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Designing and evaluating a groundwater quality Internet GIS

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A B S T R A C T

Contaminated unregulated drinking water in rural communities is a continuing health issue, leading many resource users to unknowingly consume water with elevated levels of harmful chemicals. Though geographic information systems (GIS) and Internet technology have been particularly useful for water resource management, to date, there exist few studies that specifically address the development of Internet-based GIS applications to increase user access to unregulated drinking water source information. Informed by an existing user centered development framework for Internet mapping, we created an Internet GIS that visualized groundwater contamination on the Navajo Nation in the southwest United States. We employed a usability focus group, expert review of content and pilot test of a prototype GIS application to gather empirical evidence on effectiveness for informing users of a significant water quality issue. Results suggested that the designed and deployed GIS application was appropriate for the target audience of environmental nongovernmental organization (ENGO) and institution of higher education (IHE) professionals. Usability testing and expert review confirmed the importance of these evaluation measures to ensure a high quality GIS prior to deployment. Use of existing Internet mapping guidelines was found to be insufficient for creating a refined GIS interface appropriate for the target audience. Additionally, we demonstrated that an existing user centered design and evaluation framework could be applied successfully to visualize water quality for unregulated groundwater wells in the rural southwest United States. Suggestions for continued research in the use of Internet GIS to inform rural residents about drinking water quality are provided.

Introduction

Approximately 43 million Americans obtain drinking water from unregulated sources not subject to the water quality testing requirements of the Safe Drinking Water Act; nearly all of these unregulated sources are domestic groundwater wells (Kenny et al., 2009). As a result, many domestic well owners are unaware of the quality of their drinking water, possibly consuming elevated levels of contaminants known to have negative human health consequences (Backer & Tosta, 2011). Approximately one in five unregulated sources in the United States provides drinking water that includes arsenic, uranium, nitrate or bacteria at levels exceeding human health benchmarks (DeSimone, Hamilton, & Billiom, 2009). The presence of contaminants coupled with minimal regulation requires increased understanding of unregulated drinking water source (UDWS) quality and the design new tools for disseminating water quality information (Backer & Tosta, 2011; Charrois, 2010; Lucas, Cabral, & Colford, 2011; Roche, Jones-Bitton, Majowicz, Pintar, & Allison, 2013).

Existing water resources education efforts focus on disseminating water quality information for UDWS through flyers, brochures, television and radio advertisements, along with focus group discussions regarding water quality and health impacts (Chen et al., 2007; Hanchett, Nahar, Van Agthoven, Geers, & Rezvi, 2002; Jones et al., 2006; Kreutzwiser et al., 2011; Roche et al., 2013). Internet geographic information systems (GIS) technology is also a promising tool with capacity to address the dissemination challenges of UDWS source quality.

Dynamic visualization of environmental data, using GIS technology, has been applied previously to water resource management challenges (Choi, Engel, & Farnsworth, 2005; Dymond, Regmi, Lohani, & Dietz, 2004; Saltenberger, 2011), water quality

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monitoring (Elder, 2013; Jankowski, Tsou, & Wright, 2007) and water resources data management (Horsburgh, Tarboton, Maidment, & Zaslavsky, 2008; Horsburgh et al., 2009). However, there exists limited research applying this technology for the dissemination of UDWS quality information. In particular, an Internet GIS application has the capacity to enable UDWS users to access and view water quality information in a dynamic, user-friendly environment, particularly in rural geographic locations. Since rural resource users often experience difficulty accessing and interpreting water quality test results (Kreutzwiser et al., 2011), Internet GIS applications may alleviate this problem by presenting water quality information in a comprehensible manner accessible to the general public.

The goal of this paper is to describe research results about the value of an Internet GIS for improving access to UDWS water quality information, from the perspectives of professionals associated with environmental nongovernmental organizations (ENGOs) and institutions of higher education (IHEs). Research and advocate individuals from these entities serve as a link between resource users and regulatory agencies. Furthermore, ENGO and IHE professionals' opinions about Internet GIS are critical for understanding how to effectively employ the technology to best inform water resource users about the quality of unregulated drinking water in rural areas of the United States. GIS technology represents a promising platform for raising issue awareness about groundwater contamination, potentially leading to positive changes in how UDWS consumers behave and perceive of health consequences. To examine this potential, we present an Internet GIS application designed to disseminate water quality information for UDWS on the Navajo Nation in the southwest United States.

Internet GIS

GIS experts and novices commonly use the Internet to locate, access and visualize scientific and environmental information (Butler, 2006). For example, an online mapping application with a simple interface is easily employed without training, helping viewers to grasp environmental data (Kelly & Tuxen, 2003). Internet GIS applications have low user incurred costs since they are free to access, easy to use, require no specialized software to view information and are responsive to user requests (Harrower, 2004; Peterson, 2012). Several technological advances, such as rich Internet applications (RIAs), web services, application programming interfaces (APIs) and representational state transfer (REST) technologies enhance the storage, development and dissemination of GIS applications for environmental data (Peterson, 2012).

RIAs are graphically robust and combine the distributed nature of the Internet with desktop interactivity, rapid response and high functionality (Kay, 2009). These applications reflect the cross platform compatibility, rapid deployment and efficient loading of distributed Internet services (Strode, 2012). Google Maps, introduced in 2005, is one well-known RIA example. Google Maps has proven to be a significant improvement over other contemporary mapping sites due to its ease of use and visual responsiveness to user requests (Crampton, 2009; Miller, 2006). Additionally, RIAs make use of web services and APIs to facilitate and simplify the dissemination of novel, web-based geographic information (Frew & Dozier, 2012). A webservice is a set of rules enabling machine-to-machine communication via the Internet (Goodall, Horsburgh, Whiteaker, Maidment, & Zaslavsky, 2008); APIs consist of pre-formatted code that a programmer calls using JavaScript, php, or other scripting language (Hu, 2012). The code is made accessible using representational state transfer (REST), which is a combination of Internet protocol, host and application pathways linking users to resources on a server (Battle & Benson, 2008). Clients (e.g., web browsers) access web services through an interface characterized by a unique resource identifier (URI). This interface is generic and uniform, and all resources are stateless, meaning user requests do not change the service (Zhong, Jiang, & Hu, 2012). APIs and REST facilitate the creation of Internet-based geographic information applications (Chow, 2008; Frew & Dozier, 2012; Haklay & Zafiri, 2008) since they are easy to access and incorporate into Internet applications.

Over the previous 30 years Internet GIS has progressed from a stateless, static map to a dynamic map interface that includes real time analytical processing tools that uses resources from multiple web services. APIs, RIAs and REST are crucial for the adoption of powerful Internet GIS applications (Peterson, 2012) and the storage and dissemination of environmental data benefits from these technologies. As a result, there exists much potential for using the visualization, accessibility and analysis capabilities of Internet GIS to impact positively the study of unregulated water sources.

Geospatial Internet user interface and application design

The map interface design is a critical element of a successful Internet GIS, framing the manner in which the end user interacts with GIS features and environmental data. General guidelines regarding the basic structure of an Internet GIS are available in published literature (Table 1). An effective Internet GIS application uses a clear and simple layout with consistent menus and limited options to reduce user error (Nivala, Brewster, & Sarjakoski, 2008). Online map users expect Internet maps to contain click events to view attribute information about map features (Komarkova, Novak, Bilkova, Visek, & Valenta, 2007; Krammers, 2008). This function enables the map designer to provide detailed information (including metadata) to users without cluttering the interface (Leitner & Buttenfield, 2000). Online map users also expect to re-center the map dynamically, to change map scale and view greater detail for specific areas (Harrower & Sheesley, 2005). Furthermore, the map size should be as large as possible on the webpage to maximize viewing area while minimizing the page space filled by non-map features (Harrower & Sheesley, 2005).

Table 1
A survey of existing Internet GIS design guidelines.

Design aspect	Significance to GIS design
Menus and sub-menus	Should remain concise and consistent throughout the site. Limited commands reduce user error.
Feature identification	Clicking on an object to view attribute information is useful and expected by users.
Layer control	Non-expert users rarely utilize advanced functionality including changing layers.
Panning	Panning is the ability to re-center or reposition the focus on the map on screen.
Zooming	Zooming is most effective when map landmarks are used. The landmarks should be repetitive and appropriate for the users and the scale.
Legend	Users prefer an icon with associated text to help reduce ambiguity.
Map caching	Tiled maps improve page performance and decrease loading time.
Metadata	Important so that users can assess the validity and timeliness of information. Accuracy and detection limits are useful for understanding data limitations.
Map size	Maximize screen area of map and minimize advertisements and non-map areas.
Color	Carefully choose color scheme so as to not confuse the map user.
Page layout	Use simple home page and consistent layout.
Software plugins	Limit use of plugins to maximize accessibility and avoid participant attrition due to out of date software.

Previous research regarding map legend design has indicated that map icons, on their own, may be confusing; a legend combining a textual description with the map icon effectively communicates the meaning of each map feature (Krammers, 2008). Furthermore, layer control, while useful for people with GIS training, has proven challenging for untrained users. As a result, published literature suggests that map layer controls be disabled for novice users, and that the map designer use scale dependent rendering to provide greater map detail without cluttering the interface (Nivala et al., 2008). Although plugin-based applications have powerful visualization and analytical capabilities, users need to maintain the most current version of the plugin to access the application. Researchers have suggested use of scripts, such as JavaScript, for the deployment of Internet GIS applications to maximize the number of users who are able to access the GIS using common web browsers (Komarkova et al., 2007).

Internet GIS

We applied existing design guidelines (Table 1) to create an Internet GIS application to improve access to UDWS quality information for groundwater wells on the Navajo Nation in the southwest United States. The selected study area represented an example of a pervasive water quality issue found in rural areas of the United States.

Study area

The study area was limited to the Navajo Nation (NN), which includes 27,425 square miles of land in Arizona, New Mexico and Utah, a population of 173,667 and a population density of 6.33 people per square mile (Navajo Epidemiology Center, 2013). According to the NN Environmental Protection Agency (NN EPA), 182 public water systems on the NN serve 12,000 acre-feet (AF) of drinking water annually (NNEPA, 2014); however, 30–40% of NN residents rely on unregulated drinking water sources (Leeper, 2003; US BOR, 2009). The selected study site (i.e, NN) is appropriate for this research since it illustrates drinking water quality issues representative of rural groundwater contamination. Additionally, the site represents users who live in geographically isolated areas with limited access to water quality information and public water systems.

Water quality issue in the study site

The quality of water from unregulated sources is of particular concern within rural areas of the United States since contamination affects more than one in five UDWS (DeSimone et al., 2009). Previous studies at the national level in the United States have reported that 6–11% of unregulated drinking water wells have arsenic concentrations exceeding the Safe Drinking Water Act Maximum Contaminant Level (MCL) of 10 μg per liter (Ayotte, Gronberg, & Apodaca, 2011; DeSimone et al., 2009; Focazio, Tipton, Shapiro, & Geiger, 2006). More specifically, arsenic is one of the most common groundwater contaminants in Arizona, New Mexico and Navajo Nation (Camacho, Gutiérrez, Alarcón-Herrera, de Loudres Villlba, & Deng, 2011; Fennema, 2013; Focazio, Welch, Watkins, Helsel, & Horn, 2000; Uhlman, Rock, & Artiola, 2010). Arsenic drinking water contamination represents a significant public health concern in areas that rely on unregulated sources to supply drinking water, such as the NN.

Previously collected water quality data, compiled for US Environmental Protection Agency (EPA) studies about drinking water quality throughout the NN, are available on a GIS data DVD upon request or through several interactive websites associated with researchers from Northwestern University (Navajo Nation Water Quality Project) and Western Washington University (Forgotten People Participatory Mapping and Environmental Justice). These projects did not explicitly describe arsenic contamination, which is one of the primary water contaminants of concern in the study area (Camacho et al., 2011). Therefore, a need exists to better inform NN residents about arsenic issues, since 30–40% lack public water supply access, which increases their reliance on unregulated groundwater that may expose consumers to arsenic. Geospatial technology is an untapped and promising method for disseminating arsenic water quality information on the NN. One recent study contained maps to communicate UDWS contamination and health risk information to NN residents (deLemos et al., 2009). The study reported a strongly positive view of maps for conveying water quality information to water well users; however, this study made use of paper maps and did not explore the potential benefits of dynamic visualization through an Internet GIS.

Study population

Ultimately, the drinking water consumer is most affected by the acquisition of water quality information. However, the general public often fails to understand and address water related issues (Charrois, 2010), lacking direct access to usable and comprehensible water quality information (Kreutzwiser et al., 2011). Entities, such as environmental nongovernmental organizations (ENGOs) and institutions of higher education (IHEs), work to provide timely and accurate information to resource users, addressing information disparities among the general public (Mills & Clark, 2001; Singh & Rahman, 2010). ENGO and IHE professionals assume a critical role in the dissemination of water quality information to stakeholders within environmental management (Agarwal, 2008). These entities also assume an important role in the provision of GIS technology and geospatial data for use in environmental decision-making processes (Sieber, 2002). Given these qualities, the study population is delimited to individuals from ENGOs and IHEs, as the entry point for evaluating the capacity and potential for using Internet GIS technology to inform the general public about UDWS quality issues in rural areas. The rationale for selecting this population as the initial research focus is found in each entity's capacity to reach the masses of people to whom each serves, by presenting stakeholders contemporary information about arsenic contamination in rural drinking water supplies.

Internet GIS design process

We created an Internet GIS application by adapting a user centered design framework (Fig. 1) proposed by Tsou and Curran (2008). The selected framework includes (1) determining the overall scope of the GIS and the spatial database design, (2) creating an implementation strategy for the GIS and database, (3) selecting a web map server and designing the map browser, and (4) evaluating the interface. This framework has been used previously by several researchers in the development of water resources related Internet GIS applications (Elder, 2013; Saltenberger, 2011).

Using published design guidelines (Table 1) and an existing development process (Fig. 1), we created an Internet GIS that illustrated arsenic contamination and safe drinking water access throughout the NN.

Goals and strategy

The goals for the Internet GIS application were to (1) visualize existing arsenic measurements for unregulated groundwater wells and (2) illustrate access to water hauling stations. To accomplish these goals, we created a dynamic and interactive map accessible

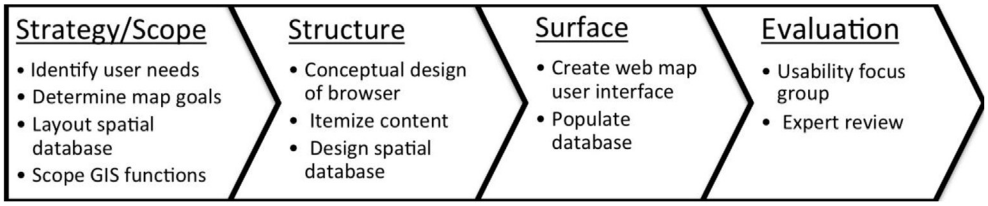

Fig. 1. Visual summary of the development and evaluation process used to create the Internet GIS.

through an Internet browser, using web services to visualize water quality information and access to water hauling stations.

Database design and data layers

To access water information, users required the ability to change map scale, re-center the map, display multiple data layers simultaneously and access instructional materials to properly employ tools and understand terminology. Spatially referenced water quality information and the locations of water hauling stations were the most important data used in this GIS application. The remaining information included base map features that provided geographic markers, which helped orient users as they employed the Internet GIS. We identified the following geospatial data layers as necessary for the mapping product:

- Unregulated drinking water sources tested for arsenic contamination
- Water hauling stations
- Public water systems
- Political boundaries
- Paved roads
- Highways
- Populated places
- Residential structures

The unregulated well attribute information included measured dissolved arsenic concentrations (μg per liter) for 239 locations, available from previous United States EPA studies (US EPA, 2000). The NN EPA provided location (latitude and longitude coordinates) and attribute information for 67 water hauling stations. We also created a layer to represent locations of existing public water systems on the NN. The remaining base map data were available from previous US EPA studies. These data were compiled into a file geodatabase with defined relationships among the data layers, employing the WGS 1984 geographic coordinate system and Web Mercator Auxiliary Sphere projection. This projection was selected so the published map services were compatible with a published topography web mapping service selected for use in the online application.

Map implementation strategy

To access the water quality information users were required to employ panning, zooming and navigation features, access map feature attribute information through click events, and use a spatial analysis function that visualized safe drinking water access (Table 2).

The spatial analysis feature (illustrated in Fig. 2) enabled a user to select any location within the NN boundary and dynamically visualize driving distances to nearby water hauling stations. After a user selected a starting location, the spatial analysis tool first calculated service area polygons using a road network layer and then executed a vector point-in-polygon spatial intersect to identify water hauling stations located within the service areas. A service area is a region that includes all streets accessible within a given distance from one or more starting locations (ESRI, 2012). The result was a set of driving distance polygons representing 5, 14 and 25 mile (one direction) driving service areas, and the water hauling stations located within the driving polygon boundaries. These distances were selected to illustrate a range of driving distances, including the average water hauling distance for an NN resident (14 miles). We also selected a driving distance service area, rather than a Euclidean distance buffer, since this more appropriately characterized water-hauling accessibility for the rural study area.

After identifying necessary online mapping features and populating a spatial database, we selected the map symbols, colors and fonts, and arranged the layout of the GIS functions in the web browser. The Internet GIS application was built using the ESRI JavaScript API (version 3.2) and HTML. JavaScript has previously been shown to be an effective scripting language for online mapping and is read natively by the web browser so there is no need to install browser plugins (Peterson, 2012). The web mapping and geoprocessing services were created with ArcGIS Server 10.1 and

Table 2
Summary of Internet GIS mapping features, functions and tools.

Mapping feature	Description
Feature identification	A mouse click event opened an information window with attribute information about the selected map feature.
Zoom and pan	Zooming enabled the user to change the map scale and panning allowed the user to re-center the map.
Reset map extent	Located on the main map page, this button reset the map to its original extent. A second button was located with the spatial analysis feature to remove the results and reset to the original map scale.
Navigation and scale	Navigation arrows were included in the map frame along with a scale bar set to English units.
Timer	A JavaScript enabled timer informed the participant of how long he or she used the Internet GIS.
Dynamic layer rendering	Data layers were set with scale dependencies so the map interface would not appear cluttered at small scales.
Instruction pane	A collapsible window was placed in the map frame with suggestions for using the GIS application.
Arsenic gauge	This widget visualized contamination levels (μg per liter) using a gauge that was linked with unregulated wells and a mouse cursor hover over event handler.
Map legend	The legend illustrated the icon and textual description of all features visible on the map. The legend content updated as the user adjusted map scale.
Spatial analysis function	This function used a geoprocessing service activated by a click event to create three service area polygons (5, 14 and 25 miles) and subsequently executed a point-in-polygon intersect function to identify water hauling stations in the service areas.
Index	Included definitions for water resources and GIS terms used in the GIS application.

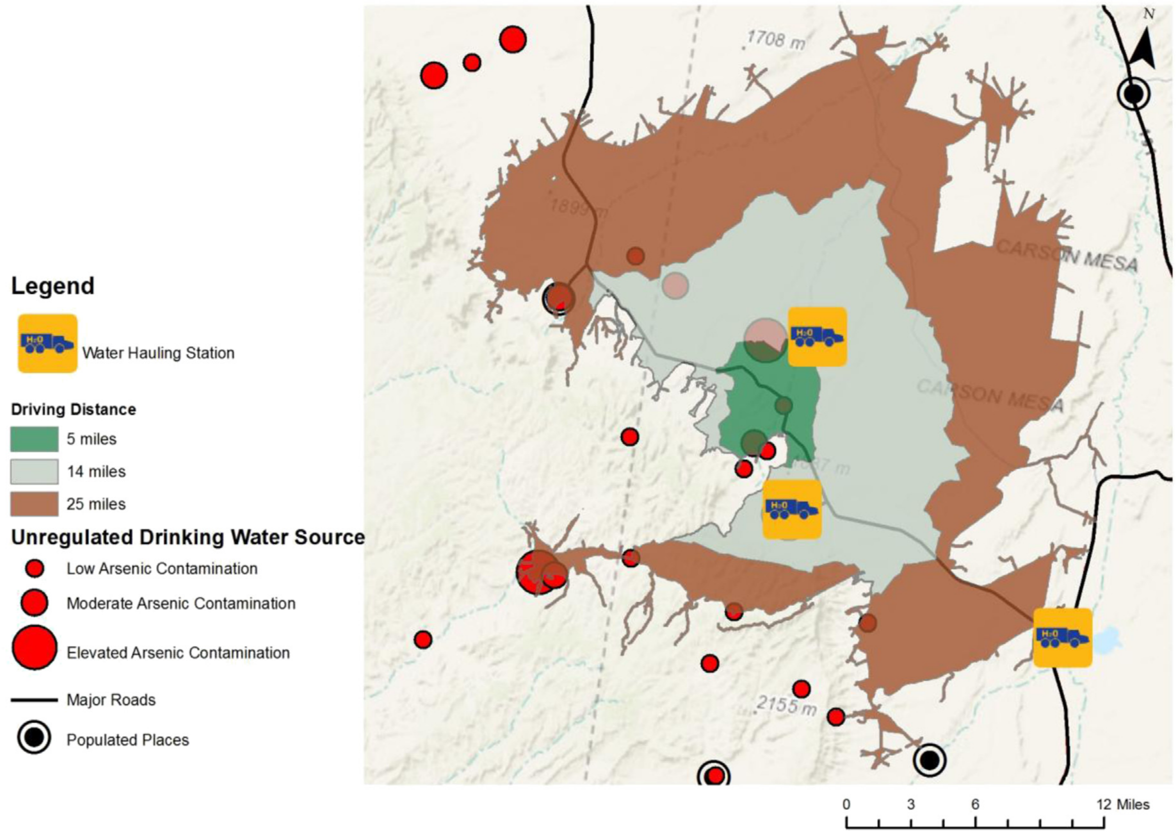

Fig. 2. Example of the spatial analysis tool output illustrating driving distance to water hauling stations.

deployed on an Amazon Elastic Cloud Computing (EC2) Amazon Machine Instance that included 3.75 GB of memory, 2 EC2 computing units, and Windows Server 2008. Cloud computing was used for the deployment of web services since it is an economically viable way to develop and maintain a web map (Zhang, 2012), was easily scalable and configurable (Mell & Grance, 2011), and reduced the need for local server infrastructure (Tsou, 2011).

Web browser design

The Internet GIS application was comprised of a single page with a main map area, collapsible map overview text window, a gauge widget that illustrated arsenic contamination (in μg per liter) and three accordion panes (Fig. 3). Users opened and closed these panes to view the map legend, a spatial analysis feature interface and an index of water resource and GIS terms. The unregulated water sources are illustrated by the graduated dots visible in the figure.

The GIS application was accessible through a website that included a home page, background information on water quality issues in the study area, details regarding the Internet GIS and information about the present study. This website included general information about NN drinking water sources, water quality and access to public water systems. The pages were intended to provide background information about the study area. The site also included contact information for the researchers and information about the broader study.

Prototype evaluation methods

After designing a prototype version of the Internet GIS application, it was evaluated with a usability focus group and expert content review. The goal for using these two evaluation methods was to refine the prototype based on expert and user review.

Usability focus group

Four ENGO and IHE professionals were recruited to participate in evaluating the Internet GIS to identify potential usability problems with the prototype design. Given the nature and purpose of the focus group, a small number of individuals were sufficient to identify major usability issues associated with the GIS application (Molich, Ede, Kaasgaard, & Karyukin, 2004; Nielsen, 1997; Tsou & Curran, 2008; Virzi, 1992). Two academic participants were recruited including a doctoral student with a research focus on western water issues and a professor of Geographic Information Science. The selected ENGO professionals worked in natural resource mapping and management including one ENGO participant who was a GIS web developer and another who had experience in using GIS technology.

The usability evaluation method was adapted from Nielsen (1997) and Nivala et al. (2008), with input and support provided by an experienced usability professional at the University of Denver. Employing Morae usability software, the usability sessions (including screen activity and task completion times) were recorded. Morae is an unobtrusive data collection software that aids data analysis and enables researchers to collect audio and visual records for quantitative and qualitative evaluation (Asselin & Moayeri, 2010). The software, which is highly relevant to the procedures used in the present study, also uses the built-in computer microphone to record participant comments and a camera mounted on the test computer monitor to record the evaluation process. At a second computer, a researcher may watch and listen to participants as they complete the tasks and record notes for later evaluation.

Five usability tasks were created to evaluate the layout and design of the website and GIS application (Table 3). The first three usability tasks were designed to evaluate website layout, content

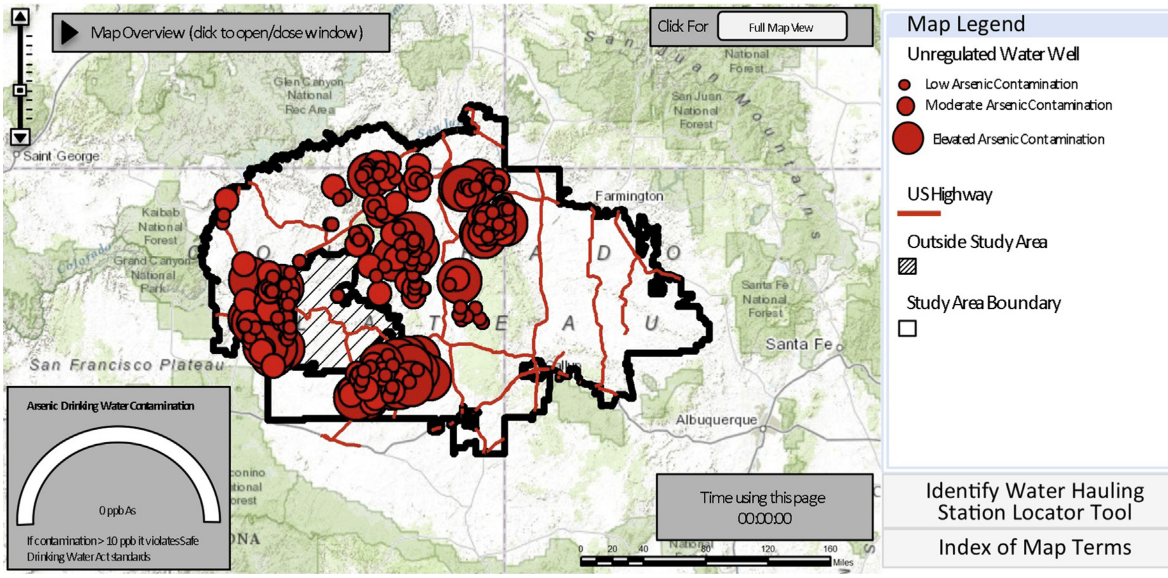

Fig. 3. Illustration of the designed and tested Internet GIS. The study area extent, arsenic gauge (bottom left corner) and map legend are visible.

and formatting using a high fidelity wireframe. A high fidelity wireframe, developed with AxureRP software, has a wide breadth of features, high degree of functionality and aesthetic refinement pertinent for website evaluation (Sauer & Sonderegger, 2009). The fourth and fifth usability tasks were designed to evaluate the layout and design of the Internet GIS application and its various functions. A proctor asked each participant to verbalize thoughts while completing each usability task (known as think aloud protocol), which Morae software recorded. Use of the think aloud protocol informed the researchers of problem-solving strategies each participant used while completing the tasks (Newman et al., 2010; Roth & Harrower, 2008). All tasks were provided to participants individually and sequentially.

The focus group members identified various usability issues that were classified into one of four categories based on severity: (1) cosmetic, (2) minor, (3) major, and (4) catastrophic (Nielsen, 1993; Nivala et al., 2008). A cosmetic issue prompts a feeling that the site is not polished and a minor usability issue makes the application difficult to use. A major usability issue represents a significant challenge for using the site and a catastrophic issue may prevent a participant from using the site at all (Nivala et al., 2008). Based on the usability evaluation, we made several adjustments to the website and GIS prototype prior to contacting NN water quality experts for review of GIS water quality information.

Usability evaluation results

Each usability participant successfully completed all assigned tasks. This indicates that, regardless of the identified usability issues, the GIS application and its functions were sufficiently designed, enabling ENGO and IHE participants to explore the visualized water quality issue. However, the goal of a usability evaluation is to improve the user experience by identifying design challenges.

Sample mean and range of completion times (Table 4) are reported for each usability task. We did not compute formal usability metrics or statistics due to the small sample size. The results indicated a range of completion times dependent upon task complexity. As previously described, tasks 1, 2 and 3 were associated with the website emphasizing site layout and formatting, while tasks 4 and 5 pertained exclusively to the Internet GIS application. Usability results indicated that the average completion time for each task increased with complexity. The first three tasks required reading the webpage for information and the final two tasks required using GIS tools and features to locate information. As

Table 3
Usability tasks administered for the website and Internet GIS prototype evaluation.

Task ID	Task(s)	Evaluated GIS feature(s)
1	• Who is the principal investigator for this study and how do you contact this person?	Website layout and the participant's ability to locate this information from headers.
2	• What is the definition of a public water supply? • What percentage of Navajo Nation residents lack access to public water supply?	Information layout, text and font size. Also, the flow from one webpage to the next.
3	• What areas within the United States experience groundwater arsenic contamination? • What are the health effects associated with arsenic drinking water exposure?	Website captions and the appropriateness of figures for conveying water quality information.
4	• What is the arsenic contamination level at the Chapter House, Red Valley drinking water well?	Layout of Internet GIS and the search, zoom and identifying features.
5	• How many wells within 5 km of the town of Cove have severe arsenic contamination? • How many wells within 15 km of the town of Tuba City have low arsenic contamination?	Spatial analysis feature interface and interpretation of results.

Table 4
Summary of mean and range of task completion times.

Task	$\overline{X}$ (s)	Range (s)
1	58	17–78
2	122	69–172
3	210	71–407
4	288	176–369
5	405	252–554

Note: refer to Table 3 for task descriptions.

a result, tasks 4 and 5 required more time to complete than tasks 1, 2 and 3.

In total, participants identified 55 usability concerns including 41 unique issues, which were classified by severity. The uniquely identified usability issues included 17 cosmetic issues, 18 minor issues and six major issues. Participants identified 22 issues associated with the website content including the size of images, font size, typeface and color. There were also 32 identified map usability issues pertaining to (a) map rendering after a scale change, (b) symbol choice for groundwater wells, (c) questions about the service area created by the spatial analysis feature and its title (d) size of the scale bar, (e) the absence of instructions for clicking on map features to access attribute information, and (f) insufficient explanations about the map symbols.

Interface changes following usability evaluation

Based on the feedback from the focus group, we made several revisions to the prototype to improve usability. Where appropriate font size was enlarged to make content more readable, the number of words on the pages was reduced to make content more approachable, and page layout was simplified by removing inset text boxes. The scale bar size was increased and a collapsible panel with suggestions for using the GIS application was added to the map page, indicating the ability to click on features and access attribute information.

During the usability evaluation, participants experienced difficulty with the spatial analysis feature due to unclear instructions. Also, the working title of the spatial analysis feature ("Driving Distance Buffer Tool") failed to convey its purpose, resulting in participants experiencing difficulty locating the feature on the GIS application page. These findings are significant in that if a participant is unable to assess and understand the tool's purpose, misuse or misinterpretation of the tool is likely to occur (Krammers, 2008). Therefore, to address these major usability issues we changed the tool title to "Water Hauling Station Locator Tool" and redesigned the interface to better communicate the tool's purpose (Fig. 4).

The original spatial analysis feature interface attempted to (1) help users identify and re-center the map on a specific region of the NN; (2) specify the desired level of water quality (low, moderate and high); and, (3) specify the driving distance (5–50 km in 5 km increments). Focus group participants reported that these options were difficult to employ correctly due to confusing instructions, ambiguous or undefined meanings of various terms (e.g., water quality level). Participants also disliked the use of kilometers and the fact that available driving distances were displayed one at a time without the option of viewing multiple distances simultaneously. Based on this input, the interface was redesigned to only require that the users indicate the starting location on the map, with multiple driving distances (changed to miles) programmatically identified (2, 5 and 15 miles), the option to specify the water quality level was removed.

Several other identified issues pertained to use of a search feature that required participants to enter a place or unregulated well name into a textbox. The input information was in turn used to query the attribute tables of populated places and unregulated well feature layers. The search function worked effectively during the usability evaluation since we provided the names of wells and towns for participants to locate. However, participants noted that the search was case sensitive and did not return results when place names were misspelled (or indicate that a misspelling occurred). Simple changes to the JavaScript code could be initiated, such as a drop down list of populated place names and unregulated water wells in the study area, to resolve these challenges. However, upon further evaluation, we determined that the search feature would likely be unnecessary for most users since it required detailed geographic knowledge of NN populated places and familiarity with unofficial names of unregulated water wells. We anticipated that many of the potential users would likely be less interested in this feature since they were not exclusively familiar with NN geography, and were more interested in broader drinking water challenges in the rural region. Therefore, we removed the textbox search feature from the prototype prior to pilot testing.

Expert content review

In addition to the focus group examination of the GIS prototype, we solicited input for content accuracy of the website and Internet GIS application from water resource professionals associated with the US EPA, NN EPA, and Indian Health Service agencies. These professionals were knowledgeable in the domain of NN groundwater contamination and drinking water. This evaluation method was employed based on research that supports expert review of geospatial content used in the development and evaluation of water resource GIS applications (Slocum, Cliburn, Feddema, & Miller, 2003). We contacted eight NN water resources experts and from this pool, five professionals agreed to provide feedback regarding the website and GIS application. The experts were contacted via email and asked for his or her professional, expert opinion on the appropriateness of the presented information for representing arsenic groundwater contamination throughout the NN.

Expert reviewer results

Three of the five individuals who expressed willingness to provide content review of the site completed the task (response rate of 60%). These individuals reported more than 20 years of experience at their respective agencies working in the areas of water and health. All total, expert reviewers provided 18 comments about the GIS application and website. The reviewer comments were positive, supporting the use of the website and GIS application. For example, each of the three reviewers stated that the website and GIS application were interesting, easy to use and accurately represented arsenic groundwater contamination on the NN. Furthermore, two reviewers stated that the spatial analysis feature accurately represented driving distances to water hauling stations on the NN and that use of a driving network was appropriate. In addition to these positive comments, the expert reviewers provided several suggestions to improve the GIS and website content. In particular, comments were expressed about the use of the color scheme to illustrate the unregulated water wells, the size of the service area for the spatial analysis feature and the visibility of metadata for the water quality information. We addressed each of these issues in the revised prototype GIS prior to the pilot test.

Improvements to the GIS application based on expert reviewer comments

The reviewers commented on the color of the symbols used to represent unregulated drinking water sources on the NN. The original symbols were green, yellow or red (in the web version)

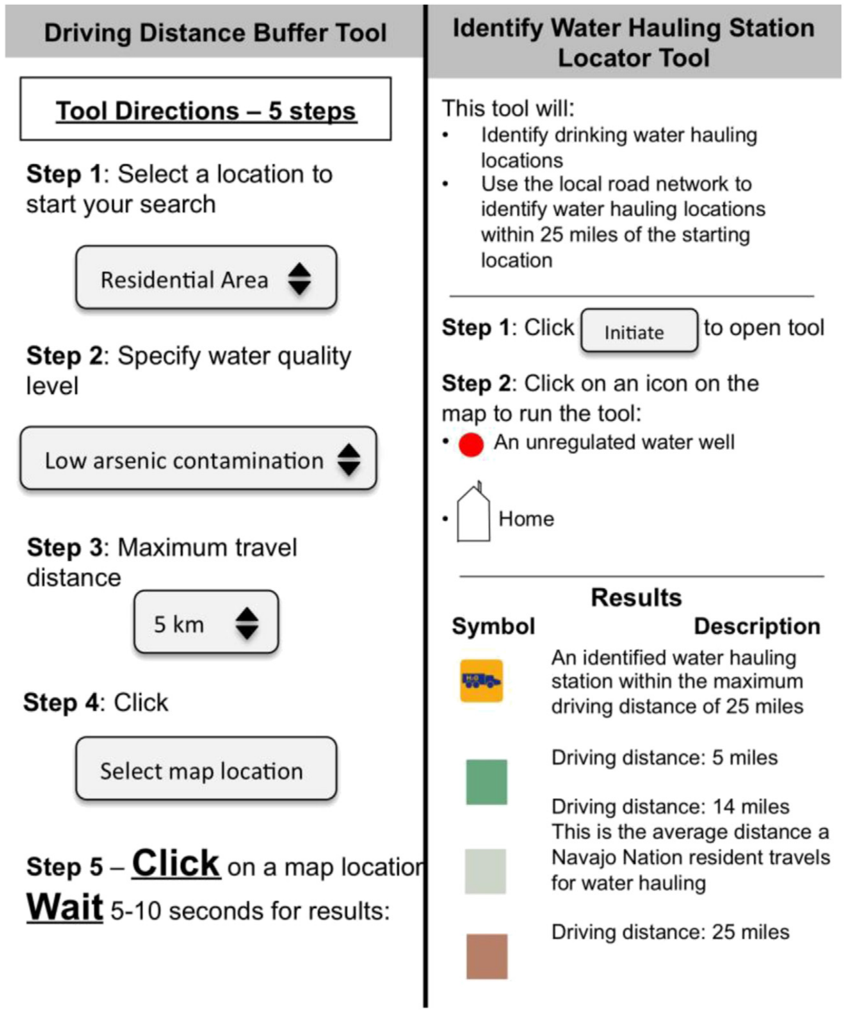

Fig. 4. Illustration of the original (left panel) and the redesigned (right panel) spatial analysis feature interface.

circles classified based on health risk associated with arsenic drinking water consumption (i.e., green low risk, yellow moderate risk, red elevated risk, in the web version). However, the reviewers pointed out that from a regulatory perspective, the use of green or yellow (in the web version) symbols might inadvertently encourage use of unregulated wells, which is counter to the policy of the NN EPA. To address these concerns, the UDWS symbols were changed to red graduated circles (classified as low, moderate and elevated contamination), with size indicating a greater concentration of dissolved arsenic in the water sample (Fig. 5).

Therefore, the revised symbols reflected the regulatory perspective of the expert reviewers by visualizing arsenic concentrations without suggesting that water be consumed from unregulated sources; though, we recognize that some resource users and non-regulatory groups may disagree with this classification.

In regards to the spatial analysis feature, one reviewer suggested increasing the size of the driving service areas. This reviewer thought the visualization of driving distances to water hauling stations was interesting and useful for policy makers who need assistance understanding safe drinking water access on the NN. The expert suggested increasing the size of the service areas (originally 2, 5 and 15 miles) to reflect larger distances, since NN residents who haul drinking water drive an average of 14 miles (one way) to reach a water hauling station. Increasing the size of the service areas makes the feature a more effective visualization tool. To address this suggestion, the service areas were increased in size to 5, 14 and 25 miles to provide a range of driving distances, including the average water hauling distance on the NN of 14 miles.

Lastly, we addressed requests for additional metadata about the water quality information. One reviewer stated that the visualized water quality information accurately represented the safe drinking water challenges on the NN, yet the source of that information was difficult to locate. To address this concern, we added metadata to the identification information window for unregulated water wells. For example, when a user identified an unregulated water well an information window was generated with attribute information for the well. The sampling date, sampling agency and measured arsenic concentration were automatically included in the window in an easy-to-read bulleted list. After making the described adjustments to the GIS application, the website and GIS were disseminated to a group of individuals from the ENGO and IHE target populations for a pilot test.

Pilot test

Pilot test design

A revised version of the prototype GIS application was developed based on results obtained from the focus group usability testing and expert content reviews. The revised version of the site

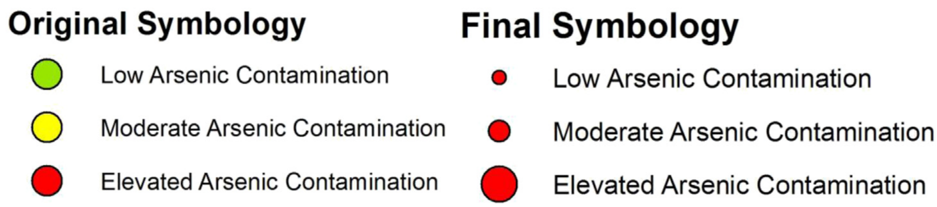

Fig. 5. Illustration of the original (left panel) and final symbology (right panel) for unregulated drinking water wells.

was piloted by a group of study participants. A stratified random sample of 30 individuals was selected from a compiled list of more than 200 potential study participants located in the western United States. We invited 30 individuals since Internet GIS studies have low participation rates (Brown & Kyttä, 2014) and a pilot test size is commonly 10–20% of the anticipated full study size (Baker, 1998). For the pilot, our goal was recruitment of 10–15 individuals (anticipated full scale study size of 100 participants). The invited pilot test participants included water managers, program managers, GIS developers, university faculty and a state water extension specialist.

The pilot test was designed to evaluate the extent to which participants successfully accessed the site, navigated to the GIS application and used it as intended. We also sought to evaluate if participants could locate a survey link on the GIS page and complete an online survey. Each participant was individually contacted via email and asked to view the website, use the GIS and complete an online survey. The survey was created using Lime Survey, which is an online software useful for the development and deployment of survey tools. The survey questions included:

1. Responding in two or three sentences, what environmental problem do you think the web GIS application illustrated?
2. With what type of organization are you primarily affiliated: ENGO or IHE?
3. How much experience do you have using web-based GIS applications?
4. How comfortable are you using the Internet?
5. Do you have prior knowledge of water quality issues in the study area?

Question 1 was open ended and designed to evaluate if GIS users could articulate, in their own words and without suggestion from the researchers, the purpose of the GIS application. The remaining survey items were multiple choice questions that enabled a respondent to select a response that best fit his or her background and experiences. Multiple choice options were provided so that answers would be standardized among all respondents.

Follow up emails were sent two and four weeks after initial contact. We used Google Analytics to monitor how people accessed the site, the number of unique visitors, and geographic locations of visitors (state level). Google Analytics is a free analytics software hosted by Google that is useful for evaluating website usage and behavior and has been previously employed in the assessment of Internet GIS applications (Veregin & Wortley, 2014; Werts, Mikhailova, Post, & Sharp, 2012).

Pilot test results

In total, Google Analytics recorded 22 unique site visitors (73% website response rate) between March 4 and April 9, 2013, which was the pilot test period. A site visit was recorded when an invited participant used a website link to access the website directly. Site sessions originated from five western US states including Arizona, California, Colorado, Idaho and Nevada and from individuals known to be abroad at the time email invitations were received. Google Analytics also indicated that of the 22 site visitors, 13 opened and used the GIS application. These same 13 individuals accessed and completed the survey.

The pilot test administration yielded relevant user feedback that informed strengths and challenges of using an Internet GIS to convey water quality information. Overall, strengths included easy access to the website and GIS application, direct access to water quality data for wells in the study area, and a demonstrated capacity to identify and articulate the visualized water quality problem. Survey results indicated that 13 participants started and completed the survey for a participation rate of 43% (13 of the 30 invited participants) and a survey completion rate of 100%. The survey results indicated that 100% of respondents stated that the GIS application visualized contamination of groundwater on the NN, with 77% specifically indicating arsenic as the contaminant of concern. This demonstrates that the GIS application successfully conveyed quality information about unregulated drinking water wells to users.

In regards to challenges associated with using an Internet GIS to convey water quality information for rural areas, seven participants (54% of survey respondents) provided critiques of the website and GIS application. One respondent mentioned that some of the language used on the website and GIS was unfamiliar and needed additional explanation; however, this participant did not indicate which terms were unclear. Other comments suggested that the map icons representing public water systems and identified water hauling stations (from the spatial analysis feature) were too similar. The remaining comments pertained to cosmetic issues such as font size and spacing, and the processing speed of the spatial analysis tool.

Demographic information about the pilot test participants was collected using the survey (Table 5). As shown, the pilot test participants were comfortable with the Internet, had more than 1 year of experience using Internet GIS applications and were aware of groundwater quality issues on the NN though did not consider themselves experts in this area.

Discussion

Pilot test results indicated that participants with a range of GIS skills and prior knowledge of water quality issues successfully used the application. The GIS application successfully illustrated the water quality issue indicating its use as a promising practice to inform rural water users of drinking water contamination concerns. The user centered design framework employed in this study led to the creation of an Internet GIS application that accurately conveyed visualized UDWS information and was appropriate for the target population. Furthermore, a development process that included a focus group usability evaluation and expert review of content led to the identification and resolution of major usability issues informing revisions prior to the pilot test. A similar process is recommended to researchers in the development of future water quality Internet GIS applications.

Table 5
Summary of pilot test participant characteristics.

Characteristic	Count (*n*)	Percentage (%)
Employment type		
IHE	9	69.2
ENGO	4	30.8
Internet comfort level		
Somewhat uncomfortable	1	7.7
Somewhat comfortable	1	7.7
Complete comfortable	11	84.6
Internet GIS experience		
None	2	15.4
1–3 years	5	38.5
3–5 years	6	46.1
Prior knowledge of NN water issues		
None	2	15.4
Some awareness but no details	3	23.1
Detailed knowledge but do not consider self an expert	8	61.5

The pilot test comments also demonstrate that it remains difficult to address all usability issues associated with a website and GIS application with a small focus group. In particular, we found that the GIS application may contain some minor issues associated with the selection of map features and concerns with the processing speed of the spatial analysis tool. Lastly, the development and use of an Internet-based application presents vocabulary challenges. Elimination of professional jargon and an easily accessible and clearly defined index helps to alleviate this problem. Considering the parameters of the identified cosmetic and other minor issues, the Internet GIS application presented in the present study illustrates the value of user centered design and Internet GIS technology for visualizing UDWS quality information.

Conclusion

The developed Internet GIS tool was a rich Internet application that relied on web services accessed via their REST endpoints to provide dynamic visualization and mapping features for water quality information. The applied design and evaluation framework enabled the creation of a website and GIS application that visualized unregulated drinking water source quality information for the Navajo Nation and is one example of a user-friendly application that enables access to water quality information for unregulated water sources. The design process and use of individuals from various backgrounds and experiences improved site terminology, greatly reduced jargon, helped amend the layout and verified content. Extensive use of pretesting methods used in conjunction with a user centered design approach provided opportunities for participants to voice opinions about the prototype application prior to full deployment, assisting researchers to create a tool appropriate for the target population. Internet GIS technology is a promising tool for outreach and education at the intersection of GIScience, public health and rural water drinking water challenges. Using the developed GIS application, additional research is necessary to build on these results, expanding to measure empirically the value of Internet GIS for disseminating water quality information regarding unregulated sources to users.

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References

Agarwal, A. (2008). The role of NGOs in the protection of environment. *Journal of Environmental Research and Development, 2*(4), 933–938.
Asselin, M., & Moayeri, M. (2010). New tools for new literacies research: an exploration of usability testing software. *International Journal of Research & Method in Education, 33*(1), 41–53.
Ayotte, J. D., Gronberg, J. M., & Apodaca, L. E. (2011). *Trace elements and radon in groundwater across the United States, 1992–2003*. U.S. Geological Survey scientific investigations report (p. 115). Reston, Virginia: U.S. Geological Survey.
Backer, L. C., & Tosta, N. (2011). Unregulated drinking water initiative for environmental surveillance and public health. *Journal of Environmental Health, 73*(7), 31–32.
Baker, T. L. (1998). *Doing social research* (3rd ed.). McGraw-Hill.
Battle, R., & Benson, E. (2008). Bridging the semantic web and web 2.0 with representational state transfer (REST). *Web Semantics: Science, Services and Agents on the World Wide Web, 6*, 61–69.
Brown, G., & Kyttä, M. (2014). Key issues and research priorities for public participation GIS (PPGIS): a synthesis based on empirical research. *Applied Geography, 46*, 122–136.
Butler, D. (2006). The web-wide world. *Nature, 439*, 776–778.
Camacho, L. M., Gutiérrez, M., Alarcón-Herrera, M. T., de Loudres Villlba, M., & Deng, S. (2011). Occurrence and treatment of arsenic in groundwater and soil in northern Mexico and southwestern USA. *Chemosphere, 83*, 211–225.
Charrois, J. W. A. (2010). Private drinking water supplies: challenges for public health. *CMAJ, 182*(10), 1061–1064.
Chen, Y., van Geen, A., Graziano, J., Pfaff, A., Madajewicz, M., Parvez, F., et al. (2007). Reduction in urinary arsenic levels in response to arsenic mitigation efforts in Araihazar, Bangladesh. *Environmental Health Perspectives, 115*(6), 917–923.
Choi, J.-Y., Engel, B., & Farnsworth, R. L. (2005). Web-based GIS and spatial decision support system for watershed management. *Journal of Hydroinfomatics, 7*(3), 165–174.
Chow, E. T. (2008). The potential of maps APIs for internet GIS applications. *Transactions in GIS, 12*(2), 179–191.
Crampton, J. W. (2009). Cartography: maps 2.0. *Progress in Human Geography, 33*(1), 91–100.
DeSimone, L. A., Hamilton, P. A., & Billiom, R. J. (2009). *The quality of our nation's waters – Quality of water from domestic wells in principal aquifers of the United States, 1991–2004. Overview of major findings* (p. 48). Reston, Virginia: U.S. Geological Survey.
Dymond, R. L., Regmi, B., Lohani, V. K., & Dietz, R. (2004). Interdisciplinary web-enabled spatial decision support system for watershed management. *Journal of Water Resources Planning and Management, 130*, 290–300.
Elder, P. (2013). *Designing and implementing a web mapping service with user-centered design and the sensor web: A case study in the San Diego River watershed*. San Diego, CA: San Diego State University.
ESRI. (2012). *Generate service areas (network analyst)* (Vol. 2014). Redlands, CA: ESRI.
Fennema, S. J. (2013). *Unregulated water source on the Navajo Nation: Assessing risk of unregulated water supplies and optimal placement of regulated water supply points*. Reno: University of Nevada.
Focazio, M. J., Tipton, D., Shapiro, S. D., & Geiger, L. H. (2006). The chemical quality of self-supplied domestic well water in the United States. *Ground Water Monitoring & Remediation, 26*(3), 92–104.
Focazio, M. J., Welch, A. H., Watkins, S. A., Helsel, D. R., & Horn, M. A. (2000). *A retrospective analysis on the occurrence of arsenic in ground-water resources of the United States and limitations in drinking-water-supply characterizations*. Water-resources investigations report 99-4279. Reston: US Geological Survey.
Frew, J. E., & Dozier, J. (2012). Environmental informatics. *Annual Review of Environment and Resources, 37*, 449–472.
Goodall, J. L., Horsburgh, J. S., Whiteaker, T. L., Maidment, D. R., & Zaslavsky, I. (2008). A first approach to web services for the national water information system. *Environmental Modeling & Software, 23*, 404–411.
Haklay, M., & Zafiri, A. (2008). Usability engineering for GIS: learning from a screenshot. *The Cartographic Journal, 45*(2), 87–97.
Hanchett, S., Nahar, Q., Van Agthoven, A., Geers, C., & Rezvi, M. F. J. (2002). Increasing awareness of arsenic in Bangladesh: lessons from a public education programme. *Health Policy and Planning, 17*(4), 393–401.
Harrower, M. (2004). A look at the history and future of animated maps. *Cartographica, 39*(3), 33–42.
Harrower, M., & Sheesley, B. (2005). Designing better map interfaces: a framework for panning and zooming. *Transactions in GIS, 9*(2), 77–89.
Horsburgh, J. S., Tarboton, D. G., Maidment, D. R., & Zaslavsky, I. (2008). A relational model for environmental and water resources data. *Water Resources Research, 44*(5), W05406.
Horsburgh, J. S., Tarboton, D. G., Piasecki, M., Maidment, D. R., Zaslavsky, I., Valentine, D., et al. (2009). An integrated system for publishing environmental observations data. *Environmental Modeling & Software, 24*, 879–888.

Hu, S. (2012). Multimedia mapping on the internet using commercial APIs. In M. P. Peterson (Ed.), *Online maps with APIs and webservices*. New York: Springer-Verlag Berlin Heidelberg.

Jankowski, P., Tsou, M.-H., & Wright, R. (2007). Applying internet geographic information system for water quality monitoring. *Geography Compass, 1*(6), 1315–1337.

Jones, A. Q., Dewey, C. E., Doré, K., Majowicz, S. E., McEwen, S. A., David, W.-T., et al. (2006). Public perceptions of drinking water: a postal survey of residents with private water supplies. *BMC Public Health, 6*(94).

Kay, R. (2009). *Rich internet applications*. In *Computerworld* (Vol. March 30/April 6) (p. 34).

Kelly, N. M., & Tuxen, K. (2003). WebGIS for monitoring "sudden oak death" in coastal California. *Computers, Environment and Urban Systems, 27*, 527–547.

Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K., & Maupin, M. A. (2009). *Estimated use of water in the United States in 2005*. Reston, VA: United States Geological Survey.

Komarkova, J., Novak, M., Bilkova, R., Visek, O., & Valenta, Z. (2007). Usability of GeoWeb sites: case study of Czech regional authorities web sites. *BIS, 4439*, 411–423.

Krammers, R. E. (2008). Interaction with maps on the internet – a user centred design approach for the atlas of Canada. *The Cartography Journal, 45*(2), 98–107.

Kreutzwiser, R., de Loë, R., Imgrund, K., Conboy, M. J., Simpson, H., & Plummer, R. (2011). Understanding stewardship behaviour: factors facilitating and constraining private water well stewardship. *Journal of Environmental Management, 92*, 1104–1114.

Leeper, J. W. (2003). Navajo Nation plans for their water future. In *48th Annual New Mexico water conference*. Santa Ana Pueblo: New Mexico Water Resources Research Institute.

Leitner, M., & Buttenfield, B. P. (2000). Guidelines for the display of attribute certainty. *Cartography and Geographic Information Science, 27*(1), 3–14.

deLemos, J. L., Brugge, D., Cajero, M., Downs, M., Durant, J. L., George, C. M., et al. (2009). Development of risk maps to minimize uranium exposures in the Navajo Churchrock mining district. *Environmental Health, 8*(29).

Lucas, P. J., Cabral, C., Colford, J., & John, M. (2011). Dissemination of drinking water contamination data to consumers: a systematic review of impact on consumer behaviors. *PLos One, 6*(6).

Mell, P., & Grance, T. (2011). *The NIST definition of cloud computing*. Gaithersburg, MD: National Institute of Standards and Technology.

Miller, C. (2006). A beast in the field: the Google maps mashup as GIS/2. *Cartographica, 41*(3), 187–199.

Mills, T. J., & Clark, R. N. (2001). Roles of research scientists in natural resource decision-making. *Forest Ecology and Management, 153*, 189–198.

Molich, R., Ede, M. R., Kaasgaard, K., & Karyukin, B. (2004). Comparative usability evaluation. *Behaviour & Information Technology, 23*(1), 65–74.

Navajo Epidemiology Center. (2013). *Navajo population profile 2010 U.S. census* (p. 53). Window Rock, Arizona: Navajo Division of Health.

Newman, G., Zimmerman, D., Crall, A., Laituri, M., Graham, J., & Stapel, L. (2010). User-friendly web mapping: lessons from a citizen science website. *International Journal of Geographical Information Science, 24*(12), 1851–1869.

Nielsen, J. (1993). *Usability engineering*. Amsterdam: Morgan Kaufmann.

Nielsen, J. (1997). Usability testing. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (2nd ed.) (pp. 1543–1568). New York: J. Wiley.

Nivala, A.-M., Brewster, S., & Sarjakoski, L. T. (2008). Usability evaluation of web mapping sites. *The Cartographic Journal, 45*(2), 129–138.

NNEPA. (2014). *Public water systems (PWS)* (Vol. 2014). Window Rock, AZ: Navajo Nation Environmental Protection Agency.

Peterson, M. P. (2012). Online mapping with APIs. In M. P. Peterson (Ed.), *Online maps with APIs and webservices*. New York: Springer-Verlag Berlin Heidelberg.

Roche, S. M., Jones-Bitton, A., Majowicz, S. E., Pintar, K. D., & Allison, D. (2013). Investigating public perceptions and knowledge translation priorities to improve water safety for residents with private water supplies: a cross-sectional study in Newfoundland and Labrador. *BMC Public Health, 13*.

Roth, R. E., & Harrower, M. (2008). Addressing map interface usability: learning from the lakeshore nature preserve interactive map. *Cartographic Perspectives, 60*, 46–93.

Saltenberger, J. (2011). *An interactive web-based atlas for the Spokane Valley-Rathdrum Prairie aquifer*. San Diego, CA: San Diego State University.

Sauer, J., & Sonderegger, A. (2009). The influence of prototype fidelity and aesthetics of design in usability tests: effects on user behaviour, subjective evaluation and emotion. *Applied Ergonomics, 40*, 670–677.

Sieber, R. (2002). Geographic information systems in the environmental movement. In W. J. Craig, T. M. Harris, & D. Weiner (Eds.), *Community participation and geographic information systems* (p. 383). London: Taylor & Francis.

Singh, H. R., & Rahman, S. A. (2010). An approach for environmental education by non-governmental organizations (NGOs) in biodiversity conservation. Asia Pacific international conference on environment-behaviour studies. *Procedia – Social and Behavioral Sciences, 42*, 144–152. Sarawak, Malaysia.

Slocum, T. A., Cliburn, D. C., Feddema, J. J., & Miller, J. R. (2003). Evaluating the usability of a tool for visualizing the uncertainty of the future global water balance. *Cartography and Geographic Information Science, 30*(4), 299–317.

Strode, G. (2012). Guidelines for implementing ArcGIS API for flex developers. In M. Peterson (Ed.), *Online maps with APIs and webservices*. New York: Springer-Verlag Berlin Heidelberg.

Tsou, M.-H. (2011). Revisiting web cartography in the United States: the rise of user-centered design. *Cartography and Geographic Information Science, 38*(3), 250–257.

Tsou, M.-H., & Curran, J. M. (2008). User-centered design approaches for web mapping applications: a case study with USGS hydrological data in the United States. In M. Peterson (Ed.), *International perspectives on maps and the internet* (pp. 301–321). Berlin: Springer.

Uhlman, K., Rock, C., & Artiola, J. (2010). *Arizona drinking water well contaminants*. University of Arizona Cooperative Extension Publication AZ1503, Tucson, AZ.

US BOR. (2009). *Navajo-Gallup water supply project* (Vol. 1). Salt Lake City, UT: US Bureau of Reclamation.

US EPA. (2000). *Abandoned uranium mines project: Arizona, New Mexico, Utah. 1994–2000*. Washington DC: US Environmental Protection Agency.

Veregin, H., & Wortley, A. J. (2014). Using web analytics to evaluate the effectiveness of online maps for community outreach. *Journal of Web Librarianship, 0*, 1–22.

Virzi, R. (1992). Refining the test phase of usability evaluation: how many subjects is enough? *Human Factors, 34*(4), 457–468.

Werts, J. D., Mikhailova, E. A., Post, C. J., & Sharp, J. L. (2012). An integrated Web GIS framework for volunteered geographic information and social media in soil and water conservation. *Environmental Management, 49*, 816–832.

Zhang, J. (2012). A high-performance web-based information system for publishing large-scale species range maps in support of biodiversity studies. *Ecological Informatics, 8*, 68–77.

Zhong, J., Jiang, N., & Hu, B. (2012). Research and design of a novel webGIS framework based on REST and RIA. *Procedia Engineering, 29*, 903–908.