

Interactive comment on “Catchments as space-time filters – a joint spatio-temporal geostatistical analysis of runoff and precipitation” by J. O. Skøien and G. Blöschl

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We would like to thank Prof. Montanari for his very thoughtful comments on the manuscript. We have addressed the comments as follows (referee comments in italics):

I have a few remarks to provide. The most important one is related to my personal doubt about the physical fundamentals of the geostatistical interpolation of runoff data. There is an on going discussion in our community about this issue that I think should be mentioned in the paper.

Geostatistical interpolation of runoff variables is indeed a new idea and it is not surprising that some colleagues will find it unusual. The paper is about space-time analysis

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rather than about interpolation, so it may not be appropriate to discuss this issue in detail in the main paper, but it is true, as mentioned in the original manuscript, that one of the potential applications is runoff estimation for ungauged catchments based on geostatistical interpolation. We realise that the prevailing paradigm is to use deterministic models and to transfer the model parameters in space rather than to interpolate runoff directly. While we do not believe that geostatistical interpolation of runoff will replace the current paradigm, because of exactly the limited physical interpretability Prof. Montanari is mentioning, we do believe that it is an attractive alternative that has been overlooked in the past. In fact, there may be situations where the geostatistical interpolation may be more accurate than the traditional regionalisation of parameters of deterministic catchment models. We have performed preliminary analyses of space-time interpolation of runoff similar to Skøien et al. (2006). These analyses indicate that, for the Austrian regional data set, geostatistical interpolation indeed outperforms the traditional deterministic methods. Specifically, the comparison is with the regionalisation study of Parajka et al. (2005) who compared a number of methods for regionalising the parameters of a deterministic catchment model based on daily runoff time series in 320 catchments. They found that the best regionalisation model gave a median Nash-Sutcliffe model efficiency of 0.67 (their Table 2). Interestingly, our preliminary geostatistical interpolation, for the same data set, gave a corresponding figure of 0.88, i.e., it provided significantly better estimates of the hydrographs. Our interpretation of this result is that the traditional deterministic approach involves a number of error sources, including errors in the inputs and the model structure as well as parameter identifiability issues (Blöschl, 2005) which are not relevant in the geostatistical approach. Indeed, the median model efficiency using local runoff data of Parajka et al. (2005) was 0.72, i.e., the decrease in model efficiency when moving from gauged to ungauged catchments was relatively slim. Much of the error comes from an inability to simulate runoff very well for gauged catchments because of the error sources mentioned above. Clearly, for different climates and different data sets the results will differ, but the main point, we believe, is that the geostatistical approach is attractive and may

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give useful results of interpolating runoff variables to ungauged catchments. Having said this, we would like to re-emphasise that the focus of this paper is on the analysis of runoff and rainfall in terms of space-time variograms; the interpolation of runoff is left for future publications.

1) First, I believe it should be acknowledged that the density of the gauging stations in the considered geographical area is indeed very high. In areas with a less dense monitoring network associated with a greater spatial variability of orography and catchment behaviours the spatial interpolation of runoff could lead to less reliable results (and less justified from a physical point of view). Spatial interpolation allows one to associate a runoff to each point in space, even over the catchment divide. Moreover, interpolation cannot represent in a feasible way the spatial variation of catchment behaviours that are very effective on the runoff formation, such as hillslope orientation, catchment slope, soil behaviours, vegetation and so forth. I am not saying that I completely distrust the spatial interpolation of runoff, but in my opinion such kind of operation should be properly justified in view of the characteristics of the study region. I believe this point should be made clear in the paper. This is especially true because in the introduction the authors state that geostatistical methods may allow one to estimate the variables of interest in ungauged locations (page 943, line 1).

Yes, the spatial correlation approach will work best if the network density is high as is the case in Austria. If fewer stream gauges are available the variograms will not be as well defined (see Skøien and Blöschl (2006ab) for sampling issues) while knowledge about the physical characteristics of the catchment and climate systems will become relatively more important. This is an important point and we have included two comments to this effect in the manuscript.

On page 951 we have changed the text to, “For example, runoff generated close to the outlet or close to the streams will reach the outlet faster than runoff generated further away. Also, $u(x, y, t)$ will be a function of catchment characteristics such as hill slope orientation, catchment slope and soil types. $u(x, y, t)$, for a certain point in space, also

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changes with time as the flow velocities change with changes in the catchment state. As an approximation, ...”

On page 966 we have changed the text to “... based on the records in neighbouring catchments. Clearly, the approach would be expected to work best if the density of the stream network is high as is the case in Austria. If fewer stream gauges are available the variograms will not be as well defined (see Skøien and Blöschl (2006ab) for sampling issues) while knowledge about the physical characteristics of the catchment and climate systems will become relatively more important. We have treated the precipitation variograms ...”

2) The subdivision of catchment in classes accordingly to their area was operated by pooling in each class about 1/3 of the total number of catchments. This criteria leads to grouping in the third class catchments whose area is varying in a range from about 251 to 131.000 square kilometres. This range appears very wide. I would suggest to discuss in the paper the pooling criteria that was used.

We agree that the range of catchment area in the third class seems to be large. Although the range of the third class is larger than that of the other two classes, it should be noted that the median is in the lower end of this class. In fact, there are only a few catchments larger than 10 000 km² in the data set, so the typical range is more similar to the other classes.

3) Regularisation of the variogram is introduced when analysing all catchment together. Why the authors do not feel that regularisation is also needed when analysing the third class of catchments, which is extended to a catchment area range from 250 to 131.000 square kilometres? This range is almost coincident to the one that is covered by the three classes all together (from 10 to 131.000 square kilometres).

See above response.

3) Among the different variogram models, a fractal approach is considered, which did

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not provide a good fit. The authors note that the reason for the poor fit is probably the reduced flexibility of this model with the respect to the other ones considered here. Indeed, the fractal variogram has a reduced number of parameters. However, the terminology used when commenting the results seems to imply that the poor performances are also given to the fractal nature of the approach. I had repeatedly the feeling that the authors wanted to convey a sort of disbelief towards fractal solutions in this context. I would suggest to better highlight the authors' opinion.

Our intention was not to convey the impression that we take exception to fractal models. On the other hand, the results indicate that a spatio-temporal fractal model of the kind applied in this paper is not recommendable. There are two reasons for the poor fit. The obvious one is the smallest number of parameters but the other, probably equally important, reason is the lack of space-time interaction, which is much more pronounced for the pure fractal model than for the stationary models with a fractal part added. We have clarified this on page 963, line 16 by adding the following:

“There are two reasons for the poor fit of the fractal model. The obvious one is the smallest number of parameters among all variogram models, so the fractal model has the least flexibility. The other, probably equally important, reason is the lack of space-time interaction of the spatio-temporal fractal variogram, i.e., the fact that the partial derivatives of the variogram $\frac{\partial \gamma}{\partial h_t}$ and $\frac{\partial \gamma}{\partial h_s}$ only depend on h_t and h_s , respectively. This lack of space-time interaction also concerns the fractal part of the other variograms, but to a lesser degree, as it only relates to a component of the entire variogram.”

4) I would suggest to include the number of parameters to be optimised for each variogram model in the table 2, 3, 4 and 5 (this indication could be provided just once, in Table 2).

We find this an excellent suggestion and have added the numbers in the table. We have also added a sentence on page 956, line 20:

“We have also included the number of parameters to be fitted, including the two pa-

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rameters of Eq. 15.”

And in the caption of Table 2:

“... Average refers to the average of the objective functions from the three catchment size classes. The number of parameters fitted consists of the parameters of the point variogram models and the two parameters of Eq. 15.”

5) In the conclusions (page 961, line 7) the authors state that the time correlation of runoff are much more persistent than those of precipitation. This is a well known results. I believe it is due to the nature of the catchment, that essentially operates as a moving average filter of precipitation (any linear stochastic processes can be represented as a linear moving average filter of infinite order). The extension in time of the moving average filter is directly related to the concentration time of the catchment. Therefore it is fully justified that a sufficiently extended catchment provides a runoff series that is much more correlated in time than the corresponding input rainfall series. I think this is a more complete justification for this results than the one provided by the authors at page 961, lines 8 and 9.

This is a good point and we have extended the relevant sentences on page 961 to “... than those of precipitation. Obviously, this is because of the time delays as rainfall passes through the catchment system. This is an effect of the catchment operating as a filter to the atmospheric forcing, with the time scale of the filter being directly related to the concentration time of the catchment. The contour lines of the variogram values ...”

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