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Interactive comment on "Multiple-point statistical simulation for hydrogeological models: 3D training image development and conditioning strategies" *by* Anne-Sophie Høyer et al.

Anonymous Referee #3

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Multiple-point simulation (MPS) is a geostatistical simulation technique first developed at Stanford University in the early 2000's. An MPS algorithm is used to reproduce spatial patterns, such as connectivity, that are depicted in a training image (TI), which contains the possible spatial configurations for any given geological object and relationships between objects. A TI contains only spatial patterns and their respective likelihoods. A frequent pattern appears more often in the TI than a rare one. The actual position of a pattern in the TI is largely irrelevant, the MPS algorithm sees a set of patterns and tries to set them together through a randomization process. In order for an MPS simulation to produce a reasonable representation of any given geological system, it must have to honor some conditioning data and have a method of accounting

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for spatial trends in the probabilities of selecting patterns from the TI.

The title of this paper suggests that, in this case, these MPS simulations are to guide subsequent hydrogeological applications. The title also suggests the main thrust of the paper is the importance of developing realistic 3-D TI's and strategies for conditioning MPS models. However, this topic is only discussed rather briefly (in 10 lines) in section 5.4 on page 7!

I thus found the paper rather confusing and yet I recognize that the authors and their organizations have considerable experience in 3-D geological modeling for hydrogeological applications, and that there is a considerable body of observational data in southern Denmark that can support the development of multiple-point simulations of the subsurface environment.

In short, while individual sentences and paragraphs use consistently good English, I became uncertain about many important details of their research and objectives. The paper is quite lengthy in its current form, yet it leaves many questions unanswered. If fact, I believe the paper raises more questions than it answers.

I therefore propose that, for publication, the authors undertake to reorganize the current text into something similar to the following:

Section 1: Introduction: This should clearly define the background, objectives, a scope of this project. These topics, I believe, include: âĂć A desire to evaluate the Miocene sediments over a 2810 sq.km. area of southern Denmark where they provide the source of most drinking water. âĂć For about 22% of the area, there is a detailed 3-D stratigraphic model (lithostratigaphic and/or hydrostratigraphic?) developed by deterministic methods (the Tonder model) âĂć Southern Denmark has some high-resolution seismic surveys that can be used as conditioning data for MPS simulations (However, the authors need to provide more information about the spatial adequacy of these surveys, not just that they total 170 km and are shown (rather poorly) on Figure1). âĂć While existing borehole records are available, they are of relatively low quality (WHY?)

and most borehole are relatively shallow, so these can provide only limited-value conditioning data. âĂć The project was undertaken to determine if MPS could produce 3-D subsurface information over the entire southern Denmark area more efficiently than deterministic modeling, yet still produce information of value to further hydrogeological models.

Section 2: The Study Area and Available Data Sources: This should summarize its geological character and assess the various data sources. This can be accomplished by revising as necessary existing sections 2 and 3 and Figures 1-5. A discussion about trends should be enhanced.

Section 3: The Experimental Process. This needs considerable expansion from existing section 4. Several questions arise from reading the existing paper. Chief among them: Was the Tonder model the source used to develop the TI? Currently this is unclear. Later the use of two TI's is noted. How were they developed/selected? What are the spatial characteristic patterns desired in the TI?

Section 4: Analysis of Results. This will combine information from existing sections 5 and 6 and some of 7. It also should address several of the limitations defined below.

Section 5: Discussion and Conclusions. This should be relatively short, but include some of the ideas in existing sections 7 and 8. It also should address the need to determine what level of subsurface detail is required to produce an acceptable groundwater management tool for regional and more site-specific applications in southern Denmark (see my final comments).

As I reviewed the current draft, I assembled a list of what I consider to be its current limitations. These include:

1) Apparently, the research so far has focused on examining the role of various hard and soft conditioning data, but only a single realization is used for each setting. This is clearly insufficient. Repeated applications of MPS will produce a sequence of slightly

different realizations even with the same conditioning setup, and it should be possible to quantitatively evaluate their similarities and compare this to the differences introduced by the changed conditioning strategies.

2) Regarding the Training Image aspect of MPS, it seems that two TI's were used. It is unclear how they were developed and what underlying geological concepts or knowledge were used to develop them. Figure 9 does not clearly show the sand/clay layers – the colors are not ideal for this, and the text (line 15 Page 7) merely states one realization has more layers than the other. Does either seem more likely with the geological knowledge available? Are these layers defined as channels or sheets (continuous layers)? How does either TI relate to conditions within the Tonder model?

3) The assessment of the results is mostly qualitative. Quantitative tools to do exist and should be used.

4) The cited literature appears to miss several important more recent studies. Attached are a few representative paper citations.

FINAL COMMENTS

MPS is an interesting and potentially powerful method for developing very useful subsurface geological models. I am aware that at least some of the authors have experimented with other simulation approaches, such as TPROGS to apparently successfully simulate facies heterogeneity in buried valleys. It would be interesting for them to include at least a short comparison between MPS and other simulation approaches. The current paper assumes the reader to be proficient in MPS concepts. This may not be true in many cases, so a short comparison in the introduction might broaden the readership and understanding of the importance of this line of investigation.

I believe the ultimate goal of this research is not to model the Miocene of southern Denmark as a purely academic exercise, but to use this information to guide groundwater management schemes. I wonder what groundwater model sensitivity analysis would

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yield in terms of necessary subsurface detail for producing acceptable groundwater resource management at regional or site-specific scales?

Obviously, somewhat less precise spatial definitions are likely to be required for regional assessments. On the other hand, site-specific studies may be unreliable if based only on MPS inputs without careful additional local conditioning. So, the question arises, “Where does MPS fit within this overall objective?” This question also reflects on the limitation noted on page 9 (lines 13-15) the present inability of MPA to handle graben structures and faults.

Despite my several criticisms, I think this is a potential important paper and hope the authors will consider reorganizing it and adding in a few details on some important methodology issues, while at the same time focusing on the TI and conditioning strategies.

SOME SUGGESTED REFERENCES:

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Kessler, T. (2012) Hydrogeological Characterization of Low-permeability Clayey Tills – the Role of Sand Lenses. PhD Thesis, Department of Environmental Engineering, Technical University of Denmark, Lyngby, Denmark. 80p.

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Straubhaar, J., Walgenwitz, A. & P. Renard (2013) Parallel Multiple-Point Statistics

Algorithm Based on List and Tree Structures. Mathematical Geosciences. 45. p. 131-147.

Straubhaar, J., Renard, P. & G. Mariethoz (2016) Conditioning multiple-point statistics simulations to block data. Spatial Statistics. 16. p. 53-71.

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