Communication of Uncertainty in Spatial Data to Policy Makers

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Abstract. - There is increasing interest in the spatial aspects of many policy decisions. To be valid decision-making tools it is important that maps not only convey what is known, but also where the uncertainties lie. This paper reports the results of tests conducted to assess the ability of various methods of error representation to accurately assist interpretation of maps. The work uses the predicted surface and associated error surface (both generated by a kriging function) to test the ability of prospective and current users to interpret the data presented, and to draw simple logical conclusions about it. The ultimate aim is to study the effect of user perception of accuracy on the real-life decisions made using interpolated spatial data.

INTRODUCTION

Maps are an effective method for communicating the spatial aspect of scientific data to policy makers. The current high priority on environmental issues means that maps may be required to show levels of pollution and their effects on different ecosystems to policy makers. Creation of these maps usually requires the use of models and interpolation techniques. This has been made easier as Geographical Information Systems (GIS) have evolved to handle the large quantities of data and perform elaborate calculations quickly. Unfortunately these developments have an associated cost, in that the new data processing methods may introduce and magnify uncertainties and errors in ways which previously have not required such consideration. Conversely, the enhanced data handling ability equips us to study these errors and uncertainties more easily and we therefore should begin to communicate this information to map users.

The analysis of sources of errors and their propagation has been an area of increasing interest since the mid 1980s (Heuvelink et al. 1989). Many researchers have investigated the topic and used various techniques (for example, see Veregin 1994). However, there have been fewer reported investigations into methods for displaying values of error and uncertainty. Maps may sometimes be presented with an estimated error, for example, digital elevation models published by the United States Geological Service are supplied.

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with an indication of their root-mean-squared-error. Any report of error is welcome, but as Lee et al. (1992) point out the magnitude of the error will vary over the area and a different approach may be more appropriate. In presenting interpolated data, associated error estimates are sometimes presented in map form (Webster et al. 1991). This allows the map user to be aware which regions within the area are likely to be prone to high errors, and to make a more informed decision in the light of this extra knowledge.

Work at the Environmental Information Centre of the Institute of Terrestrial Ecology includes presenting maps of environmental data to policy makers in Government departments. Typically these maps show levels of pollutants deposited generated by interpolating point data from across the UK. They may then be combined with suitable environmental receptor maps. The resulting maps may then be used to identify areas where the threshold of a pollutant is in excess of the ecosystem’s ability to buffer it. This research has considered methods for presenting the uncertainty in interpolated data to decision makers. Several methods of communicating uncertainty in raster data sets have been developed and tested for their ability to convey understanding of error. Ultimately we hope to assess the sources and compounding factors for all errors associated with our data.

INVESTIGATION METHODS

The emerging study area of error visualisation draws on knowledge from a wide range of disciplines: geostatistics, computing, cartography, psychology. In the development of new presentation techniques our aim was to inter-relate the knowledge and understanding of the various disciplines to ensure the solution found was reasonable.

Investigation of Interpolated Data Errors

To gain a fuller understanding of the nature of the errors present in interpolated data we generated several known data sets, resembling interpolated deposition maps. These allowed better understanding of the errors which interpolation introduced. From these hypothetical maps we sampled z-values using various sampling schemes. Kriging was chosen for interpolation of these sampled data as it gave an accessible measure of uncertainty. Using this technique a number of predicted maps and predicted error values were generated. We were able to compare the estimates with the real values, which allowed us to verify that the errors predicted with the interpolation were appropriate. We found that the predicted error values were approximately equivalent to one standard error; in that sixty-eight percent of actual errors were smaller than the predicted error. This implied that the error values could be used to define a confidence
interval. This assumption was confirmed by finding that an interval twice the predicted error included 95% of actual errors. Using the predicted error values, 68% confidence intervals were calculated for each predicted map. It should be noted that further study will address the correct use of confidence intervals for modelled error. This paper is concerned with the validity of the visualisation methods.

**Presentation of Estimated Uncertainty**

Past tests have shown that layer tint maps are the most successful method for visualisation of a landscape (Phillips et al. 1975, Phillips 1984). The colour of the layers reminds the map user of the value between the contour lines when scanning a large area of the map. The limitations when visualising a surface imply that the inclusion of uncertainty as an extra variable will pose greater problems for our visual memory. Layer tint maps were used as they are the least demanding method of display, as well as being the simplest way of handling raster data.

The simplest way of presenting the estimated uncertainty is as a separate map. However the definition of a confidence interval enables us to communicate the errors present in an entirely different manner. The use of raster data sets allows the uncertainty and confidence interval to be calculated on a cell-by-cell basis. The confidence interval can be presented in three separate maps (being the predicted map and the upper and lower limits of the interval - see figure 2), or the three maps can be combined into one image (figure 3). Either form of presentation should be accompanied by a statement of the level of confidence presented. Using the three maps separately, map users can be confident in their extraction of information. For example, the map user may check that they have selected the correct end of the confidence interval for their current use. Where the maps have been combined, the process gives rise to hatched areas where the classes from each of the three constituent maps overlap. The hatchings give an impression of the uncertainty of the information being presented, marking the extent to which the class boundary may differ in reality. It is possible to visualise the effect of the uncertainty in all three dimensions, without the need to cross refer between maps.

**SURVEY METHODOLOGY**

Having developed several visualisation methods the next phase of the investigation was to conduct a survey. This was designed to assess the level of information which could be conveyed about uncertainty in interpolated maps and test a representative selection of the visualisation techniques developed. The composition of tests which have been conducted in the past (Phillips et al. 1975,
Phillips 1982, Potash et al. 1978) were considered, and have been modified to reflect the requirements of presenting error to decision makers. We wished to check that information from the predicted map was still accessible, but more importantly to assess the ability of candidates to determine the effects of uncertainty on that prediction.

The three techniques selected to be investigated in our survey were presentation of the error on a map beside the predicted map (figure 1); presentation of a confidence interval as three separate maps (figure 2) and presentation of a confidence interval as one combined map (figure 3)

![Figure 1. - Presentation of interpolated prediction (left) and the predicted error (right).](image1)

![Figure 2. - Presentation of interpolated prediction (centre) with the confidence interval limits; lower (left) and upper (right).](image2)

**Structure of Survey**

The survey consisted of two sections: assessment of users’ skill and assessment of users’ preference.

The first section assessed the candidate’s ability to understand maps presented
using the three techniques listed above. Some maps may be used to locate areas
in which, for example, pollutant deposition values exceed an acceptable limit.
One set of questions addressed this issue, asking the candidates to mark the areas
in which the values might exceed a given level (when the error was taken into
account). A second type of question asked the candidates to mark the highest and
lowest points on the map, to assess whether they could understand the key and
layer tint used. Both question types were repeated for all three methods, as well
as for a control question in which no error was presented. A further type of
question asked the candidates to identify areas where additional data samples
were needed to reduce the resultant error.

Early in the first section, where the methods had been presented but not
explained, the candidates were asked for their opinion of the methods. This was
to gain an impression of their immediate reaction, simulating a situation where a
new method of presentation was encountered in a journal or book without
detailed explanation. The opportunity to give a more detailed response on the
three methods was given at the end of the test after the candidate had had further
experience with all three methods.

The second section contained questions which allowed the candidates to
select the method with which they "felt most comfortable" to answer questions
similar to those described above. Here, all three methods were given, on the
same page, using maps of equal size. The candidates were not limited to the use
of only one method but were asked to tick each map which they used. These
questions were used to assess the method the candidates preferred, and hence the method most likely to be popular in a real situation. The information was also used to check that the most popular method was actually the method which was used correctly.

Candidates were selected to represent as wide a selection of potential map users as possible. In all, 24 science and administrative staff participated, representing a range of mapping expertise and seniority. The level of geographical qualification held by each candidate varied from none to postgraduate. The frequency of map use varied from never to daily. The candidates were told that completing the questionnaire would take approximately 30 minutes, but that if they felt they required longer, or needed to finish sooner in order to meet their other work commitments, they could do so.

ANALYSIS OF RESULTS

The candidates' responses have been used to investigate many aspects of the presentation techniques. Most important is the comparison between the methods using error maps with methods showing confidence intervals. The comparison between the two confidence interval presentations chosen is also interesting, but we anticipate future developments in the presentation of confidence intervals will lead to altered preferences. The results outlined below should be a starting point for further investigations.

Time and Experience

Before detailed analysis of the results, it was necessary to consider the effect of external factors on the candidates' responses. As was to be expected, the candidates' levels of geographical qualification and their frequency of map use were found to be related to their performance in the survey. However, the wide range of geographical skills which civil servants and policy makers possess, made it desirable to ensure that this range of skill was also present in the survey. The requirement for sufficient explanation of the occurrence and effects of uncertainty in maps cannot be understated as we must be sure that the topic is understood correctly.

It was also important to assess the effect of the time taken to complete the questionnaire. The quality of answer was shown to have no correlation with the amount of time spent in responding. So the lack of imposed time constraint appears to have had no biasing effect on the results of the survey.

Identification of Threshold Values

The responses were scored by two methods. Initially they were assessed with
reference to the ideal response. A score was allocated to reflect the level to which the candidate had understood and implemented the idea. This indicated that the combined map gave the highest score for most candidates. This scoring method was quite arbitrary, so a second method was designed to be more quantitative. A regular grid of points was prepared on transparency, each point being marked as being above or below the threshold. The grid was overlaid on the response, and the identified points split into four categories: correctly marked, correctly unmarked, incorrectly marked and incorrectly unmarked. The counts were used to conduct chi-squared tests which identified the responses which were wrong. The percentage of candidates giving correct responses was used as an indicator of the success of the method. Occasionally a candidate had not answered the question or had marked the map in a way which was not suited for this type of analysis, so these responses have been treated as a separate category. The results for each presentation method are shown in figure 4.

![Figure 4. - Proportion of candidates identifying exceeded areas correctly. This question type was used once where no uncertainty was presented, then repeated twice for each of the three uncertainty display methods.](image)

The most visible trend was that the use of the predicted error map alongside the predicted map gave a significantly lower standard of result than where either form of confidence interval was used. Indeed, with the confidence interval presentations the scores were similar to the control example where no error was presented with the map. In situations where the map user requires a visual perception of the extremes which the uncertainty implies, the confidence interval is the more useful tool. The results also indicate that the combined map of the confidence interval was the most accurately used. This observation might be an artefact of the relatively small number of questions asked. Ideally further studies would be conducted to assess the most effective method amongst the possible confidence interval representations. Other methods for presenting the confidence interval are currently being developed.
Assessing Location For Extra Samples

Where the candidates were requested to locate areas where extra samples were needed, the majority of candidates opted to use the predicted error map. There were however, two other methods which candidates justifiably chose to use. One was to refer to both the predicted error and the original map. This reduced the uncertainty in areas where it was high and verified the “topographical” features which the map seemed to predict. The other was to use the combined map to locate areas where the cells’ confidence interval spanned two or more class intervals. This was a very interesting option, as the tint layers would ideally be selected to reflect the classes in which the map user was interested. Areas which were borderline between two classes would be the areas in which the uncertainty would have the most influence over that decision. Clarifying the boundaries in these areas would be the most cost effective action.

Candidates’ Preferences

Where candidates were allowed to choose between the three methods of presentation, the most popular method was the three separate confidence interval maps, but the use of the combined map came a close second. Some candidates opted to use both of these methods, and explained this choice, saying that the three separate maps were useful for ensuring that they selected the correct information and map. The combined map was additionally useful in spatially relating the three maps to the one area under consideration and identifying the areas on the original map.

The candidates’ opinions expressed in the free response questions often indicated quite clearly their preferences between methods. However a number of candidates made no comment. The trend for preferring the confidence interval was explained by the difficulty of superimposing the original two maps, and the simplicity of using the confidence interval. The reasons expressed for lack of conviction in the combined confidence interval were problems with the explanation, difficulties with the key and greyscale, and the presence of too much information. However a number of people expressed a preference for this method, as the shading makes it easier to visualise patterns.

CONCLUSIONS

Currently the presentation of uncertainties and errors in maps is very limited. This situation has perpetuated many untrained users’ perceptions that maps are infallible. Where maps are subject to errors and uncertainties which might influence policy decisions, these now can and should be presented. The results of
the survey presented here show that it is possible to convey information on uncertainty and error, even to people who are unfamiliar with the data. The use of a confidence interval gives an enhanced understanding of the potential effect of the uncertainty on the reported values. There are many potential methods for presenting a confidence interval, the two which have been reported here have been investigated in depth, but others have also been considered by the authors. Other methods will doubtless be developed to satisfy specific requirements.

The presentation of the error as a map in its own right is useful in the planning stages of a sampling scheme for interpolation, or where a model needs to be improved. However, the use of the combined confidence interval map has proved more effective in targeting areas where the uncertainty has the greatest effect on the data currently under consideration. The use of a confidence interval can be employed in any raster data set, and the confidence interval can be defined according to the requirements of the users and the quality of the data. The use of a confidence interval in mapping is a relatively new concept which has the possibility of being a major advancement in understanding uncertainty within maps. As information on uncertainty in critical loads and deposition estimates becomes available the communication of uncertainty to policy makers will become a standard procedure.

REFERENCES


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