Point to point reply to Referee #1

First the authors want to thank the anonymous Referee #1 for his/her review of the manuscript and for the constructive helpful comments. Find our comments and new text below each point intended with suggested additional or changed text in italics.

Referee#1 comment:
The paper presents a combination of well described and widely used methods, thus not really new.

In a revised version the authors must find a way to either completely focus on the novelty of their approach and methods or (recommended!) to show the reader the consequences of their findings. What can we learn from this study in order to better understand hillslope hydrology in general, where are the clear benefits of your approach compared to others, are your results valid for al mid hill regions (I doubt) etc.

> **Reply:**
> We understand that the novelty has not been presented clearly enough and revised the manuscript accordingly. Our major objectives are not to give new insight into hydrological processes on hillslopes rather to present a robust methodological framework to enhance spatial (statistical) significance of hydrometric point measurements. We tried to show the possibility reducing or partially substituting expensive invasive hydrometric point measurements while using minimally invasive ERT because it is capable to give comparable results but on a higher spatial scale.
>
> In our opinion, the hillslope scale is the most important scale for predicting precipitation runoff response. Therefore it is crucial to know whether there is a spatial variability in the hydrological system on hillslopes or not. Many hypotheses of model are based on punctual measurements only. Punctual hydrometric measurement alone are not sufficient in case of significant spatial heterogeneity. However, with the use of a multi-method approach as presented in our paper, it is possible to transfer hydrometric data to higher spatial scales and to obtain additional patterns of soil water saturation distribution and its dynamics on a hillslope.
>
> We changed our objectives in the introduction accordingly:

The objective of this paper is to show the potential of minimally invasive surface time-lapse ERT as a robust methodological framework for monitoring long-term changes in soil moisture and to improve the spatial resolution of punctual hydrometric measurements (e.g. tensiometer and ThetaProbes) on a~hillslope with periglacial cover beds. Furthermore, we want to show the ability of ERT for mapping spatially heterogeneous structures and water content distributions of the shallow subsurface. With a multi-method approach, we attempt to demonstrate the possibility to adequately transfer hydrometric data to higher spatial scales and to obtain additional patterns of soil water dynamics on a hillslope. These scales are fundamental for achieving a better understanding of the influence of the layered subsurface on water fluxes (e.g. infiltration, percolation or interflow) and the response to different amounts of precipitation on hillslopes.

The new title is:
Monitoring hillslope moisture dynamics with surface ERT for enhancing spatial significance of hydrometric point measurements.

Referee#1 comment:
5863/2 : : :.still uncommon. Really, I don’t agree, there are many studies nowadays. You might need to further look into the literature.

Reply:
We agree that the use of ERT for mapping shallow subsurface structure und monitoring hydrological processes has been strongly developed in recent years. However, the use on hillslopes (in particular with layered structures) over a longer period (several month in almost weekly intervals) is still rare. Furthermore, most of the cited studies deal with controlled conditions (laboratory or irrigation) or only with a few time steps over a very long or very short period. The major aspect of the paper is (as also annotated by Referee #3) to show the robustness of ERT as long-term monitoring tool in the context of hillslope hydrology.

Referee#1 comment:
As large parts of the study site show complete saturation as indicated in figure 8, the question arises if hill slope moisture dynamic addresses this issue correctly. I suggest adapting the title.

Reply:

Yes, parts of the study site show complete saturation. The aim was to show some valuable information about the subsurface water distribution, which are not comprehensible in this spatial resolution with percussion drilling or hydrometric data. It is also right that these saturated parts show almost no dynamics during the investigation period. However, these parts are restricted to deeper areas and the dynamics we are talking about is situated above the local groundwater. All data and results in the “Monitoring” section show a clear dynamics during the year. This is what is meant by dynamic in the title.

To emphasize the major objectives the title has been changed but we kept “dynamics”.

Referee#1 comment:

The material and methods section can be restructured. It is not clear why 2.2 (Hydrometrical equipment) describes sampling frequency? It is not fully clear why hydrometry is not under monitoring since the authors take measurements since years

Reply:

Thank for this suggestion. The material and methods section are restructured. “*Hydrometric Equipment*” has been moved to the monitoring section. Monitoring section has been renamed: “*Joint Hydrometric and ERT Monitoring*”. Same was done for the subsection “*Results”*.

Referee#1 comment:

5860/1 … are one of the basic units: : : which ones else?

Reply:

Sentence has been rewritten:

Besides floodplains, hillslopes are basic units that mainly control water movement and flow pathways within catchments of subdued mountain range.

Referee#1 comment:

5861/22 : : :.influence in which way? Unclear

Reply:

The paragraph has been rewritten:

In catchments of Central European subdued mountain range, the shallow subsurface of hillslopes is mostly covered by Pleistocene periglacial slope deposits (Kleber and Terhorst, *2013). These slope deposits have developed in different layers. In literature normally three layers are classified (Upper Layer – LH, Intermediate layer – LM, Basal Layer – LB: classification according to ad-hoc AG-Boden, 2005; Kleber and Terhorst, 2013). Sometimes locally a 4th layer ("Oberlage" ad-hoc AG-Boden, 2005) could be found. The occurrence of these layers can vary spatially and has different regional and local characteristics. Due to the sedimentological and substrate-specific properties, e.g. grain-size distribution, clast content, and texture, they remarkably influence near-surface water balance (e.g. infiltration, percolation) and are of particular importance for near-surface runoff, e.g. interflow (Chifflard et al., 2008; Kleber, 2004; Kleber and Schellenberger, 1998; Sauer et al., 2001; Scholten, 1999; Völkel et al., 2002a, b; Heller, 2012; Moldenhauer et al., 2013).*

Referee#1 comment:

5861/18 Ad-hoc discusses a 4th late Pleistocene layer – do you have it in the studysite?

Reply:

No, we don't have it on our study site. We added a short explanation:
5863/18 *… (LH, LM, LB, with no occurrence of the "Oberlage")*

Referee#1 comment:

5861/19 it might be important to know the LB often contains multiple layers!

Reply:

We did not mentioned this fact, because it is a very specific case and we don't have multiple layered LB on the study site.

Referee#1 comment:

5862/8 Hydrogeophysical: Aren't these geophysical methods applied in Hydrology? Hydrogeophysics uses hydrological, geophysical or sedimentological methods.

Reply:

Totally agree: Hydrogeophysics involves use of geophysical measurements for estimating parameters and monitoring processes that are important to hydrological studies, such as those associated with water resources, contaminant transport, ecological and climate investigations (AGU Hydrogeophysics Committee 2014: http://www.hydrogeophysics.org/).

Referee#1 comment:

5863/3 : : :non-invasive: : :.. no, it is invasive but at a low level. Your electrodes punch the surface, in Archaeology for example this would be severe!

Reply:

The term has been changed to: *minimally invasive*

Referee#1 comment:

5863/12 : : :approx. 7: : :. Be precise a mean slope angle doesn't tell the reader anything! Also do you mean average?

Reply:

Sentence has been rewritten:

The slope angle ranges from 0.05 to 22.5° with an average of 7°.

Referee#1 comment:

5863/19 : : :.low bulk density: : :.. be precise, avoid low/high, as compared to an Andosol a bulk density of 1.2 g/cm3 would be high.

Reply:

The correct value from the table is added to the text:

The upper layer (LH) with a thickness of 0.3 to 0.65 m consists of silty-loamy material with a bulk density of 1.2 g/cm^3 and many roots (cf. Table 1).

Referee#1 comment:

5863/23 : : :.parallel to the slope. In which way? Long axis along or across the slope (both is parallel)

Reply:

Sentence has been rewritten:

The ubiquitous sandy-loamy basal layer (LB) is characterized by even higher bulk density and longitudinal axes of coarse clasts oriented parallel to the slope.

Referee#1 comment:

5864/8 : : :.resistivity: : : I suggest you should use the terms apparent/specific ELECTRIC resistivity, just as you do in line 14 on page 5864.

Reply:

We add an explanation on the first use that in this context resistivity always refers to electrical resistivity as there is no other (e.g. mechanical) involved in the study.

Referee#1 comment:

5865/5 how was the saturation achieved, from below by suction or from above by infiltration? Also the gravel content is >50% in LB, how could this fit in a 3.6 cm diameter tube, LBs in igneous rocks often tend to have be larger stones incorporated? Could this be a major fact for some of the later observed variability?

Reply:

Added: *The saturation was done successively by stepwise injection in the middle of the soil core to achieve a better moisture distribution within the sample.*

We are aware that the size of the tube might be a problem. But when comparing the ERT water contents with water content from the ThetaProbes (cf. Figure 12), the results show similar values for all depth (LH, LM and LB). Therefore we assume that samples represent the relationship in acceptable accuracy.

Referee#1 comment:

5866/11 Because: : :.. why because? Unclear (did you test or assume?). Often roots trace the depth of the layers very nicely. The question is do you have a high enough spatial resolution in your survey. A 1 m spacing does not give you a 10-20 cm vertical resolution as you want to resolve the LH and LM. Please indicate the vertical resolution of your arrays and settings.

5874/2 you don’t have a 0.2 cm resolution!!! Be careful

Reply:

Due to the higher vertical resolution (Roy and Apparao, 1971; Dahlin and Zhou, 1994) and the combination of arrays we believe our resolution is sufficient to image the very shallow and localized resistivity changes (see also Descloitres et al., 2003).

Of course the size of resolvable lateral heterogeneities (e.g. by roots or clasts) are limited by the electrode spacing, however improved by combining Wenner alpha and beta arrays. Since time-lapse inversion schemes are used (i.e. changes are regularized), anomalies in the baseline model will hardly appear in the temporal changes. Vertical resolution is well below electrode spacing, particularly in sight of the good data quality, and the ambiguity in the inversion does not affect the main findings, e.g. on the different types of precipitation event.

We added some explanation regarding resolution properties:
Horizontal resolution of a multi-electrode array is for shallow parts of the subsurface in the order of electrode distances. However, vertical resolution is far better as the depth-of-investigation curves indicate (Roy and Apparao, 1971; Barker, 1989). This is further improved by measuring two electrode arrays (Wenner-α and Wenner-β) with different sensitivity curves so that we can expect a vertical resolution in the order of about 0.2 m in case of excellent data quality.

Referee#1 comment:
5867/3 15cm deep electrodes will further reduce the vert. resolution on the top a lot! In theory you should a point on the surface.

Reply:
By simulating real electrode sizes, Rücker and Günther (2011, Table 1) showed that the effects of the used electrode is very low (1-2%) and thus within measurement accuracy. Furthermore, the remaining effects will mainly cancel out in timelapse (difference) inversion.

We added some explanation to the text:
In the numerical computations, electrodes are considered points, which is not the case for the present ratio of length to distance. However, numerical computations with real electrode lengths show that the deviations are negligible, particularly if the points are placed at about the middle electrode depth (Rücker and Günther, 2011)

Referee#1 comment:
5967/22 use (i), (ii), (iii)

Reply:
Done.

Referee#1 comment:
5868/1ff contact resistance wasn’t measured, why? Could this influence the data?

Reply:

The contact resistance was checked, right before each single measurement. As shown by Rücker and Günther (2011, Fig. 5), the effect is negligible and systematic for all measurements thus having no influence on the dynamic results.

We add a sentence: *Contact resistance was checked before each measurement and was the range of 0.2 to max. 1 kΩ over the whole measuring period. This range is very favourable and does not influence the measurements as numerical studies show (Rücker and Günther, 2011).*

Referee#1 comment:

5869/10 so there is no influence of a frozen LH during winter?

Reply:

The soil temperature was always above 0°C from May to December.

Referee#1 comment:

5869/27 : : :may not be differentiated: : :. But it could be also due to the too low vertical resolution of your survey design?

Reply:

In this context we are talking about laboratory measurements. Because of the similar material properties it is difficult to differentiate these two layers. With similar material properties it would be only possible to see a difference within the ERT data, if the water contents were different.

Referee#1 comment:

5870/19 : : :may vary. To what extent?

Reply:

cf. 0.3 m: n_θ ranges from 0.33 to 0.58 and F_θ from 1.9 to 2.3

cf. 1.3-1.4 m: n_θ ranges from 0.35 to 0.36 and F_θ from 1.62 to 1.66

The mean squared error for ρ_{eff}/ρ_w is also higher within the first depth range: $MSE_{<0.9m}$=2.8 and $MSE_{>0.9m}$=1.4. We added the MSE to Table 3.

Referee#1 comment:

5871/20 would this also be the case with a higher resolution in your survey design?

Reply:

The results would be the same, but maybe the boundary could be located more precisely.

Referee#1 comment:

5872/11 the reader wants to see a detailed 3D map of the layers in order be able to judge this statement.

Reply:

We don't have a 3D map of the layers, but see profile section in Figure 1, near the spring the LB exceeds 3.5 m.

Referee#1 comment:

5876/7 : : :infiltrates to the upper : : : what do you mean the upper layer (LB) or the upper part of the LB?

Reply:

Yes, we mean the upper parts of LB. Sentence has been rewritten.

Referee#1 comment:

5876 :remain low. Be precise what does it mean?

Reply:

We mean they remain constant until the next time step. Sentence has been rewritten.

Referee#1 comment:

5877/LB can't have electric characteristics only the sediments within LB.

Reply:

Sentence has been rewritten:

On the contrary, the sediments within LB have their own electrical characteristics.

Referee#1 comment:

5878/3 pedophysical: : :: : : is this the right term? You didn't talk about pedology yet about sediments. Earlier you used petrophysical – did you mean this?

Reply:

We have changed the term to pedo-/petrophysical, because both is right.

We are talking about sediments but these sediments are influenced by pedogenesis.

Referee#1 comment:

5878/4 did you really derive a method?

Reply:

Sentence has been rewritten:

Moreover, from the results of field measurements and parameter determination in the laboratory we are able to monitor seasonal changes in subsurface resistivity and its relationship to precipitation and soil moisture on the hillslope scale with a minimally invasive method directly.

Referee#1 comment:

Table 1 bulk density can't be in % must be g/cm3 ? Need to know the number of samples used to develop this table (assume it was not only 1 sample?)

Reply:

The unit has been changed.

Number of samples (n) have been be added (*$n \geq 15$ per layer*).

Referee#1 comment:

Table 2 same as for table 1 "n" needed

Reply:

Number of samples (n) have be added (*$n > 11$ per sampling depth*)

Referee#1 comment:

Table 3 need explanation of F_θ and n_θ in caption

Reply:

Text has be added to the caption:

Fitted water content formation factor (F_θ) and water content exponent (n_θ) ….

Referee#1 comment:

Figure 1 source of left fig? DEM? Need coordinated, Ger outlines not known to all readers, need explanation

> **Reply:**
>
> Figures have be changed. We added the source of the left figure and an explanation of the outlines.

Additional references:

Rücker, C. and Günther, T.: The simulation of finite ERT electrodes using the complete electrode model, Geophysics, 76, 227–238, doi:10.1029/95WR02995, 2011.

Point to point reply to Referee #2

First the authors want to thank the anonymous Referee #2 for his/her review of the manuscript and for the constructive helpful comments. Find our response and new text below each point intended and text suggestions in italics.

Referee#2 comment:

However, it is not clear what new contribution is made in this work. There does not appear to be any methodological innovation presented. There does not appear to be any new insights gained regarding hydrologic processes or properties.

Reply:

We understand that the novelty has not been presented clearly enough and revised the manuscript accordingly. Our major objectives are not to give new insight into hydrological processes on hillslopes rather to present a robust methodological framework to enhance spatial (statistical) significance of hydrometric point measurements. We tried to show that it is possible to reduce or partially substitute expensive invasive hydrometric point measurements while using minimally invasive ERT because it is capable to give comparable results but on a higher spatial scale.

In our opinion, the hillslope scale is the most important scale for predicting precipitation runoff response. Therefore it is crucial to know whether there is a spatial variability in the hydrological system on hillslopes or not. Many hypotheses of model are based on punctual measurements only. Punctual hydrometric measurement alone are not sufficient in case of significant spatial heterogeneity. However, with the use of a multi-method approach as presented in our paper, it is possible to transfer hydrometric data to higher spatial scales and to obtain additional patterns of soil water saturation distribution and its dynamics on a hillslope.

We changed our objectives in the introduction accordingly:

The objective of this paper is to show the potential of minimally invasive surface time-lapse ERT as a robust methodological framework for monitoring long-term changes in soil moisture and to improve the spatial resolution of punctual hydrometric measurements (e.g. tensiometer and ThetaProbes) on a~hillslope with periglacial cover beds. Furthermore, we want to show the ability of ERT for mapping spatially heterogeneous structures and water *content distributions of the shallow subsurface. With a multi-method approach, we attempt to demonstrate the possibility to adequately transfer hydrometric data to higher spatial scales and to obtain additional patterns of soil water dynamics on a hillslope. These scales are fundamental for achieving a better understanding of the influence of the layered subsurface on water fluxes (e.g. infiltration, percolation or interflow) and the response to different amounts of precipitation on hillslopes.*

The new title is:
Monitoring hillslope moisture dynamics with surface ERT for enhancing spatial significance of hydrometric point measurements.

Referee#2 comment:
863/2. These studies are not “uncommon”. In fact, they have become quite common.

Reply:
We agree that the use of ERT for mapping shallow subsurface structure und monitoring hydrological processes has been strongly developed in recent years. However, the use on hillslopes (in particular with layered structures) over a longer period (several month in almost weekly intervals) is still rare. Furthermore, most of the cited studies deal with controlled conditions (laboratory or irrigation) or only with a few time steps over a very long or very short period. The major aspect of the paper is (as also annotated by Referee #3) to show the robustness of ERT as long-term monitoring tool in the context of hillslope hydrology.

Referee#2 comment:
The data in Table 1, Figure 2, and Figure 8 have already been presented in prior publications.

Reply:
The data from Table 1 are adapted from Moldenhauer 2013, but they are of particular importance for understanding the electric and hydraulic properties of the study site. Furthermore some values were added (percentage distribution of soil texture and porosity).

Figure 2 is adapted from a German PhD thesis. The figure summarizes different Figures of the thesis (mean values of all sensors) and has modified depth ranges and colors for better comparison with the ERT data. It is very essential for validation and interpretation of the ERT data in in hillslope hydrology context.

Figure 8 is to show the reader the spatial expansion of the local groundwater. It is not essential for understanding only for a better visualization. We removed the figure.

Referee#2 comment:

The key section on inverting the ERT data (5867/22-5868/12) does not appear to provide enough information for a reader to be able to reproduce the results.

5868/6-7. Explain what is meant by these “smoothness constraints” and “regularization strength”.
5868/9. Explain “constraint minimum length”.
5868/10. Explain “adapting the inversion parameter”. What were the final parameters used for each time step? Please provide the key parameters in the text or supporting information. How were the best parameters identified? This sounds like a subjective process. Is it reproducible?

Reply:

Smoothness constraints means to impose additional terms on the minimization problem thus finding among the equivalent models the smoothest model that explains the data within error bounds. This is a standard procedure for static models and determines the regularization strength of this smoothness term, λ (see 5868/7) for the assumed data accuracy of 1%. Similar was done for the time-lapse (difference) inversion, except that we avoided smoothness due to the above discussed artifacts (see last comment). Minimum length means to minimize the difference between the model vectors of adjacent time steps regardless of the position of the cells so that the changes are purely data-driven and not by smoothing. The λ value was also determined with respect to data fit making it an objective procedure.

We added a new subsection for data inversion:

2.3.3 ERT data inversion

For inversion of the ERT data, we used the BERT Code (Günther et al., 2006). In order to account for the present topography, we used an unstructured triangular discretization of the subsurface and applied finite element forward calculations. For static inversion, a smoothness-constraint objective function is minimized that consists of the error-weighted misfit between measured data d and model response f (m), and a model roughness

$$\Phi = \|D(d-f(m))\|_2^2 + \lambda \|Cm\|_2^2 \rightarrow \min .$$

The regularization parameter _ defines the strength of regularization imposed by the smoothness matrix C and needs to be chosen such that the data are fitted within expected accuracy, which is 205 incorporated in the data weighting matrix D. In our case, values of λ=30 provided sufficient data fit. See Günther et al. (2006) for details of the minimization procedure, Beff et al. (2013) or Bechtold et al. (2012) for specific modifications in hydrological applications. For time-lapse inversion, i.e. calculating the temporal changes in resistivity, there are three different methodical approaches: (i) either inverting the models for each point in time separately, (ii) to use the initial model as reference model for the time step, (iii) or inverting the differences of the two data sets (Miller et al., 2008). With our data, each method generates insufficient results with unsubstantiated artifacts. Changes have been calculated, which cannot be explained or related to any natural process. Descloitres et al. (2003, 2008b) showed with synthetic data that time lapse inversion may produce artifacts, especially due to changes caused by shallow infiltration (decrease of resistivity), as mostly expected in our case.

As smoothness constraints are the main reason of these problems we avoid the smoothness operator in the time-lapse inversion and minimize a different objective function for the subsequent time-steps:

$$\Phi = \|D(d^n - f(m^n))\|_2^2 + \lambda \left\|m^n - m^{n-1}\right\|_2^2 \rightarrow \min .$$

Beginning from the static inversion, the subsequent models are found by reference model inversion. Only the total difference between the models of subsequent time steps n1 and n is used for regularization (minimum-length constraints). A higher regularization parameter of λ = 100 proved optimal for time lapse inversion concerning both data fit and in comparison to the hydrometric results.

In order to find representative resistivity values as a function of depth, which are independent on small-scale heterogeneities, we subdivide the model down to a depth of 3m into seven layers according to the boundaries of the described layering (cf. Table 1) and installation depth of hydrometric devices (cf. Fig. 1) (0–0.2, 0.2–0.4, 0.4–0.9, 0.9–1.2, 1.2–1.5, 1.5–2.0 and 2.0–3.0m). The representative values are median resistivities in the layers from the stations H1a to H4a and H4b to H4a for profiles A and B, respectively.

Referee#2 comment:

5860/10. Define ERT on first use.

Reply:

A declaration of ERT will be added to the abstract and on the first use in the text:

Referee#2 comment:

5860/16. The phrase "and resulting in remarkable coincidence" is grammatically incorrect and not supported by the data. Remove.

Reply:

The phrase has been removed.

Referee#2 comment:

5860/18-23. This is a weak summary of the results from this study. Replace.

Reply:

The abstract has been rewritten:

Besides floodplains, hillslopes are basic units that mainly control water movement and flow pathways within catchments of subdued mountain range. The structure of their shallow subsurface affects water balance, e.g. infiltration, retention, and runoff. Nevertheless, there is still a gap of knowledge of the hydrological dynamics on hillslopes, notably due to the lack of generalization and transferability. This study presents a robust multi-method framework of Electrical Resistivity Tomography (ERT) in addition with hydrometric point measurements, transferring hydrometric data into higher spatial scales to obtain additional patterns of distribution and dynamic of soil moisture on a hillslope. A geoelectrical monitoring in a small catchment in the eastern Ore Mountains has been carried out in weekly intervals from May to December 2008 to image seasonal moisture dynamics on the hillslope scale. For linking water content and electrical resistivity, the parameters of Archie's law were determined using different core samples. To optimize inversion parameters and methods, the derived spatial and temporal water content distribution was compared to tensiometer data. The results from ERT measurements show a strong correlation to the hydrometric data. The response is congruent to the soil tension data. Water content calculated from the ERT profile shows similar variations as water content from ThetaProbes. Consequently, soil moisture dynamics on the hillslope scale may be determined not only by expensive invasive punctual hydrometric measurements, but also *by minimally invasive time-lapse ERT, provided pedo-/petrophysical relationships are known. Since ERT integrates larger spatial scales, a combination with hydrometric point measurements improves the understanding of the ongoing hydrological processes and suits better to identify heterogeneities.*

Referee#2 comment:

5861/19. "These up to three layered cover beds" is a poorly constructed phrase. Reword.

Reply:

The paragraph was rewritten:

In catchments of Central European subdued mountain range, the shallow subsurface of hillslopes is mostly covered by Pleistocene periglacial slope deposits (Kleber and Terhorst, 2013). These slope deposits have developed in different layers. In literature normally three layers are classified (Upper Layer – LH, Intermediate layer – LM, Basal Layer – LB: classification according to ad-hoc AG-Boden, 2005; Kleber and Terhorst, 2013). Sometimes locally a 4th layer ("Oberlage" ad-hoc AG-Boden, 2005) could be found. The occurrence of these layers can vary spatially and has different regional and local characteristics. Due to the sedimentological and substrate-specific properties, e.g. grain-size distribution, clast content, and texture, they remarkably influence near-surface water balance (e.g. infiltration, percolation) and are of particular importance for near-surface runoff, e.g. interflow (Chifflard et al., 2008; Kleber, 2004; Kleber and Schellenberger, 1998; Sauer et al., 2001; Scholten, 1999; Völkel et al., 2002a, b; Heller, 2012; Moldenhauer et al., 2013).

Referee#2 comment:

5862/1. Replace "implemented" with "prior".

5862/2-3. Tracer investigations do not necessarily integrate entire catchments. Remove.

Reply:

The sentence was rewritten:

Most of the prior studies were based on invasive and extensive hydrometric point measurements on the punctual scale or on tracer investigations. Punctual hydrometric measurements may modify flow pathways and are not sufficient in case of significant spatial heterogeneities in the subsurface. Tracer experiments, e.g. using isotopes, integrate much larger scales up to entire catchments but provide less direct insights into ongoing processes.

Referee#2 comment:

5862/3. There have been many direct measurements on the hillslope scale (in this study about 50 m). Remove.

Reply:

The sentence has been rewritten:

Internal hydrological processes may be complex and due to the spatio-temporal interlinking of near-surface processes and groundwater dynamics, there is still a lack of knowledge regarding runoff generation in watersheds (McDonnell, 2003; Tilch et al., 2006; Uhlenbrook, 2005).

Referee#2 comment:

5862/25. Define EM.

Reply:

A declaration of EM is added:

Beside hydrogeophysical methods such as electromagnetics (EM) surveys (Popp et al., 2013; Robinson et al., 2012; Tromp-van Meerveld and McDonnell, 2009)…

Referee#2 comment:

5862/26. Replace "has" with "have".

Reply:

Done.

Referee#2 comment:

5863/4. Little was done to address the objective of mapping subsurface structures in this study.

Reply:

We agree that the main focus is not the mapping of the subsurface structure. Nevertheless it is a little part of the work. The objectives have been rewritten.

Referee#2 comment:

5863/5-6. A few months of data does not represent a "long-term" study. Remove.

Reply:

The meaning of “long-term” in this context refers to the changes in water content and not the length of the investigation period. Because of our temporal resolution we may only make conclusions over 1 or 2 week intervals.

Referee#2 comment:

5863/9. What is meant by “different runoff components”? Explain or remove.

Reply:

The runoff process may consist of different components, depending on where the runoff occurs. Usually three different runoff components were differentiated: surface runoff, interflow and groundwater flow

The sentence was rewritten:

These scales are fundamental for achieving a better understanding of the influence of the layered subsurface on water fluxes (e.g. infiltration, percolation or interflow) and the response to different amounts of precipitation on hillslopes.

Referee#2 comment:

5863/13. Remove “the” before “6 ha”.

Reply:

The word has been removed.

Referee#2 comment:

5863/14. Add a sentence or two describing the vegetation and land use at the site.

Reply:

The information was added:

The altitude ranges from 521 to 575 m asl with a predominant land cover of spruce forest (Picea abies approx. 30 yr.).

Referee#2 comment:

5863/16. What is a “slope hollow”?

Reply:

A slope hollow is a slope with a concave curvature in lateral direction and in our case also in direction of the slope.

Referee#2 comment:

5864/5. ThetaProbes are not truly FDR sensors. Remove.

Reply:

We agree, as they only use a single frequency and not a “domain” of many frequencies, and removed this phrase.

Referee#2 comment:

5864/16. Use lower case theta for soil volumetric water content in accordance with convention in soil science.

Reply:

All upper case thetas have been changed to lower case.

Referee#2 comment:

5864/19. Is the correct word “insulating” rather than “isolating”?

Reply:

We agree “insulating” is better. Word has been changed.

Referee#2 comment:

5865/1. Delete “petrophysical” because the relationship in this case is primarily about soil, not rocks.

Reply:

We have changed the term to pedo-/petrophysical, because both is right.

We are talking about sediments but these sediments are influenced by pedogenesis.

Referee#2 comment:

5865/10. I do not think “mineralization” is the correct term here. Maybe “electrical conductivity”?

Reply:

This term has been changed to the term from Brunet et al. (2010): *low mineralized water*

Referee#2 comment:

5866/10. What is “hp”?

Reply:

The “hp” is part of the name of the device and means “high power”

We will add some quotation marks “*4 point light hp*”

Referee#2 comment:

5867/26-27. Give one or more specific examples of such changes.

Reply:

An increase on the surface was always followed be a decrease below and vice versa. Synthetic data with shallow decrease or increase at the surface indicated that this can be artifacts due to the smoothness constraints (Descloitres et al., 2003).

Referee#2 comment:

5868/27. Replace the phrase “causes no runoff to the spring at most” with “caused no runoff”.

Reply:

Phrase changed.

Referee#2 comment:

5869/1-2. The phrase “decreasing discharge is mainly caused by direct precipitation” does not make sense.

Reply:

The sentence has been rewritten:

Primarily base flow dominates and decreasing discharge is mainly caused by saturation excess overland flow from the area surrounding the spring.

Referee#2 comment:

5869/10. “Saturated” not “saturate”.

Reply:

Word changed.

Referee#2 comment:

5869/12. What is meant by “too slow”?

5869/13-14. This sentence does not make sense. Revise.

Reply:

The paragraph has been rewritten:

Due to the anisotropic hydraulic properties (low vertical compared to horizontal hydraulic conductivity) the percolation into deeper parts of LB decreases. The seepage water is concentrated as backwater in the LM and the upper parts of LB. Because of the high lateral hydraulic conductivity this saturated depth range is mainly involved in runoff and causes strong interflow.

Referee#2 comment:

5871/6. Provide quantitative examples of the differences. They are not obvious in the figure.

Reply:

An example at the intersection of profile A and B:

- in a depth < 1 m – average deviation 8% (σ = 5.4%)
- in the depth range 1 – 7 m – average deviation 20% (σ = 10%)
- in depth > 7 m – average deviation 43% (σ = 6.6%)

We added the example in brackets to the text:

(e.g. A_B: depth <1m: average deviation 8% (σ = 5:4%), depth 1–7m: average deviation 20% (σ = 10%) and depth >7m: average deviation 43% (σ = 6:6%)).

Referee#2 comment:

5871/7. Define “reciprocal” in this context.

Reply:

A declaration of “reciprocal” was added:

To exclude potential errors (e.g. by electrode positioning), the data quality may be evaluated by comparing normal and reciprocal measurements, i.e. interchanging potential and current electrodes (LaBrecque et al., 1996; Zhou and Dahlin, 2003).

Referee#2 comment:

5872/13-17. Poorly written (e.g. “may easier spread” and “toward to the spring”). Revise.

Reply:

The paragraph was rewritten:

Due to the slope gradient, water from the hillsides and upper parts of the catchment flows into the direction of the depression lines, where it concentrates and forms a local slope *groundwater reservoir. This results in a maximum decrease of resistivity in this zone as observed in all measured profiles at depths 1.5 to 4.5 m (cf. Fig. 5 and 8).*

Percussion drilling confirmed that the thickness of LB downslope exceeds 3.5 m. Therefore, we assume that the entire saturated zone is located within the basal layer and since it is connected to the spring, it is also the source of the base flow.

According to this, the shape of the surface may be partially transferred to the subsurface to identify regions of different hydrogeological conditions. Convex areas indicate dryer conditions in the basal layer in comparison to the concave or elongate parts of the hillslope, which may act as local aquifers.

Referee#2 comment:

5870/8. Replace “we accept” with “we assume”.

5873/5. Replace “the same depth profile” with “depth profiles of similar shape”.

5873/12. Replace “precise” with “accurate”.

5873/12-13. Delete this sentence because it is not quantitative.

5873/28. Replace “higher amounts” with “higher resistivity values”.

5874/1-2. Replace “moisture conditions” with “higher soil water contents”.

5875/8. Delete “a mainstream”.

Reply:

All suggestions were followed to.

Referee#2 comment:

5875/5. What is meant by “A first annual trend: : :”?

Reply:

It meant the first period. The sentence has been rewritten:

The first period between May and October is mainly characterized by drying.

Referee#2 comment:

5876/15. What is meant by “profile A 25 m”?

Reply:

It meant at profile A at 25 m from the beginning, approx. in the middle of the profile.

We replaced the “25m” with “*close to the hydrometric station H3a*”.

Referee#2 comment:

5878/9. Explain what is meant by “accordingly different depths take part in runoff generation”? As far as I know, runoff occurs at the surface.

Reply:

Runoff does not only occur at the surface. It can also occur in the subsurface as interflow (runoff in the unsaturated zone) or groundwater flow (runoff in the saturated zone).

Referee#2 comment:

5879/3-4. The phrase “The spring discharge consequently shows the major runoff generation: : :” does not make sense. Revise

Reply:

The sentence has been rewritten:

Due to lateral subsurface flow within LH, LM and the upper parts of LB, the discharge of the spring strongly increases.

Referee#2 comment:

Table 5. Explain the connection between the data in Fig. 9 and the data used to construct Table 5.

Reply:

Figure 9 is only a depth profile of one time step, at the time of the mapping (08/10/21). Table 5 is the correlation over the whole time series of the depth profile next to H3a. The data (θ_{Theta} and θ_{pH3a}) used to construct Table 5 are shown in Figure 12. The data of Ψ_{H3a} is not shown in a Figure, only as mean value for all tensiometer stations in Figure 2.

Referee#2 comment:

Figure 6. Specify the date for these data.

Figure 7. Specify the date.

Figure 9. Specify the date.

Reply:

The dates were added to the captions.

Referee#2 comment:

Figure 7. Explain how you estimated porosity below 4-m depth when samples were only collected to 4 m.

Reply:

The porosity was adopted from the samples of LB. We are aware that the calculation of saturation in greater depth is not quantitatively verified. But we try to explain the clear and significant change in resistivity. We are not sure if this change in resistivity is caused due to the change to the underlying gneiss or if some other material acts as aquiclude, but it shows the lower boundary of the local groundwater storage.

Referee#2 comment:

Figure 10. Explain the grey shaded regions in the figures.

Reply:

The grey shaded regions visualize the ERT time intervals and ease the comparison with the bars of daily precipitation during the steps.

Referee#2 comment:

Figure 11. I like this figure.

Thank you.

Referee#2 comment:

Figure 12. Change the symbols so that the lines can be differentiated even in a greyscale print out.

Reply:

The balck circles have been changed to triangles.

Point to point reply to Referee #3

First the authors want to thank the anonymous Referee #3 for his/her review of the manuscript and for the constructive helpful comments. Find our comments and new text below each point intended with suggested additional or changed text in italics.

Referee#3 comment:

The information given for the measurements is sometimes insufficient, especially for the deepest layers of the sub-surface.

How was measured the porosity, how many samples? Which depths and which method?

> **Reply:**
>
> The porosity (ϕ) was calculated with the Eq.:
>
> $$\phi=1-\left(\frac{\rho_{bulk}}{\rho_{particle}}\right)$$
>
> The bulk density (ρ_{bulk}) was determined with undisturbed soil cores by drying and weighting. The particle density ($\rho_{particle}$) was measured with a capillary-stoppered pycnometer.
>
> An explanation about porosity measurements and number of samples (*n ≥ 15 per layer*) have been added to the text.

Referee#3 comment:

What is the maximal sampled depth? How was estimated the porosity is the deepest layers?

> **Reply:**
>
> The maximum sample depth for undisturbed soil cores was 2 m. Below 2 m the porosity and bulk density had to be transferred according to grain size distribution, clast and compaction from percussion drilling. An explanation was added to the text.

Referee#3 comment:

Concerning the pore soil water, what is the temporal variability of the measurements?

> **Reply:**
>
> The temporal variability of the pore water resistivity is small during the year. The range (min-max) of pore water resistivity is 46.7, 16.6, 15.0, 15.5, 14.7 and 29.7 Ωm for 0.3,

0.6, 0.85, 1.05, 1.65 and 2.3 m, respectively.

We would have liked to use the exact pore water resistivity for each point in time. However, due to very dry conditions it was not possible to extract enough pore water for measuring conductivity between July and October. Because of the missing measurement during the summer and because of the small variability within the existing measurements, we decided to use the median values.

Referee#3 comment:

In general, the mean values in the Tab.2 and Tab.3 should be associated at least to standard deviation or appropriated measures of dispersion in order to show the spatial or temporal variability.

Reply:

We will add some measures of dispersion in Tab. 2.

Depth [m]	0.3	0.6	0.85	1.05	1.65	2.3
$\bar{\rho}$ [Ωm]	135.7	92.3	88.9	86.8	75.1	63.7
σ [Ωm]	16.9	5.0	4.5	4.8	5.4	7.3

We added the mean squared error for ρ_{eff}/ρ_w in Tab. 3: $MSE_{<0.9m}$=2.8 and $MSE_{>0.9m}$=1.4.

Referee#3 comment:

As drilling has been performed down to 4m deep, it would have been very interesting to put one or several piezometers in order to get more accurate information of the deep water dynamics or constrain the inversion model.

Reply:

We absolutely agree that additional measurement as piezometers would be very helpful and that the constraint of the inversion model could improve the ERT results. If we had the information about the deep water before the ERT measurements, we would have liked to do this. In further studies this must necessarily be taken into account.

Referee#3 comment:

The vertical resolution in the top layers of the soil (0.20m) seems to be incoherent with the spacing between the electrodes (1m). Could you justify?

Reply:

Due to the higher vertical resolution (Roy and Apparao, 1971; Dahlin and Zhou, 1994) and the combination of arrays we believe our resolution is sufficient to image the very shallow and localized resistivity changes (see also Descloitres et al., 2003).

We added some explanation to the text:

Horizontal resolution of a multi-electrode array is for shallow parts of the subsurface in the order of electrode distances. However, vertical resolution is far better as the depth-of-investigation curves indicate (Roy and Apparao, 1971; Barker, 1989). This is further improved by measuring two electrode arrays (Wenner-α and Wenner-β) with different sensitivity curves so that we can expect a vertical resolution in the order of about 0.2m in case of excellent data quality.

Referee#3 comment:

The calibration of the Archie's relation in laboratory proves to be satisfactory for the n_θ parameter, and the relation between n_θ and the grain size distribution is a nice result. How could you interpret the fact that F remain constant? The values n_θ and F_θ should be compared to the expected values from the literature or from values coming from other similar studies.

Reply:

We interpret this due to the fact that we use water content instead of saturation. In case we use the equation with regard to saturation, the formation factors would differ because of the different porosities (ϕ)

$$\rho_{eff} = F_\theta\, \rho_w \theta^{-n_\theta} = F_\theta\, \rho_w (S^*\phi)^{-n_\theta} = \frac{F_\theta}{(\phi)^{n_\theta}}\, \rho_w (S)^{-n_\theta}$$

In this case the formation factors would be $F = \frac{F_\theta}{(\phi)^{n_\theta}}$ (c.f. Eq. 3). With the porosities of Tab. 1, *F* would be 1.72, 2.70 and 2.59 for LH, LM and LB, respectively.

In literature the Archie equation is often referred to saturation. To compare F_θ with expected values from the literature we would need to use F. Because of the uncertainty in integrating one mean value of porosity to the entire layer, we decided to mainly use water content instead of saturation.

Referee#3 comment:

The derivation of the water content from the electrical resistivities supposes that you consider F_θ and n_θ constant, from the depth 0.9m down to much deeper. But there is no evidence that it would be the case, because the maximal depth of the core soil samples used for the calibration of Archie's relation does not exceed 1.4m.

Reply:

Because of very similar characteristics in the entire LB (grain size distribution, clast and compaction) we consider the electrical relationship from the laboratory measurement as constant for LB.

Referee#3 comment:

Why do you show the ERT below 3m deep (Fig.7 and Fig.8), whereas the layering for inversion is said not to exceed 3m (5868, 17). I suggest that depths should not be considered deeper than the bottom of the basal layer.

Reply:

The inversion does exceed 3 m. The subdivision of the ERT model in 7 different layers (as mentioned in 5868, 17) was done to compare the results with results from the hydrometric measurements. The cut-off at 3 m was chosen because there were no deeper hydrometric data to compare with. The ERT data is not limited to this depth but shows no temporal variability below. Because of the missing comparison values, no temporal variations and due to the fact that deeper parts are completely saturated anyway, we decide not to include ERT results deeper than 3 m for the interpretation of the monitoring.

Referee#3 comment:

ERT uncertainties should be presented more in details: by comparing the values of the electrical resistivities at the nodes of the electrode lines.

Reply:

An example at the intersection of profile A and B:

- in a depth < 1 m – average deviation 8% (σ = 5.4%)
- in the depth range 1 – 7 m – average deviation 20% (σ = 10%)
- in depth > 7 m – average deviation 43% (σ = 6.6%)

We added the example in brackets to the text:

(e.g. A_B: depth <1m: average deviation 8% (σ = 5:4%), depth 1–7m: average deviation 20% (σ = 10%) and depth >7m: average deviation 43% (σ = 6:6%))

Referee#3 comment:

The estimated ERT water contents are only compared to the measured Theta Probe water contents and the measured tensions at the H3a profile. This comparison should be extended to all the measured tensions. The calibration of the relation between pressure and water content would allow optimizing the comparison between both electrical resistivities and water content.

Reply:

The station H3a was chosen because at this station all of the different measurements (Tensiometer, ThetaProbes, and ERT) are in close proximity to each other.

Nevertheless, all other measured tensions were considered, because we use median soil water tension (Figs. 2 and 11) from all tensiometers in the corresponding depth.

We tried a calibration of the relation between soil water tension and water content and noticed a high variability due to strong hysteresis effects. To come to reliable conclusions with this relationship, further instigations are needed. Indeed it would be very helpful for direct comparison between resistivity and water content, and would also allow establishing or verifying the Archie equation from field data.

Referee#3 comment:

5879, 24-27: I'm not convinced that ERT could deal with the small-scale heterogeneity like preferential flows, due to the size of macro-pores or corresponding channels. I suggest that the phrase should be removed.

Reply:

We agree that on this spatial scale ERT is not suitable to deal with preferential flow. Maybe on a much smaller scale with a very high resolute ERT.

The phrase has been removed.

Referee#3 comment:

5864, 7 : characteristics of the rain gauges ?

Reply:

The rain gauges have a catchment area of 200 cm² with 0.1 mm resolution per tip and max. 7 mm*min^{-1}.

We added the characteristics to the text*:*

*Rainfall was recorded by 4 precipitation gauges with tipping bucket (Fa. R.M. Young Co. resolution: 0.1 mm with max. 7 mm*min^{-1})*

Referee#3 comment:

5865, 12 : change σ_{w25} in ρ_{w25}

Reply:

We added the value for ρ_{w25} ($\rho_{w25} = 66\ \Omega m$) to the text.

Referee#3 comment:

5866, 6 : change \ A102.5°, \ B90° in \ A102.5°, \ C90°

Reply:

Done

Referee#3 comment:

5866, 19 : what does 0.195*L* refer ?

Reply:

L refers to the length of the maximum electrode separation. The maximum electrode separation with 50 electrodes, 1 m spacing and wenner-β array is L = 3x16 m = 48 m, with a maximum pseudo depth of 9.36 m.

We added the explanation in brackets to the Text:

(L = maximum electrode separation in m)

Referee#3 comment:

5870, 1 : remind the number of samples → Figure 4 shows the aggregation of the single 15 samples into two regions with different

Reply:

We added the number of samples to the text.

Referee#3 comment:

5871, 27 : “inner” and “outer” areas should be defined before 5871, 3 because it appears in Fig.5. The definition remains unclear.

Reply:

An explanation had been added to the first section of the results “ERT mapping”:
The distribution may be divided in two main areas, the “inner” area between the depression lines and the “outer” area at the hillsides, which differ in their depth profiles. (cf. Fig. 5)

Referee#3 comment:

5891, Tab.5 : change θ_{H3a} in $\theta_{\rho H3a}$, to be coherent with the notation in the line titled “Depth”

Reply:

Done

Referee#3 comment:

5892, Fig.1 : displays 37 tensiometers, when the text mentions 76 (5864-2)

Reply:

Fig. 1 is only a schematic profile section of one of the lines along the slope (D1a, D2a, D3a, H1a, H2a, H3a, and H4a). For redundant measurement a second line exists (D1b, D2b, D3b, H1b, H2b, H3b, and H4b), which also contains 38 tensiometers.

We changed the description in the figure from D1, D2, D3, H1, H2, H3, and H4 to D1a, D2a, D3a, H1a, H2a, H3a, and H4a to avoid misunderstandings.

Referee#3 comment:

5894, Fig.3 : the figure shows 14 points for each grain size, whereas there are 15 mentioned samples in the text.

Reply:

This is a typing error. All figures and tables are right, there are 14 samples. We changed 15 to 14.

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Monitoring hillslope moisture dynamics with surface ERT ~~and~~ for enhancing spatial significance of hydrometric point ~~measurement: a case study from Ore Mountains, Germany~~measurements

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Abstract. ~~Hillslopes are one of the~~ Besides floodplains, hillslopes are basic units that mainly control water movement and flow pathways within catchments of subdued mountain range. The structure of their shallow subsurface affects water balance, e.g. infiltration, retention, and runoff. Nevertheless, there is still a gap of knowledge of the hydrological dynamics on hillslopes, notably due to the lack of generalization and transferability.

~~To improve the knowledge of hydrological responses on hillslopes with periglacial cover beds, hydrometrical measurementshave been carried out on a small spring~~ This study presents a robust multi-method framework of Electrical Resistivity Tomography (ERT) in addition with hydrometric point measurements, transferring hydrometric data into higher spatial scales to obtain additional patterns of distribution and dynamic of soil moisture on a hillslope. A geoelectrical monitoring in a small catchment in the eastern Ore Mountains ~~since November 2007.~~

~~In addition, surface ERT measurements of several profiles were applied to enhance resolution of punctual hydrometric data. From~~ has been carried out in weekly intervals from May to December 2008 ~~geoelectrical monitoring in nearly weekly intervals was implemented to trace~~ to image seasonal moisture dynamics on the hillslope scale. ~~To obtain the link between~~ For linking water content and electrical resistivity, the parameters of Archie's law were determined using different core samples. To optimize inversion parameters and methods, the derived spatial and temporal water content distribution was compared to tensiometer data~~and resulting in remarkable coincidence. The measured resistivity shows a close correlation with precipitation. Depending on the amount and intensity of rain, different depths were affected by seepage water. Three different types of response to different amounts of precipitation (small, medium, high), could be differentiated. A~~

~~period with a small amount causes a short interruption of the drying pattern at the surface in summer, whereas a medium amount induces a distinctive reaction at shallow depth (<0.9m), and a high amount results in a strong response reaching down to 2m~~. The results from ERT measurements show a strong correlation to the hydrometric data. The response is congruent to the soil tension data. Water content calculated from the ERT profile shows similar variations as water content from ThetaProbes. Consequently, soil moisture dynamics on the hillslope scale may be determined not only by expensive invasive punctual hydrometric measurements, but also by minimally invasive time-lapse ERT, provided pedo-/petrophysical relationships are known. Since ERT integrates larger spatial scales, a combination with hydrometric point measurements improves the understanding of the ongoing hydrological processes and suits better to identify heterogeneities.

1 Introduction

The knowledge of system-internal water flow pathways and the response to precipitation on different spatial and temporal scales is essential for the prediction of hydrological and hydrochemical dynamics within catchments (Uhlenbrook et al., 2008; Wenninger et al., 2004). Understanding the involved processes is of particular importance for improving precipitation-runoff and pollutant-transport models (Di Baldassarre and Uhlenbrook, 2012).

~~The hillslopes are an important link~~ Hillslopes are important links between the atmosphere and the water input into catchments~~, and they~~ . They mainly control different runoff components and residence times (Uhlenbrook et al., 2008). Several studies have addressed hillslope hydrology (Anderson and Burt, 1990; Kirkby, 1980; Kleber and Schellenberger, 1998; McDonnell et al., 2001; Tromp-van Meerveld, 2004; Uchida et al., 2006). A major problem is that the spatial and temporal variability of the hydrological response due to different natural settings – e.g. geomorphological, pedological, lithological characteristics and the spatial heterogeneity – make it difficult to generalize and to transfer results to ungauged basins (McDonnell et al., 2007).

In catchments of Central European subdued mountain range, the shallow subsurface of hillslopes is mostly covered by Pleistocene periglacial slope deposits (Kleber and Terhorst, 2013).These ~~up to three layered cover beds~~ slope deposits have developed in different layers. In literature normally three layers are classified (Upper Layer – LH, Intermediate Layer – LM, Basal Layer – LB: classification according to AD-hoc AG-Boden, 2005; Kleber and Terhorst, 2013)~~, have~~ . Sometimes locally a 4th layer (“Oberlage” AD-hoc AG-Boden, 2005) could be found. The occurrence of these layers can vary spatially and has different regional and local characteristics~~and remarkable influence on water budgets as well as on water fluxes~~. Due to the sedimentological and substrate-specific properties, e.g. ~~grain size~~ grain-size distribution, clast content, and texture, they remarkably influence near-surface water balance (e.g. infiltration, percolation) and are of particular importance for ~~near surface runoffas well as for~~ near-surface runoff, e.g. interflow (Chifflard et al., 2008; Kleber, 2004; Kleber and Schellenberger, 1998; Sauer et al., 2001; Scholten, 1999; Völkel et al., 2002a, b; Heller, 2012; Moldenhauer et al., 2013).

Most of the ~~implemented~~ prior studies were based on invasive and ~~expansive~~ extensive hydrometric point measurements ~~on the punctual scale~~ or on tracer ~~investigation, which integrates entire catchments . Due to the lack of direct measurements on an intermediate (hillslope) scale and considering the existing complexities and~~ investigations. Punctual hydrometric measurements may modify flow pathways and are not sufficient in case of significant spatial heterogeneities in the subsurface. Tracer experiments, e.g. using isotopes, integrate much larger scales up to entire catchments but provide less direct insights into ongoing processes. Internal hydrological processes may be complex and due to the spatio-temporal interlinking of near-surface processes and groundwater dynamics, there is still a ~~-~~lack of knowledge regarding runoff generation in watersheds (McDonnell, 2003; Tilch et al., 2006; Uhlenbrook, 2005). ~~Additional~~ For an efficient and accurate modeling of the hydrological behavior at the crucial hillslope scale, additional methods are needed especially to improve the understanding of these complex processes ~~, especially at the hillslope scale~~in order to enhance the model hypotheses. Hydrogeophysical methods are capable of closing the gap between large-scale depth-limited remote-sensing methods and invasive punctual hydrometric arrays (Robinson et al., 2008a, b; Lesmes and Friedman, 2006; Uhlenbrook et al., 2008).

Many studies show the potential of ~~ERT~~ Electrical Resistivity Tomography (ERT) for hydrological investigation by means of synthetic case studies for aquifer transport characterization (Kemna et al., 2004; Vanderborght et al., 2005), imaging water flow on soil cores (Bechtold et al., 2012; Binley et al., 1996a, b; Garré et al., 2011, 2010; Koestel et al., 2009a, b, 2008), ~~cross borehole~~ cross-borehole imaging of tracers (Daily et al., 1992; Oldenborger et al., 2007; Ramirez et al., 1993; Singha and Gorelick, 2005; Slater et al., 2000), or imaging of ~~tracers or irrigations~~ tracer-injection or irrigation with surface ERT (Cassiani et al., 2006; De Morais et al., 2008; Descloitres et al., 2008a; Michot et al., 2003; Perri et al., 2012). However, some research has been conducted under natural conditions to characterize water content change, infiltration or discharge by use of ~~cross borehole~~ cross-borehole ERT (French and Binley, 2004), surface ERT (Brunet et al., 2010; Benderitter and Schott, 1999; Descloitres et al., 2008b; Massuel et al., 2006; Miller et al., 2008) or a combined surface cross-borehole ERT array (Beff et al., 2013; Zhou et al., 2001).

~~Beside~~ Besides hydrogeophysical methods such as ~~EM~~ electromagnetics (EM) (Popp et al., 2013; Robinson et al., 2012; Tromp-van Meerveld and McDonnell, 2009), time-lapse ERT ~~has~~ have been frequently applied to hillslope investigation in the runoff and interflow (Uhlenbrook et al., 2008; Cassiani et al., 2009) or preferential flow context (Leslie and Heinse, 2013). However, the use of ERT for ~~mapping shallow subsurface structures and~~ monitoring hydrological dynamics on hillslopes ~~is still uncommon~~with layered structure is still rare.

The objective of this paper is to show the potential of ~~non-invasive surface ERT for mapping the spatial heterogeneities of shallow subsurface structures on a hillslope with periglacial cover beds. Furthermore, we used time-tapse ERT to monitor~~ minimally invasive surface time-lapse ERT as a robust methodological framework for monitoring long-term ~~soil moisture dynamics~~ changes in soil moisture and to improve the spatial resolution of ~~additional~~ punctual hydrometric measurements (e.g. tensiometer and ~~FDR-Sensors) . With this multi method~~ ThetaProbes) on a hillslope with periglacial cover beds. Furthermore, we want to show the ability of ERT for mapping spatially heterogeneous structures and water content distributions of the shallow subsurface. With a multi-method approach, we ~~tried to achieve a~~ attempt to demonstrate the possibility to adequately transfer hydrometric data to higher spatial scales and to obtain additional patterns of soil water dynamics on a hillslope. These scales are fundamental for achieving a better understanding of the influence of the layered subsurface on ~~different runoff components~~ water fluxes (e.g. infiltration, percolation or interflow) and the response to different amounts of precipitation on hillslopes.

2 Material and methods

2.1 Study site

The study area covers ~~the~~ 6 ha of a forested spring catchment in the Eastern Ore Mountains, eastern Germany, which is located in the Freiberger Mulde catchment (Fig. 1). Annual precipitation averages 930 mm, mean annual temperature is 6.6 °C. The altitude ranges from 521 to 575 ~~. The catchment is formed as a slope hollow with a mean slope inclination of approximately~~ m asl with a predominant land cover of spruce forest (Picea abies approx. 30 yr.). The slope angle of the catchment ranges from 0.05 to 22.5° with an average of 7°. Bedrock is gneiss overlain by periglacial cover beds with up to three layers ~~(Heller, 2012) .~~(LH, LM, LB, with no occurrence of the “Oberlage” c.f. Heller, 2012). The upper layer (LH) with a thickness of 0.3 to 0.65 m consists of silty-loamy material with a ~~low bulk density~~ bulk density of 1.2 $\mathrm{g\,m^{-3}}$ and many roots (cf. Table 1). In the central part of the ~~slope hollow~~catchment, a silty-loamy intermediate layer (LM) follows with higher bulk density and a thickness of up to 0.55 m. The ubiquitous sandy-loamy basal layer (LB) is characterized by even higher bulk density and longitudinal axes of coarse clasts oriented parallel to the slope. Down slope it may reach a thickness of at least 3 m (cf. Fig. 1).

2.2 ~~Hydrometrical equipment~~

~~Since November 2007 soil water tension has been measured using 76 recording tensiometers (UMS – T8, 10intervals) arranged in 14 survey points along the slope at 5 to 7 different depths (cf. Fig. 1). Additionally, at the survey point H3a five ThetaProbes (FDR-Sensors – Delta T devices – ML2x) were installed to measure volumetric water content. A V-notch weir with a pressure meter was used to quantify spring discharge. Rainfall was recorded by 4 precipitation gauges with tipping bucket. For determination of pore water conductivity and resistivity, soil water was extracted with suction cups (VS-pro Vakuum System Co. UMS) at four depths at three locations (S1, S2, S3; Fig. 1) and cumulated as a weekly mixed sample.~~

2.2 Laboratory work

Quality, amount, and distribution of pore water exert a huge influence on resistivity [1] and form the link between electrical and hydrological properties. The empirical relationship of Archie’s law (Archie, 1942) describes the connection between electrical resistivity and saturation in porous media. Instead of saturation we use the volumetric water content ~~Θ with:~~ θ with:

$$\rho_{\text{eff}} = F\cancel{_{\Theta}\rho_{\text{w}}\Theta^{-n_{\Theta}}}{}_{\theta}\rho_{\text{w}}\theta^{-n_{\theta}} \tag{1}$$

where ρ_{eff} is the bulk resistivity of the soil probe and ρ_{w} is the resistivity of the pore fluid. The formation factor ~~F_Θ~~ F_θ describes the increase of resistivity due to an ~~isolating~~ insulating solid ma-

[1] in this context the term "resistivity" always refers to "electrical resistivity"

trix and constitutes an intrinsic measure of material ~~microgeometry~~ micro-geometry (Schön, 2004; Lesmes and Friedman, 2006). The exponent $\cancel{n_\Theta}$ n_θ is an empirical constant, which depends on the distribution of water within the pore space (Schön, 2004).

This model disregards the surface conductivity, which may occur due to interactions between pore water and soil matrix, especially with a high percentage of small grain sizes. In our study the curve fitting could be carried out very well without considering this, thus it was not taken into account.

To investigate the pedo-/petrophysical relationship between resistivity and water content, 15 undisturbed soil core specimens (diameter $= 36\,\mathrm{mm}$, length $= 40\,\mathrm{mm}$) taken at different depths (0.3 to $1.4\,\mathrm{m}$) were analyzed. After dehydration in a drying chamber, the samples were saturated~~successively~~. The saturation was done successively by stepwise injection in the middle of the soil core to achieve a better moisture distribution within the sample. Using a 4-point array, electrical resistivity was measured for different saturation conditions during the saturation process. A calibrating solution with known resistivity was used to determine the geometric factor. Particle sizes were determined by sieving and the pipette method, using $Na_4P_2O_7$ as a dispersant (Klute, 1986, p. 393, 399–404, but with the sand-silt boundary at $0.063\,\mathrm{mm}$).

Brunet et al. (2010) described remarkable conductivity increases of ~~water with low initial mineralization~~low mineralized water , due to contact with the soil matrix. This may cause variation of resistivity with time. To minimize this effect we used spring water with high conductivity (approx. $\cancel{\delta_{w25} = 150}\sigma_{w25} = 150\,\mu\mathrm{S\,cm^{-1}}$ / $\rho_{w25} = 66\,\Omega\,\mathrm{m}$ for $T = 25\,°\mathrm{C}$). This corresponds to the mean conductivity of soil water in the study area, which is influenced by long-term contact with the subsoil.

Aside from the invariant parameters ~~F_Θ and n_Θ~~ F_θ and n_θ, the resistivity of the pore water must be known to calculate the water content from resistivity values. Because it was not possible to extract pore water under dry conditions in summer, only a few measurements of pore water conductivity could be carried out in late spring and early autumn. To calculate water content from resistivity obtained by field surveys, the median value over the entire time period of ρ_w for each depth was used (cf. Table 2). Interim values between the extraction depths were linearly interpolated.

After reforming Eq. (1), it is possible, with known parameters ~~F_Θ and n_Θ~~ F_θ and n_θ, and measured variables ρ_{eff} and ρ_w, to calculate volumetric water content:

$$\frac{\rho_{\mathrm{eff}}}{F_{\cancel{\Theta}}\cancel{\rho}_\theta \rho_w}^{\cancel{\frac{1}{-n_\Theta}}\frac{1}{-n_\theta}} = \cancel{\Theta}\theta. \tag{2}$$

As water saturation (S) is defined as the ratio between water content and porosity (Φ), it is also possible to calculate the degree of saturation using:

$$\cancel{\frac{\rho_{\mathrm{eff}}}{F_\Theta \rho_w}}\frac{\rho_{\mathrm{eff}}}{F_\theta \rho_w}^{\cancel{\frac{1}{-n_\Theta}}\frac{1}{-n_\theta}} \frac{1}{\Phi} = S. \tag{3}$$

The porosity (Φ) was calculated with:

$$\Phi = 1 - \frac{\rho_{\mathrm{bulk}}}{\rho_{\mathrm{particle}}}. \tag{4}$$

The bulk density (ρ_{bulk}) was determined using undisturbed core sample. The particle density (ρ_{particle}) was measured with a capillary-stoppered pycnometer. The maximum sample depth for undisturbed soil cores was $< 2\,\mathrm{m}$. Below, the porosity had to be transferred according to grain size distribution, clasts and compaction from percussion drilling.

2.3 Field work

2.3.1 ERT Mapping

In addition to conventional percussion drilling, at the end of October 2008 we measured 7 ERT profiles to survey the subsurface resistivity distribution (Fig. 1A–G). A and C are parallel to the slope inclination of approx. 9°, connecting inflection points of contour lines. B, D, E, F, and G are perpendicular to these profiles ($\angle$ A102.5°, ~~$\angle$ B90°~~ $\angle$ C90°). This arrangement allows identifying potential 3-D-effects, which may cause inaccurate interpretation of the subsurface resistivity distribution. To improve the mapping results aided by hydrometric data, the profiles were located close to the tensiometer stations (distance $< 2\,\mathrm{m}$). For all resistivity measurements, a Lippmann "4 Point light hp" instrument with 50 electrodes was used. Because of the expected ~~heterogeneities~~ interferences (e.g. by roots or clasts) and the multiple layered stratification of periglacial cover beds, a Wenner-α array was found to be the most suitable configuration for the study area. This is characterized by low geometric factors (K), a high vertical resolution for laterally bedded subsurface structures, and a good signal-to-noise ratio (Dahlin and Zhou, 2004). To improve the spatial resolution, a Wenner-β array was measured additionally. With an electrode spacing of $1\,\mathrm{m}$, this results in a combined dataset with 784 data points for each pseudo-section with a maximum depth of investigation of $9.36\,\mathrm{m}$ (Wenner-β: depth of investigation for radial dipole in homogeneous ground $0.195L$ (L = maximum electrode separation in m) according to Roy and Apparao, 1971; Apparao, 1991; Barker, 1989).

2.3.2 ~~Monitoring~~

Horizontal resolution of a multi-electrode array is for shallow parts of the subsurface in the order of electrode distances. However, vertical resolution is far better as the depth-of-investigation curves indicate (Roy and Apparao, 1971; Barker, 1989) . This is further improved by measuring two electrode arrays (Wenner-α and Wenner-β) with different sensitivity curves so that we can expect a vertical resolution in the order of about $0.2\,\mathrm{m}$ in case of excellent data quality.

~~Time lapse~~

2.3.2 Joint Hydrometric and ERT Monitoring

Since November 2007 soil water tension has been measured using 76 recording tensiometers (UMS – T8) arranged in 14 survey points along the slope at 5 to 7 different depths (cf. Fig. 1). Additionally, at the survey point H3a five ThetaProbes (Delta T devices – ML2x) were installed to measure volumetric water content. A V-notch weir with a pressure meter was used to quantify spring discharge. Rainfall was recorded by 4 precipitation gauges with tipping bucket (Fa. R.M. Young Co., 200 cm^2 - resolution: 0.1 mm with max. 7 $\mathrm{mm\,min}^{-1}$). For determination of pore water conductivity and resistivity, soil water was extracted with suction cups (VS-pro Vacuum System Co. UMS) at four depths at three locations (S1, S2, S3; Fig. 1) and cumulated as a weekly mixed sample.

Time lapse ERT measurements were performed with the same equipment, electrode array and spacing used for the mapping. The two time lapse profiles are congruent with profile A and B (cf. Fig. 1).

From May to December 2008, twenty seven time lapse measurements were carried out within almost weekly intervals. Contact resistance was checked before each measurement and was the range of 0.2 to max. 1 $\mathrm{k\Omega}$ over the whole measuring period. This range is very favorable and does not influence the measurements as numerical studies show (Rücker and Günther, 2011) .

To compare time lapse measurements and to apply sophisticated inversion routines, the location of electrodes needs to remain constant. For current injection we used stainless steel electrodes (diameter $= 6\,\mathrm{mm}$, length $= 150\,\mathrm{mm}$), completely plunged into the ground, thus avoiding shifting of electrodes, except for natural soil creep. In the numerical computations, electrodes are considered points, which is not the case for the present ratio of length to distance. However, numerical computations with real electrode lengths show that the deviations are negligible, particularly if the points are placed at about the middle electrode depth (Rücker and Günther, 2011) .

Subsoil temperature, especially in the upper layers, is characterized by distinct annual and daily variations. Therefore, temperature dependence of resistivity must be considered when comparing different time steps.

The installed tensiometers are able to measure soil temperature simultaneously. These data have been used to correct resistivity measurements to a standard temperature. Comparing several existing models for the correction of soil electrical conductivity measurements, Ma et al. (2011) conclude that the model (Eq. 5) as proposed in Keller and Frischknecht (1966), is practicable within the temperature range of environmental monitoring.

$$\rho_{25} = \rho_{\mathrm{t}}\,(1 + \delta\,(T - 25\,^{\circ}\mathrm{C})) \tag{5}$$

With this equation the inverted resistivity (ρ_{t}) at the temperature (T) was corrected to a resistivity at a soil temperature of 25 °C (ρ_{25}). The empirical parameter δ is the temperature slope compensation, with $\delta = 0.025\,^{\circ}\mathrm{C}^{-1}$ being commonly used for geophysical applications (Keller and Frischknecht, 1966; Hayashi, 2004; Ma et al., 2011).

2.3.3 ERT data inversion

For inversion of the ERT data, we used the BERT Code (Günther et al., 2006). In order to account for the present topography, we ~~applied~~ used an unstructured triangular discretization of the ~~surface.~~ subsurface and applied finite element forward calculations. For static inversion, a smoothness-constraint objective function is minimized that consists of the error-weighted misfit between measured data $\mathbf{d}$ and model response $\mathbf{f}(\mathbf{m})$, and a model roughness:

$$\Phi = \|\mathbf{D}(\mathbf{d} - \mathbf{f}(\mathbf{m}))\|_2^2 + \lambda \|\mathbf{C}\mathbf{m}\|_2^2 \rightarrow \min \quad . \tag{6}$$

~~To calculate~~ The regularization parameter λ defines the strength of regularization imposed by the smoothness matrix $\mathbf{C}$ and needs to be chosen such that the data are fitted within expected accuracy, which is incorporated in the data weighting matrix $\mathbf{D}$. In our case, values of λ=30 provided sufficient data fit. See Günther et al. (2006) for details of the minimization procedure, Beff et al. (2013) or Bechtold et al. (2012) for specific modifications in hydrological applications.

For time-lapse inversion, i.e. calculating the temporal changes in resistivity, there are three different methodical approaches: (i) either inverting the models for each point in time separately~~and subtract after inversion,~~ , (ii) to use the initial model as reference model for the time step, (iii) or inverting the differences of the two data sets (Miller et al., 2008). With our data, each method generates insufficient results with unsubstantiated artifacts. ~~Changes have been calculated, which~~ An increase on the surface was always followed be a decrease below and vice versa. These systematic changes cannot be explained or related to any natural process. Descloitres et al. (2003, 2008b) showed with synthetic data that time lapse inversion may produce artifacts ~~, especially due to~~ due to the smoothness constraints especially with changes caused by shallow infiltration (decrease of resistivity), as mostly expected in our case.

~~The inversion had to be adjusted in order to minimize these artifacts. The expedient results were achieved by using the second approach with different inversion parameters for the initial reference model and each subsequent time lapse inversion. The first time step was calculated with smoothness constraints of 1st order and regularization strength $\lambda = 30$. The result was used as a reference model for the next time step. The following model was calculated with the antecedent time step as reference model, a chosen constraint minimum length, and higher regularization strength ($\lambda = 100$). By using this approach with each model as reference model for the next time step and adapting the inversion parameter, we could reduce the artifacts and achieve conclusive results. In our case this provides the best fit~~ As smoothness constraints are the main reason of these problems we avoid the smoothness operator in the time-lapse inversion and minimize a different objective function for the subsequent time-steps:

$$\Phi = \|\mathbf{D}(\mathbf{d^n} - \mathbf{f}(\mathbf{m^n}))\|_2^2 + \lambda \|\mathbf{m^n} - \mathbf{m^{n-1}}\|_2^2 \rightarrow \min \quad . \tag{7}$$

Beginning from the static inversion, the subsequent models are found by reference model inversion. Only the total difference between the models of subsequent time steps $n-1$ and n is used for regularization (minimum-length constraints). A higher regularization parameter of λ=100 proved optimal for time lapse inversion concerning both data fit and in comparison to the hydrometric ~~data~~results.

In order to find representative resistivity values as a function of depth, which are independent on small-scale heterogeneities, we subdivide the model down to a depth of 3 m into seven layers according to the boundaries of the described layering (cf. Table 1) and installation depth of hydrometric devices (cf. Fig. 1) (0–0.2, 0.2–0.4, 0.4–0.9, 0.9–1.2, 1.2–1.5, 1.5–2.0 and 2.0–3.0 m). The representative values are median resistivities in the layers from the stations H1a to H4a and H4b to H4a for profiles A and B, respectively.

2.4 ~~Results~~

3 Results

3.0.1 ~~Hydrometry~~

3.1 Laboratory

~~During the period May to December 2008 the spring discharge varied between 0.07 and 1.67. Median soil water tension of the study area, related to depth and time (cf. Fig. 2), indicates the impact of soil moisture on spring discharge. During summer increasing evapotranspiration causes the drying-out of soil. The spring showed only a slight reaction to precipitation events. Rainfall could only balance the soil water deficit and causes no runoff to the spring at most. Therefore, there is almost no runoff generation in the summer season. Primarily base flow dominates and decreasing discharge is mainly caused by direct precipitation to the area surrounding the spring.~~

~~In contrast, during winter season (starting in November) at all depths lower tensions ($<90\,\mathrm{hPa}$) were measured. Less evapotranspiration results in a replenishment of the storage water reservoirs in the subsurface. Due to the moist conditions, high presaturations predominate and cause a rapid runoff response with rain and the high discharges within the winter season.~~

~~Furthermore, there is an influence of the layered subsurface on soil moisture and runoff response. Until the beginning of May and again from December the low tensions of the upper LB indicate saturate conditions, in contrast to the deeper LB with higher tensions (cf. Fig. 2). Because of the anisotropic hydraulic properties, the percolation into deeper parts of LB is too slow, and the seepage water is accumulated in the LM and the upper LB. The backwater of the saturated depth range is mainly involved in runoff and causes strong interflow.~~

3.1.1 ~~Laboratory~~

Within the separately analyzed samples, non-linear curve fitting was carried out. Using the method of least squares, the data could be fitted using a power function in the form of Archie's law (Eq. 1, $0.973 < r < 0.999$).

The exponent ~~n_Θ~~ n_θ shows a positive correlation to small grain sizes, primarily medium silt (6.3–20 μm, $r = 0.909$), but in the same case a negative correlation to grain sizes $> 630\,\mu m$ including clast content ($r = -0.852$) (cf. Fig. 3).

The amount of silt as well as the clast content are important distinctive attributes to differentiate the basal layer from the overlying intermediate or upper layer (Table 1). Two different "electrical" layers may be identified. This is due to the fact that the exponent is strongly influenced by grain size, which shows a remarkably change at the upper boundary of LB. On the other hand, grain size distribution and clast content are very similar between LH and LM, so that these may not be differentiated using ERT. Figure 4 shows the aggregation of the 14 single samples into two regions with different depth ranges.

The first depth range comprises the upper and the intermediate layer. These two periglacial layers are characterized by a high amount of silt (mostly medium silt) and comparatively low clast content. The exponent ~~n_Θ~~ n_θ ranges from 1.8 to 2.3. The second depth range is represented by the basal layer. This is characterized by a higher amount of coarse material at the expense of fine grain sizes. In this depth range ~~n_Θ~~ n_θ ranges from 0.7 to 1.8. Within each of these two depth ranges, we ~~accept~~assume, analog to the properties of the substrate, similar electrical properties with a threshold at 0.9 m. The threshold depth of 0.9 m is not developed as an exact, continuous boundary. Rather it is a short transition zone, because the samples right from this depth may have properties of the shallow or the deeper region, similar to the geomorphological differentiation between the basal and intermediate layer, whose boundary varies between depths of 0.8 to 1 m. By combining samples from different depths into two regions, it was possible to derive the parameter for Eqs. (1)–(3) for each region (Table 3).

This relationship between water content and resistivity, shown in Fig. 4 and Table 3, is only a mean value for each depth range. In the first depth range (0–0.9 m), especially close to the surface, the differences in soil or electrical properties between the samples even at the same depth may vary. This higher variation may be explained by intense biotic activity near the surface, enhancing small-scale heterogeneity compared to deeper parts of the soil.

The fitted curves of both regions are quite similar, except for ~~n_Θ~~ n_θ. The formation factors are very similar (0.577 vs. 0.587, Table 3). With high saturation, the difference of resistivity between the depth ranges is small and primarily influenced by the conductivity of the pore fluid, but increases with decreasing water content. As a result of the higher exponent, LH and LM react more sensitively to water content changes than LB, especially at low presaturations. Related to this, small water content changes cause larger changes in resistivity than in the deeper region.

3.1.1 ~~Mapping~~

3.2 ERT Mapping

At our study site the resistivity of the subsoil ranges from nearly 100 $\Omega\,\mathrm{m}$ up to more than 4000 $\Omega\,\mathrm{m}$. The distribution may be divided in two main areas, the “inner” area between the depression lines and the “outer” area at the hillsides, which differ in their depth profiles. (cf. Fig. 5) ~~.~~

At the intersection between the longitudinal and diagonal profiles, a good match of the calculated resistivity models may be found at shallow depth. With increasing depth, the differences become more notable ~~.~~ (e.g. A×B: depth <1 m: average deviation 8% ($\sigma = 5.4\%$), depth 1–7 m: average deviation 20% ($\sigma = 10\%$) and depth >7 m: average deviation 43% ($\sigma = 6.6\%$)). To exclude potential errors (e.g. electrode positioning errors), the data quality may be evaluated by comparing normal and reciprocal measurements, i.e. interchanging potential and current electrodes (LaBrecque et al., 1996; Zhou and Dahlin, 2003). For profile A and B repeated measurements with reciprocal electrode configuration were conducted. Thereby, no large errors (max $\pm 1.2\,\%$) could be found between normal and reciprocal measurements. Because of the absence of large potential errors, the increasing deviation with depth may be only explained by the inversion process, decreasing sensitivity, less spatial resolution or potential 3-D-effects.

The resistivity distribution of the subsurface is characterized by large-scale and small-scale heterogeneities, but also distinct patterns may be identified. At shallow depth up to 0.9 m, the study area is characterized by high resistivity. This comprises the upper and the intermediate layer.

Since the laboratory results indicate similar electrical properties, remarkable differences between upper and intermediate layers only occur, if water content deviates. There are areas, where the intermediate layer has higher resistivity, suggesting lower water content (cf. Fig. 6).

The hydrometric data show the driest conditions in 0.55–0.65 m (cf. Fig. 2), which is consistent with the high median resistivity of the intermediate layer at the time of data acquisition (cf. Fig. 7).

Resistivity decreases in greater depths (starting at 1 m). Thus, the basal layer is characterized by lower resistivity compared to the overlying layers. However, this is not constant in lateral direction. Two different patterns are found. In the “inner” area between the two depression lines (approx. between profile A and C), the resistivity of the basal layer is lower than in the “outer” area (the hillsides) (cf. Fig. 7). Between the depression lines LB is characterized as a connected zone of low resistivity. A calculation of saturation using Eq. (3) and the porosity from Table 1 indicates that this may be interpreted as a connected saturated zone (Figs. 7~~and ??~~).

Due to the slope gradient, water from the hillsides and upper parts of the catchment flows ~~toward the~~ into the direction of the depression lines, where it concentrates ~~within the basal layer~~ and forms a local slope groundwater reservoir. This results in a maximum decrease of resistivity in this zone as observed in all measured profiles at depths 1.5 to 4.5 m (cf. Fig. ~~??).~~

5 and 7). Percussion drilling confirmed that the thickness of LB downslope exceeds 3.5 m. Therefore, we assume that the entire saturated zone is located within the basal layer and since it is connected to the spring, it is also the source of the base flow.

~~This zone expands upslope, due to the fact that the depression lines diverge; the relief becomes smoother and does not show such strong recess (cf. Fig. 1). The water may easier spread laterally. On the other hand toward to the spring, it becomes more and more constricted.~~ According to this, the shape of the surface may be partially transferred to the subsurface to identify regions of different hydrogeological conditions. Convex areas indicate dryer conditions in the basal layer in comparison to the concave or elongate parts of the hillslope, which may act as local aquifers.

It is not feasible to relate a ~~specific~~ resistivity to the underlying gneiss or its regolith. Percussion drilling was only realized down to 4 m depth where bedrock could not be reached. If the maximum thickness of the basal layer is equal to the saturated zone, as obtained by resistivity data, the change from basal layer to underlying gneiss may be set at a depth around 4.5 m.

ERT mapping of the spatial distribution of periglacial cover beds is associated with several restrictions. In our study area, stratification is concealed by the influence of pore water, the main factor driving resistivity. On the other hand this fact may be used to improve the understanding of the moisture conditions of the subsurface.

To check the equations obtained in the lab and also to compare directly with hydrometric data, we used the water contents from the ThetaProbes at H3a. Figure 8 compares water content, calculated with temperature-corrected resistivity (~~$\Theta_{\rho\mathrm{H3a}}$~~ $\theta_{\rho\mathrm{H3a}}$ profile A close to ~~H3A~~H3a), with water content from the ThetaProbes (~~Θ_{Theta}~~θ_{Theta}) at time of mapping.

The values of ~~$\Theta_{\rho\mathrm{H3a}}$ and Θ_{Theta} show the same depth profile~~$\theta_{\rho\mathrm{H3a}}$ and θ_{Theta} show depth profiles of similar shape, but the values differ slightly. The resistivity depth profile shows a shift of $-4.5\,\mathrm{Vol\%}$ in comparison to the ThetaProbes. The different positions of the two probe locations could be one reason for this mismatch. Other reasons could be the inversion process of the resistivity data or differing pore water resistivity from the used median value (Table 2).

Because the data of the resistivity measurements and also the ThetaProbes may contain biased errors (e.g. caused by clast content or by the installation procedure), it is difficult to make reliable conclusions, which depth profile is more ~~precise. However, despite of these slight differences both methods provide comparable results .~~ accurate.

3.2.1 ~~Monitoring~~

3.3 Joint Hydrometric and ERT Monitoring

During the period May to December 2008 the spring discharge varied between 0.07 and 1.67 $\mathrm{L\,s^{-1}}$. Median soil water tension of the study area, related to depth and time (cf. Fig. 2), indicates the impact of soil moisture on spring discharge. During summer increasing evapotranspiration causes the drying-out of soil. The spring showed only a slight reaction to precipitation events. Rainfall could only balance the soil water deficit and caused no runoff. Therefore, there is almost no runoff generation in the summer season. Primarily base flow dominates and decreasing discharge is mainly caused by saturation excess overland flow from the area surrounding the spring.

In contrast, during winter season (starting in November) at all depths lower tensions ($< 90\,\mathrm{hPa}$) were measured. Less evapotranspiration results in a replenishment of the storage water reservoirs in the subsurface. Due to the moist conditions, high presaturations predominate and cause a rapid runoff response with rain and the high discharges within the winter season.

Furthermore, there is an influence of the layered subsurface on soil moisture and runoff response. Until the beginning of May and again from December the low tensions of the upper parts of LB indicate saturated conditions, in contrast to the deeper LB with higher tensions (cf. Fig. 2). Due to the anisotropic hydraulic properties (low vertical compared to horizontal hydraulic conductivity) the percolation into deeper parts of LB decreases. The seepage water is concentrated as backwater in the LM and the upper parts of LB. Because of the high lateral hydraulic conductivity this saturated depth range is mainly involved in runoff and causes strong interflow.

As the hydrometric data show, the first period from May to October was mainly characterized by drying of the subsurface. After that, humid conditions began to dominate (cf. Fig. 2). Major changes occur at shallow depth and proceed to depth, though remarkably attenuated. Each depth has its own characteristics, its own variation in time and shows different hydrological and electrical response. To better distinguish the results and to deal with the subsurface layered structure, a depth- or layer-based analysis is appropriate.

Figure 9 shows the trend of median resistivity for each depth range for the entire time series of profile A between H1a and H4a and profile B between H4b and H4a, in comparison with daily accumulated precipitation.

The resistivity of profile A clearly correlates with profile B (Table 4). This correlation is more pronounced at shallow depths. The absolute values are similar, except for the near-surface part of LH (0–0.2 m) and parts of LB (1.5–2.0 m). These two depth ranges have higher ~~amounts~~ resistivity values at profile B than A at all points in time, due to the different positions. Profile A is completely situated in one of the depression lines, in which ~~moisture conditions~~ higher soil water contents can be expected in general.

During the measuring period, the upper layer (0–0.2 and 0.2–0.4 m) reacts with similar resistivity variations as the intermediate layer (0.4–0.9 m). Resistivity of the intermediate layer may temporarily exceed the upper layer (e.g. profile A October–December).

The temporal changes in resistivity decrease with depth. Short time variations are limited down to 2 m. Below, the differences are marginal with only a continuous slight increase during the investigated period.

The variation of resistivity is significant influenced by rainfall. As shown in Table 4, the upper and intermediate layers ($< 0.9\,\mathrm{m}$) show a strong negative correlation with the cumulated amount of precipitation (ppt). This correlation decreases with depth. Upper parts of the basal layer (0.9–1.5 m) respond slightly and delayed to intense rain events or enduring dry periods. Depths $> 1.5\,\mathrm{m}$ show no direct correlation with rainfall. Water cannot infiltrate straight to greater depths because of decreasing hydraulic conductivity, evaporation, storage, or consumption of water by roots.

One problem is the temporal resolution. Because of the time intervals (usually $\geq 1\,\mathrm{week}$), we are not able to resolve the entire temporal heterogeneity of the subsurface, which may lead to misinterpretation. For example, during the period from 3 to 16 September, the amount of $33\,\mathrm{mm}$ rain seems not to affect the resistivity of profile A. However, 32 of these $33\,\mathrm{mm}$ had already been fallen until 7 September. At profile B with an additional measurement on 9 September, resistivity at shallow depth decreases first and after that increases back to the initial level of 3 September (cf. Fig. 9b). Due to the missing time step, this alteration is not traced in profile A (cf. Fig. 9a).

This issue is also evident when comparing the resistivity with the soil suction data. With the higher temporal resolution of the tensiometer it is possible to resolve short time events e.g. single rain events (Fig. 2), which cannot be rendered with the resistivity survey (cf. Fig. 9).

During the investigation period, different trends could be identified. The initial conditions in April and early May are characterized by a highly saturated subsurface. This is indicated by low soil water tension, high spring discharge, and high water content. Due to the humid conditions at the beginning of the measurements, the conductivity of the shallow subsurface is high and the observed resistivity is low relative to the seasonal variations.

~~A first annual trend covers the~~ The first period between May and October ~~. This period~~ is mainly characterized by ~~drying~~increasing resistivity. The accumulated precipitation from 9 May to 21 October is only $337\,\mathrm{mm}$. In combination with increasing evapotranspiration, this causes a ~~mainstream~~ drying of the subsurface (cf. Fig. 2). As a result of drying, at shallow depths ($< 0.9\,\mathrm{m}$) resistivity quickly increases until July. Below, the increase proceeds slightly, but continuously until October.

As mentioned above, resistivity, especially of LH and LM (up to $0.9\,\mathrm{m}$), shows a high short time variability and is strongly associated with the amount of precipitation (ppt) (Table 4). During the investigated period three different response types could be identified that are exemplarily illustrated in Fig. 10 and compared to soil water tension.

1. A small amount of precipitation (cf. 23 September–7 October, ppt $= 23\,\mathrm{mm}$) causes a short deferment of increasing resistivity of LH and LM during the summer period. The values of initial state and time step are in the same order of magnitude. Within the temporal resolution, only a slight decrease could be recorded. Deeper parts are not affected and dry continuously. Constant discharge indicates that there is no runoff generation during this period. This amount of rain is only able to balance the deficit caused by evaporation at shallow depths, at least within the temporal resolution of measurements.

2. A medium amount of precipitation (cf. 1 July–15 July, ppt $= 51.1$ mm) causes a distinctive reaction at shallow depth. Resistivity at these depths shows a sharp decrease by comparatively the same ratio (~ 0.7). However, the signal is not traced into the deeper ground (> 1.2 m), which remains completely unaffected. So vertical seepage dominates in LH and LM, which leads to recharge of soil water. The water is predominantly fixed by capillary force; hence it does not percolate into deeper layers. The short rise of discharge is caused by saturation overland flow in the spring bog.

3. A high amount of precipitation (cf. 22 October–4 November, ppt $= 102.1$ mm) results in a strong response down to 2.0 m and affects LH, LM as well as parts of LB. Such heavy rain period does not induce larger resistivity changes in LH and LM than the medium rain period, but influence deeper regions in the same order of magnitude as above. The water infiltrates to the upper, but does not reach the deeper parts of the basal layer (2–3 m). The vertical seepage is limited and therefore, the increasing spring discharge may only be caused by lateral subsurface flow, such as interflow in the unsaturated subsoil.

After the major rain event at the end of October, resistivity values remain ~~low~~constant until the next time step. Due to precipitation of 102.1 mm during the period from 19 November to 16 December, resistivity drops below the initial state and shows highly saturated conditions.

A comparison of water content obtained by ThetaProbes (~~Θ_{Theta}~~θ_{Theta}) and water content calculated from resistivity data for different depths over time at profile A ~~25 m near~~ close to the hydrometric station H3a (~~$\Theta_{\rho\mathrm{H3a}}$~~$\theta_{\rho\mathrm{H3a}}$) using Eq. (2), is shown in Fig. 11

At shallow depth (≤ 0.85 m), ~~$\Theta_{\rho\mathrm{H3a}}$~~ $\theta_{\rho\mathrm{H3a}}$ correlates closely with ~~Θ_{Theta}~~ θ_{Theta} (Table 5). However, there is a shift of the curves during the whole period. The volumetric water content from resistivity data is consequently smaller than from the ThetaProbes. In dry periods (e.g. July–October), the difference is less than under humid conditions (e.g. May).

In deeper parts the variations are attenuated. At a depth of 1.2 m there is almost no response over the year, until the heavy rain period at the end of October.

In 1.5 m depth the response of the ThetaProbes is marginal until December, but thereafter they show an increase. In contrast, ~~$\Theta_{\rho\mathrm{H3a}}$~~ $\theta_{\rho\mathrm{H3a}}$ shows already in late October a reaction to the heavy rain event, which is not reproducible with the ThetaProbes.

The same holds true for the correlation between resistivity (ρ_{H3a}) and soil suction at H3a (Ψ_{H3a}) (cf. Table 5). The resistivity of LH and LM fits well to the tensiometer data at the same depth, but in deeper parts it deviates.

These deviations between resistivity data and hydrometric measurements may have different causes. Both methods contain measuring errors, just as the laboratory and other hydrometric (e.g. soil–water resistivity) measurements. Furthermore, the ThetaProbes and Tensiometers measure punctual values. Heller (2012) demonstrated with dye infiltration experiments, that preferential flow is an important process in our study area. Hence, hydrometric point measurements may over- or underestimate soil moisture, depending on whether they are inside or outside a preferential pathway. Therefore the data are very limited, with restricted validity for the entire depth range or layer. In contrast, ERT has the advantage to integrate over a larger measuring volume, which makes it more suitable for extensive depth-related interpretations. ~~Further, with high resolution ERT it is possible to identify small-scale heterogeneities such as preferential flow pathways.~~

4 Conclusions

In drainage basins, hillslopes link precipitation to river runoff. Runoff components, different flow pathways, and residence times are mainly influenced by the properties of the hillslope, especially the shallow subsurface. The knowledge of these properties is one of the keys to characterize the runoff dynamics in catchments. According to this, we used ERT for mapping the spatial heterogeneity of the subsurface structure on a hillslope with particular focus on mid-latitude slope deposits (cover beds).

ERT lets us differentiate between LH and LM as one unit and LB as another. Like the intrinsic properties (e.g. sedimentological), LH and LM have very similar electrical characteristics. Therefore, they may only being distinguished with ERT, if water contents are different or change differently with time.

On the contrary, ~~LB has its~~ the sediments within LB have their own electrical characteristics. The ~~pedophysical~~ pedo-/petrophysical relationship, with neglecting surface conductivity, shows equal formation factors to LH and LM, but different exponents. With the lower exponent, LB is characterized by lower resistivity at the same water content. Therefore, the resistivity of LB is lower in the entire study area, which is further reinforced by the increasing mineralization of pore water with depth.

Moreover, from the results of field measurements and ~~pedophysical~~ pedo-/petrophysical parameter determination in the laboratory we ~~could derive a noninvasive method for direct monitoring of~~ are able to monitor seasonal changes in subsurface resistivity and its relationship to precipitation and soil moisture on the hillslope scale with a minimally invasive method directly. In combination with commonly used hydrometric approaches, we improved our understanding of the allocation, distribution, and movement of water in the subsurface. Different amounts of precipitation affect the subsurface moisture conditions differently and accordingly different depths take part in runoff generation.

Because pore water (amount and conductivity) is the main driver for resistivity, we arrive at some comprehensive interpretations of the subsurface moisture conditions. The high resistivities of LH and LM indicate low water contents, whereas LB is divided into two different moisture zones. On the hillsides water saturation of LB is less than between the depression lines, where low resistivity shows high water saturation and implies a local slope groundwater reservoir.

During investigation time, temperature-corrected resistivity showed distinct seasonal variations due to changes in moisture conditions, primarily influenced by precipitation and evapotranspiration. Close to the surface, these variations are very evident and decline with increasing depth, mainly limited to a depth of 2 m. This primarily affects LH, LM, and the upper parts of LB, since it may be assumed that deeper parts are already saturated and changes are only possible due to changes in water conductivity.

In summer the subsurface continuously dries, starting at the surface and proceeding to depth. This drying is temporarily interrupted by precipitation. Penetration depth and intensity of the response strongly depend on the amount of precipitation. During periods with a small amount of precipitation, infiltration is limited to LH. There is no runoff generation, and greater depths remain unaffected, which leads after repeated occurrence to drier conditions within LM compared to LH. In contrast to this, a response caused by a medium amount of precipitation includes LM and a small increase in spring discharge. The main source of this runoff is saturated overland flow from the surface surrounding the spring. With a high amount of precipitation, changes in resistivity point to vertical seepage down to 2 m. ~~The spring discharge consequently shows the major runoff generation, caused by~~ Due to lateral subsurface flow within LH, LM ~~,~~ and the upper ~~LB~~parts of LB, the discharge of the spring strongly increases.

The results from ERT measurements show a strong correlation to the hydrometric data. The average resistivity response is congruent to the average soil tension data. Water content obtained with ThetaProbes shows similar variations as calculated from the closest ERT profile. Consequently, soil moisture on the hillslope scale may be determined not only by punctual hydrometric measurements, but also by ~~noninvasive~~ minimally invasive ERT monitoring, provided ~~pedophysical~~ pedo-/petrophysical relationships are known. By the use of ERT, expansive invasive hydrometric measurements may be reduced or partially substituted without losing information, but rather enhancing the spatial significance of these conventional point measurements. A combination improves the spatial understanding of the ongoing hydrological processes and is better suitable to identify heterogeneities.

Cassiani et al. (2009) pointed out that a combination of geophysical and hydrometric data may be used for quantitative estimation of hillslope moisture conditions. Our study has shown that this may also be applied to mid-latitude hillslopes covered by periglacial slope deposits. Nevertheless, there are some restrictions requiring further improvements.

One shortcoming is the temporal resolution. Some hydrological responses especially at hillslopes may proceed very quickly. The major goal for further research should be to increase the temporal resolution of ERT measurements to at least trace single rain events. This could be realized with automated data acquisitions as described in Kuras et al. (2009).

Another aim should be to improve the spatial resolution. ~~Since preferential flow is an important process, a~~A high-resolution ERT in combination with additional cross-borehole measurements would be more suitable to deal with small-scale heterogeneities and to overcome the problem of decreasing sensitivity with depth.

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Table 1. Properties of cover beds from the study site ~~for an example profile~~ *($n \geq 15$ per layer).* – adapted from Moldenhauer et al. (2013).

Layer	Soil horizon	Color (moist)	Soil texture Clay (%)	Silt (%)	Sand (%)	Clasts (%)	bulk density ($\mathrm{g\,m^{-3}}$)	porosity	Hydraulic conductivity ($\mathrm{cm\,d^{-1}}$)*
LH	A/Bw	10YR/5/8	14	52	34	36	1.2	0.55	27
LM	2Bg	10YR/5/4	12	53	35	43	1.5	0.43	9
LB	3CBg	10YR/5/3	7	22	71	56	1.7	0.36	52

* Field-saturated hydraulic conductivity measured using the Compact Constant Head Permeameter (CCHP) method (Amoozegar, 1989).

Table 2. Median pore water conductivity ~~σ_{w}~~ $\tilde{\sigma}_{\mathrm{w}}$, resistivity $\tilde{\rho}_{\mathrm{w}}$ and mean resistivity ~~ρ_{w}~~ $\bar{\rho}_{\mathrm{w}}$ with standard deviation (SD_{w}) per depth (*$n \geq 11$ per sampling depth*).

Depth [m]	0.3	0.6	0.85	1.05	1.65	2.3
$\cancel{\sigma_{\mathrm{w}}}\tilde{\sigma}_{\mathrm{w}}$ [µS cm^{-1}]	72.4	107.8	111.6	114.7	135	156.7
$\cancel{\rho_{\mathrm{w}}}\tilde{\rho}_{\mathrm{w}}$ [Ω m]	138.1	92.8	89.6	87.2	74.1	63.8
$\bar{\rho}_{\mathrm{w}}$ [Ω m]	135.7	92.3	88.9	86.8	75.1	63.7
SD_{w} [Ω m]	16.9	5.0	4.5	4.8	5.4	7.3

Table 3. Fitted ~~parameters~~ water content formation factor (F_θ), water content exponent (n_θ) and mean squared error for $\rho_{\mathrm{eff}}/\rho_{\mathrm{w}}$ (MSE) for Eqs. (1)–(3) of the two different depth ranges.

Depth range	$\cancel{F_\Theta}F_\theta$	$\cancel{n_\Theta}n_\theta$	r	MSE
< 0.9 m	0.577	1.83	0.895*	2.8
≥ 0.9 m	0.587	1.34	0.888*	1.4

* $p < 0.01$

Table 4. Correlation between median resistivity of profiles A ($\rho_{\text{profile A}}$) and B ($\rho_{\text{profile B}}$) and between subsequent resistivity ratio of profile A ($\rho_{\text{timestep}}/\rho_{\text{initial}}$) and cumulative precipitation during the time step (ppt).

Depth [m]	$r_{(\rho_{\text{profile A}},\rho_{\text{profile B}})}$	$r_{(\frac{\rho_{\text{timestep}}}{\rho_{\text{initial}}},\text{ppt})}$
0–0.2	0.977[a]	−0.773[a]
0.2–0.4	0.988[a]	−0.770[a]
0.4–0.9	0.987[a]	−0.804[a]
0.9–1.2	0.987[a]	−0.586[a]
1.2–1.5	0.852[a]	−0.378[b]
1.5–2.0	0.831[a]	−0.078[b]
2.0–3.0	0.878[a]	0.173[b]

[a] $p < 0.01$
[b] $p > 0.01$

Table 5. Correlation of volumetric water content calculated from resistivity values ($\cancel{\Theta_{\mathrm{H3a}}}\theta_{\rho\mathrm{H3a}}$) and water content from ThetaProbes ($\cancel{\Theta_{\mathrm{Theta}}}\theta_{\mathrm{Theta}}$) and correlation of resistivity at H3a (ρ_{H3a}) and soil suction at H3a (Ψ_{H3a}).

Depth [m]	$\cancel{r_{(\Theta_{\rho\mathrm{H3a}},\Theta_{\mathrm{Theta}})}}r_{(\theta_{\rho\mathrm{H3a}},\theta_{\mathrm{Theta}})}$	$r_{(\rho_{\mathrm{H3a}},\Psi_{\mathrm{H3a}})}$
0.30	0.863[a]	0.993[a]
0.55	0.957[a]	0.904[a]
0.85	0.885[a]	0.905[a]
1.20	0.136[a]	0.120[b]
1.50	0.619[a]	0.566[a]

[a] $p < 0.01$
[b] $p > 0.01$

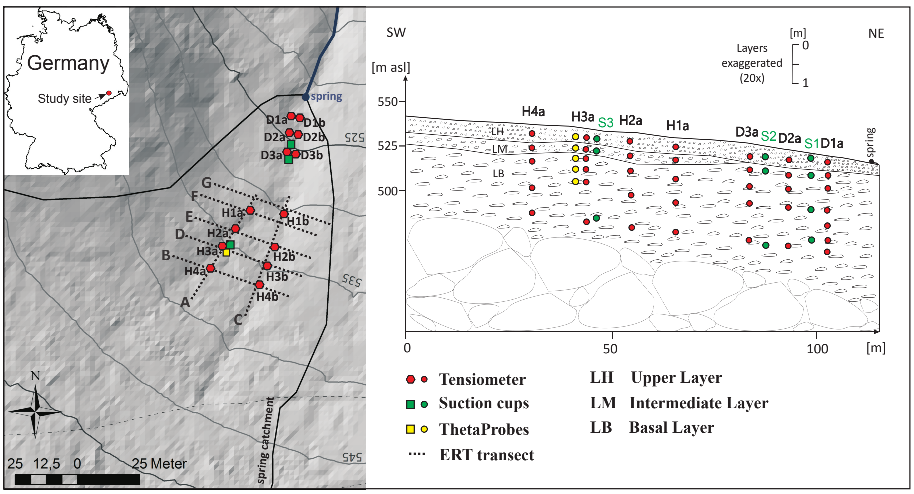

Figure 1. Study site with locations of ERT profiles and hydrometric stations (left panel) (data source: ATKIS®-DGM2,©Landesvermessungsamt Sachsen (2008)) and profile section with installation depths of tensiometers, ThetaProbes and suction cups (right panel).

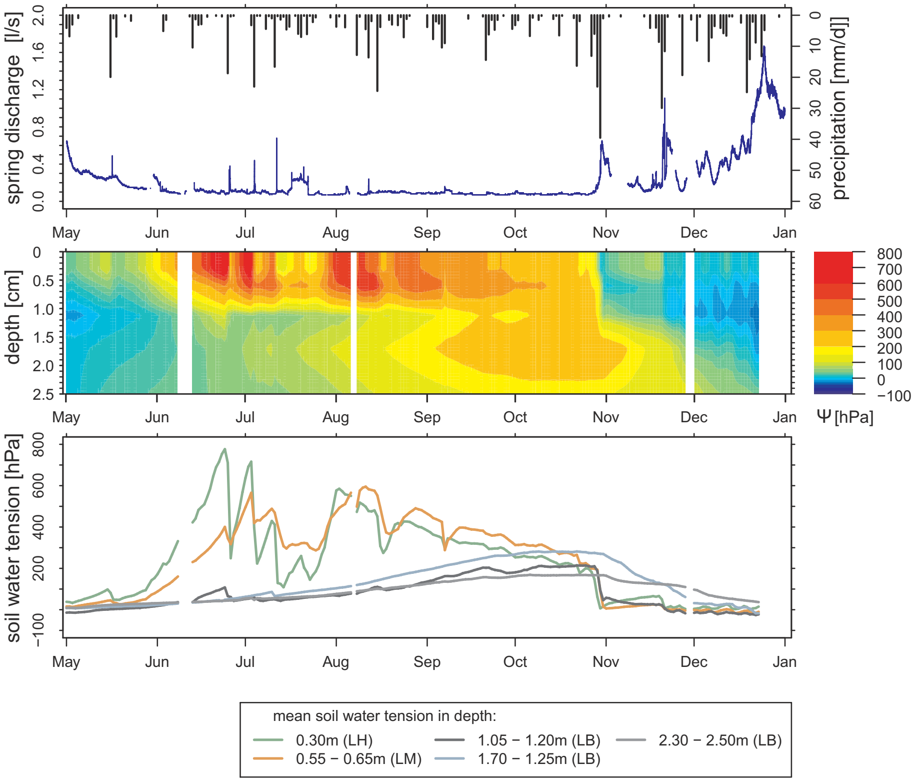

Figure 2. Spring discharge in comparison with daily precipitation (top panel), image of median soil water tension of the shallow subsurface (middle panel) and median soil water tension for different depths (bottom panel) – adapted from Heller (2012).

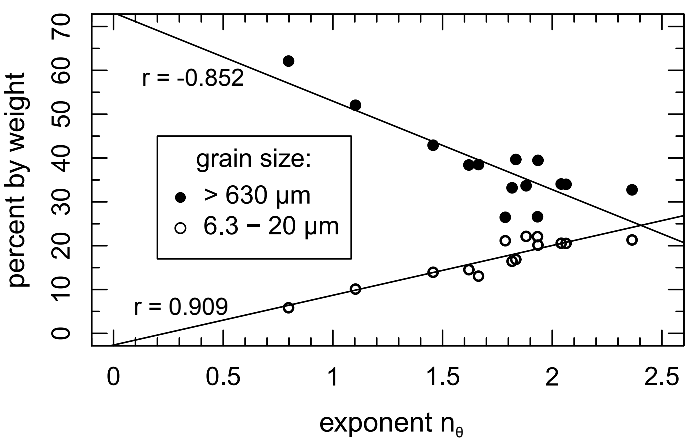

Figure 3. Exponent ~~n_Θ~~ n_θ in dependence of different grain sizes.

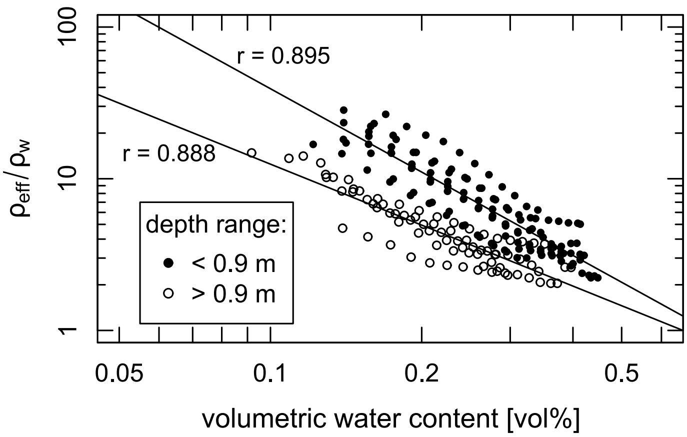

Figure 4. Volumetric water content in dependence of resistivity ratio ($\rho_{\mathrm{eff}}/\rho_{\mathrm{w}}$) for two different depth ranges.

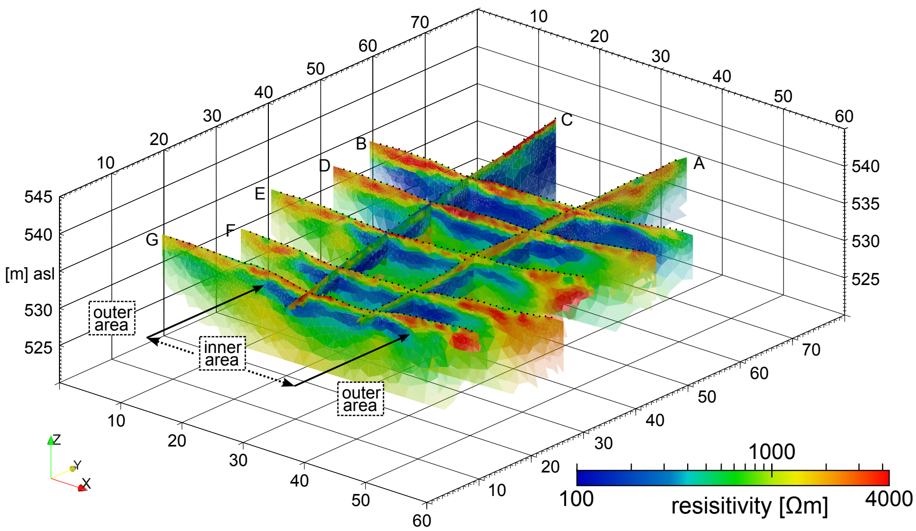

Figure 5. Resistivity results from ERT mapping (October 2008) of the study area: pseudo 3-D view of the profiles A to G.

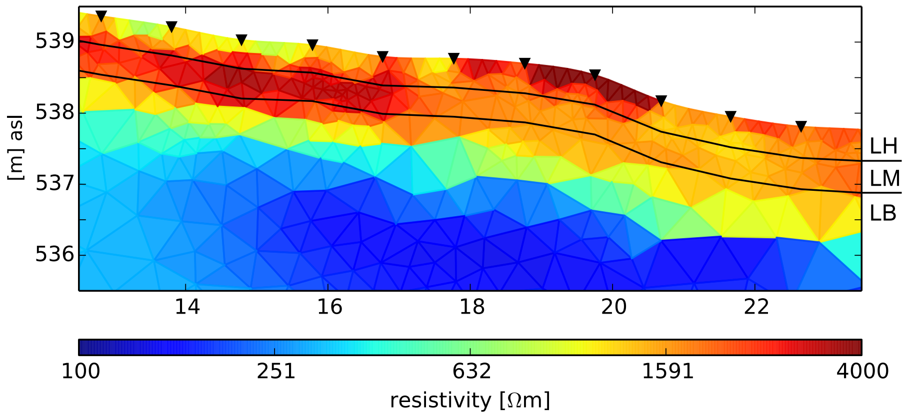

Figure 6. ERT section of profile A with plotted layer boundaries. (date: 21.10.08)

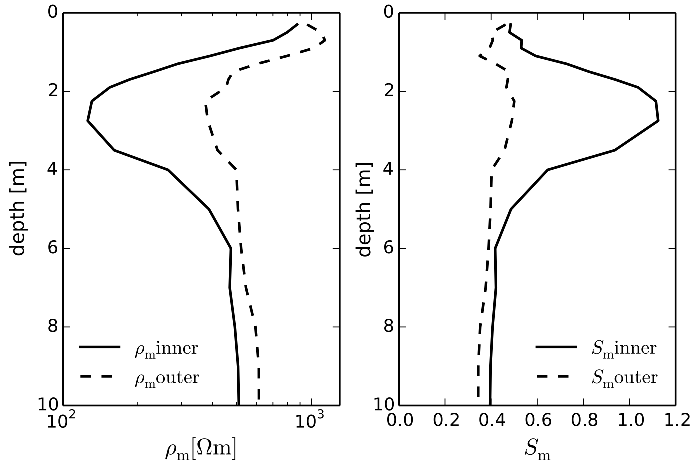

Figure 7. Median resistivity (left panel) and median water saturation (right panel) per depth for the inner region (between the depression lines) and outer region (hillslopes). (date: 21.10.08)

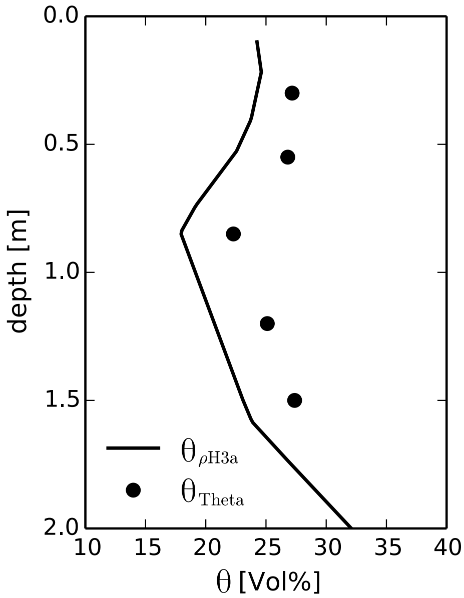

Figure 8. ~~Calculated~~ Volumetric water ~~saturation~~ content calculated from resistivity data ~~of the study site: pseudo 3-D view of the profiles A~~ close to ~~G – adapted from Moldenhauer et al. (2013)~~ H3a in comparison with ThetaProbes. (date: 21.10.08)

~~Volumetric water content calculated from resistivity data close to H3a in comparison with ThetaProbes at the time of the mapping.~~

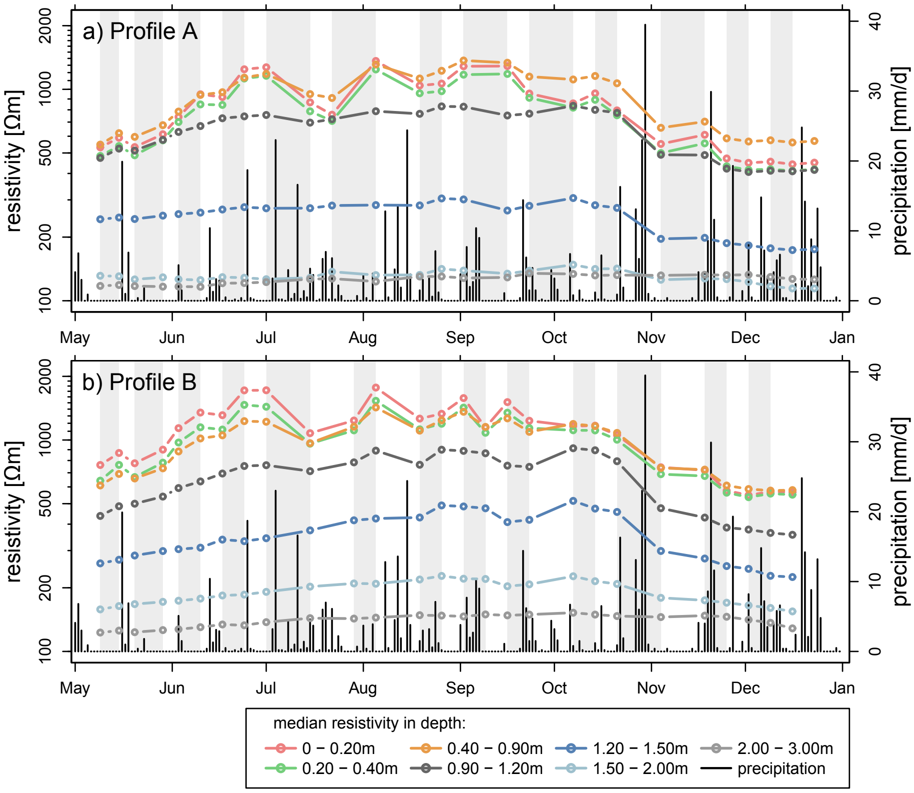

Figure 9. Trend of median resistivity for different depth ranges for **(a)** profile A and **(b)** profile B in comparison with daily precipitation (Grey and white shaded regions for visualization of ERT time intervals).

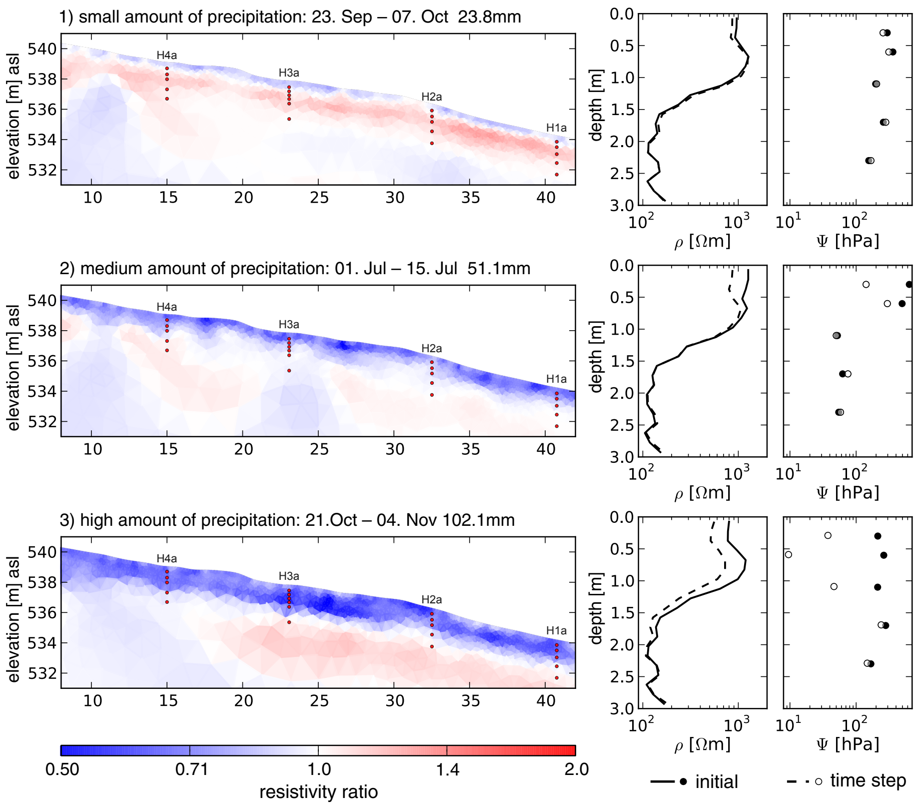

Figure 10. Ratio between subsequent resistivity (first column), median resistivity as a function of depth (second column) and median soil water tension (third column) for three exemplary precipitation responses: (1) small amount, (2) medium amount and (3) high amount.

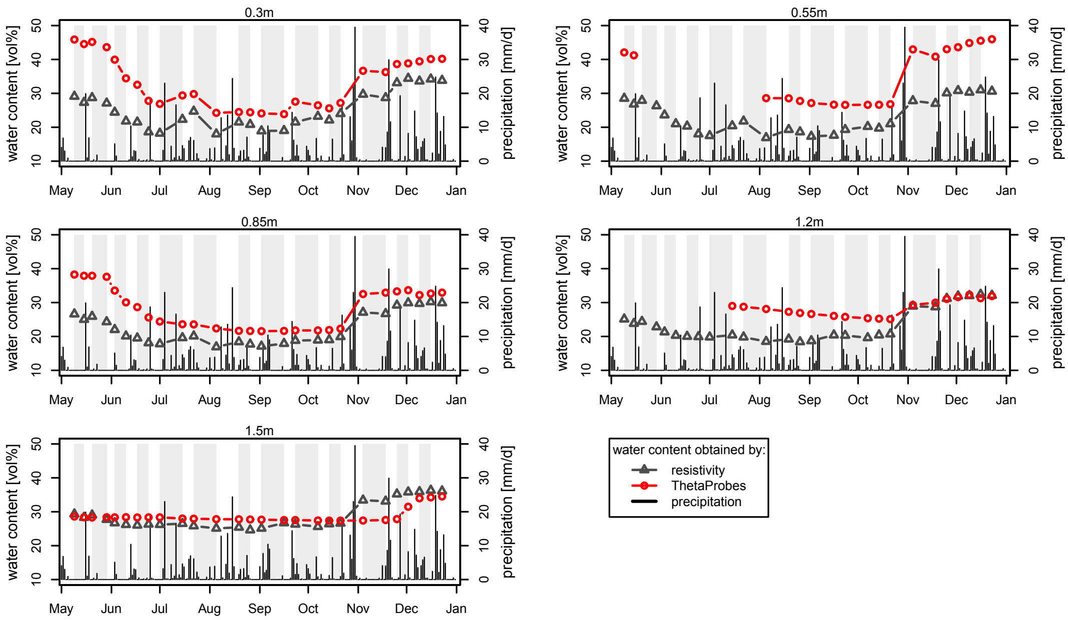

Figure 11. Trend of volumetric water content, obtained by resistivity data and ThetaProbes with daily precipitation for different depths.