THE PROTECTION OF THE MUNICIPAL WATER WELL-FIELD SERVING THE CITY OF EDMOND, OKLAHOMA USING WELLHEAD PROTECTION AREA DELINEATION

By

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THE PROTECTION OF THE MUNICIPAL WATER

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AREA DELINEATION

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CHAPTER I

INTRODUCTION

Object of Study

The Safe Drinking Water Act (SDWA) seeks to protect the nation's groundwater supplies from contamination. In addition to establishing minimum drinking water standards, it addresses the protection of groundwater quality and contains provisions for research, technical assistance, and training (Ordway and Worobec, 1989). The 1986 amendments to SDWA address the establishment of protection zones around public water supply wells in order to help prevent contamination from impacting public water supplies. These protection zones can serve as the basis for protection efforts at state and local levels. The object of this study is to establish these zones, called wellhead protection zones, for the municipal water wells in the well-field serving the City of Edmond, Oklahoma.

Location

The study area, located in north-central Oklahoma County (Figure 1), includes all of Township 14 North, Range 2 West, all

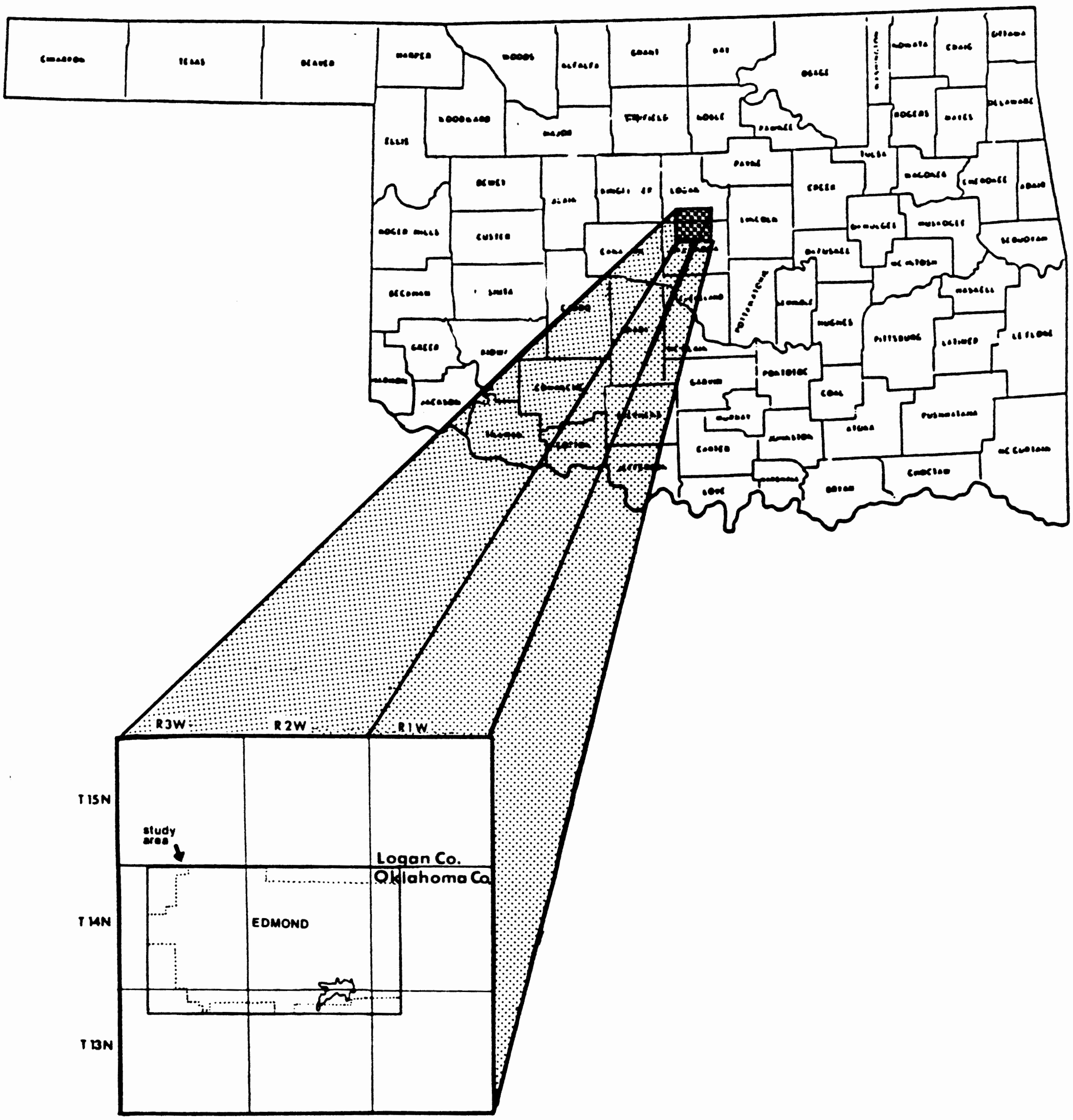


Figure 1. Location of the Study Area

except the western edge of Township 14 North, Range 3 West, and the northern 1/3 of Township 13 North, Range 2 West and Township 13 North, Range 3 West. The well-field is located within the corporate boundary of Edmond (Plate 1).

Physiography and Drainage

Burton and Wood (1968) provide a good summary of the regional geomorphology. The eastern one-half of the study area consists of sandstone capped hills that are dissected by numerous small intermittent streams. Local relief is as much as 150 feet. This portion of the study area is forested with blackjack, post oaks, and other deciduous trees, with a ground cover composed of a variety of native grasses. The western one-half of the study area, which is underlain by shale, consists of broad "flat-topped" hills. These hills are predominately covered by a variety of native grasses with sparse tree cover, occurring mainly along stream courses. In these hills, topographic relief is greater than 100 feet in only a few places.

The eastern one-half of the area is drained by Coffee Creek to the north, and Spring Creek to the south. Spring Creek empties into Lake Arcadia, which is located on the Deep Fork River, a principal drainage for northern Oklahoma County. The western one-half of the area is drained by Chisholm Creek. The drainage pattern of the streams in the

area is predominately dendritic, but in the eastern half it is influenced by fracture patterns within the bedrock.

Climate

The climate of central Oklahoma is temperate. It is characterized by weather patterns of wide temperature and precipitation fluctuations relative to the averages. According to U.S. Weather Bureau climatological data, the average annual temperature for central Oklahoma is 60°F. The coldest month, January, averages 39°F, and the warmest month, August, averages 82°F. The average annual precipitation for the area is about 32 inches (Figure 2). The greatest rainfall usually occurs in May, with an average of 5.44 inches. The driest month is usually December, with an average of 1.53 inches (Burton and Wood, 1968).

Soils

The soil associations in the area strongly reflect the lithology of the underlying bedrock. Four main soil associations have been identified by the Soil Conservation Survey of Oklahoma County (1969). The distributions and descriptions of these associations can be seen in Figure 3. In general, soils in the eastern half of the area have higher permeability, lower run-off potential, and higher infiltration rates than soils in the western half.

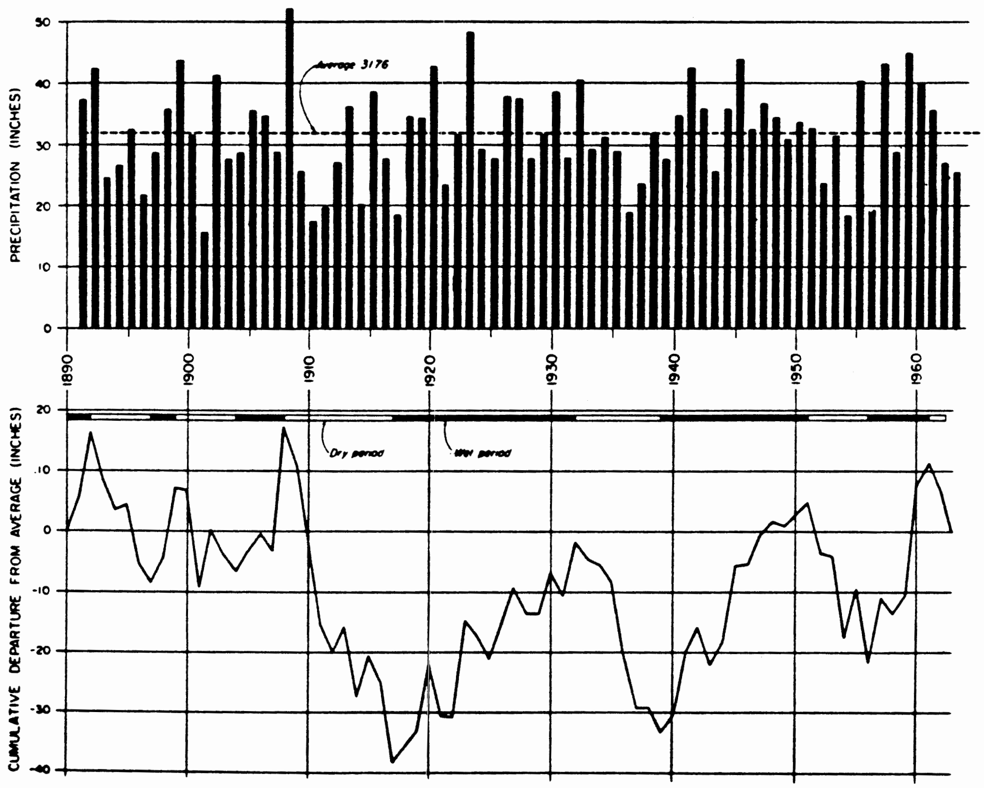
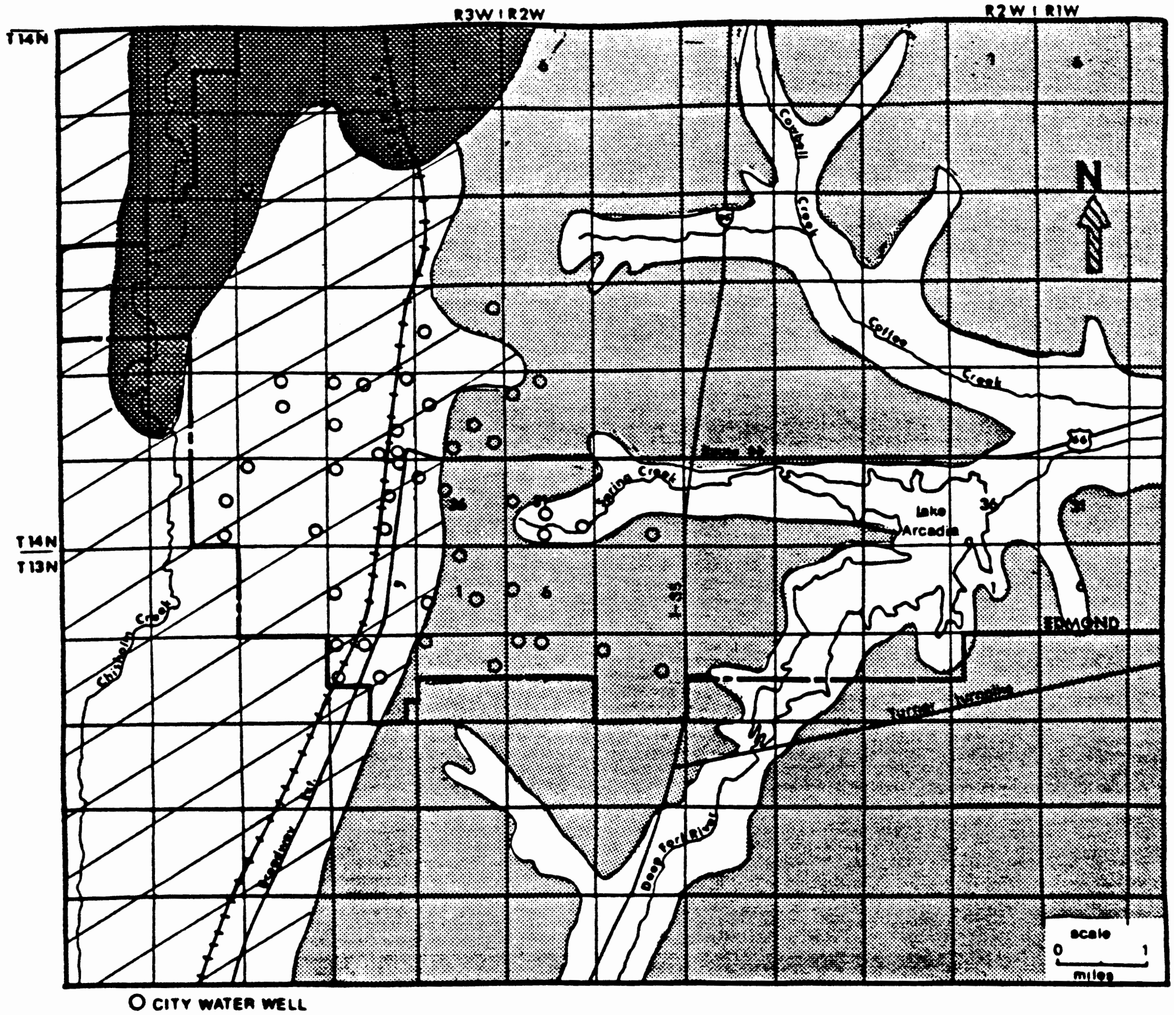


Figure 2. Average Precipitation for Oklahoma County and the Cumulative Departure from Average (Burton and Wood, 1968)



SOIL ASSOCIATIONS

Darnell-Stephenville association: Shallow and deep, gently sloping to strongly sloping, loamy soils on wooded uplands

Renfrow-Vernon-Bethany association: Deep and shallow, nearly level, loamy and clayey soils on prairie uplands

Dale-Canadian-Port association: Deep, nearly level, loamy soils on low benches along the North Canadian River and other large streams

Zaneis-Chickasha association: Deep, gently sloping to moderately sloping, loamy soils on prairie uplands

Figure 3. Soil Associations Map for the Study Area (SCS, 1969)

Land Use

Although the area is located within Edmond's corporate boundary, most of the land is not heavily urbanized. Large tracts are used for agriculture, livestock grazing, and recreation. Industry in the area is comprised predominately of light, service oriented businesses, such as auto repair and service stations. The City of Edmond has seen a dramatic increase in its population in the past 25 years, from about 30,000 to a present population of about 60,000.

Oil and gas development has occurred in the West Edmond Oil-field and the Northeast Edmond Oil-field (Plate 1). Production in the West Edmond Oil-field is predominately from the "Bartlesville Sand", Mississippi Lime, and the Bois d' Arc Frisco Lime. Production in the Northeast Edmond Oil-field is predominately from the "Bartlesville Sand" (Kennedy, 1990).

Well-Numbering System

Wells are located within this document according to their legal-location description. The address given to each well refers to its location within the rectangular subdivisions of the public lands. The address contains the township, range, section number, and the quarter-quarter-quarter of the section the well is located in (Figure 4).

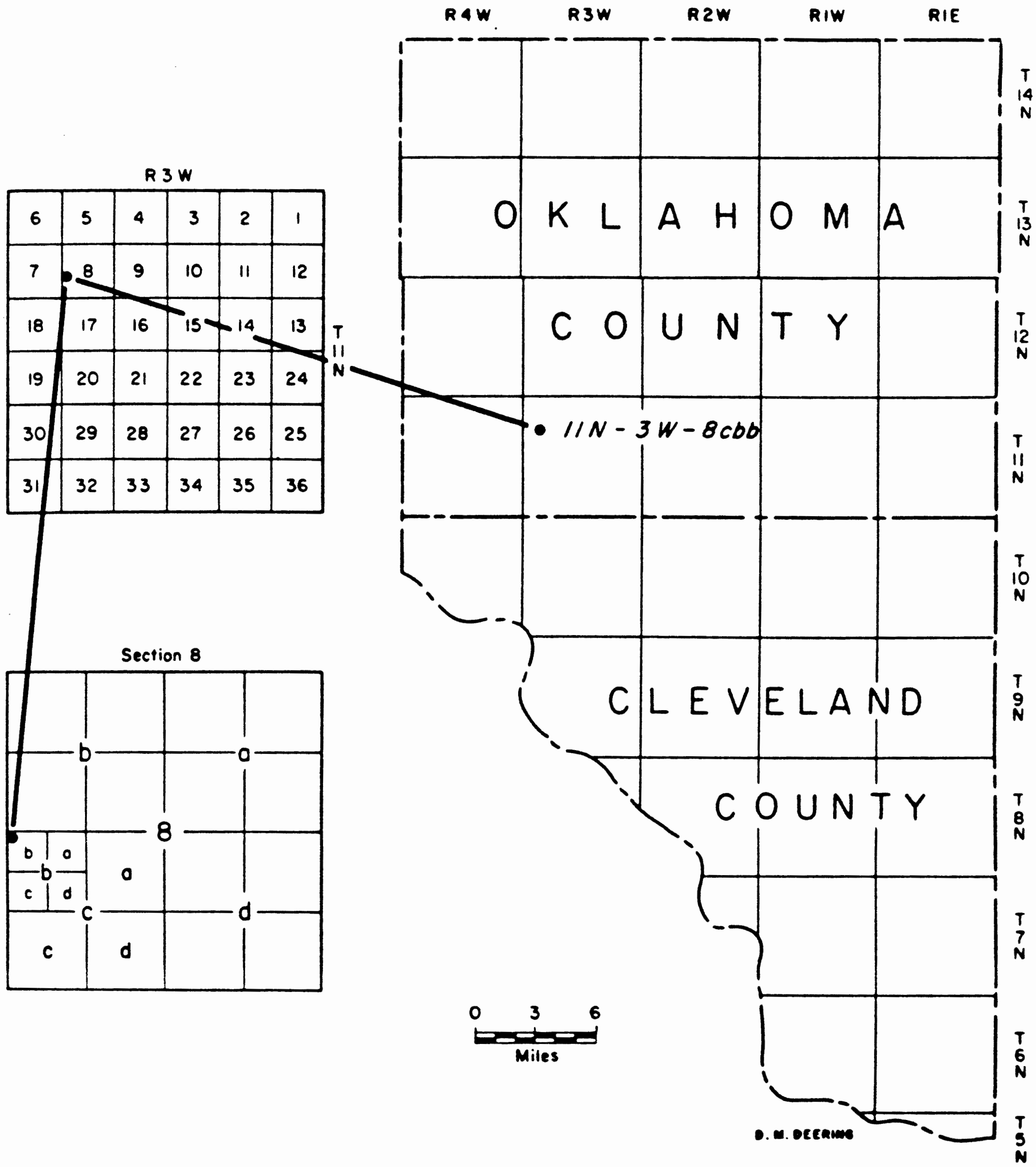


Figure 4. Legal Well-Numbering System
(Burton and Wood, 1968)

CHAPTER II

REGIONAL AND SITE GEOLOGY

Regional Tectonic Setting

The study area is on the northeastern edge of the Anadarko Basin, in proximity to the Nemaha Ridge (Figure 5). The Anadarko Basin is an assymetrical basin covering most of the southwest part of the state. The basin has a northwest axial trend. The Nemaha Ridge is a subsurface feature composed of many discontinuous uplifted features that form a narrow complex of faulted anticlines, which extends over 300 miles from south central Oklahoma to southeastern Nebraska (Lawson and Luza, 1981).

The Oklahoma City Anticline, approximately 10 miles south of the study area, was formed by tectonic activity associated with the Nemaha Ridge (Lawson and Luza, 1981). The anticline creates irregularities in the homoclinal dip of strata in the area. The maximum arching associated with the anticline is about 350 feet (Travis, 1930).

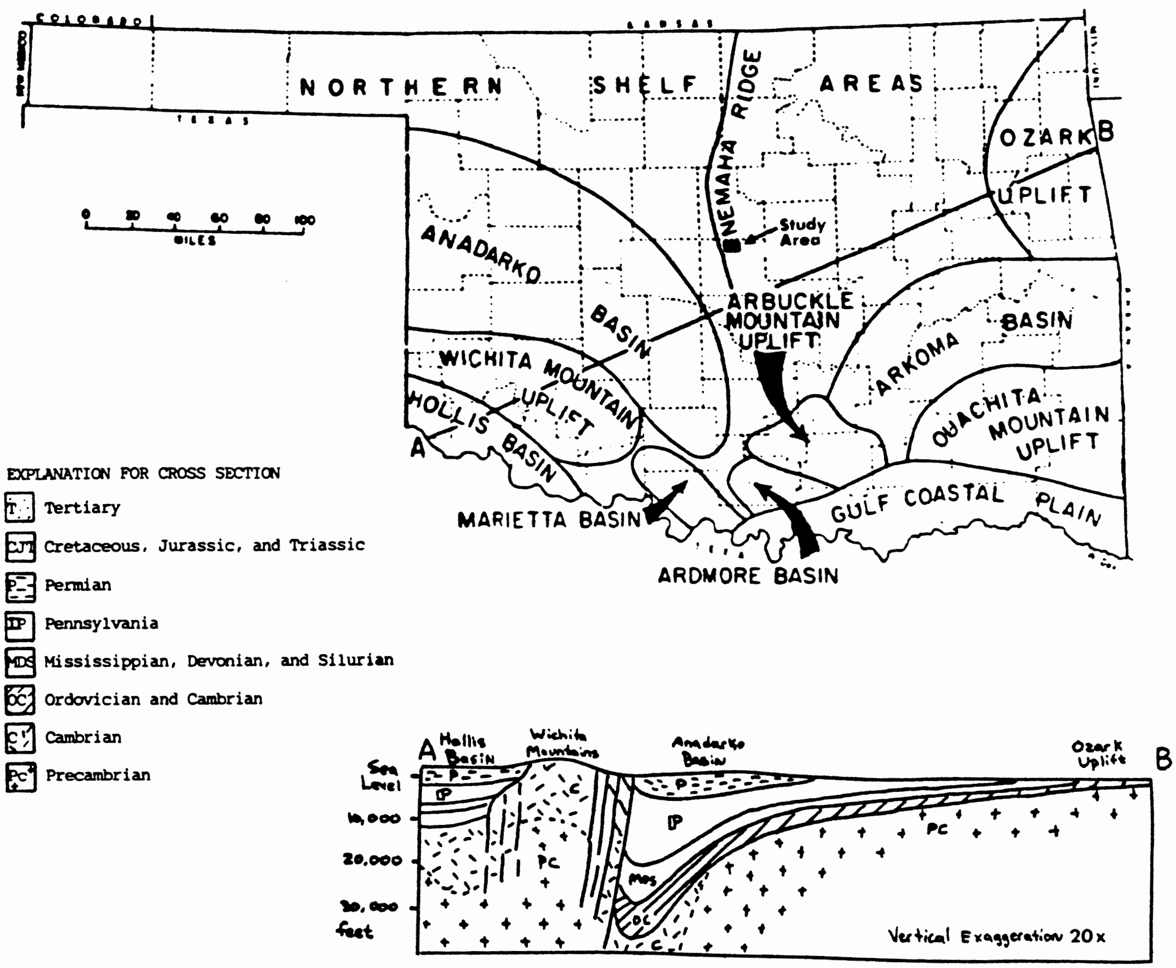


Figure 5. The Major Tectonic Regions of Oklahoma

Site Geology

Figure 6 shows the surficial geology of the study area. The rocks exposed at the surface are, in ascending order, as follows:

* Wellington Formation;
* Garber Sandstone;
* Hennessey Group; and
* alluvial and terrace deposits.

Stratigraphically below the Wellington Formation are the Permian Chase, Council Grove, and Admire Groups. Because of their lithologic similarity, the Wellington Formation and the Garber Sandstone are usually combined to form a single unit, the Garber-Wellington. This convention came to be primarily because of the importance of these units, collectively, as a groundwater supply in central Oklahoma.

Permian System

Garber-Wellington

The Garber-Wellington crops out in a north-south trending belt 6 to 20 miles wide. This belt extends from north of Logan County southward through Cleveland County. It is predominately in Oklahoma and Cleveland Counties that the Garber-Wellington is an important source of water. The Garber-Wellington crops in the eastern one-half of the study area (Figure 6).

The Garber-Wellington consist of lenticular beds of

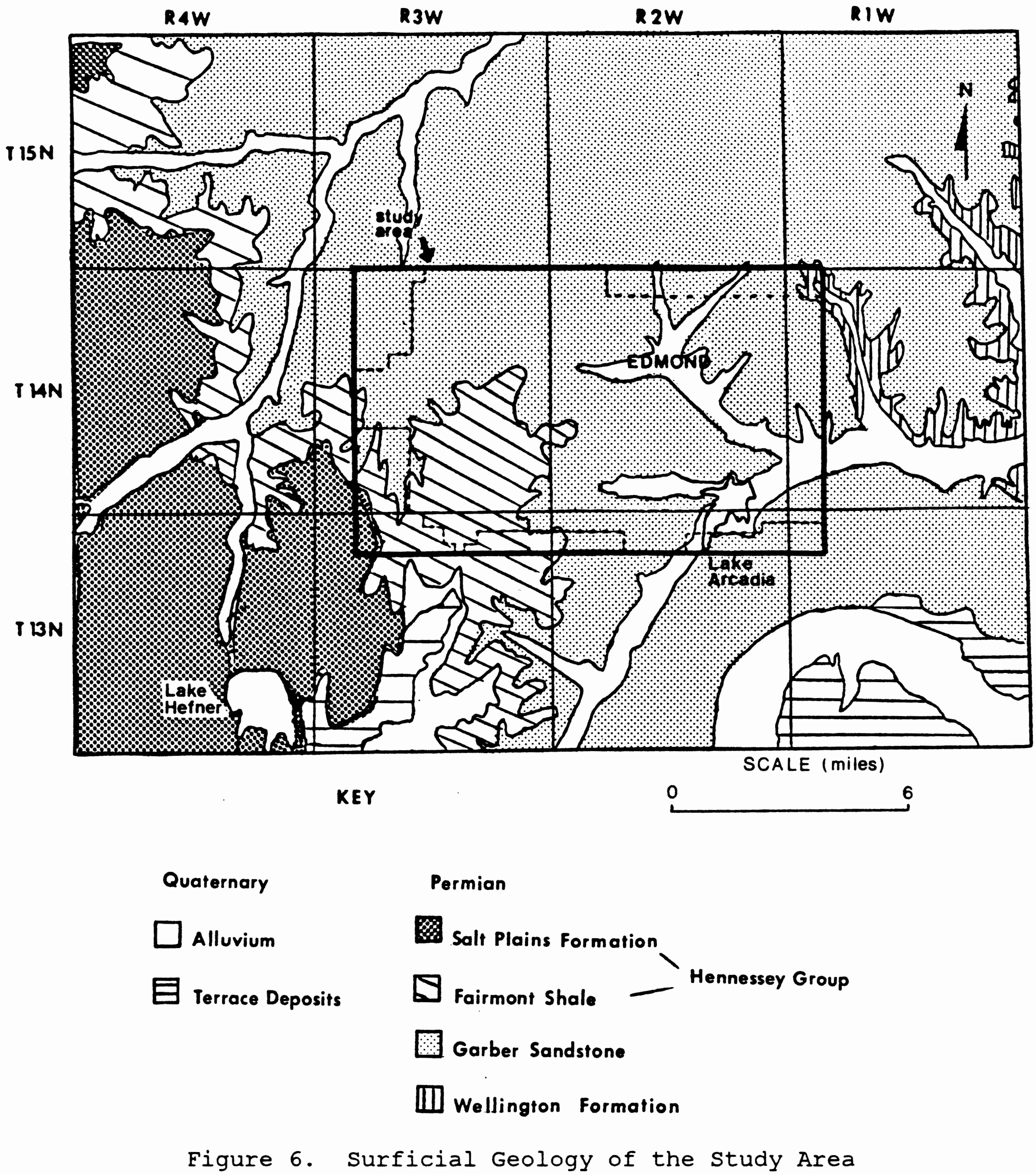


Figure 6. Surficial Geology of the Study Area (Bingham and Moore, 1975)

massive cross-bedded sandstone units, which are interbedded with shale. The sandstone beds are red to maroon, fine-grained, and their thickness ranges from 5 to 50 feet. The sand grains are predominately quartz. The shale beds are non laminated, white to red, and can be sandy to silty. The Garber-Wellington is loosely cemented by red clay and is quite friable. A few thin, discontinuous sandstone beds are cemented by calcite, dolomite, or barite. Thin layers of chert conglomerate occur at the base of some sandstone beds. Within the sandstone units, cross-bedding is well developed, and many sections that appear to be massive are actually composed of a number of cross-bedded units. The collective thickness of the Garber-Wellington ranges from 800 and 1000 feet (Burton and Wood, 1968). In the eastern portion of the study area, the Garber-Wellington is exposed and part of its thickness has been removed by erosion.

Hennessey Group

The Hennessey Group, which cropsout in the southwestern part of the study area (Figure 7), consists primarily of reddish brown, clayey to sandy shale with a few thin siltstone and sandstone beds. The shale beds are mostly massive. Where stratification is evident, it ranges from thin laminations to medium bedding. Lenticular beds of fine-grained sandstone, ranging from less than 1 to 15 feet in thickness occur near the base of the Hennessey. The contact between the Hennessey and the Garber-Wellington is believed to be conformable (Burton and Wood, 1968). The Hennessey is as thick as 650 feet elsewhere, but its maximum thickness in the study area is between 100 to 150 feet (Kennedy, 1990).

Depositional Environment

During the early Permian, regional sedimentation patterns in the mid-continent were greatly influenced by the Anadarko Basin. During this time, uplifted areas to the east were eroded rapidly, resulting in the westward transport of large volumes of sediment by the major streams. It is believed that during this time, the sediments that comprise the Garber-Wellington were deposited in a fluvial deltaic environment. The central portion of this delta complex is thought to be near Midwest City, Oklahoma, where the sand content of the Garber-Wellington is greatest, about 75 percent (McBride, 1985). The sand content within the Garber-Wellington gradually decreases away from this central region. The Permian sediments in the study area form a homocline with a northwest-southeast strike and a gradual dip to the southwest of about 40 feet/mile (Burton and Wood,1968).

Quaternary Deposits

The Quaternary deposits within the study area are alluvial deposits adjacent to the major streams (Figure 6). These deposits consist mainly of interfingering lenses of unconsolidated sand, silt, clay, and gravel. The deposits are mainly located in the floodplain and stream courses within the study area. The thickness of these sediments is probably not greater than 60 feet (Burton and Wood, 1968).

CHAPTER III

HYDROGEOLOGY OF THE CENTRAL OKLAHOMA AQUIFER

Aquifer Characteristics of the Central Oklahoma Aquifer

The Garber-Wellington constitutes an important aquifer in central Oklahoma. This aquifer is called the Central Oklahoma aquifer (COA). The COA underlies about 3,000 square miles of central Oklahoma, predominately in Logan, Oklahoma, and Cleveland counties (Christenson, 1992). Small quantities of water are obtained locally from the Hennessey Group and from alluvial and terrace deposits, yet these deposits, due to their limited permeability or extent, are not widely used as an aquifer in this area (USGS, 1954). The COA is a major source of water for municipal, industrial, and domestic uses. In 1989, groundwater withdrawals from the COA, excluding domestic use, were estimated to be 7.860 billion gallons per year (Christenson, 1992).

An understanding of how the COA functions as an aquifer is necessary in order to develop and protect this groundwater resource. The geologic framework of the COA largely controls the occurrence and movement of groundwater. Principal components of the geologic framework include the hydraulic characteristics of the rock units, geologic structure of the aquifer, and the lateral and vertical extent of the aquifer (Carr and Marcher, 1977).

Hydraulic Characteristics

Porosity and Specific Yield

Because of its origin as part of a delta system with shifting channels and alternating currents, the COA is a complex of interfingered layers of cross-bedded, fine-grained sandstone, siltstone, and shale (Carr and Marcher, 1977). Where a complete stratigraphic section exists, the combined thickness of the Garber-Wellington formations is about 1000 feet. In the eastern part of the study area where these formations are exposed, they have been partially removed by erosion. Water wells in the COA are perforated in the thick freshwater-bearing sandstone units. The hydraulic characteristics of the sandstone are directly related to the shapes, sizes, and sorting of the sand grains. The sandstone has been classified as angular to subangular, fine-grained, and well sorted (Jacobsen and Reed, 1944). The ability of the sandstone units to store water is a function of the porosity of these units. The porosity of the sandstone in the COA has been estimated to be 25%, or 0.25. The effective porosity of the sandstone is estimated to be about 0.22

(Pettyjohn, 1989). The shale beds within the COA are sandy near the top of the aquifer and become silty with increasing depth.

Recharge

Recharge to the unconfined portion of the COA is derived mainly from precipitation that falls in the outcrop area. Recharge to the aquifer has been estimated to be 130,000 acre-feet per year (Wickersham, 1979) or 15 million gallons per square mile per year (Burton and Wood, 1968). Other estimates range from 10 percent (Carr and Marcher, 1977) to between 5 and 9 percent (Bingham and Moore, 1975) of the annual precipitation.

Recharge to the confined portion of the COA is not well understood. It is possible that some water recharges the confined system by percolating through fractures that penetrate the confining shale units. The down-dip migration of water from outcrop areas to the east within laterally continuous units also may account for some recharge to the confined aquifer.

Hydraulic Conductivity, Transmissivity, and Storativity

The hydraulic conductivity of the COA has been estimated to be 35 gpd/ft^2 (Burton and Wood, 1968). This corresponds to the lithologic description of the sandstone as being fined grained, which usually results in hydraulic conductivity values in the range between 10 to 100 gpd/ft^2 (Heath, 1987). Hydraulic conductivity values can vary from one location to another and directionally within the aquifer. The ratio between the horizontal to vertical hydraulic conductivity values within the COA is estimated to be between 100:1 and 10,000:1 (Christenson, 1992). As such, the COA would be classified as an anisotropic aquifer.

Both the hydraulic conductivity and thickness of the COA are variable throughout its extent. Many different estimates transmissivity (T) values for the COA have been made. Burton and Wood (1968) estimated the transmissivity of the COA to be between 4000 and 7000 gpd/ft, Wickersham (1979) estimated 3300 gpd/ft, and Christenson (1992) estimated 2600 gpd/ft.

Aquifer tests have been performed on deep water wells in the vicinity of the Edmond well-field. The Association of Central Oklahoma Governments (ACOG) conducted an aquifer test for the City of Nichols Hills, Oklahoma, which is approximately 5 miles south of Edmond. Nichols Hills' municipal water well 10 was pumped for 8.5 hours at a constant rate, and the subsequent decline in the water level within an observation well, 29 feet away, was observed (Appendix A). The data collected from the test was plotted produce a time vs. drawdown plot (Figure 7). A transmissivity value of 1375 gpd/ft and a storativity of .0013 were obtained from the analysis.

Burton and Wood (1968) estimated the storativity of the COA to be 0.0002. The exact value of the storativity may vary throughout the COA, but it can be expected to represent a very small volume of water.

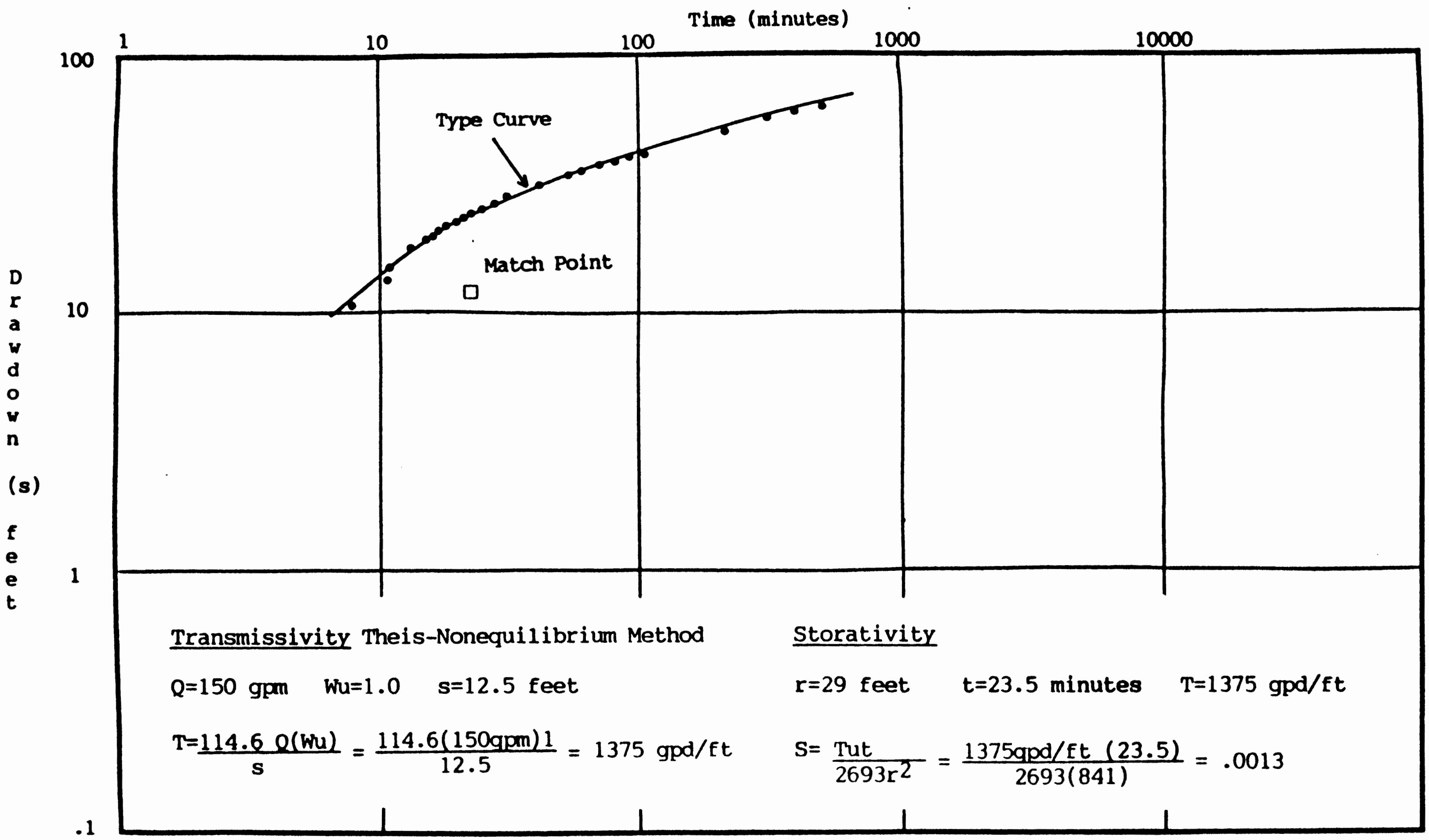


Figure 7. Aquifer Test Results from Nichols Hills' Municipal Water Well 10 (ACOG, 1980)

The assumption incorporated by the Theis non-equilibrium method that all the water produced from a well is derived from storage within the aquifer concludes that any water provided by leaky confining beds is negligible. If this assumption is incorrect and leaky confining beds supply a significant amount of water, the time vs. drawdown plot will deviate to some degree from the idealized type curve. The small amount of deviation between the plot and the type curve for the Nichols Hills aquifer test shows that there was not a significant contribution from the confining beds during the test.

Carr and Marcher (1977) described an aquifer test in Nichols Hills where a city water well was pumped for 3 days without affecting the water level in an adjacent shallow well. They concluded that only a low degree of hydraulic connection existed between the deeper sandstone units, roughly those at depths greater than 200 feet, and shallow sandstone units.

An aquifer test was conducted on community water well 6 near Oak Tree Golf and Country Club, which is located about 4 miles north of the Edmond well-field. The well was pumped for approximately 18 hours at a constant rate (Appendix A). A time vs. drawdown plot of the test data is shown in Figure 8. The results produced a transmissivity value of 2300 gpd/ft.

The variable results obtained from the aquifer tests make the selection of single representative values for the hydraulic characteristics of the COA in the Edmond area difficult. The length of time encompassed by the Oak Tree aquifer test and its close approximation of the tranmissivity estimate made by the

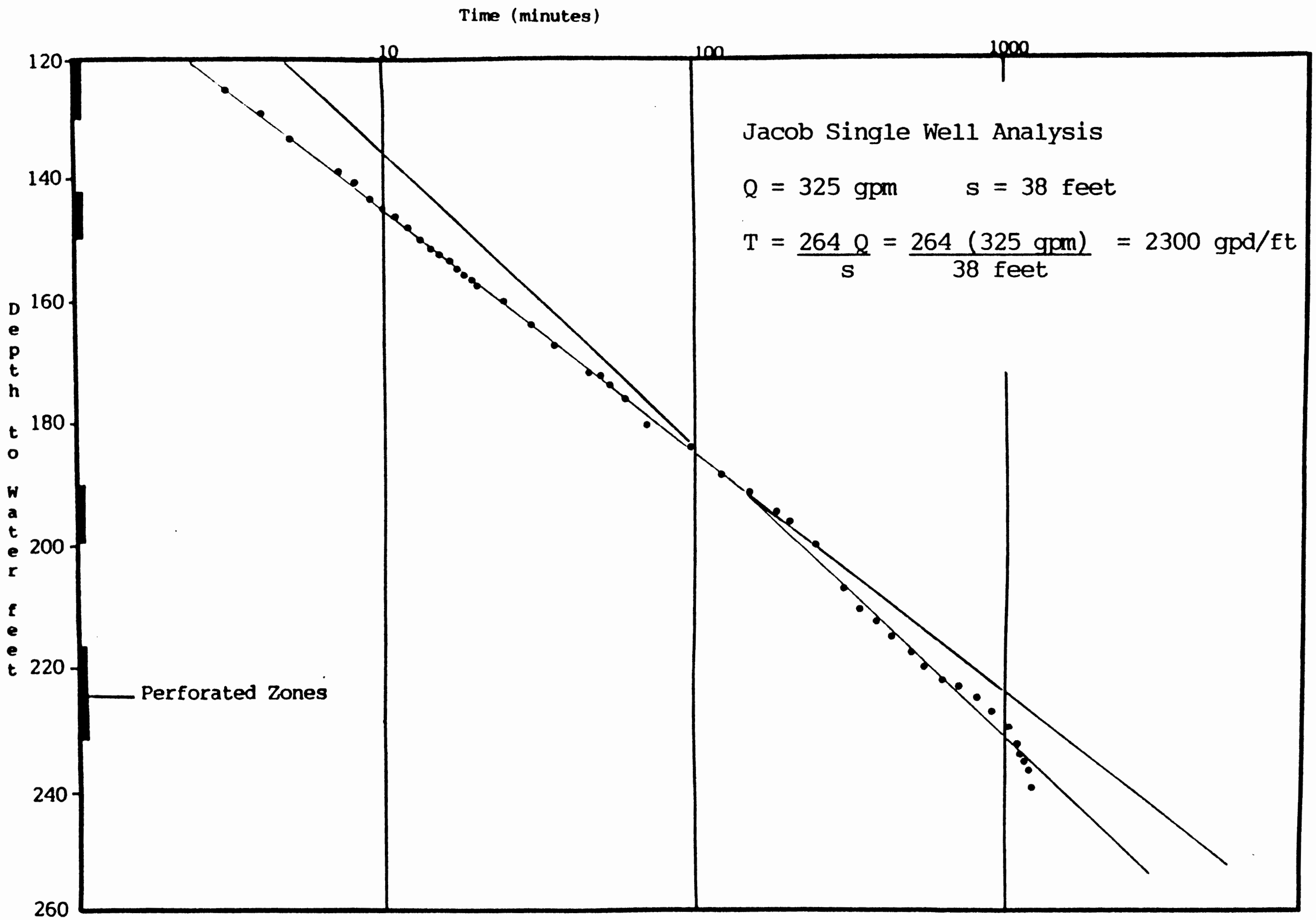


Figure 8. Aquifer Test Results from Oak Tree's Community Water Well 6 (Engineering Enterprises, 1981)

Geological Survey (USGS) provide some degree of confidence that it is a valid estimate. Since the test was conducted north of the Edmond well-field, and the total thickness of the sand in the COA is known to decrease north of Edmond, a transmissivity value of 2500 gpd/ft is believed to be a valid estimate for the transmissivity of the COA in the Edmond area.

A storativity of .0002 and hydraulic conductivity of 12 gpd/ft^2 are believed to be representative of the COA in the Edmond area.

Geologic Structure

Most of the information required for a hydrogeologic study of an aquifer is also required, to some extent, by well drillers constructing water-supply wells or oil and gas wells. An important aspect of water-well construction is the determination of the location and thickness of individual rock units. This information can be obtained from logs available from wells in the area. The logs commonly available for the municipal water wells in the Edmond well-field are driller's logs and geophysical logs. Driller's logs contain a written record of the thickness and depth of the lithologic units penetrated by the well. Geophysical logs provide indirect information on the physical characteristics of the rock units. The geophysical logs usually run in the water wells are neutron/gammma ray logs. Electrical logs run in oil and gas wells in the area can provide similar information. Figure 9 shows the responses of various geophysical logs to different lithologies.

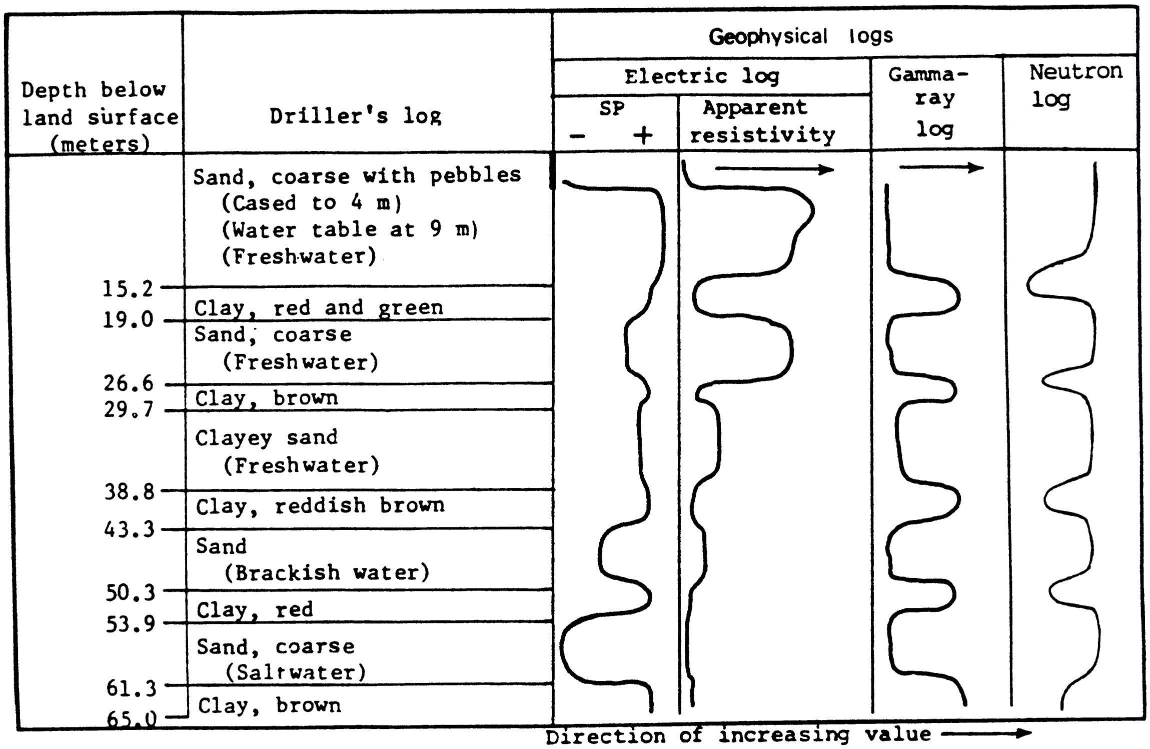


Figure 9. Responses of Various Well Logs to Different Lithologies (Heath, 1987).

Stratigraphic Cross-Sections

Figure 10 is a neutron/gamma ray log of Edmond's municipal water well 34. The log demonstrates a common signature pattern produced by the COA for these types of geophysical logs. A sandstone/shale baseline of approximately 52 API units was used to distinguish between sandstone and shale units. The selection of the baseline was a subjective decision, and a different baseline value could have been used without compromising the study. Neutron/gamma ray logs are available for most of Edmond's municipal water wells. The logs from some of the deeper water wells were used to construct stratigraphic cross-sections through the COA.

A north-south cross-section (A-A') and a northwest-southeast cross-section (B-B') (Plates 2 and 3) were prepared by correlating sandstone and shale units across the well-field. Correlation of these units was made difficult because of the similarity between various sandstone and shale units and the lack of a distinct marker bed within the aquifer. Similar trends in the logs signatures were used to correlate the units from well to well. The logs were oriented with respect to a elevation of 900 feet. The prepumping, or static, water level recorded for the wells for February, 1990 was included on the cross-sections along with known perforated intervals.

The cross-sections illustrate the highly variable nature of the units in terms of both thickness and extent. The thicker sandstone and shale units are slightly over 50 feet in

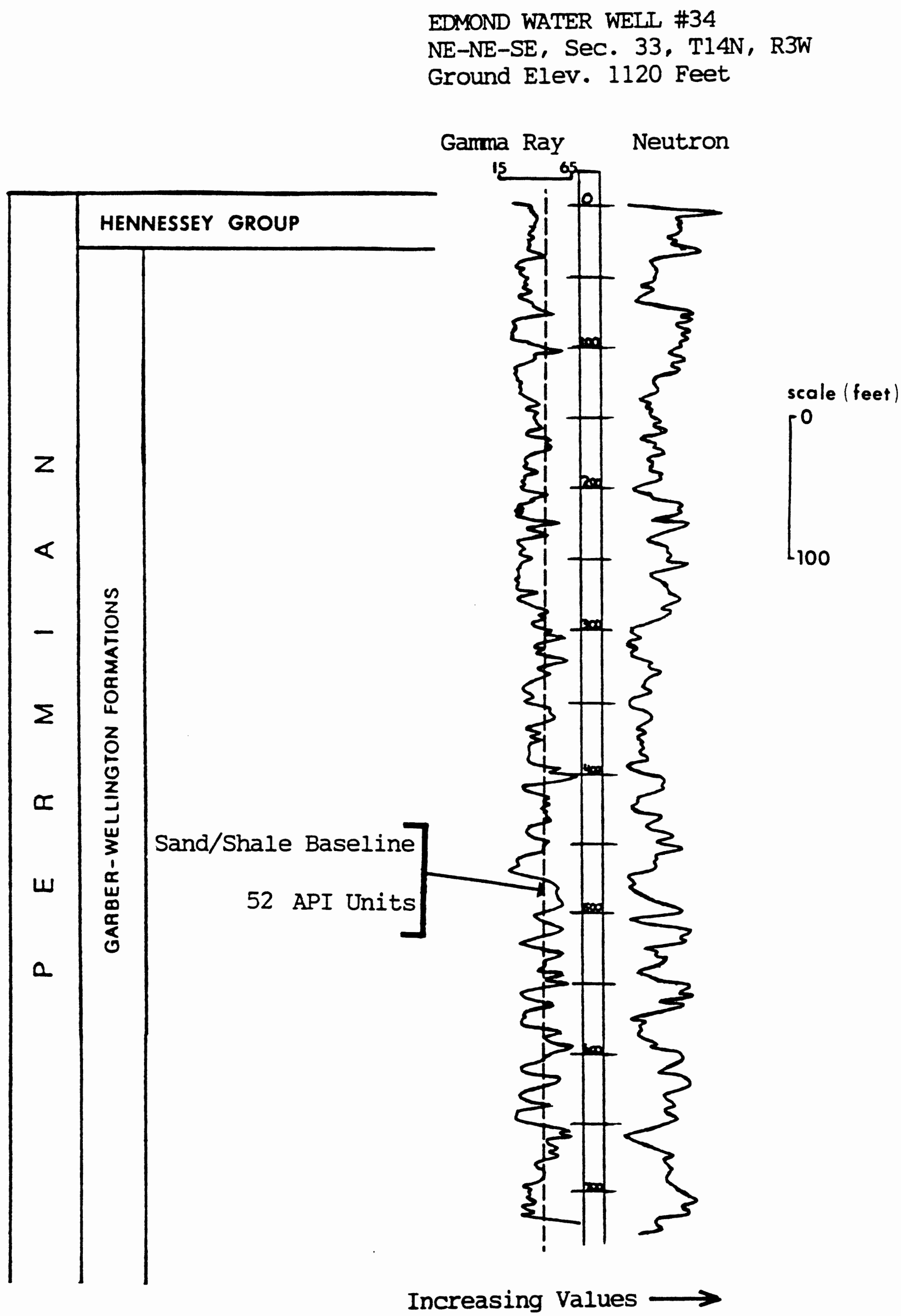


Figure 10. Neutron/Gamma Ray Log from Edmond's Municipal Water Well 34

thickness. Both the sandstone and shale units pinchout abruptly, being significantly thick in one well and being absent in a well 1/2 mile away. Some sandstone and shale units were correlated over the entire length of the cross-sections, indicating that some units possibly have appreciable lateral extent. No major structural features, such as faults or folds, are evident. Plate 2 illustrates that the structural dip of the strata is to the west-southwest at approximately 40 feet/mile. On cross-section B-B', well 27 shows that brackishwater was encountered at a depth of about 620 feet. The well was perforated in the freshwater sandstone immediately above the brackishwater sandstone.

Sandstone/Shale Ratios

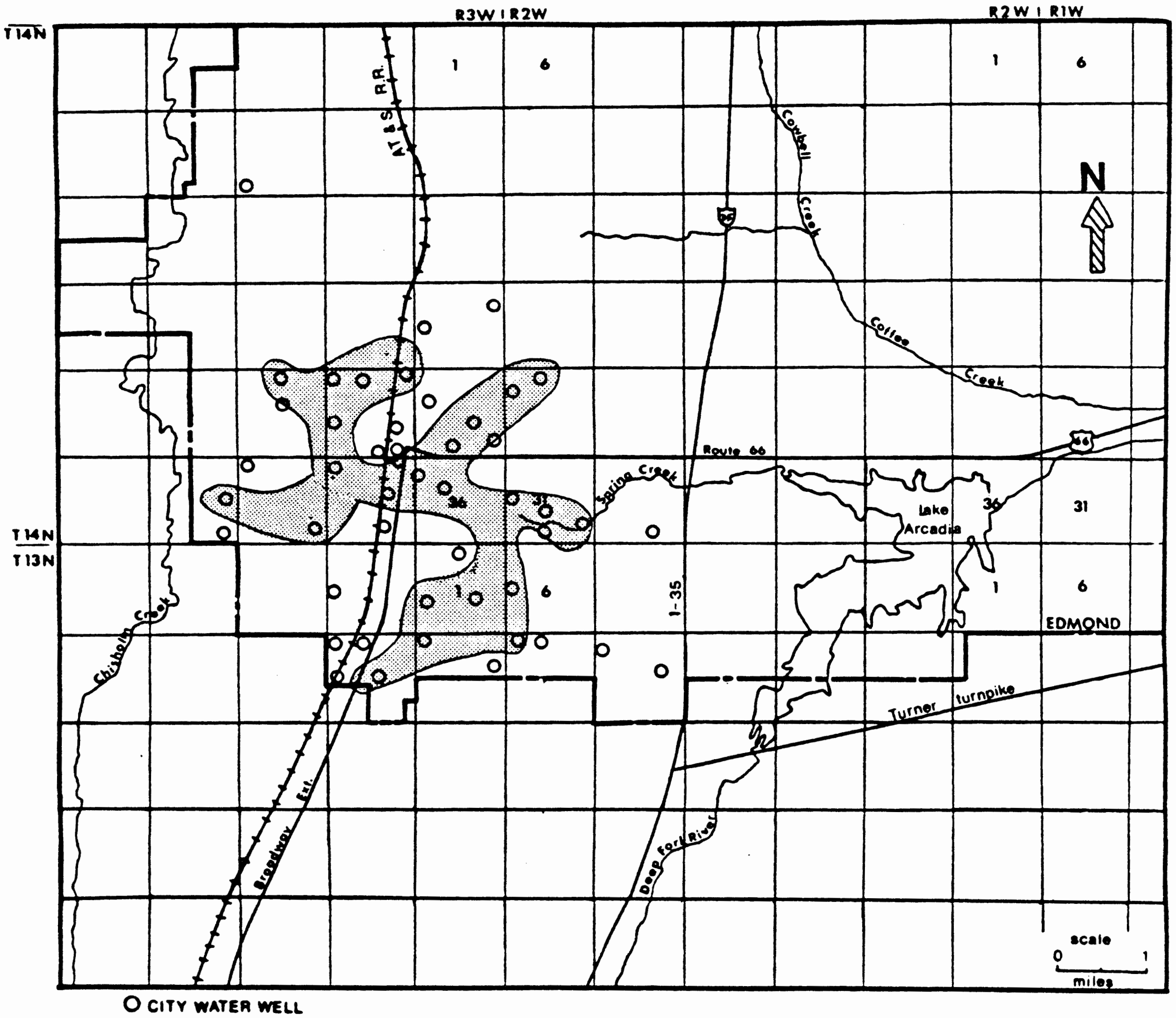
The lithologic descriptions available from drillers logs were combined with the information available on the neutron/gamma ray logs to produce lithologic records for most of Edmond's water wells (Appendix B). Using these records, the total thickness of sandstone penetrated by each well was divided by the total thickness of shale penetrated to obtain a sandstone/shale ratio.

Commonly, the total thickness of sandstone in a given stratigraphic interval is used to prepare a net-sand map. The absence of an identifiable rock unit in the interval of the COA encompassed by the logs, a unit that could be used as a marker bed to define a consistent stratigraphic interval, prohibited this approach. Sandstone/shale ratios might provide a generalized indication of any trends that exist in the relative amounts of sandstone and shale within the aquifer. The ratios were used to construct Figure 11.

Using an arbitrary sandstone/shale ratio of 1.3, an area in the central portion of the well-field was shown to contain greater sandstone content in relation to shale. The map shows generalized north-south and east-west orientations. This might suggest a channel complex during the deposition of the Garber-Wellington. If true, then transmissivity of the COA in this area should be some degree higher than elsewhere. Given the simplified nature of the driller's logs and the subjective interpretation of the neutron/gamma ray logs, the map can provide only a rough estimate of trends in relative thicknesses of the sandstone and shale in the aquifer.

Base of the Freshwater and Brackishwater Zones

Figure 12 is an electrical log from an oil well in the Northeast Edmond Oil-field. The log was started at a depth of 200 feet, which indicates the length of the surface casing. Different water-quality zones were estimated from responses of the resistivity log. The freshwater zone is characterized by high resistivity values for the sandstone and shale units. The water is more mineralized with depth, becoming increasingly brackish and eventually saline. The brackishwater zone represents a transitional zone between the COA and deeper rock units that contain water too mineralized to be used for most



EXPLANATION

Where Sandstone/Shale Ratios in the Well-Field Exceed 1.3

o Control Points

$$\frac{\text{Amount of Sandstone Penetrated by the Well}}{\text{Amount of Shale Penetrated by the Well}} = \text{Sandstone/Shale Ratio}$$

Figure 11. Sandstone/Shale Ratio Map

HARPER TURNER OIL CO.
CORA OLSON #1
SE-SE-SE-NW, Sec. 2, T14N, R2W
Ground Elev. 1074 Feet

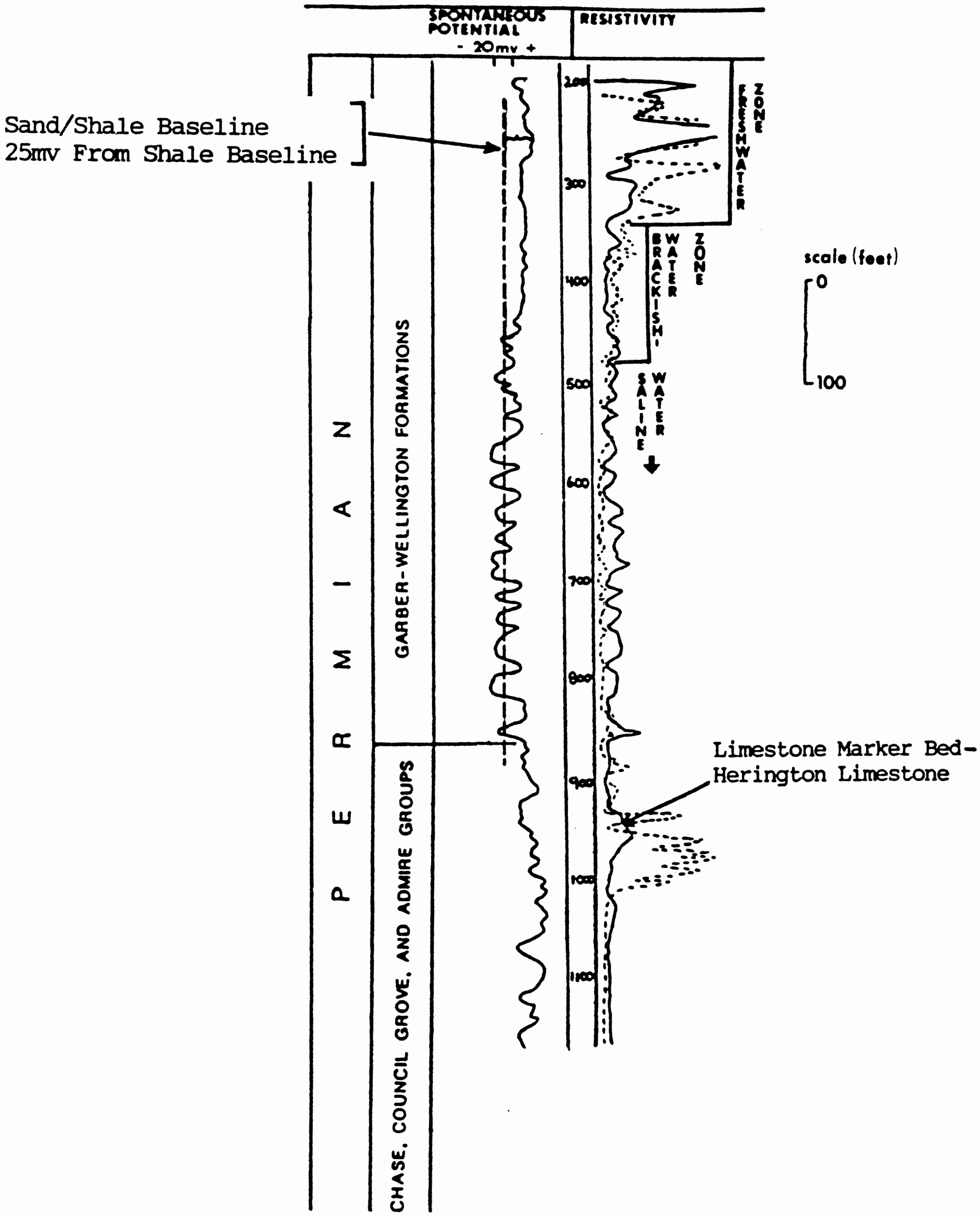


Figure 12. Electric Log from an Oil Well in the Northeast Edmond Oil-field

purposes. Delineations of these zones are based on the subjective interpretation of the log and, as such, can only serve as generalizations of the relative water-quality zones within the aquifer.

A limestone marker bed also was identified from the electric logs. The limestone was identified by Meyer (1975) as the Herington Limestone. The limestone, which actually consist of about 4 thin limestone units.

Using the electric logs, maps were constructed showing the approximate elevations of the bases of the freshwater and brackishwater zones in the COA (Plates 4 and 5).

The base of the freshwater zone is higher than 800 feet in the northeast corner, and lower than 400 feet along the southern edge of the study area (Plate 4). This trend reflects the regional pattern for the COA of increased thickening of the freshwater zone southward, reaching maximum thickness near the Midwest City to the south. The thinning of the freshwater zone to the north is reflected in the decline in well yields north of the study area (Carr and Marcher, 1977). The freshwater zone is roughly 300 feet thick in the vicinity of Edmond's well-field.

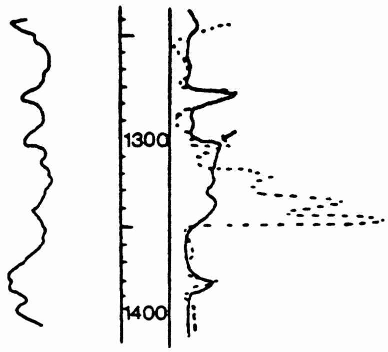
The map of the elevation of the base of the brackishwater zone shows the same general trends as the base of freshwater zone map. The base of this zone is greater than an elevation of 600 feet in the northeast and an elevation of 200 feet along the southern edge of the study area.

Geologic Structure Map

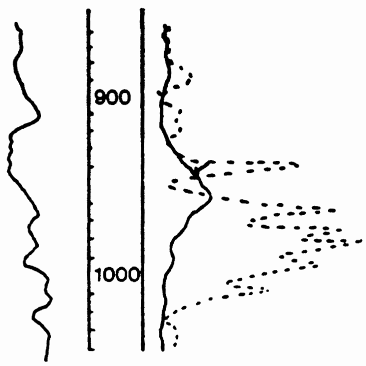
A structural contour map was prepared for the area using the elevation of the limestone marker bed (Plate 6). The resistivity signature of the limestone changes across the area (Figure 13). This makes it difficult to insure that the same stratum was correlated from log to log. The limestone is believed to be composed of four thin, laterally-persistent limestone beds (Kennedy, 1990). The first bed is about 1100 feet below the surface. Using the shallow-investigation resistivity log, a resistivity signature in the central portion of the limestone "zone" was selected as the best correlatable signature. As described above, this signature was not consistent throughout the area; therefore some error was likely introduced by the subjective interpretation of the location of this signature. Overall, a range of error of about 30 feet was incorporated into the map. Whereas the map can provide a generalized view of the major structural features in the area, any interpretation of the map should incorporate the fact that any small-scale structural features would probably not be evident.

The map reveals no major faults or folds in the area. Faults with relatively little displacement would probably not be shown. Kennedy (1990) stated that faults in the area show increasing displacement with depth, thus a pervasive fault in the deeper formations may not extend through the Permian section with displacement sufficient to appear on the map. The dip of

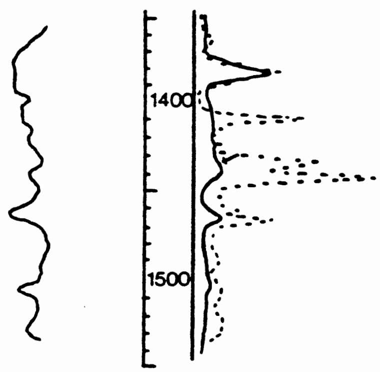
J.E. TRIGG
MORGAN #1
C-NW-NW, Sec.5, T14N, R3W
G.L. Elev. 1096



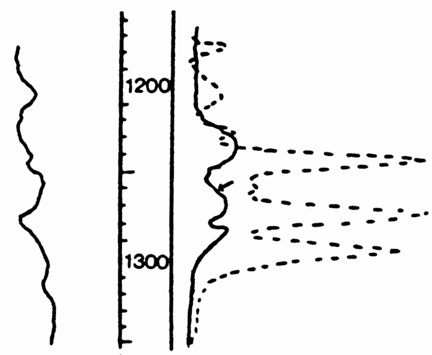
HARPER TURNER OIL CO.
CORA OLSON #1
SE-SE-SE-NW, Sec.2, T14N, R2W
G.L. Elev. 1074



POWELL BRISCOE INC.
KEEFER #1
C-NE-NW, Sec.5, T13N, R3W
G.L. Elev. 1129



FOX & FOX
LISTEN #1
SW-NW, Sec.6, T13N, R2W
G.L. Elev. 1130



← **Mapped Limestone Bed**

Figure 13. Various Electric Log Signatures of the Herington Limestone in the Edmond Area

the rock units is approximately 40 feet/mile to the west-southwest. Local irregularities are apparent in the generally homoclinal structure of the sediments.

Fractures

Investigators have proven that a definite fracture pattern exists within rock units comprising the COA. Meyer (1975) made several hundred fracture-orientation readings within the COA near Guthrie, Oklahoma, approximately 15 miles north of the study area. The results of the readings are graphically presented in a rose diagram (Figure 14). The diagram reveals two major sets of joints, N. 80°W. and N. 0°W. Two minor sets of fracture joints, N. 40°W. and N. 60°E, also exist. Melton (1955) concluded that the fractures probably formed as a result of stresses placed on rocks from the folding of the Ouachita mountains to the southeast. The fractures could affect the flow of groundwater by providing zones of increased permeability and by penetrating the confining beds separating different sandstone units. A fracture-trace analysis of the Nichols Hills area, using surface lineaments shown on aerial photographs (Harrington and Simpson, 1990) indicates that municipal water wells within the COA that are located in the vicinities of fractures, especially near intersections of fractures, show increased well yields relative to wells not located near these intersections. Modification of the land surface in the Edmond area, due to urban and residential development, hinders the study of fracture patterns using surface observation techniques.

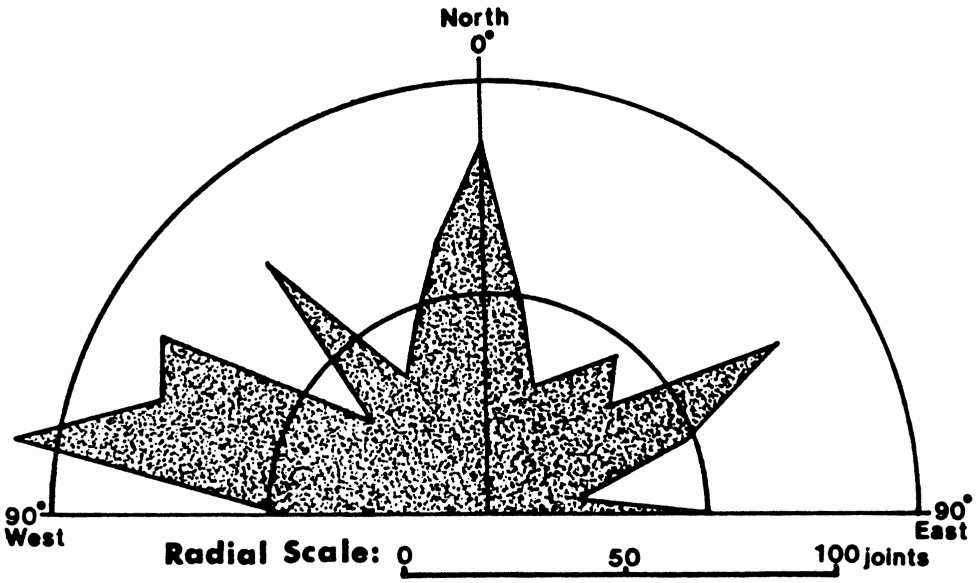


Figure 14. Rose Diagram Showing the Distribution of Fracture Orientations in the Central Oklahoma Aquifer near Guthrie, Oklahoma (Meyer, 1975)

CHAPTER IV

GROUNDWATER DEVELOPMENT IN THE CENTRAL OKLAHOMA AQUIFER

Well Characteristics

Influenced by well-drilling techniques used in the petroleum industry, most deep water wells in the COA are completed by gun-perforating the casing after it has been cemented in the borehole. The perforations are located adjacent to thick water-bearing sandstone units. The locations of the sandstone units are identified from logs. Neutron/gamma ray or driller's logs usually are prepared for most wells. Driller's logs contain lithologic information and construction details on the wells. The driller's log for Edmond's municipal water well 33 is typical (Figure 15). The log is a record of depths at which certain lithologies were penetrated during the drilling of the well. The construction details show that 22 feet of 16-inch-diameter steel surface casing was set into the hole. Five hundred sixty two feet of 10 3/4 inch diameter casing was then cemented into the hole with 430 sacks of cement. A neutron/gamma ray log was run, and from this log the well was

STAATS DRILLING COMPANY

DEEP WATER WELLS

MAILING ADDRESS: RT. 1, BOX 255C, MOORE, OKLAHOMA

City of Edmond
Driller Log
Water Well #33

0 - 21	Loose Formation
21 - 63	Sand (dry)
63 - 65	Chert
65 - 72	Sand (dry)
72 - 76	Chert
76 - 80	Sand (dry)
80 - 89	S. Shale
89 - 120	Sand
120 - 139	S. Shale
139 - 146	Sand
146 - 180	S. Shale
180 - 223	Sand
223 - 234	S. Shale
234 - 248	Sand
248 - 263	Shale
263 - 272	Sand
272 - 298	Shale
298 - 305	S. Shale
305 - 350	Shale
350 - 356	S. Shale
356 - 375	Sand
375 - 395	S. Shale
395 - 401	Shale
401 - 415	S. Shale
415 - 434	Shale
434 - 444	S. Shale
444 - 475	Shale
475 - 503	Sand
503 - 525	S. Shale
525 - 528	Shale
528 - 536	Sand
536 - 559	S. Shale
559 - 604	Sand
604 - 700	Shale (T.D.)

Casing Record:

22' 16" O.D. surface casing
562' 10-3/4 O.D. cemented top to bottom using 430 sacks portland cement.

Dresser-Atlas Gamma-ray & neutron logged - gun perforated 900 holes

212 - 221 -	54 holes
226 - 231 -	30 "
237 - 251 -	84 "
261 - 269 -	48 "
274 - 279 -	30 "
298 - 308 -	60 "
323 - 334 -	66 "
353 - 377 -	168 "
380 - 387 -	42 "
394 - 397 -	18 "
472 - 491 -	114 "
509 - 515 -	36 "
532 - 553 -	126 "
556 - 560 -	24 "

75 h.p. B.J. sub. pump set at 436' air-line setting 436' static head 108'

Staats Drilling Company

By: C.H. Staats
C.H. Staats

Figure 15. Driller's Log of Edmond's Municipal Water Well 33

gun-perforated adjacent to the sandstone units. The perforation record shows the intervals that were perforated and how many holes were used for each interval. The perforation records available for Edmond's municipal water wells indicate that they produce from an average of 200 feet of sandstone (Appendix C). A 75-horsepower submersible pump was placed at 436 feet into the hole, along with an air-line to take water-level measurements.

The type of well construction described by the driller's log is the usual method of construction for deep municipal water wells in the COA (Simpson, 1992). The method of gun-perforating the casing instead of using well screens is generally considered inefficient for some of the following reasons:

* the perforations cannot be closely spaced;
* the percentage of open space in the casing is small;
* the perforations are usually irregular in shape and size; and
* sediment can enter the well through the perforations.

In addition, incrustaceans may form within the wellbore, reducing the well's effective diameter and blocking perforations. These incrustaceans are commonly related to naturally-occurring chemical constituents in the water and do not usually pose any threat beyond reducing the effectiveness of the well. They are commonly removed by acidizing the well.

Despite the drawbacks of this method of well construction, this is generally regarded as a good method to use for wells in the COA. Occasionally, water-quality problems are associated with naturally-occurring heavy metals and radiation within the aquifer. With a perforated well, any producing units that have experienced water degradation can be sealed off, permitting the well to continue operation. With a screened well, corrective action, such as this, would be more difficult. Given the high construction cost of deep water wells, the ability to address water quality-problems in this manner could prevent a significant financial burden from being placed on the communities that rely upon the COA for their water.

Specific Capacity

The specific capacity of a well indicates how much water the well will produce per foot of drawdown. The specific capacity of a well depends on the hydraulic characteristics of the aquifer and the construction of the well. Factors that can affect specific capacity include:

* the transmissivity of the portion of the aquifer supplying water to the well;
* the storativity of the aquifer;
* the length of the pumping period;
* the effective radius of the well; and
* the pumping rate of the well.

The method of well construction also can influence the specific capacity. Wells constructed by perforating the casing generally have specific capacity values that are about half the value of screened wells in the same aquifer (Figure 16). Thus, a screened well in the COA will yield about twice as much water as a perforated well, for the same amount of drawdown.

Specific capacity values can be determined from acceptance tests performed on newly constructed wells. These tests are used to verify the well yield. Burton and Wood (1968) reported the results of an acceptance test on a water well in the Edmond area (Table I).

TABLE I

ACCEPTANCE TEST RESULTS

Location	Depth	Q	s	Time	Specific Capacity
T14N,R3W,26	743 Ft.	275 gpm	285 Ft.	8 Hrs.	0.96

Except for the test reported by Burton and Wood, records of acceptance tests are not available for Edmond's municipal wells. Records are available for monthly pumping, static water-level measurements, and total daily operating hours for each well for 1988, 1989, and 1990. Whereas during an acceptance test the drawdown measured is the result of continuous pumping at a constant rate, the drawdowns recorded in the monthly water-

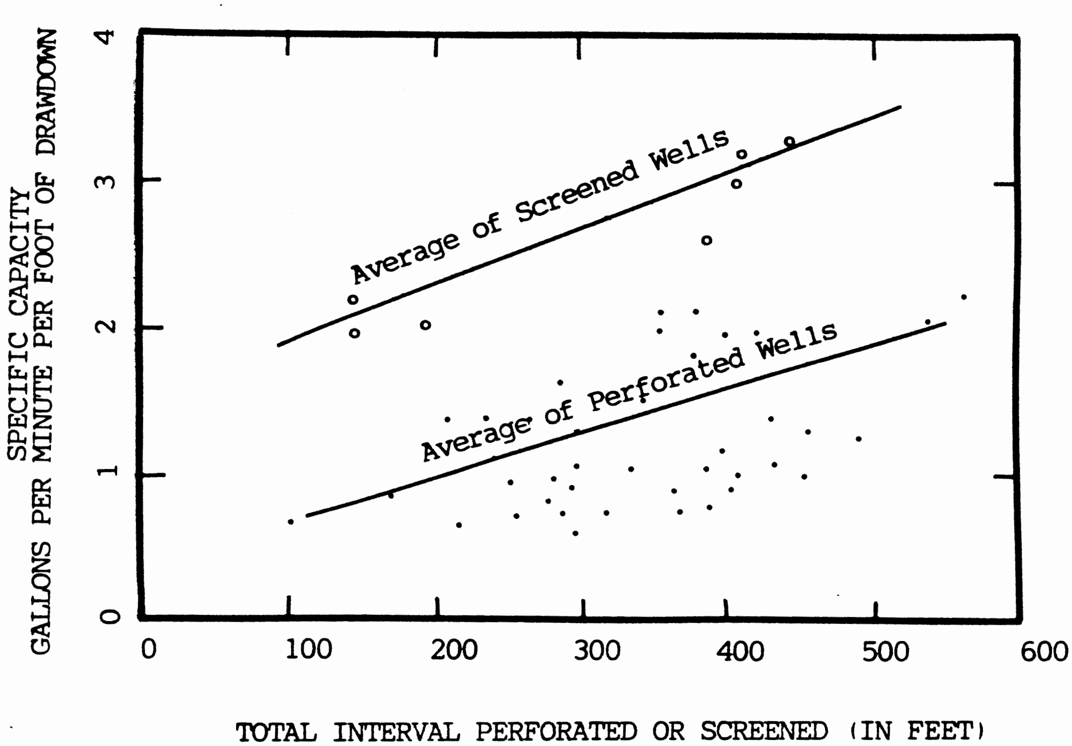


Figure 16. Graph of Specific Capacity of Screened and Perforated Wells in the Central Oklahoma Aquifer (Carr and Marcher, 1977)

level measurements are the results of pumping the municipal wells during irregularly spaced intervals throughout the month. As such, well discharge rates must be adjusted in order to approximate the conditions that create the drawdown. The total monthly hours of operation and the total monthly output of each well for the month of August, 1990 were used to calculate a continuous pumping rate. The difference between the static and pumping water levels for each well provided an estimate of drawdown, which was used, along with the approximations of continuous pumping rates, to estimate the specific capacities of most of Edmond's municipal water wells (Table II).

The estimated average value for specific capacity for Edmond's well-field is 1.2 gpm/ft. The estimated values ranged from a high of 3.6 to a low of 0.03 gpm/ft. The lower values were obtained from wells that are pumped only for a very short period during the month. Some error may have been introduced into the estimates because of factors that increase the drawdown, such as well loss and well interference. In these situations, exaggerated amounts of drawdown may have been ascribed to lower pumping rates than would be appropriate, producing specific capacity values that are too low.

The specific capacity estimates for wells can be used to estimate hydraulic conductivity and transmissivity of the COA. By multiplying the specific capacity by 2000, a rough estimate of the aquifer's transmissivity can be obtained. Using the estimated average specific capacity value of 1.2 gpm/ft, an estimate for the transmissivity of the COA of 2400 gpd/ft was

TABLE II

SPECIFIC CAPACITY CALCULATIONS

August 1990, 30 days, 744 hours

Well #	Hrs Pumped	Q Rate of Withdrawl gpm	Q_c Continuous Rate gpm	s Drawdown for August 1990	Q_c/s Specific Capacity
11	170	260	60	30	1.9
12	511	200	137	120	1.14
15	395	150	60	75	1.06
19	441	275	163	110	1.50
20	85	300	35	60	0.57
21	493	250	166	80	2.07
22	133	200	36	80	0.44
23	457	250	154	80	1.9
24	491.5	275	182	150	1.2
25	531.5	300	214	70	3.06
26	190.5	250	64	64	1.00
28	144	200	39	85	0.46
29	147.5	300	59	80	0.74
30	46	200	12	70	0.18
31	13.5	220	4	100	0.04
32	216	375	109	130	0.83
33	94.5	290	37	90	0.41
34	148	275	58	80	0.72
35	226.5	300	91	100	0.91
36	19	200	5	150	0.03
37	597	225	180	50	3.6
39	319.5	200	80	60	1.43
40	127.5	270	40	100	0.46
41	203.5	275	75	50	1.5
42	492.5	150	99	50	1.99
43	580.5	150	117	50	2.3
44	40	250	13	70	0.19
46	100	200	28	85	0.34
47	458	125	77	52	1.50
48	98	300	40	90	0.44
49	136.5	250	40	70	0.66
50	37	225	11	70	0.16
51	492	300	198	130	1.52
53	38.5	150	8	57	0.14
54	533	200	143	50	2.9
		Avg. 250			Avg. 1.2

Estimated Transmissivity- 2000 x Q/s = 2000 x 1.2 = 2400 gpd/ft

Estimated Hydraulic Conducutivity- $\frac{2000 \times Q/s}{\text{Aquifer Thickness}} = 12$ gpd/ft^2

obtained. Dividing transmissivity by the average perforated thickness of sandstone for the wells, 200 feet results in an estimated hydraulic conductivity value for the COA of 12 gpd/ft^2. These estimates agree with other determinations of the aquifier characteristics from aquifer tests.

Well Yields

The reported well yields for Edmond's municipal water wells range from 150 to 375 gpm, with an average yield of 250 gpm (Table II). The yields were obtained from records kept by the City of Edmond. The specific capacity value for a well can be multiplied by the available drawdown to estimate the well's potential yield (Carr and Marcher, 1977). Locating a water well in the COA given proper regard toward the geologic setting can significantly increase its potential well yield.

Well Interference

Overlapping cones of depression will have an additive effect on the drawdown, referred to as well interference. In this situation, the drawdown of a water well will be equal to its own drawdown plus that produced by any other nearby pumping wells. For municipal wells in the COA, well spacing less that 2000 feet produces significant well interference, thus increasing pumping cost (Harrington and Simpson, 1990).

In order to determine well interference affects in the Edmond well-field, three relatively closely spaced high-yield municipal water wells were analyzed by the computer program

Theis Well-field, which uses the Theis well functions to solve for the drawdowns. Municipal wells 37, 21, and 12, located in the southwest corner of the well-field, were chosen for the simulation (Plate 1). The computer program calculates hydraulic heads produced by the pumping of up to 20 water wells in a homogenous, isotropic, confined aquifer while taking well interference into account. The input values used for the simulation are shown in Table III.

TABLE III

INPUTS FOR THEIS WELL-FIELD SIMULATIONS

Inputs	Values
Transmissivity	= 2500 gpd/ft
Storage Coefficient	= 0.0002
Initial Head	= 1000 feet
Hydraulic Gradient	= 0.001
Pumping Duration	= 200 days

A simulation with the wells pumping at their August, 1990 continuous-pumping rates for a period of 200 days was compared to simulations of each well for the same period. The results show that well interference accounts for an increase in drawdown for well 37 of 68 feet, well 21 of 76 feet, and well 21 of 68 feet (Appendix D).

Given the geologic complexity of the aquifer, these simulations probably do not provide an exact measure of the magnitudes of drawdown and well interference. The results do indicate, however, that well interference probably does significantly affect the drawdowns of those wells that are closer than about 2000 feet apart.

Water-Level Fluctuations

Well Hydrographs

Records of water-level measurements for Edmond's well-field reflect changes in the volume of water contained in the COA. Water levels will rise when recharge exceeds discharge and fall when discharge is greater than recharge. Under natural conditions, the long-term recharge and discharge of an aquifer are in a state of natural equilibrium. Water-level measurements from areas of extensive groundwater withdrawals show the extent to which groundwater development has altered this natural equilibrium. Well hydrographs, showing the monthly static and pumping water levels for the period 1988-1990, were prepared for wells 12, 26, 33, 34, and 48 (Figures 17 to 21).

The hydrograph for well 12 shows large water-level fluctuations during 1988 (Figure 17). On most of the

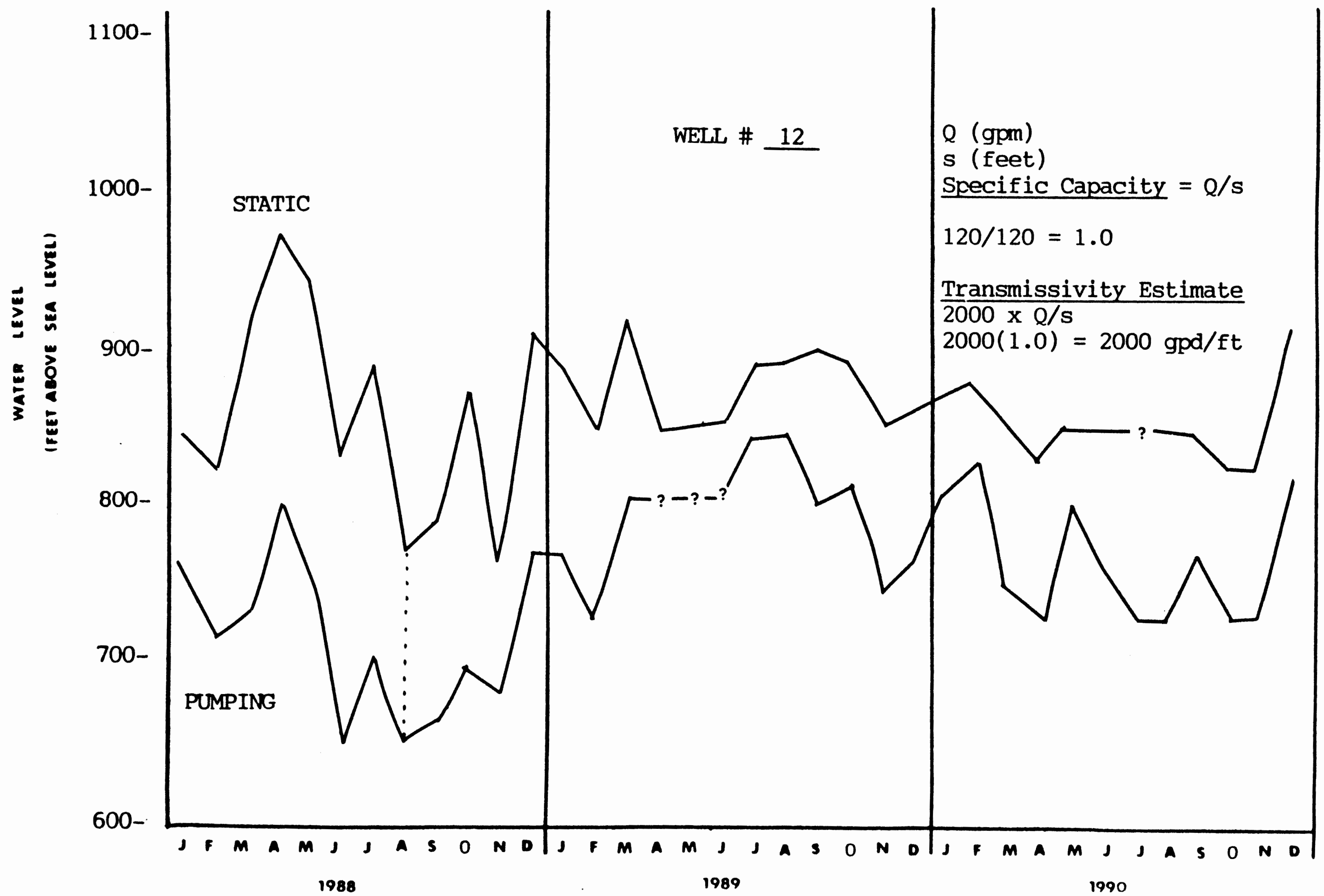


Figure 17. Hydrograph for Edmond's Municipal Water Well 12

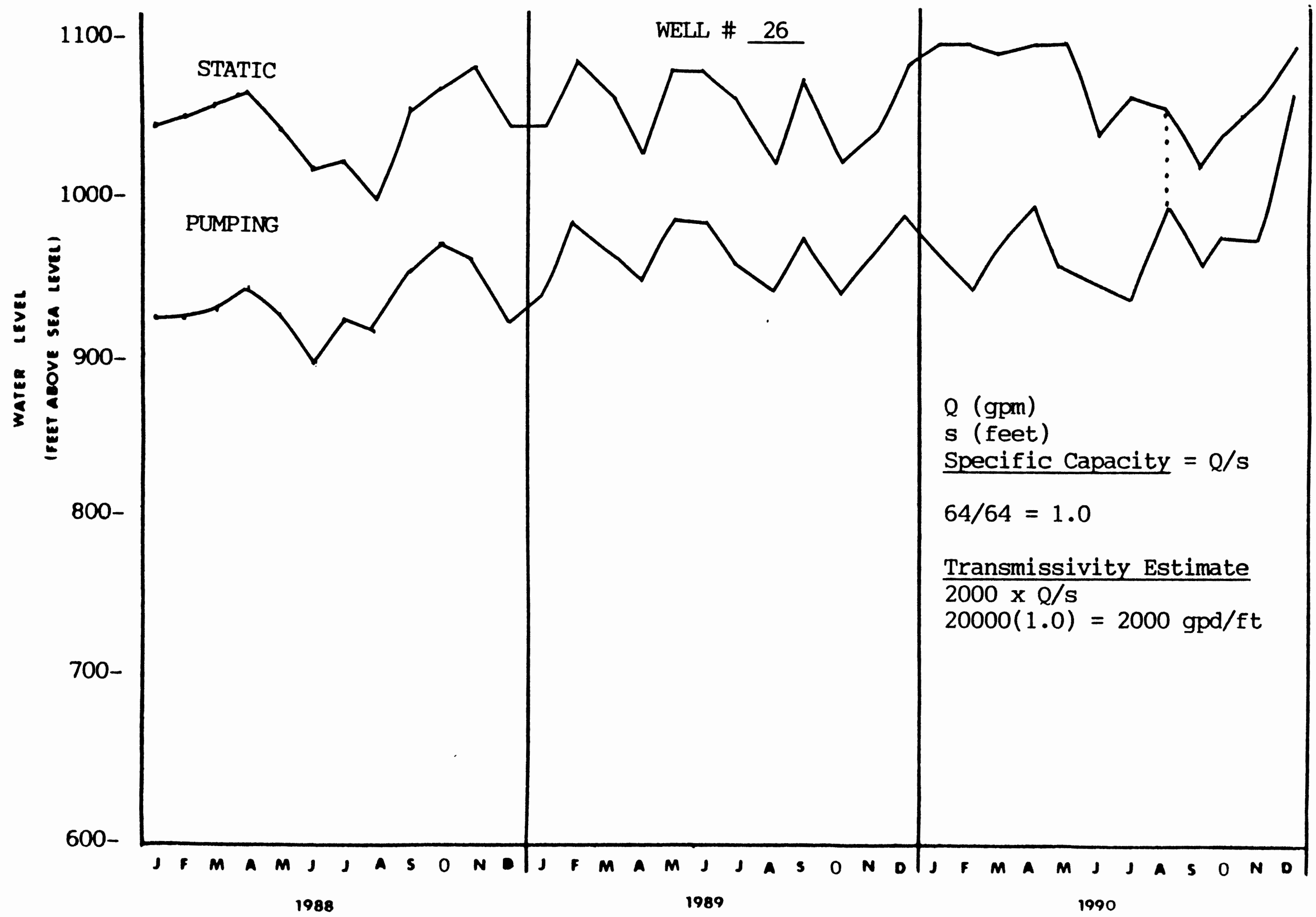


Figure 18. Hydrograph for Edmond's Municipal Water Well 26

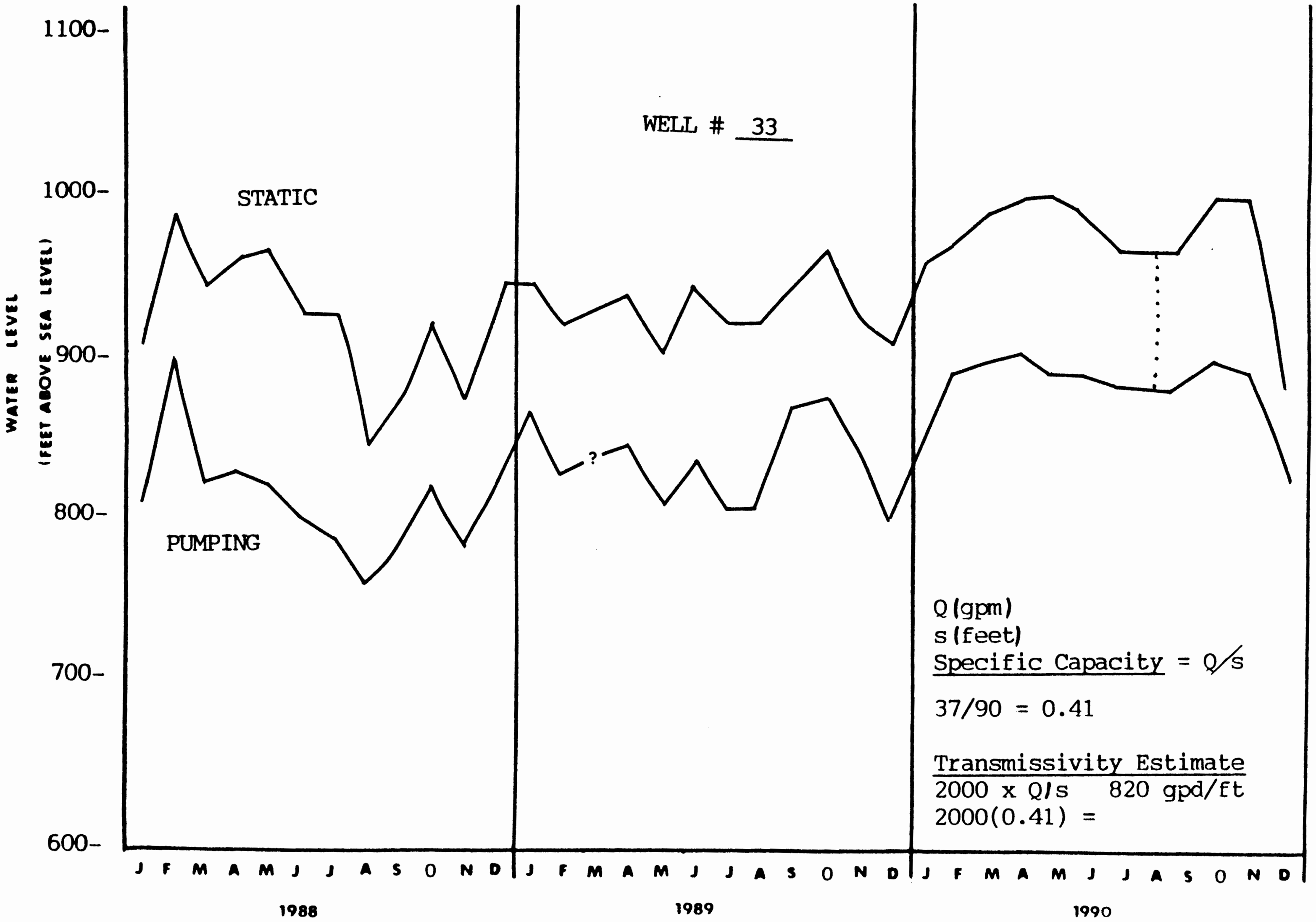


Figure 19. Hydrograph for Edmond's Municipal Water Well 33

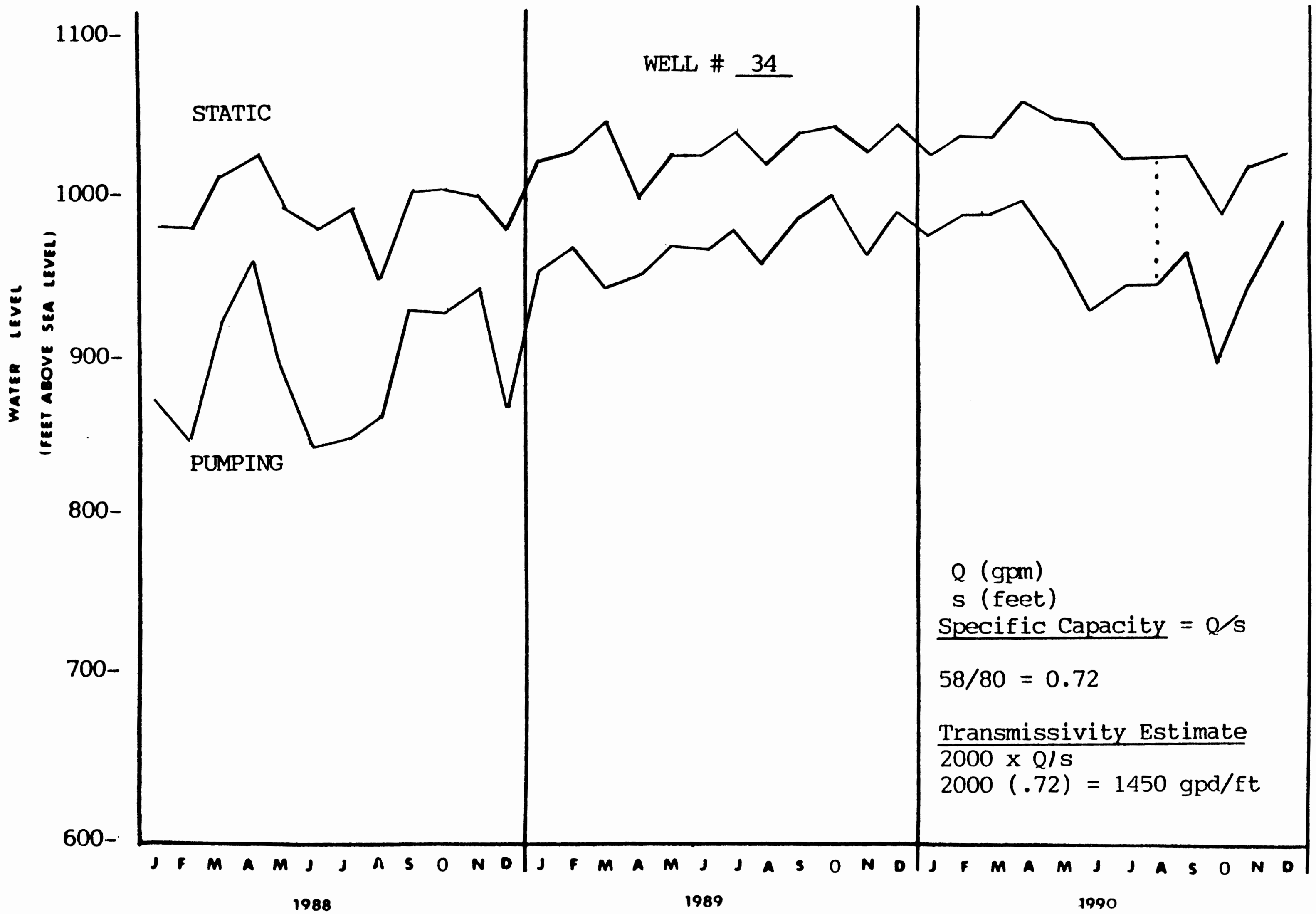


Figure 20. Hydrograph for Edmond's Municipal Water Well 34

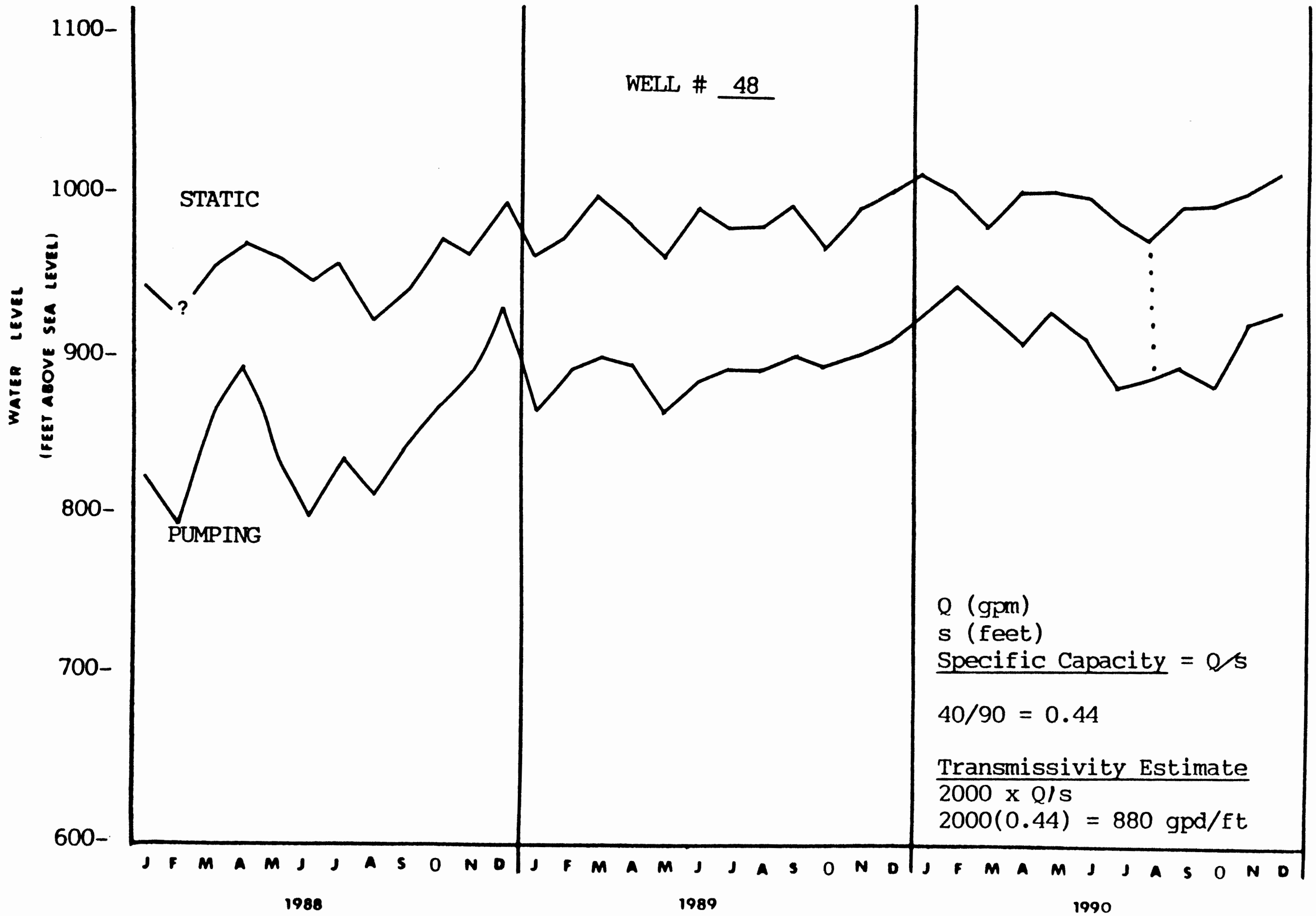


Figure 21. Hydrograph for Edmond's Municipal Water Well 48

hydrographs, water levels appear to rise steadily after 1988. This is probably due to withdrawals from Lake Arcadia, which began in 1988. Owing to production from Lake Arcadia, discharge from the well-field decreased. From 1980 to 1988, the well-field was heavily pumped, particularly during the summer months, to meet the demands of the large population increase in Edmond. Since 1988, the water-treatment plant at Lake Arcadia has supplied roughly half of the water required by the city. The effect of the reduced use of groundwater is also evident on a graph of the total output of the well-field (Figure 22).

The hydrographs (Figures 17 to 21) show evidence of seasonal fluctuations of water levels in the COA. The water levels are usually highest in the early spring and decline throughout the summer. Some inconsistencies evident in the hydrographs, such as periods where the trends of the pumping and static water levels do not coincide, could be the result of erroneous water-level measurements, well loss, or well interference.

Water-Level Maps

Unconfined Aquifer

The lack of any significant hydraulic connection between the unconfined and confined portions of the COA is evident when comparing water-level maps prepared from measured water levels. In the unconfined portion of the COA, water levels from domestic and other shallow wells reveal that the water table reflects the

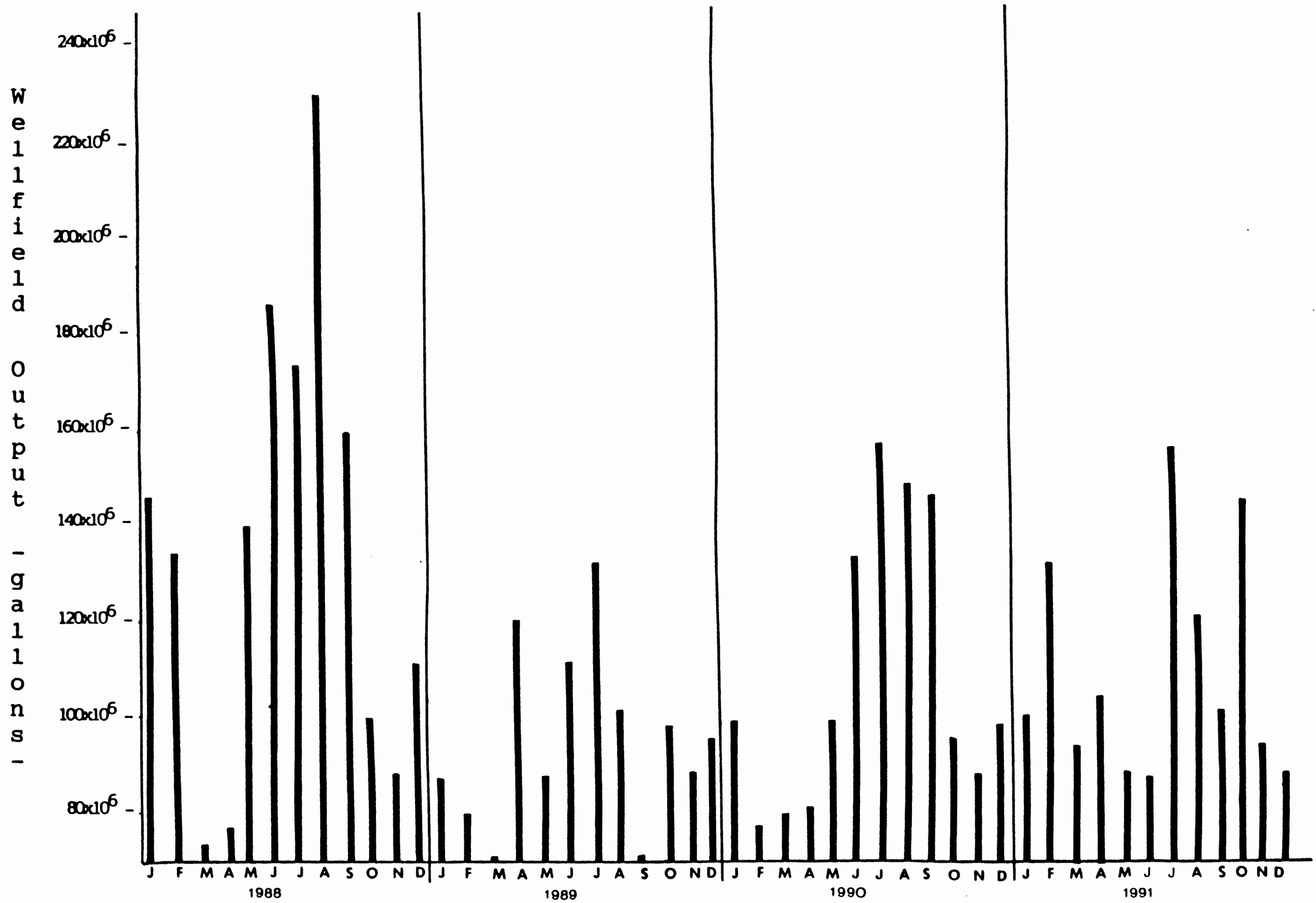


Figure 22. Graph of Edmond's Well-field's Total Output

surface topography of the area (Figure 23). This can be observed by noting that the closed contour line 1150 is near the drainage divide between Chisholm Creek and Spring Creek. The highest water-level elevations are near the central part of the well-field and they decrease eastward towards the Deep Fork River and Lake Arcadia. Water in the unconfined aquifer supplies the baseflow of the perennial streams and lakes in the area. Furthermore, the water-level map of the unconfined part of the aquifer does not indicate the presence of a cone of depression in the water table that might be associated with the well-field.

Confined Aquifer

Although the water-level map of the unconfined aquifer reflects the surface topography, water-level maps of the confined aquifer strongly reflect the effect of the well-field on the potentiometric surface of the COA. Monthly records of water-level measurements for Edmond's municipal wells for 1988, 1989, and 1990 were used to construct August pumping and static and February static water-level maps for each year (Figures 24 to 32).

The August, 1988 pumping water-level map shows the cone of depression of the well-field during a peak-use month of a peak-use year (Figure 24). The cone of depression forms an irregular circle with localized central areas of increased drawdown. The increased drawdowns in these areas could be the results of high

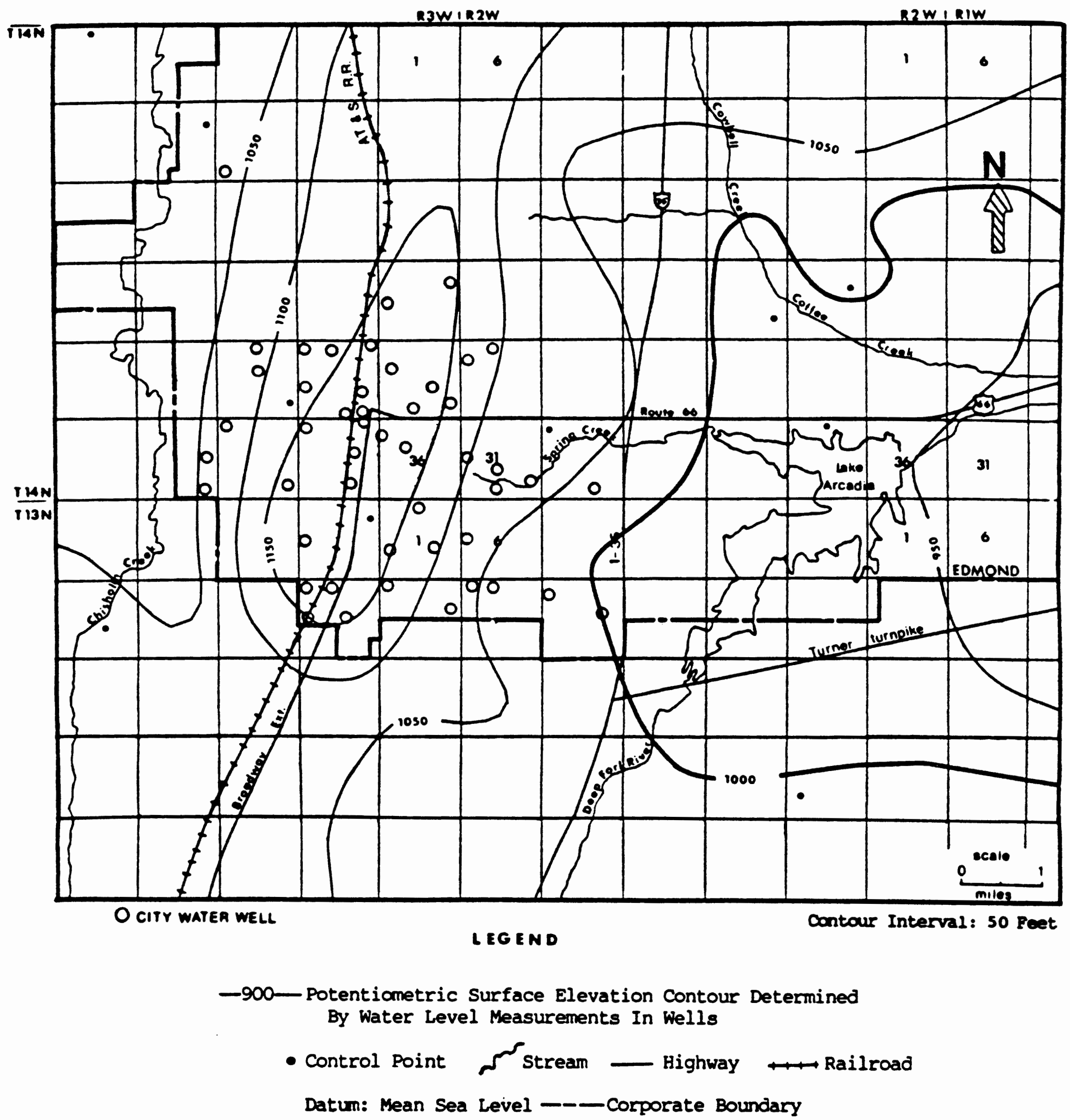
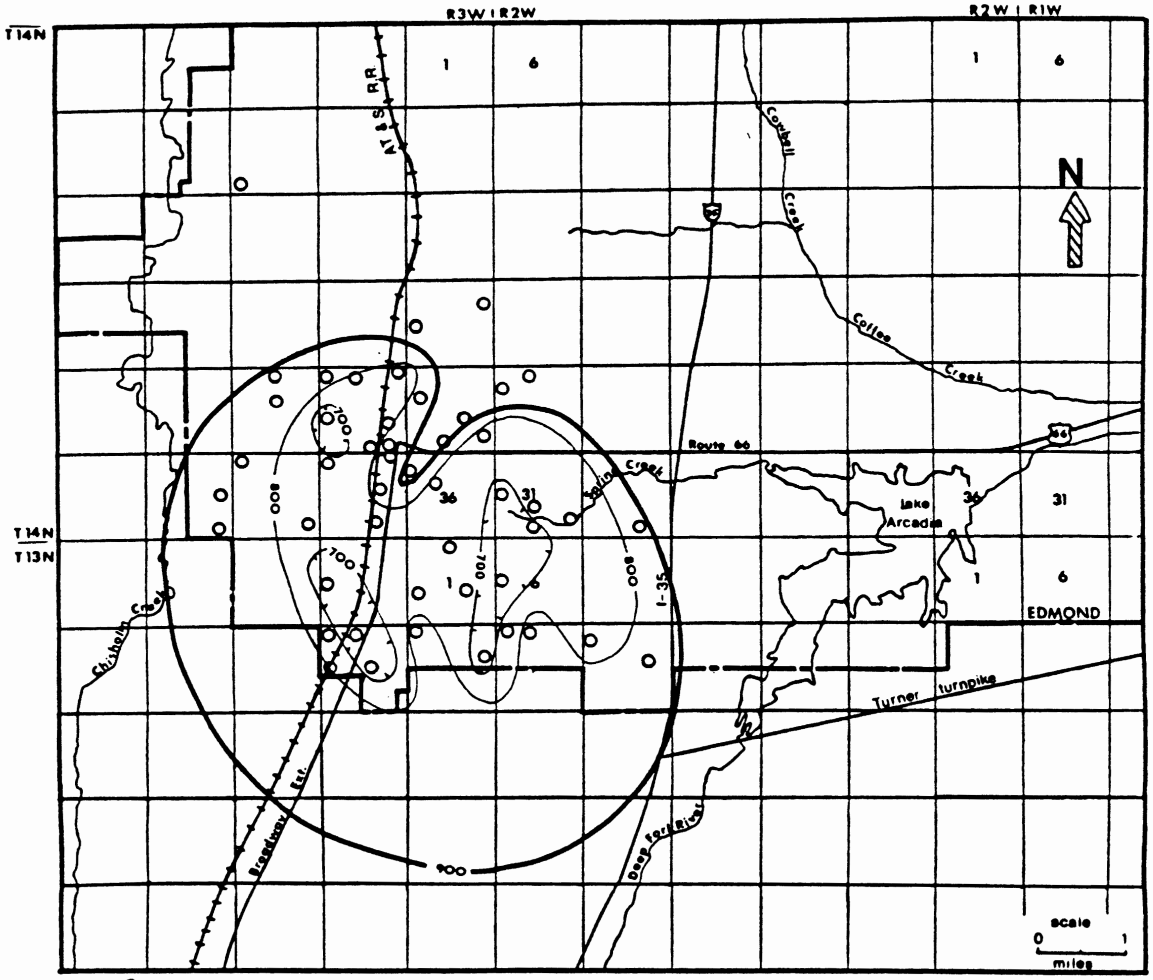


Figure 23. Water-Level Map for the Unconfined Portion of the Central Oklahoma Aquifer in the Study Area (Christenson, Morton, and Mesander, 1990)



O CITY WATER WELL

Contour Interval: 100 Feet

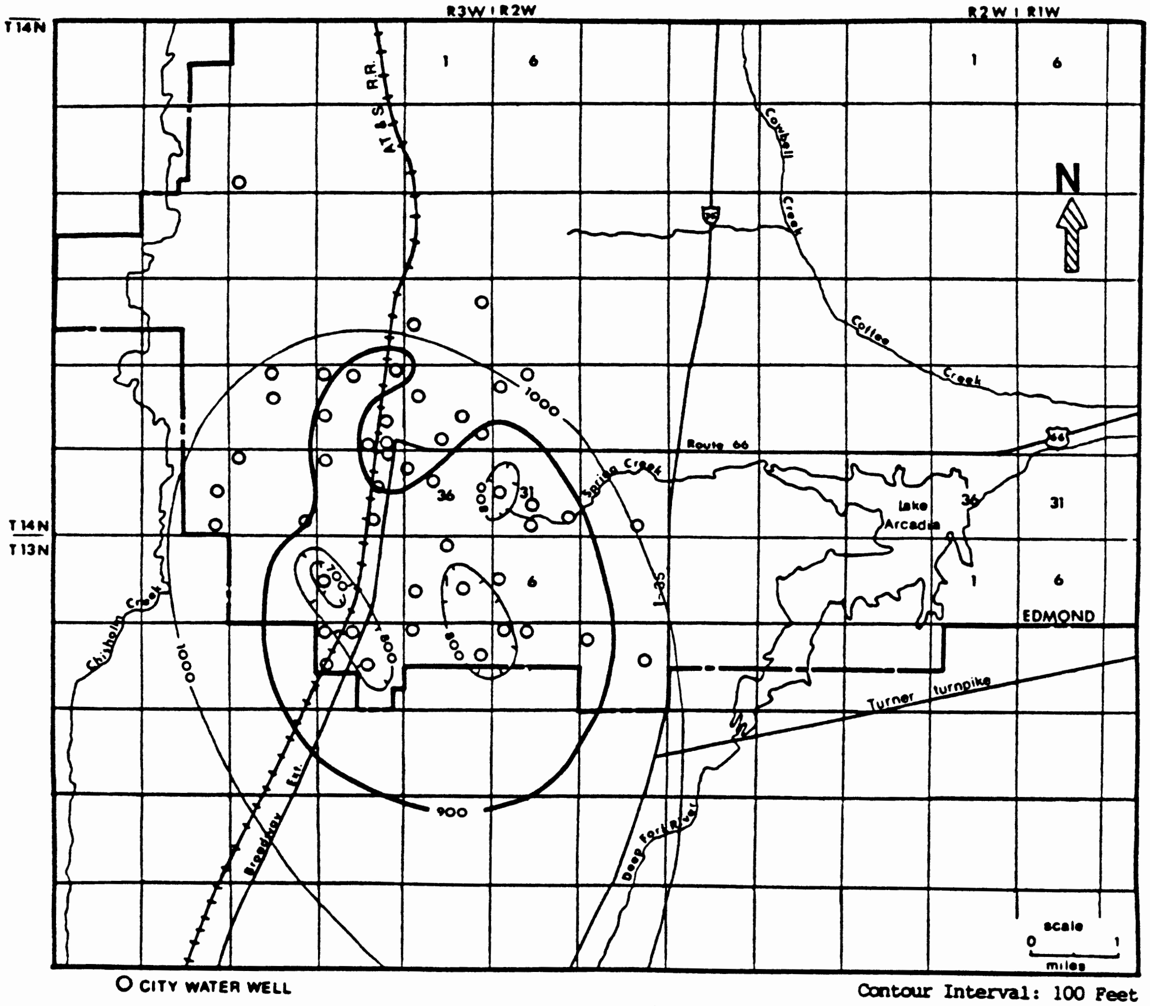
LEGEND

—900— Potentiometric Surface Elevation Contour Determined By Water Level Measurements In Wells

O Control Point Stream —— Highway Railroad

Datum: Mean Sea Level ----Corporate Boundary

Figure 24. Pumping Water-Level Map for the Confined Portion of the Central Oklahoma Aquifer in the Study Area for August, 1988



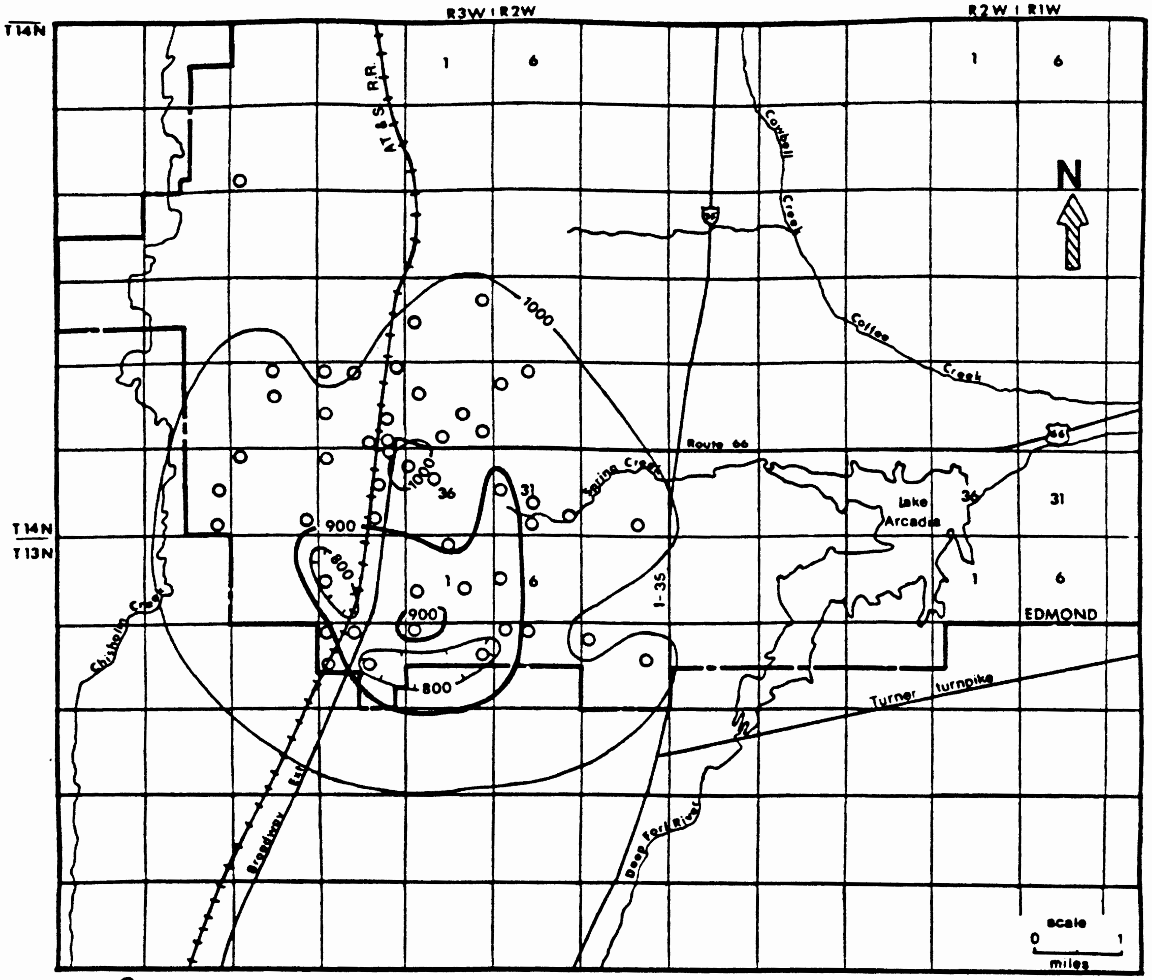
LEGEND

—900— Potentiometric Surface Elevation Contour Determined By Water Level Measurements In Wells

O Control Point Stream —— Highway Railroad

Datum: Mean Sea Level ---- Corporate Boundary

Figure 25. Static Water-Level Map for the Confined Portion of the Central Oklahoma Aquifer in the Study Area for August, 1988



O CITY WATER WELL

Contour Interval: 100 Feet

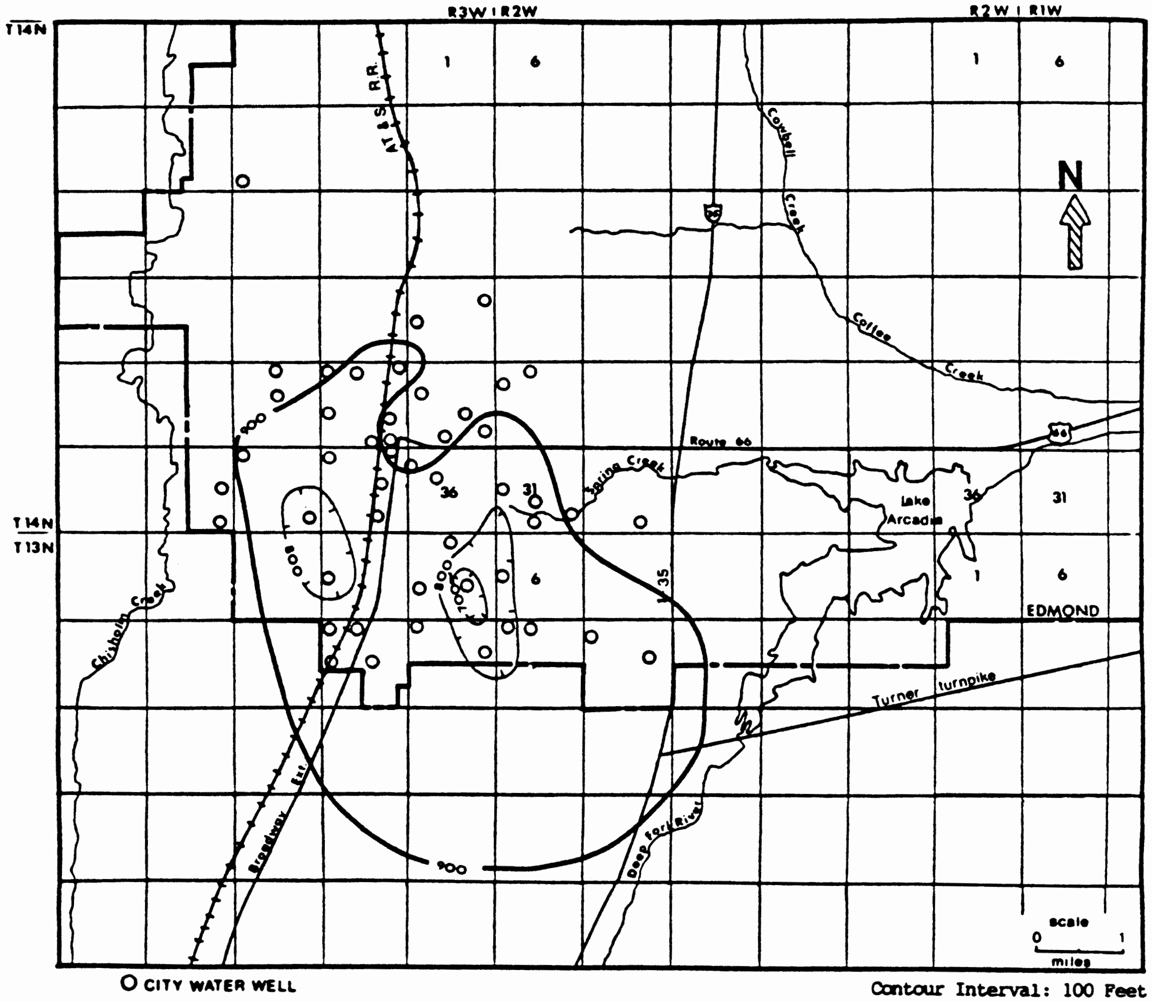
LEGEND

—900— Potentiometric Surface Elevation Contour Determined By Water Level Measurements In Wells

O Control Point Stream —— Highway Railroad

Datum: Mean Sea Level ---- Corporate Boundary

Figure 26. Static Water-Level Map for the Confined Portion of the Central Oklahoma Aquifer in the Study Area for February, 1988



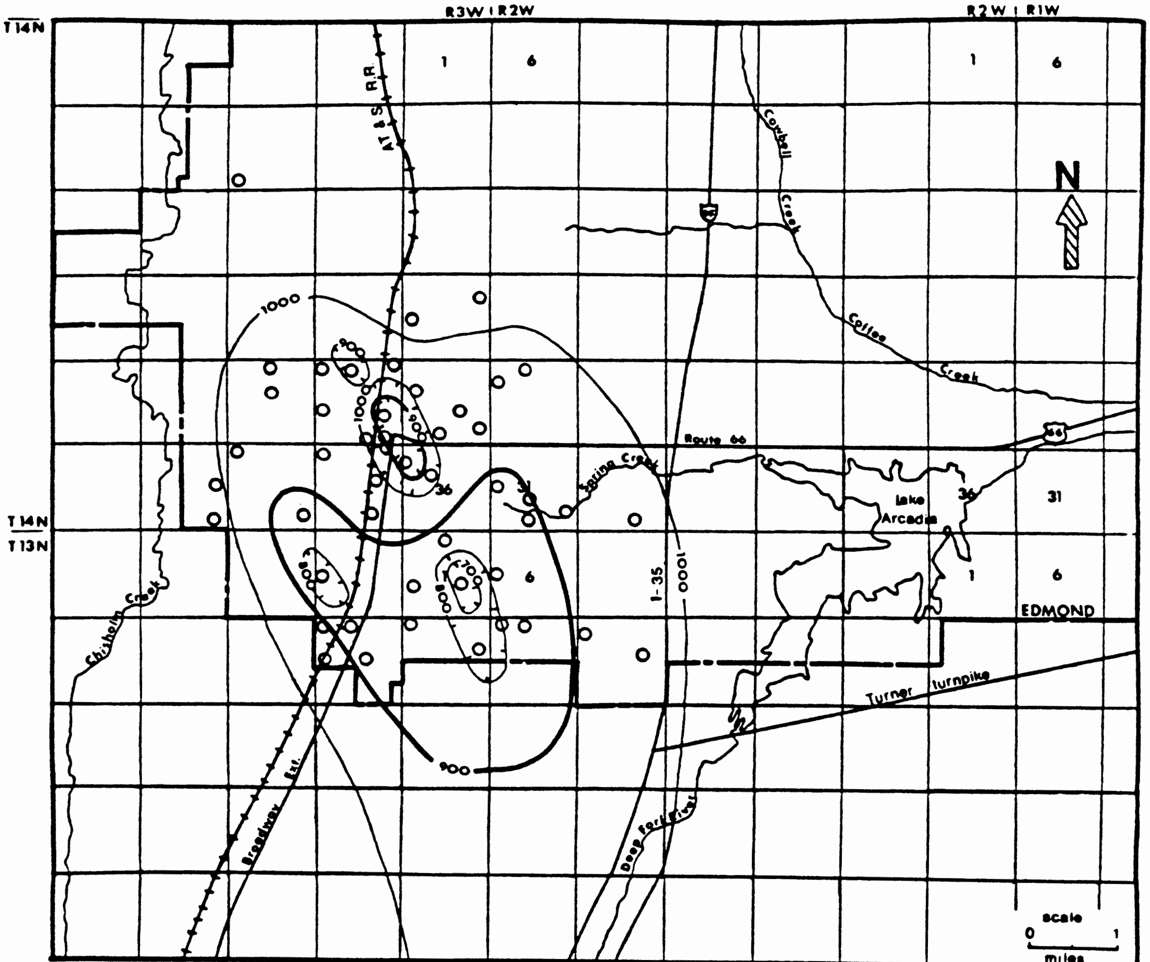
LEGEND

—900— Potentiometric Surface Elevation Contour Determined By Water Level Measurements In Wells

O Control Point   Stream   —— Highway   Railroad

Datum: Mean Sea Level   ----Corporate Boundary

Figure 27. Pumping Water-Level Map for the Confined Portion of the Central Oklahoma Aquifer in the Study Area for August, 1989



O CITY WATER WELL

Contour Interval: 100 Feet

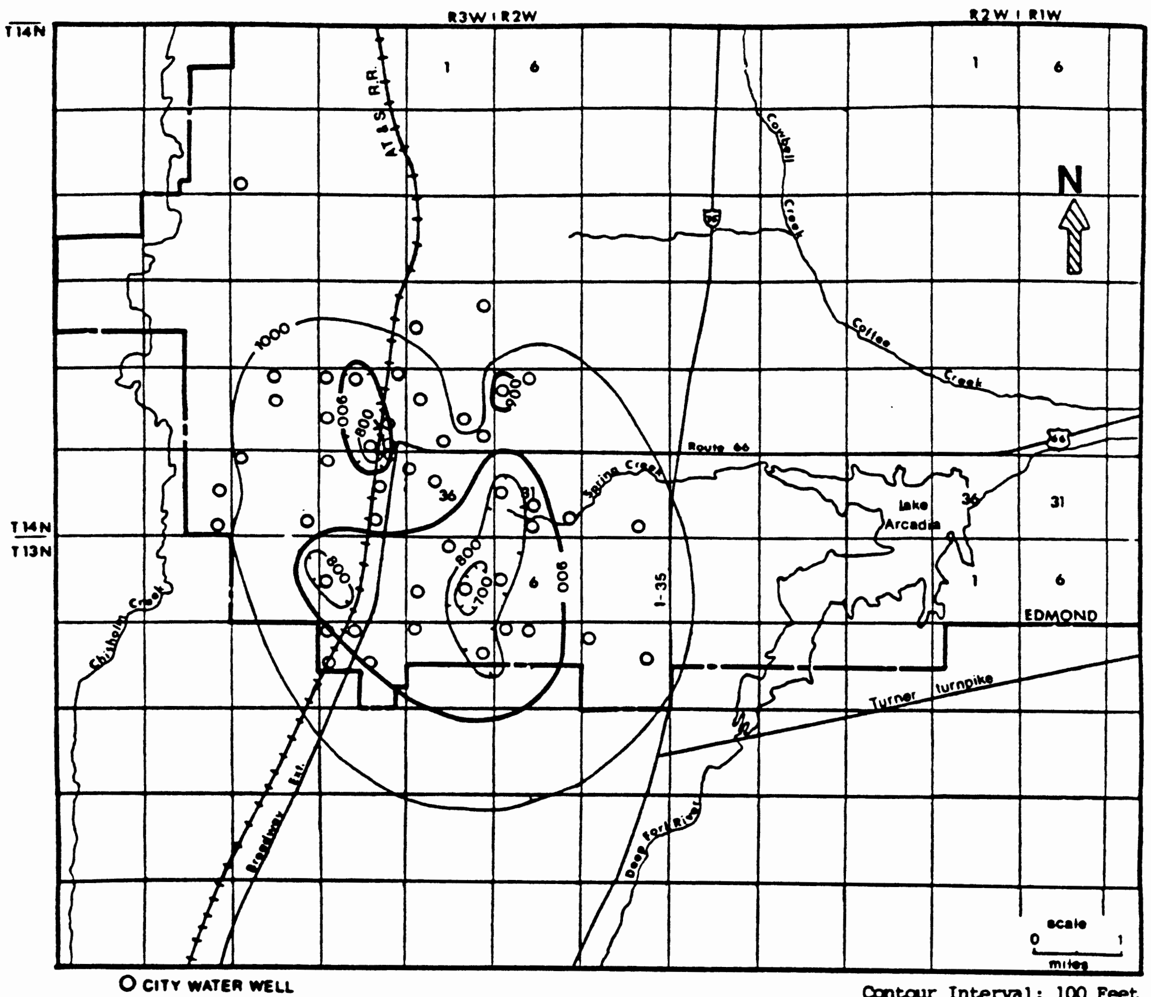
LEGEND

—900— Potentiometric Surface Elevation Contour Determined By Water Level Measurements In Wells

O Control Point   Stream   —— Highway   Railroad

Datum: Mean Sea Level ——— Corporate Boundary

Figure 28. Static Water-Level Map for the Confined Portion of the Central Oklahoma Aquifer in the Study Area for August, 1989



LEGEND

—900— Potentiometric Surface Elevation Contour Determined By Water Level Measurements In Wells

O Control Point   Stream   —— Highway   Railroad

Datum: Mean Sea Level ---- Corporate Boundary

Figure 29. Static Water-Level Map for the Confined Portion of the Central Oklahoma Aquifer in the Study Area for February, 1989

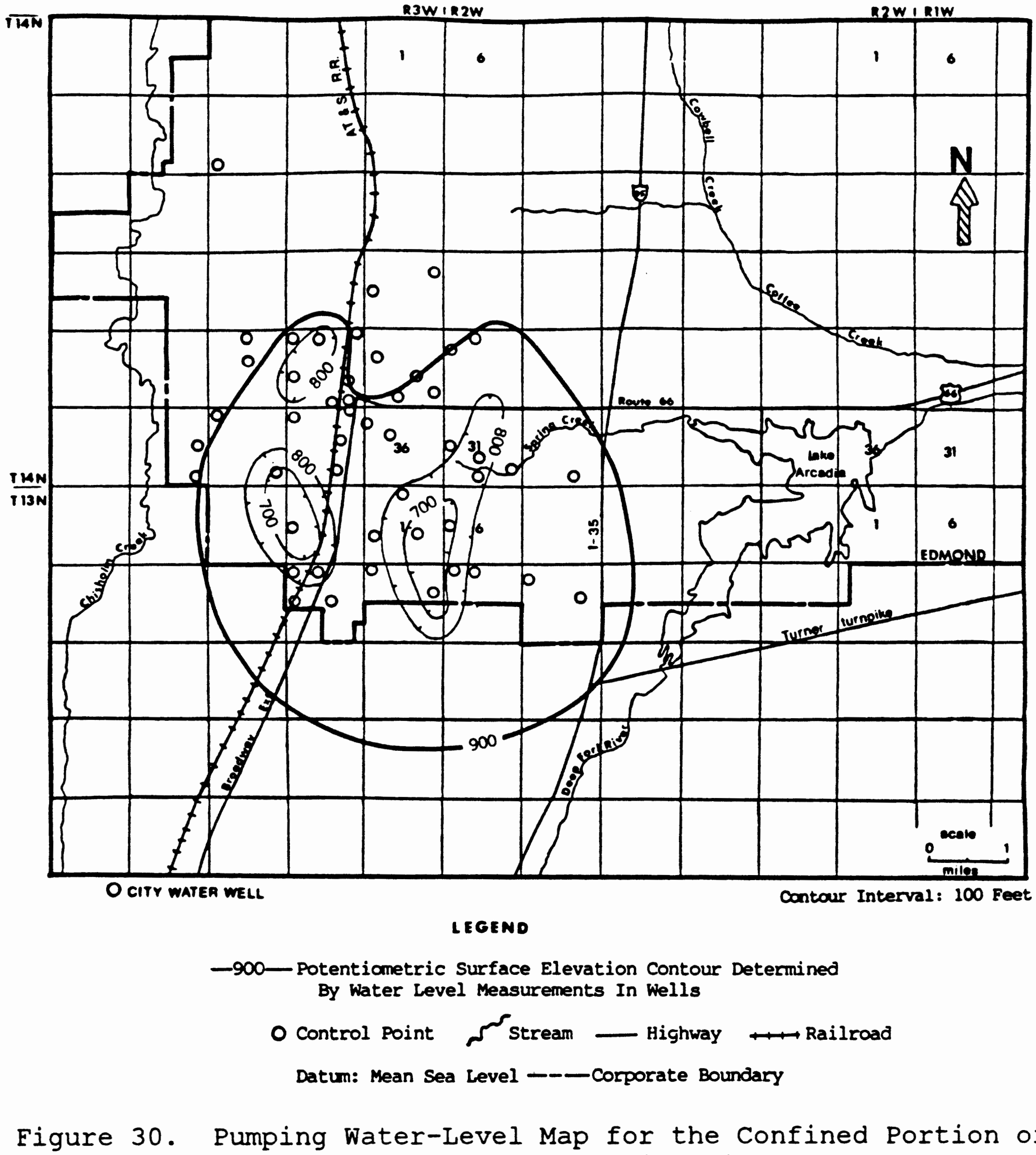
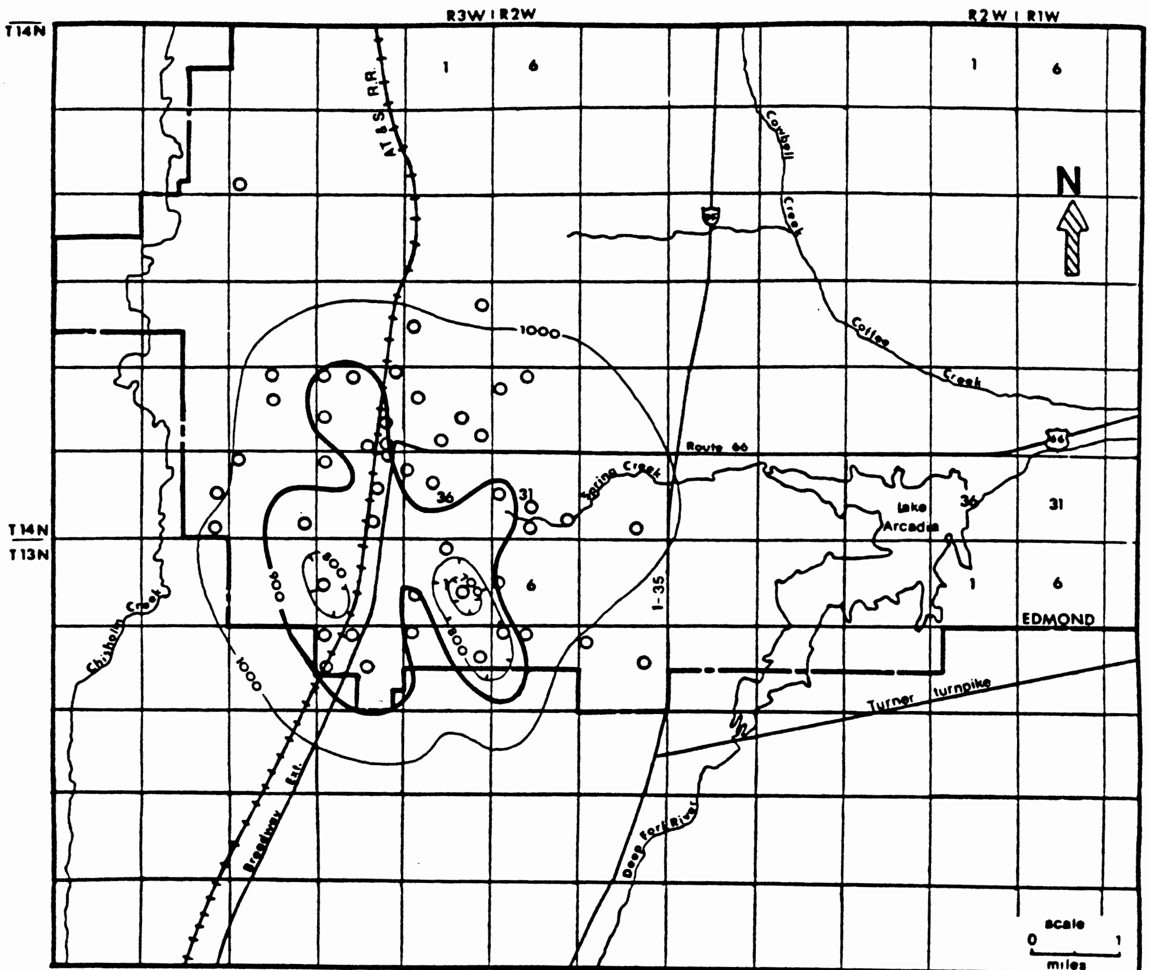


Figure 30. Pumping Water-Level Map for the Confined Portion of the Central Oklahoma Aquifer in the Study Area for August, 1990



O CITY WATER WELL

Contour Interval: 100 Feet

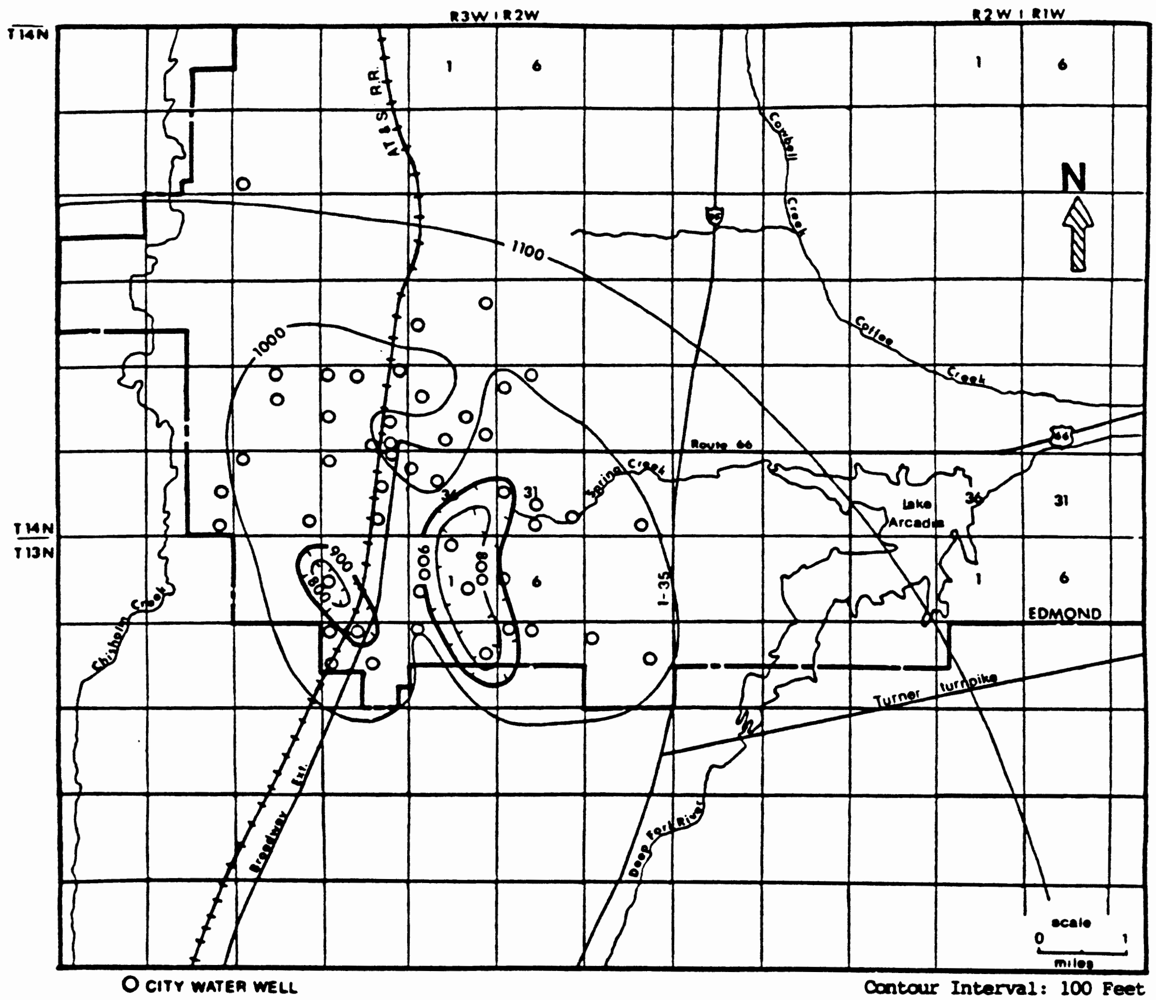
LEGEND

—900— Potentiometric Surface Elevation Contour Determined By Water Level Measurements In Wells

O Control Point   Stream   —— Highway   Railroad

Datum: Mean Sea Level   ----Corporate Boundary

Figure 31. Static Water-Level Map for the Confined Portion of the Central Oklahoma Aquifer in the Study Area for August, 1990



LEGEND

—900— Potentiometric Surface Elevation Contour Determined By Water Level Measurements In Wells

O Control Point   Stream   —— Highway   Railroad

Datum: Mean Sea Level ---- Corporate Boundary

Figure 32. Static Water-Level Map for the Confined Portion of the Central Oklahoma Aquifer in the Study Area for February, 1990

pumping, well interference, or well-loss acting alone or in combination to increase the drawdowns measured in the wells. The static water-level maps for August and February, 1988 show that the cone of depression contracts with decreased pumping (Figures 25 and 26). The August, 1989 pumping water-level map (Figure 27) shows that the cone of depression is smaller and more irregular than the previous year. This is likely the result of decreasing demand on the well-field. The static water-level maps for August and February, 1989 show further reduction in the size of the cone of depression during low-use periods (Figures 28 and 29). Localized areas of increased drawdown persist in the same general areas of the well-field. The August, 1990 pumping water level map shows a cone of depression, somewhat smaller and more regular in shape than the previous year (Figure 30). By comparing locations of the 800-foot contour in Figures 24 and 30, the reduction of drawdown within the cone of depression is evident. The static water-level maps for August and February, 1990 (Figures 31 and 32) show the cone of depression in more reduced states than do Figures 24 though 30. Water levels in the well-field probably still continue to gradually rise.

CHAPTER V

WELLHEAD PROTECTION AREA DELINEATION

Introduction to Concept

In Oklahoma, groundwater serves as the supply for approximately 600 public water systems (ODPC, 1990). Increasing concern is being shown towards the introduction of contaminants into the state's underground sources of drinking water. Recognizing the importance of groundwater supplies in the United States, Congress passed laws to protect groundwater supplies. Since the use of groundwater as a supply usually requires the installation and operation of water wells, areas surrounding wells are particularly vulnerable to contamination and must be protected.

The designation of protection areas around water wells, including the parts of an aquifer supplying water to them, and regulation of activities likely to produce contamination of the underground water supply, is a method of protection addressed by Congress. The 1986 amendments to the Safe Drinking Water Act (SDWA) mandate the establishment of protection areas, which are called Wellhead Protection Areas (WHPA's). The SDWA defines a

WHPA in Subsection 1428 (e):

> (e) DEFINITION OF WELLHEAD PROTECTION AREA--As used in this section, the term wellhead protection area means the surface and subsurface area surrounding a water well or well-field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well-field. The extent of a wellhead protection area, within a State, necessary to provide protection from contaminants which may have adverse effect on the health of persons is to be determined by the State in the [wellhead protection] program submitted under subsection (a).

The statute defines a wellhead-protection (WHP) program as one that incorporates the following elements:

* Duties of state and local agencies and public water supply systems in implementing the program;
* determination of WHPA's for each public well or well-field;
* identification of all potential sources of contamination within protected areas;
* a program that contains, as appropriate, technical assistance, financial assistance, implementation of control measures, education, training, and demonstration projects to protect water wells from contamination;
* contingency plans for alternative water supplies in case contamination occurs;
* siting considerations for new wells; and
* public participation.

The U.S. Environmental Protection Agency (EPA) does not require states to participate in the WHP programs and any state that decides not to merely forfeits any grant funds available for it.

WHPA Description and Terminology

Pumping disrupts the state of equilibrium that exists within an aquifer. In WHPA delineations, the cone of depression that results from water-well pumping is referred to as the zone of influence (ZOI). Figure 33 shows the terminology that is used regarding WHPA delineations. Within the ZOI, the hydraulic gradient steepens towards the well, which produces higher groundwater-flow velocities in the portion of the ZOI nearest to the pumping well. The regional hydraulic gradient (Figure 33) slopes away from a groundwater divide. Groundwater flows down-gradient from the divide until the cone of depression influences its migration towards the well.

The area of the aquifer that contributes water to the well is called the zone of contribution (ZOC). Any part of the aquifer which is outside the ZOC will not supply water to the well. The ZOC extends down gradient, with respect to the general slope of the water table, from the pumping well to the stagnation point, or null point. At this point, the force of gravity and the influence of the pumping well upon the flow of groundwater are balanced, producing an area with minimal water movement. When the velocity is high, the ZOC will not coincide with the ZOI. Conversely, an aquifer with a shallow hydraulic gradient will produce a ZOI and a ZOC that are nearly identical (Figure 34).

A WHPA delineation can address the time it takes a contaminant, within the ZOC, to reach a well. Figure 33 shows

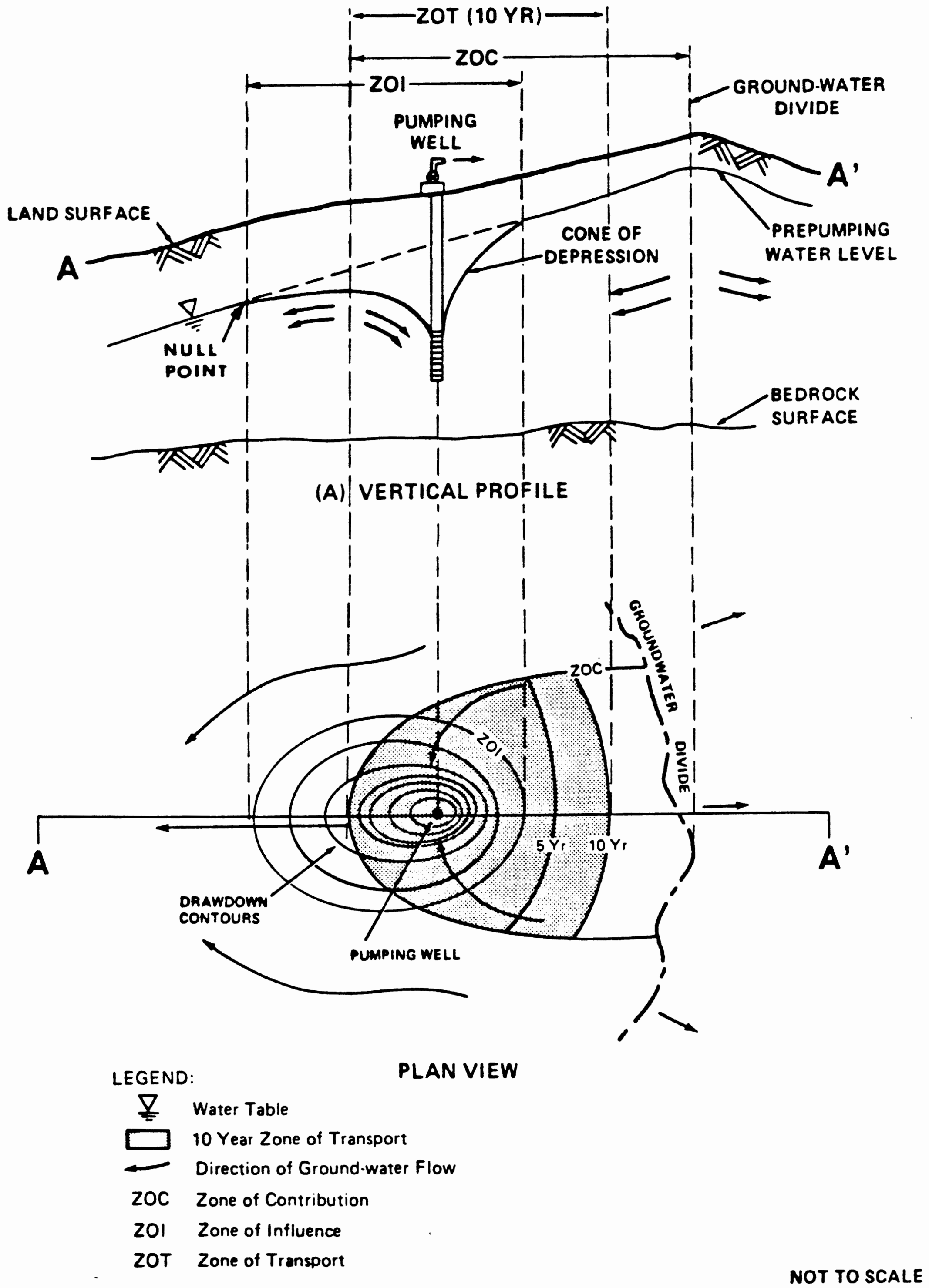
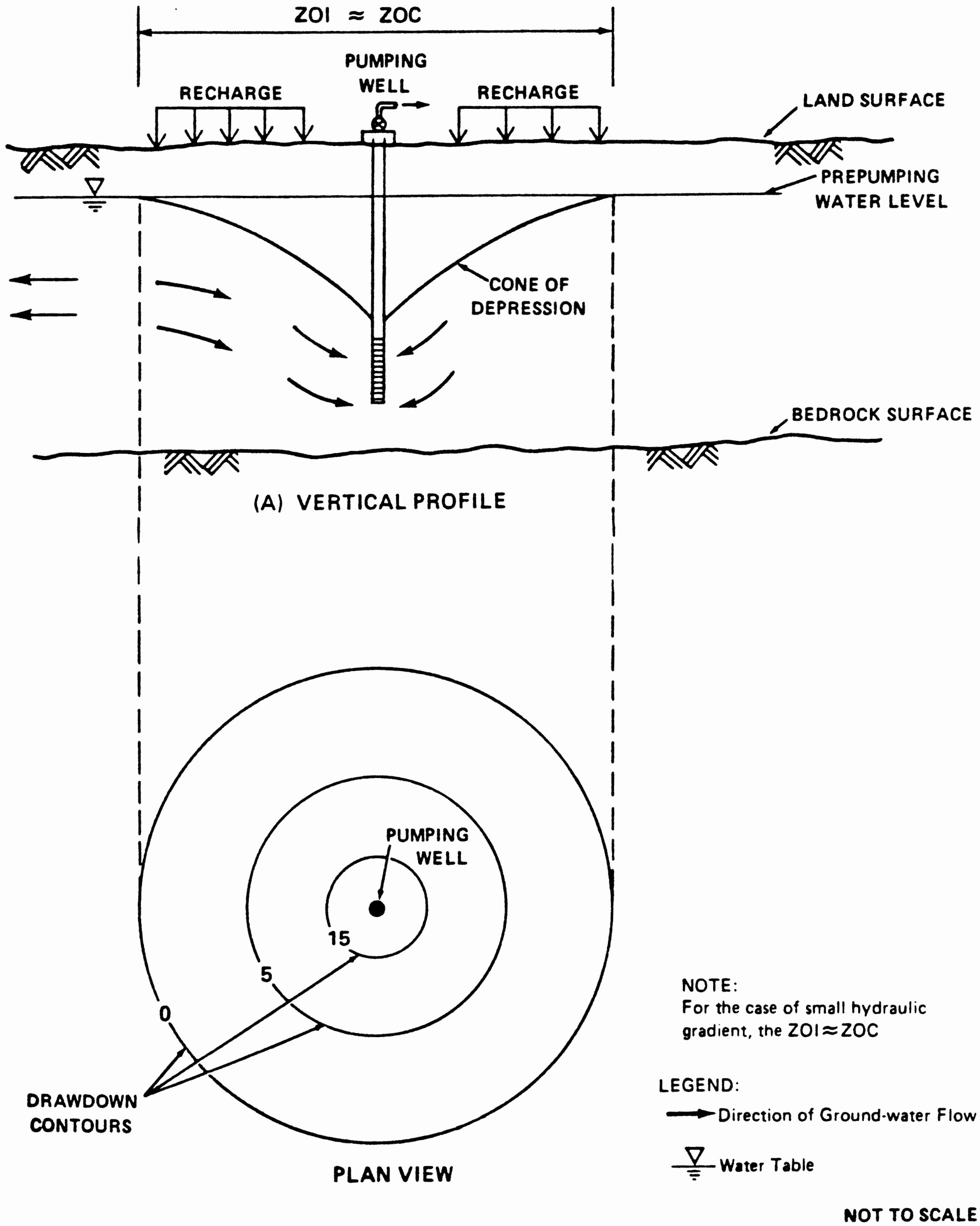


Figure 33. Terminology for Wellhead Protection Area Delineation (U.S. EPA, 1987 A)



Modified from U.S. Environmental Protection Agency, 1987 A

Figure 34. Aquifer With a Flat Regional Hydraulic Gradient, Where the ZOI and ZOC of a Pumping Well Coincide (U.S. EPA, 1987 A)

5- and 10-year time of travel boundaries, which mark the distances from which it would take a contaminant, released into the ZOC along one of the boundaries and traveling with the flow of groundwater, the respective length of time to travel to the well. If a contaminant were to be introduced into the aquifer within the 5-year ZOT boundary, it would take less than 5 years to reach the well. The delineation of ZOT's incorporates the relationship between the location of potential sources of contamination within the ZOC and the estimated length of time required for contaminants, released from these sources to migrate to the water wells (U.S. EPA, 1987 A).

The delineation of a WHPA is designed to focus upon potential sources of contamination that might affect wells in the aquifer. Management concerns usually influence decisions controlling the scope of WHPA delineations. These decisions can include defining the length of time for which it is practical to protect the aquifer, considering available resources.

To some degree, technical considerations usually are incorporated into these decisions. Protection against microbial contaminants, which generally do not survive long in groundwater systems, is usually accomplished by using WHPA's based on a TOT of 1 year. Any potential source of microbial contamination located within the 1-year ZOT would be addressed in order to minimize any contamination risk.

Factors such as the hydraulic properties of the aquifer, the pumping schedules of the well or well-field, and the nature of the contaminants are usually considered whenever possible.

When all the technical and managerial aspects of groundwater protection are considered, it may prove more effective to designate a short time period, producing small and more easily managed WHPA's, than to designate a long time period and attempt to manage large WHPA's with limited resources.

Wellhead Protection Program for the State of Oklahoma

Individual states are responsible for establishing their own wellhead protection (WHP) programs that are in accordance with federal guidelines. A draft of the Wellhead Protection Program Plan for the State of Oklahoma was released in May, 1989 (Oklahoma Department of Pollution Control, 1990). Included in the draft are the responsibilities of various state agencies regarding WHPA delineations.

Role of State Agencies and Organizations

Many of Oklahoma's state agencies provide technical assistance and information for site-specific WHPA delineations. Currently, efforts towards the consolidation of the environmental responsibilities of several agencies are underway. Some of the functions that will be ascribed to a particular agency in the following summary soon may be the responsibility of a different or newly formed agency. In addition to the various state agencies, federal, local, and private organizations also contribute valuable resources.

Oklahoma Pollution Control Coordinating Board (PCCB)

The Pollution Control Coordinating Board governs the Wellhead Protection Advisory Committee, which is composed of four citizen members and the heads of the seven state agencies with statutory responsibilities regarding prevention, control, and abatement of groundwater pollution. The committee reviews the technical merits of WHPA delineations performed for public groundwater supply systems. PCCB is responsible for the coordination of all environmental protection efforts within the State of Oklahoma (ODPC, 1990).

Oklahoma Department of Pollution Control (ODPC)

The Oklahoma Department of Pollution Control is the executive arm of the PCCB. The ODPC is the lead agency for the State Wellhead Protection Program. ODPC serves as the contact agency for those municipal water systems desiring assistance with WHPA delineations. ODPC coordinates pollution control efforts mandated under the Clean Water Act (ODPC, 1990).

Oklahoma State Department of Health (OSDH)

The Oklahoma State Department of Health is responsible for the safety of public and individual water supplies, underground injection control unrelated to oil and gas activities, regulations regarding municipal wastewater systems, and the oversight of solid and hazardous waste operations. OSDH is able to assist local water systems in site-specific WHPA delineations and pollution-source identification and assessment. OSDH serves on the Wellhead Protection Advisory Committee (ODPC, 1990).

Oklahoma Water Resources Board (OWRB)

The Oklahoma Water Resources Board is responsible for groundwater-rights allocation for public water supplies and other nondomestic uses, permitting of water-well locations, performing hydrologic studies on groundwater basins, licensing of well drillers, enforcement of construction standards, establishment of wastewater quality standards, and programs related to groundwater protection. OWRB is able to assist water systems in site-specific WHPA delineations and in pollution-source identification and assessment. OWRB serves on the Wellhead Protection Advisory Committee (ODPC, 1990).

Oklahoma State Department of Agriculture (OSDA)

The Oklahoma State Department of Agriculture is responsible for animal operations, pesticide registration, pesticide-usage control and storage, commercial fertilizer storage and application, and forestry operations. OSDA can assist in pollution-source identification and assessment after WHPA delineations have been established. OSDA serves on the Wellhead Protection Advisory Committee (ODPC, 1990).

Oklahoma Department of Mines (ODM)

The Oklahoma Department of Mines regulates all mining activities in the state. ODM works closely with operators of local water systems in the development of protection strategies to prevent chemicals or practices associated with mining from contaminating water wells. ODM serves on the Wellhead Protection Advisory Committee (ODPC, 1990).

Oklahoma Conservation Commission (OCC)

The Oklahoma Conservation Commission maintains inventories on soil conditions and land-use patterns across the State. They maintains inventory information on abandoned mine areas and are responsible for the development of Best Management Practices (BMP) designed to reduce the leaching of contaminants into groundwater supplies. The OCC can assist in pollution-source identification and assessment and serves as a member of the Wellhead Advisory Committee (ODPC, 1990).

Oklahoma Corporation Commission

The Oklahoma Corporation Commission is responsible for all oil- and gas-field operations. The Corporation Commission regulates oil and gas production and saltwater storage and injection facilities, and has the lead jurisdiction over the State's Underground Storage Tank Program. The Commission maintains records on pollution sources and can assist in their identification and assessment. The Wellhead Protection Advisory

Committee includes the Corporation Commission as an active member (ODPC, 1990).

Oklahoma Geological Survey (OGS) and United States Geological Survey (USGS)

Both the Oklahoma Geological Survey and the United States Geological Survey (USGS) are research-oriented agencies with considerable technical expertise in hydrogeology. These agencies have detailed geologic and subsurface hydrologic information on many areas of the State. Neither of these agencies is required to work with state agencies in WHPA delineation efforts, but they have cooperated extensively in the investigation of groundwater protection problems. Both agencies can provide technical support and review of WHPA delineations.

Association of Central Oklahoma Governments (ACOG)

The Association of Central Oklahoma Governments (ACOG), in conjunction with the Garber-Wellington Association, provides technical information and services to those municipalities who obtain their drinking water from the Central Oklahoma Aquifer. ACOG employs staff with technical expertise in areas including well-site investigation and groundwater protection studies in the COA.

In addition to the various State agencies, the operators of the local water systems have the responsibility and authority to protect their water supplies. They can accomplish this by the adoption of zoning ordinances to restrict activities, in the vicinity of the wells, that might release contaminants into the aquifer. WHPA delineations can provide information used by local water systems to make management decisions that balance the need to protect groundwater supplies with the need to promote economically important activities.

Wellhead Protection Area Criteria

Several factors have been established as important in the consideration of WHPA delineations. These factors, or criteria, are related to efforts directed towards the protection of wells against various contaminants. Contamination threats can be classified into three broad categories:

* direct introduction of contaminants into well casings;
* microbial contaminants; and
* chemical contaminants.

The term "criteria" is used to group all conceptual standards that form the technical basis for WHPA delineations. Five types of criteria have been established:

* distance;
* drawdown;
* time of travel;
* flow boundaries; and
* assimilative capacity.

Distance

The use of the distance criterion for WHPA delineations involves the determination of a distance, measured as a radius from a well or well-field, used to define the extent of a WHPA. The use this criterion is the most direct method of WHPA delineation. Commonly, the delineation of a WHPA based entirely upon this criterion is a policy decision made without the benefit of much technical information. This might be the case of an initial WHPA delineation intended to serve as a zone of protection to fulfill immediate needs until a more detailed site-specific delineation can be developed. The limitations of this criterion are related to the lack of consideration that is given to the processes within an aquifer that control groundwater flow and contaminant transport (U.S. EPA, 1987 A).

Drawdown

The use of the drawdown criterion for WHPA delineations involves the determination of the ZOI of a well or well-field. A drawdown value is selected to define the extent of the cone of depression, or ZOI, produced by a pumping well or well-field. The boundary of the ZOI is mapped as the WHPA. Problems may arise when the regional hydraulic gradient produces differences between the ZOI and ZOC of the water wells within an aquifer. If the regional hydraulic gradient is sufficiently steep, significant differences can exist between the ZOI and the ZOC, limiting the effectiveness of this method.

Time of Travel

The use of the time-of-travel (TOT) criterion for WHPA delineations involves the determination of the length of time required for a contaminant to reach a well under the prevailing hydraulic conditions. For aquifers with high groundwater velocities, movement of contaminants is controlled predominantly by flow through the process called advection. For aquifers with low groundwater velocities, other factors, such as hydrodynamic dispersion and adsorption, can significantly influence the movement of contaminants. It is usually difficult to determine the effects of dispersion and adsorption in groundwater flow velocity calculations. Failure to incorporate these factors can produce a TOT based WHPA delineation that is based on the maximum possible velocity of contaminant transport (U.S. EPA, 1987 A).

Flow Boundaries

The use of the flow-boundaries criterion for WHPA delineations involves determination of the location of groundwater divides or other features that control the flow of groundwater in the area of interest. Some subsurface features, such as lithologic changes within the aquifer, can act as flow boundaries. This criterion is often used in the delineation of WHPA's in fractured bedrock and karst aquifers. These aquifers have high groundwater velocities and complex conduit flow patterns. In these situations, the determination of the boundaries of the groundwater basin, within which pumping wells are located, provides the basis for the delineation of the ZOC. Deep, confined aquifers usually are not as greatly influenced by groundwater divides and streams expressed in the topography of the area. As such, the use of this criterion for WHPA delineations in such aquifers is not standard (U.S. EPA, 1987 A).

Assimilative Capacity

The use of assimilative capacity as a criterion for WHPA delineations involves the determination of the ability of the aquifer to attenuate contaminants to desired levels. The ability to attenuate contaminants depends upon the nature of the contaminants and the composition of the aquifer. These conditions are not easily determined by quantitative methods and the use of this criterion has not been frequent. It is difficult to address the threat of a wide variety of contaminants with this criterion. Where the threat of contamination is limited to one or two types, attenuative capacity analyses have been used effectively (U.S. EPA, 1987 A).

Wellhead-Protection Goals

The selection of relevant criteria is dependent upon the overall goals established for a WHPA delineation. Three general goals have been identified as relevant to the process of selecting criteria:

* reaction time;
* attenuation of contaminants; and
* protection of the zone of contribution.

Reaction Time

A protection strategy incorporating the goal of providing adequate reaction time would seek to establish a WHPA that functions as a remedial action zone. This zone should be designed to allow adequate time to respond to contamination threats (U.S. EPA, 1987 A).

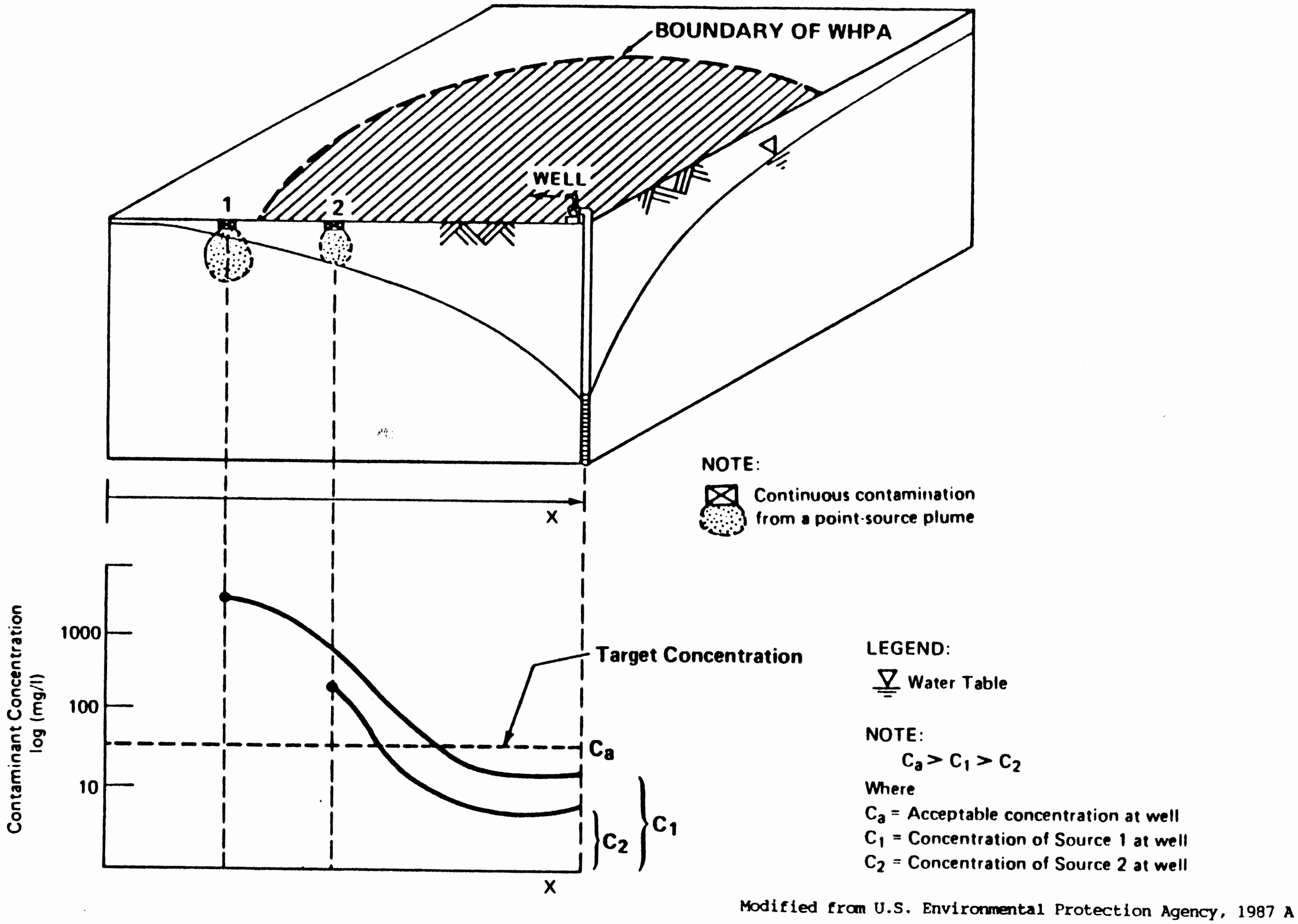
Attenuation of Contaminants

A protection strategy incorporating the goal of providing adequate attenuation of contaminants would seek to establish protection zones that, given the migration rate of contaminants, would allow time for reduction of contaminants to desired levels (Figure 35).

Protection of the Zone of Contribution

A protection strategy incorporating the goal of providing for the protection of the ZOC would seek to establish limits of the ZOC for a well or well-field in order to protect all, or a relevant part, of the area of the aquifer supplying water to the water wells.

The relationships between the goals and criteria used for WHPA delineation are illustrated in Table IV.



Modified from U.S. Environmental Protection Agency, 1987 A

Figure 35. Assimilative Capacity Criteria Used in a WHPA Delineation (U.S. EPA, 1987 A)

TABLE IV

EXAMPLE RELATIONSHIPS BETWEEN OVERALL PROTECTION GOALS AND CRITERIA FOR DELINEATING WELLHEAD PROTECTION AREAS

Overall Protection Goals	Examples of Corresponding Criteria	Example of Criteria Threshold	Advantages	Disadvantages	Hydrogeologic Factors	Management Factors
1. Delineate a remedial action zone allowing adequate reaction time to protect well from contaminant releases	TOT	5-year TOT to well (State of Florida) 10-25 year TOT (the Netherlands)	Deals directly with most threatening sources in a manner understandable to regulated community; "compatible" with existing programs	Implies capability/success of corrective action measures at all relevant sources	High confidence in accuracy of TOT determinations at specific wellhead areas	Possible ban of all high-risk activities within WHPA; controls/monitoring of all significant sources within recharge area, especially those beyond WHPA
2. Provide a zone for attenuation of contaminants to specified levels before they reach well	Assimilative capacity	Meet percentage of MCL in raw water supplying well	Most directly addresses specific contaminants of concern and "standard" in SDWA	Currently viable only for simple problems such as microbial contaminants; conservative parameters (e.g., synthetic organics) more problematic	Analysis sufficiently thorough to show that zone is extensive enough to meet target concentrations at well	Displays understanding of contamination sources, locations, contaminant characteristics, and impacts of controls
3a. Provide a wellfield management area in major portion of recharge area	Drawdown distance	0.25-foot drawdown contour (Dade Co., FL) 2 km (W. Germany)	Broadest definition: can be tailored by States as appropriate; can incorporate other options	May lead to "over-protection" in some States; "under-protection" in others	Based on reasonable application of hydrogeologic concepts to available data	Based on reasonable consideration of relevant management factors
3b. Manage entire recharge area under current and foreseeable conditions	Flow boundaries	Physical limits of aquifer and surface drainage (some parts of Massachusetts)	Can be interpreted as most protective; especially appropriate to small aquifers (e.g., less than 10-20 square miles)	Over-protective for moderate to large aquifers	Analysis shows full recharge area under existing and potential pumping scenarios	Controls extend to all potential contamination sources within recharge area

Modified from U.S. Environmental Protection Agency, 1987 A

Wellhead Protection Area Delineation

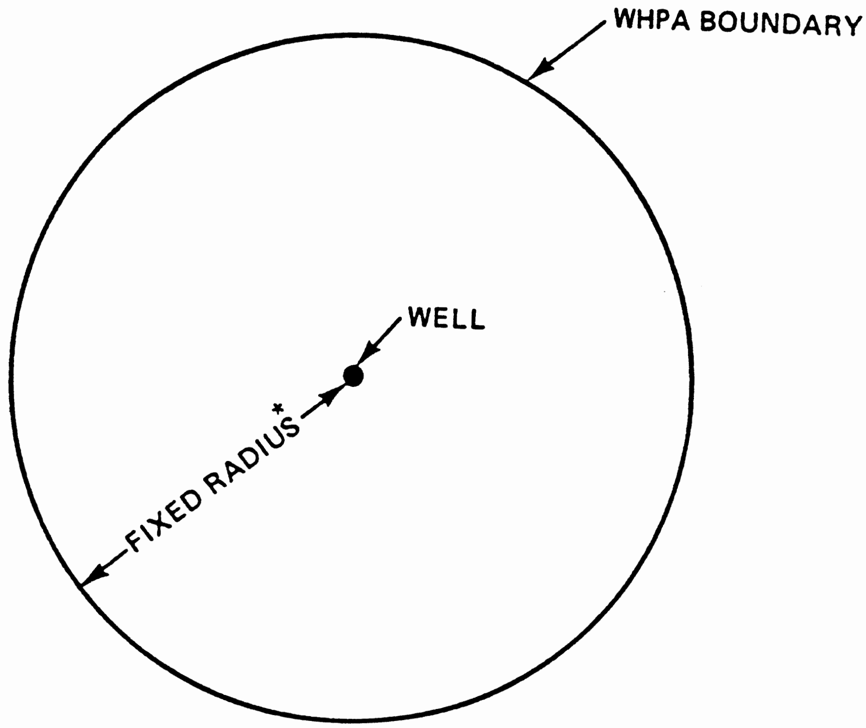
Methods

Six primary methods are used to delineate the WHPA of a well or well-field. These methods are listed below, beginning with the least sophisticated and progressing towards the most sophisticated.

* Arbitrary fixed radii.
* Calculated fixed radii.
* Simplified variable shapes.
* Analytical models.
* Hydrogeological mapping.
* Numerical-flow and solute-transport models.

Arbitrary Fixed Radii

The arbitrary-fixed-radii method incorporates the distance criterion in WHPA delineations. An arbitrary distance is delineated around the well or well-field, producing a spherical WHPA with a fixed radius, as shown in Figure 36. This method involves the least amount of technical expertise to implement. Although it may appear that WHPA's delineated by this method are not based on scientific analysis, generalized hydrogeologic conditions are usually taken into consideration. This method allows a large number of wells to be protected quickly and inexpensively. The WHP program for Oklahoma has mandated that a



* 300 foot radius used in Oklahoma's
WHP Program

Modified from U.S. Environmental Protection Agency, 1987 A

Figure 36. WHPA Delineation Using the Arbitrary-Fixed-Radii Method. (U.S. EPA, 1987 A)

WHPA with a radius of 300 feet shall be used for all public water wells until a site-specific WHPA delineation is completed. The high degree of uncertainty incorporated into WHPA's delineated from this method is the method's major limitation.

Calculated Fixed Radii

The calculated-fixed-radii method incorporates the drawdown or TOT criteria. Analytical methods can be used to define the cone of depression of a well or well-field and to obtain information about the hydraulic gradient. Travel times based on groundwater-flow velocities calculated from the hydraulic gradient can be used to produce a spherical WHPA with a fixed radius. Since this method utilizes the ZOI of a well as the basis for the WHPA, any differences between the ZOI and the ZOC would reduce its effectiveness (U.S. EPA, 1987 A).

Simplified Variable Shapes

The simplified-variable-shapes method incorporates the flow boundaries or TOT criteria. This method involves the generation of standardized forms for the shapes and sizes of WHPA's (U.S. EPA, 1987 A). These forms reflect the general nature of the aquifer and the pumping rates of the wells (Figure 37). Aquifer properties and well-pumping rates are matched to the standardized WHPA delineation that most accurately reflects their conditions. Once the standardized WHPA shapes are produced, the delineation of large numbers of wells can be accomplished quickly and easily. As with the other relatively

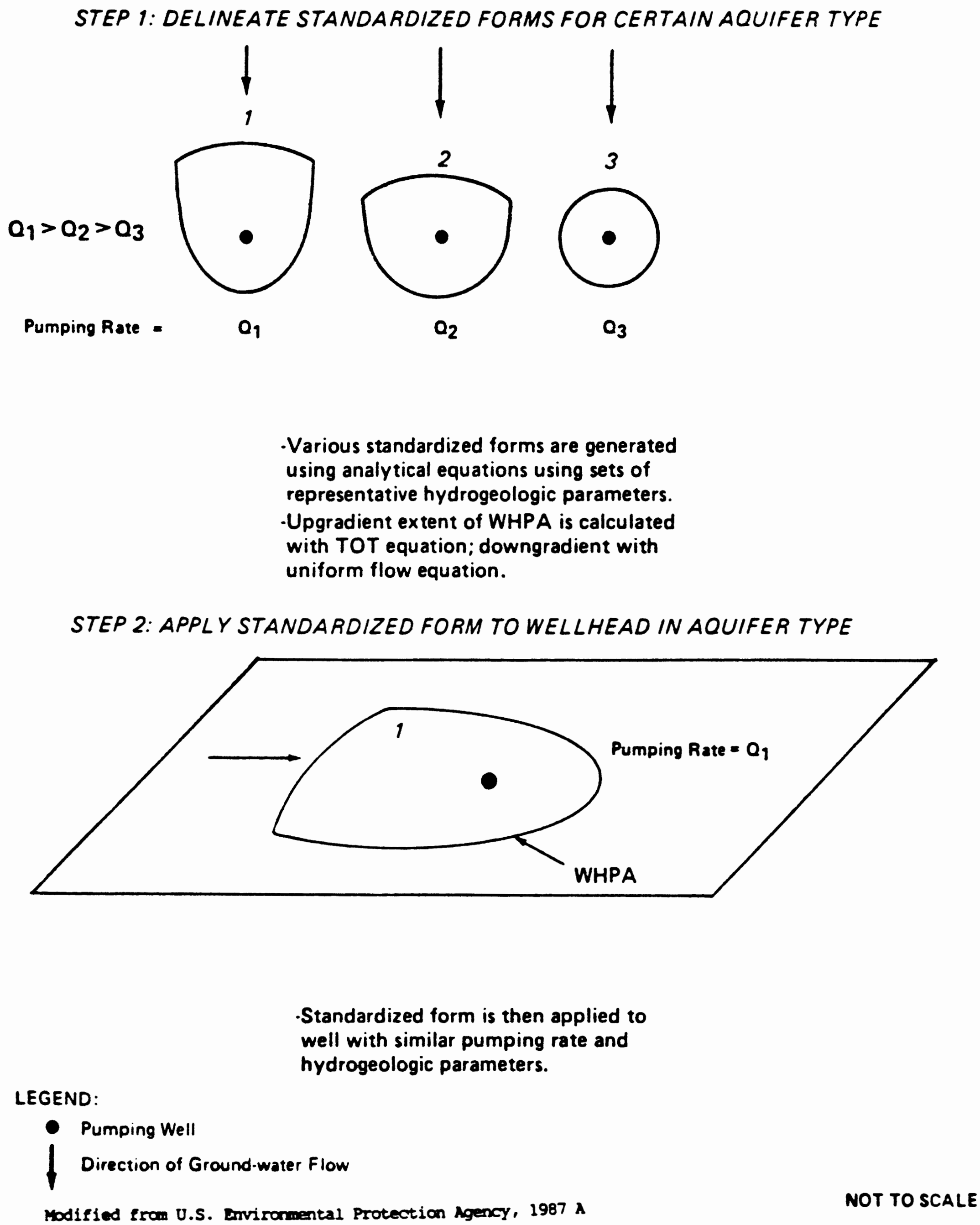


Figure 37. WHPA Delineation Using Simplified-Variable-Shapes Method (U.S. EPA, 1987 A)

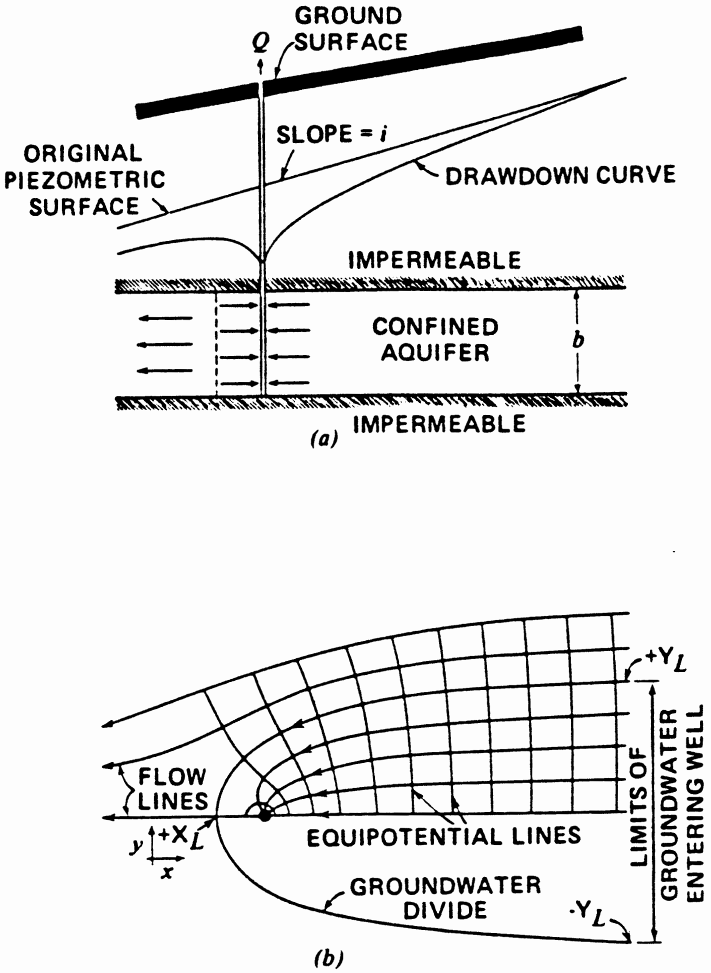
simple methods, complexities in either the aquifer composition or the pumping schedules of wells can limit the effectiveness of this method.

Analytical Models

The analytical-modeling method incorporates the drawdown and TOT criteria. Analytical methods, such as the uniform-flow equation, are used to establish the groundwater flow in an area (Figure 38). Many computer programs are available that can solve the analytical solutions using desktop personal computers. Site-specific aquifer and well-pumping characteristics are required as input data for each location. The equations used in analytical modeling have proved to be effective for a variety of situations. This method is considered the most appropriate means of modeling the groundwater flow conditions in proximity to a pumping well. Aquifer heteogeneities, which can be difficult to incorporate into the analytical solutions, may reduce the effectiveness of this method.

Hydrogeologic Mapping

The hydrogeologic-mapping method incorporates the flow boundaries and distance criteria. Hydrogeological information is used to map the locations of flow boundaries in the vicinity of a well or well-field (U.S. EPA, 1987 A). Hydrogeologic mapping is an effective method of delineating WHPA's in unconfined aquifers with high groundwater velocities and in anisotropic aquifers, such as fractured bedrock and karst



$$\underbrace{-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q}Y\right)}_{\text{UNIFORM-FLOW EQUATION}} \qquad \underbrace{X_L = -\frac{Q}{2\pi Kbi}}_{\text{DISTANCE TO DOWN-GRADIENT NULL POINT}} \qquad \underbrace{Y_L = \pm\frac{Q}{2Kbi}}_{\text{BOUNDARY LIMIT}}$$

LEGEND:

- ● Pumping Well

Where:
Q = Well Pumping Rate
K = Hydraulic Conductivity
b = Saturated Thickness
i = Hydraulic Gradient
π = 3.1416

Modified from U.S. Environmental Protection Agency, 1987 A

NOT TO SCALE

Figure 38. Semi-Analytical Techniques Used in WHPA Delineations (U.S. EPA, 1987 A)

aquifers (U.S. EPA, 1987 A). The use of this method requires extensive knowledge of the geology and geomorphology of the aquifer in order to make effective judgments as to what likely constitutes a flow boundary. This method is not suited for deep confined aquifers.

Numerical-Flow and Solute-Transport Models

The numerical-flow and solute-transport modeling method incorporates drawdown and TOT criteria. Numerical methods are used to solve for the hydraulic head and groundwater flowpath characteristics of the aquifer (U.S. EPA, 1987 A). Numerical models can be run on desktop computers. Input data required by numerical models include the pumping rates, porosity, specific yield, saturated thickness, recharge rates, hydraulic conductivity, transmissivity, and the location of flow boundaries. The models can calculate time related flow boundaries and perform particle tracking computations. Commonly, a numerical model is used to generate a potentiometric surface map for specific aquifer properties and well pumping information. The resulting hydraulic head values can then function as an input file for the generation of groundwater flow lines, to a numerical solute transport model. This method provides the potential for a high degree of accuracy in the simulation of actual conditions, and can be applied to a wide variety of hydrogeologic settings of various complexity. The high cost and extensive expertise required in the use of this method can be limiting. The density and spacing of the grid required by numerical computer models can limit their effectiveness in the simulation of groundwater flow conditions near a well.

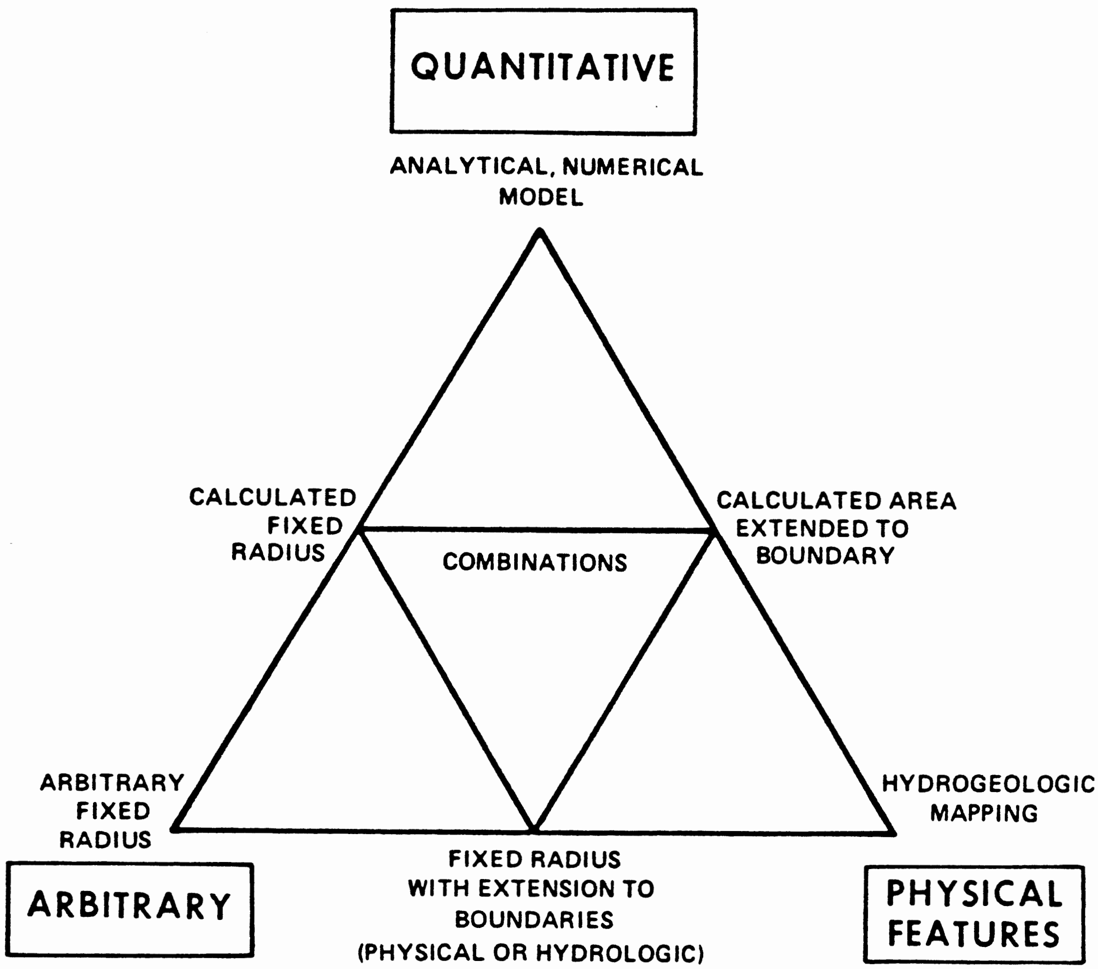
Table V shows the relationships between the various WHPA delineation methods and criteria. Some WHPA delineation methods can be illustrated as the result of combinations of different methods. The interrelationships between the various methods can be demonstrated on a triangular diagram (Figure 39). Three basic methods are represented at the corners the triangle. The other methods, shown on the sides of the triangle, are combinations of the basic methods and are shown on one of the sides of the triangle. For example the calculated fixed radii method can be seen as a combination of arbitrary and quantitative methods. The ability to select methods based on specific criteria allows for the development of WHPA delineations that best achieve the desired managerial and technical requirements.

TABLE V

RELATIONSHIPS BETWEEN WHPA DELINEATION METHODS AND CRITERIA

CRITERIA / METHOD	DISTANCE (L/M/H)	DRAWDOWN (L/M/H)	TOT (L/M/H)	PHYSICAL BOUNDARIES (L/M/H)	ASSIMILA-TIVE CAPACITY (L/M/H)
ARBITRARY FIXED RADIUS	H	N/A	N/A	N/A	N/A
CALCULATED FIXED RADIUS	N/A	H	H	N/A	N/A
SIMPLIFIED VARIABLE SHAPES	N/A	N/A	M	N/A	N/A
ANALYTICAL MODELS	N/A	H	H	N/A	M
NUMERICAL FLOW/ TRANSPORT MODELS	N/A	H	H	N/A	M
HYDROGEOLOGIC MAPPING	H	N/A	N/A	H	N/A

L–LOW
M–MEDIUM
H–HIGH
N/A–NOT APPLICABLE



Modified from U.S. Environmental Protection Agency, 1987 A

Figure 39. Interrelationships Between WHPA Methods (U.S. EPA, 1987 A)

CHAPTER VI

WELLHEAD PROTECTION AREA DELINEATION FOR EDMOND'S MUNICIPAL WATER WELLS

State Requirements for Site Specific Delineations

Municipal water wells in Edmond are currently protected by state required standardized WHPA's with 300 foot radii. Because numerous state agencies are involved in WHPA delineations, they follow general guidelines designed to promote a uniform approach towards these delineations.

Site specific WHPA delineations in Oklahoma use a multiple zone approach. Zone I provides an area that both protects wells from the direct introduction of contaminants into the well bore and microbial contamination. Zone II provides a remedial action zone to protect wells from various chemical contaminants. An optional buffer zone may be used to protect against contamination (ODPC, 1990).

Selection of the Delineation Criteria

A WHPA delineation effort for the Edmond well-field could address the entire well-field or each individual well. The most appropriate approach depends upon the WHPA delineation criteria selected. Some of the criteria can be dismissed from consideration based upon their limitations. For example, the distance criterion is too simplified to be used in any but the most elemental WHPA delineations. The flow-boundary criterion is best suited for shallow aquifers with high flow velocities, conditions that are not present in the confined portion of the COA. The assimilative-capacity criterion requires extensive data on the aquifer's capacity to attenuate specific contaminants and such data is not readily available for the COA.

By comparing the relationships between the various delineation criteria and protection goals, an initial selection of those delineation criteria that appear to be suitable may be made for additional consideration (Table IV). Drawdown and time-of-travel criteria demonstrate the greatest potential to fulfill the needs of a site specific delineation effort in Edmond's well-field.

In order to further test whether these criteria are appropriate, initial WHPA delineations incorporating each criterion were performed for comparison.

Drawdown Criterion

The use of the drawdown criterion addresses the effect the well-field has upon the potentiometric surface of the COA. As evident from potentiometric surface maps (Figures 24-32), a large cone of depression has formed within the COA. A WHPA delineation using the drawdown criteria involves the selection of a boundary to define the extent of the cone of depression, which would then be defined as the well-field's zone of influence (ZOI). In order for the ZOI to be mapped, the regional hydraulic gradient must be small enough so that no significant variation exist between the ZOC and the ZOI.

A regional potentiometric surface map of the confined portion of the COA (Carr and Marcher, 1977), shows that the average regional hydraulic gradient is about 3 feet of hydraulic head decline over a horizontal distance of 1000 feet (.003). This is not likely to produce a significant variation between the ZOI and the ZOC.

The extent of the ZOI cannot be readily determined from the potentiometric surface maps. These maps are based only on water-level measurements made in city water wells. In order to estimate the limit of the ZOI, a computer program was used to calculate hydraulic head values beyond the mapped limits of the well-field.

Approximation of the Extent of the Zone of Influence Using the Artesian Prickett Lonnquist Aquifer Simulation Model (APLASM)

The Artesian Prickett Lonnquist Aquifer Simulation Model (APLASM) is capable of simulating the drawdown of the potentiometric surface resulting from the pumping of a maximum of 40 wells in a confined aquifer. APLASM is based on partial differential equations governing the non-steady state, two dimensional flow of groundwater in a confined, homogeneous or heterogeneous, isotropic aquifer. The program uses the non-equilibrium formula developed by Theis (1935).

APLASM requires well and aquifer information to be entered into a finite difference grid. The grid can be established with widespread characteristics using a default menu. Information is entered for individual nodes within the grid, which allows the program to simulate some characteristics of a heterogeneous aquifer. Individual nodes that are given independent characteristics are identified by their respective grid coordinates and are subsequently referred to as special nodes.

APLASM incorporates several assumptions, such as:

* grid nodes fully penetrate the aquifer;
* leakage from confining beds is vertical and proportional to the difference between the head in the aquifer and the head in the source bed above the confining layer;
* hydraulic head in the source bed remains constant;
* storage in the confining bed is negligible; and
* hydraulic heads in the aquifer do not fall below the confining layer.

Table VI shows the default information used for the simulation.

TABLE VI

APLASM DEFAULT INFORMATION

	Defaults	Values
A.	Default Number Of Time Steps	= 1
B.	Default Initial Time Step	= 20 DAYS
C.	Default Number Of Rows	= 16
D.	Default Distance Between Rows	= 2500 FEET
E.	Default Number Of Columns	= 19
F.	Default Distance Between Columns	= 2500 FEET
G.	Default Transmissivity	= 2500 GPD/FT
H.	Default Storativity	= .0002
I.	Default Hydraulic Head	= 1000 FEET
J.	Default Withdrawal Rate	= 0 GPD
K.	Default Recharge Factor	= 0 GPD/FT
L.	Default Recharge Head	= 0 FEET

The default grid settings that define the number of rows and columns and the spacings between them were chosen so that each square mile section in the well-field would contain four grid squares. Default transmissivity and storativity values where based upon estimates discussed in Chapter IV. Based on the regional potentiometric surface map by Carr and Marcher, 1977, the pre-pumping hydraulic head value was set at 1000 feet.

Given the lack of data concerning the rate of recharge to the confined portions of the COA, and considering the highly confining nature of the shale units in the aquifer, recharge was set at 0 gals/day/foot and the recharge head was set at 0 feet. The impact of water derived from recharge on the formation of the cone of depression during the relatively short duration encompassed by the simulation is not likely to be significant.

The locations and pumping rates of the wells were entered by means of special withdrawal nodes. Figure 40 shows the arrangement of the grid and the location of the withdrawal nodes. APLASM simulates one well per withdrawal node, which is placed in the center of the node. To accommodate this limitation, the total discharge of all of the wells, within each grid withdrawal node, for the month of August, 1990 was summed to produce a single discharge rate for each node. Withdrawal nodes were positioned so that as few wells as possible were incorporated into each simulated well location. APLASM includes the effects of well interference in its determination of hydraulic head values. The grid coordinates and withdrawal rates used in the APLASM simulation are presented in Appendix E

Commonly, computer programs are used to generate hydraulic head values when there are few actual measured values available. The purpose for using APLASM to simulate the drawdown of the Edmond well-field is to extend the limits of the August, 1990 potentiometric surface map so an estimate of the extent of the well-field's ZOI can be made. In order to coordinate the hydraulic head information produced by the APLASM simulation and

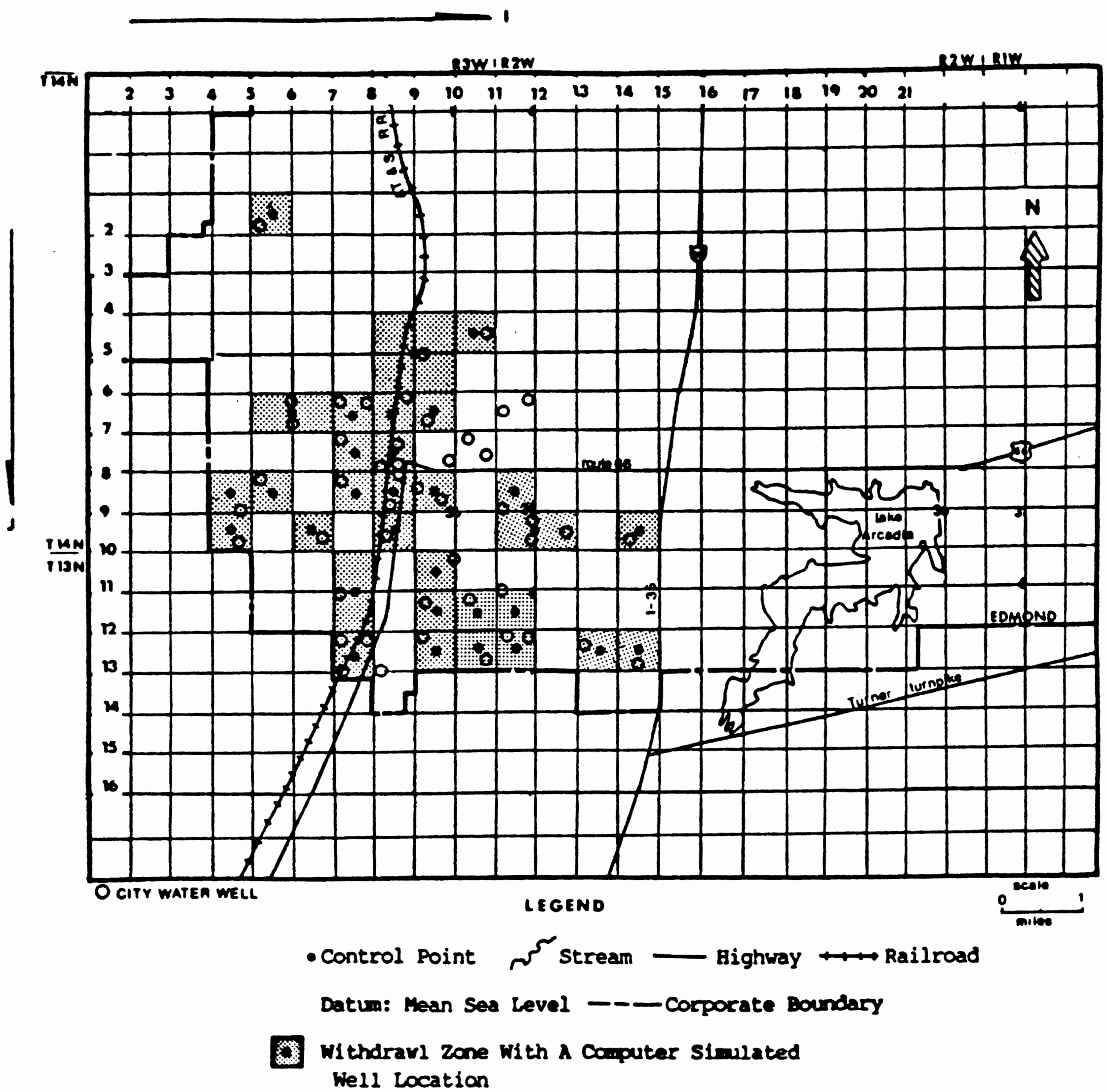


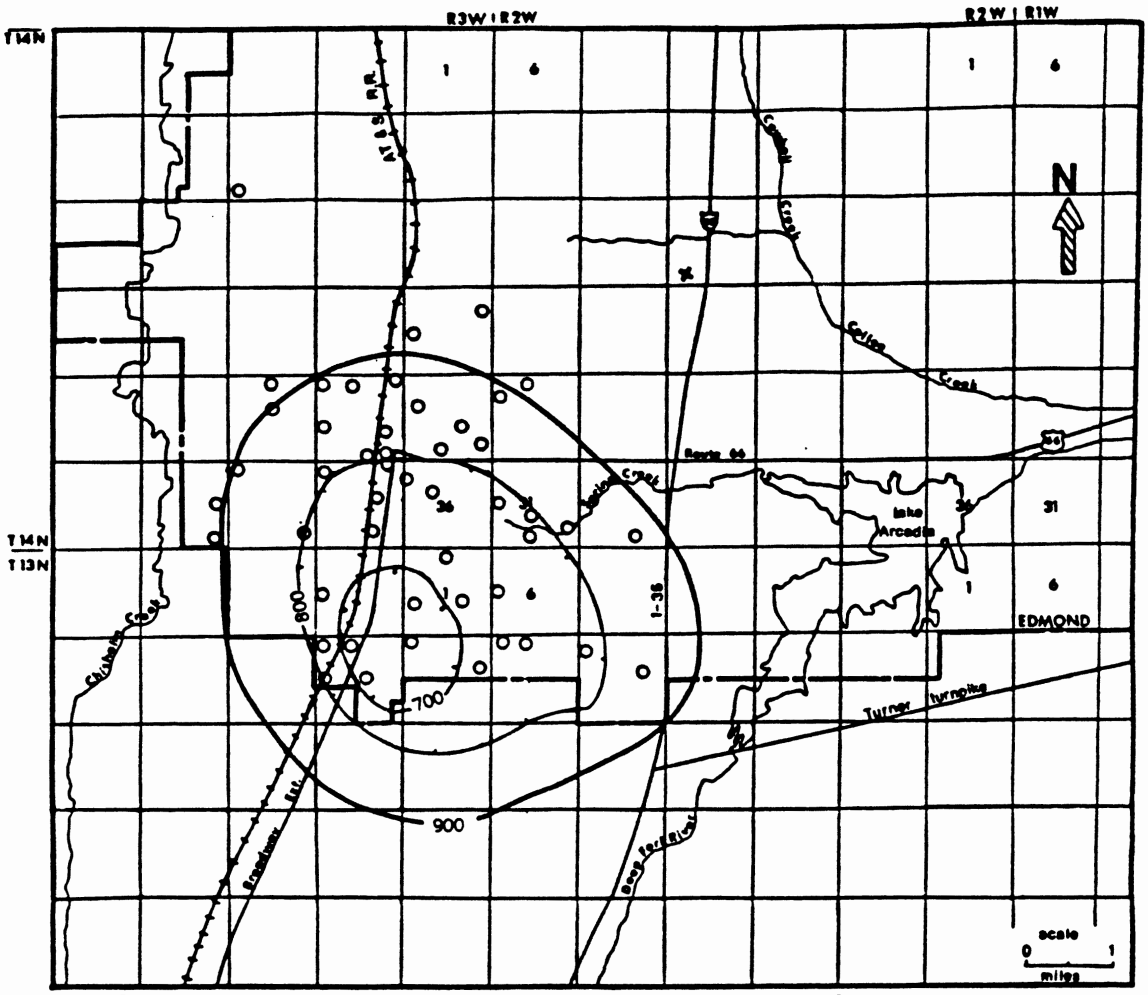
Figure 40. Grid Arrangement for the APLASM Simulation of the Drawdown of Edmond's Well-field

the information contained in the potentiometric surface map, a contour line was chosen and used as a reference point. The 900-foot contour, which clearly defines the configuration of the cone of depression, was selected.

For a simulation time step of 20 days, APLASM produced the potentiometric surface map shown in Figure 41. The model approximated the 900 foot contour line, and reproduced the magnitude of maximum drawdown shown on Figure 42. The simulation did not exactly reproduce the location of the 900-foot contour nor did it reproduce the exact configuration of localized areas of increased drawdown in the central portion of the cone of depression. Inaccuracy might have been introduced into the simulation by violation of actual conditions by the limiting assumptions and by the use of simplifying estimations of the aquifer's hydraulic properties.

The map produced by the simulation was concluded to be adequate to allow an estimation of the extent of the ZOI. Using a drawdown criterion of 2 feet, the 998-foot hydraulic head value was mapped (Figure 41). The extent of the ZOI, as estimated using APLASM, is roughly 2 miles beyond the 900-foot contour.

This exercise shows that using the drawdown criterion as a basis for WHPA delineation of Edmond's well-field would produce a very large WHPA. A WHPA of the size necessary to cover the estimated extent of the ZOI would be so large that its effective management would be extremely difficult. Thus, the use of the drawdown criterion is not appropriate for delineation efforts in



O CITY WATER WELL

LEGEND

Contour Interval: 100 Feet

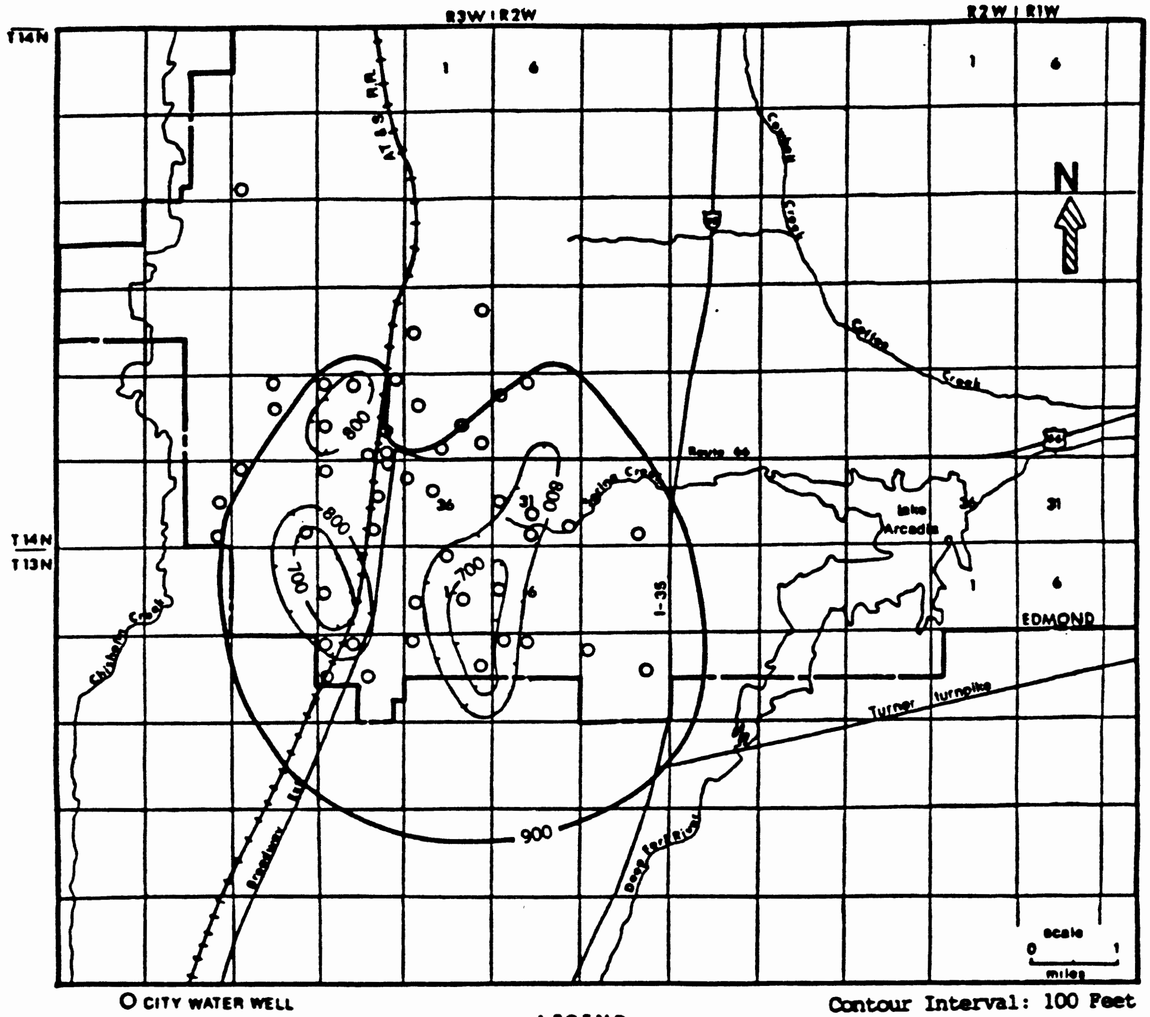
—900— Potentiometric Surface Elevation Contour Determined By APLASM Computer Simulation

• Control Point   Stream   —— Highway   Railroad

Datum: Mean Sea Level   ——— Corporate Boundary

× Estimated Extent Of The Cone Of Depression (ZOI)

Figure 41. Potentiometric Surface Contour Map of the Central Oklahoma Aquifer in the Vicinity of the Edmond Well-field for the Month of August, 1990, Determined With APLASM



LEGEND

—900— Potentiometric Surface Elevation Contour Determined By Water Level Measurements In Wells

O Control Point   Stream   —— Highway   Railroad

Datum: Mean Sea Level ———Corporate Boundary

Figure 42. Potentiometric Surface Contour Map of the Central Oklahoma Aquifer in the Vicinity of the Edmond Well-field for the Month of August, 1990

Edmond's well-field.

Time-of-Travel Criterion

The use of the time-of-travel (TOT) criterion for a WHPA delineation of the Edmond well-field would address the influence of individual wells on groundwater flow. Using this criterion, the portion of the ZOC that contributes water to a well in a given period would constitute the WHPA. In order to determine if this is an appropriate criterion for the entire well-field, a computer program was used to delineate a time-related WHPA for one of the municipal water wells.

Delineation of a Wellhead Protection Area Using the Time-Of-Travel Model

The Time-Of-Travel (TOT) computer program was used to delineate a time-related WHPA for municipal well 24. This program was written by the Oklahoma Water Resources Board (OWRB, 1990) to assist in WHPA delineations that incorporate the TOT criterion. The TOT program is an analytical model that uses the uniform-flow equations to determine a well's ZOC. Time-of-travel boundaries are calculated by using the Theis non-equilibrium equations to develop distance-drawdown data for the well and, from this information, to determine the groundwater velocities resulting from the regional hydraulic gradient and well effects.

The TOT program requires the input of the pumping rate, aquifer thickness, transmissivity, hydraulic conductivity, porosity, storativity, and hydraulic gradient (Figure 43). Since the program assumes that the well pumps continuously at a constant rate over the duration of the simulation, the August, 1990 continuous pumping rate for the well was used (Table II). The regional hydraulic gradient was determined from the potentiometric surface map shown in Figure 42.

Figure 43 shows the delineation of the 10-year ZOT for well 24, which is the same as the 10-year time-related WHPA. The results show that by using TOT criteria, WHPA delineations can be produced that are small enough to be more easily managed while still incorporating flow conditions produced by the wells.

Selection of a Delineation Method

The selection of the TOT criterion controls the selection of a delineation method. Table V shows the relationships between the various delineation criteria and methods. Three methods are applicable regarding the TOT criterion. Of these methods, the calculated-fixed-radii method is too simplified to be considered for use in this delineation. The analytical- and numerical-modeling methods are highly applicable towards the TOT criterion, and they posses a level of technical sophistication sufficiently high to permit their consideration for use in the Edmond well-field.

As a result of technological advances, complex groundwater-flow systems can be simulated with a relatively high degree of accuracy using numerical models. Although numerical

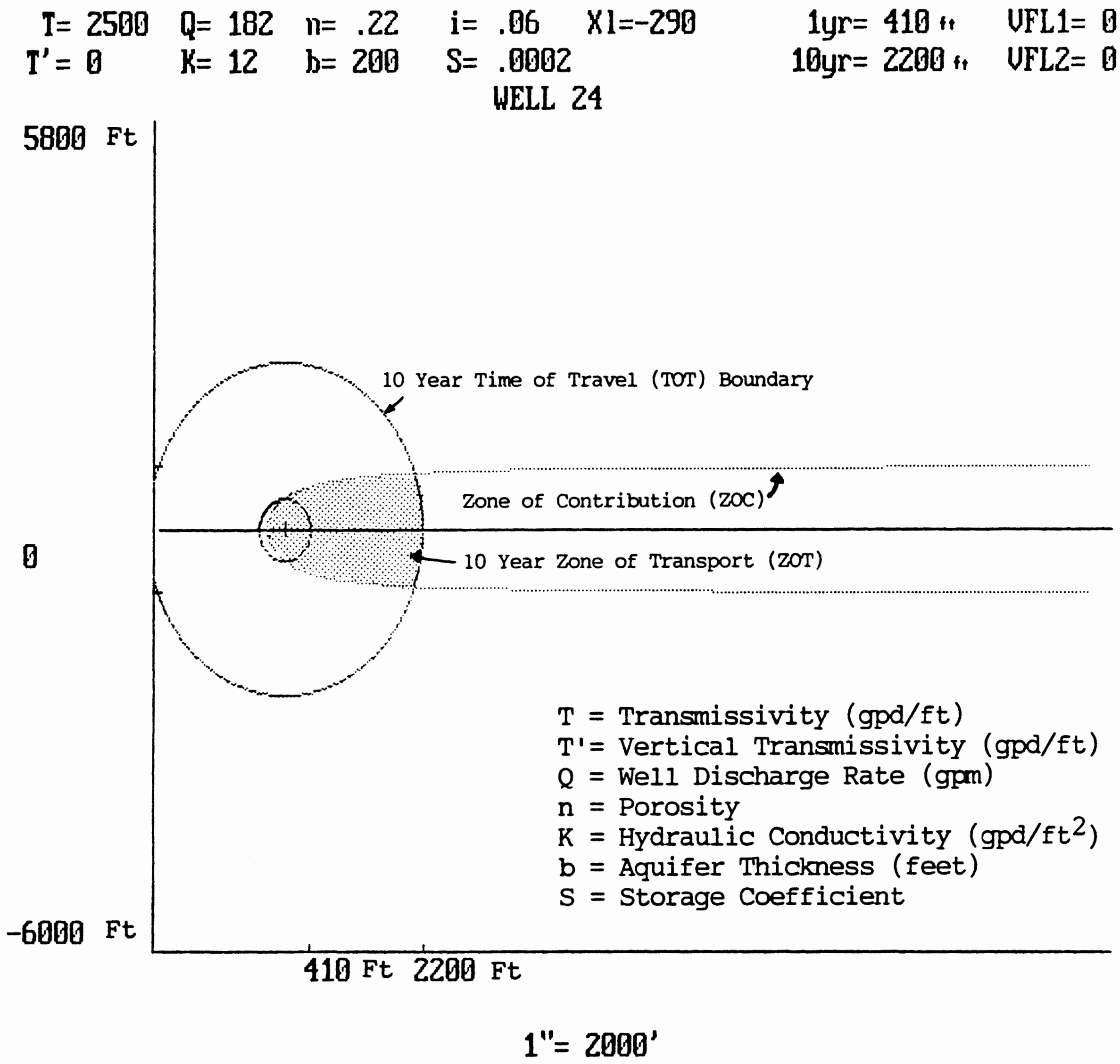


Figure 43. Delineation of the 10-Year Wellhead Protection Area for Edmond's Municipal Water Well 24 Using the Time-Of-Travel Computer Program

models are powerful tools, the high cost associated with them, in terms of both time and money, prohibit their use in this WHPA delineation effort. The use of analytical-flow models usually involves the simplification of complex groundwater-flow systems, which can limit the effectiveness of these models in some situations. The abundant potentiometric-surface and discharge data available for Edmond's well-field were used in coordination with an analytical model to enhance the model's ability to accommodate the complexities of groundwater flow in the area.

Many analytical-flow models capable of delineating time-related WHPA's are available. Some characteristics of analytical models are useful in delineating WHPA's in the Edmond well-field. Given the high probability that well interference plays a major role in influencing groundwater flow in the well-field, any model used for WHPA delineations should consider this aspect. Some analytical models can perform particle-tracking functions, where flowpath trajectories are computed and plotted. This is useful in verifying the threat from any potential source of contamination within the WHPA's.

Delineation of Wellhead Protection Areas Using the General Particle Tracking Module (GPTRAC)

The U.S EPA (1990) compiled a software package designed to assist in WHPA delineations. Included in this package is the General Particle Tracking Module (GPTRAC). GPTRAC consist of two components, a semi-analytical option and a numerical option.

GPTRAC is capable of delineating time-related WHPA's with particle-tracking computations while incorporating effects due to well interference.

GPTRAC's Semi-Analytical Option

GPTRAC's semi-analytical option uses analytical formulas based on the potential function analytical solution of a steady-state flow problem. GPTRAC computes groundwater velocities along flowpath trajectories. Flowpaths are traced by a numerical-integration procedure (U.S. EPA, 1990). In addition to flowpath generation, both forward (downgradient) and reverse (upgradient) particle tracking can be accomplished. GPTRAC incorporates several assumptions including the following:

* wells fully penetrate the aquifer;
* a steady flow field exist;
* aquifer is homogeneous;
* groundwater flow is two-dimensional;
* flow boundaries fully penetrate the aquifer;
* wells are pumped continuously at a constant rate; and
* hydraulic gradient is uniform and one directional.

A brief summary of known conditions in Edmond's well-field may highlight areas of concern. Water wells are perforated throughout most of the thick, freshwater-producing sandstone units they penetrate. The aquifer as a whole is not considered homogeneous, being a complex of interlayered sandstone and shale units. The freshwater sandstone units are themselves, however, fairly homogeneous and most likely receive relatively little water from the confining shale units. The flow field within the sandstone units is likely to be predominately two-dimensional. While flow boundaries certainly affect the flow of groundwater in the shallow, unconfined aquifer, these boundaries are not as evident in the deeper, confined portion of the COA.

The water wells are pumped individually and sporadically, yet the well-field, as a whole, continuously produces water and a fairly stable cone of depression exists as a result. Potentiometric surface maps (Figures 24-32) reveal that a fairly uniform, one-directional hydraulic gradient exists in parts of the cone of depression. In other areas, the formation of localized centers of increased drawdown have produced complex, multidirectional flow patterns. The amount of error incurred by GPTRAC's semi-analytical option is likely to be attributable to the degree to which actual conditions are violated by the simplifying assumptions.

The delineation of Edmond's municipal water wells 34, 39, and 44 were used to illustrate the use of GPTRAC's semi-analytical option in delineating time-related WHPA's. The input requirements for the model are shown in Table VII. To begin a simulation, an area, around the well or wells, is selected and defined by the input of maximum and minimum x and y coordinates (Figure 44). The average discharge for three months (August 1988, 1989, and 1990) was entered for each well. By

TABLE VII

INPUT REQUIREMENTS FOR GPTRAC's SEMI-ANALYTICAL OPTION

Program Variable	Description
For each problem –	
IUNIT:	Default units of input parameters (feet and days or meters and days)
NPWELL:	Number of pumping wells within the study area
NRWELL:	Number of recharge (injection) wells within the study area
XMIN:	Minimum x-coordinate of study area (ft or m)
XMAX:	Maximum x-coordinate of study area (ft or m)
YMIN:	Minimum y-coordinate of study area (ft or m)
YMAX:	Maximum y-coordinate of study area (ft or m)
DLMAX:	Largest allowable step length, $d\ell$ (see section 4.1)
TRANSM:	Transmissivity of aquifer (ft^2/d or m^2/d)
GRADNT:	Regional hydraulic gradient (ft/ft or m/m)
ALPHA:	Angle of ambient ground-water flow (0-360°)
POROS:	Aquifer porosity (dimensionless)
B:	Aquifer saturated thickness (ft or m)
IBOUND:	Boundary condition type (no boundary, or stream or barrier boundary on one side of study area)
NFPATH:	Number of forward-tracked pathlines
NRPATH:	Number of reverse-tracked pathlines
TMSIM:	Time period for which GPTRAC will be executed[a/] (days)
TMCAPZ:	Time value assigned to time-related capture zones[a/] (days)
For each pumping well (I=1, NPWELL) –	
XPWELL(I):	x-coordinate of well (ft or m)
YPWELL(I):	y-coordinate of well (ft or m)
QPWELL(I):	Well discharge rate[b/] (ft^3/d or m^3/d)
NSTLIN(I):	Number of pathlines to be computed to delineate time-related capture zone (default = 20)
For each injection well (I=1, NRWELL) –	
XRWELL(I):	x-coordinate of well (ft or m)
YRWELL(I):	y-coordinate of well (ft or m)
QRWELL(I):	Well recharge rate[b/] (ft^3/d or m^3/d)
For each forward tracked pathline (I=1, NFPATH) –	
FSTART(I,1):	x starting coordinate (ft or m)
FSTART(I,2):	y starting coordinate (ft or m)
For each reverse tracked pathline (I=1, NRPATH) –	
RSTART(I,1):	x starting coordinate (ft or m)
RSTART(I,2):	y starting coordinate (ft or m)

Modified from Blandford and Huyakorn, 1990

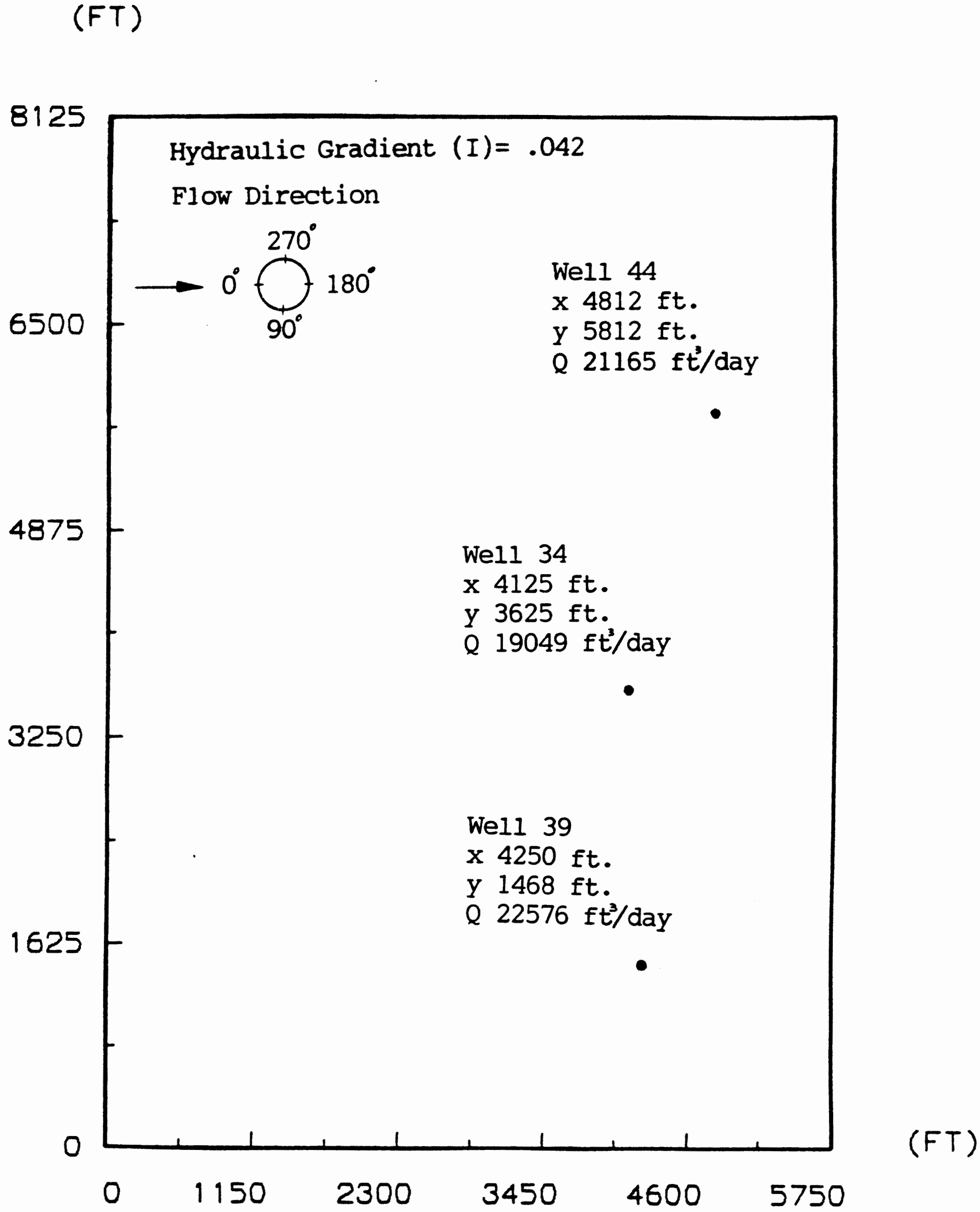


Figure 44. Area Setup for the Wellhead Protection Area Delineation for Edmond's Municipal Water Wells 44, 34, and 39 Using GPTRAC's Semi-Analytical Option

using three months of high use to determine the pumping rate of each well, the effects of an exceptionally high or low use period should be minimized, and a more representative value of the peak use pumping rate obtained. Pumping rates representative of high use periods are used in order to delineate WHPA's that will provide adequate protection for the well-field during periods of extremely high pumping conditions. The pumping rates used in the GPTRAC simulations are shown in Appendix F.

By incorporating rates from pumping periods, which precede the contribution of Lake Arcadia to the water supply, higher averaged peak rates were used for the GPTRAC delineations than would currently be expected. However, conditions might arise where the surface water reservoir may be unavailable for use and, given the increasing population growth in the Edmond area, the pumping rates used for the simulation may approximate possible future conditions. The discharge rate for each well was entered in units of ft^3/day along with the direction of the regional hydraulic gradient.

Some aquifer characteristics used for the simulations where held constant over the entire well-field, and these are shown in the Table VIII.

TABLE VIII

GPTRAC DEFAULT INPUTS

Default	Values
Transmissivity ......=	335 ft^2/day
Effective Porosity ..=	0.22
Aquifer Thickness ...=	200 feet

The time step for the simulation was set at 365 days in order to simulate a 1 year ZOC to meet the Zone I requirement for protection against microbial contaminants. Time steps of 3650 and 7300 days (10 and 20 years) were used to meet the Zone II requirement of providing a remedial action zone against chemical contamination. The number of pathlines to be traced was set at 20 for each well. Figure 45 shows the results of the GPTRAC semi-analytical simulation of the wells.

Although the direction of groundwater flow was due east, the flowpaths of wells 44 and 39 show some deflection from a true east-west line. This deflection is the result of well interference. The extent of the flowpaths defines the boundary of the respective time-related WHPA.

GPTRAC's Numerical Option

GPTRAC's numerical option uses a distribution of hydraulic head values, supplied though an input file, to determine

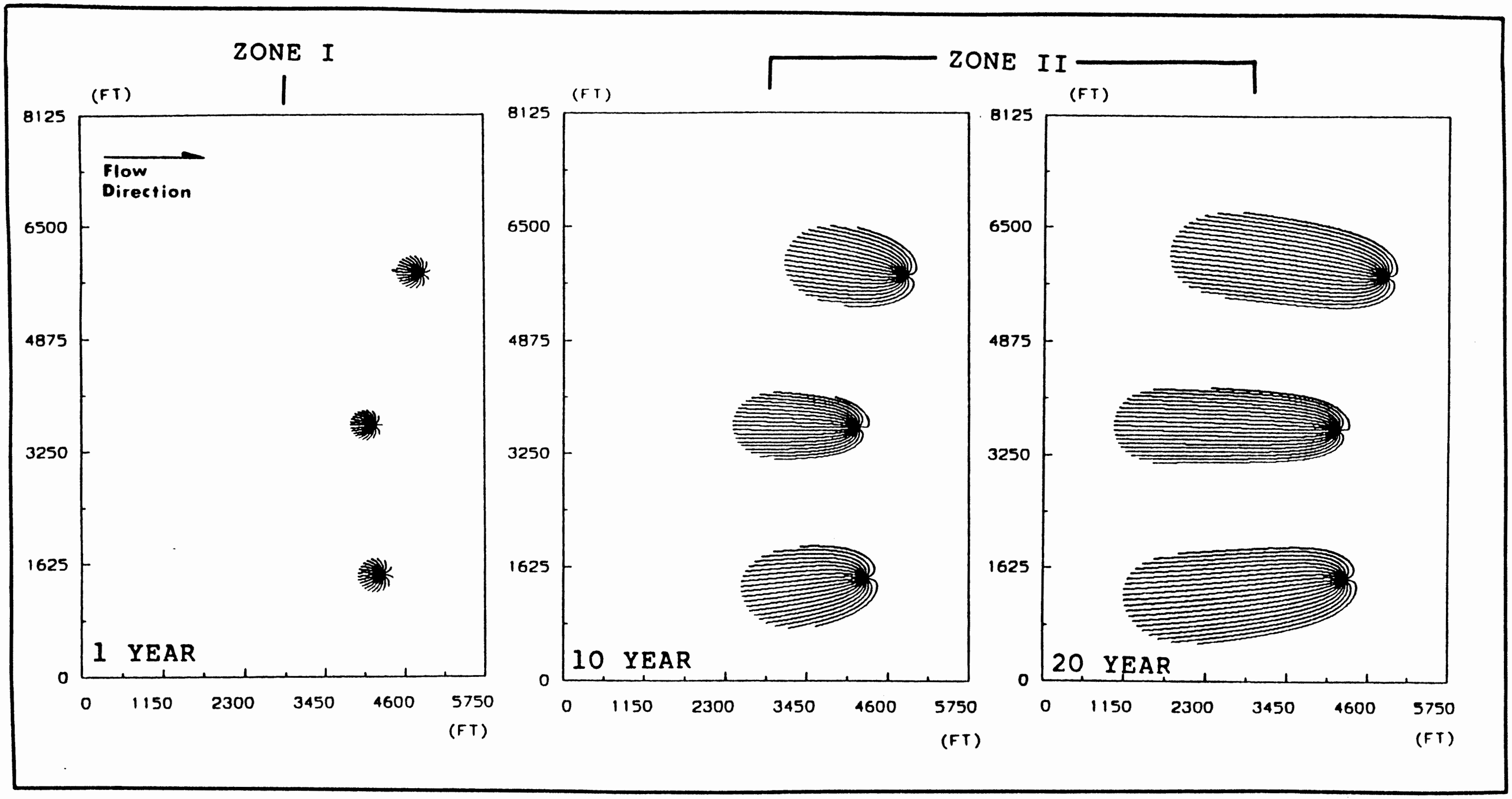


Figure 45. Results of the Delineation of Time-Related Wellhead Protection Areas for Edmond's Municipal Water Wells 44, 34, and 39 Using GPTRAC's Semi-Analytical Option

groundwater flow velocities. This is done by using numerical integration of the hydraulic head values after they are compiled into a rectangular mesh-centered grid. An Euler predictor-corrector numerical integration scheme, with successive iterations, is used to accommodate any spatial variability of velocities and curvature of flowpaths (U.S. EPA, 1990).

The numerical option of GPTRAC is capable of all the particle-tracking functions of the semi-analytical option. Because the numerical option of GPTRAC calculates groundwater flow velocities from the input file of observed or model calculated hydraulic head values, many of the assumptions and limitations inherent in the analytical option do not apply. The assumptions included in this model are that a steady flow field exist, that the flow of groundwater is two-dimensional, and that the wells are pumped continuously at a constant rate. Because the numerical option does not obtain flow velocities analytically, the aquifer need not be homogeneous. The delineation of time-related WHPA's for municipal wells 24 and 25 were used to illustrate GPTRAC's numerical option in the delineation of time-related WHPA's.

The input requirements for the model are shown in Table IX. The first step was to define a square area containing the wells to be simulated. Figure 46 shows the area that was used and the minimum and maximum x and y coordinates that define it. The input parameters are the same as for the semi-analytical option.

TABLE IX

INPUT REQUIREMENTS FOR GPTRAC's NUMERICAL OPTION

Program Variable	Description
For each problem--	
IUNIT:	Default units of input parameters (feet and days or meters and days)
NPWELL:	Number of pumping wells within the study area
NRWELL:	Number of recharge (injection) wells within the study area
XMIN:	Minimum x-coordinate of study area (ft or m)
XMAX:	Maximum x-coordinate of study area (ft or m)
YMIN:	Minimum y-coordinate of study area (ft or m)
YMAX:	Maximum y-coordinate of study area (ft or m)
NZONES:	Number of aquifer zones that have different material properties (if aquifer is nonuniform)
NROWS and NCOLS, and XGRIDL(I), YGRIDL(J) for I=1, NCOLS and J=1, NROWS	Number of grid-line rows and columns, and (if non-uniform grid,) coordinates of each grid-line row and column
FINAME	Input file name that contains head values for each node of the finite element or finite difference grid.
NFPATH:	Number of forward-tracked pathlines
NRPATH:	Number of reverse-tracked pathlines
TMSIM:	Time period for which GPTRAC will be executed[a] (days)
TMCAPZ:	Time value assigned to time-related capture zones[a] (days)
For each pumping well (I=1, NPWELL) –	
XPWELL(I):	x-coordinate of well (ft or m)
YPWELL(I):	y-coordinate of well (ft or m)
QPWELL(I):	Well discharge rate[b] (ft^3/d or m^3/d)
NSTLIN(I):	Number of pathlines to be computed to delineate time-related capture zone (default = 20)
For each forward tracked pathline (I=1, NFPATH) –	
FSTART(I,1):	x starting coordinate (ft or m)
FSTART(I,2):	y starting coordinate (ft or m)
For each reverse tracked pathline (I=1, NRPATH) –	
RSTART(I,1):	x starting coordinate (ft or m)
RSTART(I,2):	y starting coordinate (ft or m)

Modified from Blandford and Huyakorn, 1990

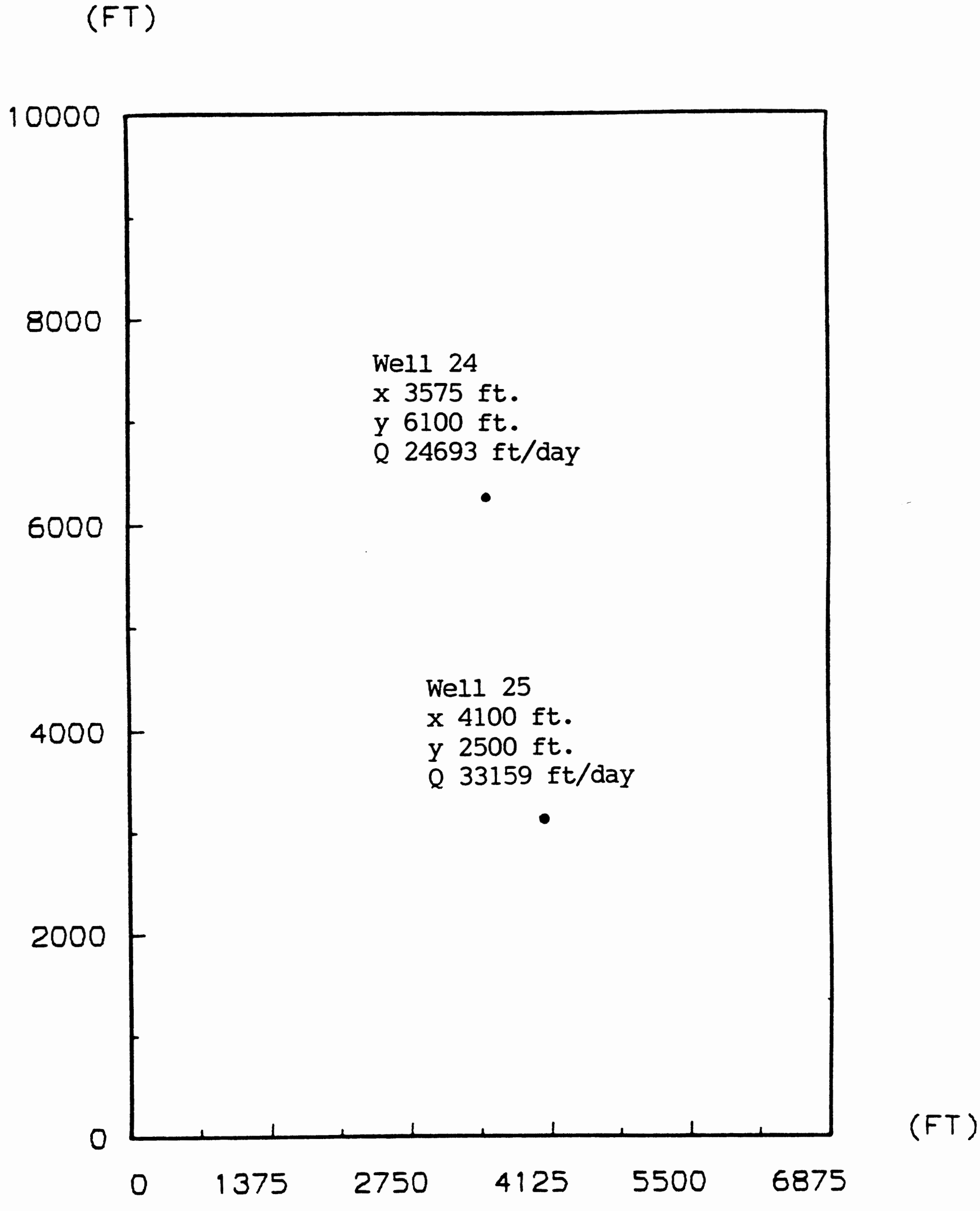
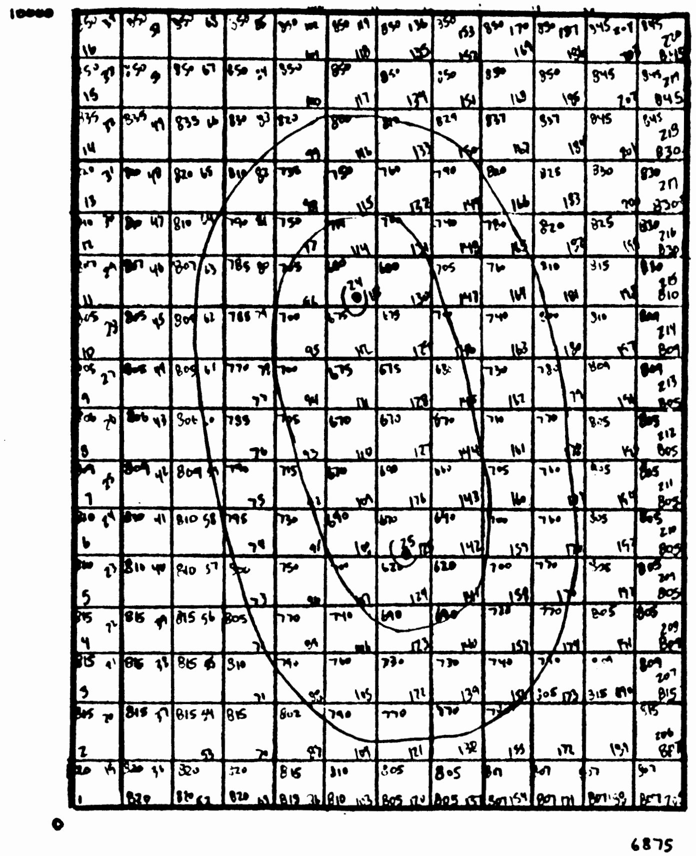


Figure 46. Area Setup for the Wellhead Protection Area Delineation for Edmond's Municipal Water Wells 24 and 25 Using GPTRAC's Numerical Option

Instead of entering hydraulic gradients, the hydraulic head file was created for the area. The potentiometric surface map for August, 1990 (Figure 30) served as the basis for the hydraulic head files. A grid was created, and hydraulic head values determined at the intersections of the grid lines (Figure 47). Some subjective judgment was used to interpolate values between points of known values. This interjected a degree of uncertainty into the model. The hydraulic head map created within the grid was then used to create an input file of hydraulic head values using a standard word-processor program. The input file (Figure 47) is read by the program and recompiled into the grid map, enabling the computation of groundwater flow velocities. The results of the delineation of time-related WHPA's for municipal wells 24 and 25 is shown in Figure 48.

The flowpaths generated for wells 24 and 25 reflect the multidirectional groundwater flow in the area by showing pronounced separation. Figure 49 shows the results of the delineation of 10-year WHPA's for the same wells using GPTRAC's semi-analytical option. Compared with the results obtained with the numerical option, the inability of the semi-analytical option to accurately simulate conditions where groundwater flow is multidirectional can be seen. The longest flowpaths computed by the numerical option are about 350 feet shorter than those computed with the semi-analytical option. This could, in part, be the result of the more sinuous flowpath pattern produced by the numerical option.



GPTRAC HYDRAULIC HEAD INPUT FILE TRIAL31.TXT

1	820.	2	820.	3	853.	4	815.	5	815.
6	810.	7	810.	8	809.	9	806.	10	805.
11	805.	12	807.	13	810.	14	820.	15	835.
16	850.	17	850.	18	820.	19	820.	20	815.
21	815.	22	815.	23	810.	24	810.	25	809.
26	806.	27	805.	28	805.	29	807.	30	810.
31	820.	32	835.	33	850.	34	850.	35	820.
36	820.	37	815.	38	815.	39	815.	40	810.
41	810.	42	809.	43	806.	44	805.	45	805.
46	807.	47	810.	48	820.	49	835.	50	850.
51	850.	52	820.	53	820.	54	815.	55	810.
56	805.	57	800.	58	795.	59	790.	60	785.
61	770.	62	785.	63	785.	64	790.	65	810.
66	830.	67	850.	68	850.	69	815.	70	815.
71	802.	72	790.	73	770.	74	750.	75	730.
76	715.	77	705.	78	700.	79	700.	80	705.
81	750.	82	735.	83	820.	84	850.	85	850.
86	810.	87	810.	88	790.	89	760.	90	740.
91	700.	92	690.	93	670.	94	670.	95	675.
96	675.	97	680.	98	719.	99	750.	100	800.
101	850.	102	850.	103	805.	104	805.	105	770.
106	730.	107	690.	108	620.	109	670.	110	690.
111	670.	112	675.	113	675.	114	680.	115	700.
116	760	117	810.	118	850.	119	850.	120	805.
121	805.	122	770.	123	730.	124	690.	125	620.
126	640.	127	660.	128	670.	129	680.	130	700.
131	705.	132	740.	133	790.	134	829.	135	850.
136	850.	137	807.	138	807.	139	780.	140	740.
141	720.	142	700.	143	700.	144	705.	145	710.
146	730.	147	740.	148	760.	149	780.	150	820.
151	837.	152	850.	153	850.	154	807.	155	807.
156	805.	157	790.	158	770.	159	770.	160	760.
161	760.	162	770.	163	780.	164	800.	165	810.
166	820.	167	825.	168	837.	169	850.	170	850.
171	807.	172	807.	173	815.	174	809.	175	805.
176	805.	177	805.	178	805.	179	805.	180	809.
181	810.	182	815.	183	825.	184	830.	185	845.
186	845.	187	845.	188	807.	189	807.	190	815.
191	809.	192	805.	193	805.	194	805.	195	805.
196	805.	197	809.	198	810.	199	830.	200	830.
201	830.	202	845.	203	845.	204	845.	205	807.
206	807.	207	815.	208	809.	209	805.	210	805.
211	805.	212	805.	213	805.	214	809.	215	810.
216	830.	217	830.	218	830.	219	845.	220	845.
221	845.								

Figure 47. Hydraulic Head File for the Wellhead Protection Area Delineation of Edmond's Municipal Water Wells 24 and 25 Using GPTRAC's Numerical Option

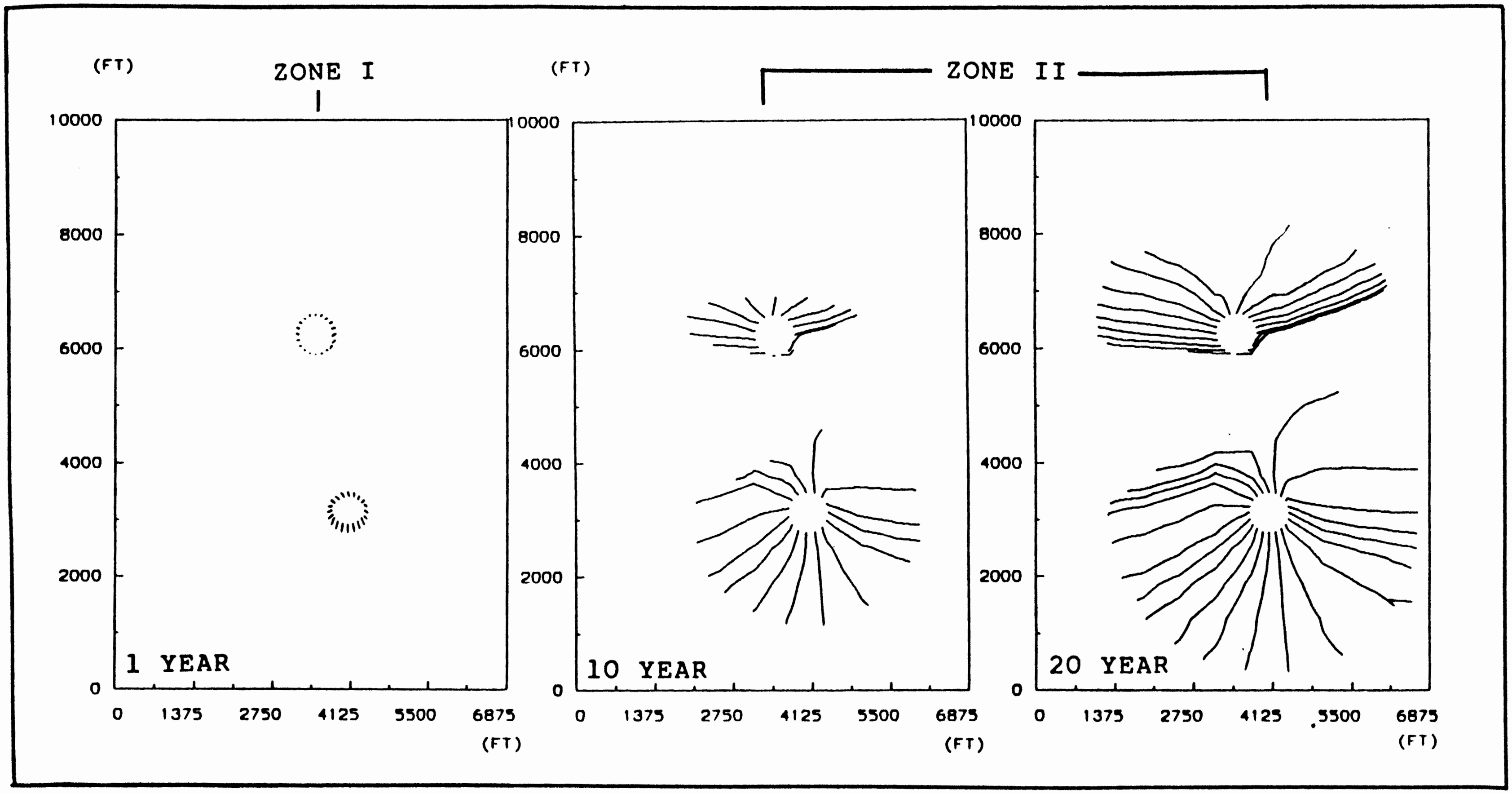


Figure 48. Results of the Delineation of Time-Related Wellhead Protection Areas for Edmond's Municipal Water Wells 24 and 25 Using GPTRAC's Numerical Option

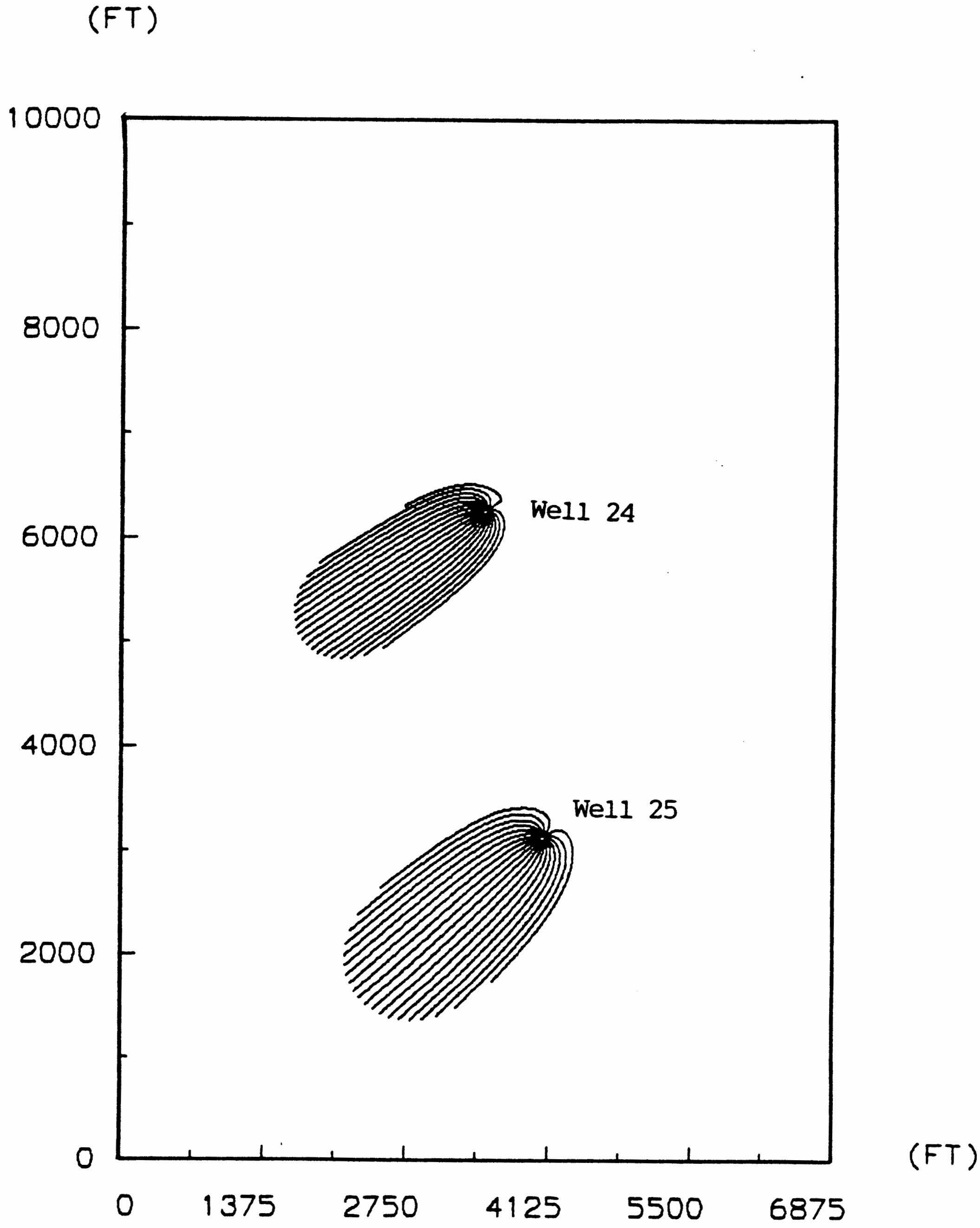


Figure 49. 10-Year Wellhead Protection Area Delineations for Edmond's Municipal Water Wells 24 and 25 Using GPTRAC's Semi-Analytical Option

While the numerical option is better suited for the simulation of multi-directional groundwater flow patterns, the semi-analytical option can better simulate flow conditions in close proximity to the wells and in areas with shallow, one-directional hydraulic gradients and low pumping rates. The numerical option is limited in these situations by the density of the grid spacings and velocity of groundwater flow. If the groundwater velocity is slow or the grid spacings large, too few nodes will be incorporated into the determination of flowpath trajectories, and a substantial amount of error will be incorporated in the results.

To demonstrate the difference between the two options under the conditions of slow groundwater flow and a shallow hydraulic gradient, the delineation of time-related WHPA's for municipal well 28 was performed using both the semi-analytical and numerical options (Figure 50). A comparison of the resulting flowpath trajectories shows that the numerical option cannot adequately simulate flowpaths under these conditions. The semi-analytical option produces WHPA's which increase in size with an increase in the length of the time step of the simulations. The numerical option does not produce WHPA's that show a logical increase in size with an increase the simulation time step. In fact, the 1-year WHPA is actually larger than the 10-year WHPA. Rearranging the grid spacings account for the limitations of the numerical option would be difficult, requiring a substantial subjective interpolation of hydraulic head values.

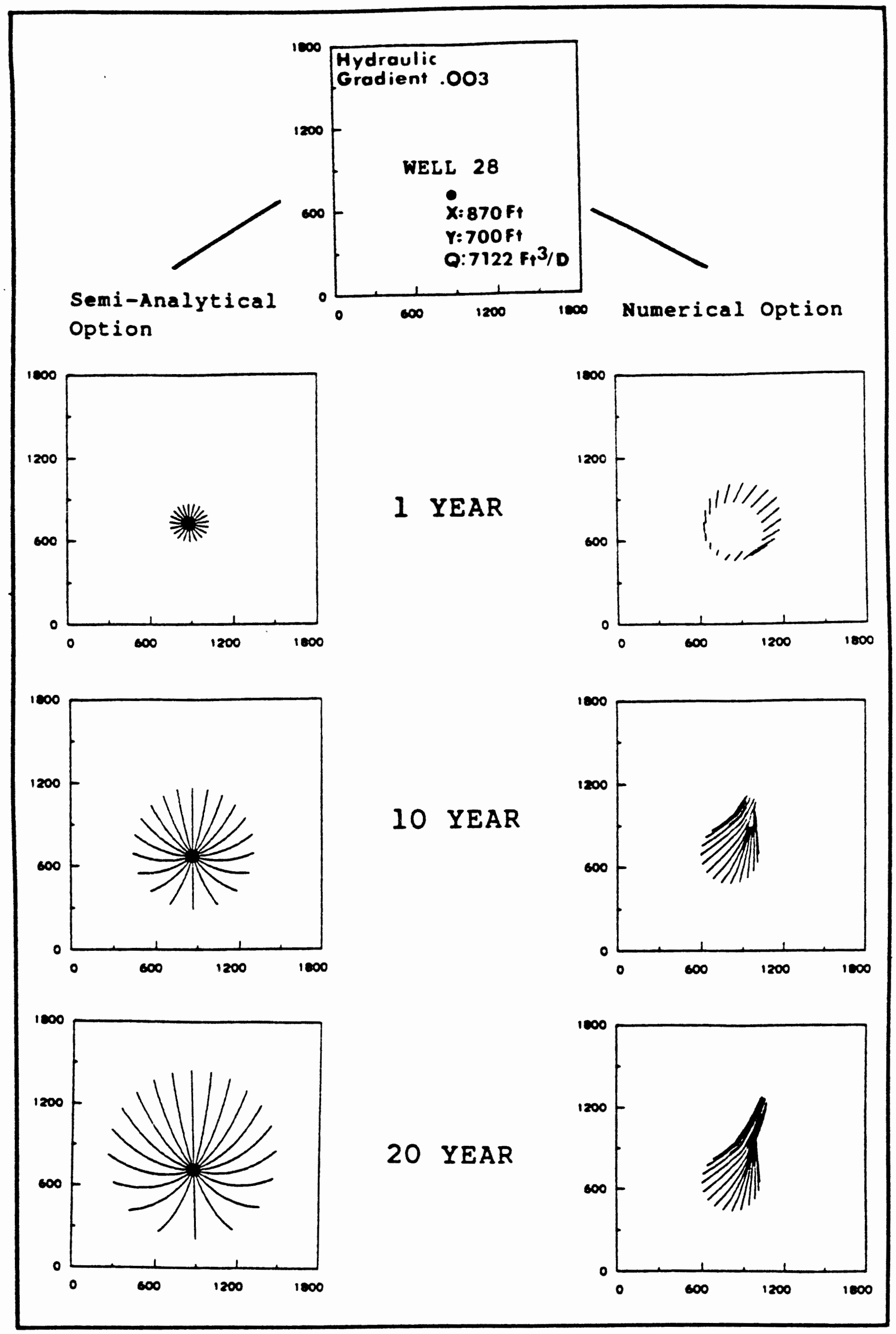


Figure 50. Comparison Between GRTRAC"S Semi-Analytical and Numerical Options in the Delineation of Time-Related Wellhead Protection Areas for Edmond's Municipal Water Well 28

The conclusion reached, based upon the results of GPTRAC's simulations, is that a WHPA delineation effort for Edmond's municipal water well-field, combining both of GPTRAC's options, can better incorporate the actual conditions of the well-field than the use of another analytical model or either option individually. The potentiometric surface information available for the well-field enables the creation of hydraulic head files over most of the area.

GPTRAC's semi-analytical and numerical options were run on each of the municipal water wells in the well-field and compared both with each other and with estimates of groundwater velocities. Based upon these comparisons, an option was selected for each water well that appeared to work best with the conditions present. Considering its superior ability in simulating flowpaths in close proximity to the wells, the semi-analytical option was used to delineate the 1-year WHPA's for all the wells. A list of the options used for the 10-and 20-year WHPA delineations for each well is located in Appendix G.

The resulting 1-, 10-, and 20-year time-related WHPA delineations for each well is shown on Plates 7, 8, and 9, respectively. These maps provide the basis for a management program to protect the municipal wells from contamination through the identification and assessment of potential sources of contamination within each WHPA. Any changes in information pertaining to aquifer characteristics or pumping rates would necessitate the delineation of new WHPA's.

CHAPTER VII

VULNERABILITY OF THE CENTRAL OKLAHOMA AQUIFER TO CONTAMINATION

Introduction to Aquifer Vulnerability Assessment

The WHPA's delineated for Edmond's municipal water wells define areas of the COA that should be properly managed in order to protect the wells, for the specified duration of time incorporated into the delineations. In order to identify potential sources of contamination, the general vulnerability of the aquifer must first be assessed.

Factors that contribute to an aquifer's vulnerability are the population density, land use, and geology of the aquifer. An aquifer that is located in an area with a high population density, is heavily used, and is composed of a strata that make it vulnerable to contamination would need to be given a high priority regarding protection efforts (U.S. EPA, 1991).

Vulnerability Assessment of the Central Oklahoma Aquifer

Population Density

Central Oklahoma is one of the most densely populated areas of the state (Figure 51). Edmond has a population of about 60,000 within an area of 62 square miles.

Population centers are commonly associated with activities that have the potential to contaminate groundwater. In the Edmond area there is little heavy industry. Most of the commercial activity in the area can be classified as either light industry, agriculture, or as being associated with petroleum production.

Water Use

Water use from the COA has shown an increasing trend (Figure 52), although in Edmond it has declined in recent years due to the water treatment plant at Lake Arcadia. Even so, the municipal well-field supplied 1.3103 $\times 10^9$ gallons in 1991, or roughly half the city's water use. For the foreseeable future, the city is likely to rely upon the COA to supply a significant percentage of their needs and any contamination of the COA that impairs its use as a water supply would be cause for concern.

Population Density of Oklahoma (Dot equals one person per square mile)

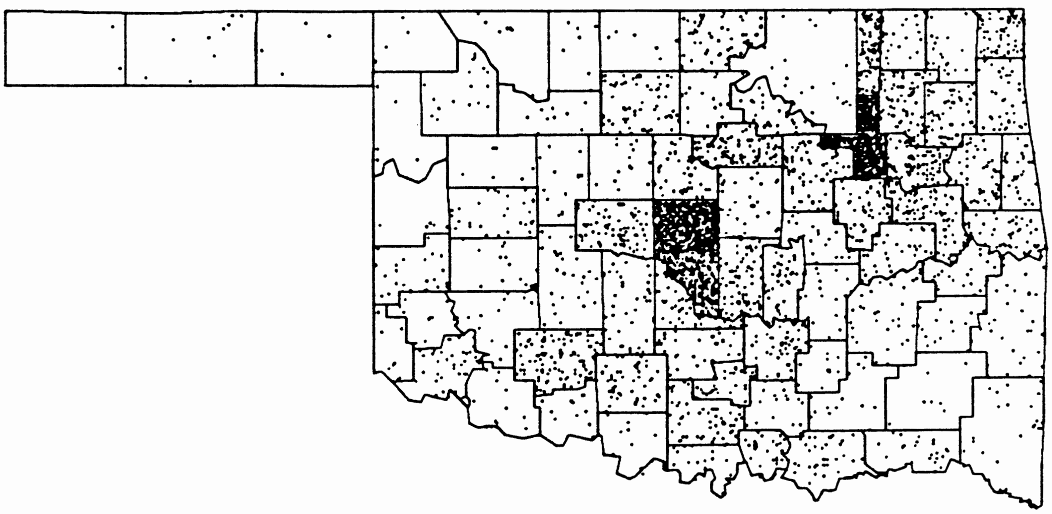


Figure 51. Population Density Map of Oklahoma (U.S. EPA, 1987 A)

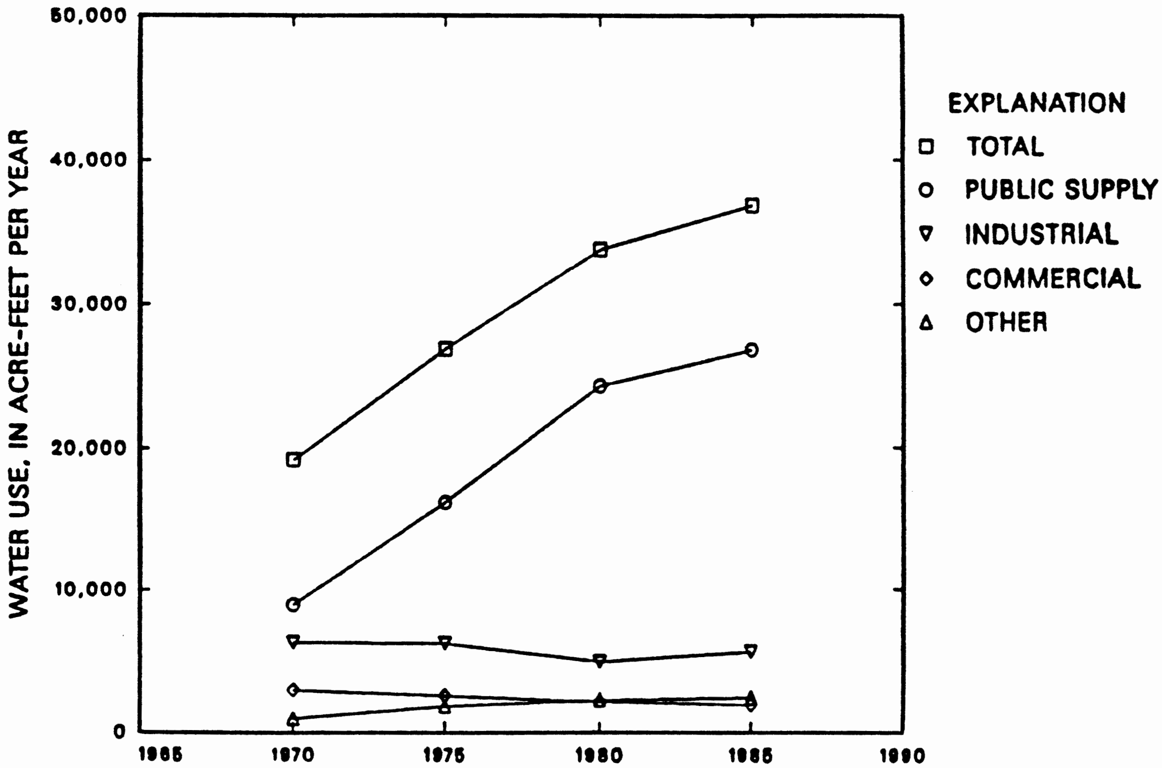


Figure 52. Reported Water Use from the Central Oklahoma Aquifer (Christenson, Parkhurst, and Schlottmann, 1989)

Geology

The relative vulnerability of the unconfined and confined portions of the COA is illustrated in Figure 53. The cross-section represents a greatly simplified illustration of the geology of the aquifer as determined from actual cross-sections (Plates 2 and 3).

The unconfined portion of the COA is represented as a sand unit that extends to a depth of 150 feet. At greater depths, the accumulative thickness of confining shale units would likely exceed 50 feet. This arbitrary thickness of confining layers is chosen as the thickness that will likely produce an adequate degree of hydraulic separation between the unconfined and confined portions of the COA.

Shallow sources of contamination, such as a landfill, and a deep sources, such as an oil well with a corroded casing, are shown in order to illustrate the effect of the shale in not only causing hydraulic separation between shallow and deep portions of the COA, but also in producing a separation with respect to the relative vulnerability of these zones. Leachate produced from the landfill may contaminate the unconfined aquifer, but the leachate is not likely to directly impact the confined portion of the aquifer. Thus, the confined portion of the COA is naturally protected by the geology of the aquifer against a wide variety of shallow sources of contamination. In order for a contaminant to be present in the confined freshwater sand units of the COA, the natural protection afforded by the shale

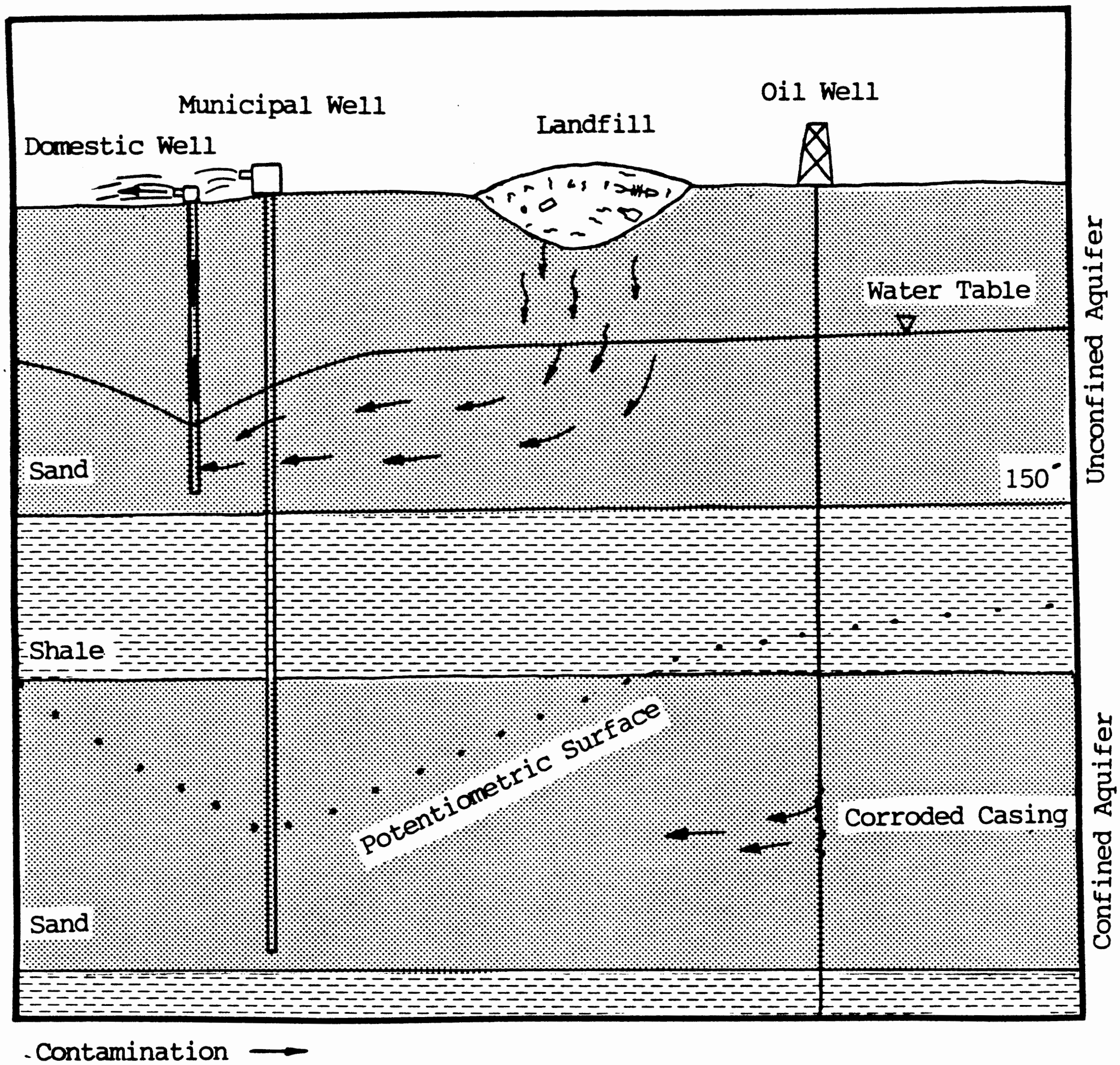


Figure 53. Idealized Cross-Section of the Central Oklahoma Aquifer Showing the Relative Vulnerability of the Unconfined and Confined Portions to Contamination

must be compromised, providing a pathway for contaminant migration into the confined zones.

Faults, fractures, and deep wells are ways in which the shale units can be compromised. No evidence was found of faults or fractures pervasive enough to likely breech the shale units. Deep well drilling activity associated with the petroleum industry and with groundwater development is common in the Edmond area.

Identification of Potential Sources of Contamination

Potential sources of contamination are usually categorized into three categories:

* sources that originate on the surface;
* sources that originate in the ground above the water table; and
* sources that originate in the ground below the water table.

Since the confining layers separate the unconfined portion of the COA from the confined portion, two categories of potential sources of contamination are relevant for the study area:

* sources that exist above a depth of 200 feet; and
* sources that exist below a depth of 200 feet.

These two categories separate potential sources of contamination into a group that can only directly effect the water quality of the unconfined aquifer and another group that can effect the water quality of both the unconfined and confined portions of the aquifer. Using land use maps obtained from ACOG (1991) and Herndon Map Service Inc. (1988), the location of some of the deep drilling activities in the area were plotted on the base map of the area (Plate 1). These sources are as follows:

* deep water wells;
* closed deep water wells;
* oil and gas wells;
* plugged oil and gas wells;
* secondary recovery (waterflooding) wells; and
* brine disposal wells.

In addition to these potential sources of contamination, seismic test holes and unreported abandoned oil and gas wells and deep water wells also might be present. A few of these sources were plotted on a simplified cross-section of the COA to show how contaminants from these sources might migrate into the freshwater sand units supplying the city water wells (Figure 54). These sources can threaten the city wells either by directly introducing contaminants into the sand units, as shown by the oil well with corroded casing, or by permitting low quality or contaminated water to migrate from another zone into the producing sand units through improperly plugged wells.

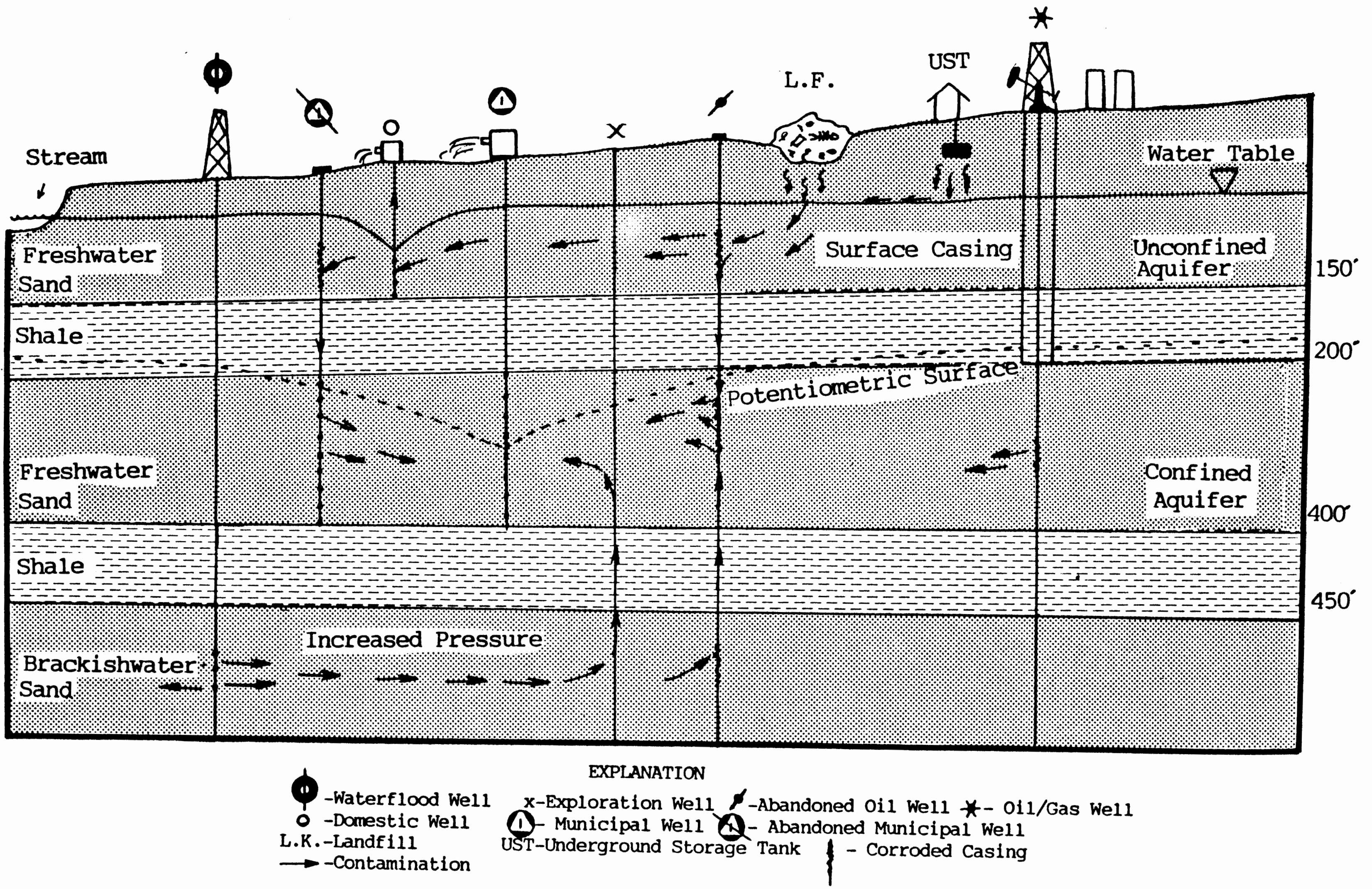


Figure 54. Idealized Cross-Section of the Central Oklahoma Aquifer Showing Some of the Potential Sources of Contamination Present in the Study Area

The natural hydraulic heads in the aquifer show that water will naturally migrate downward from the unconfined aquifer into the confined aquifer. Heavy pumping within the confined aquifer also will contribute to this pattern of water movement. Since the unconfined aquifer is more vulnerable to contamination any migration from the shallow zone into the confined zone would increase the risk of contamination. In addition, if pumping has reduced the hydraulic head in the confined zones below the level of hydraulic heads in the deeper brackishwater zone of the aquifer, water may be induced to migrate upwards from the brackishwater zone into freshwater zone. Secondary recovery and brine disposal operations either can directly introduce contaminants into the freshwater zones through openings in the casing or by increasing the pressure within deeper formations, influencing saline water to migrate upwards through improperly plugged wells or adjacent to the well bore.

Seismic test holes and unreported abandoned wells may not have been plugged at all, and present a hazard for personal injury as well as groundwater contamination (Pettyjohn, 1989).

Many of the oil and gas wells in the Northeast Edmond Oil-field were drilled in the 1950's. During this time, surface casing, intended to protect the freshwater portion of the aquifer, was commonly set to a depth of about 250 feet. At that time there were few deep water wells, and this depth was believed to be sufficient to protect the shallow water wells in the area from contamination. Thus, many of the active and abandoned oil and gas wells in this area do not have surface casing that extends to a sufficient depth to protect the confined sand units which are supplying the city water wells. In addition, since the age of these wells increases the probability that some casing corrosion has occurred, the potential for contamination is high (Canter and Fairchild, 1984).

Under normal conditions, the majority of activities associated with oil and gas production is conducted in a manner that does not unduly increase the risk of contamination beyond levels inherent in such activities. Unfortunately, it only takes a small number of improperly constructed or plugged wells to threaten groundwater supplies with contamination.

In addition to activities associated with oil and gas production, groundwater development using deep water wells can threaten the freshwater sand units if the wells are improperly constructed or plugged. Industrial, irrigation, and municipal water wells are present in the area and should be considered when addressing potential sources of contamination in the area.

Locating Potential Sources of Contamination

State and local agencies maintain list of potential sources of contamination that are under their jurisdiction. For the potential sources of contamination in the study area associated with oil and gas production, the Oklahoma Corporation Commission maintains records concerning their construction and plugging. The Oklahoma Water Resources Board (OWRB) and the

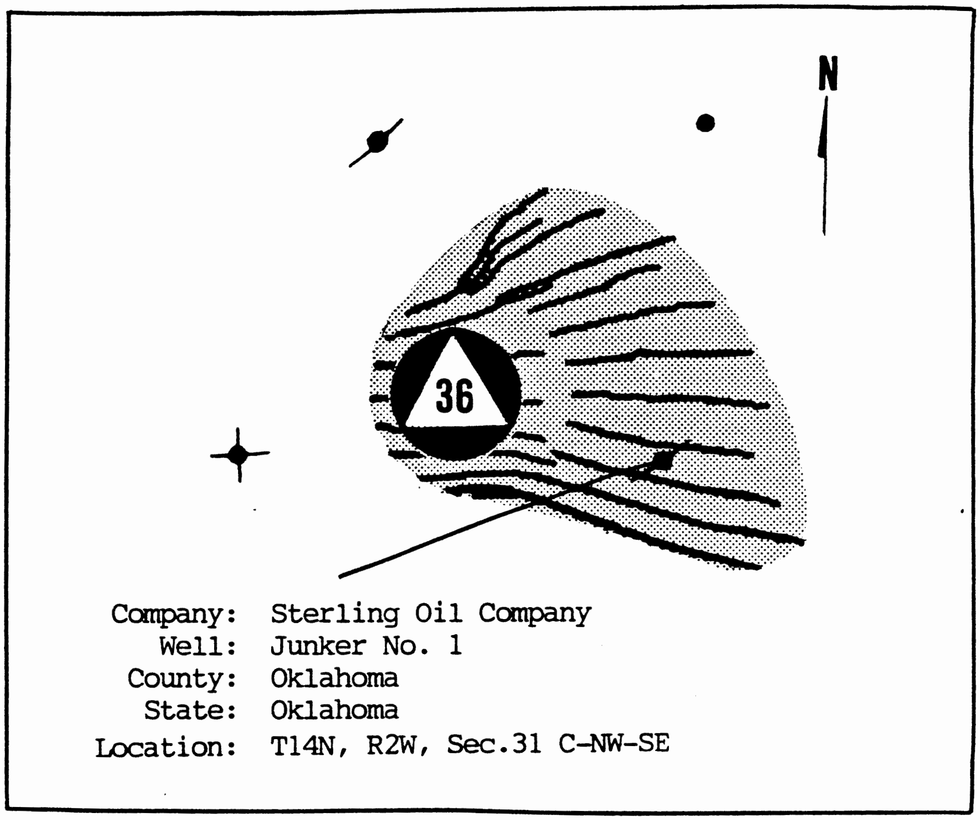
Oklahoma State Department of Health (OSDH) maintain records of water wells. In addition to these sources, the Association of Central Oklahoma Governments (ACOG) and mapping service companies can provide useful information as well.

Within each WHPA delineated, an inventory of the potential sources of contamination present can be made. In addition to consulting the state agencies and other sources, field surveys could be conducted in each WHPA delineated.

Figure 55 shows the 10-Year WHPA delineated for municipal well 36. A plugged oil well within the WHPA lies approximately 750 feet southeast of the water well. A copy of the electric log run on the oil well was obtained from the Oklahoma Geological Survey's log library in Oklahoma City. From this log the well was identified as the Junker 1, which was operated by the Sterling Oil Company beginning in 1952. Using the information available, the plugging report for the well was obtained from the well records department at the OCC (Figure 56).

The electric log shows that the well was constructed on a ground elevation of 1102 feet using 248 feet of large diameter steel surface casing and over 5500 feet of 5 1/2-inch diameter steel casing. The surface casing is intended to protect the freshwater aquifer from contamination if any leakage occurs from the interior 5 1/2-inch well casing.

In 1952, a depth of 248 feet was probably sufficient to protect most of the existing water wells in the area. With the later use of deep water wells, where the perforations usually do



EXPLANATION

-Edmond Municipal Water Well No. 36 -Plugged Oil Well
-Dry Oil Well -Oil Well - 10 Year Wellhead Protection Area

SCALE

0 1500

Feet

Figure 55. Location of a Potential Source of Contamination in the 10-Year Wellhead Protection Area Delineated for Edmond's Municipal Water Well 36

FORM NO 002

P62- 02460

640 Acres 3 5 0 0 1 0 0 7 1

PLUGGING RECORD

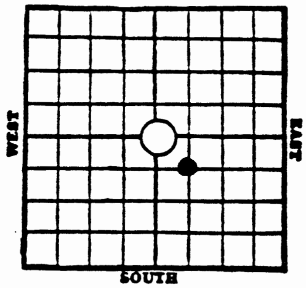
Mail To

OKLAHOMA CORPORATION COMMISSION

Oil and Gas Conservation Department

Oklahoma City, Oklahoma

NORTH



SOUTH

Locate Well Correctly

NOTICE: All questions on this form must be satisfactorily answered.

Company Operating: Midwest Pipe & Supply Co.

Office Address: Box 852 Oklahoma City, Okla.

County: Oklahoma Sec. 31 Twp. 14N Range 2W

Location in Section: C ¼ NW ¼ SE ¼

Farm Name: Junker Well No. 1 Field: Edmond

Character of Well (whether oil, gas or dry): Depleted Oil Well

Commenced Plugging: 1-2-58 Finished: 1-8-58 Total Depth: 5980'

Was permission obtained from the Corporation Commission or its agents before plugging was commenced: Yes

Name of Conservation Officer who supervised plugging of this well: V. E. Bradley

Name of producing sand: Depth top: Bottom:

Show depth and thickness of all fresh water, oil and gas formations.

SAND OR ZONE RECORDS				CASING RECORDS		
FORMATION	CONTENT	FROM	TO	SIZE	PUT IN	PULLED OUT
				5-1/2"		5018'

Describe in detail the manner in which the well was plugged, indicating where the mud fluid was placed and the methods used in introducing it into the hole. If cement or other plugs were used, state the character of same and depth placed:

Pumped plug with 10 sax cement to 5500'. Pulled casing filled hole with liquid mud. Pumped plug with 10 sax cement to 800' Filled with liquid mud and capped with 5 sax cement.

Does the above conform strictly to the oil and gas regulations? Yes

REMARKS: Why plugged? Depleted If abandoned oil or gas well, state amount and date of last production

Correspondence regarding this well should be addressed to: Midwest Pipe & Supply Co.

Address: P. O. Box 852
Oklahoma City, Okla.

I, the undersigned, being first duly sworn upon oath, state that this well record is true, correct and complete according to the records of this office and to the best of my knowledge and belief.

[signature]

Name and title of representative of company

Subscribed and sworn to before me this the 24th day of August 1962

Commission expires October 19, 1965

Roy H. D. Hamilton

Notary Public

CONSERVATION DEPARTMENT AUG 24 1962 OKLAHOMA CORPORATION COMMISSION

Figure 56. Plugging Record of an Oil Well Obtained from the Oklahoma Corporation Commission

not even begin until a depth of 250 feet is reached, surface casing extending to this depth is ineffective. The perforations for well 36 begin at a depth of 166 feet and extend to a depth of 562 feet. Thus, for 314 feet, well 36 is not protected by surface casing on the oil well. Most of the oil and gas wells in the Northeast Edmond Oil-field were constructed with less than 250 feet of surface casing.

The plugging report indicates that when the well was closed, the 5 1/2-inch casing was removed and that mud was used to seal the hole. Cement plugs were put at depths of 5500 feet and 800 feet and the well was capped with cement. If the mud used to plug the well has settled in the 34 years since it was installed, or if the cement plugs have deteriorated, then a potential pathway exist for the migration of contaminants into the freshwater sand units supplying well 36 (Canter and Fairchild, 1984).

Water Quality of the Central Oklahoma Aquifer

In order to better estimate the risk of contamination facing Edmond's well-field, a general understanding of the water quality of the COA and the factors that can influence it must be addressed. A variety of groundwater compositions are present in the COA. Generally, calcium-magnesium bicarbonate groundwater is found in the unconfined portion of the aquifer; while sodium bicarbonate groundwater is found in the confined portion of the aquifer (McBride, 1985). Sulfate-rich groundwater is present in some areas of the aquifer where ever it is overlain by the Hennessey Group. Sodium chloride-rich water is present beneath the freshwater zone throughout the COA. Using chemical and petrographic data in geochemical modeling, the predominant geochemical reactions controlling the composition of groundwater in the COA have been identified to be as follows:

* uptake of carbon dioxide;
* dissolution of dolomite and, to a lesser extent calcite;
* cation exchange of calcium and magnesium onto clay minerals with the release of sodium;
* dissolution of gypsum; and
* dispersion of freshwater with pre-existing brines.

In the unsaturated zone, recharge water picks up carbon dioxide from the respiration of plants. This appears to be the only source of carbon dioxide in the aquifer. As a result of this, dolomite and calcite within the aquifer are dissolved.

The most significant reaction in the aquifer appears to be cation exchange on the clay minerals. In the confined portion, and in clay-rich areas of the unconfined portion, of the COA, sodium concentrations are large while calcium concentrations are small. In these areas, the clays contain a large fraction of exchangeable sodium, up to 50 percent of the exchangeable cations (Parkhurst, 1992). The transition in water compositions from small to large sodium concentrations is explained by an exchange of calcium and magnesium onto the clays with the release of sodium into the water. The cation-exchange reaction causes a small amount of dolomite to dissolve to maintain dolomite equilibrium. The main effect of the dissolution of dolomite is to raise pH values in the aquifer to the range of 8.5 to 9.1 with only a small increase in bicarbonate concentration (Parkhurst, 1992)

Water analyses from some of Edmond's municipal wells were used to construct water quality maps with respect to certain constituents. These analyses are presented in Appendix H. Figure 57 shows the distribution of pH in the well-field. The values range from a low of 7.49 to a high of 9.2, with an average value of 7.82. The U.S. EPA recommends that pH values for drinking water be in the range between 6.5 and 8.5. With the exception of a single well, all the wells in the well-field meet the EPA's recommended limit. Figure 58 shows the distribution of total alkalinity values, reported as ppm as $CaCO_3$, in the well-field. The values range from a low of 232 to a high of 306 with an average value of 269. Figure 59 shows the distribution of hardness values, reported as ppm as $CaCO_3$. The values range from a low of 128 to a high of 308 with an average value of 218. The range of values for the well-field represents water that is considered moderately hard to hard. Figure 60 shows the distribution of conductivity values, reported as micromhos/cm, in the well-field. The values range from a low of 469 to a high of 624 with an average value of 527. Although there is no EPA standard for electrical conductivity, there is a 500 mg/l limit for total dissolved solids. This can

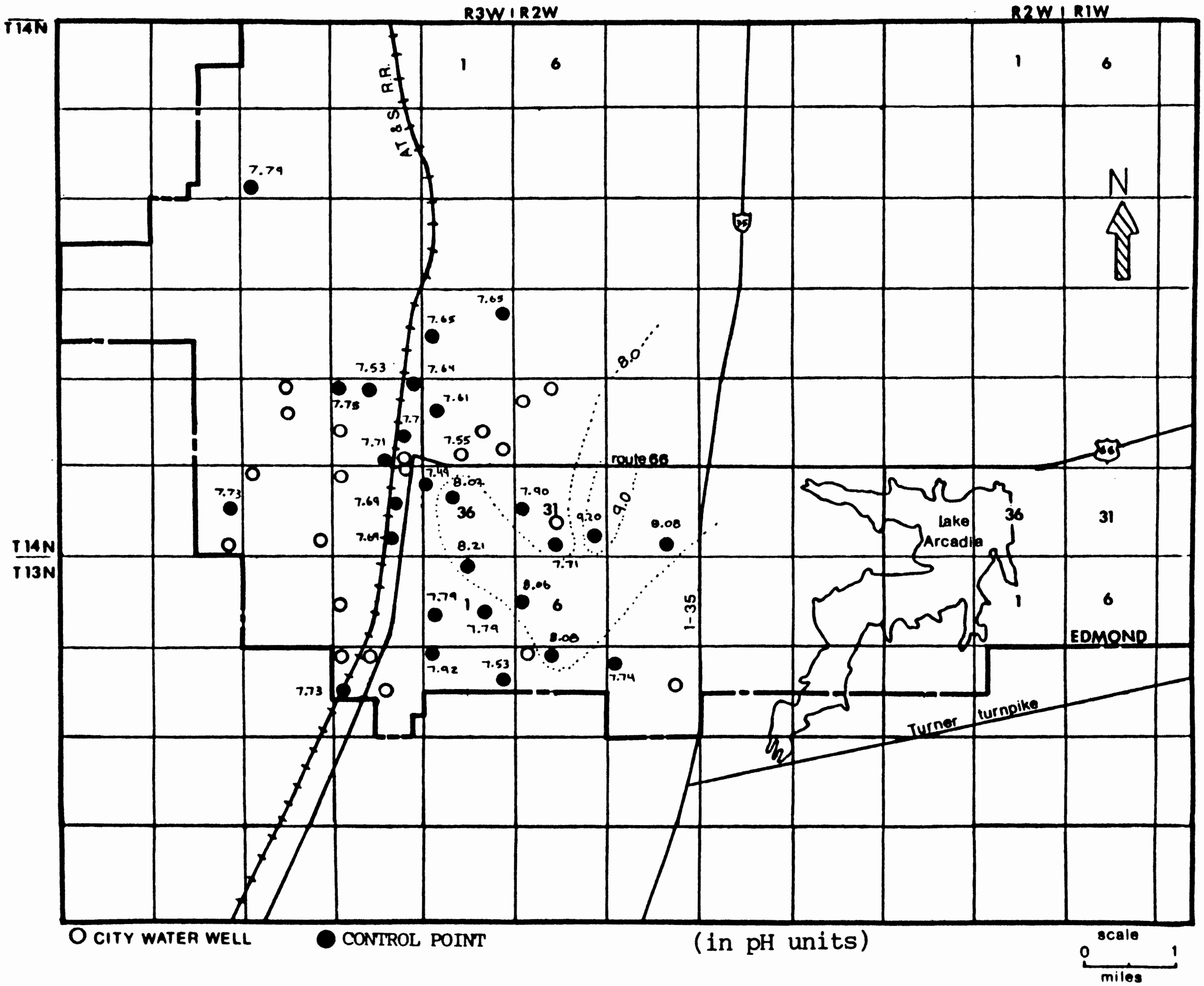


Figure 57. Distribution of pH in the Edmond Municipal Water Well-field

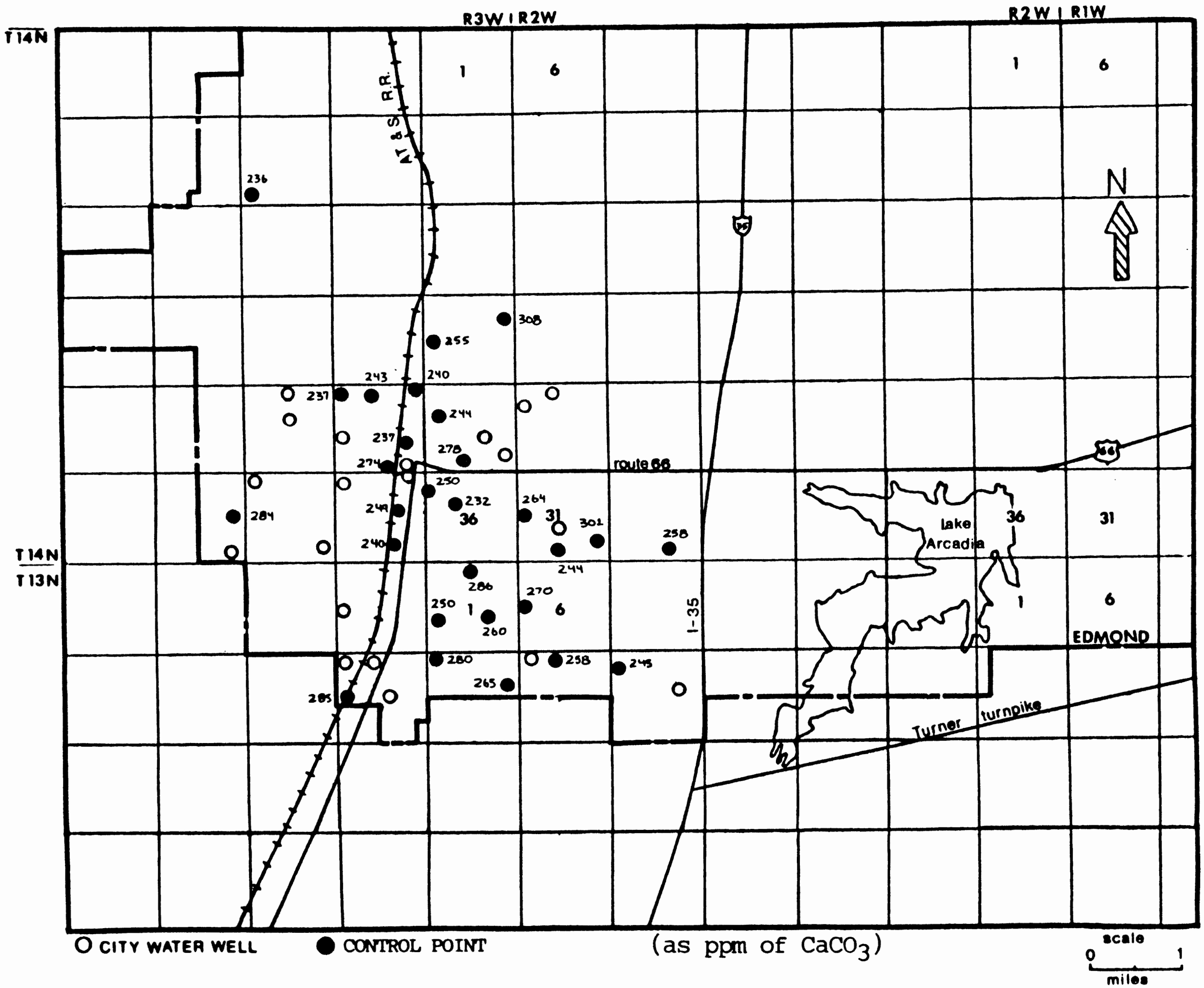


Figure 62. Distribution of Total Alkalinity in the Edmond Municipal Water Well-Field.

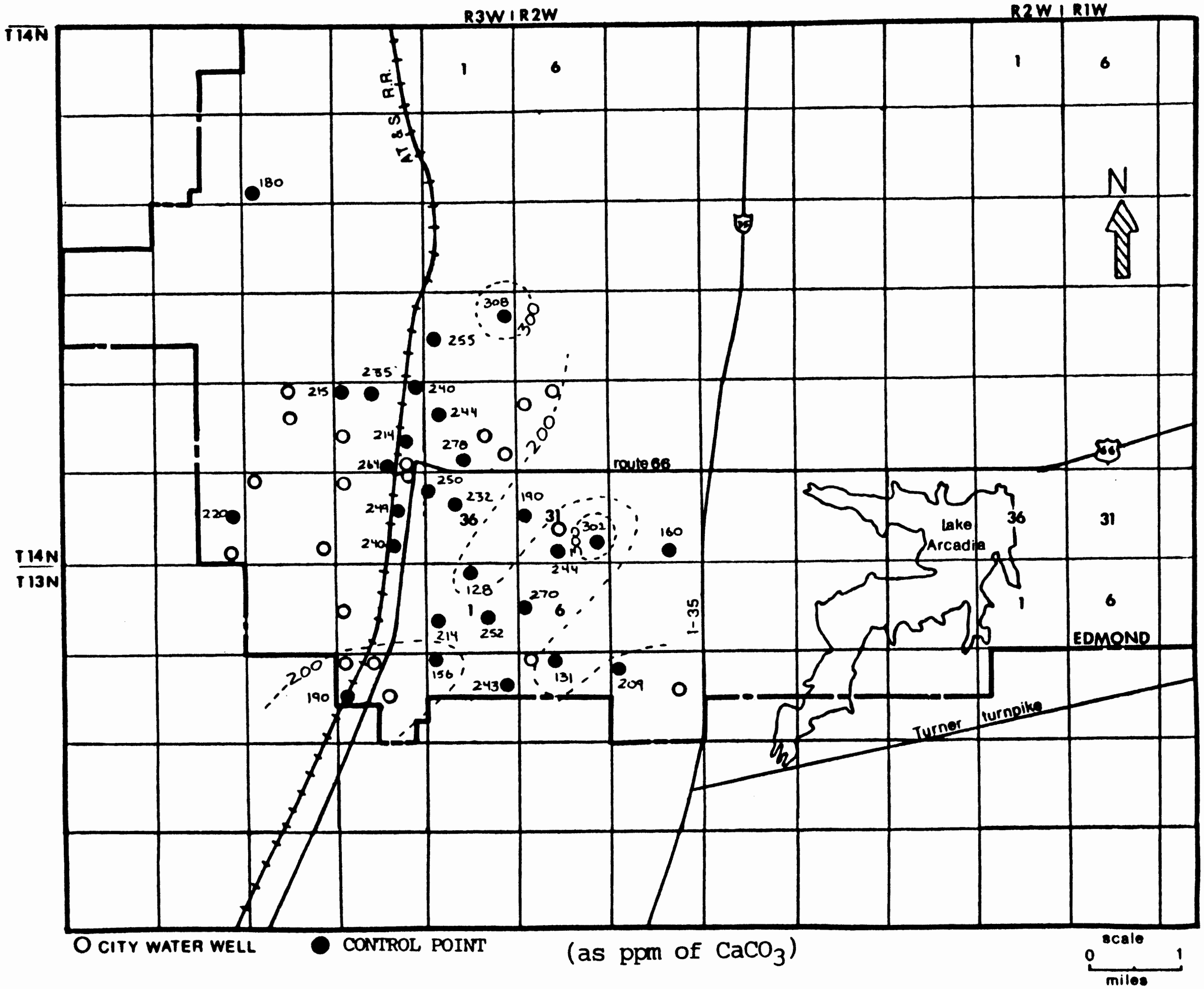
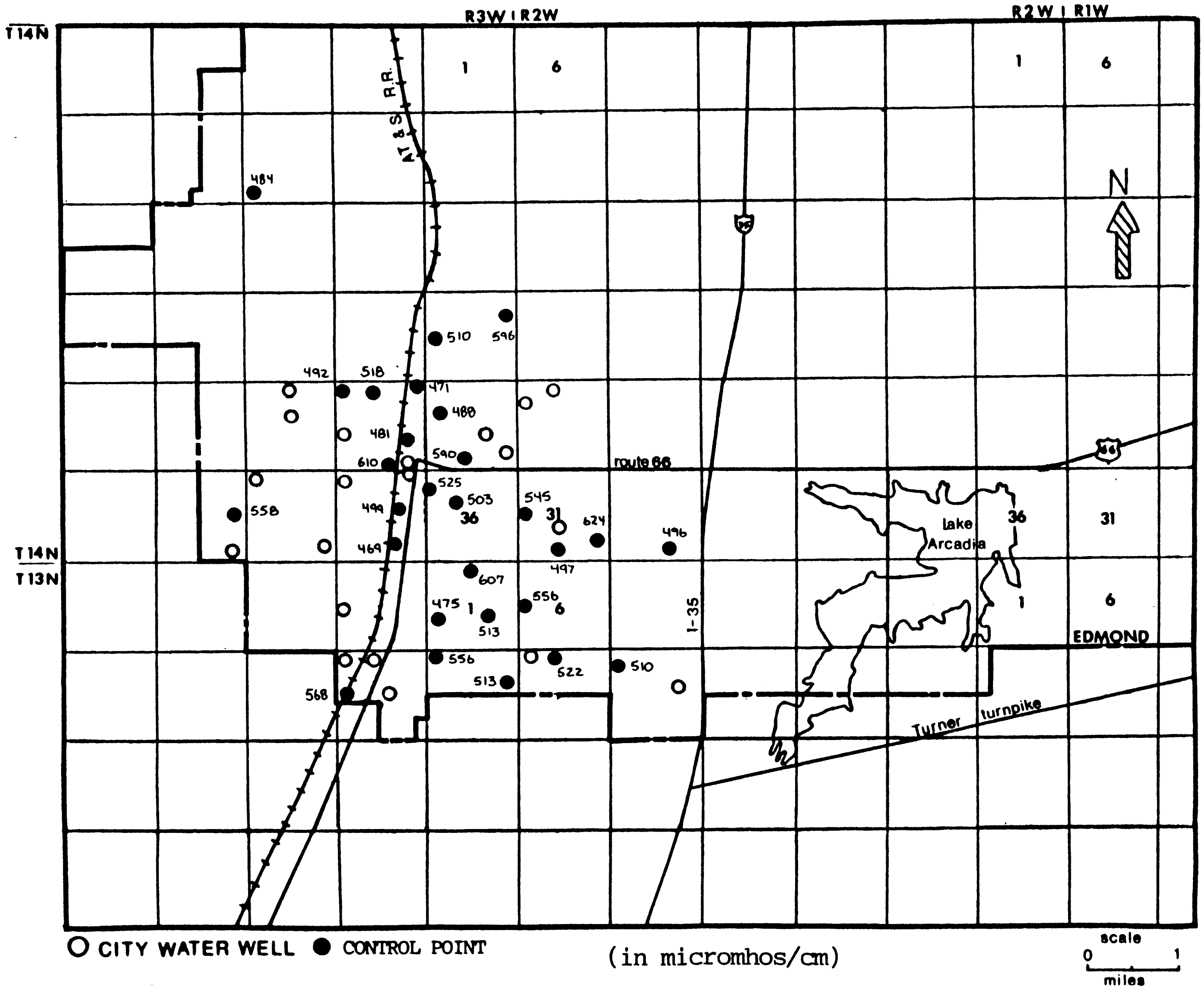


Figure 63. Distribution of Hardness in the Edmond Municipal Water Well-Field.



(in micromhos/cm)

Figure 64. Distribution of Conductivity in the Edmond Municipal Water Well-Field.

be converted to a conductivity value of about 800 micromhos/cm. None of the samples from the well-field exceed this limit.

The general character of the water in the COA in the Edmond area is moderately hard to hard and alkaline, with high pH values. Water from the aquifer meets the EPA standards for drinking water concerning the constituents measured. Scaling and encrusting on pipes and fixtures may be a problem due to the alkaline nature of the groundwater.

Natural Water Quality Concerns

The COA contains naturally occurring trace elements that may locally be present in amounts that can be cause for concern. Vanadium, chromium, selenium, arsenic, and uranium have been measured in varying quantities throughout the COA. The concentration of these elements may be aggravated by over pumping of the aquifer, which cause leakage from or through the confining units, resulting in the release of increased quantities of these elements. McBride (1985) described how the high pH values in the COA tend to decrease adsorption of these trace elements, increasing their concentration in the groundwater.

High chloride levels have been encountered by wells that have been drilled too deeply into the COA and have penetrated the brackishwater zone. Apparently, during the early stages of groundwater development in the Edmond well-field, well 6 was drilled to such a depth that it encountered water with a chloride content of 266 ppm (Benham-Blair and Affiliates, 1965).

Harrington and Simpson (1990) reported that gross alpha radiation has been a sporadic problem in the Nichols Hills' well-field. Gross alpha radiation is derived from trace amounts of naturally-occurring uranium present in the Garber-Wellington. Radiation levels have slightly exceeded EPA's recommended limit for gross alpha radiation in a few well throughout the COA.

Water Quality Concerns Associated with Human Activities

The major concern regarding water-quality degradation in the COA from human activities is with respect to oil-field brines. Local water-quality degradation may result from oil-field activities, such as seepage from waste pits, defective well construction, defective well plugging, water flooding operations, or improper brine disposal.

Conclusive evidence of oil-field contamination is not common in the study area. Several domestic water wells near the Northeast Edmond Oil-field have been contaminated by high chlorides and oil-field activity in the vicinity is generally suspected as the source. Evidence suggesting that degradation of the water quality of shallow sand units in the COA in the Edmond area has occurred can be seen from driller's logs of domestic water wells obtained from the OWRB. Figure 61 shows that the well, located near the Northeast Edmond Oil-field, penetrated brackish water at depths of 70, 130, and 180 feet into the COA. Normally, brackishwater is not encountered in this area before reaching a depth of at least 550 feet. Figure

White — Water Resources Board
Canary — Drillers Copy
Pink — Drillers Copy

#7329

STATE OF OKLAHOMA
WATER RESOURCES BOARD
1000 N E 10th St., P O Box 53585
Oklahoma City, Oklahoma 73152

Application No. ______
Aquifer ______
Steam System Code ______
Use Code ______
County ______

1. OWNER Quasar Construction Co. ADDRESS 1225 W Main Suite 232
Norman OK 73069 PHONE 364-6597

2. LEGAL DESCRIPTION OF WELL
NE ¼ of NE ¼ of SW ¼ of sec. 21 ; TWP. 14 N S; Rge. 2 EIM WIM ECM; COUNTY Okla.

3. TYPE OF WORK
☑ New Well ☐ Plugging
☐ Reconditioning Work ☐ Test

4. PROPOSED / PAST USE
☑ Domestic ☐ Irrigation ☐ Stock
☐ Municipal ☐ Industrial ☐ Test

5. DRILLING METHOD
☑ Rotary ☐ Rev. Rotary
☐ Cable ☐ Other ______

6. LOG

Material	From	To	Saturated ✓
Sand	0	4	
Sandrock	4	60	
Shale	60	70	
Watersand (salt)	70	90	
Shale	90	130	
(Salt) Water	130	160	
Shale	160	180	
(Salt) Water	180	210	
Shale	210	255	
Watersand	255	260	
Shale	260	300	
Watersand	300	320	
Shale	320	375	
Watersand	375	390	
Well cemented to 40 ft below surface. Bottom 50 ft. of hole gravel packed.	335	[illegible]	

7. NEW WELL CONSTRUCTION DATA

Dates: Started 9-20-83 Completed 9-20-83
Contractor Choctaw Pump & Supply
Driller Eugene Rotramel
Diameter Hole 7⅞ in. Total Depth 390 ft.

CASING RECORD

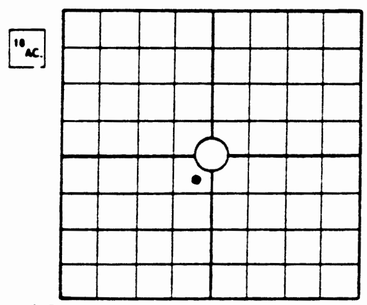
Diameter	From	To
4½ O.d. in.	3 ft.	390 ft.
in.	ft.	ft.

Surface Seal: ☑ Yes ☐ No Type: Steel
Depth of Seal: 5'7" ft. attached to 4½" steel
Gravel Packed:
Gravel Packed From 335 ft. to 390 ft.
Amount Used: ¾ ton

PERFORATION RECORD

Type 3/16 hole From 364 ft. To 385 ft.
Size ______ From ______ ft. To ______ ft.
" ______ From ______ ft. To ______ ft.

11. PLAT



NE ¼ of NE ¼ of SW ¼ of SEC 21 ;
TWP 14 N S; RGE 2 EIM WIM ECM

13. CERTIFICATION

The work described above was done under my supervision, and this report is true and correct to the best of my knowledge.

Name Eugene Rotramel License # ______
Address 3211 Effie Dr. Choctaw Phone # 390-2259
Signed Eugene Rotramel Date 9-24-

Figure 61. Driller's Log of a Domestic Water Well in the Edmond Area Showing Possible Brackishwater Contamination of Three Sandstone Units in the COA

62 shows another well in the same area that encountered brackish water below a depth of 100 feet.

The evidence suggesting there is probably some degradation of the water quality of the COA associated with oil-field activity in the vicinity of Edmond underscores the threat of contamination to the confined portions of the COA supplying Edmond's water.

White — Water Resources Board
Canary — Drillers Copy
Pink — Drillers Copy

#7330

MULTI-PURPOSE WATER WELL REPORT

STATE OF OKLAHOMA
WATER RESOURCES BOARD
1000 N.E. 10th St., P.O. Box 53585
Oklahoma City, Oklahoma 73152

Application No. ______
Aquifer ______
Steam System Code ______
Use Code ______
County ______
(Official Use Only)

1. OWNER Guy Bower ADDRESS 1519 W. Gemini
Edmond 73034 PHONE 340-0052

2. LEGAL DESCRIPTION OF WELL
NE ¼ of NE ¼ of SW ¼ of sec. 21; TWP. 14 N/S; RGE 2 EIM (Circle One) WIM ECM; COUNTY OK

3. TYPE OF WORK
☑ New Well ☐ Plugging
☐ Reconditioning Work
☐ Test Monitoring

4. USE
☑ Domestic
☐ Stock
☐ Test Monitoring

NON-DOMESTIC
☐ Irrigation
☐ Municipal
☐ Industrial
☐ Commercial
☐ Other

5. DRILLING METHOD
☑ Rotary ☐ Rev. Rotary
☐ Cable ☐ Other ______
☐ Air

6. LOG

Material	From	To	Saturated
Sand Rock - Rock - wet Slow	0	20	
Sand Rock	20	60	
Sand Rock & water	60	80	
Water sand	80	100	

SALTWATER

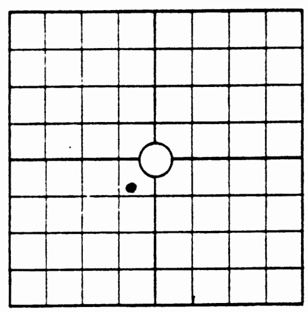
RECEIVED
APR 6 1987
Oklahoma Water Resources

7. LOCATION PERMIT
If this well is Non-Domestic, has this location been permitted?
☐ Yes ☐ No Permit No. ______

8. NEW WELL CONSTRUCTION DATA
DATES: Started 4 Dec 86 Completed Same
Contractor Poindexter
Driller David
Diameter Hole 6 3/4 in. Total Depth 100 ft.

11. PLAT

10 AC



NE ¼ of NE ¼ of SW ¼ of SEC 21;
TWP 14 N/S; RGE 2 EIM WIM ECM (Circle One)

10. PLUGGING DATA
Date Plugged 4 Dec 86
Backfilled With Earth Material To 20 ft.
Grouted or Cemented From CLAY 20 ft. To Surface ft.
Plot Location in Item 11. Show Distances From 2 Section Lines.

14. CERTIFICATION
The work described above was done under my supervision, and this report is true and correct to the best of my knowledge.
Name Poindexter Supply Co License # WD33
Address 4610 NW 10 Phone # 943-3824
Signed David A Poindexter Date 4 Dec 86

Figure 62. Driller's Log of a Domestic Water Well in the Edmond Area Showing Possible Brackishwater Contamination of Shallow Sandstone Units in the COA

CHAPTER VIII

SUMMARY AND RECOMMENDATIONS

Summary

The 1986 amendments to the Safe Drinking Water Act (SDWA) mandate the establishment of protection areas around wells serving as public drinking water supplies. These zones, called welled protection areas (WHP), are intended to protect areas of the aquifer supplying water to public water wells from contamination. The delineation of WHP's is intended to be a major part of state-level welled protection (WHP) programs. The WHP program for the State of Oklahoma requires that WHPA delineations follow a multiple zone approach.

* Zone I - to protect against the direct introduction of contaminants into the well and from microbial contaminants.
* Zone II - to protect against chemical contamination.

In order to produce accurate WHPA delineations for Edmond's municipal water wells, the geologic framework and water bearing properties of the Garber-Wellington formation, which constitutes the Central Oklahoma aquifer (COA), were examined. Previous geologic and hydrogeologic investigations, geophysical well logs from the municipal water wells and oil and gas wells, and aquifer test were used to characterize the properties of the COA.

The aquifer is composed of a complex of interlayered units of cross-bedded, fine-grained, friable sandstone and silty to sandy shale. The thickness of individual units ranges from a few feet to around 50 feet and the thickness of the Garber-Wellington in the area is about 800 to 1000 feet. Estimated geologic and hydrogeologic properties of the aquifer are summarized in Table X.

The withdrawal of water from the COA from Edmond's municipal well-field has produced a large cone of depression in the aquifer. Using monthly water level measurements and pumping schedules, the amount of water produced from the well-field was seen to have declined since 1988. This is believed to be the result of contributions from the water treatment plant at Lake Arcadia starting in 1988. The extent of the cone of depression has reflected the decreased withdrawal of water from the aquifer.

The cone of depression produces a complex pattern of groundwater flow within the well-field. In some areas, the general flow of groundwater is one-directional and uniform. In other areas it appears to be multi-directional and highly variable due to the formation of localized areas of increased

TABLE X

SUMMARY OF THE GEOLOGIC AND HYDROGEOLOGIC PROPERITIES OF THE CENTRAL OKLAHOMA AQUIFER

Geologic/Hydrogeologic Property	Description
Major Faults	None evident
Fractures	N. 80 W. and N. 40 W. N. 0 W. and N. 60 E.
Strike	NW-SE
Dip	40 feet/mile - W-SW
Folds	Homoclinal
Transmissivity	2500 gpd/ft
Hydraulic Conductivity	12 gpd/ft^2
Storage Coefficient	.0002
Recharge - Unconfined Aquifer	1.6 - 3.2 inches/year
Aquifer Thickness	200 feet
Elevation of the Base of Freshwater Zone	600 - 300 feet above sea level
Elevation of the Base of Brackishwater Zone	500 - 200 feet above sea level

drawdown.

The various criteria used to delineate WHP's are summarized in Table XI. The various methods used to produce WHP's are summarized in Table XII. Given the characteristics of the aquifer and the well-field, the time of travel (TOT) criterion was selected upon which to base WHPA delineations. The methods chosen with which to produce the delineations were the analytical and numerical modeling methods. EPA's General Particle Tracking Module (GPTRAC) computer program was used to generate the WHP's for each of the water wells in Edmond's well-field.

GPTRAC contains a both a semi-analytical and a numerical option. The model is capable of generating flowpath by performing particle tracking functions incorporating well interference effects on groundwater flow. The semi-analytical option uses the Theis non-equilibrium equations to determine the drawdown, and the resulting flow velocity, given the hydraulic properties of the aquifer, pumping rates, and time limits for the simulation. The numerical option uses numerical integration functions to determine the velocity of groundwater flow using hydraulic heads in an external file.

The semi-analytical option proved best suited for generating WHPs in close proximity to the well, when the well was not heavily pumped, and when the groundwater flow pattern in the area was generally one-directional and uniform. The numerical option proved best suited to generate WHP's in areas where the wells were heavily pumped and the groundwater flow

TABLE XI

SUMMARY OF WELLHEAD PROTECTION AREA DELINEATION CRITERIA

Wellhead Protection Area Delineation Criteria
Distance
Drawdown
Time Of Travel
Flow Boundaries
Assimilative Capacity

TABLE XII

SUMMARY OF WELLHEAD PROTECTION AREA DELINEATION METHODS

Wellhead Protection Area Delineation Methods
Arbitrary Fixed Radius
Calculated Fixed Radius
Simplified Variable Shapes
Analytical Models
Numerical Models
Hydrogeological Mapping

patterns were multi-directional and complex. The time-related WHP's were produced using the required multiple zone approach as follows:

* Zone I - 1 year TOT based WHPA; and
* Zone II - 10 and 20 year TOT based WHP's.

The resulting WHP's were mapped on the base map of the area (Plates 7,8, and 9).

The vulnerability of the COA to potential sources of contamination was found to be primarily a product of its geologic framework. The shale units provide a high degree of hydraulic separation between the sand units supplying the municipal water wells and shallower or deeper units which might contain water of lower quality. However, activities exist in the study area which could provide a pathway that would permit contaminated water to migrate into the units supplying water to the municipal wells.

Deep well-drilling activities associated with oil and gas production and groundwater development have produced the following potential sources of contamination:

* deep water well;
* closed deep water wells;
* oil and gas wells;
* plugged oil and gas wells;
* secondary recovery (waterflooding) wells; and

* brine disposal wells.

The quality of water in the COA is generally good. Some areas have problems with small amounts of naturally-occurring trace elements such as vanadium, selenium, chromium, arsenic, and uranium. These problems are mainly localized and are not a widespread concern. Brackishwater underlies the freshwater zone throughout the COA and can be a problem if it is induced to migrate upwards.

Evidence obtained from driller's logs from domestic wells near the Northeast Edmond Oil-field suggest that there has been some degree of water quality degradation within sand units of the unconfined COA in the area. Many oil and gas wells in this oil-field were drilled in the 1950's without sufficient surface casing. Many of the wells have since been improperly plugged or possibly abandoned, contributing to any oil-field brine contamination present.

Recommendations

It is recommended that the City of Edmond formulate and implement a contingency plan in order to further protect its drinking water supply from possible contamination. Some of the general guidelines of such a plan might be as follows:

* locate all potential sources of contamination within the WHP's;
* asses the apparent risk of contamination from the identified sources;

* determine appropriate responses to any contamination risk and prioritize them;

* determine a chain of responsibility to be followed in the event contamination is detected in the well-field;

* insure that the city has an alternate source of drinking water; and

* identify resources available to the community with which to meet the objectives of a contingency plan.

Accurate records of the pumping schedules and water levels of the wells should continue to be maintained and made accessible to several individuals at all times. It would be advantageous to instruct individuals from different departments about the function and general operating procedures of the well-field.

The WHP's could serve as focal points for initial inventories of potential sources of contamination inventories. At some stage it would be prudent to expand these efforts to include a broader general aquifer protection plan designed to include all potential sources of contamination within the well-field's zone of influence, or cone of depression.

In order to supplement information concerning the location of potential sources of contamination obtainable from various state agencies, field surveys could help identify those sources that are unreported. Communication with local citizens could prove invaluable in locating potential sources of contamination related to past activities of which there is presently little or no record (Pettyjohn, 1989).

Through continuous monitoring of the chemical quality of the water produced from the city water wells, sufficient background data can be maintained with which to detect any water quality degradation in time to facilitate the location of likely potential sources of the contamination.

REFERENCES

Association of Central Oklahoma Governments (ACOG), 1980, Aquifer test conducted on Nichols Hills' municipal wate well #10: Garber-Wellington Association.

Association of Central Oklahoma Governments (ACOG), 1991, Land-use map of Edmond, Oklahoma: Garber-Wellington Association.

Benham Blair and Associates, 1965, A report on the present water system and the proposed improvements to the water supply and water distribution system for the City of Edmond, Oklahoma: pp. 24.

Bingham, R.H. and Moore, R.L., 1975, Reconnaissance of the water resources of the Oklahoma City Quadrangle, cental Oklahoma: Oklahoma Geological Survey Hydrologic Atlas Number 4, scale 1:250,000.

Blandford, T.N. and Huyakorn, 1990, A modular semi-analytical model for the delineation of wellhead protection areas: Office of Groundwater Protection, U.S. Environmental Protection Agency, Washington D.C., pp. 100.

Burton. L.C. and Wood, P.R., 1968, Groundwater resources of Cleveland and Oklahoma counties: Ok. Geological Survey, Circular 71, pp. 181.

Canter, L.W. and Fairchild, D.M., 1984, Impacts of oil and gas field activities on groundwater quality: Environmental and Groundwater Institute, University of Oklahoma, Norman, Oklahoma, pp. 248.

Carr, J.E. and Havens, J.S., 1976, Records of wells and water quality for the Garber-Wellington aquifer, southern Logan and northern Oklahoma counties, Oklahoma: U.S. Geological Survey Open File Report 76-619.

Carr, J.E. and Marcher, M.V., 1977, A preliminary appraisal of the Garber-Wellington aquifer in southern Logan and Oklahoma counties, Oklahoma: U.S. Geological Survey Open File Report 77-278, pp. 23.

Christenson, S.C., Parkhurst, D.L. and Schlottmann, J.L., 1989, Groundwater quality assessment of the Central Oklahoma aquifer, Oklahoma - analysis of available water quality data through 1987: U.S. Geological Survey Open File Report 88-728, pp. 79.

Christenson, S.C., Morton, R.B. and Messander, B.A., 1990, Hydrogeologic maps of the Central Oklahoma aquifer: U.S. Geological Survey Open File Report 90-579, 6 maps.

Christenson, S.C., 1992, Geohydrology and groundwater flow simulation of the Central Oklahoma aquifer: Abstract for Groundwater Quality of the Central Oklahoma Aquifer: a symposium by the U.S. Geological Survey, Open File Report 92-116.

Dennis, P.E., 1954, Geology and groundwater hydrology of the Lake Hefner area, Lake Hefner studies technical report: U.S. Geological Survey Proffessional Paper 269, pp. 10-16.

Fetter, C.W., 1988, Applied hydrogeology (2nd ed.), Merrill Publishing Co. Columbus, OH. pp. 592.

Goff, K., 1992, Theis Well-Field: Oklahoma State University, School of Geology, Stillwater, OK.

Harrington, J.M. and Simpson, L.C., 1990, Municipal well site investigation, Nichols Hills well-field: Association of Central Oklahoma Governments, Garber-Wellington Association, pp. 82.

Heath, R.C., 1987, Basic groundwater hydrology: U.S. Geological Survey Water Supply Paper 2200, pp. 84.

Herndon Map Service Inc., 1988, Map of oil-field activity for T13N, R2 & 3W; T14N, R2 & 3W.

Isenberg, P.M., 1990, Wellhead protection area study for Norman, Oklahoma: Unpublished Masters of Science Special Report, University of Oklahoma, pp. 54.

Jacobsen, C.L. and Reed, E.W., 1944, Groundwater supplies in the Oklahoma City area, Oklahoma: Ok. Geological Survey Mineral Report #20.

Kennedy, L.G., 1990, Confining layer study in the West Edmond Oil-Field area using subsurface, remote sensing, and geochemical methods: Unpublished Masters of Science Thesis, Oklahoma State University, pp. 146.

Lawson, J.E. and Luza, K.V., 1981, Seismicity and tectonic relationships of the Nemaha Uplift in Oklahoma part III: U.S. Nuclear Regulatory Commission, NUREG/CR-2439, pp. 52.

McBride, K.K., 1985, Hydrogeochemistry and occurrence of selenium in the Garber-Wellington aquifer, central Oklahoma: Unpublished Masters of Science Thesis, Oklahoma State University, pp. 104.

Melton, F.A., 1955, Photogeology in flatland regions of low dip: Shale Shaker Digest, vol. II, pp. 31-43.

Meyer, R.D., 1975, The surficial geology of the Guthrie North Quadrangle, Logan county: Unpublished Masters of Science Thesis, Oklahoma State University, pp. 60.

Oklahoma Department of Pollution Control (ODPC), 1989, Wellhead protection program for the state Oklahoma: Oklahoma City, Oklahoma, pp. 36.

Oklahoma Water Resources Board (OWRB), 1980, Oklahoma comprehensive water plan: OWRB Publication #94.

Oklahoma Water Resources Board (OWRB), 1990, T-O-T, a computer program for the delineation of wellhead protection areas: OWRB Groundwater Division, pp. 37.

Parkhurst, D.L., 1992, The geochemical evolution of groundwater in the Central Oklahoma aquifer: Abstract for Groundwater quality of the Central Oklahoma aquifer: a symposium by the U.S. Geological Survey, Open File Report 92-116.

Pettyjohn, W.A., 1989, Development of a groundwater management and aquifer protection plan: Report to Engineering Enterprises Inc., pp. 59.

Pettyjohn, W.A., Savoca, M., Self.D., 1991, Regional assessment of aquifer vulnerability and sensitivity in the continerminuous United States: U.S. Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory, 600/2-91/043, pp. 319.

Simpson, L,C, 1992, Improving water quality and quantity in perforated water wells, a symposium by the U.S. Geological Survey, Open File Report 92-116.

Soil Conservation Service (SCS), 1969, Soil survey of Oklahoma county, Oklahoma: U.S. Government Printing Office.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: Transactions of the American Geophysical Union, vol. 16, pp. 519-524.

U.S. Environmental Protection Agency (EPA), 1985, Protection of public water supplies from groundwater contamination: Seminar Publication EPA/625/4-85/016, Center for Environmental Research, Cincinnati, OH. pp. 182.

U.S. Environmental Protection Agency (EPA), 1987 A, Guidelines for delineation of wellhead protection areas: Office of Groundwater Protection, Washington D.C.

U.S. Environmental Protection Agency (EPA), 1989, Transport and fate of contaminants in the subsurface: Seminar Publication EPA/625/4-89/019, Center for Environmental Research, Cincinnati, OH. and Robert S. Kerr Environmental Research Laboratory, Ada, Ok.

Wickersham, G., 1979, Groundwater resources in the southern part of the Garber-Wellington groundwater basin, Cleveland and southern Oklahoma counties and parts of Pottawatomie county: Oklahoma Water Resources Board Hydrologic Investigations Publication #86.

Worobec, M.D. and Ordway, G., 1989, Toxic substances control guide: Bureau of Nation Affairs Inc., Washington D.C., pp. 239.

APPENDIXES

APPENDIX A

AQUIFIER TEST DATA

Pump Test
Observation well near Well #10 Nichols Hills Well Field
7/ 5/90
DISTANCE TO PUMPING WELL FROM OBSERVATION WELL IS 29 FEET
PUMPING RATE 150 GPM
MIDDLE OBSERVATION WELL

TIME (DECIMAL MINUTES)	DEPTH (FT)	S (FT)
.00	-222	0
7.50	-233	-11
10.27	-236	-14
10.87	-237	-15
13.60	-240	-18
14.42	-241	-19
15.45	-242	-20
16.58	-243	-21
18.30	-244	-22
19.13	-245	-23
20.58	-246	-24
22.23	-247	-25
24.03	-248	-26
27.38	-249	-27
27.83	-250	-28
30.47	-251	-29
40.00	-254	-32
52.48	-257	-35
57.95	-258	-36
70.00	-260	-38
80.00	-262	-40
90.00	-263	-41
100.00	-264	-42
207.00	-274	-52
304.00	-280	-58
390.50	-283	-61
494.95	-287	-65

PUMPING TEST DATA

WELL NO. 6 Test #2

JOB Oak Tree Golf Course LOCATION N.W. Cor

DATE 5/21/81 DATA RECORDED BY G.C.S. / S.C.C.

PUMPED BY (company) Henkle Drilling PUMP TYPE & SIZE

STATIC WATER LEVEL DTW 29.93 Before Redwinding ELEV. MEAS. PT. O.O.Tube.

HEIGHT OF M.P. ABOVE G.L. ≈1' ELEV. M.P.

RATE OF PUMPING MEASURED BY 6"x4" Orifice Tube

REMARKS Pump Drive motor speed varying a little. Second Test. This test run Because contractors Pump tube sprung a leak forcing them to Shut it down to fix. Pump off 7:10 44 p.m.

WELL SKETCH ON BACK

DATE	TIME	t or t/t'	DTW	s	Q	REMARKS
5/21/81	10:30	0	39.20	0	325	
	10:33	3.16	124.46	85.26		
	10:34	4.08	129.07	89.87		
	10:35	5.08	132.94	93.74		
	10:36	6.16	136.49	97.29		
	10:37	7	138.95	99.75		
	10:38	8	140.97	101.77		
	10:39	9	143.05	103.85		
	10:40	10	144.65	105.45		
	10:41	11	146.25	107.07		
	10:42	12	147.71	108.51		
	10:43	13	149.05	109.85		
	10:44	14	150.10	111.90		

Test #2

PUMPING TEST DATA CONTINUED WELL NO. 6 PAGE 2 of 4

DATE	TIME	Minutes t or t/t'	Dtw DTW	s	Q	REMARKS STATIC 39.2
5/21/81	10:45 pm	15	151.61	112.41	325	
	10:46	16	152.55	113.35		
	10:47	17	153.85	114.65		
	10:48	18	155.00	115.80		
	10:49	19	156.15	116.95		
	10:50	20	157.11	117.91		
	10:55	25	160.05	120.85		
	11:00	30	164.03	124.83		
	11:05	35	167.08	127.88		
	11:15	45	171.41	132.21		
	11:20[30]	50	171.97	132.77		
	11:22	52	172.54	133.34		
	11:30	60	174.89	135.69		
	11:40	70	179.58	140.38		
	12:05	95	183.21	144.01		
	12:30	120	187.30	148.10		
	1:00	150	192.05	152.85		
	1:30	180	194.56	155.36		
	1:50	200	195.59	156.39		
	2:31	241	198.88	159.68		
	3:30	300	207.65	168.45		
	4:00	330	209.85	170.65		
	4:40	370	211.81	172.61		
	5:30	420	215.23	176.03		
	6:40	490	217.81	178.61		
	7:40	550	219.87	180.67		
	8:50	620	222.35	183.15		

Test #2

PUMPING TEST DATA CONTINUED WELL NO. 6 PAGE ___ of 4

DATE	TIME	t or t/t'	DTW	s	Q	REMARKS Static 39.20'
5-22-81	10:10	700	223.87	184.67	325	
5-22-81	11:30	780	224.15	184.95		Re-adjust Q to 325 gpm
5-22-81	PM 1:10	880	226.82	187.62		
5-22-81	2:50	980	228.51	189.31		
5-22-81	3:40	1030	229.96	190.76		
5-22-81	4:30	1080	233.01	193.81		∇ Between #7 & #8 Screens
5-22-81	4:55	1105	234.29	195.09		Re-adjust Q to 325 gpm
5-22-81	5:20	1130	235.57	196.37		
5-22-81	5:45	1155	236.65	197.45		
5-22-81	6:30:06	1200	240.315	201.11		Shutdown Pump off 6:30:06
	6:31:28	1201.37/1.37 877	124.15	84.95		
	6:33:45	1203.65/3.65 330	107.57	68.37		
	6:34:36	1204.5/4.5 268	103.80	64.60		
	6:35:06	1205.1/5.1 236	102.02	62.82		
	6:36.06	1206.1/6.1 198	98.65	59.45		
	6:37:06	1207.1/7.1 170	95.84	56.64		
	6:38:06	1208.1/8.1 149	93.45	54.25		
	6:39:06	1209.1/9.1 133	91.18	51.98		
	6:40:06	1210.1/10.1 120	89.15	49.95		
	6:45.06	1215.1/15.1 80	81.42	42.22		
	6:50:06	1220.1/20.1 60.7	76.47	37.27		
	6:55.06	1225.1/25.1 48.8	73.24	34.04		
	7:00:06	1230.1/30.1 40.9	70.85	31.65		
	7:05:06	1235.1/35.1 35.2	68.98	29.78		
	7:10:06	1240.1/40.1 30.9	67.45	28.25		
	7:20:06	1250.1/50.1 25	64.99	25.79		
	7:30:06	1260.1/60.1 21	63.03	23.83		

Test #2

PUMPING TEST DATA CONTINUED WELL NO. 6 PAGE 4 of 4

DATE	TIME	t or t/t'	DTW	s	Q	REMARKS
5-22-81	7:40:06	1270.1/70.1 = 18.1	61.40	22.20		
	7:50:06	1300.1/80.1 = 16	60.07	20.87		
	8:10.06	1300.1/100.1 = 13	57.75	18.55		
	8:30:06	1300.1/120.1 =	55.91	16.71		(End of data)

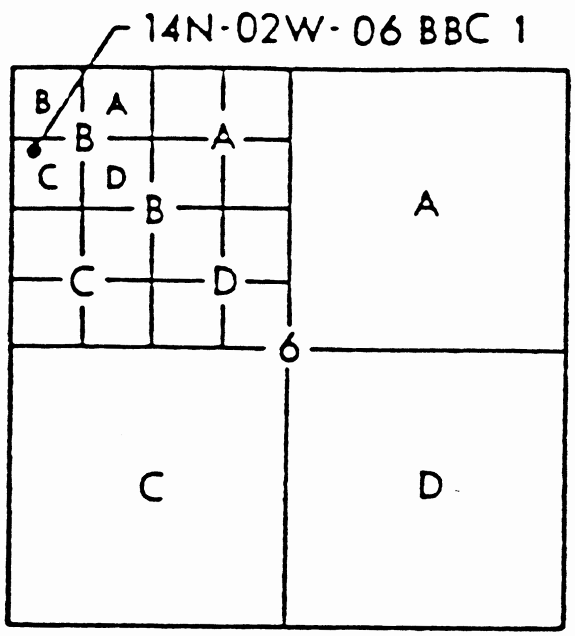
APPENDIX B

LITHOLOGY DATA SHEETS FOR EDMOND'S

MUNICIPAL WATER WELLS

WELL-NUMBERING SYSTEM USED

FOR LITHOLOGY DATA SHEETS



* Perforations

* Perforations

WELL # 9 WELL LOCATION 14N-03W-35 ACD 1
Q(gpm) 260 ELEVATION (feet) 1190 TOTAL DEPTH (feet) 643
SPECIFIC CAPACITY ______ SAND/SHALE RATIO 1.51

STRATA	THICKNESS	DEPTH
~~s~~	4	0
~~sh~~	6	4
~~s~~	20	10
sh	12	30
s	6	42
sh	6	48
s	40	54
sh	10	94
s	10	104
sh	4	114
s	22	118
sh	9	140
s	35	149
sh	19	184
s	11	203
sh	6	214
s	5	220
sh	3	225
s	18	228
sh	6	246
s	4	252
sh	4	256
s	10	260
sh	2	270
s	12	272
sh	16	284
s	10	300
sh	2	310
s	12	312
sh	4	324
s	10	328
sh	2	338
s	50	340
sh	20	390
s	16	410
sh	2	426
s	6	428
sh	4	434
s	12	439
sh	4	450
s	14	454
sh	16	468
s	18	484
sh	8	502
s	4	510
sh	4	514
s	24	518
sh	32	542

STRATA	THICKNESS	DEPTH
s	6	574
sh	14	580
s	8	594
sh	30	602
s	6	632

WELL # 10 WELL LOCATION 14N-03W-25 DBA 1
Q(gpm) 200 ELEVATION (feet) 1224 TOTAL DEPTH (feet) 724
SPECIFIC CAPACITY ______ SAND/SHALE RATIO 1.7

STRATA	THICKNESS	DEPTH
sh	↑	↑
s	4	165
sh	3	169
s	8	172
sh	3	180
s	2	183
sh	5	185
s	8	190
sh	6	198
s	2	204
sh	1	206
s	8	207
sh	7	215
s	22	222
sh	10	244
s	20	254
sh	4	274
s	2	278
sh	5	279
s	18	284
sh	14	302
s	6	316
sh	2	322
s	2	324
sh	3	326
s	8	329
sh	3	337
s	2	340
sh	4	342
s	10	346
sh	4	356
s	24	360
sh	6	384
s	6	390
sh	6	396
s	14	402
sh	8	416
s	7	424
sh	5	431
s	5	436
sh	21	441
s	14	462
sh	8	476
s	6	484
sh	4	490
s	10	594
sh	40	504
s	8	544

STRATA	THICKNESS	DEPTH
sh	8	552
s	7	560
sh	29	567
s	6	596
sh	12	602
s	7	614
sh	5	621
s	24	626
sh	24	650
s	9	674
sh	5	683
s	4	688
sh	4	692
s	↓	696

* Perforations

WELL # 14 WELL LOCATION 14N-03W-25 DDA 1
Q(gpm) 200 ELEVATION (feet) 1183 TOTAL DEPTH (feet) 737
SPECIFIC CAPACITY .71 SAND/SHALE RATIO 1.34

STRATA	THICKNESS	DEPTH
s	4	28
sh	5	32
s	24	37
sh	4	61
s	18	65
sh	4	83
s	12	87
sh	8	99
s	14	107
sh	11	121
s	14	132
sh	3	146
s	12	149
sh	7	161
s	8	168
sh	6	176
s	16	182
sh	8	198
s	8	206
sh	4	214
s	4	218
sh	3	222
s	9	225
sh	4	234
s	8	238
sh	7	246
s	8	261
sh	7	269
s	8	276
sh	4	284
s	4	288
sh	12	292
s	32	304
sh	14	336
s	9	355
sh	11	364
s	7	375
sh	10	382
s	10	392
sh	5	402
s	19	407
sh	9	426
s	9	435
sh	6	444
s	10	450
sh	3	460
s	14	463
sh	10	477

STRATA	THICKNESS	DEPTH
s	9	487
sh	6	496
s	5	502
sh	18	507
s	19	525
sh	6	544
s	14	550
sh	15	564
s	30	579
sh	12	609
s	3	621
sh	5	627
s	20	632
sh	26	652
s	16	678
sh	↓	694

WELL # 16 WELL LOCATION 14N-02W-30 BBC1
Q(gpm) 215 ELEVATION (feet) 1170 TOTAL DEPTH (feet) 775
SPECIFIC CAPACITY .60 SAND/SHALE RATIO 1.66

STRATA	THICKNESS	DEPTH
s	25	0
sh	12	25
s	44	37
sh	18	81
s	22	99
sh	12	121
s	42	133
sh	8	175
s	135	183 *
sh	17	318
s	17	335 *
sh	37	352
s	8	389 *
sh	17	397
s	15	414 *
sh	29	429
s	54	458 *
sh	6	512
s	95	518 *
sh	9	613
s	16	622 *
sh	37	638
s	27	675 *
sh	30	702
s	34	732
sh	9	766

STRATA	THICKNESS	DEPTH

* Perforations

WELL # 3 WELL LOCATION 14N-03W-26 DAC 1
Q(gpm) 285 ELEVATION (feet) 1190 TOTAL DEPTH (feet) 457
SPECIFIC CAPACITY ____ SAND/SHALE RATIO ____

STRATA	THICKNESS	DEPTH
sh	8	0
s	8	8
sh	2	16
s	14	18
sh	17	32
s	12	49
sh	2	58
s	14	60
sh	14	74
s	4	88
sh	6	92
s	8	98
sh	4	106
s	12	110
sh	7	122
s	23	129
sh	3	153
s	4	156
sh	2	160
s	7	162
sh	7	169
s	6	176
sh	9	182
s	4	191
sh	5	195
s	6	200
sh	5	206
s	35	211
sh	10	246
s	16	256
sh	6	272
s	54	273
sh	14	334
s	4	348
sh	4	352
s	16	356
sh	8	372
s	4	380
sh	22	384
s	16	406
sh	4	422
s	4	426
sh	6	430
s	12	436
sh	12	448
s	34	460
sh	18	494
s	14	512
sh	6	526
s	11	532
sh	7	545
s	12	552
sh	8	564
s	4	572
sh	3	576
s	6	579

WELL # 8 WELL LOCATION 14N-03W-36 BBC 1
Q(gpm) 130 ELEVATION (feet) 1190 TOTAL DEPTH (feet) 450
SPECIFIC CAPACITY .75 SAND/SHALE RATIO 1.7

STRATA	THICKNESS	DEPTH
sh	8	0
s	7	8
sh	3	15
s	4	18
sh	2	22
s	8	24
sh	8	32
s	38	40
sh	4	78
s	24	82
sh	18	106
s	6	124
sh	4	130
s	6	134
sh	4	140
s	6	144
sh	12	150
s	12	162 *
sh	8	174
s	6	182 *
sh	3	188
s	8	191 *
sh	9	194
s	6	208 *
sh	4	214
s	4	218 *
sh	4	222
s	9	226 *
sh	17	235
s	18	252 *
sh	10	270
s	52	280 *
sh	14	332
s	8	346 *
sh	4	354
s	27	358 *
sh	13	385
s	8	398 *
sh	2	406
s	20	408 *
sh	5	428
s	10	432 *

* Perforations

WELL # 17 WELL LOCATION 14N-03W-30 BAA1
Q(gpm) 225 ELEVATION (feet) 1210 TOTAL DEPTH (feet) 750
SPECIFIC CAPACITY 1.01 SAND/SHALE RATIO

STRATA	THICKNESS	DEPTH
sh	9	0
s	38	c
sh	11	47
s	26	58
sh	13	84
s	7	97
sh	8	104
s	72	112
sh	9	184
s	15	193
sh	6	208
s	37	214
sh	8	251
s	16	259
sh	27	275
s	12	302
sh	8	314
s	30	322 *
sh	49	352
s	6	401 *
sh	19	407
s	40	426 *
sh	17	466
s	9	483 *
sh	18	492
s	27	510 *
sh	8	539
s	18	547 *
sh	36	565
s	45	601 *
sh	58	646
s	32	704 *
sh	14	736

WELL # 18 WELL LOCATION 14N-03W-25 CDD1
Q(gpm) 370 ELEVATION (feet) 1175 TOTAL DEPTH (feet)
SPECIFIC CAPACITY SAND/SHALE RATIO 1.3

STRATA	THICKNESS	DEPTH
sh	12	0
s	58	12
sh	6	70
s	26	76
sh	13	102
s	5	115
sh	9	120
s	23	129
sh	70	152
s	14	222
sh	29	236
s	12	265
sh	26	277
s	63	303 *
sh	24	340
s	12	364 *
sh	14	376
s	5	390 *
sh	31	395
s	17	426 *
sh	9	443
s	9	452 *
sh	17	461
s	17	478 *
sh	37	495
s	13	532 *
sh	8	545
s	14	553 *
sh	30	567
s	35	597 *
sh	8	632
s	24	640 *
sh	30	664
s	12	694
sh	6	706

* Perforations

WELL # 20 WELL LOCATION 14N-03W-26 CBB 1
Q(gpm) 300 ELEVATION (feet) 1160 TOTAL DEPTH (feet) 635
SPECIFIC CAPACITY .57 SAND/SHALE RATIO 1.55

STRATA	THICKNESS	DEPTH
sh	26	0
s	15	26
sh	7	41
s	11	48
sh	19	59
s	86	78
sh	13	164
s	35	177
sh	5	212
s	24	217
sh	16	241
s	52	257
sh	8	309
s	14	317
sh	8	331
s	25	339
sh	12	364
s	10	376
sh	77	386
s	167	403
sh	10	630

WELL # 19 WELL LOCATION 13N-03W-01 ABB 1
Q(gpm) 275 ELEVATION (feet) 1140 TOTAL DEPTH (feet) 679
SPECIFIC CAPACITY 1.5 SAND/SHALE RATIO 1.3

STRATA	THICKNESS	DEPTH
sh	8	0
s	2	8
sh	3	10
s	2	13
sh	7	15
s	8	22
sh	8	30
s	10	38
sh	4	48
s	6	52
sh	3	58
s	24	61
sh	9	85
s	18	94
sh	3	112
s	8	115
sh	3	123
s	12	126
sh	8	138
s	18	146
sh	4	164
s	10	168
sh	8	178
s	4	186
sh	6	190
s	34	196
sh	40	230
s	26	270
sh	14	296
s	14	310
sh	10	324
s	28	334
sh	14	362
s	12	376
sh	8	388
s	6	396
sh	12	402
s	16	414
sh	8	430
s	10	438
sh	57	448
s	3	505
sh	6	508
s	20	514
sh	16	534
s	14	550
sh	24	564
s	12	576
sh	6	588
s	10	594
sh	26	604
s	20	630
sh	13	650
s	4	663
sh	↓	667

* Perforations

WELL # 22 WELL LOCATION 14N-02W-31 BCC1
Q(gpm) 200 ELEVATION (feet) 1095 TOTAL DEPTH (feet) 644
SPECIFIC CAPACITY .44 SAND/SHALE RATIO 1.44

STRATA	THICKNESS	DEPTH
s	3	0
sh	4	3
s	5	7
sh	14	12
s	32	26
sh	2	58
s	19	60
sh	11	79
s	7	90
sh	9	97
s	13	106
sh	5	119
s	15	124
sh	12	139
s	13	147
sh	7	160
s	15	167
sh	4	182
s	9	186
sh	10	196
s	10	206
sh	5	216
s	5	221
sh	8	226
s	10	234
sh	25	244
s	14	269
sh	27	283
s	25	310
sh	14	335
s	14	349
sh	24	363
s	21	387
sh	14	408
s	7	422
sh	11	429
s	23	440
sh	5	463
s	24	468
sh	8	492
s	21	500
sh	9	521
s	10	530
sh	3	540
s	7	543
sh	10	550
s	6	566
sh	5	560
s	6	571
sh	3	577
s	14	580
sh	6	594
s	14	600
sh	4	614
s	12	618

WELL # 21 WELL LOCATION 13N-03W-11 BBB1
Q(gpm) 250 ELEVATION (feet) 1170 TOTAL DEPTH (feet) 705
SPECIFIC CAPACITY 2.07 SAND/SHALE RATIO 1.23

STRATA	THICKNESS	DEPTH
sh	70	0
s	11	70
sh	4	81
s	127	85
sh	13	212
s	12	225237
sh	11	237
s	50	248
sh	11	298
s	9	309
sh	48	318
s	5	366
sh	33	371
s	24	414
sh	3	428
s	20	431
sh	45	451
s	21	496
sh	5	517
s	23	522
sh	32	545
s	28	577
sh	6	605
s	20	611
sh	18	631
s	8	649
sh	30	657
s	8	687
sh	10	695

* Perforations

WELL # 23 WELL LOCATION 13N-02W-07 BAA 1
Q(gpm) 250 ELEVATION (feet) 1142 TOTAL DEPTH (feet) 598
SPECIFIC CAPACITY 1.9 SAND/SHALE RATIO 1.34

STRATA	THICKNESS	DEPTH
sh	26	0
s	4	26
sh	8	30
s	6	38
sh	21	44
s	7	65
sh	2	72
s	24	74
sh	6	98
s	4	104
sh	6	108
s	10	114
sh	9	124
s	30	133
sh	4	163
s	9	167
sh	6	176
s	28	182
sh	8	210
s	10	218
sh	8	228
s	12	236
sh	22	248
s	39	270
sh	13	309
s	20	322
sh	11	342
s	22	353
sh	4	375
s	31	379
sh	10	410
s	10	420
sh	13	430
s	7	443
sh	8	450
s	10	458
sh	18	468
s	4	486
sh	5	490
s	10	495
sh	7	505
s	14	512
sh	10	526
s	40	536
sh	7	576
s	28	583
sh	19	611
s	4	630
sh	44	634
s	13	678
sh	↓	691

WELL # 24 WELL LOCATION 14N-03W-34 DDA1
Q(gpm) 275 ELEVATION (feet) 1140 TOTAL DEPTH (feet) 694
SPECIFIC CAPACITY 1.2 SAND/SHALE RATIO 1.3

STRATA	THICKNESS	DEPTH
sh	19	0
s	14	19
sh	17	33
s	60	50
sh	17	110
s	18	127 *
sh	7	145
s	35	152 *
sh	10	187
s	10	197 *
sh	10	207
s	34	217 *
sh	6	251
s	18	257 *
sh	123	275
s	20	298 *
sh	37	318
s	20	355 *
sh	30	375
s	27	405 *
sh	29	432
s	41	461 *
sh	16	502
s	13	518 *
sh	10	530
s	11	540 *
sh	43	551
s	56	594
sh	47	650

* Perforations

WELL # 25 WELL LOCATION 13N-03W-02 BCC1
Q(gpm) 300 ELEVATION (feet) 1150 TOTAL DEPTH (feet) 705
SPECIFIC CAPACITY 3.06 SAND/SHALE RATIO

STRATA	THICKNESS	DEPTH
sh	40	0
s	36	40
sh	3	76
s	70	79
sh	14	149
s	13	163
sh	30	176
s	5	206
sh	15	211
s	157	226 *
sh	12	383
s	20	395 *
sh	27	415
s	28	442 *
sh	15	470
s	35	485 *
sh	25	520
s	25	545 *
sh	27	570
s	30	597 *
sh	6	627
s	61	633 *
sh	11	694

WELL # 26 WELL LOCATION 14N-03W-10 CCC1
Q(gpm) 250 ELEVATION (feet) 1224 TOTAL DEPTH (feet) 475
SPECIFIC CAPACITY 1.00 SAND/SHALE RATIO 1.2

STRATA	THICKNESS	DEPTH
sh	24	0
s	106	24
sh	36	130
s	21	166 *
sh	3	187
s	18	190 *
sh	13	208
s	6	221 *
sh	13	227
s	15	240 *
sh	90	255
s	57	247 *
sh	53	404
s	10	457
sh	23	473
s	19	496
sh	57	515
s	8	572
sh	3	580
s	19	583
sh	16	602
s	10	618
sh	9	628

* Perforations

WELL # 27 WELL LOCATION 14N-03W-26 DCC1
Q(gpm) 225 ELEVATION (feet) 1190 TOTAL DEPTH (feet) 710
SPECIFIC CAPACITY ____ SAND/SHALE RATIO 0.9

STRATA	THICKNESS	DEPTH
st	43	0
s	54	43
sh	16	97
s	79	113
sh	7	160
s	26	167
sh	6	193
s	16	199 *
sh	54	215
s	25	269 *
sh	11	294
s	48	305 *
sh	18	353
s	6	371 *
sh	7	377
s	17	384 *
sh	15	401
s	8	451 *
sh	30	459
s	13	189 *
sh	98	502
s	23	600
sh	7	623
s	42	630
sh	47	672

WELL # 29 WELL LOCATION 14N-03W-31 DDA1
Q(gpm) 300 ELEVATION (feet) 1150 TOTAL DEPTH (feet) 532
SPECIFIC CAPACITY .74 SAND/SHALE RATIO 1.3

STRATA	THICKNESS	DEPTH
s	32	0
sh	6	32
s	18	38
sh	12	56
s	5	68
sh	2	73
s	36	75 *
sh	6	111
s	14	117 *
sh	13	131
s	10	144 *
sh	10	154
s	39	164 *
sh	15	206
s	17	221 *
sh	7	238
s	8	245 *
sh	44	253
s	8	297 *
sh	16	303
s	8	321 *
sh	52	329
s	11	381 *
sh	16	392
s	53	408 *
sh	14	464
s	29	478 *
sh	5	507

* Perforations

WELL # 31 WELL LOCATION 14N-02W-31 CDD 1
Q(gpm) 2'0 ELEVATION (feet) 1080 TOTAL DEPTH (feet) 709
SPECIFIC CAPACITY 0.04 SAND/SHALE RATIO 1.1

STRATA	THICKNESS	DEPTH
sh	10	0
s	10	10
sh	6	20
s	12	26
sh	5	38
s	9	43
sh	5	52
s	9	57
sh	4	66
s	8	70
sh	3	78
s	4	81
sh	2	85
s	7	87
sh	3	94
s	19	100
sh	4	114
s	4	118
sh	2	122
s	8	124
sh	8	132
s	9	140
sh	12	149
s	12	161
sh	12	173
s	18	185
sh	2	203
s	6	205
sh	6	211
s	8	217
sh	22	225
s	8	247 *
sh	3	255
s	8	258 *
sh	6	266
s	10	272 *
sh	7	282
s	3	289 *
sh	20	292
s	8	312 *
sh	3	320
s	6	323 *
sh	8	329
s	2	337 *
sh	2	339
s	2	341 *
sh	12	343 *
s	3	355

STRATA	THICKNESS	DEPTH
sh	3	356 *
s	2	359
sh	15	361 *
s	10	376
sh	14	386 *
s	7	400
sh	3	407
s	3	410 *
sh	15	413
s	6	428 *
sh	2	434
s	5	436 *
sh	6	441
s	15	447 *
sh	13	462
s	11	475
sh	4	486
s	12	490
sh	8	502
s	11	510
sh	7	521
s	22	528
sh	18	550
s	4	568
sh	17	572
s	4	589
sh	7	593
s	4	600
sh	6	604
s	6	610
sh	6	616
s	6	622
sh	14	628
s	22	642
sh	7	664
s	27	671

WELL # 30 WELL LOCATION 14N-02W-31 DDA 1
Q(gpm) 200 ELEVATION (feet) 1070 TOTAL DEPTH (feet) 741
SPECIFIC CAPACITY .18 SAND/SHALE RATIO 1.5

STRATA	THICKNESS	DEPTH
s	42	48
sh	8	90
s	20	98
sh	9	118
s	20	127
sh	9	153
s	6	162
sh	26	168
s	10	194
sh	7	204
s	8	211
sh	7	219
s	12	226 *
sh	10	238
s	10	248 *
sh	8	258
s	14	266 *
sh	9	280
s	6	289 *
sh	8	295
s	3	303 *
sh	24	306
s	12	330 *
sh	8	342
s	8	350 *
sh	14	358
s	38	372 *
sh	10	410
s	42	420 *
sh	12	462
s	24	474 *
sh	28	498
s	27	526 Plug
sh	9	553
s	20	562
sh	2	582
s	6	584
sh	6	590
s	13	596
sh	3	609
s	35	612
sh	17	647
s	16	664
sh	18	680
s	10	698
sh	8	708
s	↓	716

STRATA	THICKNESS	DEPTH

* Perforations

WELL # 32 WELL LOCATION 13N-02W-08 DBA 1
Q(gpm) 375 ELEVATION (feet) 1090 TOTAL DEPTH (feet) 681
SPECIFIC CAPACITY .83 SAND/SHALE RATIO 1.1

STRATA	THICKNESS	DEPTH
sh	10	0
s	4	10
sh	4	14
s	4	19
sh	16	22
s	48	38
sh	12	86
s	22	98
sh	12	120
s	10	132
sh	12	142
s	16	154
sh	22	170
s	10	192
sh	9	202
s	25	211
sh	6	236
s	15	242
sh	17	257
s	18	274
sh	2	292
s	4	294
sh	4	298
s	20	302
sh	31	322
s	5	353
sh	25	358
s	23	383
sh	5	406
s	6	411
sh	6	416
s	14	422
sh	11	436
s	51	447
sh	5	498
s	17	503
sh	56	520
s	23	576
sh	23	599
s	12	622
sh	14	634
s	28	648

WELL # 34 WELL LOCATION 14N-03W-33 DAA1
Q(gpm) 290 ELEVATION (feet) 1100 TOTAL DEPTH (feet) 740
SPECIFIC CAPACITY .72 SAND/SHALE RATIO 1.3

STRATA	THICKNESS	DEPTH
sh	20	0
s	15	20
sh	7	35
s	28	42
sh	12	70
s	24	82
sh	12	106
s	45	118 *
sh	17	163
s	45	180 *
sh	10	225
s	72	235 *
sh	33	307
s	60	340 *
sh	13	400
s	12	413 *
sh	22	425
s	11	447 *
sh	8	458
s	14	466 *
sh	47	480
s	6	527
sh	30	533
s	35	563
sh	34	598
s	33	632
sh	38	665
s	27	703
sh	10	730

* Perforations

WELL # 35 WELL LOCATION 14N-02W-32 DCD1
Q(gpm) 300 ELEVATION (feet) 1085 TOTAL DEPTH (feet) 625
SPECIFIC CAPACITY .91 SAND/SHALE RATIO .9

STRATA	THICKNESS	DEPTH
s	37	0
sh	7	37
s	60	44
sh	22	104
s	23	126
sh	51	149
s	39	200 *
sh	11	239
s	2	250 *
sh	21	252
s	10	273 *
sh	141	283
s	36	424 *
sh	6	460
s	16	466 *
sh	13	482
s	19	495 *
sh	106	514
s	5	620

WELL # 36 WELL LOCATION 14N-02W-31 CAA1
Q(gpm) 200 ELEVATION (feet) 1120 TOTAL DEPTH (feet) 599
SPECIFIC CAPACITY .03 SAND/SHALE RATIO 1.5

STRATA	THICKNESS	DEPTH
s	8	0
sh	22	8
s	36	30
sh	6	66
s	44	72
sh	17	116
s	12	133 *
sh	8	145
s	8	153 *
sh	10	161
s	49	171 *
sh	10	212
s	18	222 *
sh	6	246
s	32	270 *
sh	10	302
s	33	312 *
sh	116	345
s	16	361 *
sh	11	377
s	37	388 *
sh	7	425
s	76	432 *
sh	11	551
s	28	562 *
sh	9	590

* Perforations

WELL # 37 WELL LOCATION 13N-03W-11 BDD1
Q(gpm) 225 ELEVATION (feet) 1160 TOTAL DEPTH (feet) 700
SPECIFIC CAPACITY 3.6 SAND/SHALE RATIO

STRATA	THICKNESS	DEPTH
sh	58	0
s	16	58
sh	17	74
s	38	91
sh	6	129
s	30	135
sh	12	185
s	10	197
sh	8	207
s	7	215 *
sh	20	222
s	34	242 *
sh	32	276
s	9	308 *
sh	4	317
s	20	321 *
sh	22	341
s	5	363 *
sh	15	368
s	14	383 *
sh	17	397
s	14	414 *
sh	3	428
s	7	431 *
sh	11	438
s	24	449 *
sh	4	473
s	12	477 *
sh	11	489
s	52	500 *
sh	22	552
s	26	574 *
sh	23	600
s	20	623 *
sh	15	643
s	23	658 *
sh	19	681

WELL # 38 WELL LOCATION 13N-03W-11 BCC1
Q(gpm) ELEVATION (feet) 1160 TOTAL DEPTH (feet) 796
SPECIFIC CAPACITY SAND/SHALE RATIO 1.7

STRATA	THICKNESS	DEPTH
sh	75	0
s	16	75
sh	29	91
s	35	120
sh	10	155
s	22	165
sh	12	187
s	12	199
sh	18	211
s	5	229
sh	13	234
s	6	247
sh	3	253
s	22	256 *
sh	6	278
s	23	284 *
sh	21	307
s	43	328 *
sh	10	371
s	16	381 *
sh	17	397
s	54	414 *
sh	41	468
s	9	509 *
sh	44	518
s	15	562 *
sh	26	577
s	11	603 *
sh	23	614
s	44	637 *
sh	27	681
s	8	708 *
sh	20	716
s	46	736 *
sh	8	782
s	6	790

* Perforations

WELL # 41 WELL LOCATION 14N-03W-27 BDD1
Q(gpm) 275 ELEVATION (feet) 1135 TOTAL DEPTH (feet) 590
SPECIFIC CAPACITY 1.5 SAND/SHALE RATIO 1.37

STRATA	THICKNESS	DEPTH
sh	18	0
s	7	18
sh	11	25
s	36	36
sh	75	72
s	26	147
sh	21	173
s	12	194
sh	36	206 *
s	4	242
sh	19	246 *
s	9	265
sh	8	274 *
s	23	282
sh	28	305 *
s	34	333
sh	17	367 *
s	27	384
sh	10	411 *
s	24	421
sh	13	445 *
s	18	458
sh	21	476 *
s	86	497
sh	4	583

WELL # 42 WELL LOCATION 13N-03W-12 ADA1
Q(gpm) 150 ELEVATION (feet) 1160 TOTAL DEPTH (feet) 690
SPECIFIC CAPACITY 1.99 SAND/SHALE RATIO

STRATA	THICKNESS	DEPTH
sh	30	0
s	5	30
sh	8	35
s	12	43
sh	7	55
s	59	62
sh	15	121
s	10	136
sh	8	146
s	34	154
sh	7	188
s	17	195
sh	16	212
s	44	228
sh	46	272
s	12	318 *
sh	16	330
s	15	346 *
sh	12	361
s	7	373 *
sh	7	380
s	6	387
sh	5	393
s	16	398 *
sh	26	414
s	16	440 *
sh	7	456
s	13	463
sh	62	476
s	39	538 *
sh	40	577
s	16	617 *
sh	31	633
s	4	664 *
sh	2	668
s	7	670 *
sh	13	677

* Perforations

WELL # 44 WELL LOCATION 14N-03W-34 BBA1
Q(gpm) 250 ELEVATION (feet) 1105 TOTAL DEPTH (feet) 510
SPECIFIC CAPACITY .19 SAND/SHALE RATIO 1.18

STRATA	THICKNESS	DEPTH
sh	56	0
s	14	56
sh	20	70
s	15	90
sh	9	105
s	16	114
sh	2	130
s	26	132
sh	13	158
s	19	171
sh	5	190
s	32	195 *
sh	9	227
s	35	236 *
sh	26	271
s	9	297 *
sh	19	306
s	16	325 *
sh	12	341
s	20	353 *
sh	16	373
s	6	392 *
sh	61	414
s	9	459 *
sh	48	471

WELL # 45 WELL LOCATION 14N-03W-27 BAA 1
Q(gpm) 300 ELEVATION (feet) 1140 TOTAL DEPTH (feet) 570
SPECIFIC CAPACITY SAND/SHALE RATIO 1.5

STRATA	THICKNESS	DEPTH
sh	7	0
s	6	7
sh	3	13
s	4	16
sh	20	20
s	4	40
sh	8	44
s	29	52
sh	10	81
s	41	91
sh	8	132
s	9	140
sh	7	149
s	4	156
sh	4	160
s	2	164
sh	3	166
s	16	169
sh	4	185
s	15	199
sh	1	214
s	39	215
sh	21	254
s	11	275
sh	26	286
s	21	312
sh	3	333
s	12	336
sh	20	348
s	30	368
sh	14	398
s	18	412
sh	18	430
s	9	448
sh	25	457
s	18	482
sh	30	500
s	12	530

* Perforations

WELL # 46 WELL LOCATION 14N-03W-25 BCA1
Q(gpm) 200 ELEVATION (feet) 1200 TOTAL DEPTH (feet) 590
SPECIFIC CAPACITY .34 SAND/SHALE RATIO 1.14

STRATA	THICKNESS	DEPTH
sh	84	0
s	2	84
sh	8	86
s	8	94
sh	14	102
s	14	116
sh	15	130
s	8	145
sh	3	153
s	10	156
sh	4	166
s	13	170
sh	12	183
s	48	195 *
sh	7	243
s	13	250 *
sh	8	263
s	21	271 *
sh	25	292
s	8	317 *
sh	24	325
s	31	349 *
sh	19	380
s	22	399 *
sh	87	421
s	7	508
sh	20	515
s	4	535
sh	27	539
s	24	566 *

WELL # 47 WELL LOCATION 13N-02W-06 BCC 1
Q(gpm) 125 ELEVATION (feet) 1125 TOTAL DEPTH (feet) 636
SPECIFIC CAPACITY 1.5 SAND/SHALE RATIO 1.48

STRATA	THICKNESS	DEPTH
s	10	54
sh	21	64
s	6	85
sh	4	91
s	5	95
sh	8	100
s	10	108
sh	8	118
s	37	126
sh	10	163
s	67	173
sh	5	240
s	2	245
sh	6	247
s	19	253
sh	16	272
s	17	288
sh	14	305
s	26	319
sh	10	345
s	3	355
sh	2	358
s	6	360
sh	6	366
s	43	372
sh	14	415
s	9	429
sh	50	438
s	6	488
sh	12	494
s	8	506
sh	10	514
s	23	524
sh	3	547
s	3	550
sh	7	553
s	10	560
sh	2	570
s	2	572
sh	2	574
s	6	576
sh	23	582
s	17	605

* Perforations

WELL # 48 WELL LOCATION 14N-03W-36 BDD 1
Q(gpm) 300 ELEVATION (feet) 1160 TOTAL DEPTH (feet) 720
SPECIFIC CAPACITY 0.44 SAND/SHALE RATIO 1.63

STRATA	THICKNESS	DEPTH
s	4	10
sh	2	14
s	34	16
sh	13	50
s	26	63
sh	9	89
s	20	98
sh	5	118
s	29	123
sh	13	152
s	11	165
sh	8	176
s	26	184
sh	4	210
s	6	214
sh	5	220
s	20	225
sh	9	245
s	16	254
sh	6	270
s	31	276
sh	10	307
s	10	317
sh	10	327
s	5	337
sh	8	342
s	8	350
sh	18	358
s	14	376
sh	12	390
s	12	402
sh	23	414
s	21	437
sh	24	458
s	6	482
sh	4	488
s	8	492
sh	24	500
s	12	524
sh	2	536
s	20	538
sh	2	558
s	7	560
sh	3	567
s	18	570
sh	2	588
s	18	590
sh	6	608
s	10	614
sh	18	624
s	15	642
sh	9	657
s	↓	666

WELL # 49 WELL LOCATION 14N-03W-25 BBB1
Q(gpm) 250 ELEVATION (feet) 1150 TOTAL DEPTH (feet) 600
SPECIFIC CAPACITY 0.66 SAND/SHALE RATIO 1.6

STRATA	THICKNESS	DEPTH
s	4	36
sh	10	40
s	10	50
sh	4	60
s	13	64
sh	7	77
s	8	84
sh	16	92
s	16	108
sh	6	124
s	10	130
sh	6	140
s	14	146
sh	14	160
s	23	174
sh	9	197
s	24	206 *
sh	8	230
s	16	238 *
sh	10	254
s	32	264 *
sh	8	296
s	18	304 *
sh	6	322
s	32	328 *
sh	6	360
s	38	366 *
sh	16	404
s	14	420 *
sh	32	434
s	18	466 *
sh	6	484
s	16	490 *
sh	15	506
s	14	521 *
sh	15	535
s	12	550 SEAL
sh	11	562
s	↓	573

* Perforations

WELL # 50 WELL LOCATION 14N-03W-35 BBB1
Q(gpm) 225 ELEVATION (feet) 1170 TOTAL DEPTH (feet) 608
SPECIFIC CAPACITY 0.16 SAND/SHALE RATIO 2.0

STRATA	THICKNESS	DEPTH
s	34	0
sh	3	24
s	5	27
sh	8	32
s	52	40
sh	12	92
s	18	104
sh	3	122
s	9	125
sh	7	134
s	6	141
sh	4	147
s	9	151
sh	8	160
s	13	168
sh	14	186
s	11	200 *
sh	5	211
s	34	216 *
sh	3	250
s	19	253 *
sh	4	272
s	44	276 *
sh	7	320
s	11	327 *
sh	7	338
s	18	345 *
sh	3	356
s	9	359 *
sh	7	368
s	17	375 *
sh	6	394
s	34	403 *
sh	23	434
s	13	457 *
sh	4	470
s	29	474 *
sh	13	503
s	7	516
sh	12	523
s	6	535
sh	13	541
s	5	554
sh	17	559
s	16	570

WELL # 51 WELL LOCATION 13N-03W-12 BBB1
Q(gpm) 300 ELEVATION (feet) 1170 TOTAL DEPTH (feet) 703
SPECIFIC CAPACITY 1.52 SAND/SHALE RATIO 1.8

STRATA	THICKNESS	DEPTH
s	4	0
sh	6	4
s	14	10
sh	6	24
s	14	30
sh	6	44
s	16	50
sh	6	66
s	8	72
sh	3	80
s	25	83
sh	5	108
s	23	113
sh	4	136
s	8	140
sh	6	148
s	16	154
sh	6	170
s	17	176
sh	7	193
s	26	200 *
sh	4	226
s	38	230 *
sh	8	268
s	76	276 *
sh	8	352
s	20	360 *
sh	12	380
s	18	392 *
sh	26	410
s	9	436 *
sh	4	445
s	13	449 *
sh	14	462
s	24	476 *
sh	50	500
s	10	550 *
sh	35	560
s	22	595 *
sh	7	617
s	29	624 *
sh	5	653
s	12	658 *

APPENDIX C

PERFORATION RECORDS

WELL #	LENGTH OF PERFORATIONS
44	126
46	134
37	268
34	212
27	195
16	170
17	210
18	208
24	258
25	177
29	202
35	167
40	183
41	151
42	126
38	287

Average 193 feet

APPENDIX D

RESULTS OF THEIS WELLFIELD SIMULATIONS

THEIS WELL FIELD

This Theis well field model calculates the heads anywhere in an infinite/homogeneous artesian aquifer with given transmissivity and storage under the influences of up to 20 injection and/or pumping wells operating in the aquifer with natural flow. Injection or pumping well input include pumping rate (Q, in gpm), time of pumping (t in days),and X and Y coordinates. Both positive (pumping) or negative (injection) flow is allowed. All coordinates are in units of feet. The grid is 10x10. Unpumped natural flow gradients are input by specifying the head value at the chosen X=0 and Y=0 origin, the gradient (ft/ft) of the potentiometric surface, and the angle (moving in a counterclockwise direction from the +Y axis) of the potentiometric surface. The Theis well functions are calculated by polynomial approximations taken from Stegun and Abramowitz, Handbook of Mathematical Functions, Dover Publications, Inc., New York, New York, 1970.

```
TRANSMISSIVITY =  2500.00
STORAGE COEFFICIENT = 0.0002000
INITIAL HEAD =  1000.00
GRID SIZE (FT)           =1000.00
GRADIENT (FT/FT)         = 0.0010000
ANGLE OF GRADIENT (DEG) = 0.0100000
WELL # 1
IS LOCATED AT ( 3000.00, 3000.00)
PUMPING   180.00 GPM FOR   200.00 DAYS
WITH A RADIUS OF      0.50 FEET

WELL # 2
IS LOCATED AT ( 3000.00, 5000.00)
PUMPING   166.00 GPM FOR   200.00 DAYS
WITH A RADIUS OF      0.50 FEET

WELL # 3
IS LOCATED AT ( 5000.00, 5000.00)
PUMPING   137.00 GPM FOR   200.00 DAYS
WITH A RADIUS OF      0.50 FEET
```

Wells 12, 21, 37

	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
10000	924.43	922.01	920.58	920.37	921.40	923.54	926.49	929.95	933.62	937.32
9000	918.90	915.54	913.48	913.15	914.62	917.61	921.61	926.08	930.65	935.08
8000	912.56	907.66	904.53	904.01	906.22	910.60	916.20	922.09	927.77	933.03
7000	905.50	897.95	892.74	891.98	895.47	902.34	910.51	918.31	925.26	931.38
6000	898.42	886.02	875.56	875.95	880.71	892.96	905.36	915.36	923.53	930.39
5000	893.38	875.41	*752.83	861.65	•780.58	886.16	902.70	914.12	923.00	930.28
4000	892.59	874.79	859.48	864.72	874.87	890.16	904.23	915.19	923.96	931.21
3000	896.32	878.67	•748.52	872.71	886.29	898.01	908.89	918.32	926.32	933.15
2000	904.20	892.65	884.12	888.99	897.86	906.65	915.08	922.84	929.79	935.94
1000	913.82	907.22	903.55	904.83	909.54	915.56	921.92	928.14	933.99	939.38

```
TRANSMISSIVITY =   2500.00
STORAGE COEFFICIENT = 0.0002000
INITIAL HEAD =  1000.00
GRID SIZE (FT)              =1000.00
GRADIENT (FT/FT)            = 0.0010000
ANGLE OF GRADIENT (DEG)     = 0.0100000
WELL # 1
IS LOCATED AT ( 5000.00, 5000.00)
PUMPING   137.00 GPM FOR   200.00 DAYS
WITH A RADIUS OF      0.50 FEET
```

Well 12

	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
10000	971.55	970.41	969.43	968.76	968.52	968.76	969.43	970.41	971.55	972.76
9000	971.04	969.52	968.14	967.13	966.76	967.13	968.14	969.52	971.04	972.55
8000	970.52	968.49	966.47	964.83	964.18	964.83	966.47	968.49	970.52	972.41
7000	970.14	967.47	964.44	961.50	960.11	961.51	964.44	967.47	970.14	972.43
6000	970.13	966.83	962.50	956.76	952.42	956.76	962.51	966.84	970.13	972.76
5000	970.76	967.18	962.11	953.42	•857.95	953.42	962.11	967.18	970.76	973.52
4000	972.13	968.83	964.50	958.76	954.42	958.76	964.51	968.84	972.13	974.76
3000	974.14	971.47	968.44	965.50	964.11	965.51	968.44	971.47	974.14	976.43
2000	976.52	974.49	972.47	970.83	970.18	970.83	972.47	974.49	976.52	978.41
1000	979.04	977.52	976.14	975.13	974.76	975.13	976.14	977.52	979.04	980.55

TRANSMISSIVITY = 2500.00
STORAGE COEFFICIENT = 0.0002000
INITIAL HEAD = 1000.00
GRID SIZE (FT) =1000.00
GRADIENT (FT/FT) = 0.0010000
ANGLE OF GRADIENT (DEG) = 0.0100000
WELL # 1
IS LOCATED AT (3000.00, 5000.00)
PUMPING 166.00 GPM FOR 200.00 DAYS
WITH A RADIUS OF 0.50 FEET

Well 21

	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
10000	965.08	964.26	963.97	964.26	965.08	966.26	967.65	969.11	970.56	971.96
9000	963.30	962.08	961.63	962.08	963.30	964.97	966.81	968.65	970.39	972.02
8000	961.06	959.08	958.29	959.08	961.06	963.51	965.97	968.26	970.33	972.19
7000	958.40	954.84	953.15	954.84	958.40	962.06	965.30	968.08	970.46	972.53
6000	955.84	948.88	943.61	948.88	955.84	961.08	965.08	968.27	970.89	973.11
5000	955.14	944.61	828.94	944.61	955.15	961.29	965.63	968.97	971.69	973.96
4000	957.84	950.88	21 945.61	950.88	957.84	963.08	967.08	970.27	972.89	975.11
3000	962.40	958.84	957.15	958.84	962.40	966.06	969.30	972.08	974.46	976.53
2000	967.06	965.08	964.29	965.08	967.06	969.51	971.97	974.26	976.33	978.19
1000	971.30	970.08	969.63	970.08	971.30	972.97	974.81	976.65	978.39	980.02

TRANSMISSIVITY = 2500.00
STORAGE COEFFICIENT = 0.0002000
INITIAL HEAD = 1000.00
GRID SIZE (FT) =1000.00
GRADIENT (FT/FT) = 0.0010000
ANGLE OF GRADIENT (DEG) = 0.0100000
WELL # 1
IS LOCATED AT (3000.00, 3000.00)
PUMPING 180.00 GPM FOR 200.00 DAYS
WITH A RADIUS OF 0.50 FEET

Well 37

	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
10000	967.81	967.34	967.18	967.34	967.81	968.52	969.42	970.43	971.51	972.61
9000	966.56	965.94	965.72	965.94	966.56	967.50	968.66	969.92	971.22	972.51
8000	964.98	964.09	963.78	964.09	964.98	966.26	967.76	969.34	970.92	972.43
7000	962.97	961.64	961.15	961.64	962.97	964.78	966.77	968.76	970.66	972.42
6000	960.45	958.31	957.44	958.31	960.45	963.11	965.78	968.26	970.51	972.52
5000	957.48	953.62	951.78	953.62	957.48	961.45	964.97	967.98	970.56	972.81
4000	954.62	947.08	941.36	947.08	954.62	960.31	964.64	968.09	970.94	973.34
3000	953.78	942.36	#816.94	942.36	953.78	960.44	965.15	968.78	971.72	974.18
2000	956.62	949.08	51 943.36	949.08	956.62	962.31	966.64	970.09	972.94	975.34
1000	961.48	957.62	955.78	957.62	961.48	965.45	968.97	971.98	974.56	976.81

APPENDIX E

ARTESIAN PRICKETT LONNQUIST AQUIFIER

SIMULATION MODEL IMPUT INFORMATION

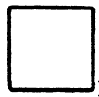
AND OUTPUT

GRID NOTATION

```
INCREASING I ------------>
 +-----+-----+-----+-----+
(1,1) (2,1) (3,1) (4,1) (5,1) INCREASING
(1,2) (2,2) (3,2) (4,2) (5,2)     J
(1,3) (2,3) (3,3) (4,3) (5,3)     !
(1,4) (2,4) (3,4) (4,4) (5,4)     !
(1,5) (2,5) (3,5) (4,5) (5,5)    \/
 +-----+-----+-----+-----+
```

Sample Node

U.L.



L.R.

Inputs
(U.L.) 4,8
(L.R.) 5,9
(Q) 51363 (gallons/day)

Withdrawl Nodes

4,8	5,9	83071 gal/day
4,9	5,10	123677 gal/day
5,1	6,2	92177 gal/day
5,6	7,7	108315 gal/day
5,8	6,9	193548 gal/day
6,9	7,10	261605 gal/day
7,6	8,7	360000 gal/day
7,7	8,8	49355 gal/day
7,8	8,9	161129 gal/day
7,10	8,12	308613 gal/day
7,12	8,13	696339 gal/day
8,6	9,7	66048 gal/day
8,7	9,8	41589 gal/day
8,8	9,9	388800 gal/day
8,9	9,10	85548 gaql/day
9,6	10,7	41032 gal/day
9,8	10,9	248903 gal/day
9,10	10,11	234460 gal/day
9,11	10,12	114532 gal/day
9,12	10,13	285677 gal/day
10,4	11,5	85645 gal/day
10,11	11,12	168532 gal/day
11,8	12,9	51290 gal/day
11,9	13,10	30910 gal/day
11,11	12,12	110806
11,12	12,13	427452 gal/day
14,9	15,10	131516 gal/day
13,12	14,13	53042 gal/day
14,12	15,13	156774 gal/day
8,4	10,6	55742 gal/day
10,12	11,13	142984 gal/day

Output for the APLASM Simulation of Edmond's Well-Field

	2500	5000	7500	10000	12500	15000	17500	20000	22500	25000
2500	988.89	985.60	978.00	963.92	939.64	937.34	957.38	968.45	975.04	979.79
5000	988.77	985.67	978.66	966.05	944.32	940.96	956.45	964.41	969.68	974.32
7500	988.00	985.02	978.69	968.84	956.87	951.04	951.94	953.00	956.02	960.86
10000	986.09	982.67	975.56	964.84	952.08	941.69	934.21	926.87	928.73	935.02
12500	982.85	978.21	968.27	952.44	931.63	913.80	899.37	896.67	903.06	914.30
15000	978.53	971.89	957.15	931.67	890.75	861.54	829.67	856.35	872.96	892.74
17500	973.85	964.79	944.33	908.88	858.21	827.11	814.41	817.44	833.30	859.37
20000	969.90	958.37	931.15	879.36	820.14	782.24	764.33	743.16	763.22	797.28
22500	968.08	955.31	924.65	864.59	803.42	752.70	735.34	735.51	733.55	765.96
25000	969.10	957.06	928.35	872.32	815.68	747.62	700.73	710.09	717.36	750.86
27500	972.45	962.67	940.53	902.41	850.58	777.24	676.75	662.10	712.58	748.53
30000	976.68	969.00	951.64	920.97	871.03	786.00	631.97	610.63	709.83	755.17
32500	980.86	974.91	961.36	936.76	894.24	818.66	675.93	656.06	749.90	789.90
35000	984.45	979.99	969.91	952.09	923.20	879.71	825.88	812.90	839.98	861.72
37500	987.07	983.71	976.31	963.85	945.38	921.41	897.64	889.44	897.25	907.93
40000	988.43	985.66	979.68	970.03	956.65	940.92	926.93	920.95	923.52	929.75

	27500	30000	32500	35000	37500	40000	42500	45000	47500
2500	984.00	988.07	991.59	994.29	996.21	997.50	998.32	998.81	999.03
5000	979.29	984.92	989.68	993.16	995.52	997.07	998.05	998.61	998.87
7500	967.67	977.83	985.56	990.70	993.99	996.08	997.38	998.15	998.50
10000	944.12	966.69	979.41	986.89	991.47	994.38	996.23	997.33	997.85
12500	929.52	956.55	972.24	981.65	987.64	991.69	994.41	996.07	996.86
15000	921.79	946.11	962.99	973.95	981.61	987.44	991.62	994.23	995.46
17500	898.84	928.06	948.58	961.48	971.57	980.75	987.52	991.70	993.64
20000	860.67	899.25	927.10	940.75	954.23	970.62	982.01	988.58	991.52
22500	836.03	876.96	900.72	905.23	922.62	957.48	975.89	985.39	989.42
25000	815.46	854.41	882.24	890.31	911.40	950.44	971.86	983.06	987.83
27500	791.13	821.20	868.25	892.66	917.63	949.02	970.14	981.88	986.98
30000	779.26	777.96	846.55	870.18	898.91	945.01	969.32	981.72	986.94
32500	805.85	797.55	859.73	880.33	906.57	949.72	971.89	983.09	987.80
35000	874.64	883.08	907.14	924.67	942.65	963.37	977.55	985.67	989.29
37500	917.09	925.78	938.33	950.21	961.98	973.63	982.52	988.12	990.75
40000	936.67	944.04	952.81	961.75	970.52	978.72	985.22	989.52	991.61

APPENDIX F

GENERAL PARTICLE TRACKING MODULE OPTION USED FOR EACH WELL FOR EACH TOT BOUNDARY

Well Discharge Rates Used for the GPTRAC Simulations

T = 4.9081 x 10^8 gallons

Well #	Percentage each well contributes to August Well-field discharge for 3 years (T) Aug. 1988	Aug. 1989	Aug. 1990	Avg. %	A * T (gal)- 744 hrs/August -60 min/hr = Average discharge (gpm) per well over 3 August pumping periods, assuming 24 hr/day continous pumping	Average discharge (gpm) x 192.5 ft^3/day/gpm for conversion to ft^3/day units
3	/	2.9	/	2.9	106	20460
9	1	0.9	7.1	3	110	21165
10	0.8	/	/	0.8	29	5644
15	2.2	2.6	2.1	2.3	84	16277
18	0.6	/	/	0.6	22	4233
19	3.9	3.1	4.3	3.8	140	26809
20	2.5	2.1	0.9	1.8	66	12699
21	5.6	4.1	4.3	4.7	172	33159
22	2.3	3.5	0.9	2.2	81	15521
23	2.5	3.5	4.0	3.3	121	23282
24	2.6	3.2	4.8	3.5	128	24693
25	4.1	3.4	5.6	4.7	172	33159
26	1.9	1.2	1.6	1.6	59	11288
27	0.56	1.8	.76	1.0	37	7122
28	1.1	1.1	1.0	1.0	37	7122
29	1.5	0.4	1.5	1.1	40	7760
30	4.0	3.2	3.2	3.5	128	24693
31	2.5	1.9	1.0	1.8	66	12699
32	3.4	0.12	2.8	2.1	77	14816
33	3.5	1.6	0.9	2.0	73	14110
34	3.5	3.1	1.5	2.7	99	19049
36	2.9	2.1	1.3	2.1	77	14777
37	4.6	4.5	4.7	4.6	170	32453
38	4.2	4.9	/	4.5	165	31748
39	3.2	4.2	2.2	3.2	117	22576
40	1.4	2.0	1.2	1.5	55	10583
41	1.3	0.9	1.9	1.4	51	9877
42	4.6	1.4	2.6	2.9	106	20460
43	2.5	3.3	3.0	2.9	106	20460
44	2.3	3.3	3.5	3.0	110	21165
45	1.3	0.2	/	0.75	27	5291
46	1.7	0.9	0.7	1.1	40	7762
47	1.0	2.0	2.0	1.7	62	11994
48	2.6	3.0	1.0	2.2	81	15521
49	1.9	3.0	1.2	2.0	73	14110
50	2.1	3.2	2.8	2.7	99	19049
51	3.1	3.9	5.2	4.1	150	28926
52	2.0	4.2	2.6	2.9	106	20460
53	1.1	0.9	3.9	1.9	70	13405
54	1.8	3.9	2.3	2.7	99	19049
8	/	0.6	3.5	2.1	77	14816
11	/	3.3	1.5	2.4	88	16952
12	4.2	/	3.6	3.9	143	27515
35	/	/	2.4	2.4	88	16932

Explanation for the Input Files for GPTRAC's Semi-Analytical Option

```
  a 1      1      0      0      1
     b 0.0    c 6875.0      d 0.0     e 6875.0
     f 10.0
     i 335.0   j 200.0     k 0.22
  n 3650.00  o 3650.00
  g 4      h 0
  21 1   r 2906.0   s 4612.0   t 33159.0    u 1   v 20
  37 2     2906.0     2812.0     32453.0      1     20
q 12 3     4500.0     4612.0     27515.0      1     20
  30 4     5250.0     2875.0     31748.0      1     20
 l 0.016000    m 68.00    p 0
  w 0
  x 0
```

- a feet and days
- b minimum x coordinate
- c maximum x coordinate
- d minimum y coordinate
- e maximum y coordinate
- f maximum spatial step length
- g # of pumping wells
- h # of recharge wells
- i transmissivity (ft2/day)
- j aquifer thickness (ft)
- k porosity (decimal)
- l hydraulic gradient (decimal)
- m angle of ambient flow (degrees)
- n time limit for simulation (days)
- o time limit for capture zones (days)
- p no boundaries
- q well number
- r x coordinate
- s y coordinate
- t discharge (ft3/day)
- u delineate capture zones
- v # of pathlines
- w # of forward tracking pathlines
- x # of reverse tracking pathlines

Semi-Analytical Option

Input File

```
1     1     0     0     1
   0.0      5000.0        0.0     5000.0
  10.0
  335.0      200.0       0.22
3650.00    3650.00
  1     0
25 1     2800.0     2600.0     7122.0     1     20
0.003000     270.00     0
 0
 0
```

Semi-Analytical Option

Input File

```
1
  1     1     0     0     1
     0.0      9375.0        0.0     7500.0
    10.0
    335.0      200.0       0.22
  3650.00    3650.00
    2     0
31  1     4781.0     1437.0     12699.0     1     20
36  2     4875.0     3375.0     14777.0     1     20
  0.020000     170.00     0
    0
    0
```

Semi-Analytical Option

Input File

```
1     1     0     0     1
   0.0      6250.0        0.0     5625.0
  10.0
  335.0      200.0       0.22
365.00     365.00
  2     0
52 1     1562.0     1718.0     20460.0     1     20
53 2     3000.0     1800.0     13460.0     1     20
0.050000     340.00     0
 0
 0
```

Semi-Analytical Option

Input File

```
1     1     0     0     1
   0.0      3750.0        0.0     8125.0
  10.0
  335.0      200.0       0.22
3650.00    3650.00
  3     0
44 1     2812.0     5812.0     21165.0     1     20
34 2     2125.0     3625.0     19049.0     1     20
39 3     2250.0     1468.0     22576.0     1     20
0.042000      0.00     0
 0
 0
```

Semi-Analytical Option

Input File

```
1     1     0     0     1
   0.0      4375.0        0.0     5000.0
  10.0
  335.0      200.0       0.22
365.00     365.00
  1     0
50 1     2906.0     2187.0     19049.0     1     20
0.000100      0.00     0
 0
 0
```

Semi-Analytical Option

Input File

```
1     1     0     0     1
   0.0      6875.0        0.0     6875.0
  10.0
  335.0      200.0       0.22
3650.00    3650.00
  4     0
21 1     2906.0     4612.0     33159.0     1     20
37 2     2906.0     2812.0     32453.0     1     20
12 3     4500.0     4612.0     27515.0     1     20
28 4     5250.0     2875.0     31748.0     1     20
0.016000     68.00     0
 0
 0
```

Semi-Analytical Option

Input File

```
1     1     0     0     1
   0.0      9375.0        0.0     5000.0
  10.0
  335.0      200.0       0.22
3650.00    3650.00
  3     0
42 1     6062.0     1125.0     20460.0     1     20
54 2     6812.0     2187.0     19049.0     1     20
23 3     8375.0     2187.0     23282.0     1     20
0.050000     180.00     0
 0
 0
```

Semi-Analytical Option

Input File

```
1     1     0     0     1
   0.0      9375.0        0.0     5000.0
  10.0
  335.0      200.0       0.22
7300.00    7300.00
  1     0
51 1     1562.0     2187.0     28926.0     1     2(
0.005000     45.00     0
 0
 0
```

Semi-Analytical Option

Input File

```
 1    1     0     0     1
    0.0     7500 0        0.0      6875.0
  10.0
  335.0      200.0        0.22
3650.00    3650.00
   3      0
52 1      4062.0     4844.0    20460.0    1    20
20 2      4062.0     2343.0    12699.0    1    20
53 3      5531.0     4844.0    13405.0    1    20
 0.060000      90.00      0
   0
   0
```

Semi-Analytical Option

Input File

```
 1    1     0     0     1
    0.0     4375.0        0.0      5000.0
  10.0
  335.0      200.0        0.22
3650.00    3650.00
   1      0
29 1      2812.0     1562.0     7760.0    1    20
 0.029000     110.00      0
   0
   0
```

Semi-Analytical Option

Input File

```
 1    1     0     0     1
    0.0     7500.0        0.0      6875.0
  10.0
  335.0      200.0        0.22
3650.00    3650.00
   2      0
45 1      1563.0     4625.0     5291.0    1    20
41 2      1563.0     2925.0     9877.0    1    20
 0.020000     315.00      0
   0
   0
```

Semi-Analytical Option

Input File

```
 1    1     0     0     1
    0.0     4375.0        0.0      3750.0
  10.0
  335.0      200.0        0.22
3650.00    3650.00
   1      0
35 1      2187.0     1562.0    16932.0    1    20
 0.019000     135.00      0
   0
   0
```

Semi-Analytical Option

Input File

```
 1    1     0     0     1
    0.0     8125.0        0.0      6875.0
  10.0
  335.0      200.0        0.22
3650.00    3650.00
   1      0
16 1      6500.0     4390.0    10000.0    1    20
 0.003000       0.00      0
   0
   0
```

Semi-Analytical Option

Input File

```
 1    1     0     0     1
    0.0     4375.0        0.0      3125.0
  10.0
  335.0      200.0        0.22
 365.00     365.00
   1      0
11 1       813.0     1875.0    16932.0    1    20
 0.027000     195.00      0
   0
   0
```

Semi-Analytical Option

Input File

```
 1    1     0     0     1
    0.0     8125.0        0.0      6875.0
  10.0
  335.0      200.0        0.22
3650.00    3650.00
   1      0
16 1      6500.0     4390.0    10000.0    1    20
 0.003000       0.00      0
   0
   0
```

Semi-Analytical Option

Input File

```
 1    1     0     0     1
    0.0     8125.0        0.0      6875.0
  10.0
  335.0      200.0        0.22
3650.00    3650.00
   2      0
49 1      1062.0     5312.0    14110.0    1    20
46 2      2312.0     4218.0     7762.0    1    20
 0.010000     210.00      0
   0
   0
```

Semi-Analytical Option

Input File

```
   1    1    0    0    1
     0.0    6250.0        0.0     4375.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
   1    0
42 1    3000.0    2375.0    20460.0    1    20
 0.060000      90.00     0
   0
   0
```

Semi-Analytical Option

Input File

```
   1    1    0    0    1
     0.0    4000.0        0.0     4000.0
    10.0
   335.0     200.0      0.22
  365.00    365.00
3  1    0
   1     800.0    1300.0    20460.0    1    15
 0.025000     190.00     0
   0
   0
```

Semi-Analytical Option

Input File

```
   1    1    0    0    1
     0.0   10000.0        0.0    10000.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
   2    0
25 1    4062.0    3125.0    35159.0    1    20
24 2    3500.0    6250.0    24693.0    1    20
 0.060000     225.00     0
   0
   0
```

Semi-Analytical Option

Input File

```
   1    1    0    0    1
     0.0    8125.0        0.0     6875.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
   2    0
49 1    1062.0    5312.0    14110.0    1    20
46 2    2312.0    4218.0     7762.0    1    2C
 0.016000     255.00     0
   0
   0
```

Semi-Analytical Option

Input File

```
   1    1    0    0    1
     0.0    8125.0        0.0     6875.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
   2    0
10 1    4812.0    2619.0     5644.0    1    20
14 2    6062.0    1456.0    20000.0    1    20
 0.015000     340.00     0
   0
   0
```

Semi-Analytical Option

Input File

```
   1    1    0    0    1
     0.0    9375.0        0.0     6875.0
    10.0
   335.0     200.0      0.22
  365.00    365.00
   1    0
15 1    4000.0    2000.0    16277.0    1    16
 0.010000       0.00     0
   0
   0
```

Semi-Analytical Option

Input File

```
   1    1    0    0    1
     0.0    4375.0        0.0     4375.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
   1    0
17 1    2187.0    1562.0    20000.0    1    20
 0.050000     350.00     0
   0
   0
```

Semi-Analytical Option

Input File

```
   1    1    0    0    1
     0.0    8125.0        0.0     8125.0
    10.0
   335.0     200.0      0.22
  365.00    365.00
   1    0
8  1    4000.0    2250.0    14816.0    1    15
 0.030000     255.00     0
   0
   0
```

Semi-Analytical Option

Input File

```
  1    1    0    0    1
     0.0    6875.0       0.0    6875.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
  2    0
33 1    2688.0    4375.0    14110.0    1    20
32 2    5750.0    2680.0    14816.0    1    20
 0.005000     227.00    0
  0
  0
```

Semi-Analytical Option

Input File

```
1
  1    1    0    0    1
     0.0    9375.0       0.0    6875.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
  2    0
43 1    4250.0    2250.0    20460.0    1    20
15 2    2031.0    2188.0    16227.0    1    20
 0.054000       0.00    0
  0
  0
```

Semi-Analytical Option

Input File

```
1
  1    1    0    0    1
     0.0    9375.0       0.0    6875.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
  1    0
19 1    3750.0    4561.0    26809.0    1    20
 0.054000     315.00    0
  0
  0
```

Semi-Analytical Option

Input File

```
1
  1    1    0    0    1
     0.0    9375.0       0.0    7500.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
  1    0
30  1    7250.0    2400.0    31748.0    1    20
 0.080000     180.00    0
  0
  0
```

Semi-Analytical Option

Input File

```
  1    1    0    0    1
     0.0    8125.0       0.0    8125.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
  2    0
18 1    6094.0    3530.0    4233.0    1    20
48 2    5762.0     900.0   15521.0    1    20
 0.038000     222.00    0
  0
  0
```

Semi-Analytical Option

Input File

```
  1    1    0    0    1
     0.0    8125.0       0.0    8125.0
    10.0
   335.0     200.0      0.22
 7300.00   7300.00
  1    0
8 1    4000.0    2250.0    14816.0    1    20
 0.000100     200.00    0
  0
  0
```

Semi-Analytical Option

Input File

```
  1    1    0    0    1
     0.0    8125.0       0.0    8125.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
  3    0
 9 1    2480.0    1230.0    21165.0    1    20
 3 2    2813.0    4900.0    20460.0    1    20
27 3    1750.0    3150.0     7122.0    1    20
 0.050000     200.00    0
  0
  0
```

Semi-Analytical Option

Input File

```
  1    1    0    0    1
     0.0    9375.0       0.0    7500.0
    10.0
   335.0     200.0      0.22
 3650.00   3650.00
  1    0
22 1    2812.0    4186.0    15521.0    1    20
 0.040000     315.00    0
  0
  0
```

Semi-Analytical Option

Input File

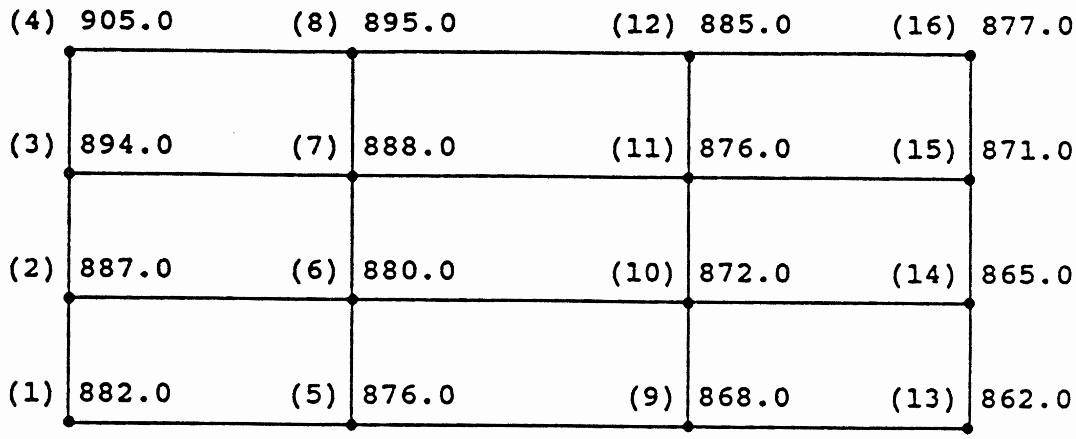
```
  1    1    0    0    1
     0.0    8125.0        0.0     8125.0
   10.0
   335.0     200.0       0.22
 3650.00   3650.00
  2    0
18 1     6094.0     3530.0     4233.0     1     7
48 2     5762.0      900.0    15521.0     1    20
0.025000    285.00     0
  0
  0
```

Explanation for the Input Files for GPTRAC's Numerical Option

```
   a 1    b 1     1     1     1
       d 0.0    e 8125.0       f 0.0    g 8125.0
  h 14   i 14   j 0
    m 335.0    n 200.0       o 0.22
c TRIAL9.TXT
  p 7300.00  q 7300.00
   k 6    l 0
27  1   s 1750.0   t 3150.0   u 7122.0   v 1  w 20
 9  2     2480.0     1230.0    21165.0     1     20
 8  3     4000.0     2250.0    20460.0     1     20
48  4     5762.0      900.0    14816.0     1     20
 3  5     2813.0     4900.0     4233.0     1     20
18  6     6094.0     3530.0    15521.0     1     20
   x 0
   y 0
```

a Rectangular Finite Element Model or Mesh-Centered Finite Difference Model
b feet and days
c Head Data File
d minimum x coordinate
e maximum x coordinate
f minimum y coordinate
g maximum y coordinate
h # of grid line rows
i # of grid line columns
j nodes numbered along y axis
k # of pumping wells
l # of recharge wells
m transmissivity (ft2/day)
n aquifer thickness (ft)
o porosity (decimal)
p time limit for simulation (days)
q time limit for capture zones (days)
r well number
s x coordinate
t y coordinate
u discharge (ft3/day)
v delineate capture zone
w # of pathlines
x # forward tracking pathlines
y # reverse tracking pathlines

Schematic Representation of Head Data File Format
for Finite Element or Mesh-Centered Finite Difference
Model Output With Nodes Numbered in the y-direction



(1) = node number

1	882.0	2	887.0	3	894.0	4	905.0	5	876.0
6	880.0	7	888.0	8	895.0	9	868.0	10	872.0
11	876.0	12	885.0	13	862.0	14	865.0	15	871.0
16	877.0								

Numerical Option

Input File

```
     1     1     1     1     1
        0.0    6875.0       0.0     6875.0
   12    12     0
      335.0     200.0      0.22
 TRIAL7.TXT
   7300.00   7300.00
     4     0
21   1      2906.0     4612.0    33159.0     1    20
37   2      2906.0     2812.0    32453.0     1    20
12   3      4500.0     4612.0    27515.0     1    20
38   4      5250.0     2875.0    31748.0     1    20
     0
     0
```

GPTRAC HYDRAULIC HEAD FILE   TRIAL7.TXT

1	870.	2	870.	3	860.	4	855.	5	852.
6	845.	7	836.	8	829.	9	825.	10	813.
11	809.	12	807.	13	863.	14	865.	15	863.
16	852.	17	851.	18	841.	19	834.	20	829.
21	825.	22	815.	23	807.	24	805.	25	859.
26	860.	27	855.	28	853.	29	851.	30	849.
31	834.	32	821.	33	815.	34	805.	35	800.
36	770.	37	856.	38	854.	39	851.	40	850.
41	849.	42	849.	43	834.	44	822.	45	807.
46	800.	47	770.	48	720.	49	850.	50	850.
51	849.	52	848.	53	848.	54	848.	55	831.
56	820.	57	800.	58	780.	59	720.	60	670.
61	847.	62	849.	63	849.	64	848.	65	848.
66	848.	67	831.	68	820.	69	800.	70	780.
71	720.	72	670.	73	845.	74	847.	75	847.
76	847.	77	847.	78	840.	79	835.	80	822.
81	815.	82	800.	83	765.	84	715.	85	836.
86	839.	87	839.	88	837.	89	839.	90	833.
91	832.	92	827.	93	820.	94	806.	95	800.
96	770.	97	835.	98	832.	99	832.	100	821.
101	829.	102	815.	103	820.	104	820.	105	821.
106	815.	107	806.	108	805.	109	830.	110	825.
111	825.	112	825.	113	812.	114	810.	115	820.
116	820.	117	822.	118	821.	119	808.	120	807.
121	821.	122	822.	123	820.	124	819.	125	814.
126	812.	127	812.	128	812.	129	819.	130	812.
131	802.	132	813.	133	820.	134	817.	135	815.
136	813.	137	811.	138	810.	139	810.	140	810.
141	813.	142	816.	143	821.	144	822.	145	816.
146	812.	147	812.	148	811.	149	810.	150	809.
151	809.	152	810.	153	810.	154	812.	155	818.
156	820.								

Numerical Option

Input File

```
     1     1     1     1     1
        0.0    9375.0       0.0     6875.0
   16    12     0
      335.0     200.0      0.22
 TRIAL12.TXT
   3650.00   3650.00
     4     0
15   1      2031.0     2188.0    16227.0     1    20
19   2      3750.0     4561.0    26809.0     1    20
43   3      4250.0     2250.0    20460.0     1    20
47   4      6562.0     2625.0    11994.0     1    20
     0
     0
```

GPTRAC HYDRAULIC HEAD FILE   TRIAL12.TXT

1	803.	2	803.	3	803.	4	819.	5	819.
6	820.	7	827.	8	830.	9	832.	10	835.
11	830.	12	830.	13	822.	14	822.	15	822.
16	822.	17	822.	18	822.	19	822.	20	822.
21	830.	22	830.	23	830.	24	830.	25	820.
26	830.	27	830.	28	830.	29	830.	30	830.
31	830.	32	830.	33	830.	34	830.	35	830.
36	830.	37	820.	38	830.	39	829.	40	829.
41	829.	42	828.	43	827.	44	825.	45	825.
46	825.	47	830.	48	835.	49	830.	50	825.
51	822.	52	820.	53	815.	54	815.	55	815.
56	820.	57	822.	58	830.	59	835.	60	840.
61	815.	62	810.	63	800.	64	790.	65	780.
66	780.	67	780.	68	800.	69	810.	70	820.
71	830.	72	840.	73	780.	74	760.	75	740.
76	720.	77	720.	78	720.	79	742.	80	754.
81	770.	82	805.	83	830.	84	841.	85	700.
86	690.	87	670.	88	630.	89	615.	90	680.
91	700.	92	700.	93	750.	94	765.	95	805.
96	820.	97	655.	98	650.	99	650.	100	650.
101	650.	102	650.	103	670.	104	700.	105	730.
106	750.	107	770.	108	809.	109	655.	110	650.
111	660.	112	665.	113	665.	114	665.	115	665.
116	680	117	690.	118	720.	119	750.	120	770.
121	700.	122	695.	123	690.	124	670.	125	680.
126	670.	127	670.	128	675.	129	680.	130	710.
131	745.	132	770.	133	740.	134	730.	135	725.
136	720.	137	700.	138	680.	139	675.	140	680.
141	680.	142	710.	143	730.	144	750.	145	800.
146	790.	147	780.	148	750.	149	740.	150	720.
151	705.	152	705.	153	710.	154	730.	155	730.
156	750.	157	860.	158	855.	159	830.	160	800.
161	770.	162	755.	163	740.	164	740.	165	740.
166	740.	167	750.	168	750.	169	860.	170	845.
171	835.	172	825.	173	820.	174	800.	175	780.
176	770.	177	784.	178	750.	179	750.	180	762.
181	860.	182	845.	183	832.	184	825.	185	820.
186	820.	187	810.	188	800.	189	789.	190	784.
191	784.	192	770.	193	850.	194	840.	195	835.
196	825.	197	820.	198	819.	199	813	200	813.
201	810.	202	809.	203	800.	204	800.		

Numerical Option

Input File

```
      1    1    1    1    1
         0.0     6250.0       0.0      4375.0
    11    8    0
     335.0      200.0       0.22
  TRIAL32.TXT
    3650.00   3650.00
      1    0
42    1     3000.0     2375.0     20460.0      1     20
      0
      0
```

GPTRAC HYDRAULIC HEAD INPUT FILE TRIAL32.TXT

1	830.	2	830.	3	825.	4	815.	5	815.
6	810.	7	815.	8	815.	9	825.	10	825.
11	815.	12	807.	13	807.	14	809.	15	810.
16	780.	17	820.	18	820.	19	809.	20	805.
21	801.	22	800.	23	780.	24	700.	25	820.
26	820.	27	805.	28	800.	29	770.	30	720.
31	690.	32	655.	33	870.	34	820.	35	800.
36	780.	37	720.	38	680.	39	670.	40	655.
41	820.	42	820.	43	800.	44	740.	45	690.
46	670.	47	690.	48	700.	49	820.	50	820.
51	815.	52	780.	53	760.	54	750.	55	740.
56	740.	57	820.	58	820.	59	820.	60	810.
61	800.	62	790.	63	800.	64	800.	65	820.
66	820.	67	835.	68	827.	69	827.	70	855.
71	860.	72	860.	73	820.	74	820.	75	830.
76	827.	77	827.	78	855.	79	860.	80	860.
81	820.	82	820.	83	830.	84	827.	85	827.
86	855.	87	860.	88	860.	89	820.	90	820.
91	830.	92	827.	93	827.	94	855.	95	860.
96	860.								

Numerical Option

Input File

```
      1    1    1    1    1
         0.0     7500.0       0.0      6875.0
    13   12    0
     335.0      200.0       0.22
  TRIAL8.TXT
     365.00    365.00
      5    0
45    1     1563.0     4625.0     16227.0      1     20
41    2     1563.0     2925.0      9877.0      1     20
52    3     4062.0     4844.0     20460.0      1     20
20    4     4062.0     2343.0     12699.0      1     20
53    5     5531.0     4844.0     13405.0      1     20
      0
      0
```

GPTRAC HYDRAULIC HEAD INPUT FILE TRIAL8.TXT

1	881.	2	892.	3	900.	4	910.	5	918.
6	923.	7	930.	8	935.	9	940.	10	945.
11	950.	12	955.	13	882.	14	887.	15	892.
16	906.	17	913.	18	929.	19	930.	20	932.
21	937.	22	940.	23	942.	24	947.	25	883.
26	887.	27	893.	28	900.	29	912.	30	930.
31	927.	32	930.	33	930.	34	932.	35	937.
36	942.	37	884.	38	882.	39	882.	40	892.
41	910.	42	922.	43	925.	44	930.	45	930.
46	937.	47	935.	48	938.	49	885.	50	884.
51	889.	52	892.	53	897.	54	900.	55	915.
56	930.	57	930.	58	931.	59	932.	60	934.
61	887.	62	882.	63	872.	64	867.	65	867.
66	870.	67	880.	68	900.	69	910.	70	920.
71	930.	72	932.	73	890.	74	860.	75	835.
76	800.	77	790.	78	809.	79	830.	80	850.
81	880.	82	900.	83	920.	84	930.	85	890.
86	860.	87	835.	88	800.	89	782.	90	781.
91	792.	92	800.	93	840.	94	872.	95	900.
96	918.	97	887.	98	867.	99	850.	100	835.
101	800.	102	784.	103	785.	104	793.	105	800.
106	830.	107	880.	108	920.	109	884.	110	867.
111	855.	112	850.	113	839.	114	820.	115	800.
116	793.	117	788.	118	812.	119	862.	120	907.
121	883.	122	875.	123	877.	124	872.	125	860.
126	850.	127	840.	128	820.	129	820.	130	830.
131	862.	132	907.	133	881.	134	890.	135	890.
136	890.	137	890.	138	887.	139	870.	140	860.
141	870.	142	885.	143	900.	144	920.	145	907.
146	910.	147	920.	148	925.	149	920.	150	915.
151	910.	152	907.	153	910.	154	920.	155	931.
156	937.	157	920.	158	920.	159	930.	160	930.
161	930.	162	932.	163	929.	164	922.	165	930.
166	937.	167	942.	168	947.				

Numerical Option

Input File

```
  1     1     1     1     1
     0.0     9375.0          0.0      5000.0
 16     9     0
   335.0       200.0        0.22
TRIAL13.TXT
  3650.00    3650.00
    4     0
51  1     1562.0     2187.0    28926.0     1    20
42  2     6062.0     1125.0    20460.0     1    20
54  3     6812.0     2187.0    19049.0     1    20
23  4     8375.0     2187.0    23282.0     1    20
    0
    0
```

GPTRAC HYDRAULIC HEAD FILE TRIAL13.TXT

1	815.	2	815.	3	815.	4	810.	5	807.
6	807.	7	807.	8	819.	9	819.	10	815.
11	815.	12	810.	13	807.	14	812.	15	822.
16	822.	17	822.	18	822.	19	820.	20	820.
21	810.	22	805.	23	820.	24	825.	25	830.
26	830.	27	830.	28	820.	29	820.	30	810.
31	805.	32	820.	33	825.	34	829.	35	829.
36	829.	37	815.	38	819.	39	815.	40	815.
41	820.	42	825.	43	822.	44	820.	45	815.
46	815.	47	815.	48	810.	49	815.	50	815.
51	810.	52	800.	53	790.	54	780.	55	807.
56	807.	57	809.	58	810.	59	780.	60	760.
61	740.	62	720.	63	720.	64	805.	65	801.
66	800.	67	780.	68	700.	69	690.	70	670.
71	630.	72	615.	73	800.	74	720.	75	720.
76	690.	77	655.	78	650.	79	650.	80	650.
81	650.	82	780.	83	720.	84	680.	85	670.
86	655.	87	650.	88	660.	89	665.	90	665.
91	740.	92	690.	93	680.	94	690.	95	700.
96	695.	97	690.	98	670.	99	680.	100	780.
101	760.	102	750.	103	740.	104	740.	105	730.
106	725.	107	720.	108	700.	109	810.	110	800.
111	790.	112	800.	113	800.	114	790.	115	780.
116	750	117	740.	118	827.	119	827.	120	855.
121	860.	122	860.	123	790.	124	780.	125	800.
126	770.	127	850.	128	850.	129	855.	130	860.
131	860.	132	845.	133	835.	134	825.	135	820.
136	860.	137	860.	138	860.	139	860.	140	860.
141	845.	142	832.	143	825.	144	820.	145	860.
146	860.	147	860.	148	860.	149	850.	150	840.
151	835.	152	825.	153	820.				

Numerical Option

Input File

```
   1     1     1     1     1
      0.0     4375.0         0.0      4375.0
   8     8     0
    335.0      200.0       0.22
TRIAL18.TXT
  3650.00   3650.00
    1     0
17  1      2817.0     1562.0     20000.0     1    20
    0
    0
```

GPTRAC HYDRAULIC HEAD INPUT FILE   TRIAL18.TXT

1	915.	2	915.	3	916.	4	917.	5	920.
6	920.	7	921.	8	922.	9	900.	10	905.
11	905.	12	907.	13	910.	14	915.	15	920.
16	920.	17	865.	18	865.	19	880.	20	880.
21	890.	22	905.	23	915.	24	920.	25	849.
26	839.	27	815.	28	815.	29	850.	30	875.
31	910.	32	917.	33	835.	34	829.	35	815.
36	815.	37	860.	38	880.	39	909.	40	917.
41	840.	42	839.	43	839.	44	845.	45	860.
46	890.	47	913.	48	919.	49	845.	50	846.
51	855.	52	865.	53	880.	54	900.	55	915.
56	920.	57	855.	58	856.	59	865.	60	875.
61	890.	62	912.	63	920.	64	920.	65	860.
66	865.	67	870.	68	885.	69	900.	70	915.
71	920.	72	920.						

Numerical Option

Input File

```
  1     1     1     1     1
     0.0     6875.0       0.0    10000.0
 12    17     0
   335.0      200.0      0.22
TRIAL31.TXT
  7300.00   7300.00
  2     0
25  1      4062.0     3125.0    33159.0     1    20
24  2      3500.0     6250.0    24693.0     1    20
  0
  0
```

GPTRAC HYDRAULIC HEAD INPUT FILE   TRIAL31.TXT

1	820.	2	820.	3	853.	4	815.	5	815.
6	810.	7	810.	8	809.	9	806.	10	805.
11	805.	12	807.	13	810.	14	820.	15	835.
16	850.	17	850.	18	820.	19	820.	20	815.
21	815.	22	815.	23	810.	24	810.	25	809.
26	806.	27	805.	28	805.	29	807.	30	810.
31	820.	32	835.	33	850.	34	850.	35	820.
36	820.	37	815.	38	815.	39	815.	40	810.
41	810.	42	809.	43	806.	44	805.	45	805.
46	807.	47	810.	48	820.	49	835.	50	850.
51	850.	52	820.	53	820.	54	815.	55	810.
56	805.	57	800.	58	795.	59	790.	60	785.
61	770.	62	785.	63	785.	64	790.	65	810.
66	830.	67	850.	68	850.	69	815.	70	815.
71	802.	72	790.	73	770.	74	750.	75	730.
76	715.	77	705.	78	700.	79	700.	80	705.
81	750.	82	735.	83	820.	84	850.	85	850.
86	810.	87	810.	88	790.	89	760.	90	740.
91	700.	92	690.	93	670.	94	670.	95	675.
96	675.	97	680.	98	719.	99	750.	100	800.
101	850.	102	850.	103	805.	104	805.	105	770.
106	730.	107	690.	108	620.	109	670.	110	690.
111	670.	112	675.	113	675.	114	680.	115	700.
116	760	117	810.	118	850.	119	850.	120	805.
121	805.	122	770.	123	730.	124	690.	125	620.
126	640.	127	660.	128	770.	129	680.	130	700.
131	705.	132	740.	133	790.	134	829.	135	850.
136	850.	137	807.	138	807.	139	780.	140	740.
141	720.	142	700.	143	700.	144	705.	145	710.
146	730.	147	740.	148	760.	149	780.	150	820.
151	837.	152	850.	153	850.	154	807.	155	807.
156	805.	157	790.	158	770.	159	770.	160	760.
161	760.	162	770.	163	780.	164	800.	165	810.
166	820.	167	825.	168	837.	169	850.	170	850.
171	807.	172	807.	173	815.	174	809.	175	805.
176	805.	177	805.	178	805.	179	805.	180	809.
181	810.	182	815.	183	825.	184	830.	185	845.
186	845.	187	845.	188	807.	189	807.	190	815.
191	809.	192	805.	193	805.	194	805.	195	805.
196	805.	197	809.	198	810.	199	830.	200	830.
201	830.	202	845.	203	845.	204	845.	205	807.
206	807.	207	815.	208	809.	209	805.	210	805.
211	805.	212	805.	213	805.	214	809.	215	810.
216	830.	217	830.	218	830.	219	845.	220	845.
221	845.								

Numerical Option

Input File

```
  1     1     1     1     1
     0.0     4375.0       0.0     4375.0
  8     8     0
   335.0      200.0      0.22
TRIAL16.TXT
  7300.00   7300.00
  1     0
16  1      2812.0     1562.0    11288.0     1    20
  0
  0
```

GPTRAC HYDRAULIC HEAD INPUT FILE   TRIAL16.TXT

1	790.	2	810.	3	815.	4	820.	5	825.
6	830.	7	830.	8	830.	9	788.	10	800.
11	815.	12	822.	13	827.	14	830.	15	830.
16	830.	17	786.	18	795.	19	810.	20	820.
21	826.	22	830.	23	830.	24	830.	25	782.
26	790.	27	805.	28	817.	29	825.	30	828.
31	830.	32	830.	33	730.	34	790.	35	800.
36	810.	37	820.	38	830.	39	830.	40	830.
41	779.	42	787.	43	795.	44	805.	45	815.
46	825.	47	830.	48	830.	49	787.	50	785.
51	790.	52	805.	53	850.	54	821.	55	829.
56	830.	57	777.	58	782.	59	789.	60	802.
61	810.	62	820.	63	825.	64	829.	65	776.
66	782.	67	786.	68	800.	69	800.	70	820.
71	827.	72	835.						

Numerical Option

Input File

```
 1    1    1    1    1
    0.0   4375.0      0.0    3125.0
 8    7   0
  335.0    200.0      0.22
TRIAL20.TXT
  3650.00   3650.00
 1    0
11 1      813.0    1875.0    16932.0    1    20
 0
 0
```

GPTRAC HYDRAULIC HEAD INPUT FILE   TRIAL20.TXT

1	820.	2	825.	3	835.	4	840.	5	840.
6	843.	7	845.	8	820.	9	825.	10	835.
11	840.	12	840.	13	842.	14	845.	15	830.
16	835.	17	840.	18	840.	19	840.	20	840.
21	840.	22	835.	23	835.	24	835.	25	835.
26	835.	27	835.	28	835.	29	827.	30	827.
31	827.	32	827.	33	827.	34	827.	35	827.
36	821.	37	821.	38	822.	39	822.	40	822.
41	822.	42	822.	43	815.	44	817.	45	819.
46	820.	47	830.	48	840.	49	850.	50	770.
51	790.	52	805.	53	817.	54	820.	55	821.
56	850.	57	750.	58	750.	59	770.	60	800.
61	810.	62	821.	63	840.				

Numerical Option

Input File

```
 1    1    1    1    1
    0.0   4375.0      0.0    5000.0
 8    9   0
  335.0    200.0      0.22
TRIAL19.TXT
  365.00    365.00
 1    0
50 1     2906.0    2187.0    19049.0    1    20
 0
 0
```

GPTRAC HYDRAULIC HEAD INPUT FILE   TRIAL19.TXT

1	820.	2	835.	3	859.	4	869.	5	875.
6	880.	7	890.	8	900.	9	920.	10	810.
11	835.	12	835.	13	869.	14	875.	15	890.
16	890.	17	890.	18	910.	19	790.	20	839.
21	859.	22	869.	23	875.	24	890.	25	890.
26	890.	27	890.	28	770.	29	825.	30	860.
31	880.	32	880.	33	885.	34	845.	35	845.
36	840.	37	770.	38	825.	39	860.	40	880.
41	880.	42	870.	43	835.	44	800.	45	790.
46	800.	47	830.	48	860.	49	880.	50	880.
51	880.	52	830.	53	800.	54	780.	55	810.
56	830.	57	860.	58	870.	59	880.	60	880.
61	880.	62	835.	63	805.	64	820.	65	840.
66	855.	67	855.	68	880.	69	880.	70	880.
71	880.	72	850.	73	829.	74	835.	75	855.
76	865.	77	880.	78	890.	79	890.	80	890.
81	890.								

Numerical Option

Input File

```
        1     1     1     1     1
           0.0     4375.0       0.0      5000.0
        8     9     0
         335.0      200.0       0.22
     TRIAL17.TXT
        365.00     365.00
        1     0
    29  1     2812.0     1562.0     7760.0     1     20
        0
        0
```

GPTRAC HYDRAULIC HEAD INPUT FILE   TRIAL17.TXT

1	970.	2	972.	3	974.	4	976.	5	978.
6	980.	7	981.	8	982.	9	983.	10	971.
11	973.	12	974.	13	976.	14	977.	15	979.
16	980.	17	982.	18	983.	19	972.	20	974.
21	975.	22	976.	23	978.	24	979.	25	980.
26	982.	27	984.	28	973.	29	974.	30	976.
31	978.	32	979.	33	980.	34	982.	35	984.
36	985.	37	974.	38	977.	39	978.	40	979.
41	980.	42	981.	43	989.	44	985.	45	986.
46	975.	47	977.	48	978.	49	975.	50	980.
51	982.	52	985.	53	986.	54	987.	55	977.
56	979.	57	980.	58	983.	59	984.	60	985.
61	986.	62	987.	63	988.	64	979.	65	981.
66	983.	67	984.	68	985.	69	986.	70	987.
71	988.	72	989.	73	980.	74	982.	75	984.
76	985.	77	986.	78	987.	79	988.	80	989.
81	990.								

Numerical Option

Input File

```
   1     1     1     1     1
      0.0    8125.0        0.0      8125.0
  14    14     0
    335.0     200.0       0.22
TRIAL9.TXT
  7300.00    7300.00
   4     0
27 1     1750.0     3150.0     7122.0     1     12
 9 2     2480.0     1230.0    21165.0     1     12
 8 3     4000.0     2250.0    14816.0     1     12
48 4     5762.0      900.0    15521.0     1     12
   0
   0
```

GPTRAC HYDRAULIC HEAD FILE TRIAL9.TXT

1	785.	2	810.	3	830.	4	840.	5	880.
6	880.	7	860.	8	840.	9	830.	10	800.
11	785.	12	790.	13	790.	14	800.	15	805.
16	812.	17	830.	18	842.	19	857.	20	850.
21	840.	22	830.	23	821.	24	815.	25	810.
26	800.	27	790.	28	799.	29	820.	30	827.
31	827.	32	830.	33	835.	34	831.	35	850.
36	850.	37	850.	38	850.	39	850.	40	850.
41	800.	42	820.	43	830.	44	830.	45	837.
46	850.	47	860.	48	870.	49	872.	50	880.
51	890.	52	890.	53	880.	54	870.	55	850.
56	870.	57	835.	58	823.	59	823.	60	840.
61	890.	62	900.	63	905.	64	910.	65	915.
66	915.	67	910.	68	905.	69	900.	70	904.
71	835.	72	829.	73	850.	74	900.	75	910.
76	910.	77	915.	78	920.	79	925.	80	925.
81	918.	82	911.	83	911.	84	915.	85	835.
86	830.	87	890.	88	931.	89	930.	90	930.
91	927.	92	917.	93	917.	94	916.	95	920.
96	922.	97	931.	98	931.	99	840.	100	849.
101	890.	102	930.	103	930.	104	930.	105	922.
106	917.	107	918.	108	912.	109	912.	110	910.
111	920.	112	932.	113	832.	114	852.	115	877.
116	923	117	928.	118	930.	119	918.	120	918.
121	919.	122	911.	123	910.	124	906.	125	910.
126	940.	127	830.	128	857.	129	864.	130	900.
131	917.	132	920.	133	920.	134	920.	135	920.
136	919.	137	917.	138	910.	139	930.	140	940.
141	820.	142	830.	143	864.	144	880.	145	907.
146	920.	147	920.	148	920.	149	920.	150	920.
151	920.	152	920.	153	930.	154	931.	155	817.
156	820.	157	832.	158	869.	159	900.	160	920.
161	920.	162	920.	163	920.	164	920.	165	920.
166	920.	167	929.	168	927.	169	800.	170	817.
171	829.	172	850.	173	880.	174	900.	175	910.
176	920.	177	920.	178	920.	179	920.	180	922.
181	920.	182	920.	183	790.	184	805.	185	829.
186	850.	187	875.	188	880.	189	900.	190	910.
191	919.	192	922.	193	922.	194	922.	195	922.
196	922.	197	780.	198	800.	199	825.	200	850.
201	870.	202	880.	203	891.	204	900.	205	907.
206	915.	207	920.	208	920.	209	920.	210	920.

Numerical Option

Input File

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    4     0
22  1     2812.0     4186.0    15521.0     1    20
36  2     4875.0     3375.0    14777.0     1    20
30  3     7250.0     2400.0    31748.0     1    20
31  4     4781.0     1437.0    12699.0     1    20
    0
    0
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GPTRAC HYDRAULIC HEAD FILE TRIAL11.TXT

1	742.	2	754.	3	770.	4	805.	5	831.
6	841.	7	859.	8	878.	9	900.	10	910.
11	922.	12	922.	13	922.	14	700.	15	730.
16	750.	17	765.	18	805.	19	820.	20	840.
21	860.	22	889.	23	910.	24	920.	25	922.
26	922.	27	670.	28	700.	29	730.	30	750.
31	770.	32	809.	33	820.	34	840.	35	860.
36	889.	37	910.	38	920.	39	922.	40	765.
41	680.	42	890.	43	720.	44	750.	45	770.
46	810.	47	830.	48	860.	49	820.	50	889.
51	910.	52	915.	53	670.	54	675.	55	680.
56	710.	57	745.	58	770.	59	790.	60	810.
61	840.	62	860.	63	860.	64	889.	65	905.
66	875.	67	680.	68	680.	69	710.	70	730.
71	750.	72	795.	73	805.	74	820.	75	840.
76	860.	77	860.	78	885.	79	705.	80	705.
81	710.	82	730.	83	730.	84	750.	85	750.
86	780.	87	810.	88	815.	89	840.	90	840.
91	850.	92	740.	93	740.	94	740.	95	750.
96	750.	97	750.	98	750.	99	770.	100	790.
101	800.	102	815.	103	830.	104	840.	105	780.
106	770.	107	784.	108	750.	109	760.	110	762.
111	762.	112	770.	113	780.	114	790.	115	810.
116	820	117	840.	118	810.	119	800.	120	789.
121	784.	122	784.	123	770.	124	770.	125	775.
126	785.	127	790.	128	810.	129	820.	130	840.
131	813.	132	813.	133	810.	134	809.	135	800.
136	800.	137	800.	138	800.	139	800.	140	805.
141	810.	142	820.	143	840.	144	818.	145	825.
146	820.	147	830.	148	830.	149	830.	150	830.
151	829.	152	815.	153	815.	154	154.	155	820.
156	835.	157	822.	158	835.	159	835.	160	840.
161	840.	162	840.	163	840.	164	829.	165	820.
166	820.	167	820.	168	822.	169	822.	170	840.
171	840.	172	840.	173	840.	174	840.	175	840.
176	840.	177	832.	178	827.	179	827.	180	827.
181	825.	182	825.	183	840.	184	840.	185	840.
186	840.	187	840.	188	840.	189	840.	190	840.
191	840.	192	832.	193	832.	194	829.	195	822.
196	837.	197	840.	198	840.	199	840	200	840.
201	840.	202	840.	203	840.	204	840.	205	832.
206	829.	207	829.	208	820.	209	840.	210	840.
211	840.	212	840.	213	840.	214	840.	215	840.
216	840.	217	840.	218	832.	219	830.	220	825.
221	820.								

Numerical Option

Input File

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    5     0
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46  2     2312.0     4218.0     7762.0     1    20
10  3     4812.0     2619.0     5644.0     1    20
14  4     6062.0     1456.0    20000.0     1    20
16  5     6500.0     4390.0    20000.0     1    20
    0
    0
```

GPTRAC HYDRAULIC HEAD FILE TRIAL10.TXT

1	900.	2	900.	3	905.	4	910.	5	880.
6	915.	7	910.	8	905.	9	900.	10	905.
11	915.	12	925.	13	935.	14	910.	15	910.
16	915.	17	920.	18	925.	19	925.	20	918.
21	911.	22	911.	23	920.	24	940.	25	949.
26	949.	27	930.	28	930.	29	927.	30	917.
31	917.	32	916.	33	920.	34	922.	35	931.
36	925.	37	940.	38	951.	39	960.	40	930.
41	930.	42	922.	43	917.	44	918.	45	912.
46	912.	47	910.	48	920.	49	940.	50	950.
51	951.	52	960.	53	925.	54	930.	55	918.
56	918.	57	919.	58	911.	59	910.	60	906.
61	910.	62	940.	63	947.	64	953.	65	961.
66	917.	67	920.	68	920.	69	920.	70	920.
71	919.	72	917.	73	910.	74	930.	75	940.
76	947.	77	953.	78	962.	79	907.	80	920.
81	920.	82	920.	83	920.	84	920.	85	920.
86	920.	87	930.	88	931.	89	947.	90	953.
91	962.	92	900.	93	920.	94	920.	95	920.
96	920.	97	920.	98	920.	99	920.	100	927.
101	929.	102	947.	103	953.	104	963.	105	880.
106	900.	107	910.	108	920.	109	920.	110	920.
111	921.	112	922.	113	928.	114	928.	115	940.
116	950	117	963.	118	875.	119	880.	120	900.
121	910.	122	919.	123	922.	124	922.	125	922.
126	922.	127	925.	128	935.	129	937.	130	942.
131	862.	132	880.	133	891.	134	900.	135	907.
136	915.	137	920.	138	920.	139	920.	140	922.
141	925.	142	830.	143	937.	144	849.	145	849.
146	869.	147	872.	148	880.	149	900.	150	905.
151	907.	152	912.	153	919.	154	920.	155	920.
156	922.	157	830.	158	842.	159	850.	160	859.
161	862.	162	872.	163	872.	164	880.	165	880.
166	892.	167	900.	168	907.	169	915.	170	812.
171	822.	172	832.	173	840.	174	850.	175	850.
176	850.	177	840.	178	840.	179	840.	180	850.
181	880.	182	900.	183	790.	184	810.	185	822.
186	837.	187	845.	188	850.	189	837.	190	837.
191	815.	192	830.	193	850.	194	875.	195	900.

APPENDIX G

LIST OF GENERAL PARTICLE TRACKING MODULE OPTION USED FOR EACH WELL FOR EACH TOT BOUNDARY

S - Semi-Analytical Option
N - Numerical Option

WELL No.	1 YEAR	10 YEAR	20 YEAR
3	S	S	S
8	S	S	S
9	S	N	N
10	S	S	S
12	S	S	S
14	S	N	N
16	S	S	S
17	S	N	N
18	S	S	S
19	S	N	N
20	S	N	N
21	S	N	N
22	S	N	N
23	S	S	S
24	S	N	N
25	S	N	N
26	S	S	S
27	S	N	N
28	S	S	S
29	S	S	S
30	S	S	S
31	S	S	S
32	S	S	S
33	S	S	S
34	S	S	S
35	S	S	S
36	S	N	N
37	S	S	S
38	S	N	N
39	S	S	S
41	S	S	S
42	S	N	N
43	S	N	N

WELL No.	1 YEAR	10 YEAR	20 YEAR
44	S	S	S
45	S	S	S
46	S	N	N
47	S	N	N
48	S	S	S
49	S	N	N
50	S	S	S
51	S	S	S
52	S	N	N
53	S	N	N
54	S	S	S

APPENDIX H

CHEMICAL ANALYSES FROM EDMOND'S WATER WELLS

APPROVED METHODOLOGY FOR WATER QUALITY PARAMETERS

PARAMETER	METHODOLOGY	STANDARD METHODS	ASTM[2]
ALKALINITY	TITRIMETRIC	2320	
CONDUCTIVITY	CONDUCTANCE		D1125-82B
CALCIUM	EDTA TITRIMETRIC	3500-Ca D	
ORTHOPHOSPHATE	COLORIMETRIC:ASCORBIC ACID	4500-P-E	
pH	ELECTROMETRIC	4500-H	
TEMPERATURE	THERMOMETRIC	2550	

[1] STANDARD METHODS. 1989. 17TH EDITION
AMERICAN PUBLIC HEALTH ASSOCIATION, WASHINGTON, D.C.

[2] ANNUAL BOOK OF STANDARDS, 1987.
AMERICAN SOCIETY OF TESTING MATERIALS, PHILADELPHIA, PA.

hardness as $CaCO_3$ (.40) = mg/l a Ca only

WATER QUALITY ANALYSIS
CITY OF EDMOND ARCADIA WATER PLANT
PWSID # 1020723 POPULATION SERVED: 47K

SOURCE	WELL# 3	WELL# 8	WELL# 9	WELL#11	WELL#18	WELL#30
DATE	3-30-92	3-30-92	3-30-92	3-30-92	3-30-92	3-30-92
TIME COLLECTED	8:56	8:35	8:47	9:35	9:22	10:30
COLLECTED BY:	JD	JD	JD	JD	JD	JD
TIME ANAL./INITIALS	RB/11:35	RB/11:50	RB/11:58	RB/12:45	RB/12:55	RB/13.05
TEMPERATURE C	17	17	18	17	17	19
pH	7.70	7.49	7.69	7.69	7.55	9.20
P. ALKALINITY	0	0	0	0	0	30
T. ALKALINITY	237	250	249	240	278	301
TOTAL HARDNESS	214	250	249	240	278	301
CALCIUM	47	64	47	41	60	6
CONDUCTIVITY	481	525	499	469	590	624
ORTHOPHOSPHATE ***	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

SOURCE	WELL#33	WELL#43	WELL#52	WELL#
DATE	3-30-92	3-30-92	3-30-92	
TIME COLLECTED	10:23	10:58	9:04	
COLLECTED BY	JD	JD	JD	
TIME ANAL./INITIALS	RB/13:40	RB/13:48	RB/13:54	
TEMPERATURE C	17	17	17	
pH	7.74	7.79	7.75	29
P. ALKALINITY	0	0	0	
T. ALKALINITY	245	260	237	
TOTAL HARDNESS	209	252	215	
CALCIUM	44	54	56	
CONDUCTIVITY	510	513	492	
ORTHOPHOSPHATE ***	<0.01	<0.01	<0.01	

COMMENTS:*** ORTHOPHOSPHATE FINISHED WATER = .01

LEGEND

JW
JOHNNY WEAVER

JD
JOHN DOYLE

PT
PATRICIA THORNTON

RB
RON BIRDSONG

pH = pH UNITS

HARDNESS=PPM AS $CaCO_3$

CONDUCTIVITY= MICROOMHOS/CM

CALCIUM = PPM

O.PHOSPHATE = PPM

ALKALINITY = PPM AS $CaCO_3$

TEMPERATURE = DEGREE CELSIUS

WATER QUALITY ANALYSIS
CITY OF EDMOND ARCADIA WATER PLANT
PWSID # 1020723 POPULATION SERVED: 47K

SOURCE	WELL#15	WELL#26	WELL#27	WELL#34	WELL#35	WELL#37
DATE	3-2-92	3-2-92	3-2-92	3-2-92	3-2-92	3-2-92
TIME COLLECTED	11:05	9:32	10:15	9:20	11:40	10:32
COLLECTED BY:	JD	JD	JD	JD	JD	JD
TIME ANAL./INITIALS	RB/12:35	RB/12:45	RB/13:00	RB/13:15	RB/13:30	RB/13:45
TEMPERATURE C	17	12	17	14	17	18
pH	7.79	7.79	7.71	7.73	8.08	7.73
P. ALKALINITY	0	0	0	0	0	0
T. ALKALINITY	250	236	274	284	258	285
TOTAL HARDNESS	214	180	264	220	160	190
CALCIUM	52	36.4	60	49.2	33.2	37.6
CONDUCTIVITY	475	484	610	558	496	568
ORTHOPHOSPHATE	<0.01	<0.01	<0.01	<0.01	0.02	<0.01

SOURCE	WELL#40	WELL#42	WELL#51	WELL#53
DATE	3-2-92	3-2-92	3-2-92	3-2-92
TIME COLLECTED	10:03	11:16	10:52	9:37
COLLECTED BY	JD	JD	JD	JD
TIME ANAL./INITIALS	RB/14:00	RB/14:15	RB/14:30	RB/14:45
TEMPERATURE C	15	17	18	17
pH	7.97	7.53	7.92	7.53
P. ALKALINITY	0	0	0	0
T. ALKALINITY	235	265	280	243
TOTAL HARDNESS	191	243	156	235
CALCIUM	41.2	54	33.6	57.2
CONDUCTIVITY	512	513	556	518
ORTHOPHOSPHATE	<0.03	<0.01	<0.01	<0.01

COMMENTS:*** ORTHOPHOSPHATE ANALYSIS WILL BE PREFORMED BY CITY COUNTY HEALTH DEPT, UNTIL OUR CHEMICALS ARRIVE.

LEGEND

JW
JOHNNY WEAVER

JD
JOHN DOYLE

PT
PATRICIA THORNTON

RB
<u>RON BIRDSONG</u>

pH = pH UNITS

HARDNESS=PPM AS $CaCO_3$

CONDUCTIVITY= MICROOMHOS/CM

CALCIUM = PPM

O.PHOSPHATE = PPM

ALKALINITY = PPM AS $CaCO_3$

TEMPERATURE = DEGREE CELSIUS

WATER QUALITY ANALYSIS
CITY OF EDMOND ARCADIA WATER PLANT
PWSID # 1020723 POPULATION SERVED: 47K

SOURCE	WELL#19	WELL#22	WELL#23	WELL#28	WELL#29	WELL#31
DATE	3-25-92	3-25-92	3-25-92	3-25-92	3-25-92	3-25-92
TIME COLLECTED	9:24	9:40	10:55	11:25	11:55	12:22
COLLECTED BY:	JD	JD	JD	JD	JD	JD
TIME ANAL./INITIALS	RB/14:20	RB/14:30	RB/14:39	RB/14:44	RB/14:54	RB/15.05
TEMPERATURE C	18	18	18	18	17	17
pH	8.21	7.90	8.08	7.65	7.65	7.71
P. ALKALINITY	0	0	0	0	0	0
T. ALKALINITY	286	264	258	255	306	256
TOTAL HARDNESS	128	190	131	255	308	244
CALCIUM	28	44	27.2	57	71.6	54
CONDUCTIVITY	607	545	522	510	596	497
ORTHOPHOSPHATE ***	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

SOURCE	WELL#46	WELL#47	WELL#48	WELL#49
DATE	3-25-92	3-25-92	3-25-92	3-25-92
TIME COLLECTED	11:43	13:18	13:30	11:48
COLLECTED BY	JD	JD	JD	JD
TIME ANAL./INITIALS	RB/15:10	RB/15:18	RB/15:25	RB/15:32
TEMPERATURE C	18	18	15	18
pH	7.61	8.06	8.02	7.64
P. ALKALINITY	0	0	0	0
T. ALKALINITY	244	270	232	240
TOTAL HARDNESS	236	193	178	216
CALCIUM	56	40	39	51
CONDUCTIVITY	488	556	503	471
ORTHOPHOSPHATE ***	<0.01	<0.01	<0.01	<0.01

COMMENTS:*** ORTHOPHOSPHATE FINISHED WATER = .01

LEGEND

JW
JOHNNY WEAVER

JD
JOHN DOYLE

PT
PATRICIA THORNTON

RB
RON BIRDSONG

pH = pH UNITS

HARDNESS=PPM AS $CaCO_3$

CONDUCTIVITY= MICROOMHOS/CM

CALCIUM = PPM

O.PHOSPHATE = PPM

ALKALINITY = PPM AS $CaCO_3$

TEMPERATURE = DEGREE CELSIUS

VITA

David A. Edwards

Candidate for the Degree of

Master of Science

Thesis: THE PROTECTION OF THE MUNICIPAL WATER WELL-FIELD SERVING THE CITY OF EDMOND, OKLAHOMA USING WELLHEAD PROTECTION AREA DELINEATION

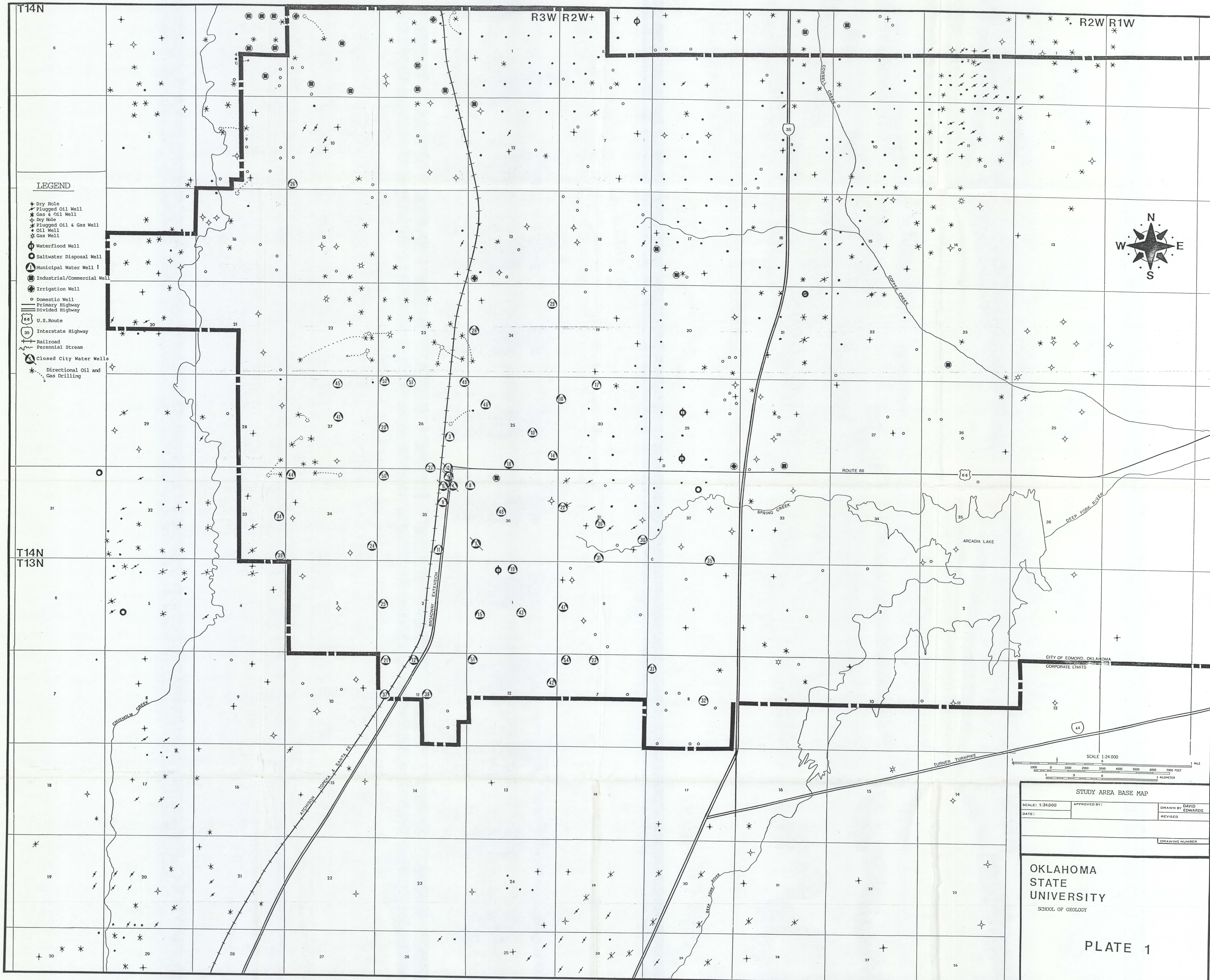
Major Field: Hydrogeology

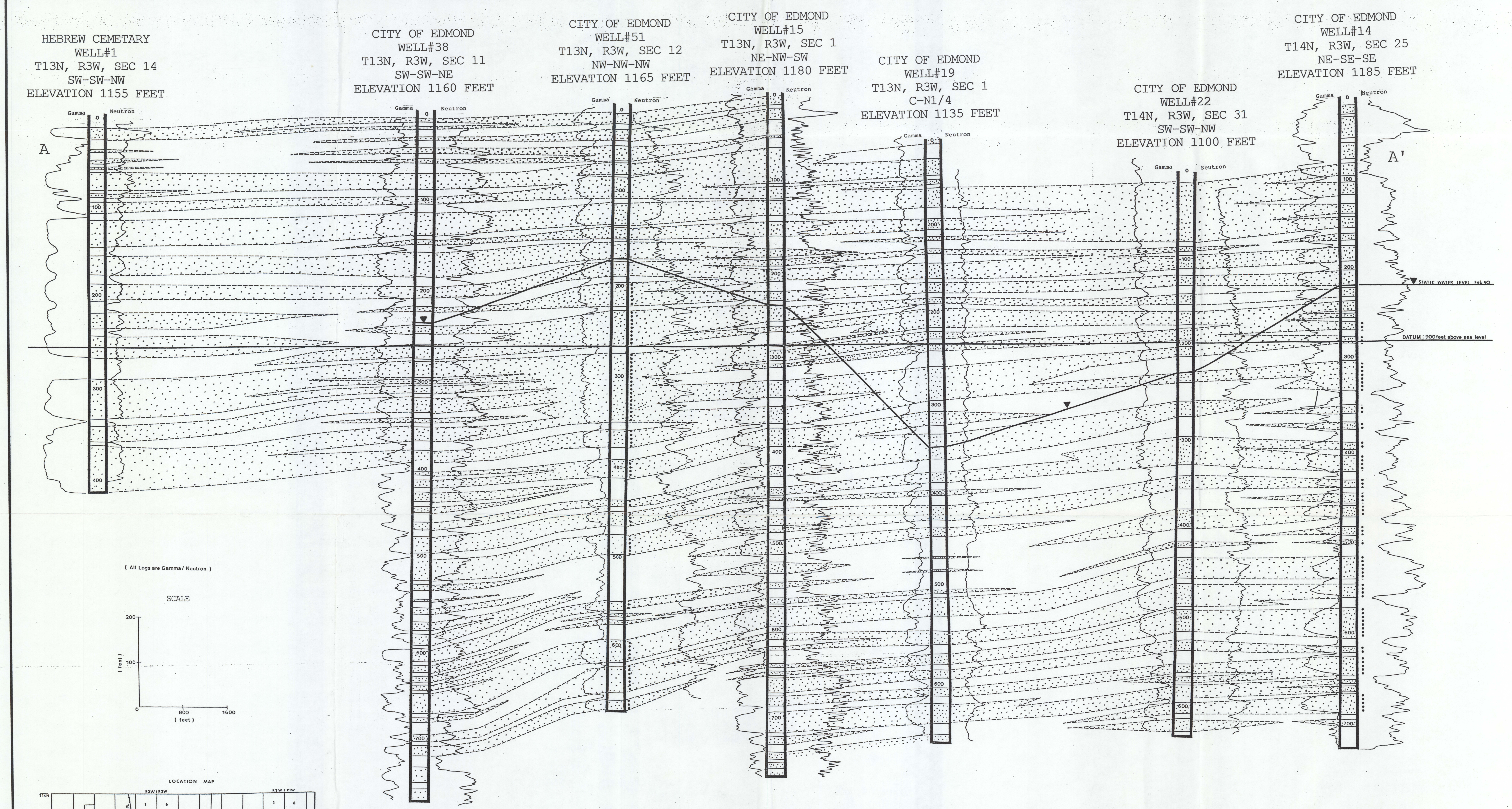
Biographical:

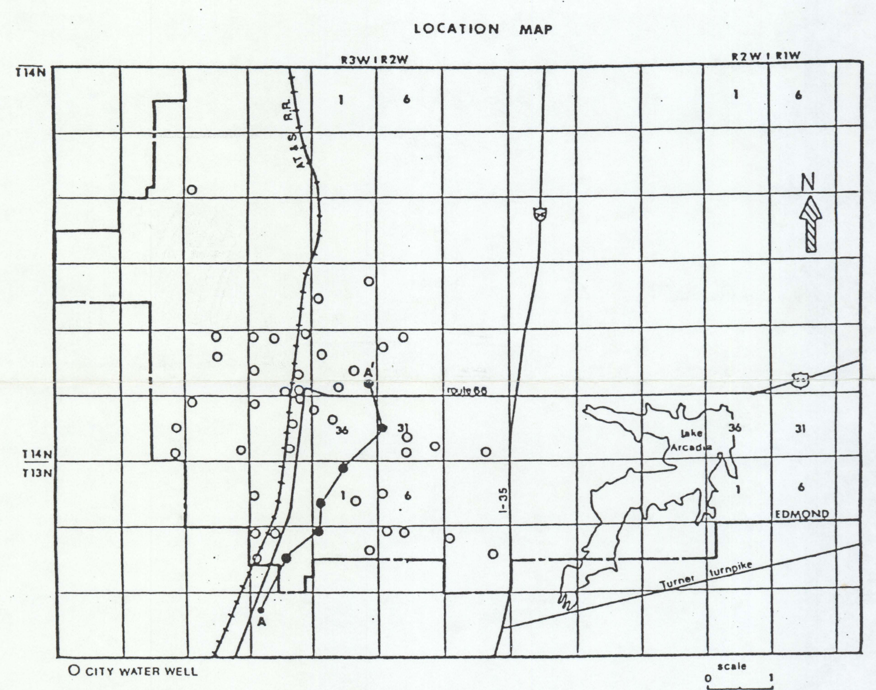
Personal Data: Born in Wichita, Kansas, November 26, 1965, the son of Earl and Deanna Edwards.

Education: Graduated from Edmond High School, Edmond, Oklahoma, in May 1984; received Bachelor of Science Degree in Geology from Oklahoma State University in Stillwater, Oklahoma in May, 1989; completed requirements for the Master of Science degree at Oklahoma State University in December, 1992.

Professional Experience: Teaching and Research Assistant, Department of Geology, Oklahoma State University, August, 1989, to May, 1991.


T14N
T13N
R3W R2W
R2W R1W
LEGEND
Dry Hole
Plugged Oil Well
Gas & Oil Well
Dry Hole
Plugged Oil & Gas Well
Oil Well
Gas Well
Waterflood Well
Saltwater Disposal Well
Municipal Water Well
Industrial/Commercial Well
Irrigation Well
Domestic Well
Primary Highway
Divided Highway
U.S.Route
Interstate Highway
Railroad
Perennial Stream
Closed City Water Wells
Directional Oil and Gas Drilling
N
S
E
W
COWBELL CREEK
COFFEE CREEK
ROUTE 66
SPRING CREEK
DEEP FORK RIVER
ARCADIA LAKE
BROADWAY EXTENSION
CITY OF EDMOND, OKLAHOMA CORPORATE LIMITS
CHISHOLM CREEK
ATCHISON TOPEKA & SANTA FE
TURNER TURNPIKE
SCALE 1:24 000
1 MILE
7000 FEET
1 KILOMETER
STUDY AREA BASE MAP
SCALE: 1:24,000
APPROVED BY:
DRAWN BY DAVID EDWARDS
DATE:
REVISED
DRAWING NUMBER
OKLAHOMA STATE UNIVERSITY
SCHOOL OF GEOLOGY
PLATE 1





STATIGRAPHIC CROSS-SECTION A-A'

EDMOND WELL-FIELD

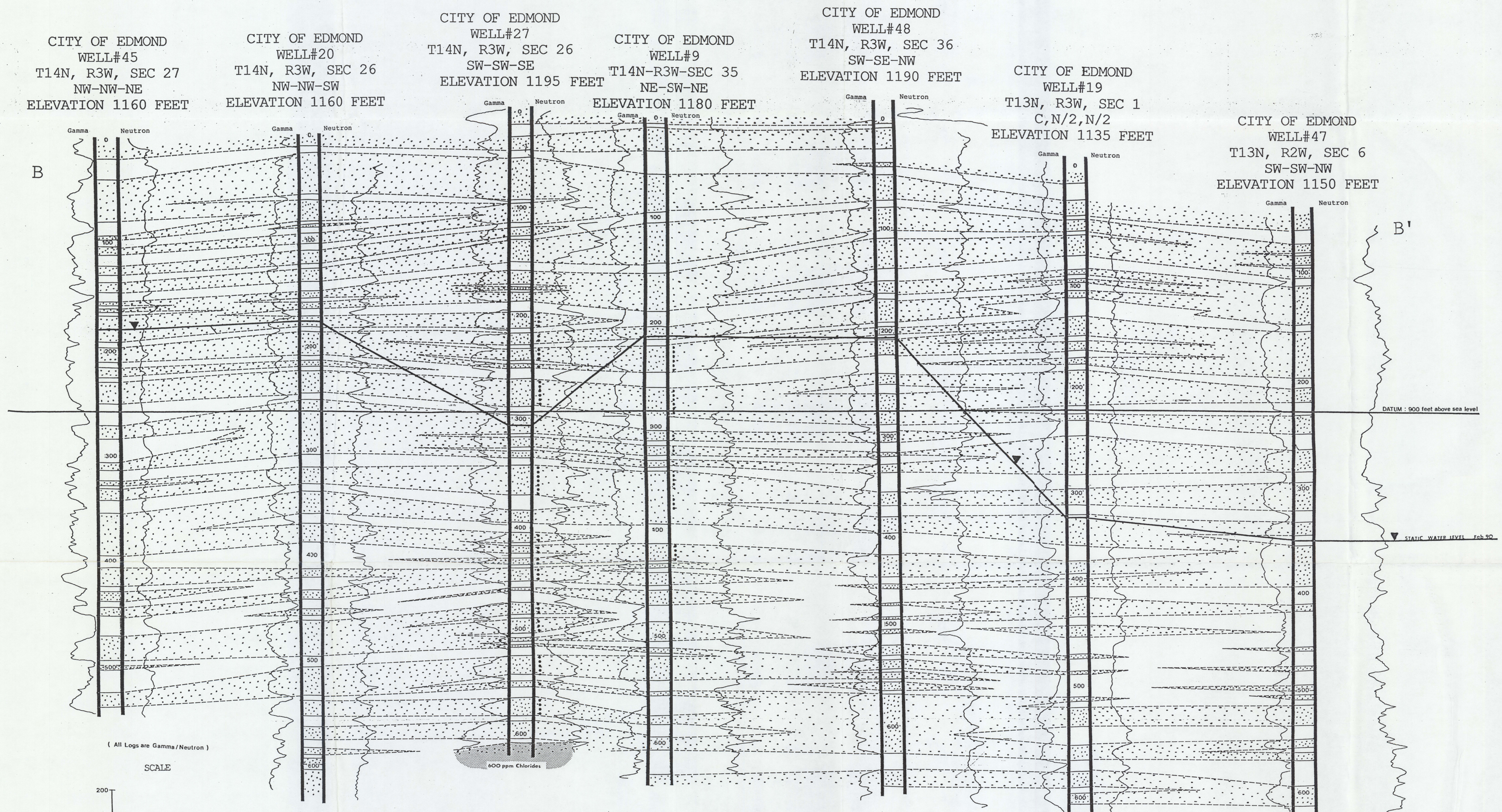
PLATE 2

SAND — PERFORATED INTERVAL (where known)

SHALE

STRATIGRAPHIC CROSS-SECTION A-A' EDMOND WELL FIELD		
SCALE:	APPROVED BY:	DRAWN BY
DATE:		REVISED
OKLAHOMA STATE UNIVERSITY		
SCHOOL OF GEOLOGY		DRAWING NUMBER

24 X 36 PRINTED ON NO. 1000H CLEARPRINT



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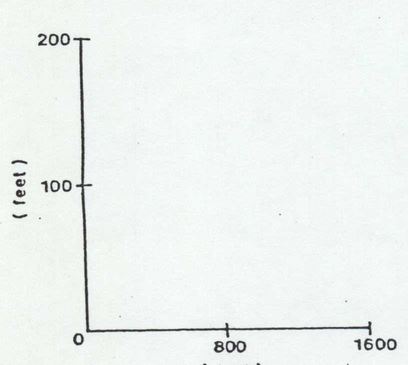
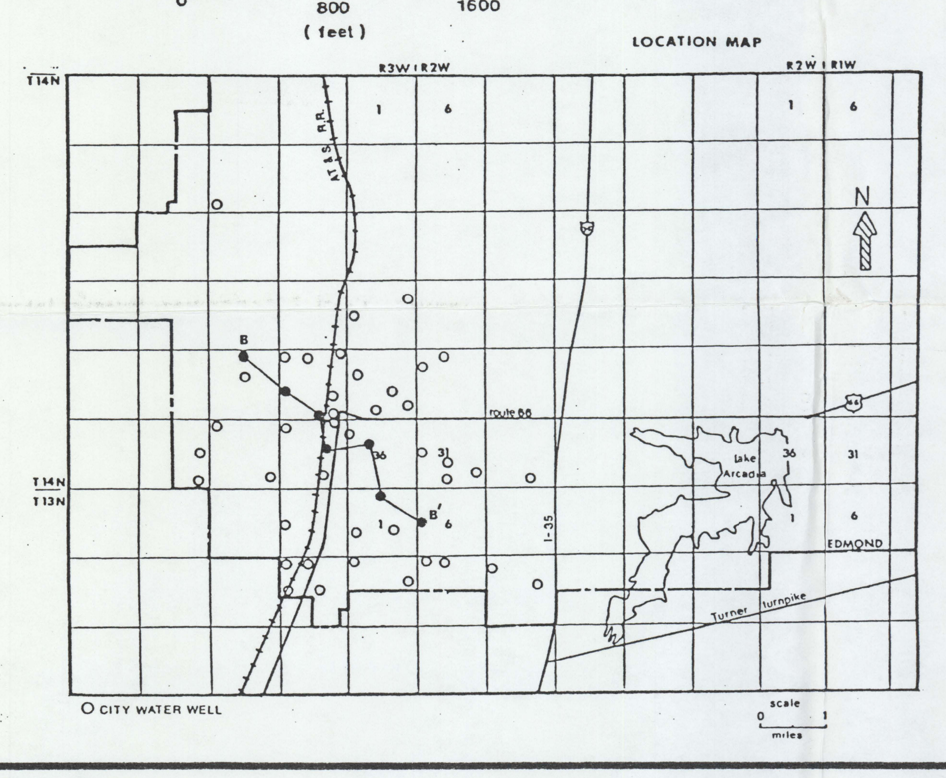




STATIGRAPHIC CROSS-SECTION B-B'

EDMOND WELL FIELD

PLATE 3

SAND — PERFORATED INTERVAL (where known)

SHALE

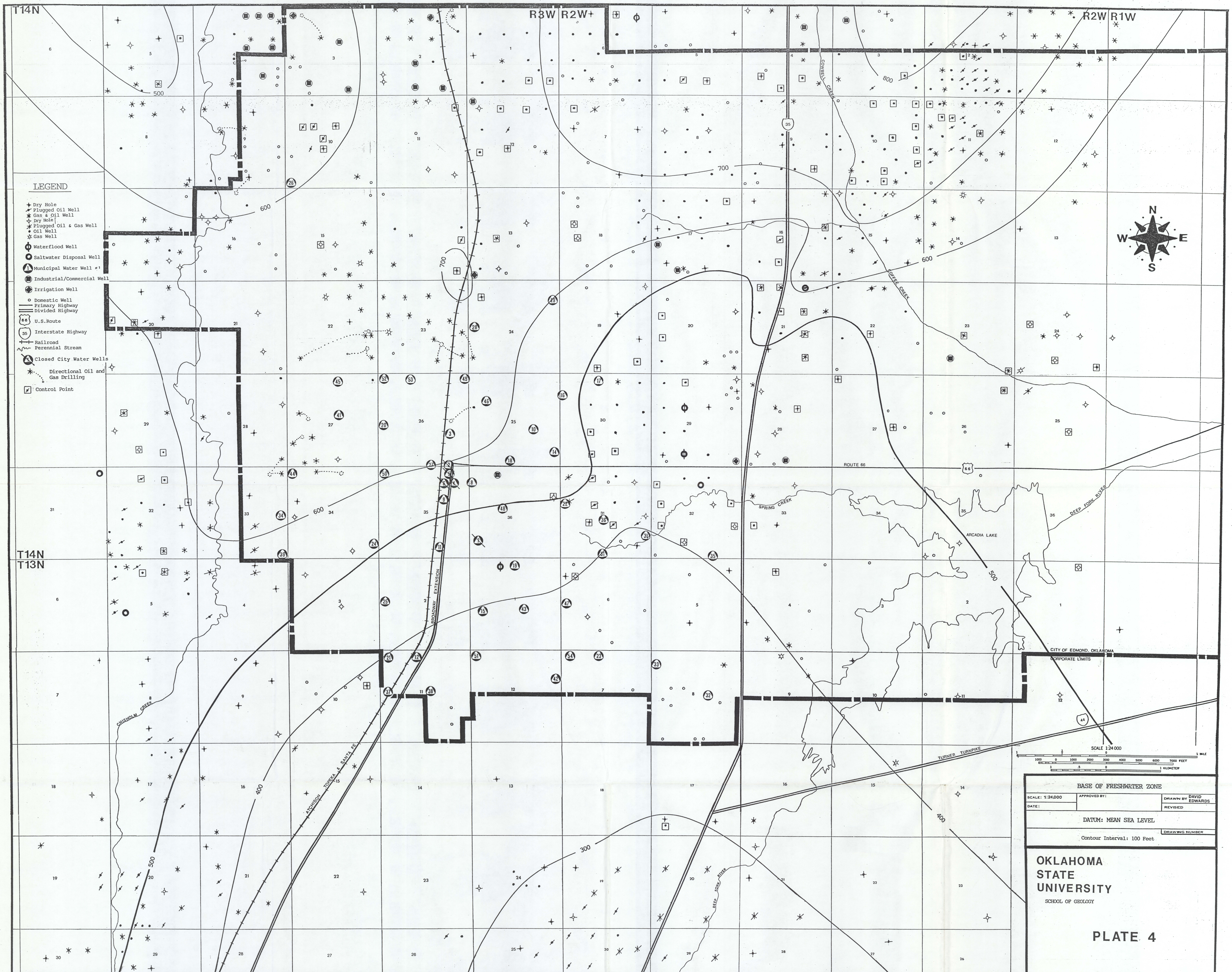
STRATIGRAPHIC CROSS-SECTION B-B'
EDMOND WELL FIELD

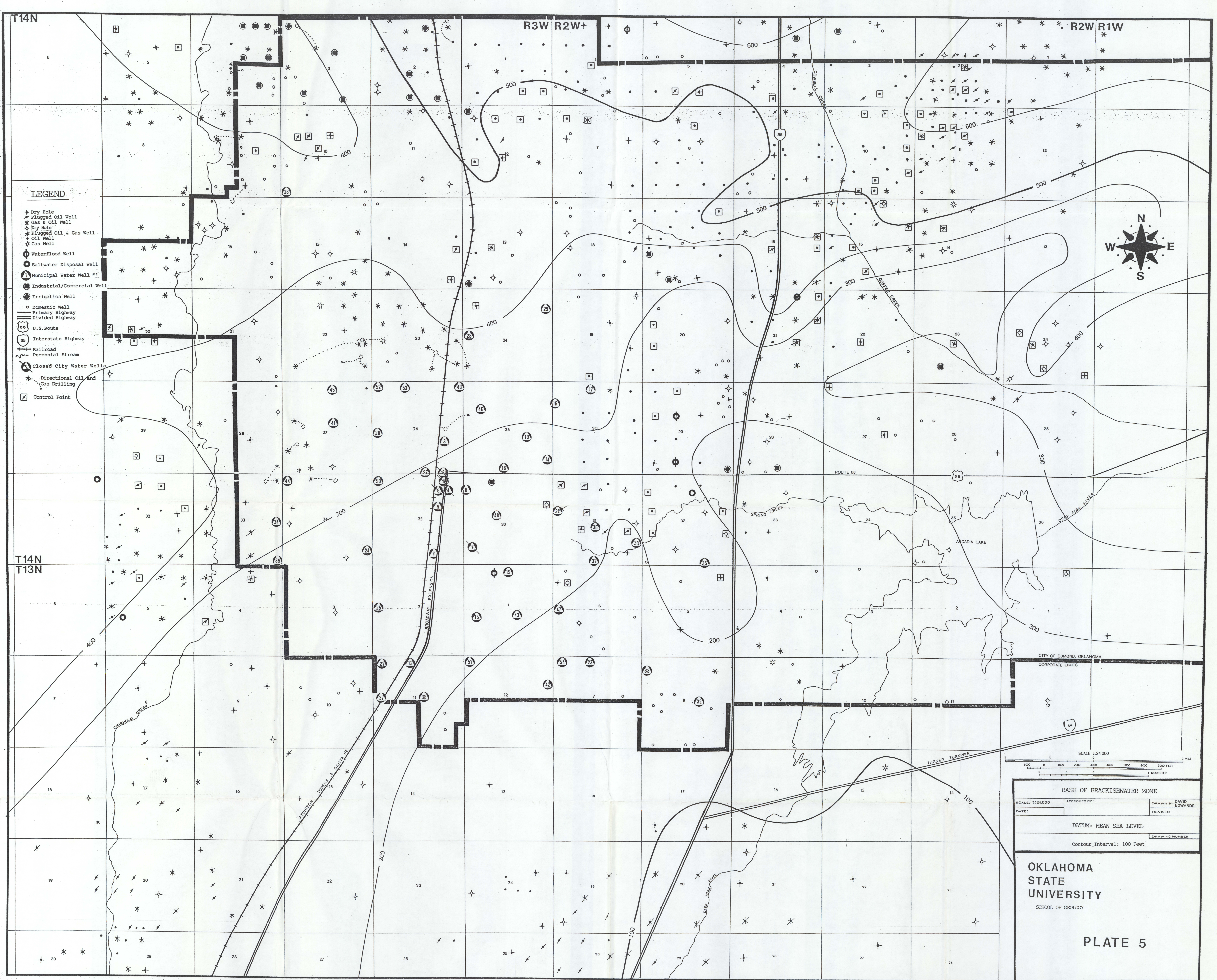
SCALE:	APPROVED BY:	DRAWN BY Dennis Edwards
DATE:		REVISED

OKLAHOMA STATE UNIVERSITY

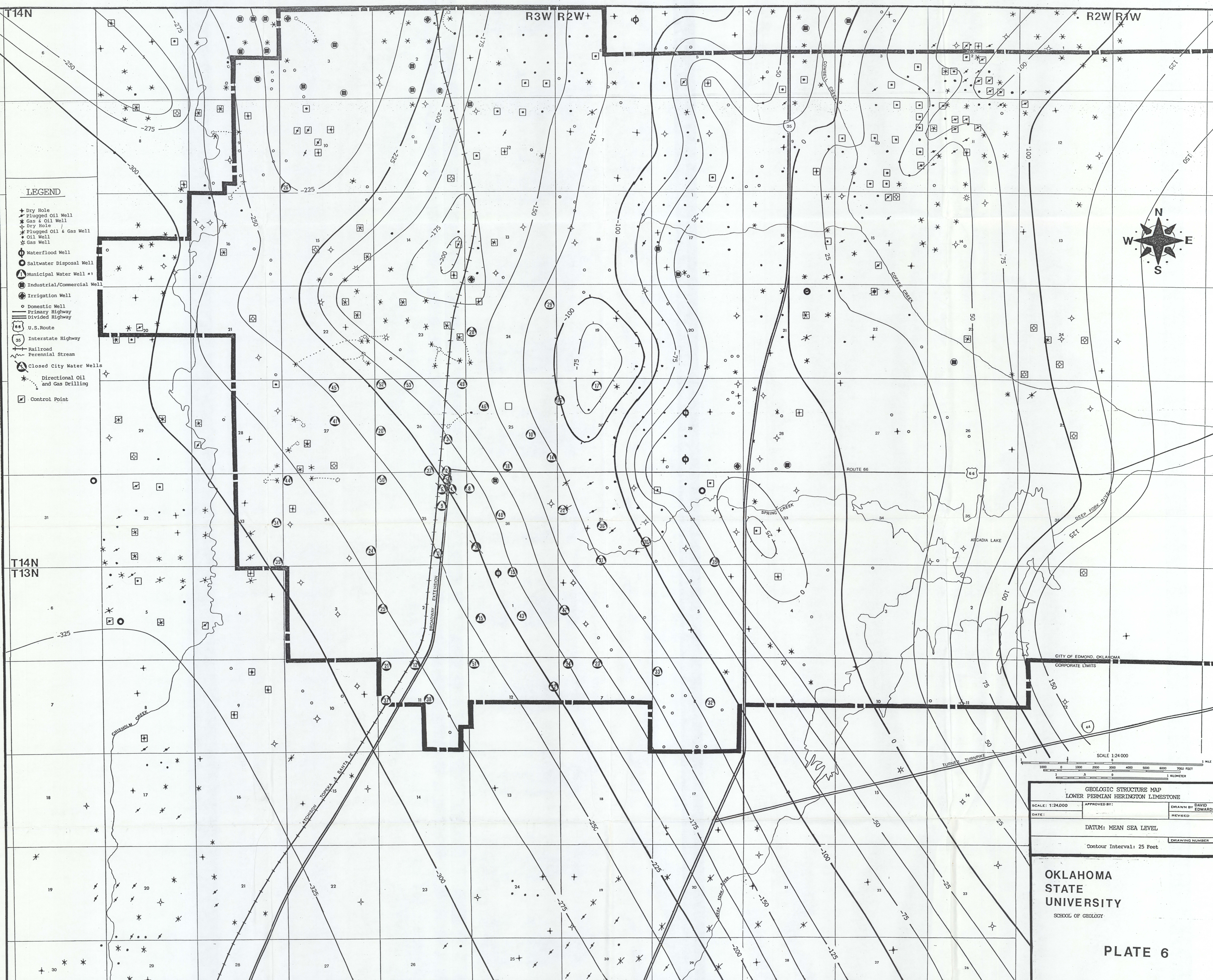
SCHOOL OF GEOLOGY — DRAWING NUMBER

24 X 36 PRINTED ON NO. 1000H CLEARPRINT

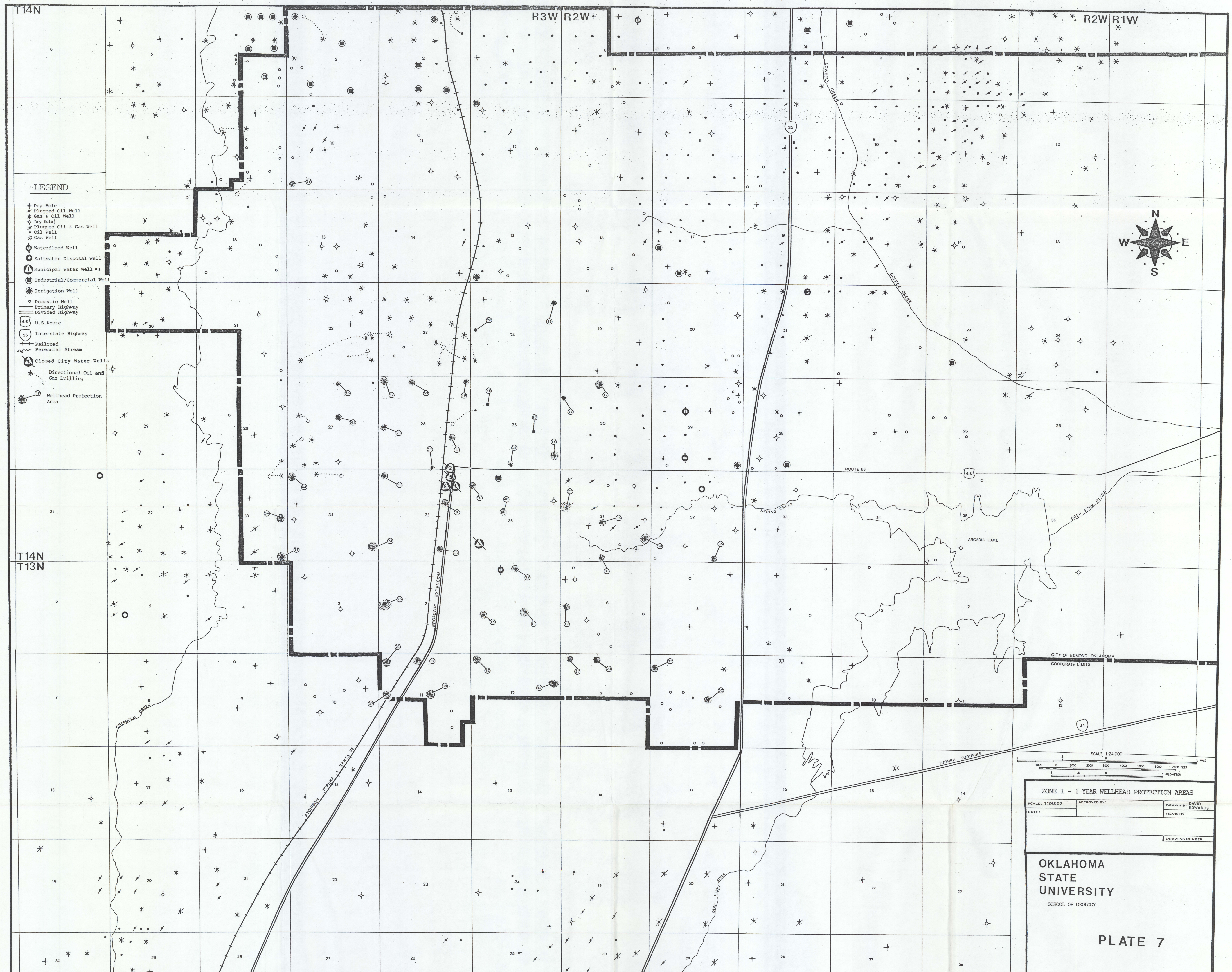

T14N
R3W R2W
R2W R1W
T14N
T13N
LEGEND
Dry Hole
Plugged Oil Well
Gas & Oil Well
Dry Hole
Plugged Oil & Gas Well
Oil Well
Gas Well
Waterflood Well
Saltwater Disposal Well
Municipal Water Well
Industrial/Commercial Well
Irrigation Well
Domestic Well
Primary Highway
Divided Highway
U.S.Route
Interstate Highway
Railroad
Perennial Stream
Closed City Water Wells
Directional Oil and Gas Drilling
Control Point
N
S
E
W
800
700
600
500
400
300
ROUTE 66
SPRING CREEK
COFFEE CREEK
COWELL CREEK
DEEP FORK RIVER
ARCADIA LAKE
CHISHOLM CREEK
BROADWAY EXTENSION
ATCHISON TOPEKA & SANTA FE
TURNER TURNPIKE
CITY OF EDMOND, OKLAHOMA
CORPORATE LIMITS
SCALE 1:24 000
1 MILE
7000 FEET
1 KILOMETER
BASE OF FRESHWATER ZONE
SCALE: 1:24,000
APPROVED BY:
DRAWN BY DAVID EDWARDS
DATE:
REVISED
DATUM: MEAN SEA LEVEL
DRAWING NUMBER
Contour Interval: 100 Feet
OKLAHOMA
STATE
UNIVERSITY
SCHOOL OF GEOLOGY
PLATE 4



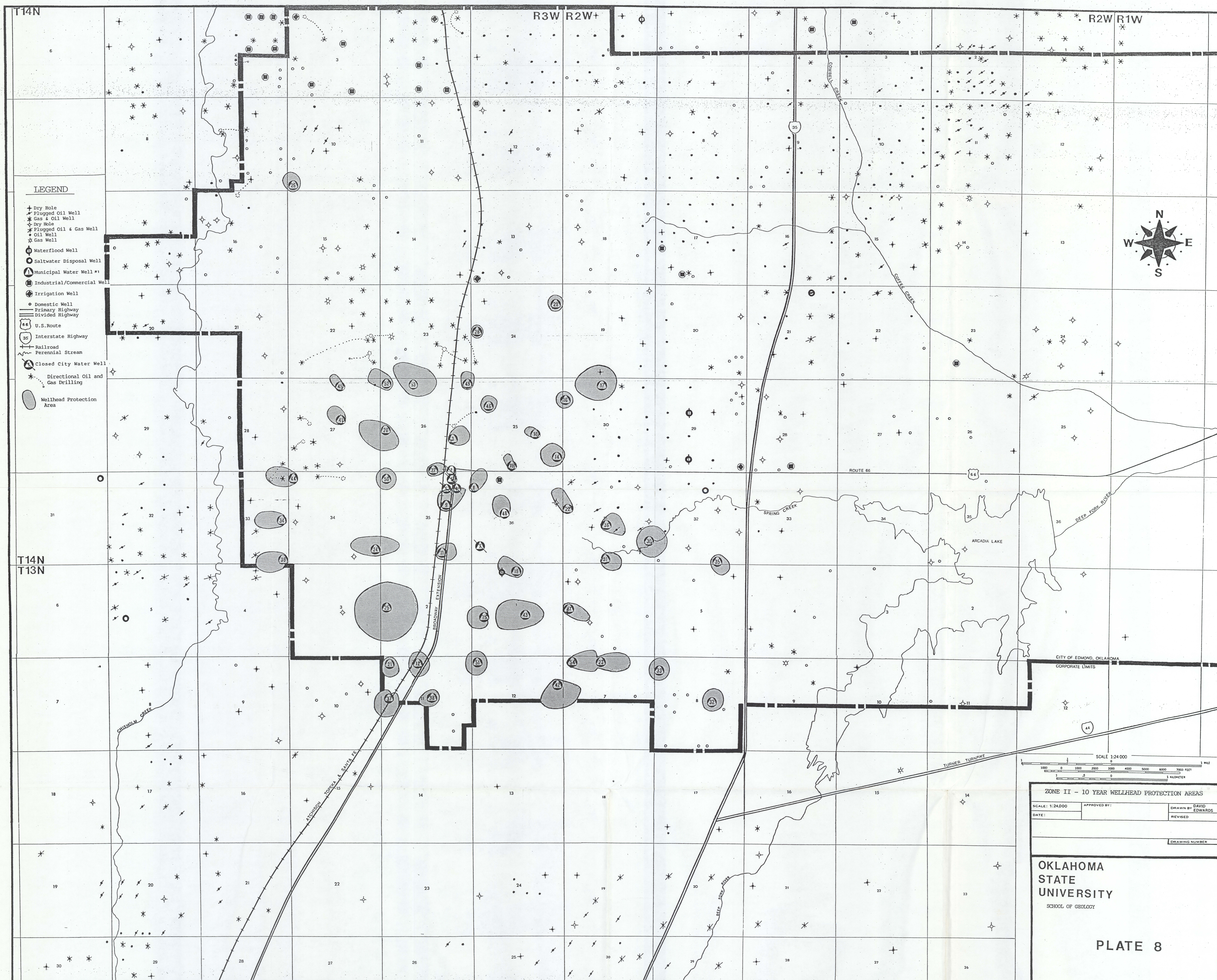
T14N
R3W R2W
R2W R1W
T14N
T13N
LEGEND
Dry Hole
Plugged Oil Well
Gas & Oil Well
Dry Hole
Plugged Oil & Gas Well
Oil Well
Gas Well
Waterflood Well
Saltwater Disposal Well
Municipal Water Well #1
Industrial/Commercial Well
Irrigation Well
Domestic Well
Primary Highway
Divided Highway
U.S.Route
Interstate Highway
Railroad
Perennial Stream
Closed City Water Wells
Directional Oil and Gas Drilling
Control Point
N
W
E
S
600
500
400
300
200
100
COWPER CREEK
COFFEE CREEK
ROUTE 66
SPRING CREEK
ARCADIA LAKE
DEEP FORK RIVER
BROADWAY EXTENSION
ATCHISON, TOPEKA & SANTA FE
CHISHOLM CREEK
TURNER TURNPIKE
CITY OF EDMOND, OKLAHOMA
CORPORATE LIMITS
SCALE 1:24 000
1 MILE
7000 FEET
1 KILOMETER
BASE OF BRACKISHWATER ZONE
SCALE: 1:24,000
APPROVED BY:
DRAWN BY DAVID EDWARDS
DATE:
REVISED
DATUM: MEAN SEA LEVEL
DRAWING NUMBER
Contour Interval: 100 Feet
OKLAHOMA
STATE
UNIVERSITY
SCHOOL OF GEOLOGY
PLATE 5



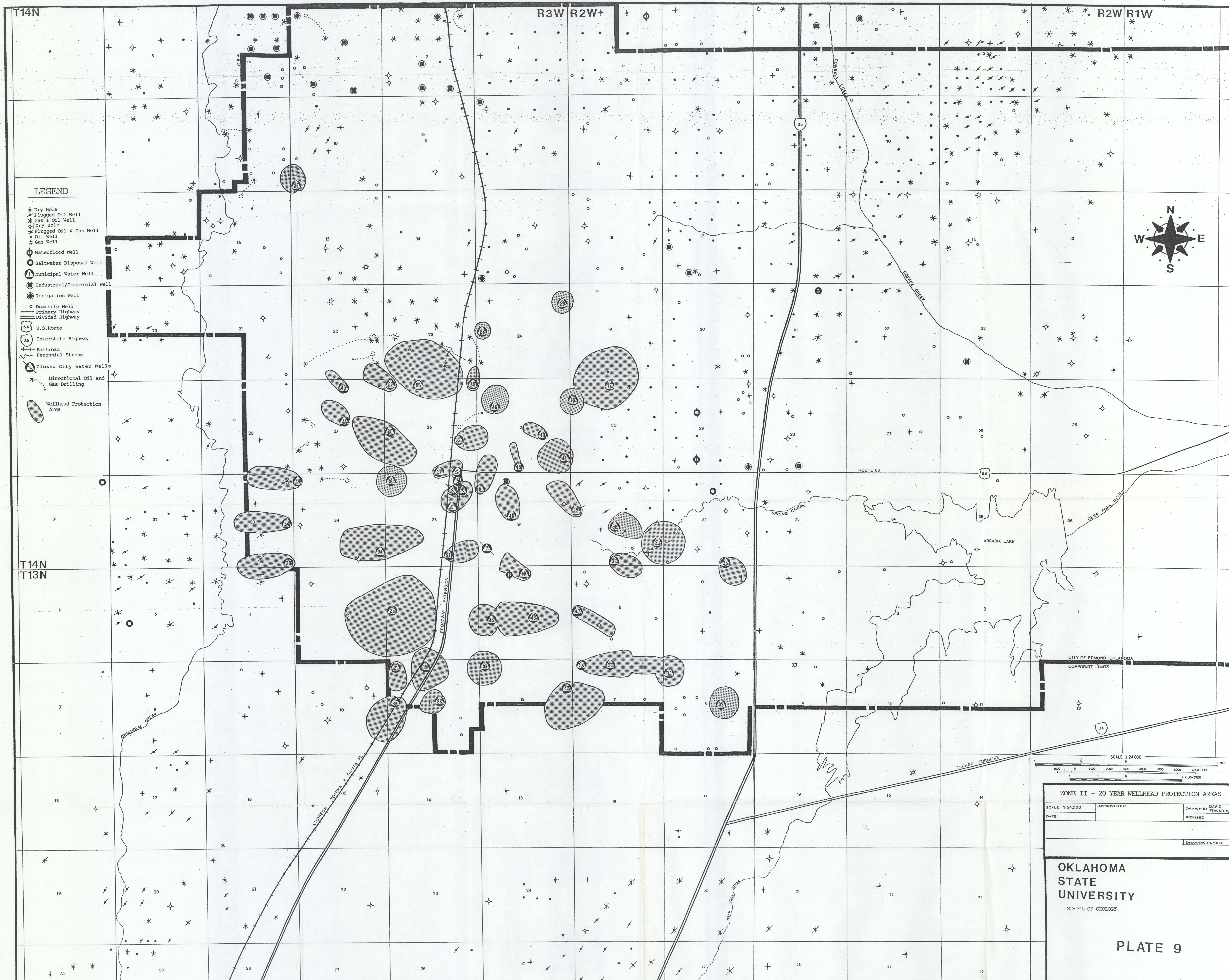
T14N
T14N
T13N
R3W R2W
R2W R1W
LEGEND
Dry Hole
Plugged Oil Well
Gas & Oil Well
Dry Hole
Plugged Oil & Gas Well
Oil Well
Gas Well
Waterflood Well
Saltwater Disposal Well
Municipal Water Well
Industrial/Commercial Well
Irrigation Well
Domestic Well
Primary Highway
Divided Highway
U.S. Route
Interstate Highway
Railroad
Perennial Stream
Closed City Water Wells
Directional Oil and Gas Drilling
Control Point
N
S
E
W
ROUTE 66
SPRING CREEK
COFFEE CREEK
COWBELL CREEK
DEEP FORK RIVER
ARCADIA LAKE
CHISHOLM CREEK
BROADWAY EXTENSION
ATCHISON TOPEKA & SANTA FE
TURNER TURNPIKE
CITY OF EDMOND, OKLAHOMA
CORPORATE LIMITS
SCALE 1:24 000
GEOLOGIC STRUCTURE MAP
LOWER PERMIAN HERINGTON LIMESTONE
SCALE: 1:24,000
APPROVED BY:
DRAWN BY DAVID EDWARDS
DATE:
REVISED
DATUM: MEAN SEA LEVEL
DRAWING NUMBER
Contour Interval: 25 Feet
OKLAHOMA
STATE
UNIVERSITY
SCHOOL OF GEOLOGY
PLATE 6



T14N
R3W R2W
R2W R1W
T14N
T13N
LEGEND
Dry Hole
Plugged Oil Well
Gas & Oil Well
Dry Hole
Plugged Oil & Gas Well
Oil Well
Gas Well
Waterflood Well
Saltwater Disposal Well
Municipal Water Well #1
Industrial/Commercial Well
Irrigation Well
Domestic Well
Primary Highway
Divided Highway
U.S.Route
Interstate Highway
Railroad
Perennial Stream
Closed City Water Wells
Directional Oil and Gas Drilling
Wellhead Protection Area
N
W
E
S
COWELL CREEK
COFFEE CREEK
ROUTE 66
SPRING CREEK
DEEP FORK RIVER
ARCADIA LAKE
BROADWAY EXTENSION
CITY OF EDMOND, OKLAHOMA CORPORATE LIMITS
CHISHOLM CREEK
ATCHISON TOPEKA & SANTA FE
TURNER TURNPIKE
SCALE 1:24 000
1 MILE
7000 FEET
1 KILOMETER
ZONE I - 1 YEAR WELLHEAD PROTECTION AREAS
SCALE: 1:24,000
APPROVED BY:
DRAWN BY DAVID EDWARDS
DATE:
REVISED
DRAWING NUMBER
OKLAHOMA STATE UNIVERSITY
SCHOOL OF GEOLOGY
PLATE 7



T14N
T13N
R3W R2W
R2W R1W
LEGEND
Dry Hole
Plugged Oil Well
Gas & Oil Well
Dry Hole
Plugged Oil & Gas Well
Oil Well
Gas Well
Waterflood Well
Saltwater Disposal Well
Municipal Water Well
Industrial/Commercial Well
Irrigation Well
Domestic Well
Primary Highway
Divided Highway
U.S.Route
Interstate Highway
Railroad
Perennial Stream
Closed City Water Well
Directional Oil and Gas Drilling
Wellhead Protection Area
N
W
E
S
COWBELL CREEK
COFFEE CREEK
ROUTE 66
SPRING CREEK
DEEP FORK RIVER
ARCADIA LAKE
BROADWAY EXTENSION
ATCHISON TOPEKA & SANTA FE
CHISHOLM CREEK
TURNER TURNPIKE
CITY OF EDMOND, OKLAHOMA
CORPORATE LIMITS
SCALE 1:24 000
ZONE II - 10 YEAR WELLHEAD PROTECTION AREAS
SCALE: 1:24,000
APPROVED BY:
DRAWN BY DAVID EDWARDS
DATE:
REVISED
DRAWING NUMBER
OKLAHOMA
STATE
UNIVERSITY
SCHOOL OF GEOLOGY
PLATE 8


T14N
R3W R2W
R2W R1W
T14N
T13N
LEGEND
Dry Hole
Plugged Oil Well
Gas & Oil Well
Dry Hole
Plugged Oil & Gas Well
Oil Well
Gas Well
Waterflood Well
Saltwater Disposal Well
Municipal Water Well
Industrial/Commercial Well
Irrigation Well
Domestic Well
Primary Highway
Divided Highway
U.S.Route
Interstate Highway
Railroad
Perennial Stream
Closed City Water Wells
Directional Oil and Gas Drilling
Wellhead Protection Area
N
S
E
W
COFFEE CREEK
COWELL CREEK
ROUTE 66
SPRING CREEK
DEEP FORK RIVER
ARCADIA LAKE
BROADWAY EXTENSION
ATCHISON TOPEKA & SANTA FE
CHISHOLM CREEK
CITY OF EDMOND, OKLAHOMA
CORPORATE LIMITS
TURNER TURNPIKE
SCALE 1:24 000
1 MILE
1 KILOMETER
ZONE II - 20 YEAR WELLHEAD PROTECTION AREAS
SCALE: 1:24,000
APPROVED BY:
DRAWN BY DAVID EDWARDS
DATE:
REVISED
DRAWING NUMBER
OKLAHOMA
STATE
UNIVERSITY
SCHOOL OF GEOLOGY
PLATE 9