GROUNDWATER EXPLORATION IN NORTHEASTERN ARIZONA USING LANDSAT IMAGERY

by

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ABSTRACT

Demands for electric power generation are rapidly increasing water-supply requirements in northeastern Arizona, where groundwater pumpage is expected to escalate sixfold during the next ten years. In a study undertaken to determine the feasibility of using satellite imagery as a tool in exploring for new sources of groundwater, lineaments detected on Landsat images of two study sites in Arizona were mapped. Literature related to well data in the two study areas was researched and the data were plotted. The lineaments then were correlated with the well data by means of a well-centered grid model. Correlations developed between lineament density and water well data in the two study sites support the hypothesis that a relationship exists between regional geologic structure and the presence of groundwater, and indicate that Landsat images can be used as a tool in delineating structural features.

INTRODUCTION

Growth of energy production requirements is placing an increasing burden on water resources in northern Arizona and the "Four Corners" area. It has been estimated (Southwest Energy Study, 1972) that regional energy generation will increase from 27 gigawatts (GW) in 1974 to 109 GW by 1990.

In northeastern Arizona, increasing amounts of groundwater are being used in energy production, as illustrated by power plant development at Joseph City and St. Johns, Arizona. The water system for the 120 megawatt (MW) plant near Joseph City consists of three wells and a storage reservoir. Present use of water is 3,600 acre-feet per year (AFY). Construction is underway to add three units that will have a generating capacity of 250 MW each. Operating the three new units will increase water demand to 13,500 AFY which will require developing additional wells. A plant under construction near St. Johns is designed to produce 600 MW of coal-fired power for regional use. This facility will require approximately 12,000 AFY. Well field exploration and initial development is underway.

In the Colorado Plateau region, groundwater occurs principally in sandstones, limestones, and other sedimentary rock units. These rocks commonly possess a dense, cemented matrix, displaying a relatively low order of intergranular porosity and permeability, and groundwater movement is controlled largely by rock fractures such as joints and faults, along which solution channels or other openings have been formed. Such fracture systems in the subsurface rock strata may project a visually detectable trace on the land surface.

In view of the geologic and water demand characteristics noted above, a study was undertaken in 1978 to develop methods of exploring for water supplies based upon faulting detectable in satellite imagery. Northeastern Arizona was the study area (Figure 1). Control sites near Flagstaff (Site A) and St. Johns (Site B) were selected for more detailed study. These sites were chosen because of the access to, and availability of, groundwater data collected as part of the St. Johns and Cholla Power Plant developments (Guyton and Associates, 1977) and the expansion of the Flagstaff municipal water supply (Harshbarger and Associates and John Corollo Engineers, 1973).

GEOHYDROLOGIC FEATURES

The general geohydrologic features and groundwater controls in the northeastern Arizona region have been summarized by Babcock, et al. (1979), and some of the key features are recounted below.

A sequence of Permian and Triassic rock units which underlie the southern Colorado Plateau is important in yielding relatively large amounts of water to wells. The formational units are, in ascend-

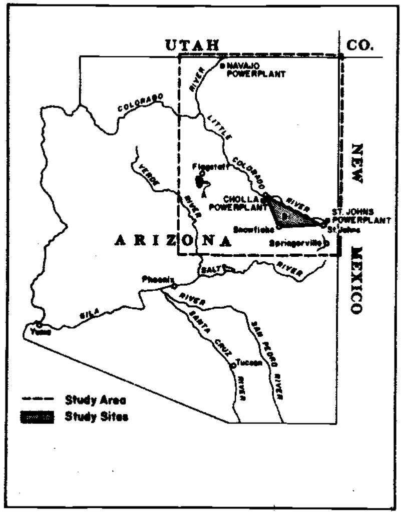

FIGURE 1. LOCATION OF STUDY AREA

ing order, the Permian Supai, Coconino, and Kaibab formations and the Triassic Moenkopi and Chinle formations. The principal water-bearing rock assemblage is the Coconino aquifer, consisting of the Coconino sandstone together with some underlying beds of silty sandstone and limy siltstone in the upper part of the Supai formation, and some overlying beds of sandstone and limestone in the lower part of the Kaibab limestone. Cracks and solution openings along bedding planes and fractures locally improve permeability and movement of water within the aquifer.

At study Site A, the Woody Mountain well field southwest of Flagstaff, recharge to the groundwater reservoir (Coconino aquifer) occurs through permeable basaltic cinder deposits on the surface and through fractures and solution openings in the underlying Kaibab limestone. Lateral movement of groundwater in the subsurface is strongly controlled by faulting, as the Oak Creek fault system directs easier flow of groundwater in a northeasterly direction.

Study Site B is in the open plateau region of northeastern Arizona. Recharge occurs in the southerly part of the site area through permeable sediments and jointed rocks, and groundwater movement proceeds towards the north-northwest, controlled by the regional dip of the aquifer formation. Movement of water is influenced locally by faulting, and yield of water to wells is substantially increased where drilling intersects joints and faults.

In order to evaluate these relationships in terms of existing wells, data on wells in the study areas were tabulated and the well parameters were studied as indicated in Phase II below.

USE OF LANDSAT IMAGERY

The application of satellite imagery to detecting and mapping geologic lineaments was first reported in 1973, at the Third Earth Resources Technology Symposium (Short, 1973). The major Landsat contribution to geologic mapping is that it shows large structural features and regional tectonic relationships. Shoemaker, Squires and Abrams (1974) and Goetz, et al. (1975) applied Landsat imagery to geologic mapping in northern Arizona, and the correlation of lineaments to the presence of groundwater was accomplished first in Arizona by Akers (1964), Cooley, et al. (1969), and Huntoon (1970), who found that water well production in northern Arizona sandstone aquifers depends on deep fracturing.

Babcock, et al. (1979) conducted a three-part, largely methodological investigation into Landsat application. Their techniques and results are spelled out in their report and by Foster, Schowengerdt, and Glass (1980), only the main points are summarized here, in order to emphasize the hydrogeologic aspects of the three-phase study.

Phase I. Lineaments within the entire study area were mapped using standard Landsat 1:250,000-scale, false-color composites. Six Landsat scenes (Figure 2) were selected for analyses, and Sites A and B were studied in detail. Contrast manipulation, spectral band ratioing and spatial filtering (edge enhancement) techniques were applied to the Computer Compatible Tapes (CCTs) that contained scenes of the two study sites.

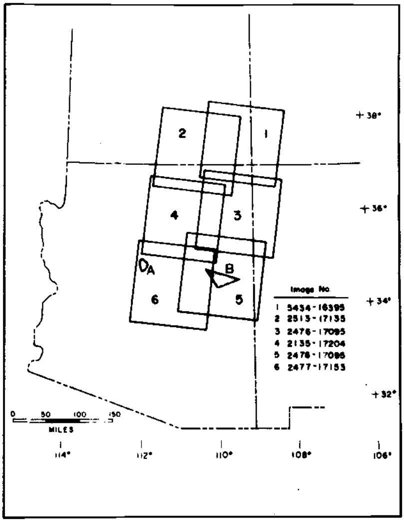

FIGURE 2. LANDSAT COVERAGE OF NE ARIZONA USED DURING INVESTIGATION

To verify structures mapped from satellite imagery, a comprehensive literature search was conducted to identify known lineaments within the study areas. All data were transferred to a 1:250,000-scale U.S. Geological Survey (USGS) topographic map. Lineaments reported in the literature were correlated to those mapped from Landsat imagery by using geographic features common to both the imagery and the USGS topographic base maps as tie points. If a structure defined in the literature and the mapped lineament both trended in the same direction within 15 degrees and were not more than 1,500 meters (m) apart, it was assumed that they were identical.

Phase II. An inventory was made within Sites A and B, of well location, depth, land-surface altitude, yield, drawdown, specific capacity, and transmissivity. From these data, four hydrologic parameters were chosen to correlate with lineament data collected during Phase I: Specific capacity (gallons per minute per foot of drawdown); transmissivity (gallons per day per foot); water temperature; and specific conductance (micromhos).

Phase III. A methodology was developed to correlate mapped lineaments with the hydrologic data. A well-centered grid model was used in which the cumulative length of lineaments (hereafter referred to as lineament density) within a specified radial distance (radius of influence) from each well was correlated with the four hydrologic parameters by use of linear regression (Figure 3).

The expected correlation signs are shown in Table 1. Specific capacity, transmissivity and water temperature should show higher correlation values where the lineament density is greatest. Specific conductance and lineament density are expected to show little or no correlation at Site A because of the excellent quality of groundwater and recharge (250 micromhos). Water quality at Site B is generally poor (300-500 micromhos), therefore recharge along fractures is expected to improve water quality and to produce a negative correlation.

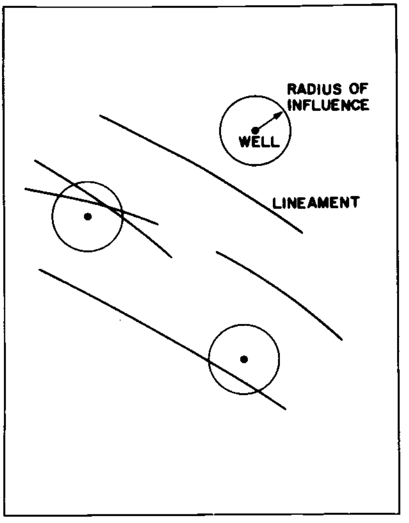

FIGURE 3. WELL-CENTERED MODEL FOR DATA CORRELATION

TABLE 1

EXPECTED SIGN OF THE CORRELATION COEFFICIENT

Hydrologic Parameter	Site A	Site B
Specific Capacity	+	+
Transmissivity	+	+
Temperature	+	+
Specific Conductance	o	-

The well-centered model was used in the final analysis to correlate the four hydrologic parameters with lineament density interpreted from 1:250,000-scale enhanced Landsat imagery of Site B and from a 1.24,000-scale verified structure map of Site A, as well as an additional site near Springerville, Arizona. Table 2 shows the results of the linear regression correlation for each site, the well radius of influence and the number of wells in the sample set.

SITE-SPECIFIC CORRELATIONS AND CONCLUSIONS

Flagstaff, Site A. Lineaments at 1:24,000-scale were mapped near Flagstaff (Harshbarger and Associates and John Carollo Engineers, 1973), allowing accurate plotting of wells relative to existing lineaments. High correlations between lineament density, specific capacity, transmissivity and temperature indicate a strong relationship between fracturing and water movement. Good correlation of water temperature and lineament density indicates the possible effects of secondary permeability on lateral water movement and mixing of higher temperature recharge water with the cooler groundwater. Specific conductance showed little correlation, owing to the good quality of the recharge and groundwater.

Snowflake, Site B. Temperature and specific conductance showed little correlation with lineament density mapped from 1:250,000-scale Landsat images. Specific capacity and transmissivity correlations were unexpectedly negative. A number of reasons for these negative results have been advanced by Foster and others (1980) and are summarized below.

Springerville. The area adjoining Site B between St. Johns and Springerville encompasses a well field that belongs to Tucson Electric Power Company. The area was the subject of earlier studies by Harshbarger and Associates (1976). Lineaments and existing wells were plotted at a scale of 1:48,000,

TABLE 2

CORRELATION COEFFICIENTS

Site	Hydrologic Parameter	Number of Wells	Correlation Coefficient	Well Radius of Influence (km)
Site A				
Flagstaff	Specific Capacity	5	0.64[1/]	0.8
	Transmissivity	6	0.99	0.8
	Temperature	4	0.78	0.8
	Specific Conductance	4	0.04	0.8
Site B				
Snowflake	Specific Capacity	42	-0.14[2/]	2.4
	Transmissivity	14	-0.67	2.4
	Temperature	74	0.09	2.4
	Specific Conductance	82	0.02	2.4
Springerville	Specific Capacity	5	0.79[3/]	1.6
	Temperature	10	0.61	1.6
	Specific Conductance	12	-0.64	1.6

1/ 1:24,000 scale structure maps (Harshbarger and Associates, and John Carollo Engineers, (1973)

2/ 1.250,000 scale enhanced Landsat imagery

3/ 1:48,000 scale structure maps (Harshbarger and Associates, 1976)

offering an opportunity to apply the well-centered model to existing data. Lineament densities were measured within a radius of 1.6 km. Specific capacity and temperature show a good correlation with lineament density, again supporting the hypothesis that lineaments enhance groundwater movement. A strong negative correlation between specific conductance and lineament density indicates a poorer water quality than water near Flagstaff.

It can be concluded that (1) the correlations developed between lineament density and water data for the Flagstaff and Springerville well fields support the hypothesis that a relationship exists between regional geologic structure and well production; and (2) small-scale Landsat imagery is appropriate for locating high lineament densities over large areas, if followed by further mapping using conventional large-scale aerial photography, and augmented by use of well parameter tabulations and conventional geologic maps to locate prime sites for test wells.

The negative results of correlative tests for the Snowflake Area (Site B), as compared with Site A, may be attributable to several factors including the following: (1) Small-scale imagery and resolution may introduce locational errors or may preclude mapping smaller lineament structures that could influence well production, (2) local well location may conform to land ownership patterns rather than to optimal production sites, or (3) geohydrologic controls may differ from one area to the other. It is essential that each area studied be treated as a distinctive geohydrologic environment for the occurrence of groundwater.

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