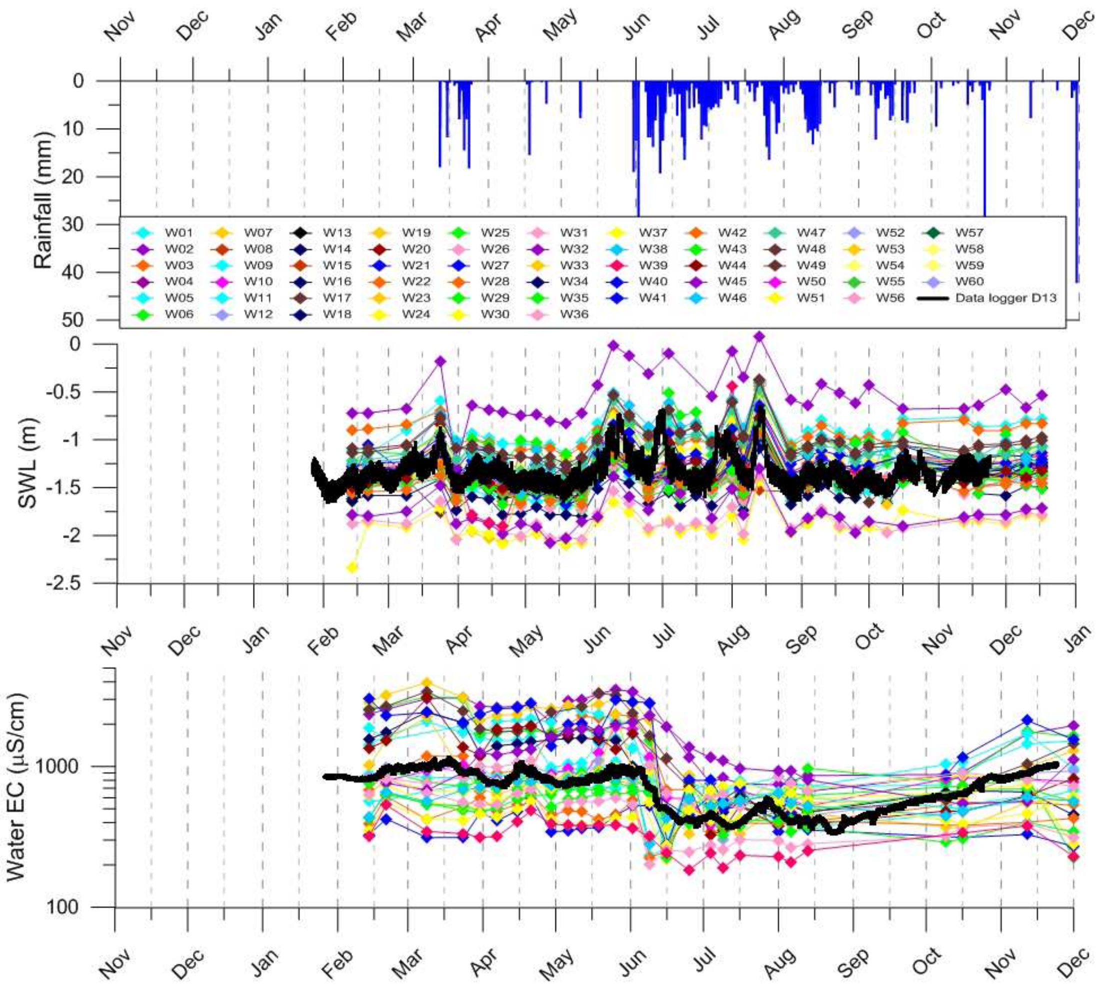

Figure 5: Rainfall, water level and EC monitoring. The black line (Data logger D13) are the data presented in the discussion paper Figure 8)

C: 5. Figure 9 is weird and does not add anything to your story. Moreover it seems to imply that CVES data are useless in this case but several papers have shown the contrary. Figure and according text should be deleted from the paper.

A -> Figure 9 just showed why the common electrical tomography was not appropriate in our case (dry sand and shallow target) because of the well known difficulty of ensuring galvanic contact between electrodes and dry sands. Of course it concerns only similar situation and for avoiding any confusion we will remove both the Figure and the corresponding text in the corrected manuscript (although reviewer#2 appreciated this section of the manuscript: not only presenting successful experiments but also less successful ones).

2/ Specific comments:

C: 5263.24 groundwater is not a factor

A -> Right, rephrased.

C: 5263.25 parameter->parameters

A -> Corrected.

C: 5263.27 direct or close

A -> Corrected.

C: 5264.02 which pore-size parameters
A -> Relaxation time T_2*. We use "pore-size parameters" because it makes sense for hydrologists. But you are right, we can also talk about the relaxation time. Corrected.

C: 5264.5-7 there is a long reference list, as most are only cited here it should be short-ened to essentials
A -> Corrected.

C: 5265.4 the statement of 50m is far too general, the investigation depth here is strongly determined by the saltwater
A -> Corrected.

C: 5265.12 which parameters?
A -> Relaxation time T_2*. Corrected.

C: 5265.22 bound and capillary water cannot be measured by MRS as the sentence sug-gests
A -> Several references already showed that MRS signal can be generated by capillary water (Boucher et al., 2006; Mazzilli et al. 2012; Roy and Lubczynski 2005).

C: 5266.8-11 either specify units for input and output values or give C_T (often C_p) units
A -> Corrected.

C: 5266.24 give references for the specified m values
A -> Corrected.

C: 5267.6 since eq. (3) uses water resistivity
A -> Corrected.

C: 5271.22 clarify what exactly you mean. As you know resistivity from TEM, the magnetic fields can be correctly computed and should be.
A -> Yes, we computed the magnetic field from the TEM resistivity. We clarified this point.

C: 5271.27 give some actual numbers of S/N
A-> Corrected.

C: 5272.14 27 percent seems to be a bit low for the given lithology
A-> The porosity calculated from sample analysis ranges in-between 28 and 34%. Although a sample can not be rigorously compared to a MRS measurement, these values are definitively reasonable for the given context.

C: 5272.16 why did you use 5 layers? 3 or 4 would be definitely enough. Keep it as simple as possible
A-> The 5 layers model is not the result of the TEM inversion alone but it is the result of the sequential inversion: the first layer is imposed by the MRS result, the second (brackish-water), third (sea-water) and last (bedrock) layers are compulsory to fit the TEM data. The question concerns the 4th layer just over the bedrock: adding this 4th layer reduces the error (RMS) from 1.9% to 0.6% which is significant for non noisy data. We interpreted this layer as a clayey weathered gneiss (I drilled several deep boreholes few kilometres from this location and I found a layer of clay-weathered gneisses) but it can also be a coarser sand.

C: 5273.4 the m value of 1.3 does not suggest anything about MRS, reformulate
A -> Corrected.

C: 5275.2+5 the referred equation should be (2), not (1)
A -> Corrected.

C: 5277.3 this section could better be called Discussion
A -> Corrected.

C: 5277.15 a linear gradient of conductivity makes more sense than of resistivity
A -> Corrected.

C: 5277.26 CS is not a usual abbreviation, FDEM sounding suits much better
A-> CS is the abbreviation used (for example) in the well known Interpex software.

C: 5278.8-10 this holds only for the EM34, not for FDEM in general
A -> It is why we used CS (for EM34) and not FDEM.

References
C: only 1 reference of the special issue is cited, although more would suit well
A -> You are right. Corrected.

C: 5280.18 add spaces around –
A -> Corrected.

C: 5283.7 insert comma after title
A -> Corrected.

C: 5283.15 Simeon->Simon
A -> Corrected.

Figures
C: Fig. 5 A 3-layer model would suffice as the results clearly show. Justify why you introduce additional complexity.
A: -> Idem than Figure 4: the 4th layer just over the bedrock is added because it significantly reduces the RMS (non noisy data). Moreover, this 4th layer is geologically consistent.

C: Furthermore it is uncommon to specify the RMS for MRS in per cent, usual is nV since the ambient noise level does not depend on the data.
A -> Corrected.

C: You show the decay time of the aquifer. Can you make any implications to pore-related parameters or even hydraulic conductivity?
A -> We can estimate hydraulic conductivity/transmissivity as explained 5275 L1-6, but we did not want to add more information on this figure which is already loaded.

C: Fig. 6B hard to see anything, better show contour map of fresh/saltwater interface
A -> We prefer to keep this figure because one can see not only the fresh/saltwater interface but also the depth of this interface as regard to ground level, and the depth to the bedrocks. This figure aims at illustrating the proposed methodology more than showing detailed results which are discussed in the text.

C: Fig. 7 show also the measured sounding curves. Are the time differences significant in terms of resolution?

A -> You are right, we should show the signals. We update the figure as below (Figure 6). Yes, the time differences are significant between February, July and October.

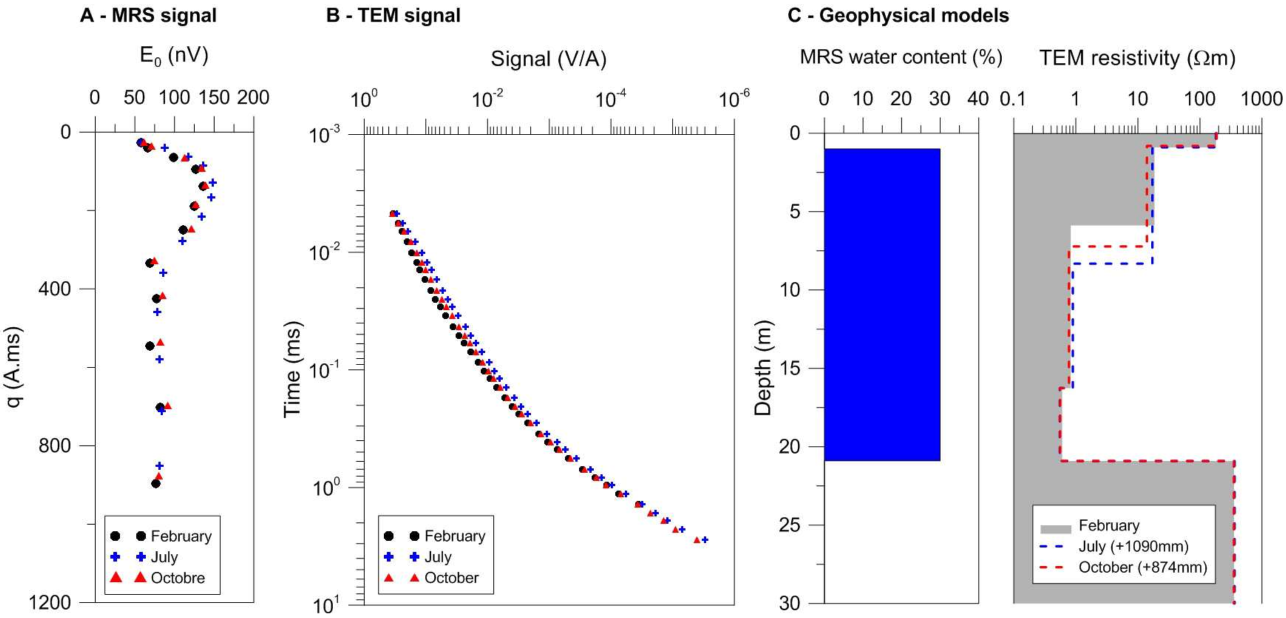

Figure 6: TEM73 and MRS1 time lapse.

References cited in this answer:

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