Uncertainty and geographic information: computational and critical convergence

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1 Introduction

The relationship between critical geography and geoinformatics has recently entered a new phase of cordiality and constructive discourse, exemplified by the NCGIA Initiative 19 [27], the Varenius project [21] and a variety of journal special issues on the topic of GIS and society (eg [28]). This new-found entente has opened the way to the re-evaluation of existing GIS-based research and to much closer cooperation between the two disciplines for the exploration of new areas of common interest. Within this context, this chapter represents an attempt to fuse of certain aspects of critical thinking on GIS with the development of new computational approaches to uncertainty in geographic information. Underlying this fusion is the contention that both subjects stand to gain from closer cooperation [41]. Such a fusion may provide a route to a more complete style of GIS-based research, acknowledging some of the important societal issues connected with GIS at the same time as accommodating some of the practical restrictions connected with computational systems.

Amongst the variety of different critiques of GIS surveyed in [42], is the tendency of GIS to promote certain types of representations, or “ways of knowing” [39], over others, for example in the association of GIS with positivist modes of thought [32]. In an attempt to combat such tendencies, John Pickles ([39]) calls for a more collaborative “pluralistic GIS”, representing multiple perspectives and containing conflicting information. Bondi and Domosh [6] highlight the contradictions that arise when GIS ignores the pluralistic and treats geographic information as objective, uncontroversially ‘true’, and free of any context. Similarly, Haraway [26] explores the importance of “partial perspectives” in understanding information. This paper argues that there is some consonance between such critical geography research and current geoinformatics research into uncertainty in geographic information.
2 Uncertainty in geographic information

Some of the more hyperbolic celebrations of GIS offer glimpses of a utopian future built using perfect, global geographic information (eg [1, 25]). In actuality, such visions are not particularly credible for one simple reason: the inherent uncertainty surrounding any information about our geographic environment. The impression of certainty usually conveyed by GIS is at odds with the uncertain nature of geographic information, a contradiction that has been acknowledged as an important research topic for nearly two decades (see [11, 22]). An established body of research in the geoinformatics literature deals with many different aspects of uncertainty in geographic information (see for example [17, 35] for an overview). While the perception that improvements in technology are inexorably moving towards the elimination of uncertainty in GIS is still evident in some geoinformatics and critical geography literature, there exists a clear recognition of fundamental nature of uncertainty in mainstream literature on geographic information (eg [19]).

2.1 Imperfection in geographic information

Uncertainty arises because information about our geographic environments is always imperfect. Specifically, such information is always to some extent imprecise, inaccurate or vague. Imprecision results from incompleteness or lack of detail in information about a geographic environment. As humans we can never observe all the rich detail in our environment. Even with the assistance of measuring instruments, the information produced using those instruments can never completely describe even the physical characteristics of a geographic environment [46]. Further, there is every reason to believe that these unobserved details matter. Work on dynamical systems indicates that even with simple systems, such details can have a profound effect upon the eventual state of a system (see texts on dynamical systems and chaos theory, eg [38]).

Inaccuracy results from incorrectness or error in observations. Traditionally, accuracy has been defined in the statistical sense of deviation of an observation from the ‘true’ value, or some observation ‘taken to be true’. In practice, since such references to truth are highly problematic, accuracy is commonly assessed by comparing observations with an independent data source of higher accuracy. While this weaker definition introduces an “awkward aspect of circularity” [23], it is usually possible to make a subjective assessment of the relative accuracies of different data sets. While unconventional, a more realistic non-circular definition of accuracy is as “the deviation of an observed value from that indicated by an independently derived data set believed to be more reliable”. Our belief in the reliability of a data set is usually founded on the use of more sophisticated instrumentation or because it is known that greater care and attention was taken during data collection. Whichever definition of accuracy you subscribe to, as humans we are certainly prone to make mistakes. While we can again improve our performance using technology and instrumentation, instruments are not infallible either. When they do fail, the resulting information is inaccurate in the sense that it does not accord well with other, more careful observations of our geographic environment. Another important and often ignored source of inaccuracy is the simplifying assumption that our geographic environment is static. Most geographic information is not
explicitly temporal, and as a consequence becomes inaccurate as the dynamic environment changes over time. The most careful observations of a dynamic environment are likely to appear inaccurate if the change over time has not been recorded or accounted for.

Vagueness concerns concepts that exhibit borderline cases, having no clearly defined boundary [31]. Taking “tallness” as an example vague concept, it is usually possible for a room full of people to identify those individuals who are tall and those who are not tall. However, we would expect some borderline cases, where it is simply not possible to determine whether borderline individuals are tall or not tall. Many common geographical concepts are vague [18], such as “near”, “north”, “mountain” and “developing world”. Vague concepts offer particular problems for classical logic, which is ill-equipped to deal with vagueness. It is entirely possible to invent precise definitions of vague concepts. This is commonly attempted in land cover surveys, for example, where vague concepts such as “broad-leaved forest” may be precisely defined according to tree species mix, height of trees, percentage crown cover, total area, etc (see for example [7]). However, such precisifications do not fundamentally address the vague nature of concepts like “broad-leaved forest”. Arbitrarily designating the boundaries of a vague concept is never entirely satisfactory as it quickly leads to absurdity. To illustrate, if our definition of “broad-leaved forest” is dependent on precise thresholds for attributes, such as density of trees, it is entirely possible that minute changes in the geographical environment, for example the germination of one new tree seedling, can cause the classification of an area to dramatically change, in this case from “not broad-leaved forest” to “broad-leaved forest”. This type of behaviour runs strongly counter to most people’s intuition about categories like “forest” and “tall”. This informal illustration is related to the sorites paradox, which has been puzzled over since ancient Greek times (see [9]).

3 Formal models of imperfection

There exists a widening variety of different formal models that are being used to manage and describe uncertainty in geographic information. This section informally introduces several different models and indicates the different interpretations of imprecision, inaccuracy and vagueness that each model can support.

3.1 Stochastic models

By far the most commonly used model of imperfection in geographic information is the stochastic model. Adopting a stochastic model assumes imperfection is the result of random variation. In the stochastic model of imperfection, observations are drawn from a population of possible observations with predictable characteristics under central limit theorem. The mean value of the population is an estimate of the ‘true’ value. Accuracy can be represented by deviation from this ‘true’ value, for example using the root mean squared error (RMSE). Precision can be represented by the spread of observations, for example using standard deviation. There exists no similar common stochastic interpretation for vagueness since the stochastic model assumes phenomena are
essentially crisp and knowable. Adopting a stochastic model of imperfection in geographic information carries the advantage of a well understood theory of natural variation dating back more than two centuries. Modern statistical techniques offer a powerful and sophisticated arsenal of analysis tools that can be applied to great effect.

There is now a significant body of research devoted to the development and understanding of stochastic models of imperfect geographic information. Bivariate statistics are commonly used to model the accuracy of planar spatial objects (eg [15, 34, 43]). Geostatistical techniques can be used provide a detailed stochastic model of the inaccuracy and imprecision of field-based geographic information (eg [29, 30]). Nevertheless, while the stochastic model offers a highly sophisticated and detailed model of certain types of imperfection, it depends on highly sophisticated and detailed assumptions that often require considerable effort to maintain. For example, the assumption of statistical independence in the stochastic model is commonly violated by spatial autocorrelation in geographic information. As a result, more flexible models of imperfection are often needed.

3.2 Fuzzy set theory
Interest in the application of fuzzy set theory to imperfection in geographic information has steadily grown over the past two decades. In classical logic, elements are classified as either in or out (Boolean truth values true or false) of a particular set $X$. In a fuzzy set, each element is identified with a real number from the interval $[0,1]$ that describes the degree of membership of that element to the set $X$.

Unlike stochastic models, fuzzy set theory naturally lends itself to a vague interpretation as well as inaccurate and imprecise interpretations. Fuzzy set theory has been successfully used, for example, to describe the accuracy of land cover classifications [24, 47]. Similarly, imprecision in geographical boundaries (eg [3, 33]) and vagueness in geographic objects (eg [45]) and map classifications (eg [36]) have all been tackled using fuzzy set-based interpretations.

While fuzzy set theory can be used to model vagueness, imprecision and inaccuracy, difficulties remain. Most importantly, the assignment of fuzzy membership values is not clearly understood [31]. Attempts have been made to map observations to fuzzy membership values using linguistic values (eg [24, 33]) or cluster analysis, a technique called fuzzy k-means (see [8]). However, the assignment of fuzzy membership values is always to some extent subjective, a feature often regarded as weakness in the application of fuzzy set theory. At the same time, this interface between the formal and subjective makes fuzzy set theory particularly interesting to some critical theorists.

3.3 Three-valued logic
In contrast to sets in classical set theory (often termed crisp sets), three-valued logic classifies elements as either in, out or indeterminate members of a set $X$. One of the commonest three-valued logical systems is rough set theory [37]. A rough set comprises a lower and upper approximation. Informally, the lower approximation $\bar{Z}(Z)$ contains all those elements that are definitely in the set $Z$. 
The upper approximation $\overline{S}(Z)$ contains all those elements that are possibly in the set $Z$.

Rough sets can assume a variety of interpretations, including inaccuracy, imprecision and vagueness [13]. Rough sets have been used to model imprecision in the spatial and semantic components of geographic information [48] and to address accuracy issues in thematic spatial information [2]. Rough sets are commonly used in a vague interpretation, for example when applied to perception of vague concepts such as nearness [14, 49]. However, rough sets are not the only possible three-valued logic. Another three-valued logic might be constructed from a fuzzy set, where membership values were restricted to three values $\{0, 0.5, 1.0\}$, for example. Worboys and Clementini [50] describe a variety of different three-valued logics tailored deal with the integration of information exhibiting particular imprecision, inaccuracy and vagueness characteristics. Three-valued logic has the advantage of simplicity, but may not be sophisticated enough to provide an adequate model of imperfection in many cases, especially when compared with the stochastic model.

### 3.4 Alternative logical models

While the stochastic model, fuzzy set theory and three-valued logics are the commonest formal models of imperfect geographic information, there exists a relatively rich literature of alternative logical models that might equally be applied to problems of reasoning with imperfect spatial information. For example, three-valued logics are themselves one class of multi-valued logics. Roy and Stell [40] explore the application of three-, four-, and six-valued logics to uncertainty in spatial regions. The truth values of these higher-valued multi-value logics form a rich variety of lattice structures that support a range of expressive interpretations.

A different approach is the application of supervaluation theory [16]. Supervaluation is an attempt to retain some of the power of classical logic, at the same time addressing some of the difficulties presented to classical logic by vague concepts. For example, in classical logic $P \lor \neg P$ is a tautology, commonly known as the principle of excluded middle. In many non-classical logics, such as rough set theory described above, $P \lor \neg P$ is not tautologous and as a consequence we lose some of classical logic’s powerful mechanisms for consistency checking. One way to address this problem is to weaken classical logic, decreasing the range of inferences that can be made from a statement. This is the approach taken in paraconsistent logics [5]. Supervaluation takes a different approach and provides a framework with which to discuss the classical truth or falsity of statements across sets of specifications. Each specification can be thought of as a different (classical) universe. A statement that is true in all possible universes is said to be super-true, while one that is false in all possible universes is super-false. Thus, within a particular specification, classical logic holds and $P \lor \neg P$ is a tautology, even though across many specifications a statement may be neither super-true nor super-false. Bennett [4] describes how supervaluation semantics can be applied to resolve some of the difficulties posed by vague geographic phenomena such as “forest”, while other interpretations of supervaluation theory are entirely feasible.
4 Imperfection and computation

The discussion above provides a flavour of the rich diversity of different formal models that can potentially be applied to imperfection in geographic information. It is evident that there is no single formalism can claim to offer a complete view of imperfection, to the exclusion of all others. Further, it seems likely that no single model can be discarded out of hand: each model has its strengths and weaknesses. Consequently, a forward step in the development of GIS would be to specify a computational framework able to allow the integration of these various models. Such integration is possible by recognising that the reason for applying many of the different formal models is to be able to resolve inconsistencies in observations.

4.1 Inconsistency in observations

The common theme underlying the diverse formal models of imperfection in geographic information discussed above is that they are used as mechanisms for resolving inconsistency in observations. For example, figure 1 illustrates the relationship between inconsistent information and the stochastic model of imperfection. In attempting to determine the location of the point feature four different observations are made. These observations are related in that they are all observations of the location of the same feature. They are inconsistent in that not all the observations are in agreement. The stochastic model can be used to resolve this inconsistency by assuming that any inconsistency is as a result of natural variation. In a GIS, this would usually translate into storing not the underlying inconsistent observations, but instead the derived characteristics of the population from which the inconsistent observations were drawn, ie the mean (‘true’) location and some measure of spread, such as the standard deviation or the size of the 95% confidence interval.

In a similar way, other formal models are used to provide a single consistent representation of inconsistent observations. For example, figure 2 (after [50]) shows two different inconsistent observations of a spatial region, such as a forest. For clarity, these two observations have been drawn disconnected,
but they are intended to be partially overlapping. Combining these two observations using three-valued logic semantics results in a region with a broad boundary. The dark coloured core of the resulting region contains those locations which were forest in both the original observations and so is definitely part of the forest (the lower approximation of the forest $\overline{S}(\text{Forest})$). The lighter shaded penumbra contains those locations which were in one or other but not both of the observations. The penumbra plus the core forms the region which is possibly part of the forest (the upper approximation of the forest $\overline{S}(\text{Forest})$). Everything outside the upper approximation is definitely not part of the forest.

![Figure 2: Rough set model of inconsistency](image)

Within both GIS and databases more generally, inconsistency is usually resolved or eradicated at the earliest opportunity, and the underlying observations are discarded. The development of relational database systems set particular store by consistency issues [12]. Over recent years, the growth in usage of object-oriented (OO) databases, modelling and software development techniques has in part been due to the improved support for consistency afforded by OO systems. Unfortunately, the information transformations used to resolve such inconsistency are commonly unidirectional. It will not usually be possible to deduce the original inconsistent observations after the inconsistency has been resolved (ie, we cannot travel against the direction of the arrows in figures 1 and 2).

In the light of this, it makes sense to consider developing database systems able to support inconsistent information, alongside the functionality to derive multiple realisations of that information using a range of different models of imperfection. A number of authors have already highlighted the importance of the retention of original surveyed observations in data quality management (eg [29]). The concept of a *measurement-based GIS* has been proposed as a system capable of storing these possibly inconsistent surveyed observations and resolving any inconsistency on-the-fly using automated survey adjustment techniques [20]. Along the same lines, the more general concept of a *consistency-based GIS* should be able to store inconsistent geographic information as well as provide various mechanisms based on the formal models described above.
in order to derive multiple consistent realisations of that information. Such a consistency-based GIS would have several advantages from a computational perspective:

- Parsimony: no information is discarded by the system, so information loss is minimised.
- Multiple-realisations: multiple different realisations of the stored information can be generated based on different formal models applied to the inconsistent information in the database.
- Context sensitivity: by retaining all available information it is possible to produce different on-the-fly realisations of the inconsistency suited to a particular user’s context.
- Updates: new information can be more easily added to the database, and revised realisations generated in the light of this new information.

Arguably the most important of these from a computational perspective is the information loss associated with premature resolution of inconsistency [10].

5 Computational and critical convergence

The discussion so far has attempted to provide an overview of current work on uncertainty, and outline some of the reasons why access to a range of formal methods for dealing with inconsistency is increasingly important. While this discussion has adopted a primarily computational perspective, there exist clear areas of commonality between the computational aspects of uncertainty and the issues of concern within critical geography, such as context and partial perspectives (section 1).

By representing and reporting imperfections in geographic information as opposed to simply trying to remove imperfections, geoinformatics researchers are deliberately trying to provide a form of context for geographic information. Using any of the formal models of imperfection described in §3 it is possible to communicate both knowledge about a geographic environment and meta-level contextual information about the status of that knowledge. While such formal models are still limited to the representation of quite specific types of context, they can at the very least indicate to users that the information to which it refers is not meant to be entirely ‘truthful’ or ‘objective’. In turn, users have more opportunity to form a personal opinion on their certainty in information.

The discussion in §4.1 argues that there are clear computational reasons for wanting to take this context a step further. By adapting GIS architectures to allow the storage and manipulation of inconsistent information should increase the flexibility of the system and minimises loss of valuable information. While motivated by computational concerns, the idea of using rather than simply resolving inconsistency in GIS is an implicit acceptance of conflict and difference. Developing such a GIS able to operate using inconsistent information would seem to be a first step on the road to pluralism and the inclusion of diverse partial perspectives into the way we use geographic information.
While inconsistency can be related to diversity, the production of a single, consistent, consensual view of geographic information remains central to many computational, logical and decision making processes. A consistency-based GIS aims to provide the functionality to resolve inconsistency and produce consistent realisations of information when necessary. Currently this task is performed on behalf of the GIS user, usually by the data producer or surveying organisation that captured the data. The uni-directional nature of the information transformations represented in figures 1 and 2 effectively “locks in” one model of uncertainty with the data. Providing users with the mechanisms necessary to perform these transformations for themselves enables users to construct multiple consistent realisations of information, using different formal models. In turn, this may help users achieve a greater understanding of the characteristics and limitations of a data set.

At the same time, particular users or applications may require particular models of uncertainty. Some models, such as fuzzy set theory, offer much greater room for the inclusion of subjectivity. Others, like the stochastic model, are much more prescriptive. With a consistency-based GIS, there is no need for the generic “one-size-fits-all” approach to uncertainty common in contemporary geographic information provision (for example, simply providing a global RMSE value with digital elevation model). Users can select which model(s) of uncertainty are appropriate to their particular expertise, application or preferences.

The ideas put forward do not require revolution in geoinformatics, nor do they suggest that critical geographic thought is without relevance to GIS. Indeed, it is highly unlikely that the reinterpretation of existing technology sketched in this paper would be radical enough to satisfy many of the more strident critics of GIS. Rather, this paper is an attempt to draw out some of the links between the two disciplines. Sieber [44] argues that the relationship between GIS and grass roots organisations needs to be re-examined to account for the sometimes beneficial as well as detrimental conforming effects of GIS. At the same time, grass roots organisations may be able to effect their own upon the GIS technology in accordance with their own objectives. In a similar vein, this paper has argued that some of the levers needed by critical geographers to influence the future development of GIS already exist, and are waiting to be pulled. Working with existing research trends in computation and geoinformatics may enable critical geography to be much more effective in the directing that development in the future.

References


