Ground Water Monitoring&Remediation

Aquifer Prioritization for Ambient Ground Water Monitoring

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Abstract

Ambient ground water monitoring programs have been developed by more than half of the states in the United States in order to determine baseline ground water quality and monitor long-term water quality trends. States have focused their resources in many cases by prioritizing certain basins (ground water or watershed), major aquifers, or sensitive areas. This study focuses on development of an aquifer prioritization approach, specifically for the state of Wyoming, that considers both the complex geology and the variety of potential contaminant sources. The focus of ground water management in Wyoming is currently on protection, with particular attention to shallow aquifers most susceptible to water quality degradation from human activities. Aquifers within the state are evaluated with respect to current water use, sensitivity based upon a modification of the DRASTIC model, and potential for surface contamination from known land uses. High-priority aquifers are designated as those aquifers that serve as drinking water sources and are most susceptible to point and non–point source pollution. Using geographic information systems, ratings are then compiled to provide a sophisticated aquifer prioritization mapping system specifically developed for targeting ambient ground water monitoring efforts.

Introduction

More than half of the states in the United States have developed ambient ground water monitoring programs in an effort to assess the current condition and long-term health of their ground water resources. Since the development of the first program in Kansas in the 1970s, 8 states followed suit in the 1980s, followed by 13 more in the 1990s, and another 4 since the year 2000. Additional statewide programs are under development and, in some cases, are being enacted in rapid response to rising public concern. For example, public water supply well closures due to the detection of Methyl tert-butyl ether (MTBE) and industrial solvents increased awareness of ground water quality issues in California and prompted legislation to mandate development of their state ambient ground water monitoring program (California EPA 2001). The State of Wyoming is also currently developing an ambient ground water monitoring plan as part of a statewide ground water protection strategy (WDEQ-WQD 2000). In this article, we outline a comprehensive geographic information system (GIS) approach to prioritize high-use aquifers in Wyoming by using information on current water use, aquifer sensitivity, and land use, including both known and potential sources of contamination.

In 2002, all 50 state water management agencies in the United States were contacted by telephone to determine the status of their statewide ambient ground water monitoring programs. Information on program content was collected when pertinent to Wyoming program development. The map presented in Figure 1 outlines the status of state programs at the time of our study. Most states have limited budgets to allocate to ambient ground water monitoring programs. In fact, 3 of the 26 states that had developed their programs are no longer actively running them due to political and budgetary constraints. In addition, at least 3 of the 26 states have embarked upon these programs only to collect baseline data, with the prospect for long-term data collection remaining uncertain. The 2002 survey of state programs revealed that the scope and associated costs of the active programs are as varied as the states themselves.

The large number of states without monitoring programs, in addition to the number whose programs are limited, emphasizes the need for methods to focus monitoring on the most critical areas, resulting in reasonable costs that can ensure long-term viability of state programs. The 2002 survey indicated that only 20% of the state programs actively monitor ground water resources throughout their entire state. More often, states have developed some rationale for limiting the scope of the ambient monitoring program to increase cost-effectiveness.

The most common method for reducing scope is to target monitoring efforts to assess what are considered to be the state's major aquifers. Major aquifers would be those that are regionally extensive and have the potential for the

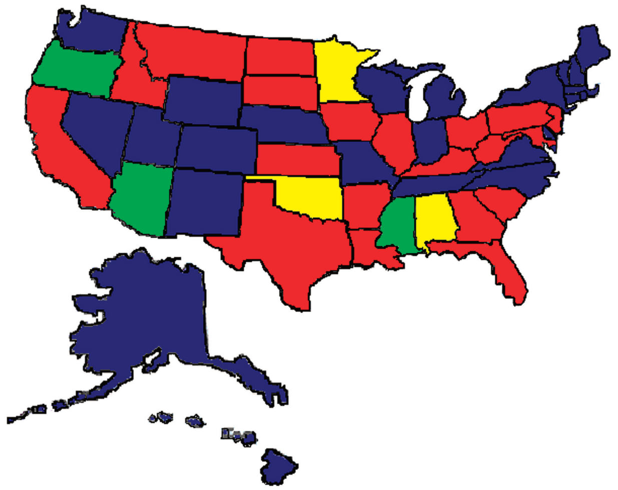

Figure 1. Status of statewide ambient ground water monitoring programs, 2002 survey.

development of substantial quantities of water. This major aquifer method, which relies solely on information on basic aquifer characteristics and water usage, is used in 78% of the state programs that limit scope. In 29% of the states that use the major aquifer method, watershed basin delineations have been successfully used to focus ground water monitoring efforts even further where appropriate surface/subsurface geologic conditions exist.

Only 22% of the state programs that limit scope use information beyond basic aquifer characteristics and water usage. Many states have used aquifer sensitivity to help determine aquifer vulnerability to pollution in the case of single contaminant types, primarily pesticides, but these targeted monitoring efforts are oftentimes independent of ambient statewide monitoring programs. North Dakota, Minnesota, Oregon, New Jersey, and California have used a variety of factors such as associated land use, population density, aquifer sensitivity, and contamination history in order to prioritize aquifers for monitoring. To our knowledge, this study proposes the first comprehensive statewide program that addresses this wide variety of factors for multiple contaminants.

Aquifer Systems

Wyoming covers nearly 253,500 km^2, and the population uses >100 different aquifers and aquifer systems (Wireman et al. 1994). A review of Wyoming's aquifer systems was necessary in order to determine if the major aquifer approach, used by the majority of state programs, was appropriate for Wyoming. In Wyoming, there are three distinct types of aquifer systems: the High Plains Aquifer system, the structural basin aquifers, and the alluvial aquifers. The High Plains Aquifer system is a thick sequence of interbedded sands and silts located in the southeast corner of Wyoming, near Cheyenne and surrounding areas. Most ground water in the High Plains Aquifer system is found in the upper Ogallala Formation and the underlying Arikaree units (Babcock 1956). The aquifer can exceed 300 m in thickness in some places and can be truly called a major aquifer.

The structural basin aquifers in Wyoming are sedimentary rocks found within or flanking eight major structural basins. Mountains surround the basins, and steeply dipping sediments outcrop on their slopes. These basins include the Powder River, Bighorn, Wind River, Green River (and Overthrust Belt), Great Divide/Washakie, Laramie, Shirley, Hanna, and Denver/Julesburg basins (Wireman et al. 1994). The structural basin regional aquifer systems include geologic formations consisting of permeable sandstones, limestones, and siltstones or formations with significant fracturing. Ground water can be found in both confined and unconfined conditions within the regional aquifer systems. Fractured bedrock or solution-enhanced karst systems (both confined and unconfined) constitute some of the most productive aquifers in Wyoming. Under certain conditions, potential contaminants can readily reach the ground water through fractures and solution cavities, thus greatly increasing the sensitivity of these aquifers to contamination (Wireman et al. 1994).

Wyoming's alluvial aquifers consist mostly of river, floodplain, and terrace deposits that border the major rivers in the state. Those valley-fill aquifers of most importance are located along the North Platte, the upper Snake, the Bear, and the Greybull rivers. Generally, these relatively shallow unconfined units are composed of sand, silt, and gravel lying on a bedrock surface. The variability in geology results in a variety of aquifer conditions (Morris and Babcock 1960; Crist and Lowry 1972). Wyoming's alluvial aquifers generally range in thickness from 3 to 30 m, but greater thicknesses can also occur (Zimmerman 1984). The alluvial aquifers are likely the most vulnerable of all aquifers because of their close proximity to the land surface (Wireman et al. 1994).

Other than the High Plains Aquifer system, Wyoming's geology does not lend itself to simple determination of major aquifers. As a result, it was decided that an ambient monitoring program should target aquifers of high use. Wyoming is the least populated state, with 493,782 people according to the 2000 Census, and population centers are typically distinct with rangeland or forested areas between them. Usage patterns may be more easily interpreted than in more populous states. With the information collected on other states' ambient monitoring programs, a scoping committee comprising members having extensive background in ground water resource characterization and management was established. Representatives from the USGS' Water Resources Division, Wyoming State Geological Survey, Wyoming Department of Environmental Quality, State Engineers Office, University of Wyoming, and the University's Spatial Data Visualization Center met on numerous occasions to conceptualize a recommended approach for Wyoming's statewide ambient ground water monitoring program. In particular, team members emphasized the importance of incorporating existing data, such as the state's GIS aquifer sensitivity coverage, into the monitoring network design. Cost savings could be achieved by focusing monitoring efforts on critical areas of shallow high-use aquifers most susceptible to impacts from human activity. A GIS approach was chosen to delineate critical areas within high-use aquifers using information on current water use, aquifer sensitivity, and land use, including both known and potential sources of contamination.

Methods

GIS Approach

ArcView 3.x and ArcInfo 7.x and 8.x (ESRI, Redlands, California) were used to generate and manipulate the spatially explicit data for this project. The spatial information was recorded in data layers, and then these layers were combined to create a final map displaying the critical areas and their determined priority for monitoring. Each data layer was generated and/or obtained from its original source as a point, line, or polygon layer. The features in the data layers were then assigned values related to the ranking of the features.

Once all the layers contributing to the final aquifer-priority layer were generated, they were converted from vector (point, line, or polygon) to raster (grid) using the ArcInfo GRID module. In the raster model, the space is subdivided into discrete cells. The location of geographic features is defined by the row, and the column describes the location of a particular cell. The dimensions of the cell define the spatial resolution of the grid (Aronoff 1989). The resolution of each grid in this work was 100 m. The mapping thus comprised 26,336,596 cells of 100 m^2. The raster (grid) model was used to characterize data for this project because this model facilitates simple algebraic map calculations needed to combine layers to create a final aquifer prioritization map.

Delineation of High-Use Areas within Aquifers

The first step in the prioritization process was to delineate the high-use regions within aquifers by using the location and depths of existing wells. Many states have prioritized their aquifers using well records or population factors to estimate water usage. An evaluation of well records from the Wyoming State Engineer's Office 1999 Well Permit Database provided well locations for permitted wells and information about the type of use of each well (i.e., domestic, irrigation, stock, miscellaneous) and the depth to water-bearing zones. The information was then correlated with the Wyoming Surficial Geology Map (Case et al. 1998) and Wyoming Bedrock Geology Map (USGS 1994) in order to develop geologic boundaries for the most highly used aquifers.

Over 84,000 water wells were located to the nearest quarter-quarter section (161,874 m^2) based on the best available information obtained from the well permit database. Since the intent of the ambient ground water monitoring program is to evaluate the long-term effects of point and nonpoint pollution from human activities originating near the ground surface, shallow wells with a total depth between 0 and 160 m were used. Total depth was used because the database did not specify perforated intervals or present consistent data on water-bearing zones. Abandoned wells and wells considered "dry" were removed from the distribution.

For development of the high-use aquifer map, all wells were buffered at 1000 m due to limited spatial accuracy and to ensure inclusion of as much of the aquifer as possible. Areas of high well concentration were compared with the Wyoming Bedrock Geology Map (USGS 1994). All bedrock units that had at least 40 wells drilled into them were considered as high-priority aquifers based on a visual assessment of the well distribution, resulting in the elimination of ~50% of the bedrock units.

The well depth map was then compared with geologic maps to identify specific geologic units used as confined or unconfined aquifers in the subsurface. The 1:500,000 Bedrock Geology Map was used first and supplemented with 1:100,000 and 1:24,000 maps where needed and where available. Shallow wells in many cases are completed in surface alluvium, thus the Surficial Geology Map was consulted to verify formation and any local structure. Wells of intermediate depth are most often completed in bedrock that crops out on the surface; therefore, both the Bedrock and Surficial Geology Maps were consulted in order to verify the formation. The Bedrock Geology Map was consulted for the deepest wells because the targeted formations depended a great deal on the thickness of the formation.

Aquifer boundaries were therefore essentially chosen by two ways. If wells were concentrated near a geologic boundary on the geologic map, that boundary was used as the polygon boundary defining the aquifer. Where wells were far from a geologic contact, the portion of the geologic unit actually used as an aquifer was hand-delineated using a polygon. These boundaries conformed to the edges of the 1000-m buffers surrounding well locations.

Aquifer Sensitivity

Aquifer sensitivity is based on aquifer and surface characteristics that influence the transport of potential contaminants from the ground surface to an aquifer. It is not related to land use or contaminant characteristics (U.S. EPA 1993). Many models have been designed to assess aquifer sensitivity, but DRASTIC and DRASTIC-like models are the most widely used for such efforts (U.S. EPA 1993; Aller et al. 1987). DRASTIC is an acronym that stands for *d*epth to ground water, *r*echarge, *a*quifer media, *s*oil media, *t*opography, *i*mpact of the vadose zone, and hydraulic *c*onductivity. The model name therefore highlights components that can influence contaminant migration to ground water. Hydrogeologic setting models, such as DRASTIC, with scoring or ranking features, are considered most appropriate for aquifer sensitivity assessments on a regional or statewide scale (American Society for Testing and Materials 2000). North Dakota, for example, used the DRASTIC model to determine aquifer sensitivity in their major glaciofluvial aquifers. They used an equal weighting of (1) the average aquifer sensitivity to agricultural chemicals (pesticide DRASTIC score); (2) the market value of agricultural production per unit land area as an estimate of the amount of agricultural chemical use per land area; and (3) permitted water usage (an estimate of risk) to determine monitoring priority (Radig 1994). Alternatively, rather than using a hydrogeologic setting model, California has an ongoing program to evaluate aquifer sensitivity or susceptibility via ground water age–dating techniques using tritium/helium-3 ($^3H/^3He$) analyses (California EPA 2001). The age-dating approach, however, is dependent on data generated by an existing ambient monitoring program, unlike modeling efforts described here, which can be used to generate sensitivity maps for extensive areas prior to development of a monitoring program.

DRASTIC models are often modified to better address local geohydrologic settings (Merchant 1994). A DRASTIC-like model was used for creating the aquifer sensitivity map for the entire state of Wyoming as part of a previous project that evaluated ground water vulnerability to pesticides (Case and Arneson 1998; Hamerlinck and Arneson 1998a). The characteristics used for the study included depth to ground water, aquifer recharge, geohydrologic setting, soils, land surface slope, and vadose zone setting (Aller et al. 1987; Hamerlinck and Arneson 1998b). The geohydrologic setting layer was developed by the Wyoming Geological Survey based on an eight-step aquifer classification scheme (Case and Arneson 1998). This layer replaced the Aquifer Media and the Saturated Hydraulic Conductivity layers within the standard DRASTIC methodology. Using GIS, these six characteristics were combined on an equal-weight basis (Hamerlinck and Arneson 1998a) to create the aquifer sensitivity map for the entire state.

Once the map of high-use aquifers was created, a subset of the sensitivity map was developed to address the delineated high-use aquifers. An example portion of the sensitivity map is depicted in Figure 2. The prevalence of high-sensitivity areas denoted in red on the map inset is likely due to alluvial aquifers along the Bear River and its tributaries in southwest Wyoming.

At this point in the project, a map of high-use aquifers <160 m below ground surface had been created, along with their associated sensitivity to potential contamination from the ground surface. In order to further identify aquifers most at risk, information about potential sources of contamination would be required. States that have selected to prioritize aquifers have mapped land uses and areas of known contamination. Other states, such as New Jersey, proportioned their monitoring wells in areas of agricultural use, urban use, and undeveloped areas. Oregon used not only areas of known contamination but also mapped land uses such as agriculture, food processing, wood production, manufacturing, and confined animal feeding operations.

Land Use

For Wyoming, a GIS data layer was created combining the results of land-use mapping from nine different land-use coverages. The selected land uses are listed in Table 1. Each of the data layers was merged when necessary and was then converted to raster grids. A brief description of

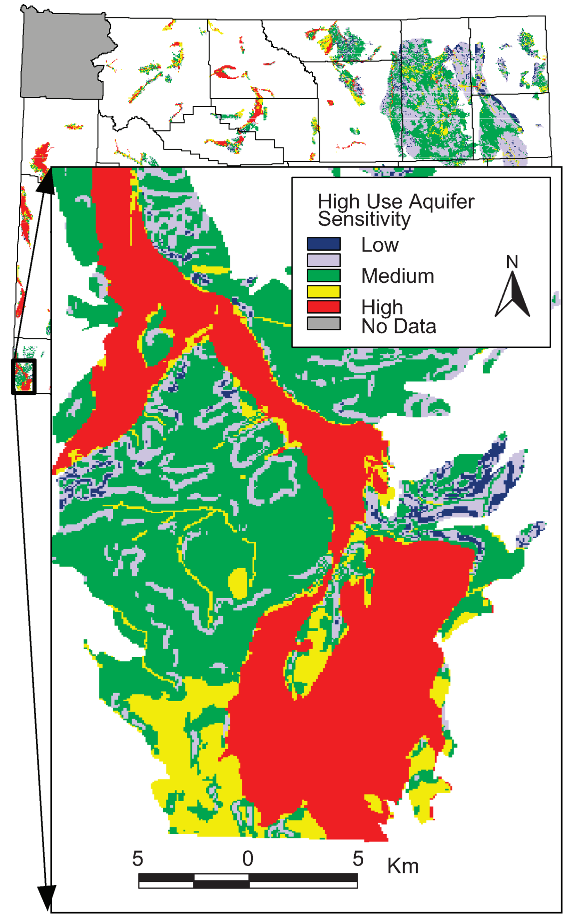

Figure 2. Example of high-use aquifer sensitivity map for a selected location in southwest Wyoming.

the derivation of each land-use layer is given in the following paragraphs.

Coal-Bed Methane Wells

The Coal-Bed Methane layer shows all the permitted coal-bed methane wells in Wyoming as of October 1999. Well locations were obtained from the Wyoming Oil and Gas Commission, Casper, Wyoming. These point data are buffered at a distance of 1000 m, which was the estimated zone of influence. This is the same value used in the derivation of aquifer boundaries. The location method and spatial accuracy of these locations are unconfirmed but assumed to be within the nearest Public Land Survey quarter-quarter section. The number of coal-bed methane wells is rapidly increasing, and this data layer was at the most risk of being outdated. However, the final aquifer prioritization map showed little impact on final rating classes due to coal-bed methane wells, primarily due to relatively low aquifer sensitivity generally prevalent in the development areas.

Rural Residential Development

Land-use patterns have been changing throughout the West, and the once-extensive ranches are being sold in favor of small property holdings for residential purposes. As a result, population centers in Wyoming are now being surrounded by areas of rural ranchette development. These developments typically rely on individual ground water

Table 1
Nine Land-Use Types Used to Develop the Composite Land-Use Layer

Land Use	Description
Coal-Bed Methane (CBM) wells	Permitted CBM wells
Rural Residential Development	Areas where agricultural land or ranches have been subdivided for development
Oil and Gas Exploration/Development	Producing reservoirs and formations of oil and gas fields and locations of oil refineries and natural gas–processing plants
Oil and Gas Pipelines	Routes of product pipelines
Potential Ground Water Contaminant Sources	Landfills, USTs, and aboveground storage tanks
Known Ground Water Contaminant Sources	CERCLA sites, RCRA sites, Ground Water Pollution Control sites, USTs, and known contaminating landfills
Agricultural Land	Dry-land agriculture and irrigated agriculture
Urban Land	Urban land and golf courses
Mining	Mining activity (coal, uranium, bentonite, trona, sand, and gravel)

wells for drinking water supplies. However, they also present a potential contaminant source due to on-site waste water disposal. As a result, rural ranchettes were selected as one land use requiring mapping, under the title of rural residential development.

The Rural Residential Development layer was derived from the Wyoming State Engineer's Office 1999 Well Permit Database, using a query of all domestic water wells in the state. The wells were then buffered at a distance of 1000 m, as in the aquifer layer development. Based on a comparison of delineated areas and known rural residential development, buffered areas >10,000,000 m^2 were considered to represent significant rural ranchette locations.

Oil and Gas Exploration/Development

The Oil and Gas Exploration layer represents the location, areal extent, name, producing reservoirs and formations, and current status of oil and gas fields, and locations of oil refineries and natural gas–processing plants in Wyoming at a scale of 1:350,000. Field boundaries were determined from well production, and completion data were available from the Wyoming State Oil and Gas Conservation Commission files as of 1999 and plotted on 1:316,800-scale field maps previously compiled and published.

Oil and Gas Pipelines

The Oil and Gas Pipelines layer represents the routes of product pipelines in Wyoming at a scale of 1:350,000. Pipeline routes were taken from the Oil and Gas Map of Wyoming (De Bruin 1996) 1:500,000 scale; minor changes and additions of new pipeline data were plotted on the 1:350,000-scale map. These pipelines were buffered at a distance of 100 m, which was the estimated zone of influence.

Potential Ground Water Contaminant Sources

The Potential Ground Water Contaminant Sources layer consists of point data sources such as landfills, underground storage tanks (USTs), and aboveground storage tanks. These point data were merged together and overlaid with the sensitivity rating layer (Hamerlinck and Arneson 1998a), changed to the 0–25 scale used in this study. The scoring is more fully described in the Aquifer Ranking. The sites were then buffered at different distances based on their sensitivity rating. In this case, the sensitivity rating was multiplied by 10 m. For example, if a potential contaminant source is located in an aquifer that has a sensitivity rating of 12, the buffer around this source would be 120 m. This method was used to indicate that contaminants located in more sensitive areas were more likely to contaminate the aquifer and thus had a larger zone of influence. The buffers were then converted to a GRID. The data set came from the Wyoming Pollution Point Source Database created by GeoResearch Inc. in 1997–1998. The layer was developed based on Department of Environmental Quality (DEQ) data collected on locations of aboveground storage tanks, other municipal and industrial landfills, and non-leaking USTs. The EPA's database of Hazardous Substance Treatment, Storage, and Disposal Sites was also used.

Known Ground Water Contaminant Sources

The Known Ground Water Contaminant Sources layer consists of a variety of point data sources, such as Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) sites, Resource Conservation and Recovery Act (RCRA) sites, State Ground Water Pollution Control Program sites, leaking underground storage tanks, and known contaminating landfills from the Wyoming Pollution Point Source Database created by GeoResearch Inc. in 1997–1998. These point data were merged together and overlaid with the sensitivity rating layer. The sites were then buffered based on their sensitivity rating, by multiplying the rating by 50 m. The larger zone of influence reflects the higher potential for release of contaminants.

Agricultural Land

The Agricultural Land–Use layer is the combination of Dry-Land Agriculture and Irrigated Agriculture from the Wyoming Vulnerability Project Land-Use layer (Hamerlinck and Arneson 1998b). The layer represents croplands of Wyoming and was originally created by interpreting 1:58,200-scale National High Altitude Program (NHAP) color infrared aerial photographs. The photos, taken in

1980–1982, were interpreted, and land-use designations were hand-drawn onto plots produced at the same scale as the photos, using a light table. The plots were then digitized as polygons into ARC/INFO 7.0.2. The source of the data was the Spatial Data and Visualization Center at the University of Wyoming.

Urban Land

The Urban Land–Use layer is the combination of Urban Land and Golf Courses from the Wyoming Vulnerability Project Land-Use layer (Hamerlinck and Arneson 1998b). Similar to the Agricultural Land–Use layer, this layer was originally created by interpreting 1:58,200-scale NHAP color infrared aerial photographs. Golf course boundaries were later updated with 1994 NHAP photos. The plots were then digitized as polygons into ARC/INFO 7.0.2. The urban land layer was converted to a GRID. The source of the data was the Spatial Data and Visualization Center at the University of Wyoming.

Mining

The Mining Layer shows mining activity in the state such as coal, uranium, bentonite, trona, sand, and gravel as of 1999. The layer was developed using the database from the Wyoming Department of Revenue and Taxation.

Composite Land–Use Map

An example of the composite map created by overlapping all the land-use coverages is shown in Figure 3. This map covers the same selected area illustrated in the sensitivity map in Figure 2. While there are nine potentially different land uses possible based on the data sets, the most that overlap in any one spot is six land uses. This was found to be true for the entire state and is so reflected in the figure legend. The example location shows pipeline areas as specific lines on the map, a community center where the highest number of land uses are located, and rural ranchette development peripheral to the community center.

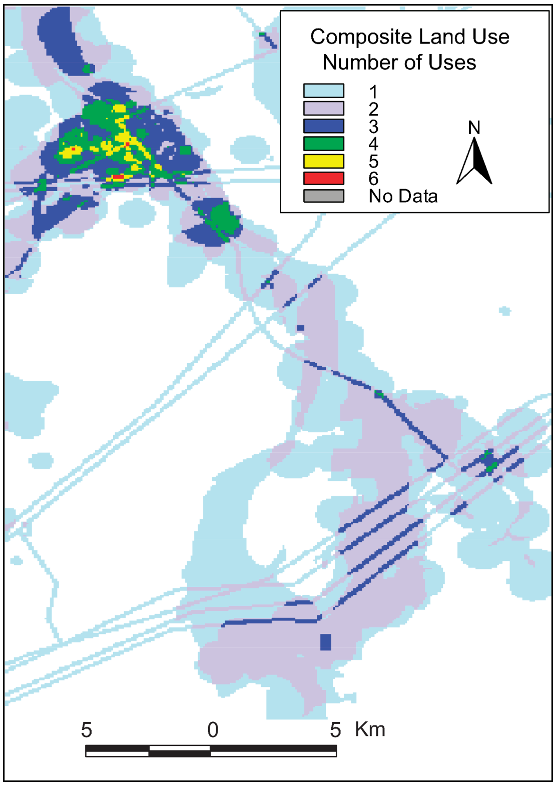

Figure 3. Example of composite land-use map for a selected location in southwest Wyoming.

Scoring Methodology

The raster GIS data model facilitated the use of algebraic map calculation to characterize priority aquifers in Wyoming. Each cell of the grid in the raster model was given a value in order to create data-rating layers.

Aquifer Sensitivity

The aquifer sensitivity data layer used in this study is the 1:100,000-scale GIS layer developed for the Wyoming Ground Water Vulnerability Assessment project (Hamerlinck and Arneson 1998a), edited based on the high-use aquifer delineation. In addition, the rating scale was modified from the original 0–70 scale. The sensitivity ratings were reclassified to a range of 0 to 25, with a score of 25 representing the highest aquifer sensitivity, to achieve final aquifer prioritization results that were similar to the final scoring of the aquifer vulnerability rating scale.

Current Water Use

A current water–use layer was developed to illustrate three aquifer categories based on use. Domestic drinking water aquifers are represented by a value of 5, and municipal drinking water aquifers are represented by a value of 10. A sole source aquifer, or an aquifer that is the community's only source of water, is represented by a value of 15. The Cloverly Formation underlying the town of Elk Mountain is the only designated sole source aquifer in the state and thus the only one to receive a value of 15.

Composite Land Use

To avoid making a judgment of the relative importance of land uses that could contribute to ground water contamination, all land uses received 5 points, except for Known Ground Water Contaminant Sources, which were given 10 points. Such subjective ratings are necessary to provide end products that can be useful for ground water resources decision making (Focazio et al. 2002). As shown in Figure 3, out of the nine land uses used, the most that overlapped were six. Thus, the maximum value of the composite land uses is 30 to 35, depending on whether Known Ground Water Contaminant Sources are one of the six land uses.

Final Aquifer Prioritization

GRID overlay techniques were employed in GIS to combine the aquifer sensitivity, current water use, and composite land-use rating layers into a final data layer. The result is a final product in raster or grid-cell form, which can be contoured or classed as necessary. Although the final map is composed of 100-m^2 cells indicating the level of priority for monitoring, it should be recognized that this map is a composite that is only as spatially accurate as the data that were used to construct it. The final product at this stage is likely most limited by the accuracy of the known aquifer boundaries. The 1000-m buffer on known wells was thought to be a liberal designation, allowing monitoring and subsequent protection of aquifers currently being used. However, efforts should continue to improve delineation of aquifers throughout Wyoming that are being developed for anthropogenic uses. As the source data (primarily aquifer delineations) are improved, the procedure for aquifer prioritization described herein will provide increasingly more accurate information, leading to better future monitoring of critical ground water sources.

Aquifer Ranking

Figure 4 shows a histogram of the prioritized aquifer rating value frequencies obtained. Potential values range from a minimum of 5 to a maximum of 70. A value of 5 designates a domestic drinking water aquifer with no overlying land uses and no aquifer sensitivity. A value of 70 would designate that the area had the highest rating for aquifer sensitivity, current water use, and composite land use. For aquifer sensitivity the highest value is 25, for current water use the highest value would typically be considered as 10 (since only the sole source at Elk Mountain can have a value of 15), and for composite land use the highest value would be 35, assuming that one of the land uses is a Known Ground Water Contaminant Source.

Rating classes were developed using a natural break categorization routine (Jenks 1977), which was also applied to the sensitivity rating distribution in the previous vulnerability project (Hamerlinck and Arneson 1998a). The calculated classes capture the natural grouping of the ratings: low = 5 to 14, low moderate = 15 to 24, high moderate = 25 to 34, and high = 35 and above. The low class represents 14% of the designated area, the low-moderate class represents 48% of the area, the high-moderate class represents 27% of the area, and the high class represents 11% of the area.

Once the selected scoring system was used to develop the ranking of aquifers, the matrix was examined to determine what effect, if any, logical changes in weighting of the various parameters had on the final aquifer map. Based on their technical expertise and familiarity with Wyoming ground water, experts from the Department of Environmental Quality, Water Quality Division, the USGS, and the Wyoming Geological Survey evaluated the matrix and determined that the scoring matrix presented a logical ranking of aquifers.

Aquifer Prioritization Map Layer

An example portion of the final map layer, which is a composite of the sensitivity, the current water use, and the land-use ratings grouped by natural breaks, is shown in Figure 5. Based on the prioritization map, ambient ground water monitoring networks are currently being designed for the delineated high-priority aquifers. Target contaminants will be selected based on the contributing land uses for each high-priority area. The prioritization map can be kept up to date by incorporating new information from the source databases as updates become available.

The mapping project was undertaken with the intent of developing a prioritization scheme for ambient monitoring purposes so that limited financial resources could be used most effectively. One of the difficulties in developing a map that essentially scores aquifers based, in part, on their susceptibility to pollution is that there is broad opportunity for misinterpretation and misuse of the instrument. The map was not intended to be accurate on a scale that could be used for land-use decisions, for example, limiting industrial development in high-priority aquifer areas. Broad publication of the final map product can only be

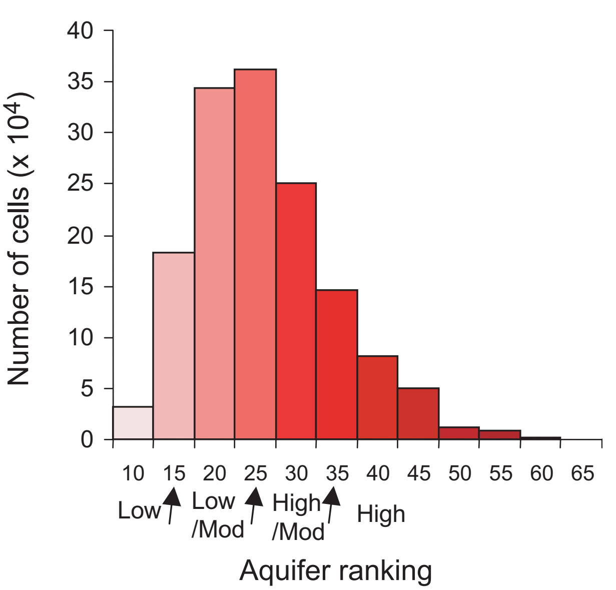

Figure 4. Aquifer prioritization histogram.

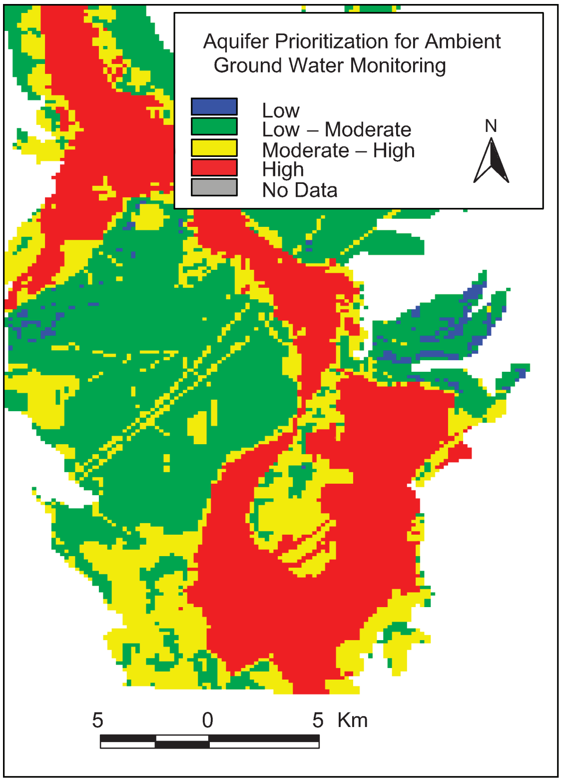

Figure 5. Example of final aquifer prioritization map for a selected location in southwest Wyoming.

accompanied by an education program to curb unintended uses of the product and gain public acceptance of an extremely useful tool.

To our knowledge, this is the most comprehensive GIS scoping system currently in use by statewide programs for ambient monitoring program development. This approach not only identifies the most critical areas to be monitored but also allows tailoring of a monitoring program based on specific sources of contamination within those critical areas. Both these attributes allow for a phased implementation of ground water monitoring and increase cost-effectiveness of monitoring programs.

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