Horwood Critique Article

Managing Uncertainty in Spatial Databases: Putting Theory Into Practice

Gary J. Hunter and Michael F. Goodchild

Abstract: *Users of spatial databases face three fundamental questions when dealing with the error or uncertainty in their products, viz., "What error is present?" (definition), "How can it be visualized?" (communication) and "How can the results be used in practice?" (management). While researchers have spent considerable effort examining the first two questions, the results of their labor will not be recognized until users start applying the techniques in practice. With tools for error visualization now becoming available, the research agenda must be widened to determine how and when these aids can best be applied. Accordingly, the purpose of this paper is to discuss the techniques available and present a strategy for managing uncertainty in spatial databases.*

"Effective use of . . . information for analysis and decision-making presupposes that the information is correct or reasonably reliable. Information on the quality of data is essential for effective use of GIS data: it affects the fitness for use of data for a particular application, the credibility of data representation and interpolation, and the evaluation of decision alternatives."

(Beard *et al.* 1991, p. iv)

As users of spatial databases, also known as geographic information systems (GIS), become more remote from the basic tasks of data collection and processing, questions will arise which relate to the inherent error or uncertainty of the products derived. If a product, such as a map or report, is required for a specific task then users should be satisfied that its quality, or fitness for use (based upon a knowledge of product error), is sufficient for the purpose at hand.

The quotation above aptly describes the potential consequences of not paying due consideration to these aspects, *viz.* the use of wrong data, in the wrong way, to arrive at the wrong decision. In fact, there are now cases of competing spatial databases being employed by agencies contesting critical land management decisions, in which it is becoming a standard tactic to discredit opposition arguments by attacking both the validity of their data collection, analysis and reporting methods, as well as the uncertainty of their database products. Of course, assessing product quality is not so difficult for expert users, since they tend to know what questions to ask and when to ask them. But as Figure 1 shows, the situation can be quite different at the other end of the spectrum and can vary widely among users in between these two extremes.

However, the problem of quality assessment does not rest solely with users and their products. As shown in Figure 2, while the producers of primary data sets have responsibility for accurately reporting the error in their products, vendors should be able to document and track error within their systems, plus provide a means of displaying it.

To date, the research agenda has focused upon the primary issue of error modeling (definition) but more recently has shifted to error visualization (communication). The aims of this paper are first, to bring readers up to date with developments in error visualization, and second to extend the debate by examining how users might handle such information operationally (management)—as a means of understanding the effects of error upon their decision-making and to determine what uncertainty they are prepared to tolerate in their products.

Progress in Error Visualization

This section of the paper briefly discusses the range of error visualization techniques being developed at present. For visualization to take place, error models first need to be developed and hence the progression in research over the past decade from error modeling to error visualization. While this is not the only means of

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FIGURE 1. User Skills vs. Understanding of Error (After Beard et al., 1991, p. 10)

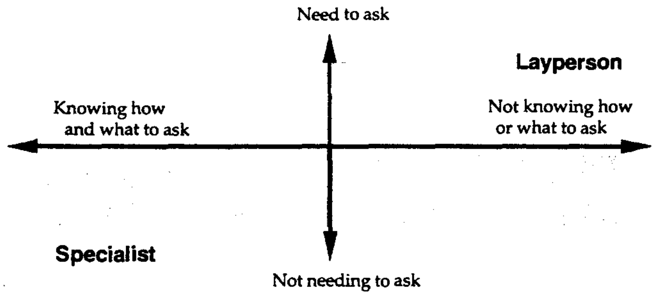
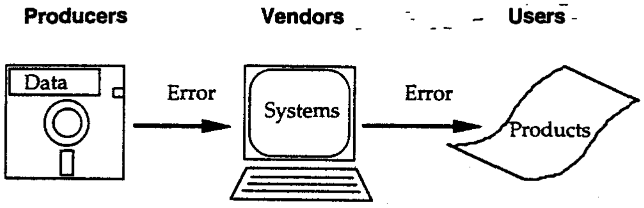


FIGURE 2. Participants in the Error Debate



communicating uncertainty (since users trained in spatial statistics can become quite comfortable dealing with more abstract measures of error), there are many concepts that are either impossible or else too difficult to represent as single numbers, and hence the move to computer graphics and visualization techniques to convey uncertainty. The subject has received added impetus since being named as one of the research initiatives for the U.S. National Center for Geographic Information and Analysis (Buttenfield and Beard 1991).

For land suitability analyses, Lowell (1992) has examined the creation of uncertainty surfaces and argues that there should be such a surface (or secondary map) developed for every layer in a spatial database. He gives examples of their application in land use classification and suitability analysis. Palmer (1991) also develops probability maps, this time for the purpose of determining site visibility, whereas Fisher (1991a) handles visibility uncertainty differently by producing simulated outcomes of reality under terms of uncertainty.

Leung *et al.* (1992) apply the theory of fuzzy logic to display uncertainty not only in classified scenes in remote sensing, but also to fuzzy classification of cells in spatial databases—in cases where a pixel has a mixture of classes or else has a probability of several class memberships. Their methodology has been incorporated into a toolbox which offers several techniques for visualizing uncertainty. Of particular interest is the realization tool, which allows different visualizations of the error model to be displayed with user-defined levels of spatial independence. In other words, users are presented with different illustrations of the same dataset based on the levels of uncertainty observed in the real world.

For an animated approach to the problem, Fisher (1992) employs methods in which uncertainty is conveyed to users by randomly varying data displays in real time. He presents the examples of dot mapping, map-unit inclusions in soil mapping, and classification of remotely sensed images. In the former case, the positions of dots representing populations within polygons are continuously changed to convey to users the fact that dot mapping refers to a distribution throughout an areal unit and not just the location where dots happen to appear. For soil mapping inclusions, the display of grid cells which contain more than one soil type is continuously varied to reflect sampling uncertainty. With this technique, users are gradually able to discriminate between the areas being mapped and the noise (or uncertainty) within the data. Finally, the variability of pixel classification in remote sensing was examined and Fisher chose to randomly assign pixel displays (in real time) in proportion to their probability of being correct.

Other authors have tackled the problem of variation of homogeneity in soils as well, with Maclean *et al.* (1992) choosing to construct variability diagrams which are developed after analyzing detailed information held in the soil survey reports. The variability maps are then used in conjunction with the original digitized soil maps to give users a measure of the uncertainty within the soil map. Fisher (1991b), on the other hand, uses simula-

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In 1985, URISA established the Horwood Critique Prize in memory of Dr. Edgar Horwood of the University of Washington, who founded URISA in 1966. The objective of the prize is to challenge information systems professionals to more critically interpret developments in the field. The prize is given annually to the author(s) of a paper published in the previous annual *URISA Proceedings* representing the best critical analysis of an urban, federal, regional or local system design, implementation or application; technology policy or issue; or contextual environment.

Papers are judged on their candor, critical insights, and conclusions and methods employed in the critique. All papers appearing in the Proceedings are judged in the competition. In this issue of the URISA Journal, we are featuring the 1994 Horwood winner, "Managing Uncertainty in Spatial Databases: Putting Theory into Practice," by G.J. Hunter and M.F. Goodchild. In keeping with the critical intent of these papers, comments are welcome.

tion techniques to display soil map-unit inclusions. When handling soil survey data, Bregt (1991) finds it useful to examine the uncertainty derived during the kriging process, and uses the error estimates produced to produce choropleth maps of probability and isoline maps with confidence limits for subsequent applications of the data.

To test the effectiveness of error visualization, Schweizer and Goodchild (1992) have performed experiments to determine the usefulness of simultaneously displaying thematic attributes and their uncertainty on choropleth maps through the use of color. Palmer (1991) would like to take this testing further and establish laboratories in which practitioners would be invited to use spatial databases for real-life problems while under observation

Finally, while not dealing with error as such, Brunsdon (1991) suggests that much more information may be obtained from spatial data if it is treated differently. By constructing probability surfaces for police call-out records, as opposed to simply plotting points on a map, he argues that more useful information can be gained by police and city planners, who gain a better sense of likelihood of incidence occurrence.

Visualization of Spatial Data Quality Challenge

Spatial database users will also be interested in the international "Visualization of Spatial Data Quality Challenge" presently underway (Beard 1992). The challenge is jointly sponsored by the U.S. National Center for Geographic Information and Analysis; the U.S. Environmental Protection Agency (EPA) Center for Environmental Statistics; the U.S. Department of Agriculture Soil Conservation Service (SCS); and the Statistical Graphics Section of the American Statistical Association.

The event invites participants to develop techniques for visualizing data quality, with the objective being to provide a catalyst for experimental research on effective ways of managing and communicating the quality of spatial data. The challenge provides the opportunity to draw together researchers from many different disciplines in pursuit of a common goal. Researchers entering the event are provided with a choice of datasets and problems in which the quality of the data or process outcomes must be conveyed.

Indeed, the EPA and SCS are actively using the challenge to gain a better understanding of uncertainty in their own databases and study a range of possible solutions. The SCS, for instance, specifically wants participants to examine topics such as conveying the uncertainty of digitized boundaries as a function of display scale, and visualizing the variation in 'distinctness' between soil boundaries. On the other hand, the EPA asks researchers to examine time-series data relating to dissolved inorganic nitrogen readings in Chesapeake Bay and to display the uncertainty in 3-D space and/or time for this variable. Thus, the challenge is helping two major agencies to understand and manage their spatial database uncertainty.

Error Management Issues

From an operational viewpoint, spatial database users face two key issues relating to quality, *viz.*, "What is the quality of products created?" and "What quality is needed for their tasks?" Plainly, the answer to the latter rests solely with the user, but a solution to the former could be answered by using tools such as those just discussed. While none of the techniques describes quality *per se* (since assessment of 'fitness for use' remains subjective), they may help assess the error or uncertainty in a product from which value judgments are to be made. Clearly, the requirements of each user will be different and no single visualization approach will suit everyone's needs. Considerations such as the likely applications and products, the role of GIS in the decision-making process, the nature of decisions to be made, and user experience, all have a role to play in solving the problem.

Variation In Use and Application

One parameter in managing uncertainty is the variation that occurs in the use and application of spatial databases, as a result of different types of data, procedures and models requiring different approaches to visualizing error (Table 1)

It is already well established that different applications place different levels of importance on data quality components, *viz.* positional accuracy, attribute accuracy, currency, consistency and completeness, and separate

TABLE 1. A Taxonomy of Spatial Information Usage (After Beard 1989a, pp. 8–9)

- Siting—finding optimal locations, e.g., siting a fire station or a waste site
- Logistics—movement or distribution through space, e.g., emergency response, military movement
- Routing—optimal movement through a known network, e.g., school buses, garbage, mail
- Navigation—way finding, may or may not involve a known network, e.g., ground, sea, air
- Inventory—count and location of objects for a given time period, e.g., census, tax rolls
- Monitoring/analysis—examination of processes over space and time, e.g., ecological, zoological, geological, epidemiological studies

approaches to visualizing each of these may need to be adopted. Already, various authors have developed taxonomies of spatial database usage, and Table 1 shows the results of a study by Beard (1989a) in which various application areas have been grouped around common uses.

To illustrate the different forms of uncertainty that apply for some of these categories, consider the following examples: navigation exercises are primarily concerned with positional error; siting activities are affected by error in both position and attribute; the integrity of census inventories can be seriously affected by attribute error; and routing tasks depend on high levels of completeness and logical consistency in the database.

In other words, variation in usage of spatial databases, when combined with differences in significance of the various data quality components, are likely to have a considerable impact upon the choice of error visualization techniques – and at this time insufficient is known about the relationship between these two parameters.

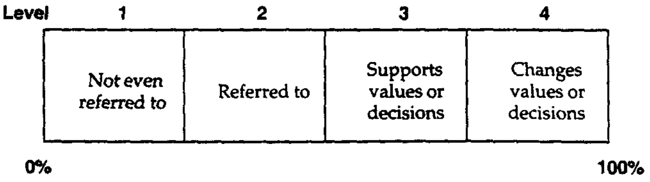
Variation in Impact of Spatial Databases upon Decision-Making

Readers will be familiar with typical definitions of spatial databases which include a statement to the effect that they are designed to provide improved or more effective decision-making, but as Zwart (1991) and Calkins (1989) point out, in many cases the actual impact these systems have on decision-making is simply not known. In discussing impact evaluation, it is argued that the following two questions must be answered (Zwart 1991, pp. 79–80):

- Whether the information produced by a [spatial database] is used in making a decision, and if so, how is it used?
- In what kinds of decisions is [the] information used and do these, in turn, contribute to the fulfillment of the decision-maker's goal or the program's aims?

This variation in impact is represented in Figure 3 which illustrates the degrees of utilization that any information system (in general) might attain within an organization. At the lowest level the database is not even referred to, while at the other extreme the system lends support to decisions or may even change them (although Zwart suggests this does not happen as often as people might believe).

FIGURE 3. Degrees of System Utilization (After Zwart, 1991)



Placing his work into the context of this paper, the importance of understanding product uncertainty should be greatest for those databases that impact upon decision-making at levels 3 or 4. As for levels 1 and 2, databases in this situation are either new and take time to gain acceptance within an organization, or else failing because they cannot deliver appropriate products and applications to users.

However, another reason for poor utilization might be a lack of confidence in the system, implying users either cannot obtain sufficient information about the quality of the database to overcome the risk of using its products, or else they find the level of error in the database unacceptable. How often is it heard, for instance, that users are dissatisfied with a system because (1) the data are too old (currency unacceptable), (2) the features have not been digitized accurately enough (positional error too high), or else (3) not enough is known about the origins of the data (integrity doubtful). Another aspect worth considering is the nature of the decisions for which the products are to be used. As Beard (1989a) points out, decisions may vary anywhere between the extremes listed in Table 2—with the need to measure and manage uncertainty likely to be different in each case.

To summarize, spatial databases which have a high impact upon decision-making deserve to have greater emphasis placed on understanding the uncertainty of their output—thereby preserving the integrity of decisions they are associated with. At the same time, less utilized databases might be failing as a result of either uncertainty levels that are unacceptable to users, or else a lack of knowledge about their uncertainty. While the former is a matter for system administrators and users to get together and resolve, in the latter instance the addition of uncertainty visualization tools could help promote user acceptance. Finally, the nature of the decision for which the database is employed should also be considered, with more emphasis placed upon measuring uncertainty relating to decisions which carry political, high risk, controversial or global implications.

TABLE 2. Variation in the Nature of Decisions (Beard 1989a, p. 9)

Routine	—	Non-routine
Non-political	—	Political
Minimal risk	—	High risk
Non-controversial	—	Controversial
Indefinite	—	Definite
Local implications	—	Global implications

Variation in User Knowledge

As shown previously in Figure 1, the specialist user approaches product uncertainty in a far different manner to the novice. Based on Bedard's (1987) work, Coward and Heywood (1991) look upon this aspect as being a measure of meta-uncertainty (in other words knowledge about uncertainty). They argue that in the three phases of gaining spatial database knowledge (ignorance, learning and knowledgeable phases), while users at first exhibit very little knowledge of uncertainty this is followed by a considerable rise once they learn to question their products, and then finally decreases in the knowledgeable phase as they become experienced enough to assess and account for error (Figure 4).

To cope with this variable, Miller *et al.* (1989) suggest different visualization approaches be used for different users. For instance, novices might find fuzzy boundary depiction useful to remind them of the positional uncertainty of soil polygon possesses. Alternatively, skilled users may prefer to use spatial statistical measures and detailed data lineage reports.

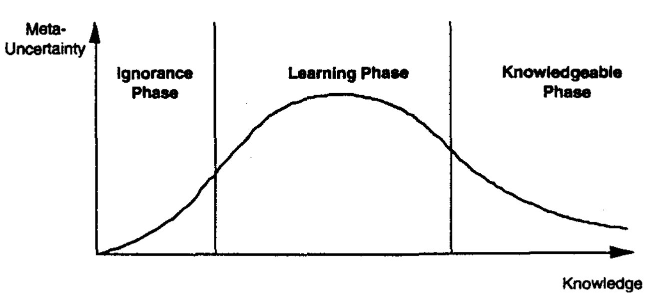
Similarly, there may be differences between how senior executives deal with uncertainty and how analysts cope with the matter. Different visualization approaches might be required because of variations in their respective decision-making roles and perspectives. At this time it is still not known what forms of error visualization are most useful to each type of user and this area requires further research.

Approaches to Error Management

Uncertainty Reduction and Absorption

One way of managing error in spatial databases lies in uncertainty reduction and absorption. With regard to parcel-based land information systems, Bedard (1987) recognized that actions such as field checking of observations, strengthening geodetic control networks, defining and standardizing technical procedures, mandatory registration of all rights in land, and improved professional training, all contribute to insuring "... the precision and crispness in the description and location in space and time of [a] spatial entity" (Bedard 1987, p. 181). In other words, the process of formalizing procedures and requirements helps reduce uncertainty between the model (as defined by the database) and the real world. To this list of methods for reducing uncertainty, Burrough (1991) would add the use of better data processing methods; collecting more data; improving spatial/temporal resolution; collecting different data; using better models; and improving model calibration.

FIGURE 4. User Meta-Uncertainty vs. Spatial Database Knowledge (After Coward and Heywood 1991)



Prisley and Smith (1991) give a good example of uncertainty reduction in relation to forest resource management. They note that through understanding error propagation in the algorithms used to calculate timber volumes and areas, knowledge can be gained as to when inventory methods should be improved to reduce variation and, conversely, when they can be relaxed yet still achieve the desired results. Similarly, Smith *et al.* (1991) have examined the variation in results obtained when using different algorithms to calculate grid-cell slopes, and note that when applied in a decision-making context the choice of algorithm can have a significant impact upon the decision taken.

Another useful example of uncertainty reduction is cited in Smith and Honeycutt (1987), in which they use decision tree theory to evaluate whether or not to employ various spatial data collection and analysis methods in the exploration for copper. Their technique links two variables, (1) the costs of using increasingly accurate survey methods, with (2) the probability of finding copper with each method, to give an expected return upon investment for each option. The advantage of this approach is that alternative decisions can be evaluated prior to conducting the fieldwork.

However, regardless of the amount by which uncertainty is reduced the task can never be 100 percent successful simply because no model will ever perfectly reflect the real world. Thus, there will always be some residual uncertainty which users must decide to either absorb (accept) if they wish to use the data, or else walk away from. The amount of uncertainty absorbed can be considered as the risk associated with using the data or product (Miller *et al.* 1989). In some cases, there is institutional uncertainty absorption such as when a government takes responsibility for guaranteeing land title information to be correct. Another way of absorbing uncertainty (this time on the part of the data supplier) is to issue legal disclaimers with the dataset. While these statements are common today (and often inserted at the request of legal advisors), many data producers have taken the approach (now becoming mandatory in several data exchange standards) of preparing data quality statements from which users may make their own evaluation of the suitability of data for their purposes.

Another illustration of error absorption is given by Laws *et al.* (1989) who describe a case study which linked land use planning to the types of decisions to be made and the uncertainty in the datasets acquired for the task. Rather than use error reduction, the authors analyzed the uncertainty in their data and held that as a constraint upon their decision-making—adopting the attitude that they had to learn to live with the data at their disposal. They then looked at the types of decisions to be made and determined limits for which the data could be used. At the state planning level, they decided the data were appropriate for non-binding advisory and management decisions, whereas for regulatory and land-purchasing decisions (which are binding and subject to judicial review) the data were judged suitable only for initial screening and indication of areas worthy of more detailed assessment. At the local level, planning boundaries had to be identified and once again the data were deemed suitable only for initial screening of parcels in conjunction with re-zoning decisions, but quite acceptable for allocation of non-binding incentive area allocations.

Looking to the Future—Intelligent Systems

A vision for the future which is being increasingly talked about is the application of "smart" systems to handle uncertainty. Burrough (1991) suggests that intelligent systems would help decision-makers evaluate the consequences of employing different combinations of data, technology, processes and products, to gain an estimate of the uncertainty expected in their analysis *before* they embark on an exercise. Such a system would help strike a balance between data collection costs and required product quality. While the concept is new to spatial databases, the simulation process is already widely used in geodetic surveying where proposed locations of survey stations and *a priori* estimates of the precision of survey observations are input to network adjustment programs to compute the expected precision of the final network coordinates—without going into the field.

Nijkamp and Scholten (1991, p. 745) have also explored the potential of intelligent systems to overcome uncertainty, and suggest that systems should be able to answer questions such as "What are the optimum uses of a given data input?" and "What is the optimum data input . . . for a given set of uses?" Although developing the means for answering these questions is still in its conceptual stage, Stoms (1987) discusses some examples of knowledge-based systems which he is aware of that are already starting to use various methods of reasoning under uncertainty for specific applications. He foresees spatial databases being embedded in decision-support systems of the future to provide decision-makers with measures of reliability of the evidence set before them and the conclusions that they might draw from that information.

In other research, Wesseling and Heuvelink (1991) have developed a technique for handling the propagation of errors in quantitative spatial operations. The package, ADAM, includes a modeling descriptive language which permits users to keep track of error in specific applications (for example, when running agricultural models) under different models of uncertainty (such as the Monte Carlo method). Another prototype uncertainty sub-system is being implemented in The Netherlands by Drummond and Ramlal (1992). It is embedded in the ILWIS system and, using land suitability analysis as an example, permits probability overlays to be created for each map product to support decision-making.

Finally, coming from a different perspective, Beard (1989b) has examined the misuse of spatial information and suggests that databases be re-designed to help prevent misuse. Systems might be structured so that the validity of mathematical operations could be verified before processing, data resolution would be automatically assessed to see if it is appropriate for a given operation, and illegal or illogical operations would be identified. In circumstances deemed to be misuse, users could be given explanatory warnings prior to execution of their instructions, which, if they choose to override them and proceed with the operation, would be added as notations on the product lineage report. This approach has the advantage of catering for novice users and acting as an educational tool.

Future Research

Future error research cannot stay confined to the academic sector and should be conducted jointly with the user community to reflect the need for solving management aspects of the issue. Several research topics have been identified throughout this paper. In addition, there needs to be more attention paid to error propagation, which is proving to be not only a technical issue but also a human one. The reason being that intuition tends to underestimate the impact of uncertainty in spatial products with the result that too little attention is paid to how error advances from data input to final products. The consequences are that without good connections between input and output uncertainty, a knowledge of input error has little impact or value. Accordingly, the suggested areas for research are:

- Error propagation from data input through to output;
- Identifying which data quality components are significant for different uses, and what visualization methods are most appropriate for each;

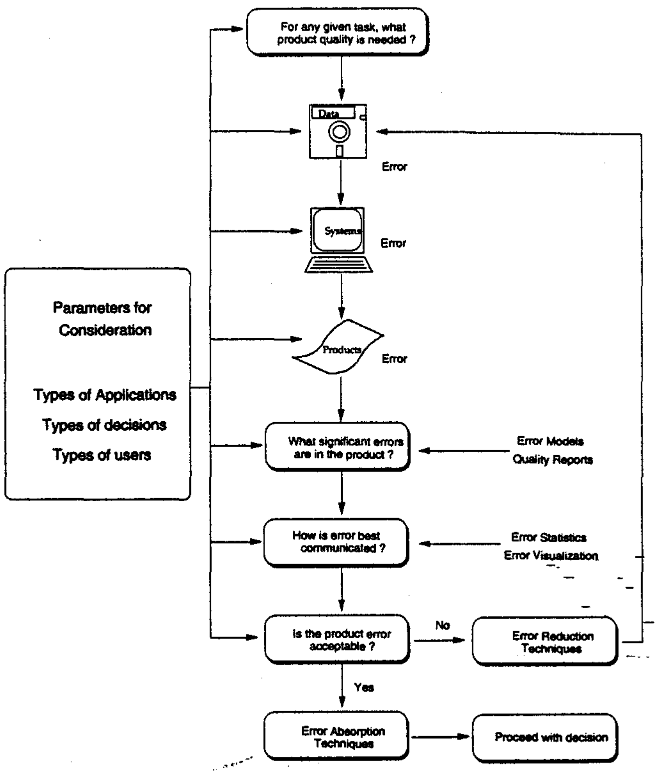
- Identifying which techniques for visualizing uncertainty are most useful for users with different skill levels and positions within an organization;
- Identifying which visualization tools are appropriate for spatial databases with differing impacts upon decision-making processes, and different types of decisions; and
- Educating users to understand and apply error visualization tools.

To better understand the last four problems, what is required is the equivalent of a functional requirement study or cost/benefit analysis; in which people, systems, decisions and applications are studied and identified to determine what errors are present in system products, and what levels of uncertainty can be tolerated for given tasks. Knapp (1993) is already working in this field and her use of task analysis procedures to understand agency goals and tasks is designed to select appropriate visualization techniques which can support user objectives.

Summary: A Strategy for Managing Uncertainty

To synthesize the authors' thoughts on this topic, Figure 5 illustrates a strategy for managing uncertainty in spatial databases. The strategy begins with a consideration of the product quality required which is affected by the application, its users, and the decisions to be made. If this is not known in advance, it may be considered later in the strategy when an error assessment has been made. Then data and systems are combined to provide the products. The significant errors are then identified using information such as quality reports and error models, and consideration is given to the best methods of communicating error again in the context of users, decisions and applications. Having communicated uncertainty to the user, a choice must be made between error reduction and reworking through the strategy, or absorbing the uncertainty and proceeding to a decision.

FIGURE 5. A Strategy for Managing Uncertainty in Spatial Databases



Conclusion

To date, the bulk of the research into spatial database error has been in the development (definition) of error models and understanding error propagation. This is important work which must be continued since there is still much that remains unknown, especially in the propagation area which provides the vital link between uncertainty in input and uncertainty in output. Following on from this work has been research into visualization (or communication) of error to users. Finally, there are management aspects to be considered relating to how users can apply information about error in an operational sense. This paper has discussed the range of error visualization techniques being developed by researchers, and considered how the problem of error might be handled in practice by presenting a strategy for managing uncertainty. While there is still considerable research to be conducted in this subject, the authors suggest that the thrust of the research agenda must now shift to take into account the operational requirements of spatial database users.

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References

Beard, M.K. 1989a. "Dimensions of Use and Value of Geographic Information." In H. Calkins, H. Onsrud and N. Obermeyer (eds), *Summary Report and Proceedings of the Initiative 4 Specialist Meeting: Use and Value of Geographic Information,* NCGIA Technical Report 89-7, University of California, Santa Barbara, pp. 8–10.

Beard, M.K. 1989b. "Designing GIS to Control the Misuse of Spatial Information." In Proceedings of the URISA '89 Conference, Boston, Massachusetts, Vol. 4, pp. 245–55.

Beard, M.K., Buttenfield, B.P. and Clapham, S.B. (eds.) 1991. "Executive Summary, Scientific Report for the Specialist Meeting on

NCGIA Research Initiative 7: Visualization of Spatial Data Quality." NCGIA Technical Paper 91-26, University of California, Santa Barbara, 54 pp.

Beard, M.K. 1992. "Call for Participation: Visualization of Spatial Data Quality Challenge." NCGIA, University of California, Santa Barbara, 4 pp.

Bedard, Y. 1987. "Uncertainties in Land Information Systems Databases." In Proceedings of the ACSM-ASPRS Auto Carto 8 Conference, Baltimore, Maryland, pp. 175–84.

Bregt, A.K. 1991. "Mapping Uncertainty in Spatial Data." In Proceedings of the 2nd European Conference on GIS (EGIS '91), Brussels, Belgium, Vol. 1, pp. 149–54.

Brunsdon, C. 1991. "Estimating Probability Surfaces in GIS: An Adaptive Technique." In Proceedings of the 2nd European Conference on GIS (EGIS '91), Brussels, Belgium, Vol. 1, pp. 155–64.

Burrough, P.A. 1991. "The Development of Intelligent Geographical Information Systems." In Proceedings of the 2nd European Conference on GIS (EGIS '91), Brussels, Belgium, Vol. 1, pp. 165–74.

Buttenfield, B.P. and Beard, M.K. 1991. "Visualizing the Quality of Spatial Information." In Proceedings of the ASPRS-ACSM Auto-Carto 10 Conference, Baltimore, Maryland, pp. 423–7.

Calkins, H.W. 1989. "Position Paper on the Use and Value of Geographic Information in Decision-Making." In H. Calkins, H. Onsrud and N. Obermeyer (eds.), *Summary Report and Proceedings of the Initiative 4 Specialist Meeting: Use and Value of Geographic Information*, NCGIA Technical Report 89-7, University of California, Santa Barbara, pp. 14–6.

Coward, P. and Heywood, I. 1991. "Aspects of Uncertainty in Spatial Decision-Making." In Proceedings of the 2nd European Conference on GIS (EGIS '91), Brussels, Belgium, Vol. 1, pp. 233–42

Drummond, J. and Ramlal, B. 1992. "A Prototype Uncertainty Sub-System Implemented in ITC's ILWIS PC-Based GIS, and Tested in a Dutch Reallotment Project." In Proceedings of the 3rd European Conference on Geographical Information Systems (EGIS '92), Munich, Germany, Vol. 8, pp. 234–43.

Fisher, P.F. 1991a. "First Experiments in Viewshed Uncertainty - The Accuracy of the Viewshed Area." *Photogrammetric Engineering and Remote Sensing*, Vol. 57, No. 10, October, pp. 1321–27.

Fisher, P.F. 1991b. "Modeling Soil Map-Unit Inclusions by Monte Carlo Simulation." *International Journal of Geographical Information Systems*, Vol. 5, No. 2, pp. 193–208.

Fisher, P.F. 1992. "Real-time Randomization for the Visualization of Uncertain Spatial Information." In Proceedings of the 5th International Symposium on Spatial Data Handling, Charleston, South Carolina, Vol. 2, pp. 491–94.

Knapp, L. 1993. "Task Analysis and Geographic Visualization." In Proceedings of the 1993 ACSM-ASPRS Annual Conference, New Orleans, Louisiana, Vol. 3, pp. 190–99.

Laws, D., Gross, M. and Fabos, J. 1989. "Information Resources and Public Decision-Making." In Proceedings of the URISA '89 Annual Conference, Boston, Massachusetts, Vol. IV, pp. 160–74.

Leung, Y., Goodchild, M.F. and Lin, C-C. 1992. "Visualization of Fuzzy Scenes and Probability Fields." In Proceedings of the 5th International Symposium on Spatial Data Handling, Charleston, South Carolina, Vol. 2, pp. 480–90.

Lowell, K.E. 1992. "On the Incorporation of Uncertainty into Spatial Data Systems." In Proceedings of the GIS/LIS '92 Annual Conference, San Jose, California, Vol. 1, pp. 485–93.

MacLean, A.L. 1992. "The Use of Variability Diagrams in a GIS to Improve the Interpretation of Digital Soil Maps." In Proceedings of the 1992 ACSM-ASPRS Annual Conference, Washington D.C., Vol. 3, pp. 66–76.

Miller, R.G., Karimi, H.A. and Feuchtwanger, M. 1989. "Uncertainty and Its Management in Geographic Information Systems." In Proceedings of the CISM National Conference on GIS, Ottawa, Canada, pp. 252–60.

Nijkamp, P. and Scholten, H.J. 1991, "Information Systems: Caveats in Design and Use." In Proceedings of the 2nd European Conference on GIS (EGIS '91), Brussels, Belgium, Vol. 1, pp. 737–46.

Palmer, J.F. 1991. "Representing Error in GIS Modeling." In *Scientific Report for the Specialist Meeting on NCGIA Research Initiative 7: Visualization of Spatial Data Quality*, M.K. Beard, B.P. Buttenfield and S.B. Clapham (eds.), NCGIA Technical Paper 91-26, University of California, Santa Barbara, October 1991, pp. C-143–8.

Prisley, S.P. and Smith, J.L. 1991. "The Effect of Spatial Data Variability on Decisions Reached in a GIS Environment." In *GIS Applications in Natural Resources*, M. Heit and A. Shortread (eds.), Colorado: GIS World Inc., pp. 167–70.

Schweizer, D.M. and Goodchild, M.F. 1992. "Data Quality and Choropleth Maps: An Experiment with the Use of Color." In Proceedings of the GIS/LIS '92 Conference, San Jose, California, Vol. 2, pp. 686–99.

Smith, G.R. and Honeycutt, D.M. 1987. "Geographic Data Uncertainty, Decision-Making and the Value of Information." In Proceedings of the ACSM-ASPRS GIS '87 Conference, San Francisco, California, pp. 300–12.

Smith, J.L., Prisley, S.P. and Weih, R.C. 1991. "Considering the Effect of Spatial Data Variability on the Outcomes of Forest Management Decisions." In Proceedings of GIS/LIS '91 Conference, Atlanta, Georgia, pp. 286–92.

Stoms, D. 1987. "Reasoning with Uncertainty in Intelligent Geographic Information Systems." In Proceedings of the ACSM-ASPRS GIS '87 Conference, San Francisco, California, pp. 693–700.

Wesseling, C.G. and Heuvelink, G.B.M. 1991. "Semi-Automatic Evaluation of Error Propagation in GIS Operations." In Proceedings of the 2nd European Conference on GIS (EGIS '91), Brussels, Belgium, Vol. 2, pp. 1229–37.

Zwart, P. 1991. "Some Indicators to Measure the Impact of Land Information Systems in Decision-Making." In Proceedings of the URISA '91 Annual Conference, San Francisco, California, Vol. 4, pp. 77–89.