Hydrol. Earth Syst. Sci. Discuss., 6, S699–S709, 2009
www.hydrol-earth-syst-sci-discuss.net/6/S699/2009/

Hydrology and Earth System Sciences Discussions

Interactive comment on "Mapping rainfall erosivity at a regional scale: a comparison of interpolation methods in the Ebro Basin (NE Spain)" *by* M. Angulo-Martínez et al.

M. Angulo-Martínez et al.

Received and published: 11 June 2009

Dear Editor,

we really appreciated the thorough review of our manuscript. The reviewers pointed out some elements lacking in the article which will add to the article for its enrichment. In the following lines we provide answers to all the comments and suggestions made by the reviewers. We are also finishing now a revised version of the manuscript, in which we have incorporated new analysis as suggested by the reviewers. We will soon be ready to submit the revised manuscript for its evaluation.

We believe that we have addressed all the questions made by the reviewers in a convenient way, and we hope our answers will satisfy them.

Thank you very much for the editorial work.

Yours sincerely,

Answers to reviewer #1

QUESTION 1: The conclusions need to be revised according to the results. Where is it proven for instance, that the spatial pattern is correctly represented by the methods?

ANSWER 1: We agree that the conclusions should be revised according to the results, especially after a closer analysis of the kriging methods and the incorporation of GLS method instead of OLS. We have elaborated the conclusions in the revised version of the manuscript. With respect to the spatial pattern, we believe that the spatial pattern is correctly represented by the methods because the patterns that were present in the point sample were well captured in the interpolated surfaces. Besides, the main spatial patterns of the two variables coincide with previous studies, based on subjective non-automatic techniques, for example with the map of ICONA (ICONA, 1988).

QUESTION 2: Discuss the complementary character of R and EI30. Why are both criteria used/required?

ANSWER 2: It is true that both indices are closely related. The R factor summarizes the erosivity of all the erosive events occurred during the year, being a sum of the EI30 values of all events. It was defined for its use in the RUSLE equation, and it has been widely used to characterize rainfall erosivity. As several authors have highlighted, few extreme rainfall events are usually responsible of 80% of the R factor (the Pareto principle). The average EI30, is calculated as the mean erosivity of all rainfall events. Since the frequency distribution of EI30 is highly skewed (it follows a logarithmic, or even double logarithmic, law), the average EI30 is in fact most correlated with the highest erosive events. As we have found in our study area, the spatial distribution of both indices does not necessarily coincide, due to differences in the frequency of low, moderate and extreme erosive events within the region. We hence believe that the

HESSD

6, S699–S709, 2009

Interactive Comment

average EI30 index complements the information given by the R factor alone, and that is the reason why we decided to include it in our study, despite not being commonly reported in many studies. We have elaborated on this topic in the revised version of the manuscript.

QUESTION 3: Briefly describe the theory of the geostatistical approaches, at least the main characteristics, assumptions, etc. of the used methods in comparison.

ANSWER 3: We have elaborated the explanation of the geostatistical approaches in the revised manuscript. The following paragraphs have been added to the manuscript for completing the theory of the geostatistical approaches: Kriging methods assume that the spatial variation of a continuous climatic variable is too irregular to be modelled by a continuous mathematical function, and its spatial variation could be better predicted by a probabilistic surface. This continuous variable is called a regionalized variable, which consists of a drift component and a random, spatially correlated component (Burrough and McDonnell, 1998). Hence, the spatially located climatic variable z(x) is expressed by: z(x)= m(x)+ e(x)+ r(x) where m(x) is the drift component, i.e. the structural variation of the climatic variable, e(x) are the spatially correlated residuals, i.e. the difference between the drift component and the sampling data values, and r(x) are spatially independent residuals. The predictions of kriging-based methods are currently a weighted average of the data available at neighbouring sampling points (weather stations). The weighting is chosen so that the calculation is not biased and the variance is minimal. A function that relates the spatial variance of the variable is determined using a semi-variogram model which indicates the semivariance between the climatic values at different spatial distances. Several types of kriging methods have been proposed, depending on how the drift component m(x) is modelled (see, e.g., the reviews by Isaaks and Strivastava, 1989; Goovaerts, 1997; Burrough and McDonnell, 1998). Simple kriging (SK) assumes a known constant trend (expect value), m(x) = 0, and relies on a covariance function. However, neither the expectation nor the covariance function are known, so simple kriging is seldom used. In ordinary kriging (OK), the

HESSD
6, S699–S709, 2009

most common type of kriging, an unknown constant trend is assumed, $m(x) = E(z(x))$, and the estimation relies on a semivariogram model which is estimated from the sample. SK and OK both assume stationarity of the spatial field, i.e. that the expected value of the variable does not change in space. This is often not true with climatic variables, which tend to show spatial trends due to differences in the exposure to the atmospheric factors. Universal kriging (UK) allows incorporating non-stationarity by assuming a general linear trend model, where p defines the order of the polinomial model on the spatial coordinates of the point, $f(x)$. This process is often called trend removal, and it is interesting because it can capture a real spatial structure present in the data. However, it increases the complexity of the kriging model by adding more parameters for estimation. A two-dimensional quadratic surface, for example, adds five parameters beyond the intercept parameter that need to be estimated. As it is well known, the more parameters to be estimated, the more uncertain the model becomes. Spatial structure can also arise in climatic data due to co-variation with other geographical factors such as the elevation or the distance to the sea. Co-kriging (CK) allows considering the influence of external variables (co-variates) by analysing cross-correlation between the autocorrelated errors of the different variables, $e(x)$, $r(x)$, etc. In our study we compared OK, UK and CK methods. The order of the trend removal component was determined by the lowest root mean square error, computed by a leave-one-out bootstrap process. In the case of CK we used the elevation, as determined by a digital terrain model (DTM), as the spatially distributed co-variate; the kriging method used was the best one from the previous methods, i.e. OK and UK. Spatial correlation may occur at different distances when different directions are considered; this characteristic is called anisotropy. Since the Ebro basin has a marked NW-SE structure, the effect of including anisotropy in the model was also evaluated. All geostatistical analyses were done with the ArcGIS 9.3 software.

QUESTION 4: How are the variograms inferred? Which variables are used for co-kriging? How is the mean for simple kriging estimated?

HESSD

6, S699–S709, 2009

ANSWER 4: The semivariogram models were fitted by the ordinary least squares (OLS) method. The elevation was used as co-variate in CK. The mean for OK was computed as the sample average. All computations were done automatically by the software used. All these questions have been described in the revised manuscript (see answer to question 3).

QUESTION 5: The application of regression residuals for interpolation in kriging implies methodological inconsistencies. Residuals from the regression theoretically need to be independent, but for kriging they are assumed to be dependent; i.e. they are related to the distance between the station locations in order to estimate a variogram. This problem has usually only little practical relevance but should at least be mentioned.

ANSWER 5: We totally agree. It is true that ordinary least squares (OLS) regression is often used with spatially distributed variables without checking for the validity of the assumption of spatial independence of the model residuals. Autocorrelation has the effect of reducing the degrees of freedom of the sample, and hence affecting the computations of OLS. Unfortunately, there is no consensus on how to check for spatial dependence. As such, combining OLS regression with kriging is inconsistent, since both methods make opposite assumptions about the model residuals. We have thus preferred to use generalised least squares (GLS) regression in our revised manuscript, which is a generalization of OLS and does not suffer from autocorrelation of the residuals.

QUESTION 6: There are too many validation criteria involved. It is difficult for the reader to judge the results. I would suggest reducing the number of criteria to some most significant but complementary ones (e.g. bias, mean absolute error, coefficient of determination and variance conservation).

ANSWER 6: We agree that the profusion of validation criteria is confusing. The revised manuscript will contain only the following statistics: Mean, Standard deviation, Willmotts D, MAE and MBE.

HESSD

6, S699–S709, 2009

Interactive Comment

QUESTION 7: Figs. 2 and 3. Discuss the differences between the spatial pattern of R and EI30. This issue is related to comment 2. I would assume it has something to do with the frequency of rainfall events, which is considered in R but not for EI30.

ANSWER 7: The differences between both indices are explained in the answer to comment 2. In general, the R factor is most related to the highest events occurred during the year, whilst the average EI30 is related to the normal erosive events. Thus, differences between both indices are related to differences in the frequency distribution of erosivity. By comparing figures 2 and 3, differences can be found especially in the high values registered in the mountainous areas. High values of EI30 are located at the southeast and medium altitude mountains immediately to the south of the axis of the Pyrenees range. The highest values of the R factor are found on the axis of the Pyrenees coinciding with the highest altitudes, where the importance of extreme events is enhanced by the topographic effect. As explained before the R factor summarizes all the erosive events occurred during the year, whereas the average EI30 is highly skewed and depends most on the really extreme events. Since different geomorphological processes are triggered by events of different magnitude, we consider that the information of both indices is complementary. These differences have been highlighted in the revised manuscript.

QUESTION 8: I would recommend thinking about carrying out the analysis not only for the whole year but also for different seasons, which would consider the different climate conditions e.g. prevailing convective and frontal rainfall events. The results would also benefit a better land use management which depends on the seasons.

ANSWER 8: We agree that a seasonal analysis would add useful information. However, we decided to reject a seasonal approach due to relatively small sample we had, since the study period (1997-2007) is short. In addition, the RUSLE R factor criterion considers rainfall events erosive only if at least one of this conditions is true: i) the event rainfall depth is greater than 12.7 mm.; or ii) there is at least one peak intensity greater than 6.35 mm in 15 min during the event. Splitting the sample by seasons resulted

HESSD

6, S699–S709, 2009

Interactive Comment

in too few events for some observatories and some seasons, especially in winter and summer. We are now focused on analyzing the seasonal pattern of rainfall erosivity based on a different approach using daily rainfall series, which are much longer than the ones used in this article.

QUESTION 9: Before interpolation a structural analysis should be carried out based on variograms. The results would reveal the spatial characteristics of the target criteria and explain also part of the uncertainty of the results. This includes also a discussion of the anisotropy, especially since this feature is used for kriging with anisotropy but not discussed.

ANSWER 9: This question has already being answered in answers 3 and 4, though here refers more specifically to anisotropy. Kriging models have been repeated more carefully for evaluate all the options available, including anisotropy. This issue has been discussed in the revised manuscript, and the results comparing isotropic and anisotropic models have been included.

QUESTION 10: Some more information about the application of kriging will be useful e.g. how many neighbours are included, what search radius is applied, etc. This would also help to assess the results e.g. like smoothness of the maps.

ANSWER 10: This question has been partially addressed in answers 3 and 4. As for the number of neighbours included in the kriging analysis, we performed a comparison by varying this parameter between 3 and 9, allowing finding the best setting for each specific model. These results have also been included in the revised manuscriupt.

QUESTION 11: Tables 5 and 6: the performance measures (e.g. looking only at R2, MAE, and D) provide a significant different ranking of the interpolation methods. This is unusual in this extent and should be double-checked and discussed.

ANSWER 11: Different validation statistics serve different purposes, and it is possible that one model performs better according to one criterion and worse according to an-other. We agree, however, that some of the validation statistics used give very similar information, and they should be reduced in number. This is the case between R2 and the D statistic, of which we have decided to keep only the second one.

QUESTION 12: Tables 5 and 6: I cannot see from the validation criteria, that the mixed models (e.g. the last two methods in both tables) are outperforming the other ones as concluded by the authors. For instance in the interpolation of R (Tab. 5) the last two mixed methods are never best or second best according to the criteria R2, MAE and D?.

ANSWER 12: We agree. Differences among methods were narrow. Validation statistics didn´t show that mixed models yielded the best results, though their map appearance seemed the best one. We agree that this is a subjective choice, and it has been removed from the revised manuscript. Only one validation criteria should be selected in order to rank the methods, which we have decided to be the D statistic since it is a very robust model performance and has been used by many authors for model comparison. This part has yet to be rewritten in the revised manuscript, with an explanation of the information the different validation statistics add.

QUESTION 13: The paper would much benefit from a quantification of uncertainty for R and EI30 e.g. utilising the estimation variance from kriging (requires Gaussian assumption) or by using an indicator approach (Goovaerts, 2001).

ANSWER 13: We found this the most interesting suggestion. Following it, we have assessed the local uncertainty by means of Gaussian geostatistical simulation (GGS; also known as multi-Gaussian model), where the conditional cumulative distribution function at any location is characterized by its mean and variance. The use of conditional simulation for estimating the variance associated to kriging estimation has been explained in the revised manuscript. Maps of the prediction standard error have been also added to the revised manuscript. Their interpretation is of great importance to help understand the variability of the variables analyzed in the study area.

HESSD

6, S699–S709, 2009

QUESTION 14: Figures 4 and 5: it should be indicated on the figures or in the text of the legend which axis represents predicted and which represents observed values.

ANSWER 14: This information has already added to the figures legend: observed values (ordinate axis) and predicted values (abscissa axis).

Answers to reviewer#2

QUESTION 1: Abstract/introduction: The abstract is to the point and includes the necessary information, and the introduction presents the motivation and the general background information in a comprehensive way.

ANSWER 1: (No answer is needed.)

QUESTION 2: Materials and methods: The description of the study site is adequate and the climate measurements are suitable to gain the monitoring data to support the investigation of the different methods. A small drawback is the fact that the authors mention the strong seasonality in the target area but do not describe how it looks like.

ANSWER 2: This coincides with a suggestion of reviewer 1 to undertake seasonal analysis. We agree that a seasonal analysis would add useful information. However, we decided to reject a seasonal approach due to relatively small sample we had, since the study period (1997-2007) is short. In addition, the RUSLE R factor criterion considers rainfall events erosive only if at least one of this conditions is true: i) the event rainfall depth is greater than 12.7 mm.; or ii) there is at least one peak intensity greater than 6.35 mm in 15 min during the event. Splitting the sample by seasons resulted in too few events for some observatories and some seasons, especially in winter and summer. We are now focused on analyzing the seasonal pattern of rainfall erosivity based on a different approach using daily rainfall series, which are much longer than the ones used in this article.

QUESTION 3: The different methods are well presented (in a comprehensive way), but the following are for some reasons interesting but not included: External Drift Kriging

HESSD

6, S699–S709, 2009

Interactive Comment

(EDK) as a combination of geostatistical and regression methods which is quite easy to apply and therefore of interest for a broader public; Indicator Kriging (IK): IK can help to also consider outliers in the interpolation (and this is important for erosion modelling). However, the data support might be too small but IK should be discussed at least; Geostatistical Simulation (GS): GS especially is a method to maintain the inherent heterogeneity of the input data. The authors state that the lost of the variability is the main disadvantage of the different methods, application or at least extensive discussion of GS methods is therefore a must. If the authors don´t apply GS, they have to argue why.

ANSWER 3: There has been some confusion about the differences between some hybrid interpolation methods, in special related to kriging with external drift (KED) and regresion-kriging (RK). Different authors use the same names for different approaches and different names for the same approach, (Hengl, T. et al 2003). What we have called regression model + residuals coincides with what is usually known as regression-kriging (RK), since the drift component m(x) is defined externally through some auxiliary variables, and the residuals from the regression are fitted separately and then summed up. In the case of KED this process is doing together. This has been elaborated in the revised manuscript. Related to indicator kriging (IK), we believe that it is not suitable for our study, since we were not interested in evaluating the probability of exceeding some thresholds. In the study area, high or outlier values which constitute hazardous thresholds at the northwestern part are normal for the rest of the area. Besides, the study period is too short, it may not include enough events for good estimates of the probability of the most extreme events. We agree that evaluating the uncertainty of the spatial models is of paramount interest. This was also suggested by reviewer 1. We have assessed the local uncertainty by means of Gaussian geostatistical simulation (GGS; also known as multi-Gaussian model), where the conditional cumulative distribution function at any location is characterized by its mean and variance. The use of conditional simulation for estimating the variance associated to kriging estimation has been explained in the revised manuscript. Maps of the predicted variance have been also added to the revised manuscript. Their interpretation is of great importance to help understand the variability of the variables analyzed in the study area.

QUESTION 4: Results: The results are well presented. Some questions to be clarified: for Simple Kriging (SK), the mean of the variable has to be known for each site (or cell) of the resulting map. Where do the authors have this information from? Cokriging is an interpolation technique that allows one to better estimate map values by kriging if the distribution of a secondary variable sampled more intensely than the primary variable is known. The question now is what was the secondary variable in this study?, How many neighbours were used in the interpolation? The number of neighbours has a strong influence on the variability of the results.

ANSWER 4: All kriging analysis have been repeated for evaluating all options available, including the number of neighbours, anisotropy, etc. The co-variate used in co-kriging was the elevation, since it obtained the highest correlation in the regression analysis. All these questions have been incorporated to the revised manuscript.

QUESTION 5: Discussion: The discussion reads well, but as mentioned before additional methods should be included in the investigation (EDK, GS) and discussed (IK). Also, the influence of the number of neighbours in the interpolation should be discussed.

ANSWER 5: All these suggestions have been followed, and additional discussion has been added to the revised manuscript.

Hengl T., Geuvelink, G.B.M. and Stein, A. 2003. Comparison of kriging with external drift and regression-kriging. Technical note, ITC. Available on-line at: http://www.itc.nl/library/Academic_output/

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 6, 417, 2009.