Earth Surf. Dynam. Discuss.,
https://doi.org/10.5194/esurf-2019-57-AC2, 2020

Earth Surface Dynamics Discussions
Open Access
EGU

Interactive comment on "Modelling Bedrock Topography" *by* Nils-Otto Kitterød and Étienne Leblois

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Received and published: 28 March 2020

Reply to Anonymous Referee #2

We appreciate the opportunity to address the review given by the Anonymous Referee #2. Before going through individual comments, we think it is important to underline the basic motivation for the study: The manuscript is a call to the research community to pay more attention to the importance of the bedrock topography – for both engineering purposes and to understand the hydrological response in many catchments. We also want to underline the value of public data and encourage authorities to invest more resources on constructing databases that are public available. Such databases will increase the information value of wells, boreholes and test drillings. By combining such

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data with digital maps we might be able improve management of natural resources. The comments from Referee #2 does not reflect this aspect of our work. In line with the above, it is not our ambitions to publish novel methods for estimation of the bedrock topography in this very manuscript. We consider the manuscript as an invitation to use public data and reproduce our results. The methods we use are common knowledge, as the Referee #2 correctly underlines, and they are implemented in open access software. We welcome more research on this subject and shall also contribute later using more advanced methods. With these intentions in mind, we do not find the paper is "... misleading and dangerous for the readers of Earth Surface Dynamics ...". This statement conveys a serious underestimation of the readers knowledge and competence, especially to make a distinction between topic-based and method-based contributions.

Below we comment the main objections addressed by Referee #2.

"1. The authors should have never published results that poorly characterize the attribute of interest. The solution to the smoothing and the poor connectivity of extreme values is to use stochastic simulation instead of kriging (Mariethoz and Caers, 2015)."

Reply: This statement indicates that stochastic simulation is the only option to characterize the 'attribute of interest'. We find this statement somewhat of a general nature. Here answers to some implied aspects:

Firstly,

- we agree that a stochastic approach is needed to express uncertainty. In the long run, stochastic simulation is far better than kriging as it produces members that make uncertainty propagation to any dependent study feasible, what a kriging map and a variance map does not;

- we find that inverse modelling of the Poisson equation should not be excluded as an efficient method for estimation of the local trend (alternative methods like deep

neural network might also be interesting to explore). A local trend is an accepted concept, in combination with a random function approach, and will remain useful even in a conditional simulation setting.

Secondly,

- stochastic simulation is not one method but comprises a multitude of different ones and should be selected and applied with care. While standard covariance-based geostatistical simulation techniques would produce a preliminary ensemble of solutions, we all know a correct handling of extreme values and connectivity issues does introduces extra challenges, that are not necessarily handled depending on the technique. As Referee #2 points out, we think simulation is a way to go, but we would not like readers to believe it is easy and enough per se.

Does Referee #2 mean that we should wait to address the topic of sediment thickness and bedrock topography until we have found the perfect method? We disagree! There will always be developed better methods. As underlined above, our paper is an invitation to employ the same kind of data we used and to improve the results. We do not claim our work to be the final solution!

Independent of what method that is applied, it will always be interesting to estimate the most likely realization and to minimize the estimation variance. In this paper we suggest to do inverse modelling of the Poisson equation, which might be developed further to include non-stationary parameters. That said, we agree that some stochastic simulation methods need to be explored further, but this is left for further work. We want to comfort Referee #2 that we are aware on stochastic modelling approaches, as may be obvious from responses above or from publication record (c.f. the list of references below).

“2. The research is based on geostatistical literature of more than 20 years ago (Journel and Huijbregts, 1989; Isaaks and Srivastava, 1989; Deutsch and Journel, 1998). “

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Reply: It is true that we give credit to these authors, and we think it would be a great mistake not to do so. As mentioned above, we do not intend to publish novel geostatistical methods, our ambition is to draw attention to the bedrock topography and how to utilize public available data to estimate the most probable realization. The reference is to refer readers to one easily available textbook among many others.

"3. Kriging with trend is a more advanced form of minimum mean square error method that automatically accounts for trend (e.g., Remy et al., 2009)."

Reply: Yes, we agree, but there exists a multitude of other advanced methods. Our purpose, however, was not to apply the most advanced method, rather on the contrary! We suggest to apply simple methods that are easy to implement for people that need an estimate of the bedrock topography. Because the number of information increase for every day, it is important to do regular updating of the calculations. We too like advanced methods and shall engage ourselves into their exploration, but at this point we think it is more urgent to include bedrock topography as a basic frame in everyday management of natural resources.

"4. The attribute of interest is not a continuous variable. Indicators should be used to model the two populations, the populations of thickness and the population where the attribute is missing."

Reply: Yes, we agree that using indicators (for example so-called indicator kriging) is an interesting option, but there exist also other more advanced methods to include non-stationary statistics. This is also something that can be explored in future studies. But again, we do not accept this as an argument that our manuscript would be ". . . misleading and dangerous to follow . . .".

"5. It is not true that ordinary kriging is a method based on multi-Gaussian statistics."

Reply: Yes, ordinary kriging only considers the two first moments, expected value and variance, and does not request the assumption of multi-Gaussianity. However multi-

Gaussianity makes everything easier were the variance can be seen as describing confidence intervals, this is why it is a very common extra assumption. We agree to mention in the study that we are dealing with multi-Gaussian statistics and to make clear it is an extra assumption not required by kriging.

“6. The authors define a second variable that is a function of the first one: D/L.”

Reply: That is true, we introduce D/L as a less formal estimation procedure, but we do not recommend this approach because of the significant uncertainties. In pristine areas with sparse information, the horizontal distance to exposed bedrock L, is used by drill operators to get a primary indication of the sediment thickness. This was the motivation for using L in the estimation procedure. We underline in the manuscript that this should not be regarded as a formally correct estimation procedure because we regard L first as a stochastic variable by estimating D/L, and then in a second step we regard L as a deterministic value that we calculate from digital maps. It should be noted, however, that this approach is not new in geostatistics. Geostatistical theory has been driven by practical problems and pragmatic solutions. Afterwards, theory was developed which in some cases also did made the practical implementation more soundly.

“7. Cross-validation has some problems that compromise any conclusions that can be obtained from it.”

Reply: It would be useful if the Referee #2 could be more specific on this point because it is not easy to understand exactly what is meant by “some problems”. We are working on empirical data that is quite complex, and there will always be some questions that will remain unanswered. Anyway we will re-read the paper carefully on this point and revise the conclusions if necessary.

“8. The value of cross-validation is further compromised in this case for using too small a sample-measurements (10?) which explains the anomalous results in section 6.2.”

Reply: We agree that the number of samples in the local area was small, but it is not

limited to 10 measurements as the Referee #2 seems to indicate. It was 10 measurements sampled prior to 2010 that was used for cross-validation by leaving-one-out. In addition, we used 15 measurements for independent (jack-knife) cross-validation. We agree that it is not possible to draw general conclusions given the limited number of observations. It is pertinent to underline that we used the global GRANADA dataset for statistical inference, and that we compared the local dataset with statistics from the global dataset. Even though no general conclusions can be drawn because of the limited number of samples, we identified several ways for improvements, for example re-analysis of digital Quaternary maps with respect to uncertainty of spatial coordinates form the horizontal interface between sediment cover and the exposed bedrock.

Final remark.

Upon concluding this answer, we see most of the comments of Referee #2 were motivated by a feeling that our contribution did not make enough references to existing or currently developed techniques. The great help we get in this is the opportunity to make this more explicit, here and also in the revision to come: the purpose of our contribution is to promote a neglected topic, and the rusticity of suggested approaches is by design. After closure of the open discussion, we will take all comments into account and revise the manuscript. If the paper is accepted for publication, we would like to attach the raw data as supplementary material if the editor allows.

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