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Managing uncertainty in GIS

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As the use of GIS matures, 'second generation' problems are starting to emerge. There is now growing concern amongst data producers, vendors, system integrators, and users alike at their inability to deal effectively with uncertainty in their geographical information outputs. Mandatory data quality reporting in some jurisdictions, protection of reputations, the threat of litigation, and the basic scientific need to understand just how good our information is – all these have an impact upon the issue. This chapter discusses management approaches to the issue of uncertainty and places in overall context the previous technical chapters dealing with modelling, detection, propagation, and communication of uncertainty.

1 INTRODUCTION

'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: 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: iv)

In the past decade, growing concern has been expressed by many members of the GIS community at their inability to deal effectively with uncertainty and to manage the quality of their information outputs. Their anxiety is well founded for reasons such as:

- the requirement in some jurisdictions for mandatory data quality reports when transferring datasets;
- the need to protect individual and agency reputations, particularly when geographical information is used to support administrative decisions subject to appeal;
- the necessity to safeguard against possible litigation by those who allege to have suffered harm through the use of products that were of insufficient quality to meet their needs;
- the basic scientific requirement of being able to describe how close their information is to the truth it supposedly represents.

As the progression is made from paper maps to digital geographical information, we sometimes forget that the traditional hardcopy map often contained valuable forms of accuracy statement – such as reliability diagrams and estimates of horizontal and vertical positional error. While these descriptors were not perfect, they at least represented an attempt by map makers to convey product limitations to map users. This approach, however, assumed a knowledge on the part of users as to just how far the maps could be trusted. Unfortunately, in the digital age much of this information is missing from GIS outputs; new users of this information are also often unaware of the potential traps that can lie in misuse of their data and the associated technology (see Fisher, Chapter 13; Guptill, Chapter 49).

While most international spatial data transfer standards encourage data quality statements to accompany datasets upon transfer (Moellering 1991), in some jurisdictions the requirement has now become mandatory. Also, although it is possible for data producers to provide minimal statements in which the various quality components are simply documented as 'unknown', the reality is that users are more likely to turn to products from producers who take the time and effort to report – to the best of their knowledge and ability – the accuracy of the information being supplied. Fortunately, many primary data producers are now providing detailed quality documentation in accordance with recognised quality accreditation programmes (for example, ISO 9000). An excellent example is the report for the Geodata Topo-250K product by the Australian Surveying and Land Information Group (AUSLIG 1992). However the same attention is not always paid to reporting quality for secondary (derived) products.

In addition, with geographical information being increasingly used for decision-making, the lack of accuracy estimates has the potential to harm the reputations of both individuals and agencies and the public's confidence in them – particularly in cases where administrative decisions are subject to judicial review and the use of GIS may be called into question. Moreover, in natural resource and environmental disputes it is now common for GIS to be used by more than one party. Cases of 'GIS v. GIS' are occurring in which the armoury of legal tactics invariably includes arguments designed to discredit an opponent's use of GIS, together with the spatial operations and models employed to support a particular finding (see Onsrud, Chapter 46, for a broader discussion of such legal aspects).

The era of consumer protection increasingly has an impact upon the issue. Unofficial reports have already been received that the threat of litigation is looming in several countries where users of geographical data are claiming compensation for alleged damages arising from use of datasets that were of a quality inappropriate to their needs (for example where attributes are incorrect or missing from cadastral and road network databases). While we would not think of purchasing a microwave oven or video recorder without an instruction booklet and a warranty against defects, it is still common for organisations to spend thousands of dollars purchasing geographical data without receiving any quality documentation or assurance whatsoever.

Usually this is not a problem when data are distributed free of charge because there is the tacit understanding that 'you only get what you pay for'. However, with geographical information sales now becoming big business in some countries, the laws of consumer protection are coming sharply into focus and it will be increasingly difficult to argue in future that geographical data are somehow 'different' from other commodities traded within the community.

Finally, there is the need to understand the accuracy of geographical data and derived products simply as part of the broader advancement of our scientific knowledge. If the collection, manipulation, analysis, and presentation of geographical information is ever to be recognised as a field of scientific endeavour, then it is inappropriate that GIS users remain unable to describe just how close their information is to the truth it represents (see also Guptill, Chapter 49).

The obligation to resolve the various issues associated with uncertainty clearly does not rest solely with the end-users of geographical information. Data producers have a responsibility to report accurately on the quality of their products while software and hardware vendors and system integrators should be providing the tools needed to enable the documentation, tracking, auditing, and communication of information on data quality within their products: the participants in the 'uncertainty debate' are depicted in Figure 1.

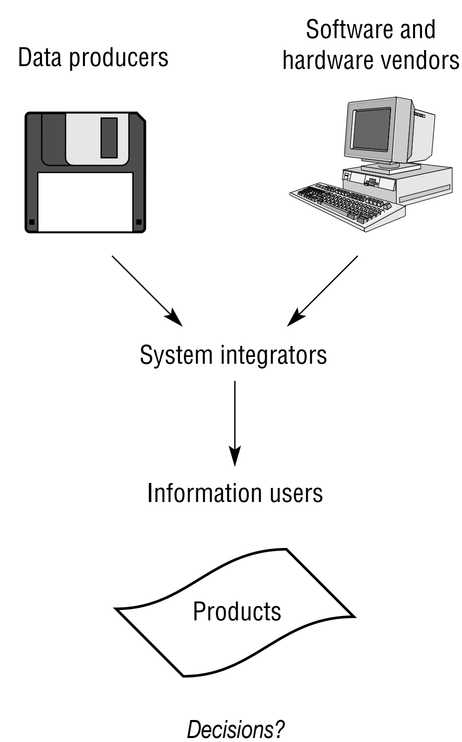

Fig 1. Participants in the uncertainty debate.

2 A STRATEGY FOR MANAGING UNCERTAINTY

In developing a strategy for managing uncertainty, we need to take into consideration the core components of the uncertainty research agenda:

- developing formal, rigorous models of uncertainty;
- understanding how uncertainty propagates through both the spatial and decision-making processes;
- communicating uncertainty to users in more meaningful ways;
- designing techniques to assess the fitness for use of geographical information and to reduce uncertainty to manageable levels for any given application;
- learning how to make decisions when uncertainty is present in geographical information – in other words, being able to absorb uncertainty and thus cope with it in our day-to-day operations.

The strategy for handling uncertainty is presented in Figure 2. To begin with, consideration is given to the type of application, the decision(s) to be made, and the intended audience for the information. It is now recognised that the way in which GIS is used can vary markedly between users having differing skill levels and responsibilities, as can the effect of different types of applications and decisions (for example, low v. high risk, non-controversial v. controversial, local v. global) and the degree to which system outputs are utilised within the decision-making process (Hunter and Goodchild 1993).

Ideally, such prior knowledge permits an assessment of the final product quality specifications to be made before a project is undertaken. However, in pilot applications this may be unclear and, indeed, a specific aim of some projects may be to assess the uncertainty of the outputs based on alternative configurations of data, systems, and processes. Thus, from a pragmatic viewpoint, it is recognised that product quality requirements may not be known in advance, and hence the strategy provides for it to be considered later in the process after an uncertainty assessment has been made. Data, software and hardware, and spatial processes, are next combined to provide the necessary products.

Given that uncertainty in an information product can be detected, the next consideration is communication of the various uncertainties. As Hunter and Goodchild (1996a) have shown, visual means of communication offer a number of options

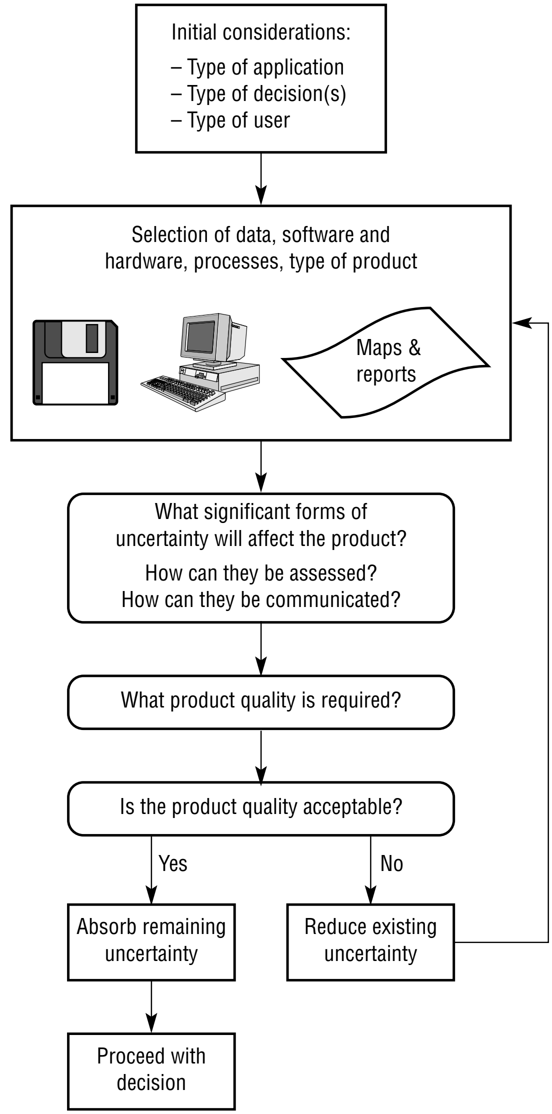

Fig 2. A strategy for managing uncertainty in GIS.

for this task together with emerging techniques in the aural, virtual reality, and multimedia fields (see also Beard and Buttenfield, Chapter 15). However, there is no single optimum technique and again the methods chosen will vary for each user, application, and decision task.

The user is then required to decide what product quality is acceptable for the application and whether the uncertainty present is appropriate for the given task. Often, it is only when confronted with quantitative information that users can decide whether their needs will be met by the product available to them. There are two options available at this stage. The first is to reject the initial product as being unsuitable and then select uncertainty reduction techniques to create a more accurate product that meets the needs; the second option is to absorb (accept) the uncertainty present and proceed with the product's use for its intended purposes.

This, then, is the proposed strategy for handling uncertainty in geographical information. It unavoidably necessitates answering several questions which may be difficult to answer in some applications. However it is suggested that, without answers to any one or more of these questions, the treatment of uncertainty cannot be conducted effectively.

3 DETERMINING PRODUCT QUALITY

In determining the significant forms of uncertainty in a product, trade-offs in one area may have to be made at the expense of others in order to achieve better accuracies. For example, some users find it acceptable that adjacent objects – such as a road, a railway, and a river – are shown in their correct relative positions even though they have been displaced for cartographic enhancement. In other cases, attribute accuracy or logical consistency may be the dominant considerations, for example in emergency dispatch applications where missing street addresses or unclosed road intersection segments can cost lives.

Sometimes, one form of uncertainty in a dataset can transform into other unwanted forms. Bassoglu and Morrison (1977) encountered this problem when they mapped changes in historical US County boundary segments for statistical purposes. They found that, while the US Bureau of the Census Dual Independent Map Encoding (DIME) boundary files available at the time were suitable for small scale analysis (the data were digitised at a scale of 1:5 000 000), apparent positional inaccuracies of up to 14 miles (23 km) were discovered when comparison was made with other data captured at a scale of 1:1 000 000. In this case, early verification of data quality disclosed a potential problem, but not all users can be expected to go to such lengths. Had the original data been used without due care in applications requiring areal estimates, the size of the positional errors present had the potential to cause serious attribute errors. Indeed, products are often used for purposes other than those originally intended and it is unreasonable to expect a map digitised at 1:5 000 000 scale not to have some degree of generalisation or positional error better than the accepted standard of 0.5 mm at source scale.

There is also the well-known case described by Blakemore (1985) which provides a good example of the lack of understanding of geographical data accuracy requirements. It concerns a file of boundary coordinates for British administrative districts collected for a government department as a background for thematic maps. Because of the intended internal use of the dataset, the agency did not require highly accurate positional recording of the boundaries and emphasis was placed more on attribute accuracy. As often happens, the dataset became extremely popular because of its extent and convenient format. However, secondary users soon started to experience problems with point-in-polygon searches after some locations 'seemed suddenly to be 2 or 3 km out into the North Sea' (Blakemore 1985: 346). Clearly, initial in-house convenience can sometimes override data quality concerns relevant to other users.

In cases where the data quality requirements are unknown, Burton (1989) recommended a questionnaire survey of potential users which details the estimated costs for each combination of collection, conversion, and compilation procedures. Dealing specifically with land parcel mapping, he commented that users soon take a pragmatic approach to the 'cost v. accuracy' issue when they are forced to strike a balance between the two.

Having decided which forms of uncertainty will have a major impact upon the quality of a product, some form of quantitative assessment and communication of uncertainty must be undertaken, as discussed in earlier chapters. It deserves to be noted here that researchers are already starting to develop a solid body of knowledge in these two areas and that software designers are now considering the inclusion of basic error analysis functions in their products in response to growing user demand. For example, one major vendor is considering including a function to compute the uncertainty of derived polygon areas caused by errors at control points during digitising. In addition, the Idrisi software package already incorporates several basic uncertainty assessment techniques (see Eastman, Chapter 35).

Another new approach is the use of simulation to distort or perturb map features in such a way that multiple, but equally probable, versions of the original map are created. From these, the uncertainty in the final output can be assessed visually. Examples of this procedure have been documented for grid-cell data in Hunter and Goodchild (1995) and for vector data in Hunter and Goodchild (1996b). These two models also allow the effects of error propagation in the final product to be displayed, even though there are no formal models of propagation *per se*.

At this point, it is the user who must ultimately decide whether the level of uncertainty present in a product is acceptable or not. This implies that there is really no such thing as bad data – just data that do not meet a specific need. For example, a road centreline product has been digitised from source material at a scale of 1:25 000 and, while it would probably have poor positional accuracy for an urban utility manager, it may be quite acceptable for a marketing agency wanting to plan advertising catchment areas. Similarly, street addresses associated with the centreline segments would probably need to be error free for an emergency dispatch system whereas the marketeer would most likely be content if perhaps 80 per cent of addresses were up to date. So quality clearly relates to the purpose for which the product is to be used – which is the very essence of the 'fitness for use' concept.

4 UNCERTAINTY REDUCTION

Having identified the measure of uncertainty in a product, there are two options – reduce the uncertainty to a satisfactory level or else accept it. Uncertainty is reduced by acquiring more information (in order to have a more complete set for the decision-making task) and/or by improving the quality of the information available (which may also entail collecting more information). However, it needs only to be reduced to a level acceptable to the decision-maker.

From a practical perspective, Bédard (1987) recognised that, for land parcel-based systems, actions such as field checking of observations, strengthening geodetic control networks, defining and standardising technical procedures, mandatory registration of all rights in land, and improved professional training, all contribute to ensuring 'the precision and crispness in the description and location in space and time of [a] spatial entity' (Bédard 1987: 181). In other words, the process of formalising procedures and requirements helps to reduce uncertainty between the model (as defined by the database) and the real world. To this list of methods for reducing uncertainty, Burrough (1992) would add the use of better data processing methods, collecting more data, improving the spatial/temporal resolution, collecting different data, using better models, and improving procedures for model calibration.

Prisley and Smith (1991) gave a good example of uncertainty reduction in relation to forest resource management. They noted that by developing an understanding of 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 the resultant uncertainty 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. They noted that, when applied in a decision-making context, the choice of algorithm can have a significant impact upon the decision taken.

5 UNCERTAINTY ABSORPTION

'If we can't have perfection, then we must learn to optimise, to make the best of a bad situation. To paraphrase an old homily: we need the strength to change what we can and the strength to live with what we cannot, and we need the wisdom to recognise the difference.' (Hudson 1988: 206)

Hudson's quote aptly describes the final stage in the strategy for managing uncertainty – accepting that it may be either too costly, impossible, or impractical to reduce uncertainty any further. Openshaw (1989) suggested this step might not necessarily require hard quantitative assessments but instead may involve a more pragmatic approach on the part of users. He commented that 'what many applications seem to need is not precise estimates of error but some confidence that the error and uncertainty levels are not so high as to render in doubt the validity of the results in a particular data specific situation' (Openshaw 1989: 265).

The amount of uncertainty absorbed can be considered to be the risk associated with using the data or product (Miller et al 1989). Sometimes there may be institutional uncertainty absorption applied, for example when a government agency takes responsibility for guaranteeing land title records to be correct. In such cases, the integrity of the information is extremely high and has gradually developed over many decades. Bédard (1987) suggested that another way to absorb uncertainty is for government agencies to authorise a particular dataset as being the 'official' version – implying its acceptance by the government as being more reliable than other competing datasets.

Another form of uncertainty absorption is given in Laws et al (1989) who described a case study linking land use planning to the types of decisions to be made and the uncertainty in the datasets acquired for the task. Rather than use uncertainty reduction techniques, the authors analysed the uncertainty in their data and held it as a constraint upon their decision-making – adopting the attitude that they simply had to work with the data at their disposal. They then examined the types of decisions to be made and determined limits for which the data could be used in each case. At the US State planning level, they decided the data were appropriate for non-binding advisory and management decisions. For regulatory and land purchasing decisions, however (which are binding and subject to judicial challenge), the data were considered suitable only for initial screening to give an indication of areas worthy of more detailed field inspection and evaluation. At the local level, planning boundaries were required to be identified and, once again, the data were deemed suitable only for initial screening of parcels in conjunction with re-zoning decisions but still quite acceptable for assignment of non-binding incentive area funding allocation.

Barthel et al (1992) also advocated recognising the limitations of geographical information, especially with respect to environmental assessment and natural resource planning in 'data poor' developing countries. They note that low data quality is especially significant in many African countries and that GIS are best suited to identification of areas for further study, rather than acting as a definitive planning tool. Even in more developed countries, we sometimes have little choice but to acknowledge inherent data limitations – for instance when using aggregated census statistics (see Martin, Chapter 6). While researchers would usually prefer to receive household-level values, they accept that the process of aggregation actually helps ensure integrity of the dataset, given that residents of most countries would object to the release of individual household statistics and would more than likely be uncooperative or else provide false information. In the case of census data, we acknowledge that the aggregated statistics provided are the best we can obtain and that it is simply not feasible (nor probably legal, given recent trends in data privacy laws) to collect the data ourselves.

Self-insurance is the common means for governments to protect themselves against various forms of uncertainty. This occurs, for example, when a government is prepared to pay from general revenues for harm that results from decisions based on negligently prepared maps and charts. Another form of self-insurance by governments occurs when the government develops a special fund to cover losses associated with a specific agency activity (Epstein et al 1996).

A new means of absorbing uncertainty, which is only just arriving in the information marketplace, is to take out private insurance cover as protection against potential liability claims for damages allegedly suffered by data purchasers. This option is likely to grow in popularity in the next few years – particularly for private sector producers of datasets specifically tailored for use by clients in high risk areas, such as emergency dispatch (Epstein et al 1996). Although details are limited for commercial reasons, discussions with producers who have taken out such policies reveal that the assessment process is laborious, requiring proof of recognised quality assurance accreditation such as ISO 9000 (including all subcontractors employed), production of detailed data quality statements (which will need to be kept up to date), adherence to industry standards and accepted practices, and placement of copies of the data as supplied to customers into locked vaults maintained by independent escrow companies – implying that all data updates will also need to be stored. Significantly, insurance companies will expect clients to 'sign off' the likely types and quantities of errors in the data, as well as requiring them to advise of any circumstances which might increase the insurer's exposure to risk. The costs of insurance policies are not small but for some private companies it seems to be the only solution to the liability protection issue. Indeed, some government agencies (in Australia at least) are also now estimating the risk associated with their geographical information products and, if their exposure to liability is deemed to exceed the amount they are prepared to fund from the 'public purse', then they too will seek private insurance protection.

Of course, one traditional means of absorbing uncertainty on the part of the data supplier has been to issue legal disclaimers with datasets. However, the benefit of disclaimers would seem to be diminishing with the advent of stronger consumer protection laws. Whilst disclaimers are still common today (and are often inserted at the request of legal advisers), many data producers have taken the additional step of preparing detailed data quality statements which might help lessen the financial impact of any costs awarded against them in a legal action.

Finally, Rejeski and Kapuscinski (1990) noted that some environmental risk managers prefer to adopt the average or worst case scenarios when evaluating their data. In so doing, they are placed in a position which is more acceptable to them when faced with absorbing any remaining uncertainty. However, regardless of the approaches available, Bédard (1987) contended that – whereas uncertainty reduction techniques tend to be technical in nature – uncertainty absorption approaches are almost exclusively institutional and that ultimately people and agencies have to take responsibility for their data and their decisions.

6 FUTURE DIRECTIONS

One vision for the future being increasingly mentioned in the literature is the application of 'intelligent' systems to handle uncertainty. Burrough (1991) suggested that such systems could 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 analyses before they start. These systems would help strike a balance between data collection costs and the required product quality. While the concept is new to GIS, simulation procedures are already widely used in geodetic surveying and photogrammetry where proposed locations of survey stations and *a priori* estimates of the precision of observations are input to network adjustment programs to check the expected precision of the final network coordinates – before going into the field.

Nijkamp and Scholten (1991) have also investigated intelligent systems and suggest they should be able to answer questions such as 'What are the optimum uses of a given set of data inputs?' and conversely, 'What are the optimum data inputs for a given set of uses?' Although techniques for answering these questions are still in their early stages, Stoms (1987) discussed examples of knowledge-based systems that are already starting to use various methods of reasoning for specific applications under conditions of uncertainty. He foresees GIS being embedded in decision-support systems of the future to provide decision-makers with measures of reliability of the evidence set before them and of the conclusions they might reasonably draw from that information.

Elmes and Cai (1992) have investigated incorporation of a data quality module in a decision-support system to advise on the management of forest pest infestations. Their view was that such a system should be able to advise non-expert users as to whether the system is capable of meeting their specific requirements. By examining user needs in an introductory online question and answer tutorial, the system would help to determine whether those needs can be met by examining the lineage of the data to be used, the spatial processes to be employed, and the nature of the outputs to be provided. Users would then be presented with a range of measures to portray the uncertainty of their results, including sensitivity analyses, summary statistics, and the range of values that any pixel may possess at any stage in the overall process.

From a different perspective, Beard (1989) has examined the usage of geographical information and suggests that databases might be redesigned to help prevent misuse. Systems could be structured so that validity of mathematical operations may be verified before processing, whereby data resolution and type would be automatically assessed to see if they are appropriate for a given operation. In circumstances deemed to be a possible misuse, users would be given explanatory warnings prior to executing their instructions which, if they choose to override them, would be added as notations to the product lineage report. This approach has the advantage of catering for novice users by acting as an educational tool.

Similarly, Paradis and Beard (1994) have discussed the development and application of a data quality filter for decision-makers which would be embedded in a GIS. It operated by the user initially defining a set of quality requirements relating to lineage, accuracy, consistency, and resolution. With these constraints in place, as a user retrieved data for processing, only those data meeting the specifications were permitted to pass through the 'filter'. The result was displayed and 'encourages users to become intimately involved with their actual data requirements, contemplate trade-offs, define a realistic error budget, and participate in comprehending the effects of a GIS function on a dataset'. (Paradis and Beard 1994: 25)

Finally, Agumya and Hunter (1996) have argued that the uncertainty debate must now advance from its present emphasis on the effect of uncertainty in the information to considering the effect of uncertainty on the decisions which rely on it. In other words, users should be asking 'How good are their decisions?' rather than 'How good is their information?' Accordingly, the authors have proposed a method of assessing the fitness for use of geographical information which aims to determine acceptable levels of uncertainty by analysing the risks associated with decisions based upon use of that information. Through a study of the decision science literature, they have defined 'risk' as 'the probability that an adverse event will result from a decision, multiplied by the cost of that event'. According to their approach (illustrated in Figure 3), for each decision task it is necessary to determine what the uncertainty in the information translates into in terms of the risk associated with that decision.

7 CONCLUSIONS

In this chapter the issue of managing uncertainty in GIS has been discussed. It is recognised that there is now increasing concern amongst data producers, software and hardware vendors, system integrators, and users alike at their inability to deal effectively with uncertainty in their information products. A strategy for managing uncertainty has been presented. This includes: consideration of the significant forms of uncertainty affecting a product; quantitative assessment and communication of this uncertainty; determining what product quality is required and whether the actual quality available is acceptable; and development of techniques for uncertainty reduction and absorption.

While earlier chapters have dealt with the aspects of detecting, modelling, and communicating uncertainty (Beard and Buttenfield, Chapter 15; Fisher, Chapter 13; Heuvelink, Chapter 14), this chapter has primarily focused on uncertainty reduction and absorption. If the quality of an information product fails to meet our needs for the task at hand, then uncertainty reduction must take place – which by and large is a technical issue. On the other hand, when uncertainty reduction becomes either too costly, impossible, or impractical, we must learn to live with what we have and ultimately accept (or absorb) the residual uncertainty. This is usually achieved through institutional rather than technical means. Ultimately, however, it is unavoidable that people and agencies must assume responsibility for their data and decisions.

As for the future, research initiatives are continuing in areas such as 'intelligent' systems (see also Birkin et al, Chapter 51) and data quality 'filters', while answers are also being sought in other areas such as risk management. The complexity of the problem is such that the answers will not all come at once. However, geographical information users are now expecting solutions and it is the task of not just the data producers, but also the software

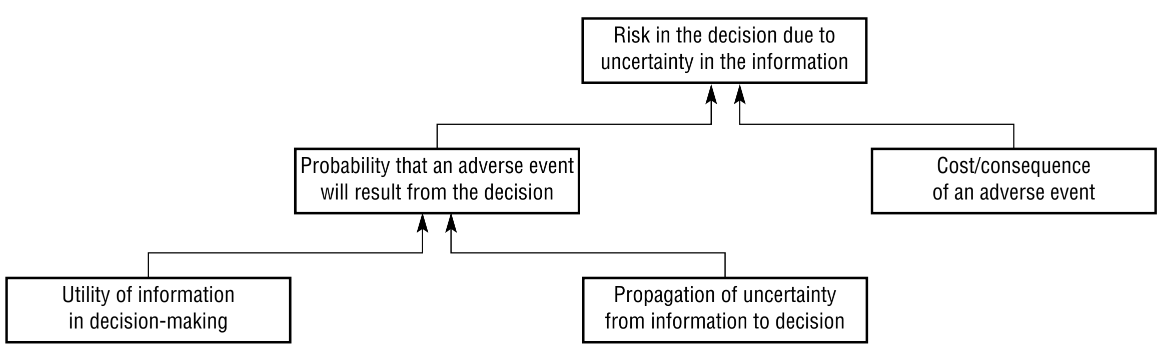

Fig 3. Estimating risk in the decision which is traceable to uncertainty in the information.

and hardware designers, system integrators, researchers, and the users themselves to work together to achieve their common goal.

References

Agumya A, Hunter G J 1996 Assessing fitness for use of spatial information: information utilisation and decision uncertainty. *Proceedings GIS/LIS 96 Conference, Denver*: 359–70

AUSLIG 1992 *Product Specification: Geodata Topo-250K*. Canberra, Australian Surveying and Land Information Group

Barthel K M, Morgan G, Ventura S J 1992 Reliability of geographic information systems for environmental assessment in data poor regions. *Proceedings GIS 92 Symposium, Vancouver*: 1–7

Bassoglu U, Morrison J L 1977 An efficient hierarchical data structure for the US Historical County Boundary Data File. *Proceedings, 1977 ACSM Fall Technical Meeting*: 31–53

Beard M K 1989a Designing GIS to control misuse of spatial information. *Proceedings URISA 89 Conference, Boston* 4: 245–55

Beard M K, Buttenfield B P, Clapham S B (eds) 1991 Executive summary. Scientific report of the specialist meeting on NCGIA Research Initiative 7: visualisation of spatial data quality. *Technical Paper 91–26.* Santa Barbara, NCGIA: iv–v

Bédard Y 1987 Uncertainties in land information systems databases. *Proceedings, Eighth International Symposium on Computer Assisted Cartography (AutoCarto 8)*: 175–84

Blakemore M 1985 High or low resolution? Conflicts of accuracy, cost, quality and application in computer mapping. *Computers and Geosciences* 11: 345–8

Burrough P A 1992c The development of intelligent geographical information systems. *Proceedings, Second European Conference on GIS (EGIS 91), Brussels* 1: 165–74

Burton L L 1989 Analysis of the county level land information system in the State of Florida: user trends and perceived accuracy requirements. *Proceedings GIS/LIS 89 Conference* 1: 348–65

Elmes G A, Cai G 1992 Data quality issues in user interface design for a knowledge-based decision support system. *Proceedings, Fifth International Symposium on Spatial Data Handling, Charleston* 2: 303–12

Epstein E, Hunter G J, Agumya A 1996 Liability and insurance for use of geographic information. *Proceedings URISA 96 Conference, Salt Lake City* 1: 294–301

Hudson D 1988 Some comments on data quality in a GIS. *Proceedings 1988 ACSM-ASPRS Annual Convention* 2: 203–10

Hunter G J, Goodchild M F 1993 Managing uncertainty in spatial databases: putting theory into practice. *Journal of the Urban and Regional Information Systems Association* 5: 55–62

Hunter G J, Goodchild M F 1995a A methodology for reporting uncertainty in spatial database products. *Journal of the Urban and Regional Information Systems Association* 7: 11–21

Hunter G J, Goodchild M F 1996a Communication of uncertainty in spatial databases. *Transactions in Geographical Information Systems* 1: 13–24

Hunter G J, Goodchild M F 1996b A new model for handling vector data uncertainty in GIS. *Journal of the Urban and Regional Information Systems Association* 8: 51–7

Laws D, Gross M, Fabos J 1989 Information resources and public decision-making. *Proceedings URISA 89 Conference, Boston* 4: 160–74

Miller R G, Karimi H A, Feuchtwanger M 1989 Uncertainty and its management in geographic information systems. *Proceedings, Canadian Institute of Surveying and Mapping National Conference on GIS, Ottawa*: 252–60

Moellering H (ed.) 1991a *Spatial database transfer standards: current international status*. Oxford and New York, Elsevier

Nijkamp P, Scholten H J 1991 Information systems: caveats in design and use. *Proceedings, Second European Conference on GIS (EGIS 91), Brussels*, 1: 737–46

Openshaw S 1989b Learning to live with errors in spatial databases. In Goodchild M, Gopal S (eds) *Accuracy of spatial databases*. London, Taylor and Francis: 263–76

Paradis J, Beard M K 1994 Visualisation of spatial data quality for the decision-maker: a data quality filter. *Journal of the Urban and Regional Information Systems Association* 6: 25–34

Prisley S P, Smith J L 1991 The effect of spatial data variability on decisions reached in a GIS environment. In Heit M, Shortread A (eds) *GIS applications in natural resources*. Fort Collins, GIS World Inc.: 167–70

Rejeski D, Kapuscinski J 1990 *Risk modelling with geographic information systems: approaches and issues*. Washington, Office of Information Resources Management, US Environmental Protection Agency

Smith J L, Prisley S P, Weih R C 1991 Considering the effect of spatial data variability on the outcomes of forest management decisions. *Proceedings GIS/LIS 91 Conference, Atlanta* 1: 286–92

Stoms D M 1987 Reasoning with uncertainty in intelligent geographic information systems. *Proceedings GIS 87 Conference, San Francisco*: 693–700