Monitoring-Network Design for Ground-Water Quality, Wind River Indian Reservation, Wyoming

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Abstract

Ground water is an important resource for the Wind River Indian Reservation in Wyoming. A strategy is being developed to protect and to continue the use of this resource in a sustainable manner. Ground-water-quality monitoring is often focused on aquifers with known point sources of contamination or delivered public water-supply quality. The monitoring network being designed differs from the traditional approaches by taking into account water-use areas, point- and non-point source land-use activities, hydrogeological characteristics, natural levels of constituents, and the ground-water resource as a system.

A methodology is being developed to prioritize aquifers and areas within individual aquifers that should be foremost in the water-quality monitoring program so resources can be applied in the most efficient manner. This is being accomplished by the use of a geographic information system to relate water-use areas, land use, hydrostratigraphy, and aquifer sensitivity. Well locations are then selected within these areas using a stratified-random design. A statistical analysis of existing data for each aquifer will assess the variance for selected constituents to establish the minimum number of monitoring points within each stratum. Multiple lines of geochemical evidence and statistical analysis of data from areas not affected by land use will address natural levels of constituents within aquifers.

Introduction

Ground water on the Wind River Indian Reservation (WRIR) (figure 1) is a valuable resource for the Eastern Shoshone and Northern Arapahoe tribal members and others who live on the reservation. In addition to being the major source of water for the rural population on the reservation, ground water is also used for municipal, industrial, commercial, mining, livestock, and irrigation purposes (U.S. Geological Survey, digital data, July, 2001). Protection of ground water is necessary for the continued economic success and quality of life on the reservation, therefore, a strategy is being developed to continue to use this resource in a sustainable manner. A ground-water-quality monitoring network is a critical component for the careful management of the resource; however, monitoring can be costly. A methodology is being developed to prioritize aquifers and areas within individual aquifers so resources can be applied in the most efficient manner. In addition, the U. S. Environmental Protection Agency, within Section 106(e) of the Clean Water Act, has requested that each state begin monitoring ground-water quality and provide their findings within their biennial 305(b) report (Anzzolin and Siedlecki, 1998). The guidelines were updated for the 1996 reporting cycle to report ambient ground-water quality on an aquifer-specific basis. The WRIR has begun to provide a comprehensive 305(b) report for surface-water quality and with the implementation of this program will have the ability to provide information regarding ground-water quality as well.

Background

The Wind River Environmental Quality Commission (WREQC) is responsible for maintaining the integrity of the environmental resources of the WRIR. This mission includes the inventory and assessment of the water resources of the WRIR. The WRIR relies almost entirely on ground water for public supply and domestic self-supplied drinking water. Table 1 shows a summary of ground-water use based on an inventory of wells conducted as part of an earlier study (Daddow, 1996).

Land uses on the WRIR, including Urban areas, rural domestic areas, agricultural lands, landfills, oil and gas fields, mining, and pipeline utility corridors all have the potential to affect the quality of the ground-water resource. Because of the possible interaction between ground water and surface water, activities that affect surface-water quality (urban runoff, sewage disposal, agricultural return flows) also have the potential to affect ground-water quality. Additionally, activities that occur in the subsurface (such as waste disposal through underground injection) could affect ground-water quality. Assessing the effects of various activities on the ground-water resource is complicated by site-specific hydrogeology. Some aquifers are more vulnerable to potential contaminant sources than others, depending on their hydrogeological characteristics as well as proximity to potential contaminant source(s). In addition, naturally high concentrations of constituents such as trace elements and radiochemicals need to be considered when evaluating ground-water quality in relation to land use.

Table 1, Water uses for inventoried wells (Daddow, 1996).

Water Use	Number of Wells	Percentage of Total Wells
Public Supply	24	1.8
Domestic	674	49.7
Irrigation	10	0.7
Livestock	105	7.7
Industrial	32	2.4
Unused	386	28.4
Unknown	126	9.3
Total	1357	100

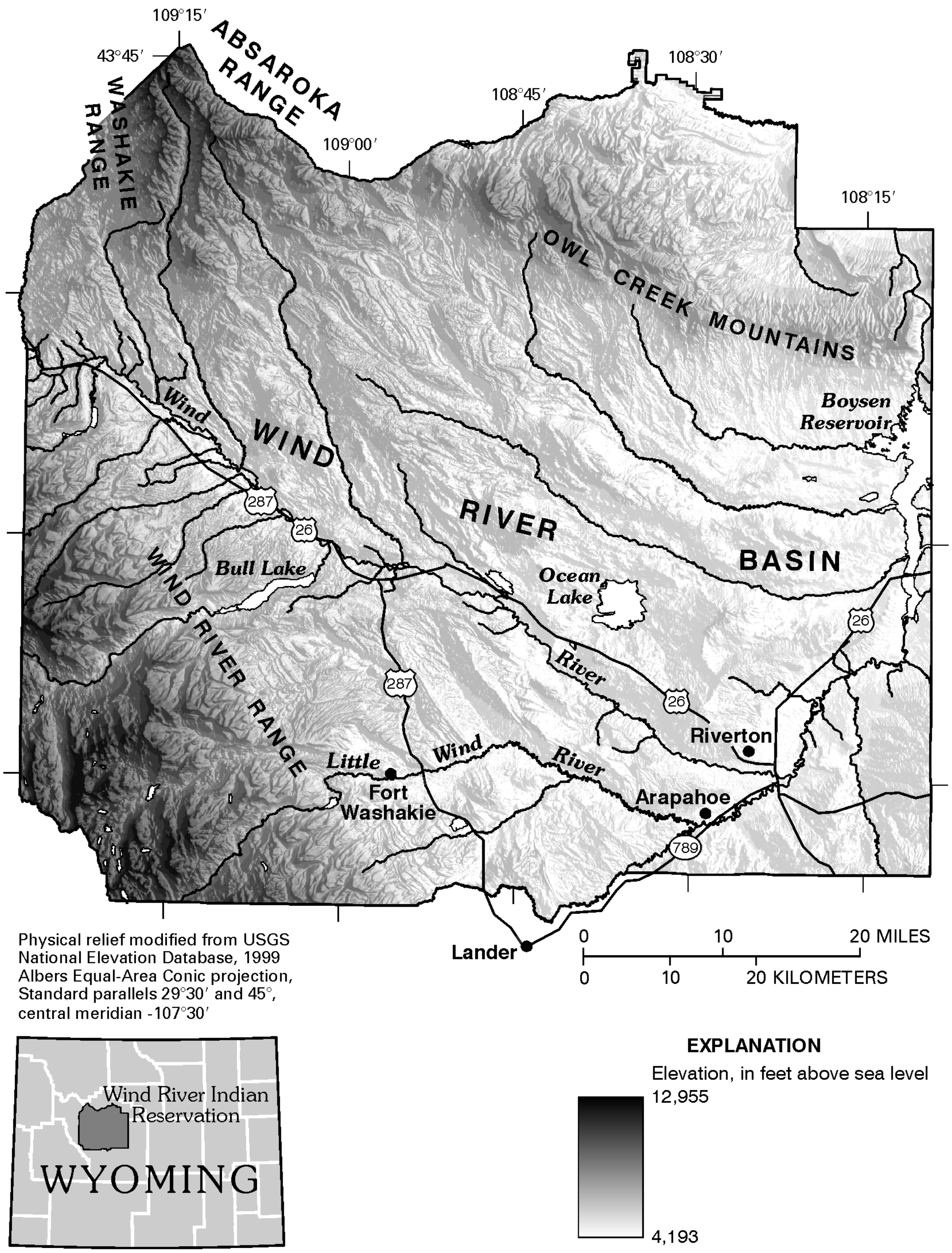

Figure 1. Location and physical relief of the Wind River Indian Reservation, Wyoming.

Ground-water-quality monitoring is often focused on aquifers with known point sources of contamination. In areas with known contaminants, such as underground storage tank locations, ground water is monitored in conjunction with some type of early warning or remedial action to ensure that contaminants in the ground-water system are being addressed. Public drinking-water supplies are monitored by sampling delivered water rather than water in aquifers.

The WRIR network design draws upon network designs that have been developed in several states. The State of Minnesota developed a network with individual network components to satisfy multiple objectives. The components include an early warning network, a network of private and public-supply wells, a network of private-supply wells chosen randomly, and a special-study network (Minnesota Pollution Control Agency, 2001). The State of Idaho has a comprehensive ground-water-quality program, implemented in cooperation with the U. S. Geological Survey (USGS). Each year, about 400 sites are sampled, with about 100 of those being long-term sites that are resampled every year (Idaho Department of Water Resources, 2001). Ohio maintains a water-quality network consisting of public water systems and industrial, commercial, and residential wells (Ohio Environmental Protection Agency, 2001). New Jersey's ambient ground-water-quality network is a cooperative program with the USGS and the New Jersey Department of Environmental Protection (Serfes, 1998). The program was redesigned in 1997 to assess water-quality status, trends, evaluate transfer relations by aquifer type and land use, and also to identify emerging water-quality issues.

The network design described herein attempts to improve traditional approaches by considering water-use areas, point- and non-point source land-use activities, hydrogeological characteristics, natural levels of constituents, and the ground-water resource as an aquifer system. A network of this type will allow development of management strategies based on an assessment of the resource in relation to multiple land uses and their potential effects on water quality, the identification of areas for continued monitoring to identify potential trends or changes in water quality, and a network to monitor water levels over time.

Environmental Setting of Study Area

The WRIR was created in 1863 with the signing of the first Fort Bridger Treaty. Since establishment, the reservation boundaries have changed many times. Presently, the reservation size is just over 3,500 mi^2 in Fremont and Hot Springs counties within Wyoming. The 2000 census indicates that 6,864 Eastern Shoshone and Northern Arapahoe tribal members live on the reservation, about 30 percent of the total reservation population of 23,250 (U. S. Census Bureau, 2002).

Physiography

The reservation is located in the Wyoming Basin Physiographic Province of the Rocky Mountain Region (Raisz, 1972). Most of the reservation lies in the western half of the Wind River Basin, a large structural basin with a total area of about 8,500 mi^2 (Keefer and Van Lieu, 1966, p.B2). The basin shares its name with the Wind River Mountain Range which forms the southwestern boundary of the basin. The northwestern boundary consists of the Washakie and Absaroka mountains. The Owl Creek Mountains, Big Horn Mountains, and Casper Arch make up the northern and northeastern boundaries, and the southern boundary consists of the Granite Mountains. The northeastern part of the reservation extends north over the Owl Creek Mountains and into the southern end of the Big Horn Basin.

The reservation includes areas of rugged badlands, plains, terraced-stream valleys, foothills, high plateaus, moutainous sub-alpine, and alpine glaciated terrain (Daddow, 1996). Land surface altitudes range from about 4,100 ft above sea level near the northeastern boundary of the reservation to nearly 13,000 ft in the Wind River

Mountains at the southwestern boundary. Altitudes in the central part of the reservation range mainly between 4,800 and 6,000 ft (Daddow, 1996).

Climate

Climate on the WRIR ranges from the relatively arid area of the Wind River Basin, to the wetter, high alpine and sub-alpine mountainous areas. A climate station located at South Pass City, on the Southeastern end of the Wind River Mountains is the closest station that is representative of climate in the high elevation areas of the WRIR. Annual average total snowfall was 115.5 inches with an annual average precipitation of 13.55 inches at the South Pass City climate station (National Weather Service, 2002). Temperatures range from an average monthly maximum of 76.4 degrees Fahrenheit, in July, to an average monthly low of 0.8 in January. Climate in the area of the WRIR within the Wind River structural Basin where the majority of land use occurs is represented by a climate station at Fort Washakie, a community centrally located on the WRIR. Annual average total snowfall was 60.2 inches with an annual average precipitation of 11.79 inches at the Fort Washakie climate station (National Weather Service, 2002). Temperatures range from an average monthly maximum of 85.6 degrees Fahrenheit in July, to an average month low of 3.1 in January.

Hydrogeology

The geology of the reservation is dominated by the Wind River Basin and associated mountain ranges. Only about 14 percent (Daddow, 1996) of the reservation lies outside the Wind River Basin. A detailed overview of the geologic history of the basin was described by Keefer (1970). The following is a brief overview of reservation hydrogeology, for a more detailed description the reader is refered to Richter (1981), McGreevy and others (1969), Keefer and Van lieu (1966), Daddow (1996), and Johnson and others (1996). A generalized cross section perpendicular to the basin axis is shown in figure 2. Most of the ground water used on the WRIR comes from the lower Tertiary aquifers (primarily the Wind River Formation) and unconsolidated Quaternary deposits.

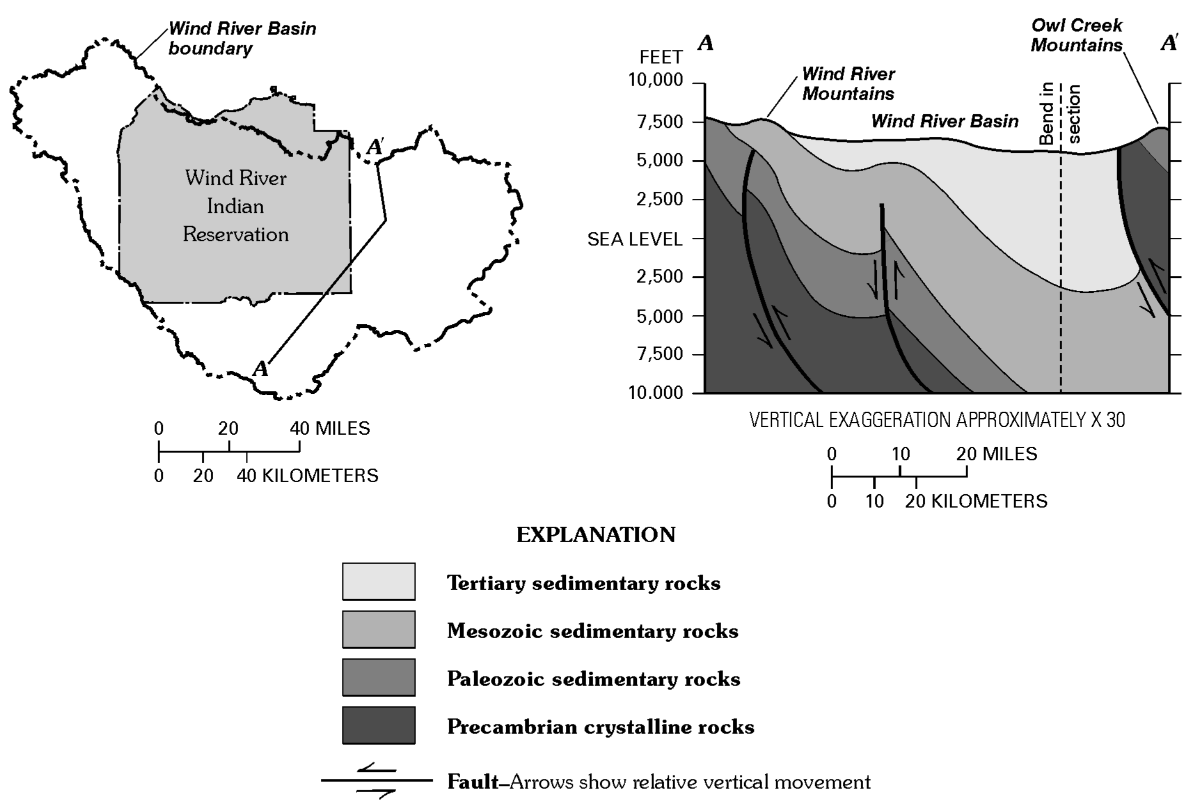

Figure 2. Generalized cross section, Wind River Basin from south to north (modified from Whitehead, 1996, and the American Association of Petroleum Geologists, 1972).

Quaternary deposits on the reservation include flood-plain alluvium, slope wash and alluvium, terrace deposits, and glacial deposits (Daddow, 1996, p. 15). The maximum thickness of these deposits is probably around 200 ft (Richter, 1981, p. 87) but generally they are less than 50 ft thick. Daddow (1996) reported that water yields from wells in Quaternary deposits on the reservation ranged from 2 to 60 gallons per minute (gpm) while dissolved solids ranged from 109 to 4,630 milligrams per liter (mg/L). The Tertiary Wind River and Fort Union Formations are the thickest sedimentary formations on the reservation. In the basin trough their combined thickness is greater than 10,000 ft. The lithology and thickness of these two formations vary greatly in different parts of the reservation. The Wind River Formation makes up the surfical deposits (outcrops) in much of the central and eastern parts of the reservation. Daddow (1996) reported that water yields from wells in the Wind River Formation ranged from 0.1 to 350 gpm while dissolved solids ranged from 211 to 5,110 mg/L. This great variabilty is in part a result of the varied lithology of the formation. Mesozoic rocks on the reservation consist mostly of siltstone, sandstone, and shale. Smaller amounts of claystone, conglomerate, coal, bentonite, limestone, dolomite, and gypsum are also present. Daddow (1996) reported that water yields from wells in Mesozoic rocks ranged from 0.5 to 90 gpm while dissolved solids ranged from 182 to 6,060 mg/L. In general the median values for dissolved solids in Mesozoic rocks were around 1,000 mg/L except in the Cody Shale which had a median value of 2,540 mg/L. Paleozoic rocks are comprised mostly of sandstone, shale, limestone, and dolomite, with some chert. In the Late Paleozoic, phosphatic beds and gypsiferous shale were also deposited. Water quality and well yield records are sparse for Paleozoic formations. Richter (1981, p. 54-71) reported that water yields from selected wells (mainly oil and gas well tests) in Paleozoic rocks ranged from several tens of gpm up to 1,500 gpm. He also reported flows of less than 10 gpm from springs along the Owl Creek Mountains. According to Richter (1981, p. 98-105) dissolved solids in Paleozoic rocks range from less than 500 mg/L to more than 3,000 mg/L. Generally, lower dissolved solids are found near outcrops and at shallower depths. Many of these rocks are cliff forming and are exposed in steep walled canyons on the northeast flank of the Wind River Mountains and in Wind River Canyon through the Owl Creek Mountains. Precambrian Igneous and metamorphic rocks form the cores of the Wind River, Washakie, and Owl Creek Mountains on the reservation. These rocks, which are widely exposed in the Wind River Mountains and in Wind River Canyon through the Owl Creek Mountains, are typically either granite, granite gneiss, or schist, although locally mafic dikes are present (Keefer, 1970, p. D8).

Land Cover and Land Use

Both ground-water quality and quantity can be directly affected by land cover and land use. The relation between intensity of land use and potential effects upon ground water is less straightforward, but probably more important than the areal extent of a given land-use setting. Agricultural land use on the WRIR is an example of a setting with broad aerial extent but only moderate intensity. Urban land use on the reservation is an example of land use with a small aerial extent but intensive use. Other land uses such as range, have broad aerial extents but mostly low-intensity use (such as grazing) and may be less likely to affect the ground water.

The National Land Cover Dataset (NLCD) (U.S. Geological Survey, 2000) was the primary source of land cover and land use data for this study. Rangeland is the largest land use on the reservation (82%) with about 22% of the total reservation area covered by upland grasses and forbs and nearly 60% covered by shrubland. The Wyoming Department of Agriculture (WDA) does not have statistics for the reservation itself, but estimates that the total head of cattle in Fremont County was approximately 120,000 and the total head of breeding sheep was approximately 14,000 in 2001 (Wyoming Department of Agriculture, 2001, p.45 & 58); the majority of the WRIR is within Fremont County. Forest represents about seven percent of the land cover on the reservation. There have never been any large-scale silviculture operations or other development on the reservation's forested lands. Similar to the forested cover, agricultural land comprises about seven percent of the WRIR. Pasture and hay, which make up 5.3% of the total land-use area, are the largest agricultural land uses on the reservation. Row crops and small grains make up just 1.5% of the total land-use area while fallow lands make up 0.2%. According to land-use data compiled by the Wyoming Water Resources Center (1998) there are nearly 190,000 acres of irrigated agricultural land within the resevation boundaries. Most of this land is irrigated by surface water except for a few small areas near Riverton and in the Owl Creek drainage were irrigation wells are used. Open water and wetlands both make up about 1.5% of the land use on the reservation. The three largest open water bodies on the reservation (Boysen Reservoir, Ocean Lake, and Bull Lake), either supply irrigation water or receive irrigation drainage. On the lowlands there are numereous irrigation reservoirs, stock ponds, and natural lakes. In the Wind River Mountains there are more than 220 high mountain lakes (Daddow, 1996, p. 38). Wetlands occur throughout the reservation boundaries, but are concentrated in irrigated areas, in the Wind River Mountains and along perennial streams. Urban land use comprises just 0.1% of the total land use on the reservation. The City of Riverton with a population of 9,310 (U.S. Census Bureau, digital data, November, 2001) is the largest urban area followed by the unincorporated communities of Arapahoe, Fort Washakie, Ethete, and Crowheart.

Approach

The goal of this effort is to design and provide the information needed to implement a ground-water-quality monitoring network to protect and use ground water in a sustainable manner. The network designed will be used to characterize ground-water quality on the WRIR, assess the ground-water resource in relation to multiple land uses and potential effects on water quality, identify areas for continued monitoring to detect trends or changes in water quality, and monitor water levels over time. Specific objectives to accomplish this goal were to prioritize the important ground-water resources on the WRIR, design the network, provide a report documenting the prioritization and network design, and provide a plan to implement the network.

Aquifer Prioritization

Aquifers are prioritized for ground-water-quality monitoring to identify particular aquifers and areas within aquifers to be sampled using limited resources. The State of Wyoming formed a task force with representatives from the Wyoming Department of Environmental Quality (WDEQ), U. S. Geological Survey, Wyoming State Geological Survey, and the University of Wyoming to develop a statewide prioritization of aquifers (currently in draft) for the design of a ground-water quality network. The process described herein for aquifer prioritization, modified this original effort to take into account local aquifer systems, detailed hydrostratigraphy, criteria used to weight the effects from different land uses, updated land use/land cover information, and stratification based on aquifer unit and land use. The approach is similar in concept to the statewide prioritization program that is currently in development so that the monitoring network design and implementation will be compatible with the state program. Aquifer prioritization is accomplished by creating separate spatial data layers that are representative of important characteristics (water-use areas, aquifer units, land use, and aquifer sensitivity to potential contamination) and then combining them to develop priority areas. The areas that are delineated then become the strata for network design.

The prioritization began with a compilation of well information and ground-water use to identify areas within aquifers that are currently used the most. The inherent assumption in this approach is that areas in aquifers with the highest use of ground water will be selected as priority areas. Areas in aquifers used for drinking water will be given the highest priority within the water-use layer of the aquifer prioritization. Well inventory and water-quality information was obtained from multiple sources and combined into a single, comprehensive database. Data sources included the WRIR well inventory database, well inventory and water-quality data from the USGS National Water Information System, well inventory data from the Wyoming State Engineer's Office database, and well inventory and water-quality data from the University of Wyoming Water Resources Data system. Almost 17,000 individual well records were merged into one database which now houses information for approximately 6,000 wells on the reservation, over 15,000 water-level records, and more than 1,000 water-quality records.

Structural contour maps (Johnson and others, 1996; Keefer and others, 1993; Hogle and Jones, 1992; and Barlow and Haun, Inc., 1992) were digitized and used to identify the tops and bottoms of hydrogeologic units (figure 3) to provide the vertical dimension for the network stratification.

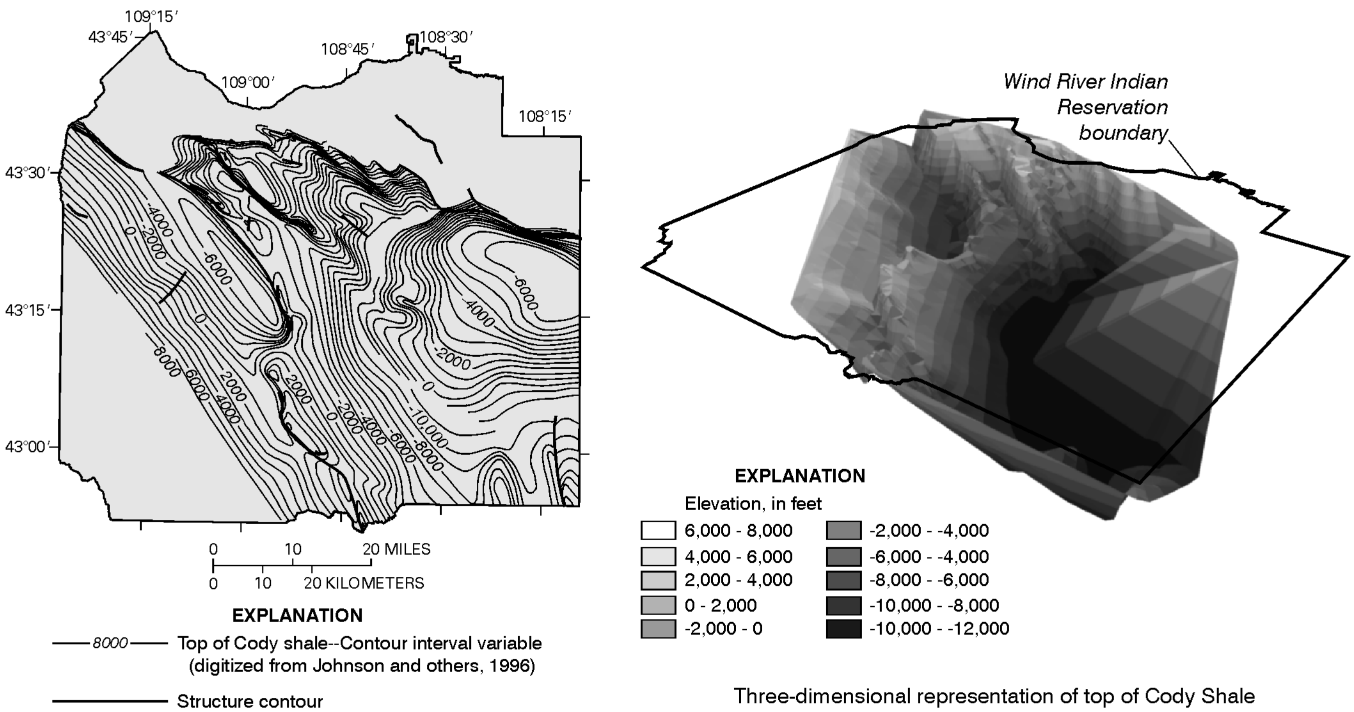

Figure 3. Vertical stratification of the hydrogeologic units, Wind River Indian Reservation (Cody Shale is a geologic unit used to represent bottom of Upper Cretaceous aquifers).

Formation surfaces that represented the tops or bottoms of aquifer units were used in conjunction with maps of the WRIR showing the surficial extents of aquifer units (figure 4) to conceptualize the hydrogeologic framework. Existing wells will then be associated with aquifers so aquifer codes can be assigned to the producing interval of individual wells and the areas and types of ground-water use within individual aquifers can be delineated. For the Quaternary aquifer system a different approach was taken to assign aquifer codes since few thickness contour maps were available. When wells were located within the areal boundaries of the Quaternary aquifers, their depth was examined on an individual basis to determine if they were completed in the Quaternary aquifers. In most cases, wells with completion depths of 50 feet or less, were assumed to be producing water from the Quaternary aquifers.

This combination of information will provide the first level of stratification for the network design, namely the aquifer-system layers. Within each aquifer, three areas will be delineated; areas with little to no ground-water use, areas with significant ground-water use, and areas with significant drinking-water use. Little quantitative information exists as to the actual volume of ground-water withdrawals in the area so water use will be characterized by using well density as a surrogate for the amount of water use.

A land-use analysis will be used to represent areas on or near the land surface that are potential contaminant sources for underlying ground water. The areas that will be identified are urban, agricultural, rangeland, forested, oil and gas, and rural domestic. Information concerning these areas will be taken from the NLCD, WRIR data on oil and gas fields and National Pollutant Discharge Elimination System (NPDES) sites, and the WDEQ database of known and potentially contaminated ground-water sites. Rural domestic drinking-water wells will be used as a surrogate to represent rural domestic land use and then will be integrated with the NLCD. Potential point-source-contamination sites (such as NPDES sites) will be integrated into the overall land-use area where they are located resulting in areas of potential point- and non-point-source contamination.

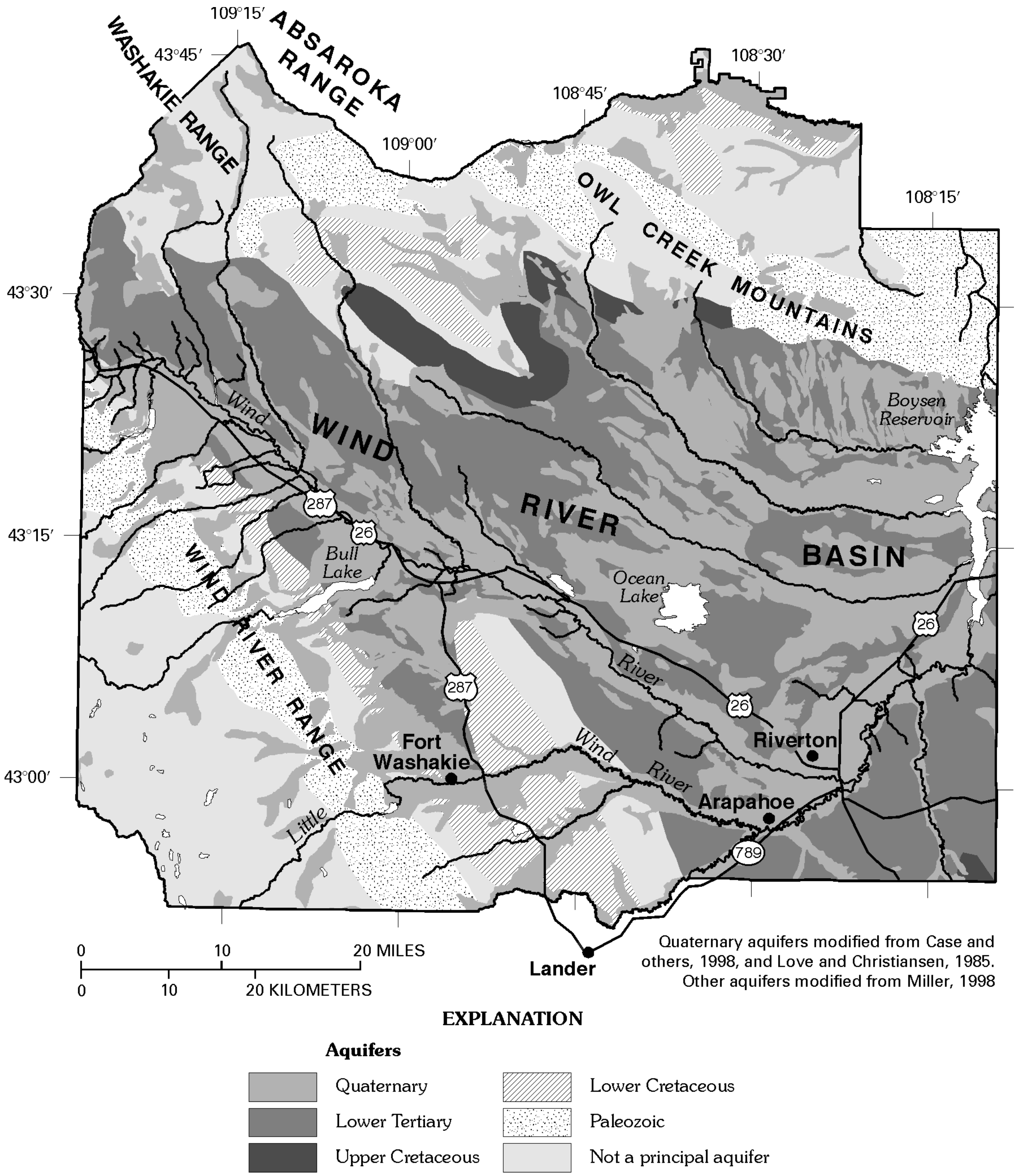

Figure 4. Surficial extent of aquifers in the Wind River Indian Reservation.

Another important layer for the aquifer prioritization is a representation of the inherent natural hydrogeologic characteristics of an aquifer that would make it susceptible or sensitive to contamination. When inherent susceptibility is coupled with potential anthropogenic sources of contaminants (such as pesticides), the term aquifer vulnerability is generally used. In the context of this paper, aquifer sensitivity is used, rather than the more common term susceptibility, because of previous work by the WDEQ and the University of Wyoming. Wyoming has generated a statewide analysis of aquifer sensitivity (Spatial Data and Visualization Center, 1998) and a statewide analysis of aquifer vulnerability (sensitivity coupled with a particular potential anthropogenic source) to pesticides. The sensitivity model was generated with a modified DRASTIC approach (U.S. Environmental Protection Agency, 1993) and used data layers that were overlaid to perform a spatial coincidence analysis. These layers were: (1) depth to initial ground water based on well permits, (2) net aquifer recharge estimated from soil types and precipitation, geohydrologic setting determined from geology, soils, land surface slope, and (3) vadose zone characteristics interpreted from geology and water levels.

Areas will be prioritized for the network design by overlaying grids from the analyses previously described onto layers representing the aquifer units. One layer will represent the three water-use areas. Separate layers will be used to represent land use, and one layer will represent aquifer sensitivity. Layers that have spatial data represented in vector form will be rasterized to convert polygon information into grids. Each grid cell will then be assigned a weight according to its' relative importance in the prioritization. Scales and weighting schemes have not been developed yet. Weighting of individual cells will be based on reviews of literature, discussions with tribal managers, and knowledge of hydrogeological conditions. For example, in the water-use layer, a higher weight will be given in areas where the ground water is being used as a source of drinking water (both public supply and domestic supply). Similarly, urban and agricultural land will be given a higher weighting than range or forest. The grids will then be stacked and the cell weights summed to provide a priority score. This analysis will be performed separately for each aquifer unit. Priority scores will be statistically analyzed to categorize priority areas into three or four bands across aquifer units.

Alternative Aquifer Prioritization

Recognizing the qualitative nature of both, assigning weights to land uses and the aquifer sensitivity maps, an attempt was made to assign relative risks on the basis of actual data and probabilistic techniques. Recent techniques (Rupert, 1999; Rupert, 2001) have been developed to address the qualitative nature of aquifer sensitivity maps and provide quantitative, probabilistic relations between potential for contamination, land use, and hydrogeological characteristics. The application of this technique, or other techniques utilizing actual geochemical data (such as isotopes) is preferable when there is sufficient ground-water-quality data to develop the relationships. If successful, priority areas can be delineated based on an actual calculated probability of contamination from a combination of land use and hydrogeological characteristics. Unfortunately, the existing data for the reservation did not have the geochemical resolution (very low detection limits and chemical speciation information) to allow for statistical relations to be developed. The analysis was useful however, as it provided land use weighting information that indicated no statistically significant differences in median nitrate concentrations below a variety of land-use types.

Network Design

Strata for the network design will be aquifer system, priority level, and land use. Within the top two strata (aquifer system and priority level), ground-water-sampling locations will be selected using a spatially based, stratified-random method following the general approach of Scott (1990). Figure 5 illustrates this process. The priority level within an aquifer will be divided into zones, each having an approximately equal areal extent. Each of the zones will be further divided into equal-area grid cells where one cell is randomly chosen so that a single well will be selected (existing or new) in each zone for inclusion in the network. It is expected that not all randomly chosen sites will be included in the network because permission will be required to install wells and/or sample existing wells. Therefore, alternate locations will be randomly selected within each zone to maintain the random design.

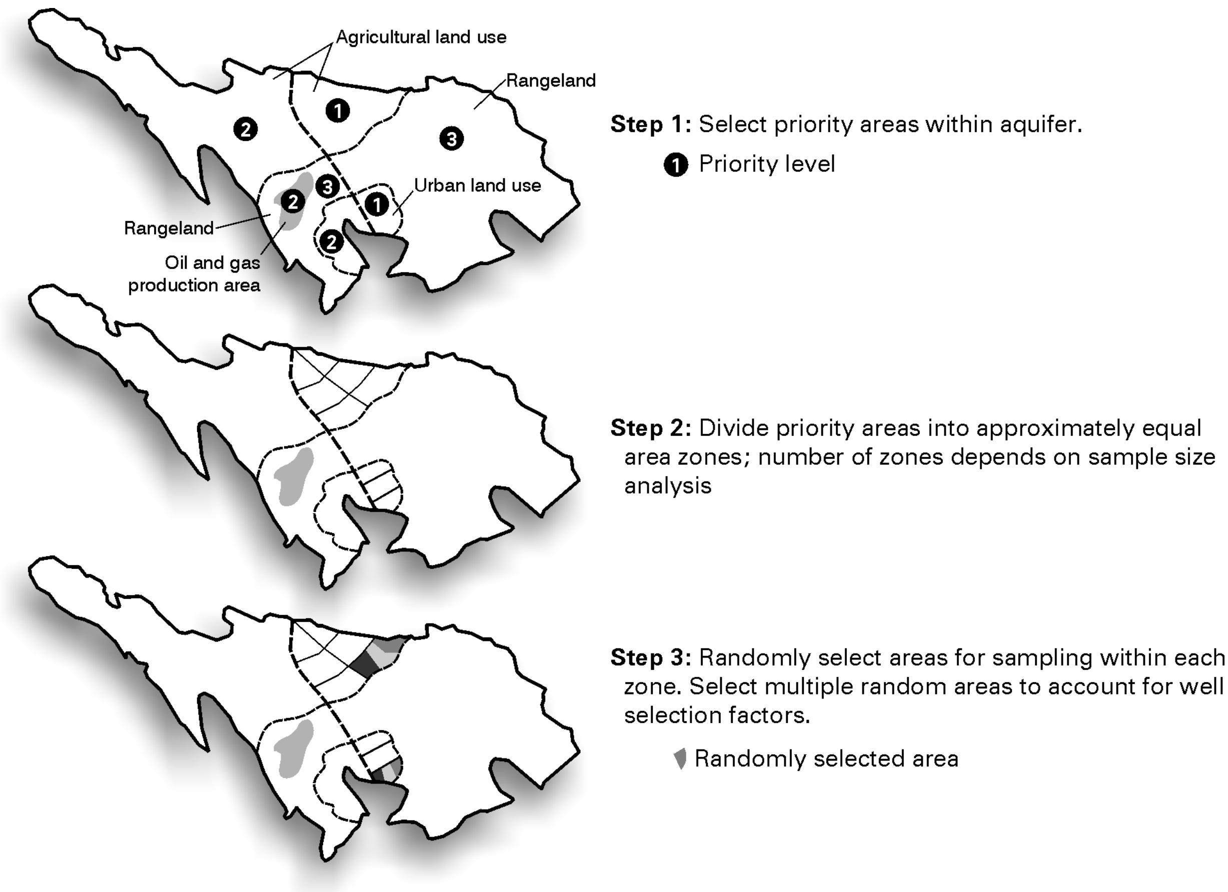

Figure 5. Spatially-based, stratified random design.

This stratified-random design ensures that monitoring wells are spatially distributed and randomly selected to provide the ability to examine statistical relations in water quality between and within aquifer systems and ensures that limited resources are efficiently applied. Relations between ground-water quality and land use will be examined by ensuring an adequate number of monitoring locations within a particular land use and aquifer system. The actual number of sampling locations will be selected using specific water-quality characteristics. A statistical analysis of existing data for each aquifer and selected land uses will be performed to assess the variance for selected constituents. This analysis, coupled with the areal extent of the strata, will be used to select the sample size. Cells will be selected as sample locations that represent an area of land where either an existing well will become part of the network, or a new monitoring well will be installed.

Once the stratified randomization has been completed, existing wells within sample cells will be evaluated for use in the monitoring network. Screening criteria that consider well characteristics will be established to ensure that existing wells being considered for long-term sampling will provide samples that will be representative of water in the aquifer. If, after the evaluation of existing wells is completed, and the minimum number of wells needed is not met, locations will be selected for the installation of new monitoring wells. In addition to selecting wells for water-quality sampling, a subset of new and existing wells will be selected to install water-level recorders to measure water levels over time.

Network Implementation

Although the effort described here does not include the implementation of the network, the final component will be to provide implementation guidance. Sampling frequencies and analytical methods have not yet been proposed. However, general guidance will be to sample all network wells and analyze the ground-water samples for a wide variety of constituents. This initial sampling will provide comprehensive baseline information and will be used to facilitate the design of long-term monitoring. Subsequent sampling can then be based on site-specific results so the sampling frequency, analytical methods, and even which wells are sampled, can be varied depending on the results from the initial sampling. At some point after data collection begins, the aquifer prioritization will be revisited and possibly updated after examination of geochemical and isotopic data. Multiple lines of geochemical evidence and statistical analysis of data from areas not affected by land use will address natural levels of constituents within aquifers.

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