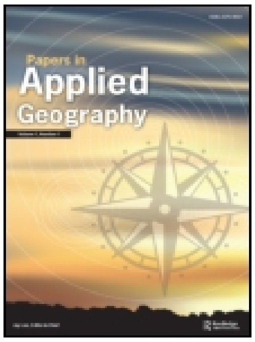

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RESEARCH ARTICLE

An Interdisciplinary Approach for a Water Sustainability Study

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ABSTRACT

Interdisciplinary research is often challenging as a result of the different backgrounds of researchers from different disciplines. Such difficulty frequently hinders the understanding, communication, and collaboration among researchers from different disciplines. Meanwhile, research methods in geography can effectively link and synthesize different discipline-specific information. In this study, we show the application of geographic information systems (GIS) for the spatial analysis in a water sustainability project. We also show that GIS, as a spatial decision support system, could be effectively used for managing both hydrologic and social factors. With GIS, the project was able to integrate multidisciplinary data sets and visualize spatial information via a Web platform for sharing and communication. Our study demonstrated that geographic research methods could be effective when facilitating collaborations among the humanities, social science, and engineering to quantify social objectives and constraints, and providing insight in solving grand challenge problems.

KEYWORDS
Inter-discipline; water sustainability; geospatial data integration; collaboration

Water resource management is a difficult challenge to the sustainability of aquatic ecosystems due to increasing demands, climate change, and their degradation (Raskin, Hansen, and Margolis 1996; Godfray *et al.* 2010; Duan, Fedler, and Hochmuth 2012). Effective management of water resources not only requires extensive knowledge in hydrological modeling, water conservation, and treatment, but also needs to take into account socioeconomic factors, public policy, and social behavioral feedback in decision-making processes (Sedlak and Schnoor 2013; White 2013; Singh, Khedun, and Mishra 2014). Researchers have suggested an interdisciplinary approach to addressing challenges to water-related issues that theoretically integrate human factors into the hydrological models with social feedbacks (Wiek and Larson 2012; Sivapalan *et al.* 2014). Given the complexity of such issues, an interdisciplinary approach was often needed to effectively confront these challenges. Interdisciplinary research often requires researchers with very different backgrounds to understand and communicate with each other, however. Such collaborations frequently press researchers beyond their own expertise, which greatly challenges the success of such collaborations.

We argue that research methods in geography can be a useful tool to facilitate interdisciplinary water resource research by synthesizing and visualizing various discipline-specific information, identifying geospatial relationships among information coming from different sources in different formats, and facilitating decision-making processes through map analyses. In this study, we explored the

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application of geographic research methods in interdisciplinary research by using a recently funded Mellon Grand Challenge Exploratory project, "Equitable Water Policy Decision Making," as an example. Although the project is still in the stage of building its final model, we showcase here three major contributions made possible by this project: (1) synthesizing multidiscipline information by an integrated geodatabase that took into account both physical and social factors related to water resources, and could be easily utilized by all the researchers in the project; (2) visualizing spatial information by using a Web-based platform to display and communicate information between research teams, which helped to remove the barrier of domain expertise; and (3) analyzing spatial and temporal patterns across disciplines. The first two contributions allowed researchers from different disciplines to understand, visualize, and use information from each other; and the third one allowed the team to discover spatial and temporal relationships beyond disciplinary boundaries.

Previous studies

Geography research methods have been proven an effective tool in multidisciplinary data integration, but they now face various new challenges (Li 2007; Kawabataa *et al.* 2010; Kong 2015). Geographic information system (GIS)-based modeling, analysis, and data integration have been applied in many different research fields, such as health, environment, and transportation (Corwin and Wagenet 1995; Goodchild 2000; Murray *et al.* 2009). In addition, by integrating data from various disciplines, GIS promotes the crosswalk between disciplines (Alibrandi 1998; Koedam *et al.* 2004; Wang 2013). Geography research methods have also been integrated in multicriterion decision-making processes for more than two decades (Carver 1991; Church, Loban, and Lombard 1992; Pereiraa and Duckstein 1993; Malczewski 1996).

Studies have found that GIS techniques and procedures have an important role to play in analyzing decision problems by integrating spatially referenced data in a problem-solving environment, including the application of GIS in hydrology and water resource (Cowen 1988; Malczewski 1996; Chakhar and Martel 2003). In recent years as we stepped into the era of big data, multidisciplinary information is available in a variety of formats from many different data sources. This information includes spatially referenced data, as well as nonspatial data. How to integrate these data sets into a well-organized spatial database to truly promote interdisciplinary research is a challenge that GIScience faces (Yi, Li, and Cheng 1999; Kong 2015).

Moreover, the recent development of Web GIS provides even more possibilities to promote interdisciplinary research (Kim and Kim 2002; Batty *et al.* 2010; Golhani, Rao, and Dagar 2015). Web GIS enables the non-GIS users to visualize spatial information on their Web browser or even mobile devices, which erases the technology barrier of using GIS and integrates spatial thinking across teams in a multidisciplinary project development (Kong, Zhang, and Stonebraker 2015). By placing the spatial information and some simple mapping capability on the Web, researchers can easily visualize and overlay information from other disciplines.

Different from previous water resource spatial decision-making tools, the project discussed in this study was designed to develop a system dynamic model that emphasized the progress and interactions between hydrological modeling and public policy research, allowing the simulation of water resource dynamics in different natural and policy scenarios. In this study, we used a new approach that integrated the relational geodatabase and the Web GIS platform to facilitate the research and communication among researchers, decision makers, and the general public. We demonstrated that our approach could be an effective way to link multidisciplinary data sets, visualize spatial information across teams, conduct geospatial analyses between disciplines, and inform decision makers as well as the general public about our research outcomes.

The equitable water policy decision making project

The overarching goal of the Equitable Water Policy Decision Making project was to explore decision-making tools for water sustainability that utilized both hydrological and social data sets, and accounted

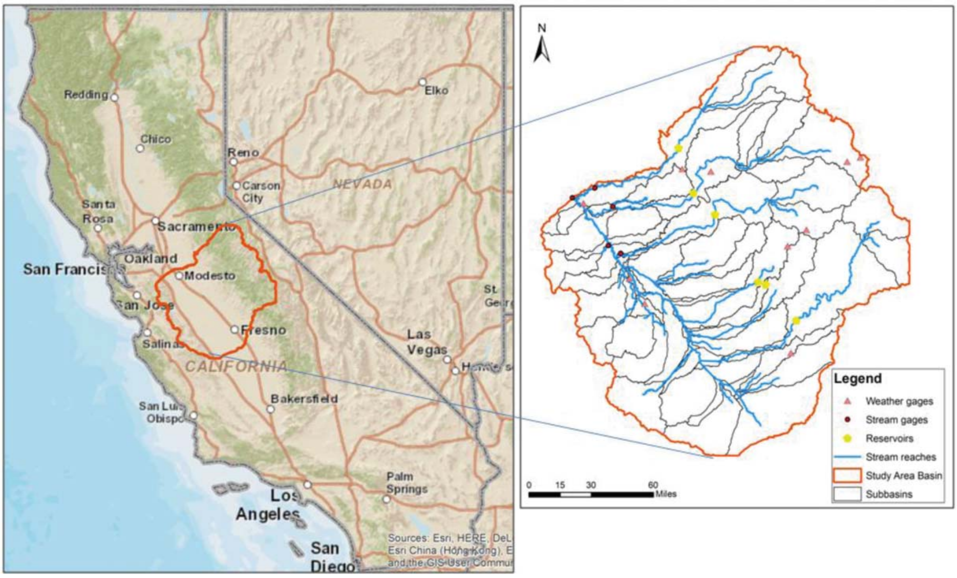


Figure 1. Study area: San Joaquin River watershed in California.

for the feedback loops between the policymaking process and human behavior. Aided by the available "big data" in land cover, hydrology, soil, population, newspapers, and social media, the objective of the project was to construct a water sustainability model designed to take into account the human politics and the feedback effects of policy on social information and water resource use.

The study unit in the project was defined by the watershed divides of the San Joaquin River (SJR), which has an outlet near Vernalis, California (Figure 1). The SJR basin was identified as an ideal location for the study objectives, as water was a strained resource in the region. Even during years with normal precipitation, there was usually a stiff competition among several players for the resource (Hanak *et al.* 2011), which often became aggravated during recurring drought years. Starting in 2013, the study area had been facing one of the most severe droughts on record. In January 2015, the governor of California declared a drought state of emergency and imposed strict conservation measures statewide. Thus, we selected the time period between 2013 and 2015 as our focus.

The overall project included five components, as depicted in Figure 2. Both the hydrological model outputs and policy constraints served as the inputs for the decision-making tools, which generated physically and financially feasible policy options by calculating the physical consequences and the costs and benefits of individuals and groups (businesses, communities, and governments) in the study area. The social feedback component provided the social consequences of hydrological conditions such as

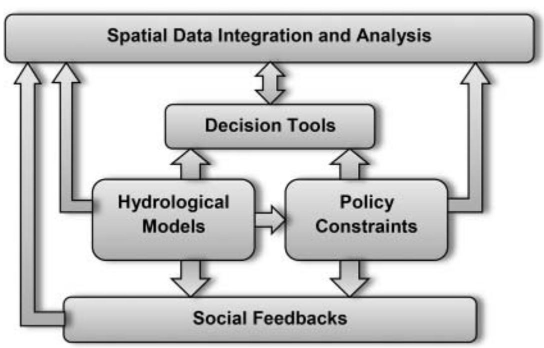


Figure 2. Project layout and team structure.

drought or flood and water policies. The spatial database served as the data warehouse for the overall project, which collected information from the other four teams in the project as well as other background information, and facilitated information exchange among teams. In addition, spatial analysis could provide insights about the relationships between water availability and social feedbacks.

Method and data source

The project team included researchers from engineering, political science, communication, and geography. The "big data" used in this study were distinguished from traditional large databases with three Vs: volume, variety, and velocity (Laney 2001; Baru, Bhandarkar, and Nambiar 2013). The data sets involved in this project had "big" volume, especially for some satellite-imagery-derived data sets and social media data. These data were available in a variety of formats, and some of them required domain experts' knowledge to be utilized. In addition, some of the data sets had the characteristic of great velocity, which included frequently updated information. Therefore, it was difficult for researchers to understand, access, interpret, and analyze another discipline's big data set.

To integrate all of the information in a centralized geodatabase, we had routine group meetings to discuss the needs of different research teams, and then designed the geodatabase with considerations of needs from all aspects. This process started with the collection of the basic information requirements from each individual research team, including the existing information from the spatial data research team. We then laid out the proposed database diagram based on the initial information. During each routine group meeting, the database diagram was discussed and updated accordingly. We added new data that emerged from the interdisciplinary collaboration. For example, when expanding the public policy research to a spatial scale, the researcher requested the addition of zip code boundary into the database. The database diagram was updated periodically until all researchers' data expectations were met.

In the next stage, we implemented the database according to our design. There were four categories of information included in the database: geography, social-economic, hydrology, and social feedback. The geographic data were collected from the U.S. Census Bureau and U.S. Geological Survey with the consideration of both hydrological and political research, including county, zip code, census tract, watershed boundaries, land cover, river, outlet locations, and so on. Selected socioeconomic variables were collected into the database according to their relevance to water demands. We collected these variables for 2012, 2013, and 2014 in the study area from the SimplyMap database at the basic census-tract level. To incorporate the variables for hydrological study, we reviewed the hydrological model, the Soil Water Assessment Tool (SWAT), used by the hydrology team. The relevant SWAT model outputs and parameters were identified and included in the existing database for further analysis.

To study the social feedback of the drought in California, we identified related news reports, Google search trends, and tweets as the major data source. Because the social feedback sources, including media reports and social media, did not have a definite spatial extent, we had to expand our interest area to the whole state of California during the data integration. Although some social media such as geotagged tweets could provide relatively accurate location information, it was estimated that only 1 percent of tweets were geotagged (Gomba 2012), which greatly limited the communication study in our case. Therefore, we included all tweets with geospecific words such as *California* as key words, instead of using geotagged tweets.

The news reports were collected from the LexisNexis Academic database, which included full-text access to newspaper articles as well as federal and state court cases and laws. The numbers of articles from the LexisNexis database related to the California drought were collected for each month during the study period. Similar information was collected from the Google trends of *California drought* search. As for the related social media feedback, the research team purchased proprietary tweets from Crimson Hexagon, retrieved with the location key words and at least one key word related to water or drought or climate. To reduce costs, only one randomly generated day's tweets were purchased for each week from January 2013 to February 2015. The information provided in these tweets includes the time, title, contents, author, name, location, and so on. The data set was cleaned to get rid of the tweets with other water-related topics, such as the key words of *heater, plumber, plumbing*, and so on. After this initial cleaning process, we were left with 99,367 relevant tweets.

To promote spatial thinking across the project development, we provided a Web-based map application that connected the geodatabase to the Web. Researchers from multiple disciplines could easily select the variables they were interested to make a map, or overlay multiple information. At the final stage of the project, this Web application could serve as a communication point for the decision makers once the decision simulation tools were fully developed and integrated into the Web page.

Capacities enabled by geography methods

Database integration

An ArcSDE geodatabase was designed and developed to serve as the central data warehouse with information from different data sources. The enterprise database not only provided the project team with an online platform to share information, but also built the relationships between different tables across disciplines so that team members could easily integrate information from other research areas. Database connection information was provided to all the team members to fit their analysis environment. For researchers who used ArcGIS software (ArcGIS Desktop, Release 10.2.2, 2015, Environmental Systems Research Institute, Redlands, CA), the ArcGIS connection information was provided. For researchers who use statistical software or modeling tools, we provided the database connection method and instruction so that their software such as R and MATLAB could read the data tables. Database components are described in the following paragraphs.

Spatial and social data

A simplified version of the database diagram for spatial and social data is shown in Figure 3. According to different needs in the socioeconomic aspects of the research, we included spatial boundary files at different scales, from country boundary, to states in the United States, counties, zip codes, and census tracts. For socioeconomic factors, the database included data from basic census-tract level during the study period, with linkages to the census tract ID in the spatial file. Thus, these data could be spatially aggregated if needed. The Twitter data were related to countries and states. Furthermore, if the tweets included city information, we added the x, y coordinates of the city point to the Twitter data table.

Hydrological data

The database diagram of hydrologic data is shown in Figure 4. Serving for the SWAT model used in this research, we included all the parameters and variables relevant to the project. The SWAT model was developed in a GIS environment. Most of the inputs were spatial data, including 10-m resolution raster data, as well as vector data for watershed, river, outlet, weather station, and reservoir locations. The weather and reservoir measurement data were saved as tabular data with time and observation information linked to their location files.

Model for data resample

In addition to the originally collected data tables, we also developed a geoprocessing model to resample the data by geospatial unit. The resampling was particularly needed for socioeconomic data, which were originally collected at the census tract level, but the research team was working with different geographical units, such as watershed, county, or zip code. Appropriate assumptions were made during the resampling process. For example, domestic water use for each subbasin was resampled in proportion to its population share, whereas the irrigation needs were assumed to be proportional to the agricultural area in that subbasin.

Data documentation

To remove the interdisciplinary barriers and improve the quality of communication, we documented the geodatabase in two means. First, the detailed database diagram was updated and shared in a timely

Figure 3. Database diagram of spatial and social economic information.

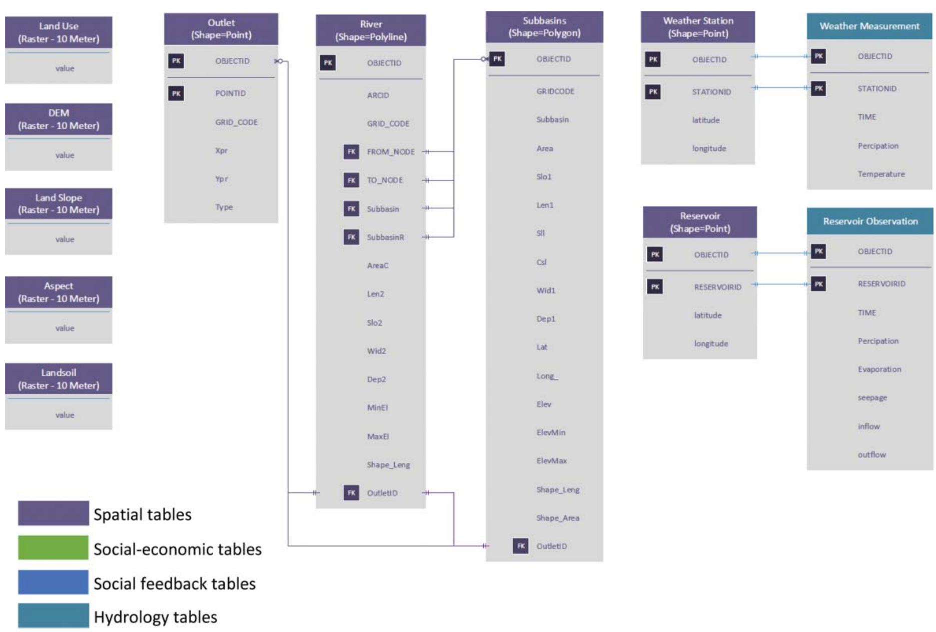


Figure 4. Database diagram of hydrologic information.

manner between teams. The diagram helped team members to have an overall understanding of the available information and project progress, and encouraged them to use information across their discipline boundaries. Second, data documentation allowed the teams to better understand and use the data. Data documentation in this project included a data source listing and a data dictionary. The data source listing documented where and when the data had been collected. A data dictionary is a collection of the data objects' descriptions, including the meaning of each column in the table, measuring units, and so on.

Web-based spatial data visualization

GIS provided the opportunity to visualize spatial information and associated tabular data, which encouraged spatial thinking and facilitated discussion across disciplines. The mapping capability was usually limited by software availability and GIS training, though. In a multidisciplinary project, it might not be possible for every researcher to learn GIS and visualize spatial data on his or her own. To facilitate collaboration from the spatial perspective, we took advantage of Web GIS and visualized the information from our geodatabase using a Web browser.

To create such a Web interface assisting interdisciplinary discussion, we collected inputs from the different research teams. According to their feedback, the Web application was to be developed in two stages. The goal for the first stage was to facilitate discussions between researchers within the project team. At this stage, the application should include basic functions to enable users to (1) summarize and preview spatial information in each discipline; (2) overlay layers either by turning on and off or changing the transparency; and (3) resample and display the spatial data by different spatial units (i.e., county, zip code, census tract). Figure 5 is a screenshot of this first version of the application. The second stage of the Web application was to develop when the decision model was completed. At the second stage, the application was to be expanded with the model to allow decision makers and the general public to adjust variables and simulate water availability under different scenario.

Spatial pattern analysis and coupling

Spatial pattern analysis

Social media contents such as tweets could reflect how society's concerns about a particular topic of interest. By integrating the research topic-related tweets into a geodatabase, we could analyze the

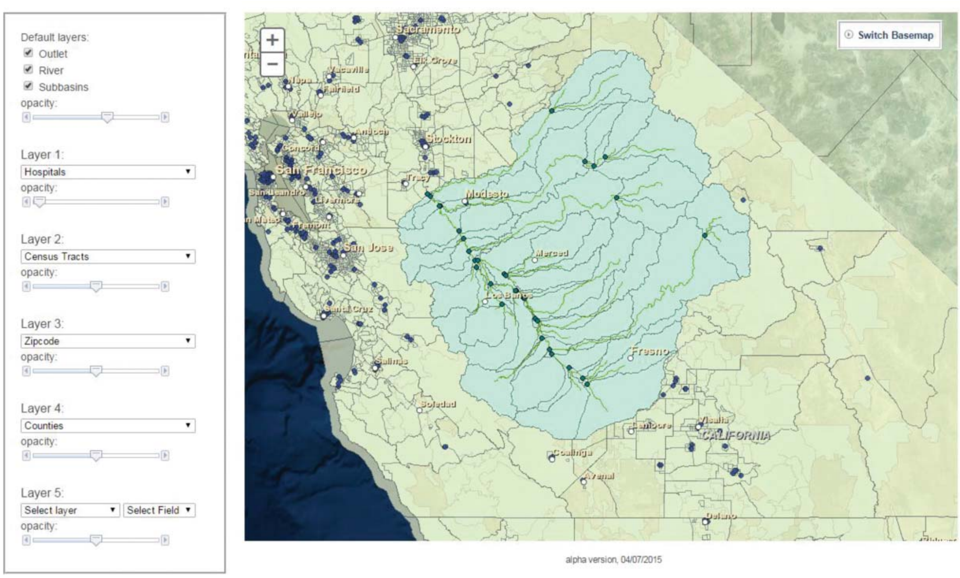


Figure 5. Screenshot of the first version of Web map application.

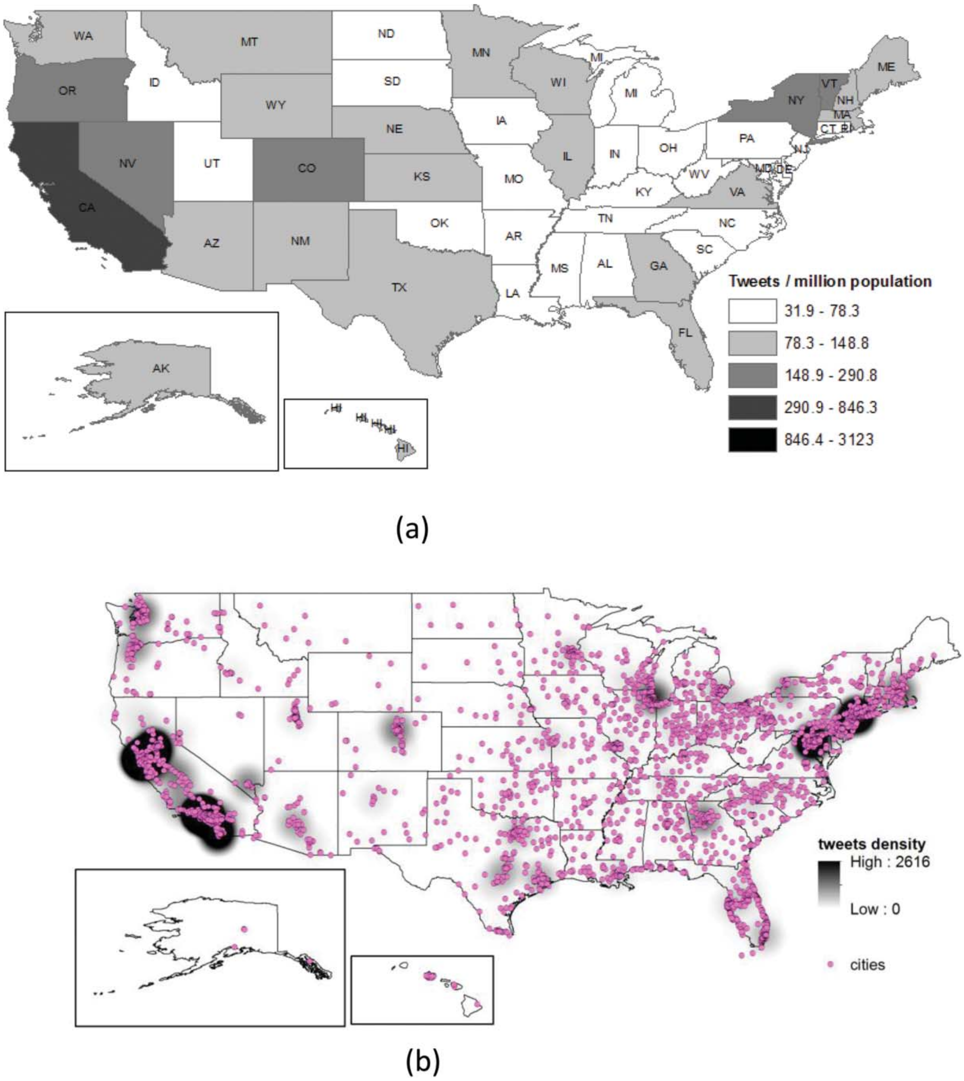


Figure 6. Spatial pattern of social media data related to California drought. (a) Spatial distribution of tweets related to California drought (averaged by population). (b) Kernel density of tweets related to California drought with city information.

spatial distribution pattern of Twitter users and understand which part of the state or country was more concerned about the California drought. For example, we mapped the number of tweets for each state with a normalization by population size (Figure 6A). As expected, the map indicated that California users along with those in its neighboring states, such as Oregon and Nevada, seemed most affected by the drought; interestingly, Twitter users in other parts of the country, including the District of Columbia, New York, Vermont, and Massachusetts, also showed great interest in the drought issue. In addition, tweet density is spatially related to the distribution of cities (Figure 6B). The density was especially high in two metropolitan areas of California, as well as two metropolitan areas in the northeastern United States.

The contents within tweets reflected the users' major concerns about the research topic. We identified the most frequently mentioned key words within the collected tweets. In addition to the tweets retrieval key words we used, other meaningful key words that were frequently used included rain, snow, precipitation, change, farmers, mandatory, restrictions, governor, and more. The spatial pattern of the tweets' contents could tell stories about how geographic locations influenced people's attitude

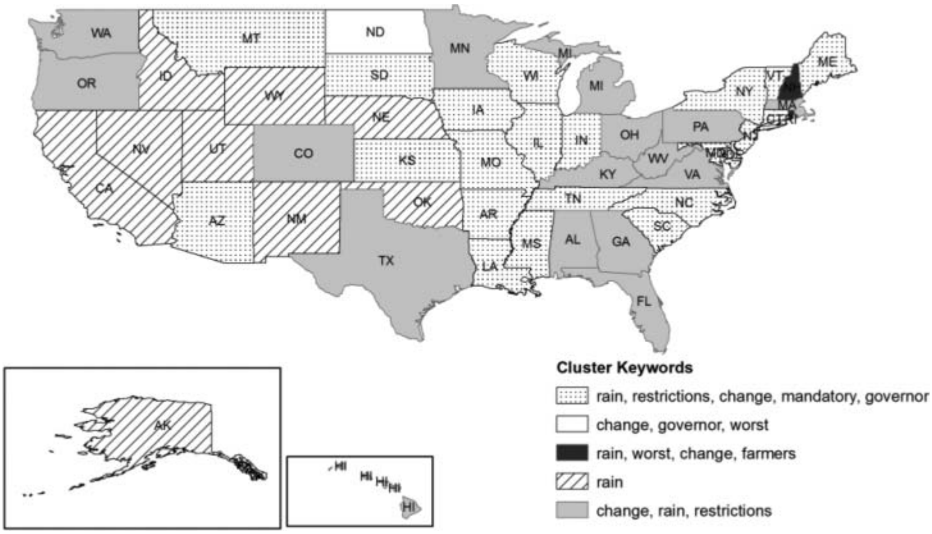


Figure 7. Tweets content clusters by state.

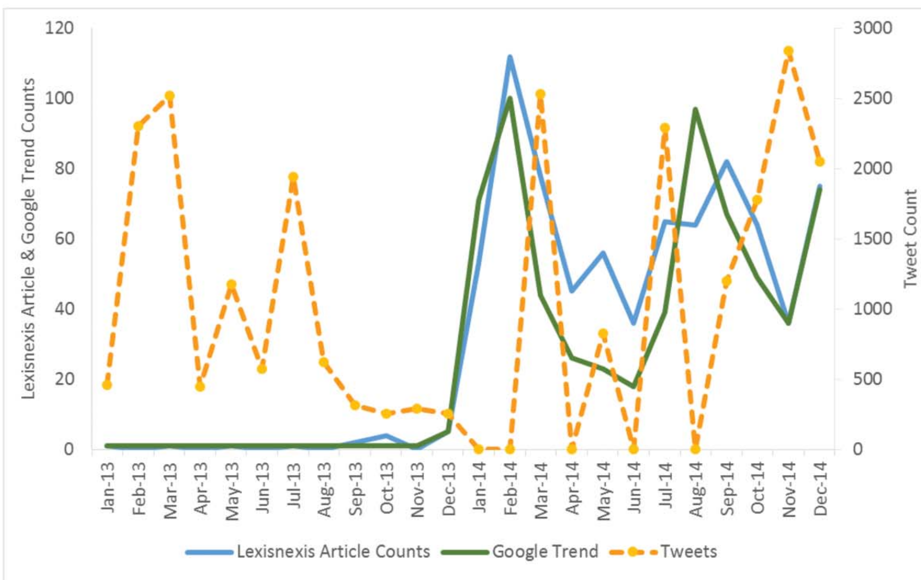
toward the drought. We calculated the frequency of the top twenty key words in the tweets, and then did a spherical k-mean cluster for the fifty states in United States. Figure 7 shows the clustering analysis results with main key words in each cluster. In the western part of the United States, including California and surrounding states, *rain* was the only most frequently mentioned key word in the tweets, accounting for 0.794 in the cluster. For most other states, including those northeastern states with high tweets counts, Twitter users talked more about the change, rain, and government restrictions.

Coupling of spatial patterns

The centralized geodatabase also made it possible to visualize and compare multidisciplinary data sets by time and to associate various spatial patterns across different disciplines. For example, we used month as the time unit to visualize and compare temporal relationships between the drought and social feedback (Figure 8). The severity of drought was measured by two methods—the Standard Precipitation Index (SPI) and reservoir water storage. The SPI is a drought index calculated based on the cumulative probability of a given rainfall event (Mckee, Doesken, and John 1993), which was negative for drought and positive for wet conditions. As the dry or wet conditions become more severe, the index became more negative or positive. Figure 8A suggests that the region experienced a drought from the beginning of 2012 to the end of 2014. The region experienced a substantial shortage in water storage starting in the middle of 2013, which continued to worsen throughout 2014.

The social feedbacks showed very interesting temporal patterns about the drought condition (Figure 8B). In 2013, when the precipitation just appeared to be less than normal and the water storage was not seriously influenced by this condition, both the LexisNexis article and Google users did not pay too much attention to the drought. Starting from 2014, as the problem of low precipitation and water storage persisted in the region, more articles and searches related to the drought were observed. There was a small decrease of those two counts between April to June 2014, as the SPI values got slightly less negative in the region and the reservoir storage increased due to the seasonal fluctuation. The counts increased after that time period as the drought conditions worsened. In contrast, Twitter users started talking about the California drought at the beginning of 2013, as the drought had just started in some areas and the reservoir water storage appeared to be less than normal, even though there was not much media attention at that time. Then, it went to a relatively quiet period. Starting from 2014, as the drought became a bigger problem in the region and the media started to feature more articles about the drought, more and more Twitter users expressed interests or concerns about

(a)



(b)

Figure 8. Temporal patterns of drought condition and social feedback. (a) Drought condition dynamic during the study period, measured by twelve-month Standard Precipitation Index (SPI) and total volume of water stored in thirty-four major reservoirs in study area. (b) Social feedback related to California drought during the study period.

this issue. This temporal tweets distribution pattern showed that social media contents can reflect ongoing social problems in a more timely manner than the media reports. In turn, social media contents were also influenced by the media reports.

Discussion and conclusion

Our study demonstrated that geographic data integration, visualization, and analysis were effective ways to facilitate interdisciplinary research. By integrating multiple discipline information into a geodatabase with spatial visualizations, researchers in different disciplines can better understand each other's domains. Throughout the first year of the project's weekly meetings, the geodatabase structure and Web map were the two major topics used frequently in project discussion. In addition, data integration has enabled spatial and temporal analysis across disciplines. In our initial analysis, social media and newspaper articles have shown different patterns around a drought event. Social media users responded much sooner than the media reports in our study case. Spatially, related social media contents were not just limited to the region that is experiencing the drought. People in different geographic locations also care about the event albeit from different perspectives.

Our next goal is to make use of the current research results to develop a model for making water policy decisions. A system of differential equations will be built and solved to estimate future water availability. The model will be integrated into the Web GIS interface, which allows the decision makers to simulate different physical and social scenarios in predicting water availability and social feedbacks.

From this study, we also learned some limitations and challenges. The biggest limitation of geospatial data integration in this study is that the system only works well with quantitative data. There are many qualitative social variables, or variables that do not tie up with geographic locations existing in the model building process. At this stage of the project, this information can only be kept with each individual research team. Furthermore, a geodatabase connection requires technical skills and learning curves. It might be a minor issue for teams with GIS or technology background, but might be a larger issue for those researchers who are not familiar with relational databases. The challenges that we will be facing soon is the data management issue. The current database only includes information from our data collection period. As the project develops, there will be many intermediate file generated, which might increase the database size rapidly. How to document, manage, and preserve related information in the long term will be a topic to pursue in the future.

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