CHAPTER 2 - METHODS

OBJECTIVES

Project objectives were to identify trans-international boundary aquifers, quantify the hydrogeologic characteristics of each aquifer, characterize and quantify the available water supply of each aquifer, determine the direction of groundwater flow and its relationship to the streams, and incorporate the information into a GIS compatible data set for the region. The project was designed to gather and compile the best currently available hydrogeologic data and information along the United States/Mexico international border in southwestern New Mexico for data exchange with the Republic of Mexico.

APPROACH AND DATA SOURCES

Design of Project

The project consists of four primary parts: quality control, data acquisition, evaluation, and interpretation. Each of these parts is described in more detail in the following sections. The delineation of the groundwater aquifers was the most involved task as it required refinement of the surface geology mapping, the identification of hydrogeologic units as well as a review of existing geohydrologic models with analysis of surface and subsurface water chemistry. A number of geographic information system (GIS) coverages were developed or acquired in order to facilitate the intrepretation and assessment of the groundwater aquifers. All known existing aquifer information, both digital and hard copy, was gathered and utilized.

Quality Assurance

Prior to initiation of the study, the project's Quality Assurance Project Plan was developed in order to maintain a high level of accuracy and was approved by the Environmental Protection Agency (EPA) Region 6. The plan described details of the project's organization, objectives, functional activities, and specific quality assurance and quality control activities designed to achieve the data-quality objectives for this project. Projects undertaken by the New Mexico Water Resources Research Institute (NMWRRI) express data quality objectives based upon acceptable confidence, representativeness, comparability, and completeness. The "Trans-International Boundary Aquifers in Southwestern New Mexico" study employed only methods and techniques that have been determined to produce measurement data of a known and verifiable quality and that are of sufficient quality to meet the overall needs of the project.

The completeness of data is basically a relationship of how much data can be acquired compared to the total potential data. Every effort was made to identify data sources. The project was a reconnaissance level program intended to identify and assimilate data that had been collected in past efforts. The project did not obtain any new data. The sensitivity of the data collection procedures that were used is important only in evaluating the usefulness of the data, for the identification and characterization of transboundary aquifers, and the inclusion of the data in the composite database. All analytical results were considered to be potentially useful and were not to be discarded.

Data Collection

The data collection phase of this project involved the compilation, verification, and documentation of well data, water quality information, and data concerning the geology of the area. The data were collected from various federal, state, and local governmental entities.The first task was to compile existing well data from water related agencies and entities, evaluate the accuracy of the data and location of the wells, and transpose data from the various database formats into a document format agreed upon for international data transfer. Well data were collected from the United States Geological Survey (USGS), New Mexico Environment Department (NMED), the New Mexico Office of the State Engineer (NMOSE), and other sources. These individual pools of information were also checked against existing data summaries of data compiled by other entities. This information was incorporated into a common database format. The second task was to prepare all data for incorporation into GIS format. All well data were assembled and incorporated into a GIS compatibleformat and presented on maps of the region. A literature review was conducted, an extensive bibliography of previous studies was compiled, and documents of interest acquired.

Geology

An intensive literature review, coupled with limited field work during this project, was necessary for completion of a surface geology map and characterization of the hydrogeologic framework at a map scale of 1:125,000. The primary data sources for the surface hydrogeologic map for this project were maps created by more than 25 geologists during the past 50 years (notably Anderson et al. 1997, Bryan 1995, Bromfield and Wrucke 1961, Cooper 1959, Drewes et al. 1985, du Bray and Palliser 1999, Erb 1979, Rattè and Gaskill 1975, Seager 1995, Seager et al. 1982, Vincent and Krider 1998, Wrucke and Bromfield 1961, Zeller 1959, 1962, 1970, 1975, Zeller and Alper 1965).

Water Well Information

Water well information was derived from the USGS Ground Water Site Inventory (GWSI), the NMOSE and the NMED. Figure 2-1 illustrates the distribution of water wells in the area. The points are color coded based on the date range of latest measurement and if water quality samples were collected. Data have been collected for a number of years. Every attempt was made to identify any other data that had been collected by other programs and evaluate its potential contribution toward the composite database and use in identification and characterization of the transboundary aquifers.

Water Well Location Accuracy

An acceptable level of confidence in the water-well location data was achieved by statistical analysis of the true location and recorded location for a sample set of the total well population. To determine the accuracy of the water level monitoring wells, a random sample set of 43 well locations was drawn from the 779 water wells that had data recorded since 1990. The accuracy of the geographical location was determined by comparing recorded location in the data set and field reading by global positioning system (GPS) of this selected sample set.

The GPS was set to collect location information using the geographic coordinate system and the NAD27 datum. The GPS data were transferred from the GPS unit to an office computer in order to process and correct the raw data to obtain the most accurate location information possible. Sample location errors, the difference in distance between the recorded location and the GPS measured location, were computed in meters.

These sample location errors were used to compute a 95% confidence interval for the mean location error in the population of wells. The finite population correction factor was used in the estimation process. The 95% confidence interval was computed as,

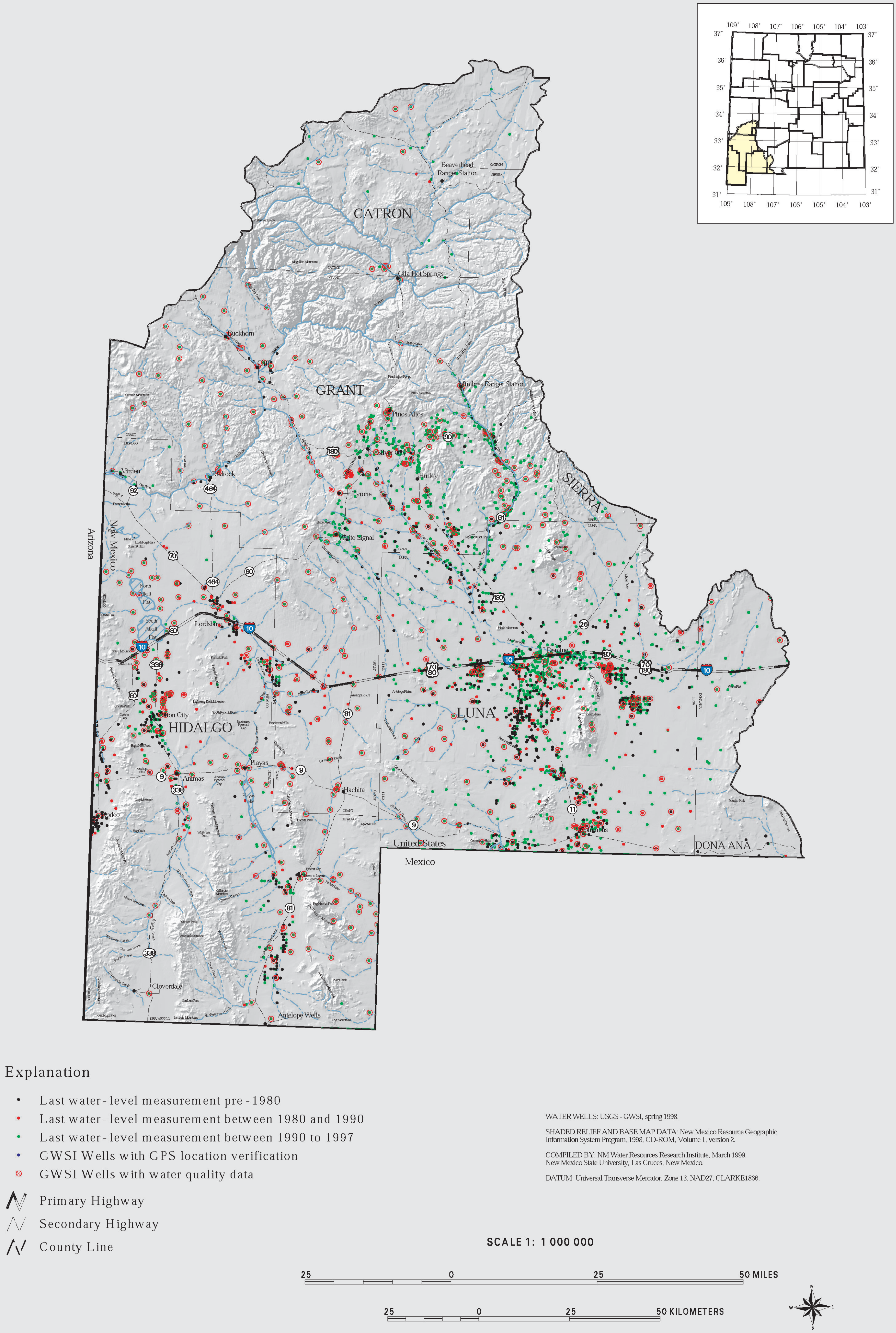
$$\bar{x} \pm t_{(0.025,n-1)} \frac{s}{\sqrt{n}} \sqrt{(1-f)}$$

where $\bar{x}$ and s are the mean and standard deviation of the sample location errors, respectively, n is the sample size of 43, $t_{(0.025,n-1)} = 2.325$ is the critical value from Student's t-distribution, and $(1-f) = 1 - 43/779$ is the finite population correction factor.

The sample of 43 wells resulted in a mean location error of 167.5 m with a standard deviation of 122.5 m. Thus it is estimated that the mean location error in the population falls between 125 and 210 m. In this region, this is equivalent to estimating the mean location error of the population between 4 and 7 seconds of longitude or latitude. In general, this level of error is satisfactory for locating a majority of the monitored water wells. In areas where the density of wells is high, this level of location error would not allow the identification of the data set well. In such areas, data set remarks and other field notes are required.

Geology Mapping

An integral step toward identifying trans-international boundary aquifers was to gather information concerning the surface and subsurface geology of the region. The surface geology maps for the state of New Mexico are available at a scale of 1:1,000,000 and 1:500,000 and many areas are now mapped at 1:250,000 scale. However, geologic mapping at 1:125,000 and larger scale is incomplete. In particular, a large portion of the study area (west of 108$^{\mathrm{N}}$ longitude) has yet to be mapped at a scale of 1:125,000, and information on the framework of hydrogeologic units that constitute much of the transboundary aquifer system has never been integrated with the surficial geologic mapping. The resulting three-dimensional portrayal of the region's complex hydrogeologic framework (Plate 1) will serve as a good template for organizing information needed for development of a new generation of groundwater-flow models.



WATER WELLS: USGS - GWSI, spring 1998.

SHADED RELIEF AND BASE MAP DATA: New Mexico Resource Geographic Information System Program, 1998, CD-ROM, Volume 1, version 2.

COMPILED BY: NM Water Resources Research Institute, March 1999. New Mexico State University, Las Cruces, New Mexico.

DATUM: Universal Transverse Mercator. Zone 13. NAD27, CLARKE1866.

Figure 2- 1. Map of wells in database.

Geologic Information

Refinement of the surface geology and identification of surface and subsurface hydrogeologic units were based upon the available geologic maps, cross sections, thorough literature review, and consultation with professional geologists. The latest statewide surface geology map, in digital form, is available from the USGS as a 1997 Open-File Report OF-97-52 (Anderson et al. 1997). The map is at 1:500,000 scale and in Arc/Info format. The New Mexico Bureau of Mines and Mineral Resources (NMBM&MR) provides paper maps of various scales, and numerous reports on the geology within and surrounding the study area. These maps and reports provided large-scale geologic data for much of the area. For areas in which geologic maps and/or reports were not available, other sources of information were used, such as orthophotography. The surface mapping began by generalizing the mapping units of available large scale maps to a 1:125,000 resolution for the Basin and Range portion of the study area and 1:250,000 resolution for the Intermontane Plateau region (north of 33° latitude). Orthophotography, and/or field work were used to complete the coverage for areas without large scale maps and/or reports.

Hydrogeologic map-unit definitions generally follow the hydrostratigraphic unit and lithofacies subdivision classification introduced by Hawley and others (1995), in the Rio Grande basins between Albuquerque and El Paso. However, they were tailored to better fit existing geohydrologic conditions in the study area, wherever they differed from those in the Rio Grande rift basins to the north and east. *Hydrostratigraphic units* comprise the basic mapping classes along with the structural features (i.e., faults and folds, and bedrock units) that form major inter- and intra-basin hydrologic boundaries. The hydostratigraphic units include major mappable (at 1:125,000 scale) subdivisions of fluvial, alluvial, eolian, and piedmont slope deposits of mostly unconsolidated sediments. The subdivisions are defined on the basis of genetic origin, position, and age of the stratigraphic sequence of deposits. *Lithofacies assemblages* are fundamental map-unit subdivisions that are primarily textural and mineralogical units (ranging from sand and gravel to silt and clay) that control basic aquifer properties (such as permeability distribution patterns). The hydrogeologic framework conceptual model is described in detail in Chapter 3, and forms the basis of the aquifer system mapping unit classes shown on Plate 1.

Methods of Aquifer Delineation

Aquifer delineation was based upon thorough investigation of surface and subsurface geology, analysis of water quality, examination of water-level data sets, and extensive review of the literature. The first task was to gather existing data from the various agencies and obtain any previous groundwater investigations. The second task was to assemble and present the information in a useful form for evaluation. GIS technology was utilized extensively in this task. Third, the products of the delineation and characterization were then developed into a digital data set. Further evaluation and intrepretation derived the saturated thickness, volume of usable (less than 10,000 TDS) and marginal-quality water in storage, potential recharge zones, recharge mechanisms, and direction of groundwater flow. The final tasks determined the depth-to-groundwater in each aquifer, conceptualized profile flow models to simulate the potential pathways that groundwater will traverse, and evaluated the potential for interaction between aquifers and surface water. This included evaluation of the potential for transboundary subsurface groundwater flow. Information was compiled using existing data collected from observation wells and river loss and gain studies over the years. Groundwater flow directions were evaluated throughout the year and the loss and gain of the rivers due to interaction with the surrounding aquifer was noted.

Methods of Water Quality Analysis and Mapping

Water quality mapping and analysis were performed in each basin to define regions of good, marginal, and poor quality groundwater. Water quality data were collected from the public domain information in the U.S. and Mexico. These data included STORET data, New Mexico Environment Department public drinking water data, USGS groundwater quality data, and Comision Nacional Del Agua (CNA) groundwater quality data, contained in Instituto Nacional de Estadistica, Geografia e Informatica (INEGI) water quality sheets. These data were transposed from the various databases into a standardized database format for validation.

Validity Check of Hydrochemical Analyses

The ion balance equation was used to validate hydrochemical analysis of standard inorganic constituents:

$$\text{Charge Balance} = \frac{3\text{cations} - 3\text{anions}}{3\text{ions}} \quad x\ 100$$

where all values are summed in meq/L. Charge balance analysis is applied to cations that include Ca, Na, K, Mg, and to anions that include Cl, SO_4, HCO_3, and NO_3. The residual error should be less than 5%. Standard inorganic analyses that do not conform to the mass balance equation within this range of error were not used in the data sets.

Presentation and Interpretation of Water Quality Data

Standard hydrochemical constituents are presented graphically as spatial pattern diagrams after the method developed by Stiff (1951). Concentrations of cations are plotted to the left of a vertical axis and anions are plotted to the right of the axis, with all values presented in meq/L. These diagrams allow the determination of "hydrochemical facies" in which the dominant cation/anion pair(s) is shown (e.g., Na-SO_4-Cl facies). Stiff diagrams are placed at the appropriate well location on x-y maps and are color coded by total dissolved solids (TDS) concentrations.

Water quality analyses were further classified by Piper plots (1944). This method expresses specific cations as meq/L percentages of total cations on a trilinear diagram. Similarly, anions are plotted by their respective percentages on a separate trilinear diagram. The two points from any specific analysis are then projected onto a central diamond-shaped plot that is parallel to the upper edges of the trilinear diagrams. This method allows the classification of waters by hydrochemical facies and has the added benefit of allowing hydrochemical mixing trends and evolutionary trends along flowlines to be identified. For example, the points represented on the cation and anion triangles in Figure 2-2 are, respectively, sodium and sulfate dominated, which classifies these waters as a Na-SO_4 facies.

Chloride, sulfate, and nitrate in groundwater are also plotted on basin maps. Their values are listed by a color-coded symbol. The color code identifies samples which contain certain ranges of concentrations that are less than, or exceed, threshold values such as the drinking water standard for a particular constituent. Drinking water standards for chloride (250 mg/L), sulfate (250 mg/L), and TDS (500 mg/L) are USEPA National Secondary Drinking-Water Standards, also known as recommended maximum concentration levels. These are maximum desirable concentrations for potable waters, although most humans can tolerate higher concentrations of these inorganic constituents. Drinking water standards for nitrate (10 mg/L NO_3-N) are USEPA maximum contaminant levels (MCL). The MCL is the concentration that must not be exceeded in drinking water due to health concerns.

Classification of irrigation water quality is provided by the classification system of the U.S. Salinity Laboratory (Richards 1954). This graphical procedure plots sodium absorption ratios (SAR) against specific conductance, and delineates zones that vary from low to very high sodium and salinity hazard. The SAR is defined by:

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}}$$

Specific conductance is not available for many of the chemical analyses of waters in the U.S., and for none of the analyses in Mexico. Therefore, specific conductance was estimated by multiplying groundwater TDS by 1.33 (Hem 1985).

Mineral saturation states were computed by PHREEQC (Parkhurst 1995). PHREEQC calculates a saturation index, which represents the degree of equilibrium between water and minerals on the basis of the amount of dissolved ionic species in solution, and the amount that would be present if the water-solute system were at equilibrium between water and minerals at the sample temperature. Equilibrium with respect to a given mineral is indicated by a value of zero. Negative values suggest undersaturation and positive values reflect oversaturation.

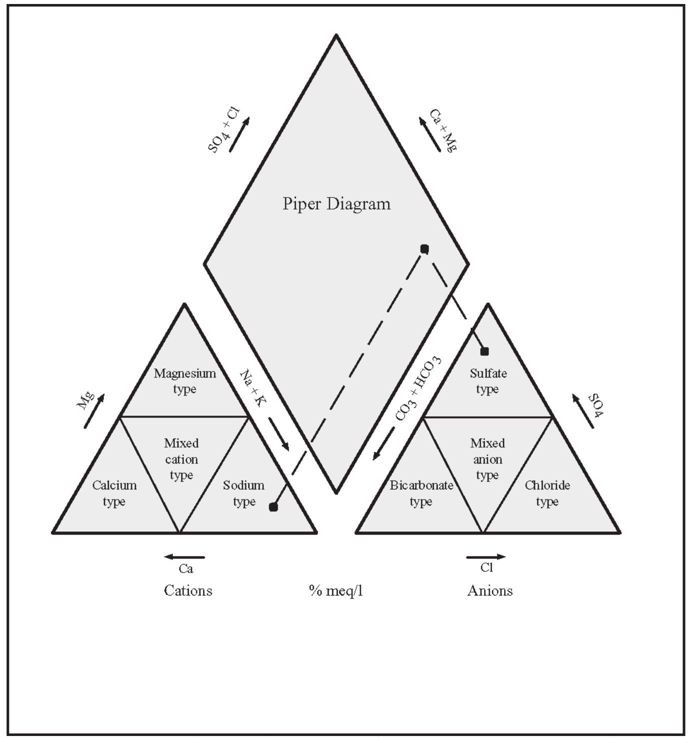


Figure 2-2. Piper diagram showing representation of hydrochemical data. *In this diagram, the points plotted in the sodium and sulfate dominated regions in the triangles designate the sample as a sodium-sulfate (Na-SO_4) hydrochemical facies.*

Susceptibility to Contamination

In a region where water quantities and quality are of great concern, identifying areas susceptible to contamination is important. A 1997 study in the region by the New Mexico Department of Health, Border Health Office (BHO) showed that 10 to 20% of the wells sampled had contaminants that could pose a serious health risk (Border Health Office 1997). The most serious constituents were coliform bacteria, lead, fluoride, uranium, nitrate and arsenic (Border Health Office 1997). The presence of coliform bacteria is an indicator of contamination. However, the Border Health Office report did not identify actual sources of contamination (Border Health Office 1997).

Groundwater quality varies due to its depth, distance from recharge areas, type of aquifer in which it occurs, and its proximity to mineralized zones and ore bodies. Aquifer susceptibility to the influx of point-source and nonpoint-source contaminants is dependent upon the character of the overlying soils and sediments, the aquifer's chemical and physical properties, and the shape of the water table. These characteristics interact and must be considered holistically to determine the relative natural sensitivity of each aquifer to contamination.

Groundwater resources within the state's farming areas may be susceptible to contamination from applied agricultural chemicals (Creel et al. 1998). This is due to some groundwater aquifers being relatively near the soil surface, farmlands being intensively cultivated, and irrigation practices. Leaching is one route by which groundwater may become contaminated by agricultural chemicals. As a part of this study, an assessment of the degree to which groundwater aquifers may be susceptible to contamination was performed.

Most of the agricultural cropland, approximately 490 km^2 (120,000 acres; USDA 1997), in the study area is located in the following basins: Mimbres Basin, Animas Valley, Playas Valley, San Simon Valley, and Virden Valley. In these basins, the perennial and intermittent streams have a complex history of meandering and flooding. This results in a diverse and intricate pattern of soil types and geomorphic features. The soils have textures ranging from clay to gravel and often have stratified profiles with cemented zones.

The most efficient approach to assessing groundwater aquifer sensitivity is to employ a regional Geographic Information System (GIS) to determine and map the relative sensitivity of aquifers to contamination sources. The National Water Well Association (Aller et al. 1985) developed the DRASTIC model to assess aquifer sensitivity. The model combines data sets that describe the depth to groundwater (D), recharge rates (R), aquifer material (A), the composition of soils (S), land slope (T), impact of vadose zone materials (I), and saturated hydraulic conductivity (C). DRASTIC has been the most commonly used aquifer sensitivity assessment method; however, it is not intended to predict the occurrence of groundwater contamination (USEPA 1993). Most recently, this method has evolved beyond a simple sensitivity rating to a descriptive approach identifying areas with similar hydrogeologic characteristics (i.e., hydrogeologic setting) and assesses individual areas susceptibility to potential groundwater contamination (Hearne et al. 1992). This type of analysis is much more useful to local decision makers. An understanding of the hydrogeologic setting, which determines the basic processes under which groundwater contamination occurs, must be incorporated into the process of designing alternative management strategies. This project incorporated such information and techniques. It also required that data be gathered at appropriate scales and with sufficient map accuracy.

This analysis utilized techniques and data types similar to those used in the assessment of the Mesilla Valley (Creel et al. 1998), with the exception of the soil media parameter. In the Mesilla Valley assessment, the soil media parameter was derived from the large-scale (1:24,000 scale) county level digital soil survey data (SSURGO). The 1:24,000 scale digital soil survey data were not available for all of southwest New Mexico (the region of this study). However, the smaller scale State Soil Geographic Data Base (STATSGO) is available in digital form.

The STATSGO series was designed to be used primarily for regional, multistate, river basin, state, and multicounty resource planning, management, and monitoring. Map-unit composition for STATSGO is determined by transecting of sampling areas on the more detailed maps and expanding the data statistically to characterize the whole map unit. Each map unit may contain up to 21 components for which there are attribute data, but there is no distinction as to the location of these components within the delineation. The STATSGO map unit is accurate at a scale of 1:250,000 (USDA 1994).

The aquifer media, vadose media, and hydraulic conductivity parameters were defined by using the geologic map created for this project. The geologic map is modified to show areas of similar characteristics, such as bedrock versus non-bedrock, based on surficial geology. These delineations are based on lithofacies assembledges described earlier. A lithofacies is a unit of media, made up of the sum of its features, that can be characterized by the type of rock present. For example, a portion of an aquifer system could consist of a "fluvial sand" lithofacies. The term "fluvial" indicates that the "sand" was deposited in a river system.

Depth-to-water-table information, collected by the USGS on an extensive network of wells, was available in digital form and was utilized.

DRASTIC Mapping

The DRASTIC model can effectively identify areas that are susceptible to both nonpoint and point sources of contamination. The output of the model can be produced in map form.

DRASTIC Model Modification

The DRASTIC model rates relative sensitivity of land units by integrating information on vadose zone geology, soils, recharge, hydraulic conductivity, slope, aquifer media, and depth to groundwater. It was designed to allow flexibility so that the local hydrogeological setting and its parameters could be weighted appropriately. The hydrogeological setting is described by the spatial representation of designated mapping units. The mapping units incorporate the major hydrogeological factors which affect and often control groundwater movement. The weighting of a parameter is determined by the importance of that parameter given a particular activity. Agricultural plays a prominent role in the region and, therefore, the parameters are weighted accordingly (Aller et al. 1985). The DRASTIC model was modified to incorporated these considerations.

Hydrogeologic Parameters

The hydrogeological factors are depth-to-water table (D), net recharge to the aquifer (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I) and hydraulic conductivity of the aquifer (C). These factors, or parameters, comprise the acronym DRASTIC. Each of the parameters consists of a range of values; the values are mapped separately (mapping unit) and assigned a rating. The rating is then multiplied by a weighting factor consistent with the primary activity of the region.The product of the value rating and the weighting factor result in an index value for each mapping unit within a parameter. The parameter index values for the seven DRASTIC parameters are then added together to form the DRASTIC index.

The DRASTIC index is a quantitative measure of the DRASTIC parameters and can vary greatly over a wide range. The index provides a relative measure of one area's sensitivity compared to other areas within a region. In general, the higher the DRASTIC index, the greater the susceptibility of the groundwater aquifer to point and nonpoint source contamination. However, mapping of the individual DRASTIC index values results in numerous small polygons. There is simply too much detail in a quantitative map, at a regional scale, to be useful.

Each of the polygon index values was arranged in ascending order and plotted on *x-y* graphs (*x* values were the polygon number and *y* the DRASTIC index value) Visual inspection identified natural breaks which allowed grouping of the values into 3 groups (high, medium, and low). The polygons were assigned to one of these groups, which were referred to as the natural sensitivity (NATSEN) index groups. These three groups are described as: *low* - indicates the groundwater aquifer is very well protected and contamination risk from nonpoint sources is low; *moderate or mid-range* - indicates the groundwater aquifer is somewhat protected, but more than one of the parameters are conducive to contamination; *high* - indicates the groundwater aquifer is much more susceptible to contamination due to a number of hydrogeologic conditions. Details for each parameter and the result of the regional DRASTIC model is described in Chapter 3.

Geographic Information Systems

Spatial data for this project have been developed in Arc/Info 7.1 for UNIX format. These files can also be used with Arc View. The data sets that comprise many of the figures can be found on the enclosed CD-ROM. Non-measurement digital sources of data include existing groundwater databases for the U.S., literature sources, and data that were developed from processing software. Digital data sets for the Republic of Mexico were derived from published maps and published reports located in the general geologic literature. Existing data sets include published maps of Mexico and U.S. sources, such as digital elevation models, well location files, coverages of roads, railways, city boundaries, and other digital infrastructure files; well location files; agricultural activity files; and meteorological files. These data have come from entities that are known for developing and maintaining high-caliber databases, including the USGS, United States Department of Agriculture, EPA, CNA, and INEGI. Data from these sources are in the public domain and are considered acceptable for the purposes of this investigation.

Data from other sources required quality analysis. Existing GIS coverages were compared with hard-copy maps to ensure that digitizing was of an acceptable quality to include in the database. Occasional errors or inaccuracies may not necessarily exclude the coverage from inclusion in the GIS database. Quality of coverages was evaluated and details are included in the metadata descriptions.