

An Operation-based Communication of Spatial Data Quality

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Abstract— Improving users' awareness of the imperfections in spatial data has been a research issue explored within Geographic Information Sciences (GIS) for more than 30 years. However, little practical progress has been made toward this objective. Currently, most spatial data producers document information about spatial data quality as part of metadata. However, this information remains largely ignored by GIS users, which leads to the risk of users making poor decisions based on spatial data. As users increasingly make use of various GIS functionalities, GIS still lack the necessary mechanisms to effectively warn the users of the existence of quality issues in the spatial data being used. This becomes even more problematic in a web environment where data and services of unknown qualities can be shared and combined in the same application. In this paper we present an approach which aims at improving the use of quality information by providing it to the users in a more efficient way than existing approaches used for consulting metadata. We use an operation-based approach to link data quality information to the individual operations used in GIS applications. A conceptual framework for associating quality information with GIS operations is presented. Then, a prototype implementing this concept into a GIS software is described and discussed.

Index Terms— Spatial data quality, GIS operations, GIS applications, Communication of spatial data quality, Risk

I. INTRODUCTION

THE endemic presence of uncertainty in spatial data can undermine the reliability of decisions based on GIS analyses (e.g. [29]). Such uncertainty, that can result from a number of causes (e.g. data acquisition techniques used, human error, simplification done by the data model) has been a major concern among the researchers in the field of GIS. In order to help GIS users avoid or reduce undesired consequences of using “imperfect” spatial data, users should be made aware of the quality of spatial data [7, 26, 33]. Improving awareness about data quality (or, quality-awareness) in GIS has received increasing attention in the research community (e.g. [21, 42, 45]).

Since the first warnings about the potential impacts data uncertainty can have on decisions (e.g. [11]), early developments towards the improvement of quality-awareness in GIS has been mainly implemented through the publication

and implementation of a number of metadata standards (e.g. [23, 24, 37]). At the same time, the scientific community has improved its understanding of spatial data uncertainty and how it relates to decision-making (e.g. [15, 26, 27]).

Improving quality-awareness within GIS is currently studied from various perspectives, including a) improving current models for documenting spatial data quality by developing a comprehensive and flexible structure for organizing and reporting quality information [27, 45], and b) developing tools for improving the usability of quality information through improved management and communication [17, 21, 45].

However, these approaches only provide a partial solution to the problem and have not yet led to any implementation in commercial GIS software. Hence, they have been of little practical help to end-users. The only step GIS software have done in this direction is their recent ability to manage metadata (e.g. in ArcGIS ArcCatalog), as those metadata can include some information about data quality that can be consulted by GIS users. Furthermore, the increasing availability of online GIS data and services is likely to increase the risk that GIS users - particularly the novice ones, “misuse” the data.

One specific problem that has been raised is the loose association that exists between the documented data quality information and the actual manipulation of the data for a given application [39, 49]. Accordingly, users fail to relate the documented quality information to their individual applications of spatial data.

The objective of this work is to conceptualize and design a new approach to improve the usability of spatial data quality information in GIS applications by increasing the interaction between the data quality information stored in metadata and GIS operations.

The remainder of this paper is organized as follows: Section II provides a short review of the literature related to the modeling and communication of uncertainty and spatial data quality in GIS. In Section III, we look at spatial data quality information and GIS operations and how they can be connected. In Section IV, we present a framework for communicating quality information based on GIS operations. Section V presents a prototype implementing the concepts into a commercial GIS software. In Section VI, we discuss the results obtained by this work and conclude in the section VII.

II. UNCERTAINTY AND QUALITY IN GIS

Reference [34, p. 36] defines spatial data uncertainty as “the lack of knowledge of the true value or the value that would be discovered if one were to visit the field and make an observation using a perfectly accurate instrument”. Reference [27] classifies uncertainty into three types: error, vagueness and ambiguity. Error is the difference between a data value and the ideal, true value [1], such as an inaccurate recording of tree-heights. Vagueness arises in the case of “poorly-defined” objects [27], such as a “mountain” which may lack well-defined extents [47]. Finally, ambiguity occurs when doubt exists as to how a phenomenon should be classified, as conflicting perceptions of that phenomenon may exist [27]. Examples of ambiguity include the mapping of territories disputed by neighboring countries (as a case of *discord*), and the lack of sufficiently-detailed categories, such as in soil classifications where classes may fall between two or more larger classes (as a case of *non-specificity*) [27].

Uncertainty affects the quality of spatial data. It can be associated with the three basic dimensions describing spatial data: the spatial, temporal and thematic dimensions [6, 30, 40].

Since the 1980s, spatial data quality information has been increasingly documented using national or international metadata standards (e.g. [23, 24, 37]). This practice even became mandatory in 1994 for US organizations getting federal funding [13].

Data quality is typically documented under five to seven quality elements [17], the five most famous being: spatial accuracy, thematic accuracy, logical consistency, completeness and lineage [19]. These elements can be defined as the following [38]: positional accuracy represents the accuracy of the position of features; Thematic accuracy represents the accuracy of quantitative attributes and the correctness of non-quantitative attributes, in addition to the classification of features and their relationships; Completeness describes the presence, or absence of features and their attributes and relationships; Logical consistency represents the degree of adherence to logical rules of data structure, attribution and relationships; Lineage describes the history of a dataset, recounting the dataset’s life-cycle from collection and acquisition through compilation and derivation to its current form.

Although now fairly widely implemented, metadata standards used for documenting data quality have been argued to be limited in their usefulness. Criticisms relate, to only name a few, to the fact that a) standards emphasize only on error, avoiding ambiguity and vagueness [27], b) users are unfamiliar with the technical terminology used in the standards [9, 35] and c) quality reporting is confined to a predefined structure [1, 5, 43]. While there have been efforts to address these shortcomings, studies such as [17, 36, 41, 44, 45, 46] have on the other hand focused on improving the management and communication of spatial data quality information. As suggested by [45], improving the usability of quality information in GIS is hindered by the lack of

appropriate tools that would effectively manage, or “store, manipulate, query, update and display” quality information ([45], p. 230). According to [16], the creation of such tools should permit improved management and communication of spatial data quality, leading to an improved usability of spatial data. Prototypes of such tools have been developed by [10, 17, 20, 36]. For instance, the tool developed by [36] provides users with an interface that displays quality information using different visualization techniques (cf. Fig. 1).

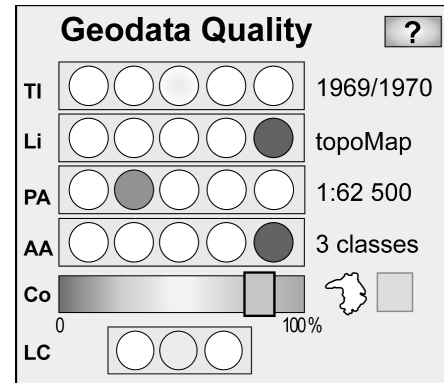


Fig. 1. Visualization of spatial data quality information by Huth et al [36] using traffic lights and a quality slider (TI: temporal information, Li: lineage, PA: positional accuracy, AA: attribute accuracy, Co: completeness, LC: logical consistency)

III. GIS OPERATIONS AND SPATIAL DATA QUALITY

Currently, with the absence of appropriate tools, the only mechanism by which users can assess if the quality of their data is appropriate for their application is to access the metadata stored separately from the data, go through them, find the relevant metadata for the task at hand and then try to understand how it can impact the analysis they intend to perform. If this is technically possible, most users don’t do it [2] and those that attempt to do it often fail to locate the information they are looking for in the metadata or fail to understand the technical terms used to present them [9]. This current inability to associate quality information with users’ tasks and applications limits the overall usefulness of quality information.

The tasks users perform using GIS software typically involve a number of different operations (or *services* in the context of distributed GIS). According to [48], a task, such as a site selection, can be modeled by a sequence, or *chain*, of operations. The concept of chaining GIS operations and services to perform applications has been a recurring theme in the GIS literature (e.g. [3, 4, 28, 30]). Depending on the application, operation chains may include several operations acting as building blocks to carry out the intended task. Spatial data entering this chain are “transformed” [12], leading to an output.

Having GIS applications composed of different operations is an approach that has been used for modeling how errors propagate through a sequence of GIS operations [40]. As such, modeling the uncertainty that results from empirical GIS

operations has been the focus of a number of studies related to error-propagation, error-modeling and sensitivity analysis (e.g. [14, 31, 50]). Individual models have been developed for computing the error resulting from certain GIS operations, such as the viewshed analysis [25] and the overlay operations [50, 51]. Developing error-propagation models for GIS operations is however an ongoing research and is yet to produce comprehensive methods to determine the error resulting from a larger number of GIS operations [32].

If available, error propagation models could provide the users with an estimate of the error in the output of an operation. While research on such models is pursued, other approaches have been proposed for improving the usability of spatial data quality information. As described earlier, users may be provided with tools and interfaces improving the communication of spatial data quality [17, 36]. Such approaches can alert the users to problems with the data prior to performing an operation. The same approach could be used to improve users' awareness of data quality at the time they are using GIS operations. As such, improving quality-awareness through GIS operations involves associating mechanisms developed earlier for improving the communication of quality information [17, 21, 45] with GIS operations. In this regard, [8] suggested to link spatial data quality information with GIS operations to increase awareness of quality information when using GIS. They called for the identification of a set of rules for linking data quality information to GIS operations.

Works such as [30] can help in defining a conceptual association between quality information and GIS operations. Reference [30] discusses the effects of GIS operations on uncertainty in each of the underlying dimensions of spatial data: spatial, temporal and thematic dimensions. Since no spatial data are perfect, these three dimensions are inherently uncertain to variable degrees. Once used by a GIS operation, the uncertainty in each dimension can be altered. The resultant uncertainty in each dimension is asymmetrically affected depending on the type of the operation performed [30, 40]. For example, if an operation relates primarily to the spatial dimension (e.g. distance measurement) the resultant uncertainty would be primarily on this dimension. Therefore, the different spatial data quality dimensions, which comprise quality information, relate to GIS operations in terms of applicability and magnitude.

The next section focuses on the conceptual architecture of a system that can link data quality information with GIS operations.

IV. LINKING GIS OPERATIONS AND SPATIAL DATA QUALITY

Current GIS operate under the assumption that the input data are perfect and that GIS operations are not impacted by the quality of the data. In other words, they do not consider data quality in their functioning, even when it is documented in the metadata and stored by the same software. This typically leads to aberrations such as allowing a user to measure a distance between two objects on a map and get the

answer in meters with a precision of six decimals (i.e. micrometers), while the spatial accuracy recorded in the metadata stored by the same software clearly state that the data are accurate at $\pm 50\text{m}$. Fig. 2 presents a simplified view of how GIS software perform operations. As illustrated, the metadata describe spatial data, including their quality (link ①) and the spatial data are used by GIS operations (link ②). Link ① may be carried out by using a sub-system for consulting metadata (e.g. ArcCatalog in ArcGIS) or by having users directly read the text within metadata files. Link ② largely represents the process of specifying the input data in an operation's interface. Therefore, as illustrated in Fig. 2, while a direct link exists between spatial data and the two other components (metadata and GIS operations), metadata, and thus quality information, are not directly accessed by GIS operations. The absence of a connection between GIS operations and quality information has been illustrated by the dashed line in the Fig. 2.

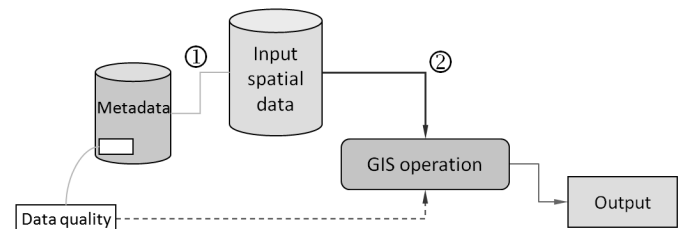


Fig. 2. Process of consulting quality information when using a GIS operation. The user would locate the quality information related to the operation through the connection between spatial data and their metadata (link ①).

Existing literature on uncertainty propagation could help creating the missing link between quality information and some GIS operations. According to [12], GIS operations “transform” the geometric and/or thematic dimensions of spatial data. With the addition of the temporal dimension to the geometric and thematic dimensions, the quality of these two dimensions is undermined to varying degrees when used by an operation (cf. Section III). For example, the output from the “select by attribute” operation is mainly affected by the quality of the thematic dimension of spatial data, while a “distance measurement” operation is mainly affected by the quality of the spatial dimension.

Using such an approach can allow to link the applicable quality elements to the right GIS operations, with the possibility to assess the magnitude of this link (e.g. state that positional accuracy has more impact than logical consistency on a distance measurement). Such an assessment of the magnitude would require further research in error-propagation, while the relevance of each quality element for a given operation is simpler to assess. Such an approach has been mentioned by [22] which states that expert systems could provide rules. An example of such rule is “positional accuracy can only apply to geometric information” (pp. 185-186). Such rules could be extended to state which quality elements apply to which GIS operations. For example, a distance measurement operation may be impacted by issues with

positional accuracy, completeness and logical consistency, while lineage is not immediately applicable and thematic accuracy would not be considered at all (cf. Table 1).

Table 1. Examples of GIS operations and the related quality elements

Quality element \ Operation	Distance Measurement	Select by Attribute	Select by Location
Positional accuracy	X		X
Thematic accuracy		X	
Lineage			
Completeness	X	X	X
Logical consistency	X	X	X

V. A PROTOTYPE FOR COMMUNICATING SPATIAL DATA QUALITY THROUGH GIS OPERATIONS

In this section, we present the implementation of the system described conceptually in the previous sections. A prototype has been developed in Visual Basic in ESRI ArcGIS 9.2 using a 1:50,000 scale topographic map provided by Geomatics Canada and an XML metadata file following the recent North American profile of the ISO-19115 metadata standard. The implementation has been done on the existing operation in ArcGIS “MEASURE”, which is used for measuring the distance between objects on the ArcMap interface.

The development of this tool is based on two modifications related to GIS operation: a) extending the operation’s code to include instructions for accessing the appropriate spatial data quality and b) creating a database indicating which quality elements apply to which operation (see Fig. 3). The original code of the MEASURE operation has been obtained from the ESRI ArcScripts website¹. Once modified, the newly developed tool (i.e. the quality-aware MEASURE operation) could be added to the ArcMap interface, performing the regular distance measurement as well as communicating the related spatial data quality. The steps by which the tool performs these two tasks are described in following.

The extended code is activated when an operation is executed by a user. Steps ① to ③ of Fig. 3 present the regular use of a GIS operation where a user selects the operation (①), specifies the input dataset (②) and the operation returns the results to the user after the data have been processed by the operation’s code (③). In the modified version of the operation, the operation continues by accessing the database storing the applicable quality elements for the given operation (④ and ⑤) and returns the list of elements to the program (⑥). Based on the list, the extended operation then retrieves the values of each of the quality elements from the metadata (⑦) and displays them to the user in a quality report (⑧, see Fig. 4).

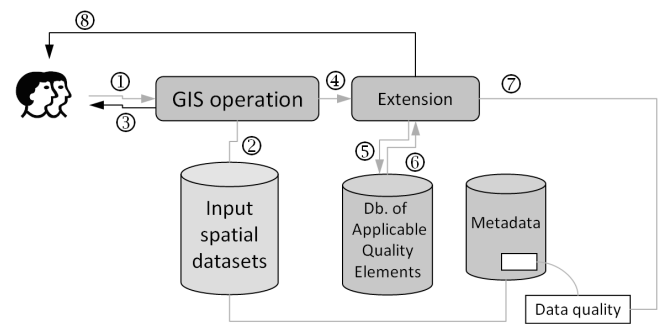


Fig. 3. Modifications made to GIS operations

The display of the quality report provides the GIS user with each of the applicable quality elements (left side of the figure) for each of the datasets involved (right side of the figure). For example in Fig. 4, the user is provided with the positional accuracy information for each individual layer ($\pm 10m$) which results in an overall error of $\pm 20m$ in the measurement.

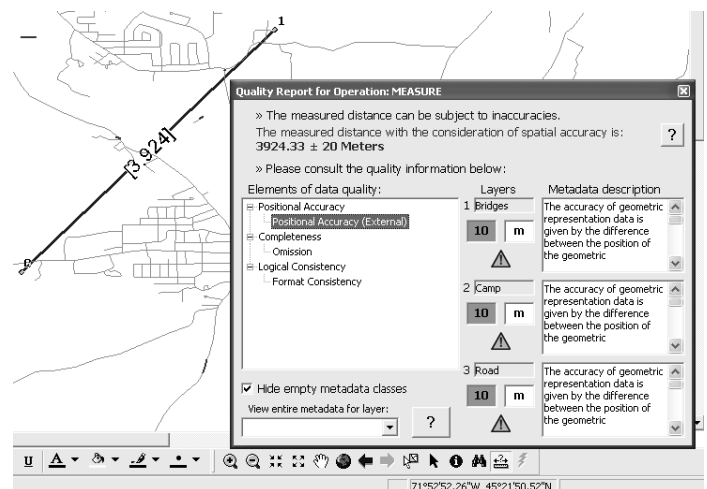


Fig. 4. Quality report provided to the user. When measuring a distance, users are directly provided with the relevant information about positional accuracy, completeness and logical consistency.

VI. DISCUSSION

The usefulness of the conceptual framework developed in this work and its implementation into a GIS software may be discussed by comparing it to previous approaches that share similar objectives. Compared to previous approaches, the following advantages and disadvantages can be attributed to the operation-based approach presented in this paper.

First, basing the communication of data quality information on GIS operations can be an effective way to relate data quality information to users’ applications. Compared to previous approaches that provide a separate sub-system for communicating quality information (e.g. [17, 36]), this approach communicates relevant quality information simultaneously with the execution of GIS operations. As such, if GIS operations are viewed as the building blocks of GIS tasks and applications [48], then improving users’ awareness of quality in GIS operations should in turn improve user’s awareness of quality while they carry out GIS applications.

¹ <http://arcscripsts.esri.com>

Second, compared to previous approaches for communicating data quality (e.g. [18, 36]), basing the communication of quality information on GIS operations can reduce the number of quality elements communicated to those immediately applicable to the operation and thus prevent the user from an overload of information. For example, for the case of the MEASURE operation, the number of quality elements was reduced from five to three.

The approach developed still presents a number of limitations that would deserve attention in further studies. The prototype used basic capabilities for visualizing uncertainty, such as changing the color of some elements of the report, depending on the level of uncertainty (cf. Fig. 2). More advanced visualization techniques used in interfaces developed by, for instance, [17, 20, 36] (cf. Fig. 1) could be considered for future work. Also, when using this approach, users may be unaware of the magnitude of the effects of the different quality elements involved in the operations. As such, it would be useful to provide users with a ranking of quality elements for each operation, based on their importance for the given operation.

In order to confirm the usefulness of the approach for GIS users, 25 users have been asked to complete a test that asked them to go through a scenario using a standard GIS operation and then using the modified operation. All the participants noted an increased awareness of data quality when using the quality-aware version of the GIS operation.

VII. CONCLUSION

This paper presented an approach that facilitates the consultation of spatial data quality information within GIS operations in order to make GIS users more aware of potential risks related to the use of spatial data. This goal is achieved by directly connecting GIS operations to the relevant spatial data quality information stored in metadata. The approach requires an expert to identify the data quality elements relevant for a given application and then stores this information into a database. Once this database has been created, the system can be automated without requesting any input from a GIS expert. This database can then be queried by GIS when users activate an operation, gathering and displaying the relevant metadata to the user. A prototype was developed to demonstrate how this concept can be used for communicating relevant quality information within GIS software. This study provided an approach that can have implications on existing sub-systems developed for communicating quality information (as they are not based on GIS operations), as well as enabling the development of new and more robust tools for communicating quality information based on GIS operations.

This research addressed the general objective of improving the use of data quality information by linking spatial data quality to the use of the data. While the study of error-propagation through GIS operations currently remains a research challenge, this approach is a step forward towards a more proactive awareness of data quality information in GIS operations. Different aspects of this work would deserve to be

explored further. This includes applying frameworks such as the Geographic Activity Models (GAM) [48] for further connecting spatial data quality to user tasks and applications using GIS operations.

ACKNOWLEDGMENT

The Natural Sciences and Engineering Research Council of Canada (NSERC) and the Memorial University of Newfoundland (MUN) are acknowledged for funding this research. Dr. Jean Brodeur of the Centre for Topographic Information of Sherbrooke (CIT-S), Natural Resources Canada (NRCan), is acknowledged for providing the metadata used for the prototype. We also thank Dr. Gary Hunter and two anonymous reviewers for their comments on the manuscript.

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