Perceptions of Digital Elevation Model Uncertainty by DEM Users

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Abstract: *A survey of digital elevation model (DEM) users was conducted to investigate how respondents use elevation data and how they perceive and address DEM uncertainty arising from unknown error in the elevation data. The information reported here is based on 216 survey responses received between June 4, 1998 and June 4, 2000. DEM users from 26 countries and various organizations and industries participated in the survey. Half of the respondents recognized that their work is "sometimes" or "always" affected by uncertainty, and 55% indicated that uncertainty is "very important" or "somewhat important." Respondents reported that they would spend a minimum amount of time to assess DEM uncertainty. The methods used by the small group of respondents who "always" account for uncertainty (21%) were varied. There does not appear to be consistent procedures for addressing uncertainty among the community of DEM users. The effects of DEM uncertainty should be explicit, and procedures for addressing it should be consistent so that conclusions from DEM-based analyses take uncertainty into account.*

Introduction

The digital elevation model (DEM) is a computer representation of the earth's surface; it provides a base dataset from which topographic parameters can be digitally generated. The routing of water over a surface is closely tied to surface form, and hydrologic features are often extracted from DEM data. DEMs are used to perform cost analyses and view shed analyses for resource management as well as business applications. The DEM is a model of the elevation surface and, like other models, the data are subject to error. Error is the departure of a measurement from its true value. In geographic analyses that use spatial data, we often do not know or do not have access to the true value. Our lack of knowledge about the reliability of a measurement's representation of the true value is referred to as uncertainty. DEM errors are elusive and constitute uncertainty.

DEMs have broad applications, are used in many domains, and are an important component of decision making. Users of DEMs bear a professional responsibility to assess their contributions to such decision making efforts. To make such assessments, users must first be aware of the impact of DEM errors. This survey was designed to identify users' awareness of DEM uncertainty and determine their willingness to address it. Specifically, the survey identifies DEM users, uses of DEMs, whether these users are aware of DEM uncertainty, and whether the users perceive that uncertainty affects their DEM applications.

Background

Digital Elevation Models

DEMs represent elevation data and are the principal digital data source for slope and aspect map coverages used in geographic information system (GIS) analysis for resource management. Elevation data can be represented digitally in many ways including a gridded model (where elevation is estimated for each cell in a regular grid), a triangular irregular network, and contours. There are many types of DEM products. The United States Geological Survey (USGS) collects and processes elevation data and distributes it in digital formats. USGS DEM data are available in many different forms that vary in horizontal and vertical resolution as well as accuracy. Highest resolution DEMs correspond to data contained in USGS 7.5-minute quadrangles at 1:24,000 scale with a resolution of 10 or 30 meters. The USGS also provides 15-minute DEMs for Alaska that correspond to 1:63,360 scale plural quadrangles, 2-arc-second DEMs that correspond to one half of 1:100,000 scale maps (available for the contiguous United States and Hawaii), 1-degree 3 by 3-arc second DEMs that correspond to 1:250,000 scale maps (available for the entire United States), global 30-minute DEMs with 1-km2 resolution (GTOPO30), and global 5-minute resolution DEMs (ETOPO5). Numerous other vendors also provide DEM products. Conventional synthetic aperture radar (SAR) is used to produce high-resolution imagery from either aircrafts or space. DEMs can be derived from the photogrammetric SAR images (Maune 2001). There are many private vendors of DEM data such as SPOT Image, which produces DEMs from orthoimagery (Spot Image Corporation 2002). In many situations DEMs are not available or an even higher resolution of DEMs is required by researchers. In these situations, researchers often generate their own DEMs from surveyed or digitized elevation points.

Sources of possible error in DEM datasets include: (1) data errors due to the age of data, incomplete density of observations, or results of spatial sampling; (2) measurement errors such as positional inaccuracy, data entry faults, or observer bias; and (3) processing errors such as numerical errors in the computer, interpolation errors, or classification and generalization problems (Burrough 1986, Wise 1998).

All DEMs have limitations based on production methods and the data from which they were derived. For example, elevation values in USGS DEMs (and potentially other DEM products) are subject to three types of errors: blunders, systematic errors, and random errors. Blunders are vertical errors associated with the data collection process and are generally identified and removed prior to release of the data. Systematic errors are the result of procedures or systems used in the DEM generation process and follow fixed patterns that can cause bias or artifacts in the final DEM product. When the cause is known, systematic bias can be eliminated or reduced. Random errors remain in the data after blunders and systematic errors are removed (United States Geological Survey 1997).

DEM vendors generally provide users with a measure of vertical accuracy in the form of the root mean square error (RMSE) statistic. The RMSE encompasses both random and systematic errors introduced during data production. The RMSE is expressed as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (y_i - yt_i)^2}{N}} \qquad (1)$$

where: y_i refers to the ith interpolated elevation, y_{ti} refers to the ith known or measured elevation of a sample point, and N is the number of sample points. The RMSE for USGS DEMs is calculated by comparing the DEM with 28 elevation points that reflect the "most probable" elevations at those locations, not actual elevations. [In a 30-meter USGS DEM, there are approximately 161,355 elevation values; the 28 verification points used for calculating the RMSE constitute 0.017% of the dataset.] The RMSE expresses the degree to which interpolated values differ from these true values. True elevations are the "most probable" elevations and do not always reflect actual elevations. These test points are obtained from field control, aerotriangulated test points, spot elevations, or points on contours from existing source maps (United States Geological Survey 1997). The RMSE can also be calculated for a particular DEM if data of higher accuracy (such as that obtained from a global positioning system (GPS) or total station survey) are available.

The RMSE, while a valuable quality-control statistic, does not provide the DEM user with an accurate assessment of how well each cell in the DEM represents the true elevation. It provides only an assessment of how well the DEM corresponds to the data from which it was generated. This is currently the only value provided to DEM users as an indication of DEM quality. The impact of uncertainty on results from DEM analyses is difficult to quantify.

Digital Elevation Model Error

Errors in spatial data (e.g., incorrect elevation values assigned to a point) are spatially autocorrelated (Ehlschlaeger 1998). For example, an error in a surveyor's benchmark measurement will affect resulting elevation values developed from that point. This spatially dependent error is unknown, thus uncertainty regarding this error is spatially dependent. This can create systematic errors in DEMs and poses a problem for non-spatial statistical methods used to define map accuracy that do not directly incorporate spatial autocorrelation of uncertainty (such as the RMSE). Systematic errors are not easily detectable and can introduce significant bias. Many studies have investigated methods to identify systematic errors in DEMs. Brown and Bara (1994) used semivariograms and fractal dimensions to confirm the presence and structure of systematic errors in DEMs and suggested filtering as a means to reduce the error. Theobald (1989) reviewed the sources of DEMs and DEM data structure to identify how bias and errors are produced in DEM generation. Polidori et al. (1991) used fractal techniques to identify interpolation artifacts in a 40-meter DEM created from a 1:25,000 scale map; they suggest that the fractal dimension can be used as a DEM quality indicator by revealing directional tendency or excessive smoothing in the DEM. Lopez (1997) developed a method based on principal component analysis to locate random errors in DEMs and extract uncorrelated patterns. Random errors were shown to be weakly correlated with neighboring points, thus the points of low correlation could indicate random error (Lopez 1997). Monckton (1994) examined the spatial structure of error in a DEM by using the spot height data provided on paper maps. The study highlighted the statistical impurity of the RMSE – the mean error in the study deviated from zero indicating a bias, while the RMSE is based on the assumption that the mean is zero and normally distributed. Monckton suggested that it is the responsibility of the supplier to provide users with spot height elevations to assess the DEM. The USGS does not provide information on the location of the 28 data points used to generate the RMSE.

The Impact of DEM Error

The impact of DEM error on derived parameters has been investigated. In each of these studies, different methods for representing DEM uncertainty were developed and implemented. Fisher (1991) evaluated the impact of DEM error on view-shed analyses. Lee et al. (1992) and Lee (1996) simulated errors in a grid DEM and determined that small errors introduced into the database significantly affected the quality of extracted hydrologic features. Liu (1994) simulated errors in DEMs to evaluate uncertainty in a forest-harvesting model. Ehlschlaeger and Shortridge (1996) evaluated the impact of DEM uncertainty on a least-cost-path application. Hunter and Goodchild (1997) investigated the effect of simulated changes in elevation at different levels of spatial autocorrelation on slope and aspect calculations. Holmes et al. (2000) used a GPS to quantify errors in a USGS 30-m DEM and found that these errors had a significant impact on derived terrain attributes.

Bridging Research and Practice

Research demonstrates the existence of DEM errors and the impact that these errors have on DEM-derived data. However, there is no evidence that the DEM user community is either aware of DEM uncertainty or has integrated methods to account for uncertainty in the myriad DEM-derived data products and applications based on DEM data. The purpose of this survey was to identify: (1) DEM users, (2) the types of DEMs most frequently used, (3) the purposes of DEM use, and (4) the DEM users' perceptions of the impact DEM uncertainty on their analyses. Such data can potentially contribute to designing procedures that will enhance the decision-making that DEMs inform.

Survey Methods Using the Internet

As of September 2002, approximately 606 million people use the Internet worldwide (NUA 2002). Internet use in the U.S. is growing at a rate of 2 million new Internet users each month (CyberAtlas 2002). The Internet provides a valuable medium for collecting survey data. Marketing agencies, polling organizations, government offices, and a growing number of researchers take advantage of the Internet as a tool for conducting survey research (Sills and Song 2002). Web surveys are rapidly becoming an effective and accepted method for obtaining information and are being incorporated more widely in academic research (Sills and Song 2002, Stanton 1998). However, the use of the Internet for conducting survey research poses some challenges when compared with traditional survey techniques. Samples for mail and phone survey responses can be elicited from a known sample size, whereas the web has no population lists. Response rates are one group of criteria used to gauge how representative "pen-and-paper" survey responses are. Response rates are difficult to compute for online surveys. Surveys are often targeted to email addresses contained on various user group lists or list-servers, which makes random sampling difficult (Kaye and Johnson 1999). The concern about the non-randomness of online survey respondents is not unique to online surveys. Online surveys are based on a sampling technique referred as "purposive" sampling, a technique whereby subsets of a larger population can be identified and solicited (Babbie 1990:97). Although responses may not be representative of an entire population with this method, they are likely to be representative of the subset of the population that is the target. Web surveys provide a mechanism for this type of survey approach (Kaye and Johnson 1999, Mertler 2002). Benefits of online surveys include faster response rates, easy transfer of responses to databases for analysis (minimizing potential errors due to data compilation), cost savings (no postal costs), and wider geographic coverage (international audience) (Mertler 2002). It is clear that there is a need for additional research to compare the relative effectiveness of web-based surveys to traditional survey methods, and to investigate the effectiveness of survey design methods. The use of online surveys is on the rise. This research incorporates such a survey. The rationale for using the Internet for purposive sampling of DEM users is as follows: (1) DEM users are a small group of widely dispersed professionals who are likely to connect with like-minded professionals via the Internet. (2) A web-based survey of DEM users could access these users through professionally-related user groups. (3) A web-based survey would access DEM users internationally and in various work settings, potentially providing a diverse sample joined by a common interest.

Objectives and Hypotheses

DEMs are an important source of data for GIS analyses. As their name implies, DEMs are models and as such have limitations. These limitations have been documented in the literature. However, because errors in DEMs are difficult to identify, our lack of knowledge about the impact of these errors on DEM analyses (uncertainty) is difficult to quantify. It is unclear whether DEM users are aware of DEM uncertainty and any potential issues that may be associated with DEM use given that uncertainty. The purpose of this investigation was to provide an initial inquiry into the handling of uncertainty by users of DEMs. The survey was designed to elicit the following information:

1. Who is using DEMs?
2. What are DEMs being used for?
3. Is DEM uncertainty recognized?
4. Is DEM uncertainty accounted for?
5. How much effort would DEM users expend to evaluate DEM uncertainty?

The survey was based on the expectation that DEM users: (a) are generally unaware of the implications and impact of DEM uncertainty on their analyses; (b) often do not account for this uncertainty in reporting results from DEM analyses; and (c) would prefer simple methods for addressing this issue.

Methods

In this research, the web-based purposive sampling methodology is applied to achieve its purpose. Many DEM vendors do not distribute information about their customer base, and generating survey participation through DEM vendors could bias the sample. Many DEMs are available via the World Wide Web, thus this was deemed the most appropriate vehicle for targeting survey participants. Survey participants were targeted through an announcement sent to GIS-related newsgroups and user lists on the World Wide Web (Table 1).

Subscriber Lists	Newsgroups
GIS-L	infosystems.comp.gis
IDRISI-L	sci.geo.satellite.nav
ESRI-L	sci.geo.hydrology
AI-Geostats-L	sci.image.processing
	swnet.infosystems.gis
	comp.soft-sys.gis.esri

Table1: Target Audience for DEM User Survey

Survey questions were drafted to obtain information from the DEM user community. The survey was written in hyper-text-markup-language (html) and placed on a World Wide Web site where survey participants could answer 14 survey questions (Table 2). The survey was structured so that respondents could check a button next to the selected response. Some questions allowed more than one button to be selected, while others were limited to one response. In various questions, respondents were offered an opportunity to fill in additional information ["other"] when it was likely that the response option offered might not satisfy all possible situations. Survey responses were automatically emailed to the author once participants submitted their form by pressing a "submit survey" button, after which a web page would appear thanking them for their participation and verifying that the survey responses had been submitted.

The survey was first posted on June 4, 1998. A majority of the responses (85%) were received in the first month of posting (June 1998), with 90% of the responses received in the first year. The survey remained online on the author's website, and results

Table 2: Survey Questions and Response Options.

Question	Response Options
What types of DEMs do you use?	USGS 7.5 minute 30-m, USGS 7.5 minute 10-m, USGS 15-minute, 2-arc-sec, GTOPO30, ETOPO, SPOT, SAR, Self-generated, Other
How often do you work with DEMs?	Always (20-31 days/month), Often (5-20 days/month), Sometimes (1-5 days/month), Never (less than 1day/month)
For what purpose do you use DEMs?	Map visualization, Hydrologic modeling, Terrain modeling, Business applications, Land use planning, Other
What products do you derive from DEMs?	Maps of slope, aspect, concavity and convexity, contours, model parameter generation, watershed boundaries, ridge detection, channel detection, drainage delineation, view-shed analysis, cost analysis, and other
Do you account for DEM uncertainty in reporting results from applications?	Always, Sometimes, Rarely, Never
How do you account for DEM uncertainty?	Report RMSE, Error maps, Visualization, Other
Does unknown error (uncertainty) in the DEM affect the outcome of your applications?	Always, Sometimes, Rarely, Never, Don't Know
How much additional effort would you expend to evaluate DEM uncertainty (person hours per month)?	0, 1-10, 10-25, 25-50, 50-75, 75-100, 100+
How do you perceive the importance of accounting for DEM uncertainty?	Very important, Important, Somewhat Important, Not important, Don't Know
What GIS software package(s) do you use?	ArcInfo, ArcView, ERDAS, Idrisi, Grass, MapInfo, Other
Within what type of organization are you employed?	Academic, Research, Federal government, State government, Local government, Business, Non-profit, Other
Within what type of industry are you employed?	Conservation, Defense/Intelligence, Utilities, Engineering, Forestry, Hydrology, Resource Management, Planning, Transportation, Other
What is your age?	18-24, 25-34, 35-49, 50+
What country do you live in?	

continued to filter in over a 24-month period. Although the majority of the responses reflect 1998 data, all responses received between June 4, 1998 and June 4, 2000 were included in the analysis. The demographics of both sets of responses (1998 and later) were comparable.

Survey Analysis

Percentages were computed for each survey question based on the number of responses received for that question. Data were further evaluated to investigate perceptions of those who use certain types of DEMs such as the USGS 7.5-minute 30-meter DEM product or self-generated DEMs and those who use DEMs for specific purposes such as terrain modeling, topographic parameter calculation (such as slope, aspect, convexity, or concavity), hydrologic modeling, and map visualization.

Results: Survey Questions

Demographics

DEM users from 26 different countries responded to this survey. Participants residing in the United States comprised 53.6% of the response pool. Other participants were from Canada (7.7%), the United Kingdom (6.7%), Australia (6.2%), Germany (4.1%), Spain (3.6%), South Africa (3.1%), New Zealand and Mexico each 1.5%, and Norway, France, Switzerland, Brazil, Indonesia, and Italy each 1.0%, Sweden, Russia, Iran, Yugoslavia, Slovakia, Greece, the Netherlands, Denmark, Columbia, Chile, and Uganda each 0.5%. Respondents were in the following age ranges: 35 to 49 years (48.5%), 25 to 34 (40.0%), 50+ (9.0%), and 18 to 24 (2.5%). Respondents were affiliated with the following types of organizations: academia (27.4%), research (26.5%), federal government (15.0%), business (11.8%), state government (7.5%), non-profit (3.1%), local government (2.5%), and other (6.2%). The industry most respondents were affiliated with was resource management (23.7%). The remaining respondents identified the following areas: hydrology (13.7%), planning (10.3%), engineering (9.4%), conservation (9.1%), forestry (6.6%), transportation (4.0%), defense (3.7%), utilities (2.6%), and other (16.9%); where identified, the "other" category included hazard assessment, agriculture, climatology, cartography and mining exploration, and oil and gas industries.

Many respondents reported using ArcInfo software (30.6%) or ArcView software (28.1%). Idrisi users comprised 13.4% of the responses; ERDAS was used by 5.6%, MapInfo by 5.0%, and GRASS by 3.5% of respondents. Approximately 13.8% of the respondents reported using other GIS packages. Where indicated, these included SPANS, ArcCAD, Intergraph, Terra Firma, ILWIS, and Surfer.

Type of Digital Elevation Model

The largest proportion of respondents use the USGS 7.5-minute DEM (19%) or a self-generated DEM (17.1%). The USGS 1-degree DEM is used by 13.1% of respondents and USGS GTOPO30 DEM is used by 11.8% of respondents. The USGS 7.5-minute 10-meter resolution DEM is used by 10.8% of the respondents, USGS 2-arc-second by 4.7%, SPOT by 4.4%, ETOPO5 by 3.8%, SAR by 3.6%, the USGS 15-minute DEM format was reported used by 2.5% of respondents, while 9.1% of DEMs fell in the "other" category.

DEMs in the "self generated" or "other" categories were defined as follows: "Arc/Info DEMs (variable resolution) generated from DLG data and tagged vector files, created DEM from vector polygon files of 1:250,000 topographic maps"; "Digitized contour lines from 1:5000 topographic maps, additional automatic generated height points in valleys and ridges (with SPANS 7.0), linear interpolation with TIN, mean-filter for smoothing the TIN-edges, result 6.25m grid DEM"; "Official DHM 25 from the Swiss Topographic Institute, 1:25,000 contour lines with height-points, TIN-interpolated to a 6.25m grid DEM"; "1-km DEM generated from 1:250,000 contour maps"; "DEM created using TOPOGRID in Arc/Info"; "1:6000 photography-random points; Create own DEMs by running surface modeling routines on CAD contour (vector) maps"; "DEMs created from DLGs"; "Generated from Canadian 1:20,000 map sheets"; "We use photogrammetric methods to update DEMs where significant earthwork has been performed"; "DEMs created from contour lines using Surfer software and Idrisi"; and "Extract point elevation information from contours and coded lake shores, 'grid' using TIN in Surfer, check and correct."

The Frequency of DEM Use

Respondents were asked about their frequency of DEM use in ranges of "always" corresponding to 20-31 days per month, "often" meaning 5-20 days per month, "sometimes" (1-5 days per month), or "never" (less than 1 day per month). Almost half of the survey respondents "sometimes" work with DEMs (47.4%), while 36.7% of respondents "often" work with DEMs. Only 14.9% of respondents "always" work with DEMs, while 0.9% reported working with DEMs less than 1 day per month.

The Purpose of DEM Use

The reported uses of DEMs were: terrain modeling (28.3%), map visualization (27.1%), hydrologic modeling (18.5%), land use planning (10.4%), and business applications (0.9%). Other uses of DEMs (14.8%), where reported, included: "climate modeling," "soil erosion processes overburden for coal resources," "roadway design and determining proposed projects disturbance to different slope ranges," "geologic visualization and interpretation," "environmental analysis," "simulator databases – wide area elevation datasets for use in real-time image generators," "estimates of ground elevations for hydrologic analysis," "radiometric correction," and "as a link to relate geochemical samples."

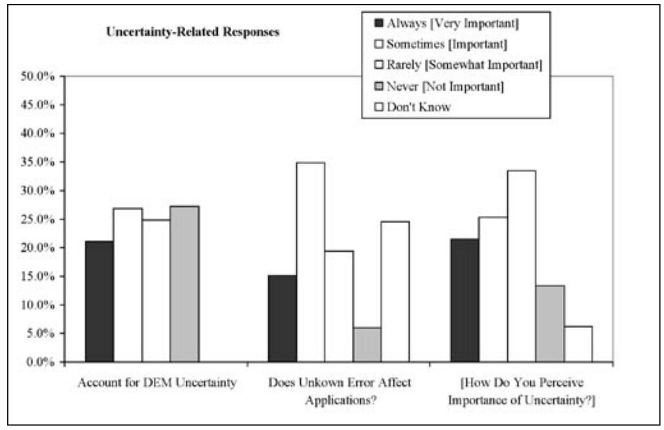

Figure 1: Responses to uncertainty-related survey questions

Products Generated from DEMs

Most DEM users who responded to the survey create maps of slope aspect, convexity, and/or concavity (17.5%), followed by shaded relief (17.0%) and contour maps (15.5%). Other DEM products include: watershed boundary delineation (10.8%), drainage network delineation (8.9%), view-shed maps (7.6%), channel network definition (6.3%), model parameter generation (5.6%), ridge detection (4.8%), and cost analysis (2.3%). Some respondents who indicated "other " uses (3.6%) indicated "roadway design cut and fill estimates," "point elevations for groundwater analysis," "slope and aspect maps which are used with digital geologic maps to prepare earthquake-triggered landslide hazard maps for local government planning"; and "the Minnaert Model."

The Perception of Uncertainty

Uncertainty-related responses of survey participants were almost equally divided (Figure 1). Half of the respondents perceive that they are affected by unknown error "always" or "sometimes." Almost half of the respondents "always or "sometimes" account for DEM uncertainty (47.8%) and a similar percentage (46.9%) indicated that uncertainty is "very important" or "important."

Do Users Account for Uncertainty?

Over half of the DEM users who responded to the survey "rarely" (24.9%) or "never" (27.3%) account for uncertainty in the DEM. However, approximately one-quarter of DEM users (26.8%) "sometimes" account for uncertainty, while 21.1% "always" account for uncertainty. Reporting of the RMSE was the most common method for reporting uncertainty (21.4%) followed by visualization (19.3%), error maps (12.8%), and simulation techniques (8.4%).

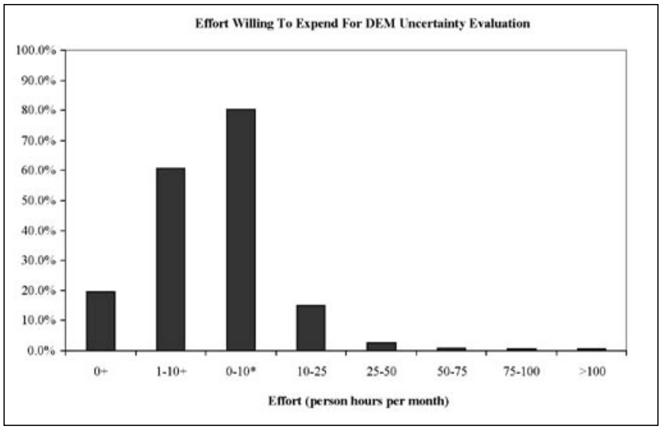

Figure 2: Effort DEM users would expend to evaluate DEM uncertainty.

+ Data derived from Version 2 of the survey, with 0 separated from 1-10.

* Data derived from Version 1 of the survey, with 0-10 the first range. Other values include results from the entire dataset.

Other methods (15.9%) for evaluating uncertainty in DEMs, when noted, included: "Physically correct instances of incorrect terrain depiction (i.e., nonexistent hills) in the GTOPO30 data"; "Visual spot checks and the software have a routine whereby elevation is given for the cross hairs as they move across the surface"; "Compile, clean and rectify onto tiles"; Quote source and accuracy"; "View DEM with man-made features superimposed"; "We have determined a minimum map resolution that is depicted on the final map product. Areas smaller than the minimum are essentially considered to be within the noise range and are removed"; and "Compare elevation values from the DEMs against values in the original topographic maps, and reported the range of difference, average difference and standard deviation".

Are Users Affected by Uncertainty?

Approximately one-third of respondents believe that they are "sometimes" affected by DEM uncertainty (34.9%). Almost a quarter of respondents did not know whether DEM errors affected the outcome of their analyses (24.5%). One-fifth (19.3%) of DEM users believe that they are "rarely" affected by DEM error, 6.1% believe they are "never" affected, while 15.1% of the respondents perceive they are "always" affected by unknown error in their DEMs. DEM users believe that the effects of uncertainty in their DEMs are "somewhat important" (33.5%) or "important" (25.4%). Approximately one-fifth of respondents perceived uncertainty as "very important" (21.5%). One-seventh (13.4%) of survey participants perceive DEM uncertainty as "not important," while 6.2% "do not know."

Time Allotted to Evaluate Uncertainty

DEM users would prefer to spend minimal time in evaluating DEM uncertainty (Figure 2). The original survey form lumped the minimum level of effort into one range of 0-10 person hours per month. Of the 147 survey participants who responded using this form, 80.3% would spend 0-10 person hours per month. A subsequent version separated the category into two groups of 0 person hours per month and 1-10 person hours per month. Of the 51 participants who responded using this form, 19.6% would not devote any time to uncertainty evaluation (0 person hours per month) while 60.8% would devote 1-10 person hours per month.

Results – Responses By DEM Application and Type

The survey identified USGS 7.5-minute and self-generated DEMs as the most commonly used DEM form. The use of DEM for terrain modeling, map visualization, hydrologic modeling, and topographic parameter generation were identified as the more common uses of DEM data. Responses of users in these categories were evaluated to determine their perceptions of DEM uncertainty (Figures 3-6).

The majority of respondents who perceive they are "always" or "sometimes" affected by uncertainty include self-generated DEM users (59.3%), USGS 10-m DEM users (58.3%), the use of DEMs for hydrologic modeling (54.5%), the use of DEMs for terrain modeling (53.2%), and the use of DEMs for topographic parameter generation (52%) (Figure 3). The majority of self-generated DEM users and USGS 10-m DEM users perceived DEM uncertainty as "very important" or "important" (66.3% and 55.1%, respectively). The majority of DEM users who utilize self-generated DEMs (61.3%), USGS 10-m DEMs (52.9%), or use DEMs for hydrologic modeling (51.5%) or topographic parameter generation (51.3%) "always" or "sometimes" account for uncertainty. When uncertainty is accounted for, reporting of the RMSE was the most frequent method reported utilized (average 22.0%) followed by visualization of errors (19.2%). Users of the USGS 30-m DEM product generally do not perceive DEM uncertainty as an important issue (61.6%) and 57.3% of users in this category "rarely" or "never" account for uncertainty.

Conclusions

DEMs are used in many parts of the world for various purposes. The major reported uses of DEMs were in terrain modeling, map visualization, and hydrologic modeling. The largest percentages of respondents were employed in resource management, academia, and research.

Half of the DEM users who responded recognize that their work is "sometimes" or "always" affected by uncertainty (50%). However, a large number (25%) of users reported lack of awareness as to whether DEM errors affected their work at all. On the other hand, 21.5% of users recognized that uncertainty was "very important" and this same proportion of users reported that they "always" account for uncertainty in their work (21.1%). Results from DEM users who responded to this survey indicate that although many DEM users deem uncertainty in the DEMs they use to be somewhat important, they indicated an unwillingness to devote much time to evaluate the impact that this uncertainty might have on their applications. These results suggest that GIS programs that are developed to assist DEM users in evaluating

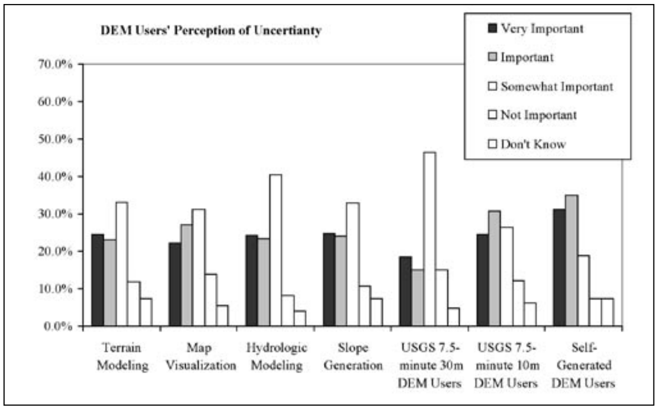

Figure 3: Survey participants' perception of importance of accounting for DEM uncertainty

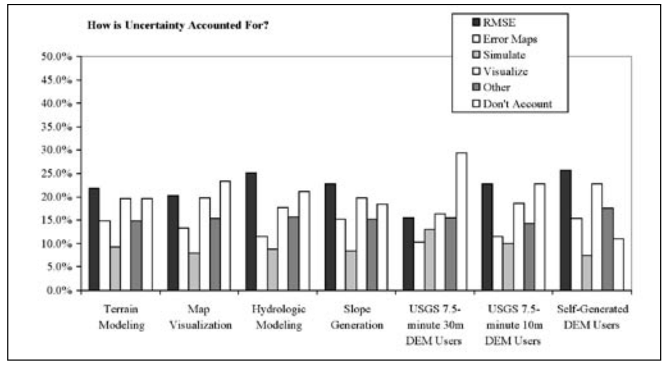

Figure 6: How is uncertainty accounted for?

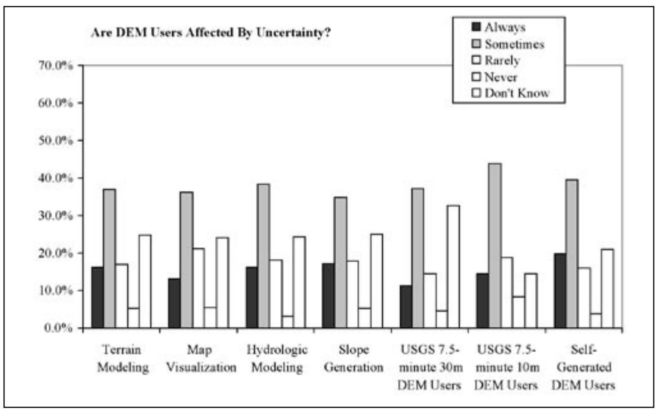

Figure 4: Does DEM uncertainty affect outcomes of participants' applications?

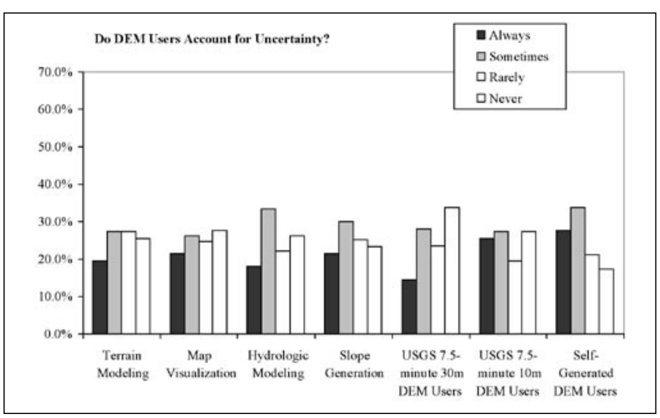

Figure 5: Do Survey participants account for uncertainty?

uncertainty should take little time to implement if they are to be widely integrated by DEM users. The need for educating users who are currently not aware of uncertainty in DEM data is another conclusion from this survey.

The methods used by the small group of respondents who do account for uncertainty are varied. There do not appear to be any consistent procedures that have been adopted by the community of DEM users. There are no consistent methodologies that are applied to DEM data to address problems of uncertainty, apart from the RMSE, which is provided for some DEM data or computed from higher accuracy sources. Decisions about managing the uncertainty in the data are defined by individual DEM users. This may be idiosyncratic; methods are not generally subject to peer review or established procedures. Nevertheless, this survey suggests that DEM users appear to be trying out various methods to clarify, reduce, communicate, and limit the effects of uncertainty on DEM applications in their work. Indeed many DEM users indicated some willingness to commit limited time and resources to identifying and accounting for uncertainty in their work. Therefore, tools that could easily be utilized might assist DEM users to more precisely specify the limits of accuracy of their DEM-derived products and/or further refine their products.

As demonstrated by the survey, DEM data have wide applications. DEMs are the underpinning of environmental analyses throughout the world. Land use planning and water resource utilization are basic applications. The products derived from DEM data are critical for such planning and decision-making. These products are assumed to be valid and reliable representations of reality. Scientists who apply DEM models are expected to provide the most accurate data possible in presenting their findings to other professionals, public officials and other end users. The results of this survey indicate that there is much room for examination of the extent and accuracy of data in the application of DEMs.

Effects of DEM uncertainty should be explicit for various types of applications for responsible use of DEM and derived data.

Procedures for addressing uncertainty should be consistent so that the nature of error can be validly presented and conclusions from DEM-based analyses incorporate DEM uncertainty. This survey highlights the current need for researchers who study DEM error and vendors who disseminate DEM data to assist consumers in quantifying the role and relevance of error and provide tools for DEM uncertainty management in applications.

About the Author

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