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The Role of GIS to Enable Public-Sector Decision Making Under Conditions of Uncertainty

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The role of GIS to enable public-sector decision making under conditions of uncertainty

Abstract

Uncertainty is inherent in environmental planning and decision making. For example, water managers in arid regions are attuned to the uncertainty of water supply due to prolonged periods of drought. To contend with multiple sources and forms of uncertainty, resource managers implement strategies and tools to aid in the exploration and interpretation of data and scenarios. Various GIS capabilities, such as statistical analysis, modeling and visualization are available to decision makers who face the challenge of making decisions under conditions of deep uncertainty. While significant research has lead to the inclusion and representation of uncertainty in GIS, existing GIS literature does not address how decision makers implement and utilize GIS as an assistive technology to contend with deep uncertainty. We address this gap through a case study of water managers in the Phoenix Metropolitan Area, examining how they engage with GIS in making decisions and coping with uncertainty. Findings of a qualitative analysis of water mangers reveal the need to distinguish between implicit and explicit uncertainty. Implicit uncertainty is linked to the decision-making process, and while understood, it is not displayed or revealed separately from the data. In contrast, explicit uncertainty is conceived as separate from the process and is something that can be described or displayed. Developed from twelve interviews with Phoenix-area water managers in 2005, these distinctions of uncertainty clarify the use of GIS in decision making. Findings show that managers use the products of GIS for exploring uncertainty (e.g., cartographic products). Uncertainty visualization emerged as a current practice, but definitions of what constitutes such visualizations were not consistent across decision makers. Additionally, uncertainty was a common and even sometimes helpful element of decision making; rather than being a hindrance, it is seen as an essential component of the process. These findings contradict prior research relating to uncertainty visualization where decision makers often express discomfort with the presence of uncertainty.

Introduction

The collection, transformation, analysis and visualization of data and information introduce uncertainty into all geographic data. Broadly, uncertainty refers to incompleteness in knowledge, or what is not known about the relationship between a predicted (or measured) value and the actual value. The term uncertainty covers a wide range of data characteristics, including for example, error, accuracy, precision, and quality. Additionally, the form of uncertainty relevant to any given problem or situation may change depending on the user and purpose of the project. Furthermore, the manner in which uncertainty is displayed or communicated has the potential to introduce an additional source of uncertainty, by influencing both the viewer's interpretation and decision making process

(Hope and Hunter 2007). For informed, effective decisions to be made, decision support and model results should indicate the presence of uncertainty in a manner that does not negatively affect the usability of the information.

A broad range of literature addresses uncertainty, through presenting and evaluating effective mechanisms for portraying spatial uncertainty and understanding the impact of representing uncertainty in maps as part of the decision-making process (for reviews see MacEachren, A.M. 1992; MacEachren, A.M. and C.A. Brewer, 1998; Blenkinsop, S., P. Fisher, et al. 2000; Bastin, L., P. F. Fisher, et al. 2002; Bostrom, A., L. Anselin, et al. 2007; Goodchild, M.F. 2007; Moss, R. H. 2007; Pebesma, E. J., K. de Jong, et al. 2007). A common approach for representing uncertainty is an adaptation of Bertin's (1982) visual variables. Additional graphic elements, such as transparency and clarity, have also been proposed (MacEachren 1992; Slocum et al. 2004). Representation techniques then fall into two general categories (Gershon 1998), intrinsic and extrinsic. *Intrinsic* techniques integrate uncertainty in the display by varying an existing object's appearance to show associated uncertainty, while *extrinsic* techniques rely on the addition of geometric objects to highlight uncertain information. Past research has found that using visual cues (such as color saturation and texture) as indicators of uncertainty in maps affects decision making by increasing the number of correct siting decisions when certainty information was portrayed using explicit representations of lighter color values, finer texture, and pastel shades (Leitner and Buttenfield 2000). Including certainty information in this case resulted in similar or faster decision times compared to a basic map with no certainty information presented. Similar benefits of including uncertainty information in decision-making process are noted by Aerts et al. (2003), who reported that participants in an online survey found that inclusion of uncertainty tends to clarify, rather than complicate, the represented issue. These techniques offer a diverse toolbox for representing uncertainty for decision making, but all focus on explicit representation, where the uncertainty is specified and defined separately from the underlying data.

Given the breadth of research dedicated to uncertainty, we focus specifically on the impact of uncertainty in decision-making processes. Research shows that decision makers often view uncertainty as a constraint to making decisions, thus leading them to avoid solutions that employ uncertain information, exhibit bias toward initial solutions, undervalue negative or contrary evidence, and over-rely on the results of prior outcomes (MacEachren et al. 2005). Brugnach et al. (2007) found that policy makers' lack of confidence in computer models inhibited their adoption as tools for policy formulation, which stemmed from the perception that computer models are potentially unreliable tools that could produce misleading or biased inputs to the decision-making process. They found that even the *potential* that a tool could introduce undue uncertainty into the decision-making process was sufficient to cause some people to shy away from those tools (Brugnach et al. 2007). Similarly, Borowski and Hale (2007) identified a disconnect between water managers and researchers regarding the role and importance of models, the transferability of models to specific settings, the role of participatory modeling in water management, a lack of confidence in models, the need for improved user interfaces, and model integration. They concluded that structural differences between research and policy communities, such as divergent interests, accountability, and reward structures, lead to different attitudes and assumptions about the role of models in water management.

Despite an apparent indifference to uncertainty (as represented by researchers), decision makers regularly contend with uncertainty in their decisions. This suggests a possible discrepancy between actual decision making processes and the representation methods developed by researchers. Bringing uncertainty representation from theory to practical application requires an integrated understanding of the uncertainty present, the ways in which decision makers interact with that uncertainty, and the effect uncertainty has on their willingness to use the information. This type of integrated uncertainty research and communication between researchers and practitioners is critical (Foody 2003). The ways that public-sector managers engage with uncertainty, and the tools they use towards that end, is one area of uncertainty representation not addressed in the literature. Our research begins to fill this gap by explicitly defining two types of uncertainty and illustrating how they were conceived through a case study involving water resource professionals in Phoenix, Arizona.

Interviews with water resource professionals lead us to create a distinction between explicit and implicit uncertainty, which when thoroughly understood, can bridge the gap between theory and practice. Explicit uncertainty is defined by the direct identification of gaps, errors, and unknowns displayed or represented through quantitative values (such as error bars) or qualitative estimations (certain versus uncertain). Much of uncertainty research described earlier focuses on explicit representations of uncertainty. In explicit representations, uncertainty is conceived as specific values, to evaluate as unique information, related to, but not the same as, the underlying data. Implicit uncertainty, by contrast, is linked to the decision making process, where uncertainty is an inherent characteristic of the data. Implicit uncertainty is more subjective and context dependent, where experience informs definition, interpretation and, potentially, representation. Implicit representations support exploration of the relationship between uncertainty and decision outcomes. When considering decision making under uncertainty, implicit uncertainty, more so than explicit, relates to the subjective nature of individual decision making, where heuristics are often used to determine a course of action.

These distinctions in uncertainty were identified through a study that aimed to ascertain the manner in which public-sector managers' interact with uncertainty in practice. We wanted to better understand if, when, and how uncertainty is addressed through GIS and visualization. Water managers often rely on GIS data and projections when working through resource decisions and planning processes, for example, based on expected climate conditions and water demand rates. This makes water managers an ideal case study for evaluating public sector managers' interaction with GIS and uncertainty in decision making. Bridging the gap between uncertainty representation research and practical application requires evaluating the ways decision makers use the technology, in this case GIS, as well as their methods of contending with the uncertainty present. To this end, our research examined two questions. First, how is GIS used by water managers for decision making? Second, how do water managers deal with uncertainty in their use of GIS? We illustrate how answering these questions built our dual framework for uncertainty.

Methods

Study Area

The case study focuses on water managers in the Phoenix metropolitan region, which is an appropriate study site for examining uncertainties faced by managers and how they are addressed in decision making. Water managers in Phoenix exist at the confluence of three major threads of uncertainty (1) climatic variability, (2) population growth and urban change, and (3) a complex institutional and policy framework.

Phoenix is located in the Sonoran Desert, a region characterized by a relatively arid environment, reoccurring periods of drought, and long, hot summers. Rainfall is highly variable, both inter-annually and seasonally, but is generally punctuated by two annual precipitation peaks. The summer monsoon, occurring during July and August, is characterized by short, localized, intense rainstorms. The winter storms, which occur from November through March, provide much of Arizona's surface water supplies. In the mountains to the north of Phoenix, snow accumulates during the winter months and provides spring runoff that recharges reservoirs in central Arizona. Drought and climate variability threaten these local and regional water sources (Ellis et al. 2008). Within Arizona, a drought has been underway since 1999 (USGS 2005), greatly affecting the area's watersheds and storage reservoirs (Figure 1). Managed by Salt River Project, the region's reservoirs have been below capacity in recent years. Meanwhile, recent research highlights the potential for even longer periods of drought as well as human-induced climate changes, both of which could seriously impact water supplies in the southwestern U.S. (Ellis et al. 2008; Monroe 2008).

Rapid growth in the Western States increases the potential for water shortages in the Phoenix area (Piechota et al. 2004). In the case of Phoenix, the current Maricopa County population of 3.7 million is projected to grow to 6.1 million people by 2030 (MAG 2007). The changes to land and water usage that result from this rapid growth create a formidable management situation for water providers trying to meet growing demand (Jacobs and Holway 2004). In the short term, Phoenix's water supply remains promising, with multiple sources of renewable surface water augmented by the use of groundwater. In the long term, however, net water consumption is projected to increase 30 percent, while water supply is anticipated to increase only 25 percent (Carter et al. 2000). Under conditions of prolonged drought and rising demand due to population growth, the long-term reliability of water sources depends on highly variable climate dynamics, the rate and form of growth and urbanization, as well as the nature of institutions governing resource use and management.

The institutional and policy framework in which water managers must operate adds an additional dimension of complexity to resource planning and decision making in Arizona. This framework is composed of federal, state, and local laws governing the use and quality of water, the doctrine of prior appropriate dictating the primacy of certain water users over others (for surface water), and international treaties guaranteeing a certain level of flow in the Colorado River as it crosses into Mexico (Carter and Morehouse 2001). In Arizona, the Groundwater Management Act of 1980 governs water use from nonrenewable aquifers through water supply- and demand-side programs aimed at safe yield by 2025 (Jacobs and Holway 2004; Larson et al. 2009). Consequently, recent policies emphasize the use of renewable surface water, especially from the Colorado River, but the state's junior rights in the basin make this an uncertain source of water during times of shortages.

Data collection

Data were collected from a series of semi-structured interviews with open-ended questions in July and August 2005. Twelve interviews were conducted with an array of water resource professionals involved with management decisions in the Phoenix metropolitan area. Four topic areas were addressed in the interviews. The first two topics (1) water management and (2) science, politics, and social values, were discussed by White et al. (2008). The third and fourth topics, (3) uncertainty and (4) computer analysis tools, are the subject of this study. The respondents were selected using stratified purposive sampling (White et al. 2008) to highlight preselected subgroups within the sample and allow for comparisons within and across subgroups. Selection of respondents focused on water mangers that operate at the nexus of science and policy, representing three institutional perspectives: state water suppliers (n = 4), local water utility managers (n = 4), and city water planners (n = 4). Respondents represented a variety of professional backgrounds and experiences, including executive planning, hydrology, business management, water rights, environmental science, and conservation.

Responses to the primary interview questions for topics three and four were transcribed verbatim from audio recordings. Speech patterns, such as "um" and "uh", were excluded from the transcripts. Significant pauses or changes in the direction of the interviewee's response were indicated in the transcribed text by a series of three periods. Unclear words were indicated by the inclusion of the statement "(unintelligible)" in the transcript to hold the place of the unrecognizable statements. The interviews were imported into QSR NVivo 7 for storage and analysis, as further described below.

Analytical approach

This research adopts the methodological framework developed by Miles and Huberman (1994), who emphasize three concurrent flows for qualitative analysis: data reduction, data display, and conclusion and validation. We describe how we implemented this approach in detail.

Data reduction consists of reducing and reconfiguring a large volume of data to something manageable, from which meaning can be extracted. Initial deductive codes were developed using the research questions and previous literature as a guide to explain how GIS and uncertainty are incorporated into water resource decision making. Example codes include climatic uncertainty, visualization, scenario analysis, and GIS for decision making. A full list of deductive initial start codes is included in Table 1. The list of initial start codes was provisional as broader issues were expected to emerge through the examination of the transcribed interviews. Moreover, some start codes were expected to be rejected once coding began due to their absence in the interview texts.

Verification of the codes followed the process described in White et al. (2008).

Beginning with the list of start codes, approximately ten percent of transcribed interviews were coded by two independent coders to develop a more comprehensive coding system. During this process, new coding categories inductively emerged from the data that addressed the primary research questions. The test transcript was comparatively reviewed for discrepancies and commonalities. Discrepancies and differing interpretations were discussed between the two coders, with resolution occurring when the research team agreed on the proper coding for a segment of text. This process continued until intra-rater and inter-rater reliability was achieved at ≥ 89% (Rust and Cooil 1994). Following verification of codes, the relevant portions (topics three and four in the interviews) for all the transcripts were coded.

The coding process yielded multiple levels of codes. This initial phase of coding is a form of data reduction, although it yields the largest number of categories. The first level, descriptive codes represent an initial series of passes through the text of the interviews using the start codes as well as developing new codes that emerged from the interviews. The number of categories was then reduced by finding commonalities among the descriptive codes and emergent themes. Pattern codes and interpretive codes were developed from themes that emerged from descriptive coding.

Pattern codes aide in the exploration of relationships among concepts and facilitation of a constant comparative approach (Strauss and Corbin 1998). They serve to reduce large amounts of data into smaller units of analysis through identification of broader themes or patterns within the interview texts. In this research, these codes assist in understanding the phenomena and processes discussed by water managers. For example, communication processes emerged as a pattern evident across multiple segments of texts. The relevant segments of text included not only direct descriptions of communicating uncertainty to the public or decision makers, but also simplification of complex issues to be understandable to a lay person.

With focus on capturing complex dynamics and contextual distinctions interpretive codes aid in discovering the underlying rationale and behaviors behind phenomena that emerge through descriptive coding (Miles and Huberman 1994, 57). These codes help to identify instances where the same word has different meanings for different respondents or contexts. For example, at first, discussions of uncertainty visualization that emerged from the interviews appeared consistent with visualization techniques discussed and proposed in geographic visualization literature. However, upon further examination, what emerged was a lack of agreement on what "visualization" meant to water managers. Some managers viewed visualization as charts and graphs (information visualization), while other defined visualization as complex data displays, such as those achieved through GIS (geographic visualization).

The second phase of analysis is data display. In this phase, cross-case analysis was used to allow for patterns and relationships to emerge across the interviews and for descriptive, preliminary conclusions to be drawn from the transcripts as a whole. Meta-matrices bring together coded segments from each interview to allow for comparison (Miles and Huberman, 1994). QSR NVivo 7 allows recall of all references to a particular code in an interview, so that all references made regarding a single theme can be viewed together. The matrices generated in this manner are dynamic, allowing for the addition or removal of coded segments without having to re-create the matrix, and keeping the coded segment of text related to the original text. An example a meta-matrix is shown in Figure 2.

The final phase of analysis is conclusion drawing. Conclusions were developed throughout the analytical process by noting the patterns (referred to as pattern codes above) and themes associated with the clustering and counting of codes, and relations between variables (as described in Miles and Huberman 1994). Clustering refers to aggregating discrete codes into larger categories based on similar characteristics or patterns. Counting is the summing of the variables that emerge from the coding process. Noting the relations between variables involves the correlation of coded segments of interview texts and the attributes of interview subjects. Through conclusion drawing, patterns emerge from the coded segments and interviews, and begin to fit together into a coherent picture.

Pattern Codes: The Resulting Emergent Themes

Many of the start codes developed deductively at the outset of this research, which were descriptive of the effects of uncertainty on decision making, were dropped due to lack of appearance in the interviews. Of the 31 original start codes (Table 1), 22 were sustained and 9 were dropped. Thirty-four codes (see Table 2 for final descriptive codebook) emerged through repeated interaction with the interview transcripts. Six pattern codes (Table 3) and eleven sub-codes emerged from the analysis. These represent emergent themes within the interviews, and loosely fit into two categories.

The first category encompasses the *use of GIS in decision making*. These include the *positive views* of GIS among the water managers, *new techniques* (from perspective of water managers) envisioned for the use of GIS, and *vague conceptions of the meaning of visualization* by water managers. The second category involves the *use of GIS to address uncertainty in decision making*. These codes include *communicating uncertainty,* differentiated between communicating to the public or decision makers; *generalized methods of coping with uncertainty*, differentiated between managerial and technical methods of addressing uncertainty; and, *methods of visualizing uncertainty*, the extent to which organizations employ visualization techniques to manage uncertainty.

Results

The resulting emergent theme pattern codes appear to distinguish several commonalities in the ways water managers use GIS for decision making and deal with uncertainty in their use of GIS. Respondents identified a range of uses in their organizations (Table 4), with a majority of the applications falling into seven general groups (for example, decision making, analysis or visualization of problems). While all respondents seemed to be aware of the general use of GIS in their organizations, a distinction emerged in approaches to GIS application and addressing uncertainty. Based on these distinctions, respondents fit into two general categories, policy oriented or science oriented, which are similar to the classification in White et al. (2008).

Policy oriented managers view decision making in the context of policy decisions, with GIS emerging as a policy support tool within the organization. These managers stress the importance of communicating results to decision makers and the public, focusing on methods to improve this communication. Similarly, policy oriented managers often refer to novel uses of GIS for communicating information to decision makers and the public. Here novel uses may be existing capabilities known to researchers or analysts, but unknown to the water manager. In the interviews, policy oriented managers focus on general references to the use of GIS in an organization, without specific instances or references to decisions made. While these managers are aware of the uncertainty inherent in water management data, practices and GIS output, they maintain their focus on supporting policy decisions through communicating information to policy makers and the public, and not detailed analysis of specific uncertainty data.

Conversely, science oriented managers emphasize scientific information in decision making, including the specific use of GIS as an analysis tool. Discussions focus on specific references and example of decision making activities or GIS application. Responses stress analysis and technical issues, focusing on the practical application of GIS, including references to applications such as modeling, projections, data issues, and visualization. Exposure to the analytical and technical aspects of GIS appears more extensive for science oriented managers. They are aware of the uncertainty inherent in water planning, identifying the importance of both explicit evaluation of the uncertainty through statistical exploration, and a more implicit, integrated discussion of uncertainty when communicating information to policy makers and the public. Although the focus of these managers is not communication of results, their discussions of uncertainty and GIS applications distinguishes between analytical/technical and communication uses.

Similarities between the two groups are many, including an overall positive view of GIS and the need to address a multitude of uncertainty sources. Although the science oriented managers did not focus specifically on communication, a majority identified the need to communicate results to policy makers and the public in a manner that supported evaluation and ultimately making a decision. While the managers' approaches to dealing with uncertainty differ, a common distinction emerged in uncertainty discussions. This distinction is defined here as implicit and explicit uncertainty. Implicit uncertainty is linked to the decision-making process, and while understood, it is not displayed or revealed separately from the data. This is related to implicit representation, which includes methods such as scenarios, where projections are represented as a range of outcomes or the impact of differing climate change projections on ground water use. In contrast, explicit uncertainty is conceived as separate from the process and is something that can be described or displayed, almost as if separate from the underlying data. Likewise, explicit representation includes methods such as statistical evaluation and graphic representation of source uncertainty. Policy oriented managers approaches to addressing uncertainty most often involve implicit uncertainty, which reflects their focus on supporting policy decisions and communicating with policy makers and the public. Science oriented managers refer to both explicit and implicit uncertainty, making the distinction that direct statistical evaluations are beneficial for their analysis, but that more generalized uncertainty information better supports decision makers' evaluation of the data. The distinctions between implicit and explicit uncertainty emerged throughout many of the results of this research, including uncertainty sources and addressing uncertainty with visualization.

Uncertainty Sources

Water managers consistently recognized uncertainty as an inherent factor in their decision making. A variety of sources of uncertainty emerged in the interviews, including climatic uncertainty, data uncertainty, water supply, and long-term climate change. Less frequently science, legal issues, future land use, and institutional issues were also identified. Several broad classifications of uncertainty sources emerged from this research (Figure 3), with climatic uncertainty the most common type discussed.

Climatic uncertainty encompasses direct observations of uncertainty related to climate, along with long-term climate change. One water manager remarked "the types of decisions that we have to deal with have to do really with the uncertainty of the hydrologic cycles and a lack of quality information in the past." Another water manager refers to the importance of climate uncertainty, indicating:

> "I think it affects the water resource managers quite a bit when you're looking at climate forecasts which...can be very iffy. But that would affect your decisions on how much you're going to draw down a reservoir, whether you're going to pump a little bit more. Climate variability will impact those decisions I think more than certain policy decisions."

Technological uncertainty includes issues related to data, science and models. Remarks relating to this form of uncertainty were often more general, even with science oriented managers, who expressed that "there's uncertainty in the information". Managers conveyed the pervasiveness of uncertainty saying "it is the rare situation where I think you have all the information you would like to make a decision."

Uncertainty in water availability, represented by water supply and land use, often coincided with discussions of climate and technology. For example, in discussing climate uncertainty, one water manager indicated that, "...reservoirs are always empty...runoff peaks come sooner and larger, or at different time and larger and you can't capture them." Similarly, another water manager noted, "the types of decisions that we have to deal with have to do really with the uncertainty of the hydrologic cycle and a lack of quality information in the past." This uncertainty is seen as part of the process and often a focus of the organization. "The whole reason SRP exists is the uncertainty with surface water supply and building reservoirs....when it comes to water there's always a level of uncertainty..., technically, that there's a level of uncertainty with all our water decisions."

While a majority of managers in this study are classified as policy oriented (and generally tend towards references to implicit uncertainty), a majority of the source discussed above tend towards explicit uncertainty. Less frequently, uncertainty sources are discussed implicitly, tending towards more general evaluations and the impact of uncertainty on actual policy decisions. The need to implicitly represent uncertainty to support the decision process was expressed by several respondents indicating that managers "... need to figure out some way to be able to reduce that uncertainty down for your decision makers and the public so that the problem analysis and the decision making process become manageable to them". The preponderance of explicit references here is a reasonable result, as consideration of source uncertainty occurs during the initial evaluation and analysis of water issues, when projections and models are developed. These types of tasks require explicit evaluation of uncertainty, including statistical evaluation. This contrasts to the end of the process where results are communicated to decision makers, and overall uncertainty is more of a concern than the specific individual source uncertainty.

Addressing Uncertainty with GIS

Water managers identified several methods for addressing uncertainty, with visualization being one of the most prevalent. While visualization of uncertainty emerged as a prevalent theme among water managers, the specific use of GIS toward that end appears to be less well developed or known among water managers. Interestingly, all managers indicated that visualization techniques were used, although only two indicated GIS was used for this purpose specifically. A majority of managers did not provide specific examples of ways in which visualization was used, just that they did so, and a common definition of uncertainty visualization does not emerge from the discussions. The definition of visualization alone varies from information visualization techniques such as charts, graphs, and tables, to geographic visualization such as maps and GIS representations. Uncertainty visualization, as it is used by the managers, appears to focus on visualizing uncertain results, data or scenarios. For example, one manager stated: "we definitely analyze uncertainty and represent it visually, particularly if it's a technical issue in a legal case." Four respondents indicated they use graphs and charts to visualize uncertainty, while one indicated illustrations were used. Another municipal water manager listed the use of GIS along with other tools, saying it "depends on the type of uncertainty we're dealing with. Spatial uncertainty we may deal with maps and spatially. If it's time scale, you may just simply use a chart...It varies pretty widely depending on what the issue is and what the nature of the uncertainty is."

Methods for addressing uncertainty include both explicit and implicit discussions, with the form of uncertainty relating to where managers are in the decision process. Managers address uncertainty many times throughout the decision process, including analyzing the presence of the uncertainty (explicit), balancing uncertainty and risk with potential decision outcomes (implicit), and communicating uncertainty to policy makers or the public (implicit). During the analysis process, water managers want to understand the magnitude of uncertainty present. Magnitude is expressed explicitly, as margin of error, range, degrees of probability, limits and parameter estimation. This explicit evaluation allows water managers to "...quantify the range that you think you are operating in" and implement technical solutions to problems. When evaluating the relationships between uncertainty and outcomes, or communicating uncertainty to decision makers and the public, explicit representations are not seen as necessarily beneficial for this evaluation or communication.

Water managers indicate that communicating the presence and sources of uncertainty to decision makers is important, however, they also indicate negative or complicating effects of explicitly and directly communicating uncertainty information (see Table 5). When one water manager was asked if he wanted to know about uncertainty in a decision setting, he responded positively, but added: "there are times when it can complicate it too much" and “higher level decision makers don’t want to hear about degrees of uncertainty and probability and degree of variance.” A second manager suggested that policy makers need to be aware of uncertainty, but that it complicates the decision process. A third also expressed that it poses complications, but that it is a “necessary part of the process.”

It is worth noting that throughout these interviews, mangers express an acceptance towards uncertainty in the data and the decision process, which contradicts prior research results indicating uncertainty is seen as a negative to be avoided. When speaking about expressing uncertainty information to decision makers, it is seen as something “that might help them make their decision better”, and although it does “complicate decisions”, managers believe that ultimately it may “fortify the decisions you’re making”.

Water managers acknowledge that decisions must continue regardless of the presence of uncertainty. They identify the need to make uncertainty “transparent” to decision makers to support decision making. One manager noted that if you try to make decision makers “think in terms of complexity and uncertainty, they can’t...they’ll debate it forever and never take an action”. This results in a level of caution in the decision making process, where managers must balance uncertainty and risk with the potential consequences of decisions. In these situations, water managers want to understand the relationship between the uncertainty and the potential outcomes of their decisions. At this level of the decision making process, implicit evaluation becomes important with consideration of context (such as the form of uncertainty) and the relationship between uncertainty and potential outcomes. At the communication level, water managers focus on methods to “reduce the uncertainty down for decision makers and for the public so that the problem analysis and the decision making process becomes manageable to them”.

Similar to the discussions of uncertainty sources, the stage of the decision process appears to influence whether managers are focusing on explicit or implicit uncertainty. References to explicit forms of uncertainty appear to occur more often in discussions about the beginning of the decision process, before information is presented to decision makers. Implicit uncertainty references occur more in discussions about the later stages of the decision process, when the focus shifts to evaluation of scenarios or analysis as a whole occur, or results are communicated to decision makers.

Discussion

Uncertainty Requires Context

Since policy oriented managers and decision makers are often not working directly with GIS throughout the decision process, the type of uncertainty they come across, and the effect of that uncertainty on their interpretation of the information, may differ from that of the analyst or science oriented manager. The usability of uncertainty information and uncertainty visualization is subjective and context dependent here, suggesting that the level of detail and control in uncertainty representation should vary based on whether the user is the analyst, water manager, or decision maker. Explicit representations, such as statistical analysis or maps of error data, might be appropriate for the analysts and domain experts. Conversely, implicit representation, such as ranges of scenario outputs or potential policy implications, might better suit the decision framework of some water managers and decision makers. While some water managers in this study expressed familiarity with statistical representations of uncertainty, they indicate that presenting similar information to decision makers and the public often negatively affects the decision process. This is an important distinction to consider when developing uncertainty visualization tools, as it requires a shift from quantitative and explicit uncertainty representations, to methods that consider context, support exploration of relationships between uncertainty and outcomes, and the needs of the user. This complicates the vision of developing standard uncertainty representation tools for use in GIS, requiring a better understanding of the presence of uncertainty in specific domains, such as water management, or for use by different users. However, the benefit of harnessing the acceptance of uncertainty observed in this study outweighs the difficulty of incorporating multiple conceptions of uncertainty.

Communication of Uncertainty

Decision makers accept uncertainty as integral to the decision process, and understand that they must address the presence of uncertainty and the affect it may have on their decisions. These results seem to contradict prior research (Brugnach et al. 2007), which suggests decision makers avoid using uncertain information in general. This is significant, in that it suggests that users may be willing to use uncertainty if it is represented in a manner that matches their understanding, with uncertainty integral to the data. In the application settings, the interpretation of uncertainty is often implicit, being somewhat subjective and depending on experience and context for the user. Instead of calling the uncertainty out separately, a more suitable and usable option might be to develop representations more consistent with the existing decision support structures, such as a decision space of multiple scenario outcomes.

Adapting existing methods is one way to build upon current practices in addressing uncertainty in decision making. A significant method of addressing uncertainty that emerged was visualization. However, the consensus among water managers in this study that visualization was a useful method was tempered by a lack of agreement on what the terms "visualization", and more specifically “uncertainty visualization” means. Visualization to one water manager meant charts and graphs, while others associated visualization with maps and displays such as those created through GIS. While the interviews demonstrate that visualization of uncertainty is seen as common, the explicit *visualization* of uncertainty using GIS was not found in this research. This is consistent with prior uncertainty visualization research where theory does not appear to translate to application and practice. One interesting possibility is that there is a disjoint between how researchers and managers define uncertainty visualization. As seen in this research, managers refer to the visualization of uncertainty in their decision making process. Although this visualization does not fit the definition of explicit uncertainty visualization used by researchers, it fits the decision making schema of the water managers.

This research suggests that water managers are aware of, and willing to address, uncertainty in many forms. Water managers discuss the sources and presence of this uncertainty, often explicitly analyzing the magnitude of the uncertainty present. Even with explicit evaluations, uncertainty is not considered as separate from the underlying problem, but as an integral, implicit characteristic. This contrasts to the approach of uncertainty visualization research, which visualizes uncertainty explicitly, as a separate piece of information.

Similarly, when exploring the relationship between uncertainty and potential decision outcomes, or presenting information to decision makers and the public, waters managers indicate that representing uncertainty is important. However, managers also stress that explicit representations often negatively affect the decision process. Here, it is not beneficial to evaluate the exact quantity of uncertainty present, but instead, to elucidate the relationship between uncertainty and potential decisions (and outcomes). Complex representations that require decision makers to work through the uncertainty separately often result in delayed decisions or an inability of decision makers to act on the provided information.

As managers appear to accept the presence of uncertainty in the decision process, and indicate that their practices already incorporate uncertainty visualization, it is worth questioning why there is such apathy among users regarding demand for uncertainty visualization tools in GIS. Viewing decision making under uncertainty as a process offers a flexible interpretation of uncertainty, which evolves from explicit during initial analysis and discovery to implicit for evaluation and making the decision. If explicit representations are not beneficial for evaluating potential outcomes or presenting information to decision makers and the public, then apathy towards existing uncertainty visualization methods is reasonable, as existing tools do not provide the necessary flexibility. Reframing uncertainty research to build on how water managers address uncertainty in decision making offers an opportunity to bridge the gap between research and practical application.

Conclusions

The importance of GIS as a decision support tool in water resources management organizations is well known and confirmed by the water managers in this study. Water managers themselves are typically not directly charged with the daily operation of a GIS, but tend to be the recipients of the output of analyses and maps. In this manner, managers derive benefits directly from the use of GIS in their organization, without being the direct users of GIS themselves. The benefit is evidenced in the unanimously positive view of GIS in these organizations.

Uncertainty visualization, as defined in GIScience and visualization research, is not adopted by water managers in this study. Water managers identify uncertainty as important for decision making, indicating that differing forms of representation are appropriate for different decision tasks and users. Explicit evaluation is desirable for initial analysis of uncertainty, but may complicate the decision process if presented to decision makers and the public. Existing representation methods are not viewed as sufficient to support exploration of relationships between uncertainty and outcomes or communicating with decision makers and the public. This suggests that decision makers are open to addressing issues related to uncertainty, are willing to use uncertainty visualization, and currently do so in their decision making. They just do not use GIS for this purpose, at least not in a manner consistent with existing explicit representations of uncertainty.

Future uncertainty visualization research might capitalize on this willingness, incorporating users' understanding of uncertainty and visualization. Implicit representations incorporate the subjectivity and context, offering methods to explore the relationships between uncertainty and decision outcomes, and communicating those relationships to decision makers. For water managers, possible options for implicit representation include the use of scenarios to represent uncertain model results or graphs to communicate uncertain model variables. These are ideas already familiar to water managers, and allow for contextual and experiential interpretation. The disconnect between researchers implementation of uncertainty visualization and water managers' use of uncertainty, combined with a lack of understanding of the technical capabilities of GIS, might explain why GIS is not used for uncertainty visualization in practice. Education of managers, along with an expansion of the definition of uncertainty visualization to incorporate these varied approaches, might result in a demand for uncertainty visualization in GIS software and applications.

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