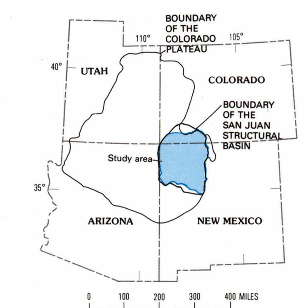

Figure 1. Location of San Juan structural basin, Colorado Plateau, and study area.

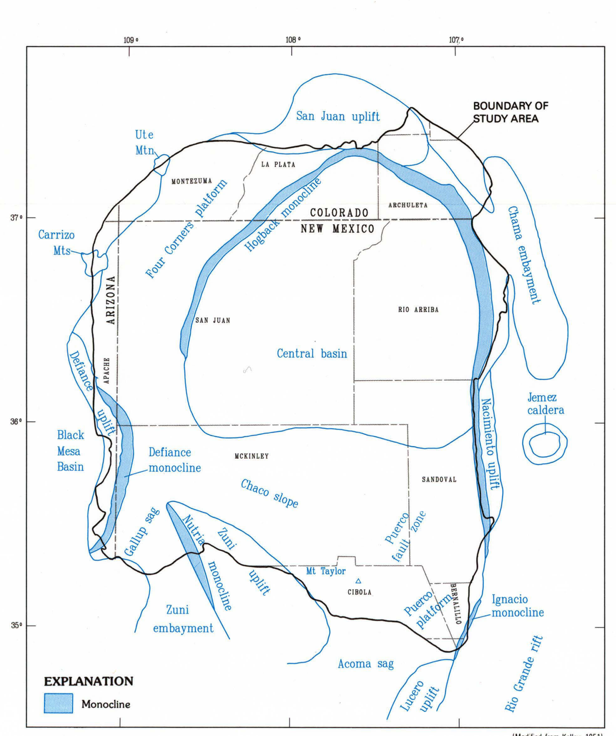

Figure 2. Structural elements of the San Juan structural basin and adjacent areas.

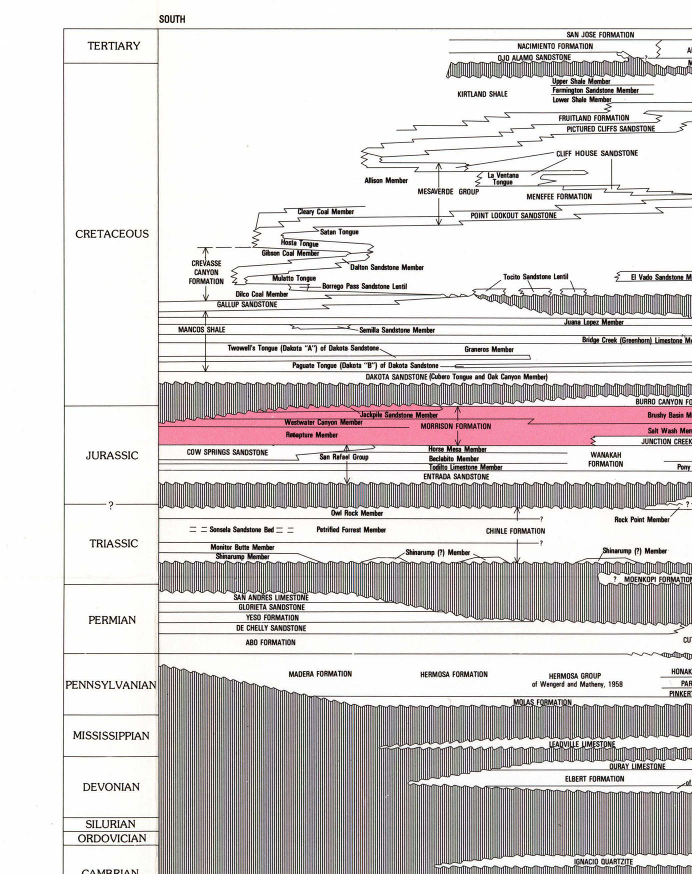

Figure 3. Time- and rock-stratigraphic framework and nomenclature.

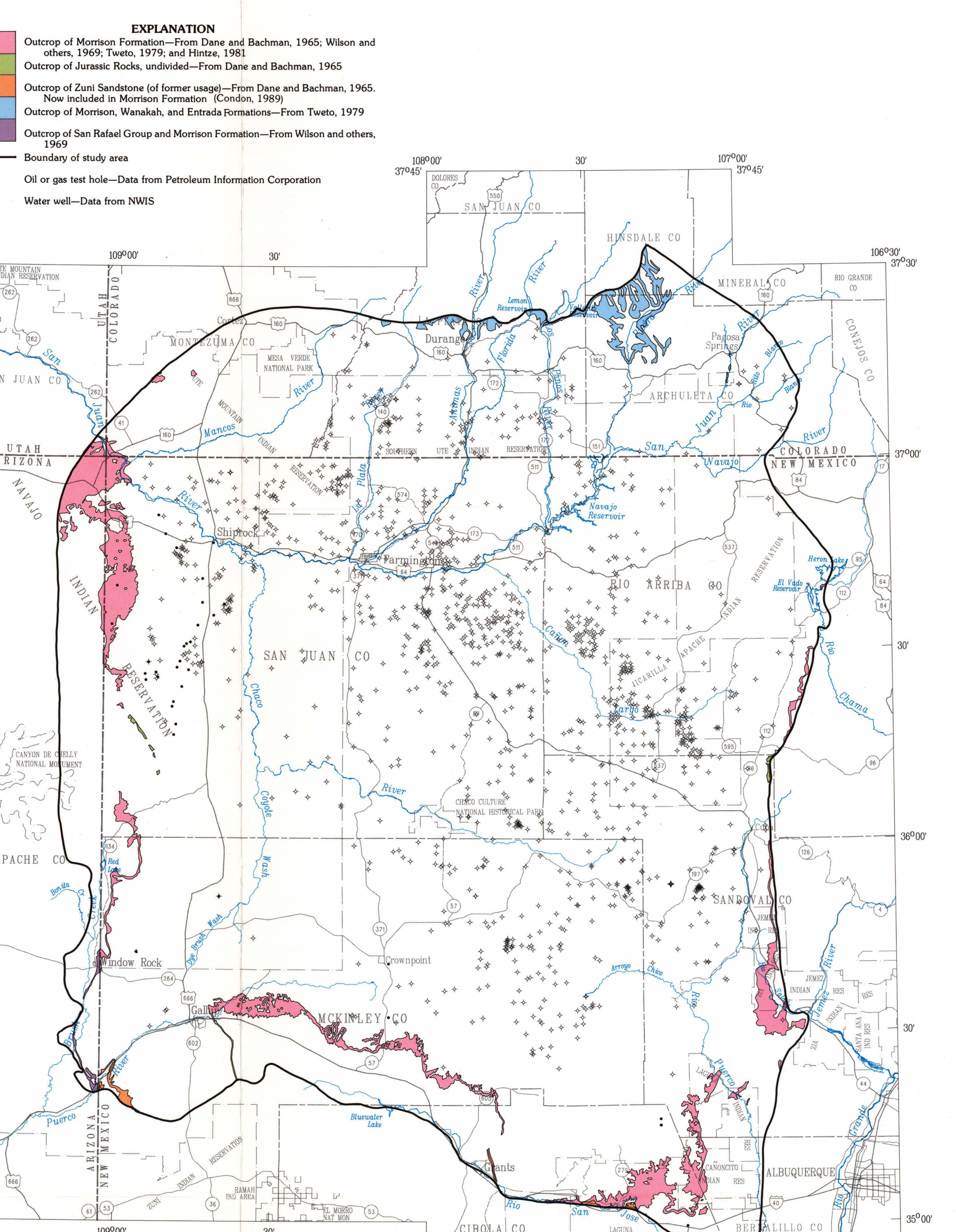

Figure 4. Location of oil or gas test holes and water wells used to compile depth to and altitude of the top of the Morrison Formation.

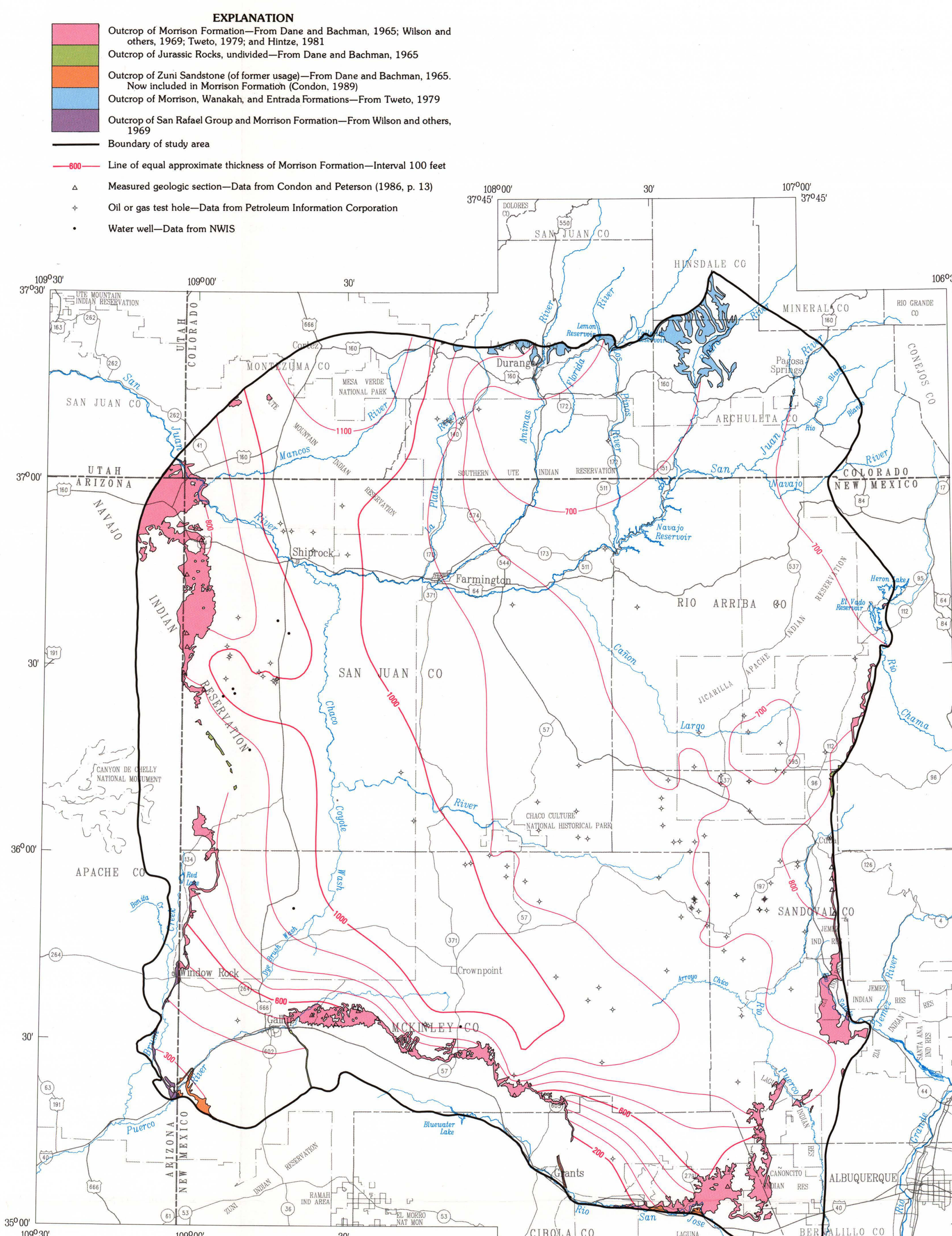

Figure 5. Approximate thickness of the Morrison Formation.

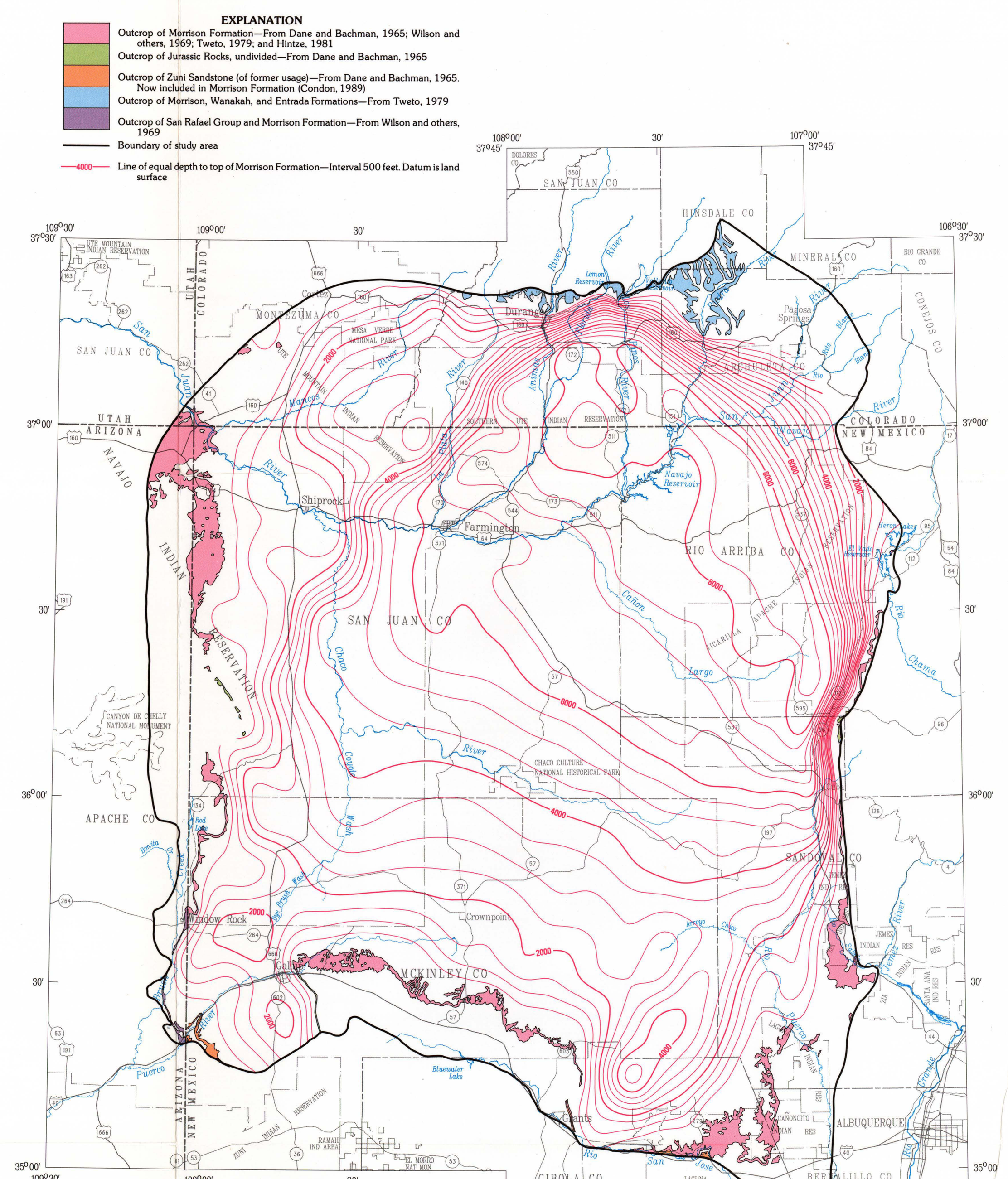

Figure 6. Approximate depth to the top of the Morrison Formation.

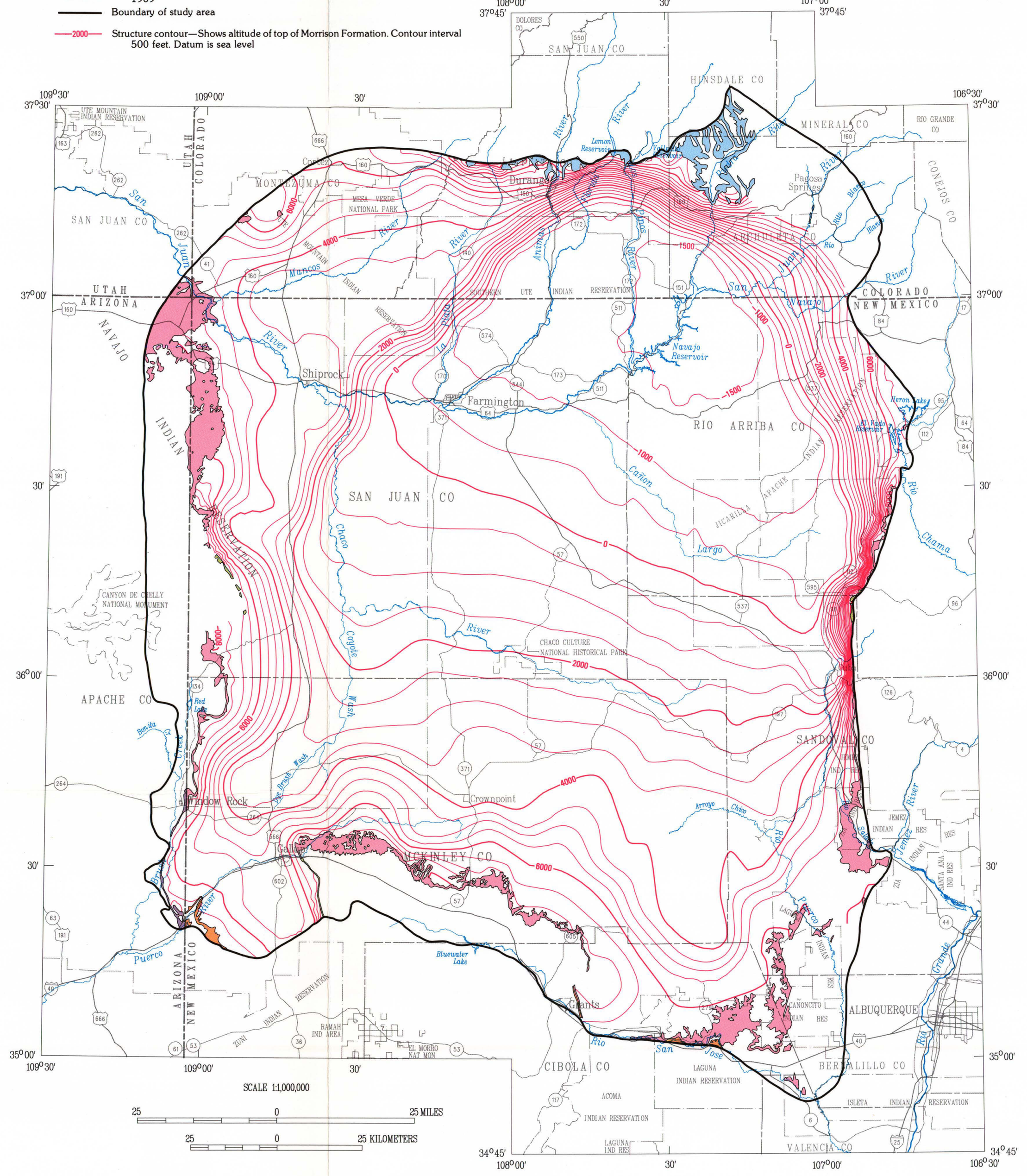

Figure 7. Approximate altitude and configuration of the top of the Morrison Formation.

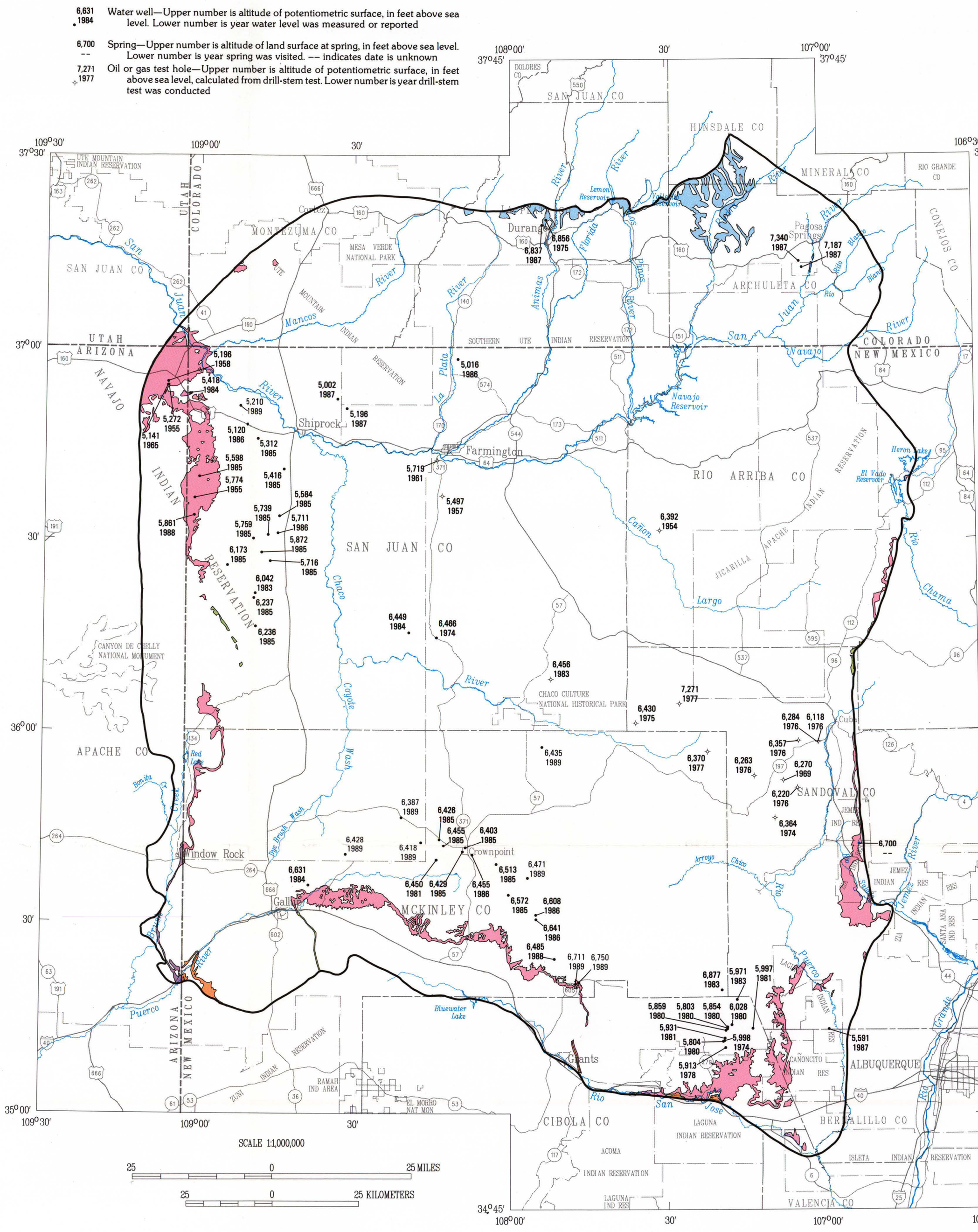

Figure 8. Altitude of potentiometric surface of water in the Morrison Formation at selected water wells, springs, and oil or gas test holes.

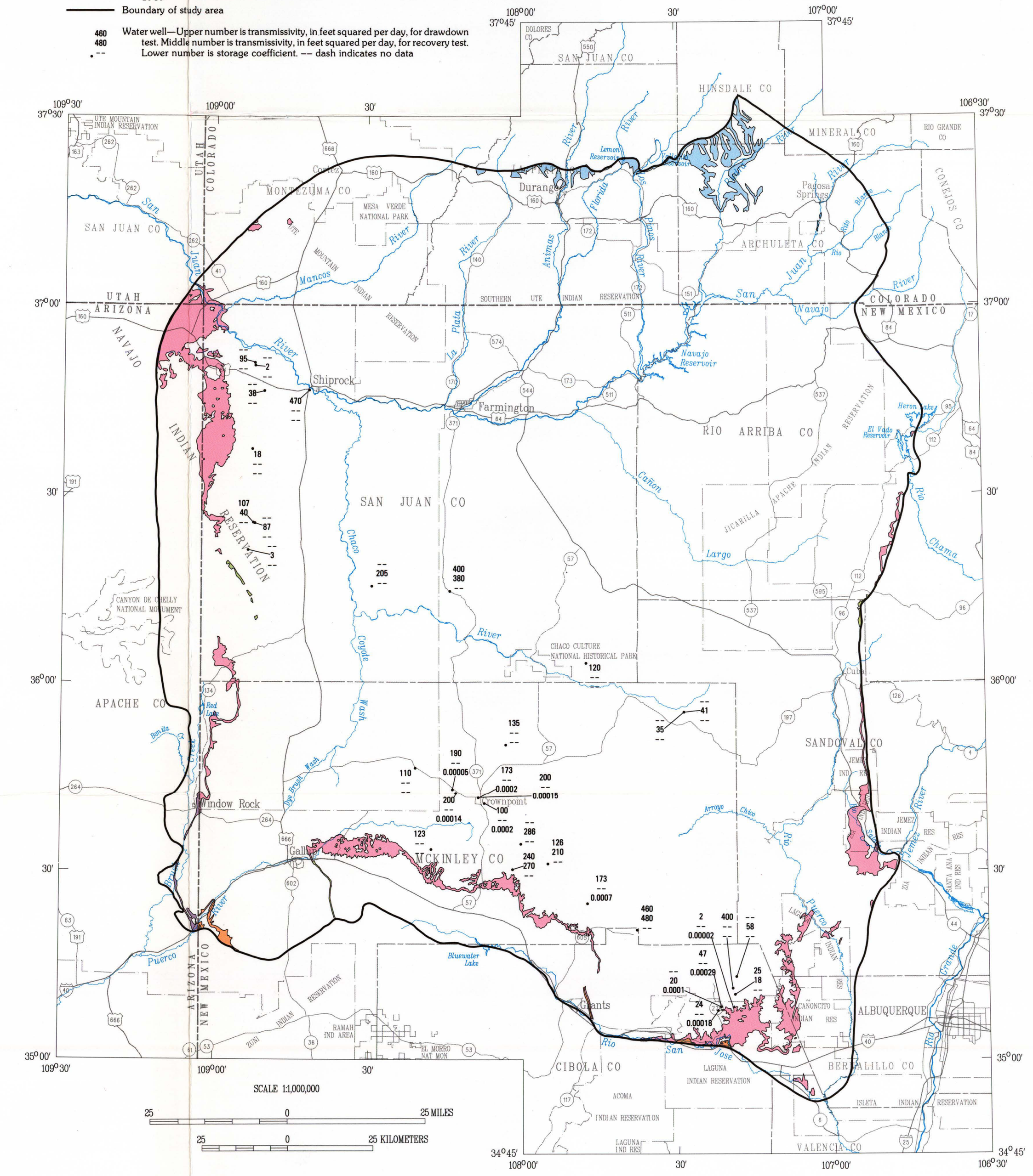

Figure 9. Values of transmissivity and storage coefficient at selected water wells completed in the Morrison Formation.

CONVERSION FACTORS

Multiply inch-pound unit	By	To obtain metric unit
inch	25.4	millimeter
foot	0.3048	meter
foot per day	0.3048	meter per day
foot squared per day	0.09290	meter squared per day
gallon per minute	0.06309	liter per second
gallon per minute per foot	0.2070	liter per second per meter
mile	1.609	kilometer
pound per square inch	6.8948	kilopascal
square mile	2.590	square kilometer

Temperature in degrees Celsius (°C) can be converted to temperature in degrees Fahrenheit (°F) by using the following equation:

$$°F = 1.8 \times °C + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

INTRODUCTION

This report is one in a series resulting from the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) study of the San Juan structural basin that began in October 1984. Previous reports in the series describe the hydrology of the Gallup Sandstone (Kernodle and others, 1989) and the Dakota Sandstone (Craigg and others, 1989) in the San Juan structural basin. The purposes of the study (Welder, 1986) are to: (1) Define and evaluate the aquifer system; (2) assess the effects of past, present and potential ground-water use on aquifers and streams; and (3) determine the availability and quality of ground water.

The Morrison Formation is a major water-bearing unit in the regional aquifer system. The purpose of this report is to summarize information about the hydrogeology of the Morrison Formation, of Late Jurassic age, in the basin. Data used in this report were collected during the study or were derived from existing records in the U.S. Geological Survey's national, computerized National Water Information System (NWIS) data base, and the Petroleum Information Corporation's data base. All data available for the Morrison Formation were included in the discussions in the text; however, not all the data could be plotted on the illustrations.

The San Juan structural basin is located in New Mexico, Colorado, Arizona, and Utah, and has an area of about 21,600 square miles (fig. 1). The structural basin is about 140 miles wide and about 200 miles long. The study area is that part of the structural basin that contains rocks of Triassic or younger age and, therefore, the study area is less extensive than the structural basin. Triassic through Tertiary sedimentary rocks are emphasized in this study because the major aquifers in the basin are present in these rocks. The study area is about 140 miles wide (about the same as the structural basin), 180 miles long, and has an area of about 19,400 square miles.

Altitudes in the study area range from about 4,500 feet in the northwest to about 11,000 feet in the southeast. Annual precipitation in the high mountainous areas along the north and east margins of the basin is as much as 45 inches, whereas annual precipitation in the lower altitude, central part of the basin is generally less than 8 inches. Mean annual precipitation in the study area is about 12 inches.

The population of the study area in 1980 was about 190,000 (Welder, 1986). The economy of the basin is supported by exploration and development of petroleum, coal, and uranium resources; urban enterprise; farming and ranching; tourism; and recreation.

REGIONAL GEOLOGIC SETTING OF THE SAN JUAN STRUCTURAL BASIN

The San Juan structural basin is a northwest-trending asymmetric structural depression formed during the Laramide orogeny (Late Cretaceous-early Tertiary) at the eastern edge of the Colorado Plateau (fig. 1). Structural boundaries of the basin are well defined in many places, whereas in other places, the basin merges gradually into adjacent depressions or uplifts (Kelley, 1951, p. 124). The structural boundaries, as defined by Kelley (1951, p. 124–127), principally consist of large, elongate, domal uplifts; low, marginal platforms; and abrupt monoclines as shown in figure 2. Faulting is common especially in the southeast part of the basin. Maximum structural relief in the basin is about 10,000 feet (Kelley, 1951, p. 126).

The San Juan structural basin contains a thick sequence of sedimentary rocks ranging in age from Cambrian through Tertiary, but principally from Pennsylvanian through Tertiary (fig. 3). The maximum thickness of the sequence of rocks is about 14,000 feet (Fassett and Hinds, 1971, p. 4). These sedimentary rocks dip from the basin margins toward the troughlike structural center (the deepest part of the basin). Older sedimentary rocks crop out around the basin margins and are successively overlain by younger rocks toward the center of the structural basin. Volcanic rocks of Tertiary age and various deposits of Quaternary age also are present in the basin.

GEOLOGY OF THE MORRISON FORMATION

The Morrison Formation is of Late Jurassic age (Cadigan, 1967, p. 6) and crops out around the basin margins. Major sandstones in the Morrison Formation typically form erosion-resistant cliffs and dip slopes, whereas shale units form topographic saddles and dip slopes.

The Morrison Formation is present throughout the San Juan structural basin (Green and Pierson, 1977, p. 151). The Morrison Formation conformably overlies the upper part of the Wanakah Formation or Cow Springs Sandstone of Late Jurassic age (Condon and Peterson, 1986, p. 24). In the north part of the basin, the Morrison Formation conformably overlies and probably intertongues with the Junction Creek Sandstone of Late Jurassic age (fig. 3). The Morrison Formation is unconformably overlain by the Dakota Sandstone of Late Cretaceous age throughout most of the San Juan Basin; however, in the north part of the basin, it is conformably overlain by the Burro Canyon Formation of Early Cretaceous age (fig. 3; Green and Pierson, 1977, p. 151).

The Morrison Formation generally consists of yellowish-tan to pink, fine- to coarse-grained, locally conglomeratic sandstones, which are interbedded with sandy siltstones and green to reddish-brown shales and claystones; minor limestone beds also occur in the formation (Woodward and Schumacher, 1973, p. 3–5; Green and Pierson, 1977, p. 151; and Stone and others, 1983, p. 38). These strata were deposited in various continental environments including stream channels, flood plains, and lakes (Green and Pierson, 1977, p. 151).

In the San Juan structural basin, the Morrison Formation consists of five members (Gregory, 1938; Craig and others, 1955; Cadigan, 1967; Green and Pierson, 1977; Owen, 1984; Aubrey, 1988). These members, in ascending order, are: the Salt Wash Member, Recapture Member, Westwater Canyon Member, Brushy Basin Member, and Jackpile Sandstone Member.

The geologic characteristics of the Westwater Canyon Member make it the most important hydrologic unit of the Morrison Formation. Kelly (1977) described the hydrogeology of this member in the south part of the basin. The Westwater Canyon Member is composed of yellowish-gray to tan, pink or light-brown, fine- to coarse-grained locally conglomeratic sandstone, interbedded with shale or claystone (Craig and others, 1955, p. 153; Woodward and Schumacher, 1973, p. 3). Grains increase in size toward the west-central part of the basin until the member consists wholly of conglomeratic sandstone (Craig and others, 1955, p. 154). Thickness of the Westwater Canyon Member increases from about 100 feet on the north, east, and south sides of the San Juan Basin to about 300 feet in the west-central part of the basin (Craig and others, 1955, p. 154).

Data used to compute the depth to and altitude of the top, and thickness of the Morrison Formation were obtained primarily from oil and gas test holes from the Petroleum Information Corporation's data base with supplemental information from NWIS for water wells and from outcrop altitudes. Additional data used to compute thickness were obtained from measured stratigraphic sections reported by Condon and Peterson (1986, p. 13). The location of the test holes and wells is shown in figure 4. Depth to and altitude of the top of the Morrison Formation in the southwest part of the study area were determined from a geologic and structure-contour map prepared by Hackman and Olson (1977) because insufficient data were available from oil and gas test holes.

The thickness of the Morrison Formation is shown in figure 5. Thickness ranges from about 200 feet near Grants, New Mexico, to about 1,100 feet in the northwest part of the basin.

Depth to the top of the Morrison Formation ranges from zero in areas of outcrop to about 8,500 feet in the northeast part of the study area (fig. 6). The rapid increase in depth in the area northeast of Grants, New Mexico, is due to the local topography of Mt. Taylor (fig. 2).

A depth-to-top map (fig. 6) differs from a structure-contour map in that a structure-contour map represents some particular geologic horizon referenced to a horizontal datum; thus, the effects of topography are removed. In the configuration of the top surface of the Morrison Formation (fig. 7), the datum used is sea level.

The altitude and configuration of the top of the Morrison Formation are shown on the structure-contour map (fig. 7). Because the Morrison Formation is a key marker bed in the San Juan structural basin, the overall structural configuration of the basin also is shown in figure 7. The top of the Morrison Formation decreases from a maximum altitude of about 10,000 feet above sea level along the northern basin margin to about 1,500 feet below sea level in the northeast part of the basin.

WATER IN THE MORRISON FORMATION

The Morrison Formation is a source of water for domestic, livestock, and industrial supplies in areas where drilling depths and pumping levels are economically feasible and where water quality is suitable for most uses. Water wells generally are near the margins of the basin. In much of the rest of the basin, oil and gas test holes have penetrated the Morrison Formation; water is not known to be produced from these test holes for domestic or livestock supplies. However, in some areas, water may be produced from the Morrison Formation for use in oil or gas recovery projects for other producing formations.

The altitude of the potentiometric surface of water in the Morrison Formation at selected water wells, springs, and oil or gas test holes is shown in figure 8. The altitude of the potentiometric surface in water wells was determined from measured or reported depths to water or was calculated from pressure-gage readings on flowing wells. Interpretation of completion data for the water wells shown indicates these wells only derive water from the Morrison Formation. The water-well and spring data were collected from 1932 to 1989. The altitude of the potentiometric surface in oil and gas test holes was calculated by analyzing shut-in pressures from drill-stem tests conducted from 1954 to 1983; these data were obtained from Petroleum Information Corporation. Drill-stem tests were selected for analysis if the length of time allowed for shut-in pressures to stabilize was greater than 1 hour.

The purpose of the drill-stem test is to determine the potential for oil or gas production, not to determine the potentiometric surface; therefore, the best water-producing zones commonly are bypassed and hydrologic data are from less permeable zones. These data generally are all that are available for aquifers in the deeper parts of the basin.

The final shut-in pressure was converted to equivalent-freshwater hydraulic head according to the procedure outlined by Miller (1976, p. 17). The following equation was used:

$$h = (FSIP \times X) - PRD + LS, \qquad (1)$$

where
- h is the altitude of the potentiometric surface, in feet above sea level;
- $FSIP$ is the final, bottom-hole shut-in pressure, in pounds per square inch, measured by the pressure-recording device;
- X is a factor to convert FSIP to equivalent-freshwater hydraulic head, in feet;
- PRD is the depth to the pressure-recording device, in feet below land surface; and
- LS is the altitude of the land surface, in feet above sea level.

A value of 2.307 feet of water per pressure increment of 1 pound per square inch was used for X. This value was chosen assuming the water is at a temperature of 4 degrees Celsius with a density of 1.0 gram per cubic centimeter.

Water in the Morrison Formation occurs under both water-table and artesian conditions. Recharge to the aquifer is from infiltration of precipitation on outcrops, from infiltration of streamflow on outcrops, and from vertical leakage of water through confining beds. Although all members of the Morrison will yield water, the Westwater Canyon Member is the most productive aquifer.

Within the basin, areas of stress from ground-water development in the Morrison Formation generally represent areas of uranium-mine dewatering. Sufficient data do not exist to allow an estimate of water levels for predevelopment conditions. The water levels shown in figure 8 are the most recent data available. These data have not been contoured because they do not represent a specific time interval. Generalized ground-water gradients can be determined where sufficient data exist.

Transmissivity, storage coefficient, and hydraulic-conductivity data for the Morrison Formation are available from drawdown and recovery tests conducted at 31 wells in the study area (Stone and others, 1983, table 5; Risser and others, 1984, p. 23). The transmissivity ranges from 2 to 480 feet squared per day with a median value of 115 feet squared per day. The storage coefficients calculated from aquifer tests at nine wells range from 0.00002 to 0.0002. Hydraulic-conductivity values for three wells range from 0.025 to 0.39 foot per day. Transmissivity and storage coefficient data are shown in figure 9.

The reported or measured discharge from 53 water wells completed in the Morrison Formation ranges from 1 to 401 gallons per minute; the median discharge is 32 gallons per minute. The specific capacity at 32 of these wells ranges from 0.01 to 3.98 gallons per minute per foot of drawdown and the median is 0.42 gallon per minute per foot of drawdown. These data are shown in figure 10.

The locations of nine selected water wells that derive water only from the Morrison Formation and that have four or more water-level measurements are shown in figure 11. The water-level hydrographs for these wells show both short- and long-term changes in water level. Short-term fluctuations primarily result from periodic changes in discharge from wells and from seasonal changes in recharge. Long-term changes primarily result from prolonged ground-water discharge from wells, from discontinuation of discharge from wells, and from changes in rates of recharge due to long-term climatic variations.

One of the major influences on water levels in the Morrison Formation has been aquifer dewatering associated with uranium mining. The location and approximate extent of selected uranium mines in the study area are shown in figure 11. Uranium mining had a modest beginning in the late 1940's, but by the early 1950's the industry was well established. Ore production increased in the mid-1960's and overall mining activity peaked in the late 1970's. By 1981–82, low demand and prices forced the closure of some mines (primarily the open-pit and underground operations). By 1986 all but one mine had ceased operation. Ground-water levels in the Morrison declined as a result of increased mine dewatering and ore leaching during the growth years of the industry. Later, as mining activity decreased and eventually almost came to an end, ground-water levels began to recover.

All of the wells in the southern part of the study area for which water-level hydrographs have been drawn exhibit some degree of response to uranium-mining activities. Operation of the mines requires the removal of ground water from the aquifer; this results in a reduction in potentiometric head in the aquifer. The rate and extent of reduction are less near the outcrop, where water in the aquifer is under water-table conditions, than in confined areas in the interior of the basin where the Morrison Formation is a confined aquifer. The primary uranium ore body is the Westwater Canyon Member of the Morrison Formation.

Three methods of ore extraction have been used in the study area. Open-pit mining techniques were used in the area east of Grants, New Mexico (and to a much lesser extent in the discovery area west-northwest of Grants). This mining method commonly can use gravity flow and existing drainages to remove mine seepage. Open-pit mines usually are within or very near the outcrop area of the formation; the effects of dewatering for open-pit mining are buffered by water-table storage coefficients and reduced transmissivity of the water-bearing units (a function of reduced saturated thickness). Also, the regional base elevation for ground-water discharges usually is only slightly altered from preexisting natural conditions.

Deep underground mining methods were used east, north, and northwest of Grants, New Mexico, and northeast of Gallup, New Mexico. Underground mining still is being used at one mine north of Grants. This mining practice usually has more immediate and intense impact on regional ground-water levels than open-pit mining because the aquifer is under confined, artesian conditions rather than unconfined, water-table conditions. Typically, potentiometric heads in the artesian part of an aquifer will respond two or three orders of magnitude faster to a change in withdrawal than in the unconfined part. Also, at any specific time after initiation of withdrawal, equal changes in potentiometric head in the artesian part of the aquifer will be measured at distances of at least one order of magnitude greater than in the unconfined part.

In situ leaching techniques were used at several mines in the Crownpoint, New Mexico, area. Commonly, a leach solution is injected into the mineralized zone in a pattern of wells forming a square. At the center of the square a single well is used to extract the leachate that contains the uranium. In the process, more fluid is extracted than is injected, causing a net decline in pressure head that propagates through the artesian aquifer.

Potentiometric heads in well 1 show the effect of systematic ground-water development for municipal and rural-domestic water supplies. The moderate recovery of water levels in this well, starting in 1986, also reflects the efforts of the Navajo Nation to curb unregulated discharge of water from flowing artesian wells on tribal lands. There also is the possibility that some of the post-1986 recovery is due to discontinued uranium-mine dewatering as described below.

Well 2 was drilled by the National Park Service south of Chaco Culture National Historical Park in New Mexico to monitor mining-induced changes in water level and water quality in the Morrison Formation. The water-level hydrograph for this well shows a potentiometric head decline of about 130 feet until 1986. From 1986 to the present the potentiometric head has recovered 55 feet. Wells 3 and 4 show a similar pattern of decline until 1986 followed by a post-mining recovery of ground-water levels.

Well 5 is located in Crownpoint, New Mexico, in a former area of in situ uranium mining and within a few hundred feet of a municipal water-supply well. The water-level hydrograph for this well shows that both the short- and long-term potentiometric heads are strongly affected by nearby public-supply withdrawals and mining activity. Because measurements were discontinued in 1986, no estimate of post-mining recovery can be made.

Well 6 is located in the immediate vicinity of a now idle underground mine. The water-level hydrographs for this well shows a very rapid recovery in potentiometric head since 1986 although the rate of recovery of potentiometric heads in this area is slowed somewhat by the need to fill mine shafts and vents as the heads recover.

The water-level hydrograph for wells 7 and 8 show a steady decline throughout the period of record. The potentiometric heads in wells 7 and 8 are still being influenced by mine-dewatering activities north of Grants, New Mexico.

Well 9 is located within the outcrop of the Morrison Formation and is situated a few tens of feet east of a fault. The effect of this fault is to isolate the well from mine-dewatering activity to the west in the vicinity of well 8. The shallow depth to water and relatively moderate changes in water level over time demonstrate the dominant influence of local recharge and unconfined storage coefficient on seasonal and long-term changes of water level in this well.

QUALITY OF WATER FROM THE MORRISON FORMATION

Physical and chemical data collected from 1948 to 1986 were retrieved from the NWIS and Petroleum Information Corporation's data bases. The number of samples, range, and median value for selected water-quality properties and constituents are listed in table 1.

The temperature data shown in figure 12 are from water wells and oil or gas test holes. The temperature of ground water is extremely variable (table 1 and fig. 12). Temperature of water from 33 water wells, which ranged from 6.0 to 48.0 degrees Celsius, is representative of the temperature in shallower parts of the basin. Temperature of water from six oil or gas test holes, which ranged from 50 to 76 degrees Celsius, is representative of bottom-hole temperatures measured during drill-stem tests.

Selected primary drinking-water standards are listed in table 2 (U.S. Environmental Protection Agency, 1986a). Concentrations of fluoride generally were small; 3 of 50 samples contained fluoride at a concentration greater than the primary drinking-water standard of 4 milligrams per liter (fig. 13; table 2). The concentration of nitrate, as nitrogen, was less than the standard of 10 milligrams per liter in all 21 water samples. The concentration of arsenic in 5 of 19 samples exceeded the standard of 0.05 milligram per liter; the concentration of selenium in 1 of 17 samples exceeded the standard of 0.01 milligram per liter (table 2). Water from the Morrison Formation contains radioactive elements derived from decay of uranium-ore deposits. The primary drinking-water standard for radium is 5 picocuries per liter as radium-226 plus radium-228 (table 2). Radium-226 is a daughter product of uranium-238 decay. Although no data are available for radium-228, 5 of 17 samples analyzed for radium-226 exceeded the standard; the concentration of radium-226 in these five samples ranged from 5.6 to 110 picocuries per liter.

Secondary drinking-water standards are listed in table 3 (U.S. Environmental Protection Agency, 1986b). Water from 42 wells was analyzed for pH and selected data values of pH are shown in figure 14. The pH of 13 samples exceeded the secondary standard of 8.5 pH units. The concentration of sulfate from 22 samples exceeded the secondary drinking-water standard of 250 milligrams per liter. The concentration of chloride from one sample exceeded the standard of 250 milligrams per liter.

The quality of water from the Morrison Formation, on the basis of dissolved-solids concentration, is variable (table 1). Dissolved-solids concentrations from samples at selected wells are shown in figure 15. Water wells from which water was analyzed generally are located near outcrops of the Morrison in the northwestern and southern parts of the basin and are few in the rest of the basin. The concentration of dissolved solids generally increases from near the outcrop areas toward the center of the basin. For example, near the outcrop in the northwestern part of the basin, the concentration of dissolved solids generally is less than 300 milligrams per liter; it increases to about 5,000 milligrams per liter downdip about 25 miles to the northeast.

The specific conductance of water can be easily measured with a meter at the sampling site. Because specific conductance correlates with the concentration of dissolved solids (Hem, 1985, p. 67), a measurement of specific conductance can be used to estimate the concentration of dissolved solids by multiplying the specific conductance by 0.65, an average ratio of the concentration of dissolved solids to specific conductance derived from values for 45 samples.

Ions contributing to the concentration of dissolved solids (fig. 16) predominantly are sodium, sulfate, and bicarbonate (reported as alkalinity). Alkalinity is the capacity of the solution to neutralize a strong acid (Hem, 1985, p. 106) and consists primarily of bicarbonate and carbonate ions for water from the Morrison Formation. Water from the Morrison Formation is generally a sodium sulfate type; however some water is a sodium bicarbonate type. Water from one well along the east edge of the basin near the outcrop of the Morrison is a calcium chloride type (fig. 16).

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