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Challenges in conditioning a stochastic geological model of a heterogeneous glacial aquifer to a comprehensive soft dataset

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Author comment to review #3: Fabrizio Felletti

We would like to thank Fabrizio Felletti for his review to our manuscript. We appreciate his concerns about the completeness of the description of the geological/sedimentological model in our study. The depositional system is not addressed in detail in the manuscript nor is the assumption of a simplified binary sand/clay model discussed. We have revised the manuscript and added a more detailed description of the depositional environment and supplemented with discussions on the limitations of simulating a binary system. We are assured that the reviewer's suggestions merit a revision that increases the scientific quality of the publication.

> *This is an interesting paper that shows how a vast conditioning dataset (SkyTEM) can be incorporated in the stochastic modeling process (TProGS simulation). The categorized SkyTEM dataset is used to define the lateral model of spatial variability, whereas borehole data are used for the vertical direction.*
>
> *The subject is very interesting and I feel the paper suitable for the publication, after revisions.*
>
> *My principal concerns are on the geological/sedimentological model. The geostatistical approach (and the way to incorporate soft data for conditioning the TProGS simulations) is essentially correct and well explained. In my opinion, the authors should devote more attention to describe the depositional environments, facies and facies associations, lateral and vertical facies transition, sedimentological logs description, etc. This part is completely missing and the authors do not characterize the degree of heterogeneities of the depositional system. These informations are essential to evaluate the results of the simulations.*

We agree that the depositional system is not well described in the manuscript. Since we decided to simulate a binary sand/clay system a more detailed description of the facies system is neglected. Please find a revised section on the geological description of the study site in Appendix I (lines 3-24). We tried to depict the geological units and the depositional environment better. However we don't want to go in too much detail, because we see the focus of this study in the simulation of a binary system using TProGS and not in the stochastic simulation of a detailed sedimentological system. The lateral and vertical facies transitions are well presented in Figure 4 of the manuscript. A new figure will be added to the revised manuscript (Figure 2 below) that shows one borehole log and nearby SkyTEM data. The borehole log clearly underlines the distinct heterogeneity of the glacial sequence; thin lenses of meltwater-sand are embedded in a predominant clay environment. The figure also contributes to the discussion on mismatches between the two data types.

> *The authors describe (and simulate) the geology as "binary": sand or clay. In my opinion this is an excessive simplification of the reality. A geological model built only with two facies, defined uniquely on texture,*

difficultly could be used for an hydrogeological flow modeling, as Authors state later in the text . Unfortunately the geology is not "binary". Within your glacial deposits, don't you have any gravels, sandy-gravels, gravelly sand, muddy sand, etc? The choice of using only two categories to describe your deposits certainly simplifies the simulation but definitely reduces excessively the degree of heterogeneity of these sediments.

Considering only a binary system is a crude simplification of the sediments in the glacial sequence. As the reviewer stated correctly we will expect a broad range of facies within the glacial deposits. However we decided to simulate a two category system because of several reasons. The vast SkyTEM data is a unique element of our study. Classifying the resistivity range in multiple facies is peculiar, because the thresholds that separate sand from clay or sand from gravel are difficult to assess and are always study site specific Jorgensen et al. (2003).This makes it very challenging to determine a deterministic geological model from SkyTEM data. This study uses a probabilistic approach to integrate borehole data with geophysical data and to allow for soft conditioning. It would be even more peculiar using multiple facies in a probabilistic approach than in the deterministic approach. The histogram probability matching method would require multiple dimensions if more than two facies were addressed. Additionally, gravel/sandy gravel is found in only a few lithological descriptions of the boreholes, and is thus less abundant than the other more dominating facies. This might lead to an extremely uncertain correlation with the geophysical data. Another reason lies in the 100m resolution of the subsequent hydrological flow simulations. Less abundant facies like gravel or silty clay will not be represented on that scale, although they might be observable on the scale of the TProGS simulation (20m x 20m x 2m). Also, for the hydrological modeling, simulating a binary hydrofacies system helps to avoid the problem of over-parameterization. Please find the relevant section of the revised discussion below:

"Simulating a binary system is a crude simplification of the broad range of sediments in the glacial sequence. However, classifying the SkyTEM data into discrete facies or deriving the soft information on facies membership are peculiar in a multi facies environment. Additionally less abundant facies (e.g. gravel) will show extremely uncertain correlations in the histogram probability matching method. Last the less abundant facies might be represented on a 20m domain, but it will often not be visible on the 100m domain chosen for the subsequent hydrological flow simulations. Dell'Arciprete et al. (2010) present a study where geostatistics are successfully implemented to simulate small scale heterogeneities in a multi facies environment."

Your dataset contains 112 boreholes. In my opinion, you should show at least some borehole stratigraphy. Why don't you show a correlated geological cross-section or a stratigraphical scheme?

The two figures below present cross sections of the interpolated geophysical data and coinciding boreholes. The stratigraphy in the boreholes underlines the heterogeneity; thin lenses of sand/meltwater sand are confined by clay. Figure 1 is presented in Refsgaard et al. (2014), where a local comparison of SkyTEM and borehole data was conducted; only 10% of the boreholes show bad agreements. In total, 35 good quality boreholes which are closer than 50m from the nearest flight line were considered. Figure 1 (c) nicely shows the transgression from Pleistocene to Miocene sediments and the good agreement in the elevation of the transgression between the two data types. Figure 1 (b) illustrates a good fit between sand and clay indicated by the borehole logs and high and low resistivity fields in the SkyTEM data, respectively.

Figure 2 underlines some of the associated problems of the data integration. The lithological description from the borehole interprets thin layers of meltwater sand confined by clay in the top few meters. The SkyTEM data with a vertical resolution of two meters cannot capture this small scale variability. This supports our choice of using geophysical data only for the lateral transition probabilities. Figure 2 with additional discussion will be added to the revised manuscript.

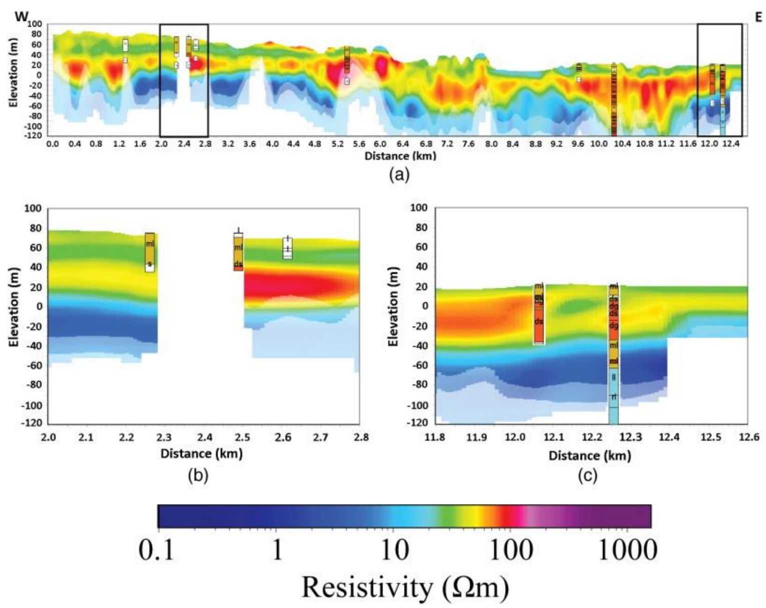

Figure 1. A SkyTEM crosssection in the Norsminde catchment with borehole data (a). A zoom to the western and eastern part is presented in (b) and (c), respectively. Borehole legend: dg = glacial gravel, s = sand, ds = diluvial sand, l = clay, ml = moraine clay, ll = plastic clay and rl = Eocene clay. All displayed boreholes are located within less than 50 m from the profile. Refsgaard et al. (2014)

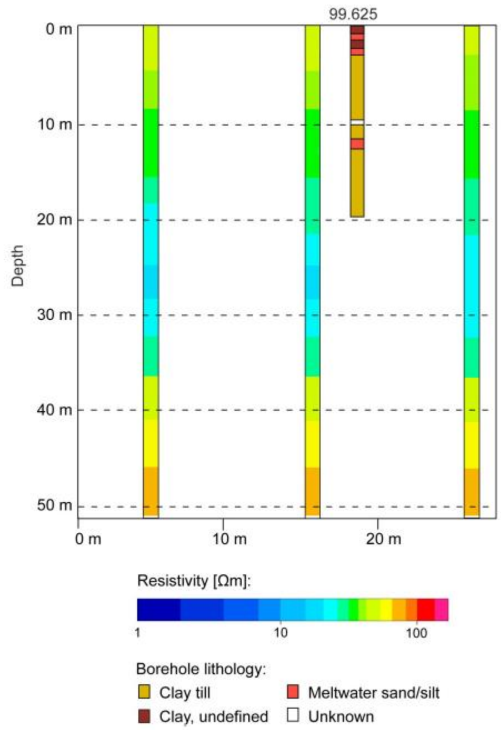

Figure 2. Side-by-side comparison of borehole lithological data and AEM vertical sounding data at borehole number 99.625. He et al. (2013b)

It is not clear the vertical resolution of the SkyTem method. Is it possible to characterize facies heterogeneities at a depth of 20-30 m with this method? If I understand, in vertical direction you computed 40 cell, 2m thick. Consequently your investigation depth is 80 meters. Is it correct? In this case, how can you compute the horizontal transition probabilities at different depths, if your computation is exclusively based on relatively low resolution SkyTem data.

The SkyTEM method allows large penetration depths. However it has to be considered that the support scale will increase with depth, as the penetration of the subsurface is shaped as a cone, with 15-20m on the surface to a larger support scale in large penetration depths (at 30m depth the lateral support size will be in the range of 50m). Therefore the near surface heterogeneities will be better represented than the heterogeneity in deeper layers. The maximum penetration depth of the SkyTEM method depends on the sediment (low conductance clay allows larger depths) and is typically in the range of 100m to 120m.

It has to be acknowledged that the resolution of the SkyTEM method limits the observation of thin sand features and that the support scale varies over depth. However the lateral heterogeneity is still much better represented by the SkyTEM data than by the sparse borehole data. We did not compute transition probabilities at different depths, although we consider this as an interesting exercise to assess stationarity issues over the vertical extend and the effect of measurements with a variable support scale. We used global transition probabilities, representing the entire glacial till, therefore simulations carried out at 20m and 80m are based on the same geostatistical attributes. The TProGS simulations are referenced to the sea level and the simulation was carried out from 20m – 100m above sea level.

The glacial sequence which defines the model domain is between 10m and 40m thick. The simulation domain is rectangular and the vertical extend is set to 80m to consider changes in topography.

Could you better explain Section 4.5, "Performance criteria" ?. I think it is not clear enough.

The first paragraph of section 4.5 "Performance criteria" is rewritten. Please see section 4.5 rewritten below:

"Five performance criteria are defined to evaluate an ensemble of realizations of the geology. They aim for validating the ensemble with respect to the TProGS input, namely the defined model of spatial variability (mean length and proportion) and the soft conditioning dataset. The five performance criteria test the self-consistency of TProGS and thus if all input parameters and data are treated accordingly. The glacial structure in the Norsminde catchment represents only approximately 20% of the entire TProGS simulation domain and deviations in simulated spatial statistics between the entire model domain and the simulation target are expected."

Section 4.5.3: What do you mean with the term "geobody"? You have to define what a geobody is. Which order of architectural element of a depositional system do you refer?

Please find the definition of a geobody on page 15230, lines 15-16: "A geobody is defined as one connected 3D cluster of the same facies". Hence it is a distinct sand feature that is confined by clay. The architectural elements are interpreted on a 20m x 20m x 2m scale. The definition will be expanded in the revised manuscript.

Section 5.4.3. Geobody connectivity . You should better explain which nature of connectivity you expect . I suggest you the following reference where different type of connectivity are discussed:
Giudici M., Bersezio R., Felletti F., Baratelli F., Cattaneo L., Cavalli E., dell'Arciprete D., Mele M., Pessina L., Vassena C. (2012) – A multidisciplinary study of sediments' connectivity and transport parameters for aquifer analogues. Models – Repositories of Knowledge, IAHS Publ. 355, pp. 223-228

The study by Giudici et al. (2012) present a study on sediment's connectivity using the aquifer analogues method at two study sites in the sandy-gravel fluvio-glacial Po Plain in northern Italy. It is difficult to compare the connectivity structures observed in the Po plain with the Norsminde catchment. The alpine outland is characterized by thick outwash plains with predominately sand and gravel. Opposed there are mainly clayey till sediments in the Norsminde study site. The nature of the connectivity of the high permeable unit in the Norsminde catchment is difficult to categorize, because of its irregular patterns caused by deformation and a diverse topography.

Appendix I

Study Site

Figure 1 shows the 101 km2 Norsminde catchment, located on the east coast of Jutland south of Aarhus. The topography allows a separation between an elevated western part, with changing terrain and a maximum elevation of 100 m and a flat and low elevated eastern part, where the coastline represents the eastern boundary. Glacial morphologies, namely moraine landscapes are predominant in most of the catchment. The geological stratigraphy indicated by borehole logs encompasses Paleogene and Neogene marine sediments underlying a heterogeneous stratigraphy of Pleistocene glacial deposits. The Paleogene sediments are characterized by very fine-grained impermeable marl and clay. Above the Neogene sequence shows sandy formations encased by a clay-dominated environment with Miocene marine sediments. The entire Miocene sequence varies in thickness up to 40 m and the sandy formations reach thicknesses of more than 10 m. The Miocene sequence is only present in the western part of the catchment where the stochastic modeling is conducted and forms the lower boundary of the simulation domain. Thus, only the upper Pleistocene glacial sequence is modeled. The glacial deposits in the western part of the catchment contain both sandy and clayey sediments, where clay is predominant. Borehole logs indicate that the Pleistocene clay spans from glaciolacustrine clay to clay till. Within the clay environment, the sandy units are allocated in small units and vary between gravel, meltwater-sand and sandy tills. The total thickness of glacial sediments varies between 10 and 40 m with heterogeneous distributions of the mostly glaciofluvial sand features between less than a meter and 20 m in thickness. The subject to the stochastic modeling, the delineated Pleistocene glacial sequence in the western part, provides interesting challenges like distinct heterogeneity and a diverse terrain.

Appendix II

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