MILESTONE REPORT

THE AREAL EXTENT AND HYDRAULIC CONTINUITY OF PERCHED GROUND WATER IN THE VICINITY OF THE PANTEX PLANT

W. F. Mullican III, A. E. Fryar, and N. D. Johns

INTRODUCTION

Ground-water contamination at the Pantex Plant is currently restricted to a perched aquifer(s) above the regional Ogallala aquifer water table. Therefore, the areal extent and hydraulic continuity of this unit are critical factors in the overall hydrologic characterization required for the design of effective remediation activities. Another important question is determining whether any privately owned domestic wells are producing from the perched aquifer(s) in areas downgradient from and hydrologically connected to known or possible contaminated areas on the Pantex Plant. It should be noted, however, that a continuous saturated zone is not the only scenario by which point-source and non-point-source contaminants could migrate. All recharging ground water that is perched will eventually move through the fine-grained, low-permeability zone that underlies the perched aquifer(s) and resume a downward track to the Ogallala aquifer. In addition, the results of this study clearly illustrate areas where there is no perched aquifer(s), and thus there may be no perching layer, within the boundary of the Pantex Plant. In these areas where a perching layer is absent, there will be no retarding effect created by the perched aquifer(s) on the vertical movement of recharge to the Ogallala aquifer.

A conceptual understanding of the perched aquifer(s), especially with respect to its areal extent and hydraulic continuity, is evolving as additional data become available. In March 1992, for example, five wells were known to be producing from the perched aquifer(s), all of which were within the boundary of the Pantex Plant. This data set has been expanded, as of June 1993, to include 34 monitoring wells within the boundary of the Pantex Plant and 2 domestic wells in the area but outside the boundary of the Pantex Plant. In addition, 11 domestic wells that were initially considered as possibly producing from the perched aquifer(s) (Mullican and Fryar, 1992) are now thought to be producing from the Ogallala aquifer on the basis of regional hydrologic gradients. A complete listing of locations, owners, depth to water, and water-level elevations is provided in table 1. The locations of these wells are illustrated in figure 1.

Previous reports describing the perched aquifer(s) have incorrectly assigned formal hydrostratigraphic nomenclature to the hydrologic unit in question by using the term "Perched Aquifer." This formal designation is incorrect (North American Commission on Stratigraphic Nomenclature, 1983), and in this report and in future Bureau of Economic Geology (BEG) reports, when describing the shallow aquifer proximal to and underlying playa 1 (where contamination has been documented), the term "perched aquifer" will be used. It has not been possible, even with the greatly expanded data base of monitoring wells on the Pantex Plant and nearby domestic wells, to clearly establish that all the wells producing from a perched aquifer are in hydraulic communication (exhibit hydraulic continuity). Therefore, the shallow aquifer away from playa 1 in general will be referred to as the "perched aquifer(s)" to illustrate that there is, at least regionally, probably more than one distinct or separate perched aquifer.

METHODS

Both physical and chemical data have been analyzed to delineate the areal extent and hydraulic continuity of the perched aquifer(s) in the region of the Pantex Plant. Physical data consist of static water-level measurements taken in onsite monitoring wells or offsite domestic wells that might be producing from the perched aquifer(s). This measurement, in combination with the land-surface elevation at the water well, allows determination of the water-level elevation at the well site according to the equation:

$$\text{Water-level elevation} = \text{land-surface elevation} - \text{static water level.}$$

Table 1. Summary of perched and southern Ogallala aquifer wells in the Pantex Plant area.

	Well I.D.	Alternate I.D.	Owner/ Operator	Water-level measurement Date	Water-level measurement Source	Land-surface elevation (ft)	Reference elevation (ft)	Static water level (ft)	Water-level elevation (ft)	Well location Longitude			Well location Latitude		
1	BEG PTX-2	OM-105	DOE	4/9/92	6	3540.00	3540.00	308.00	3232.00	101	34	40	35	18	20
2	BEG PTX-3	PM-106	DOE	10/6/92	5	3535.00	3535.00	233.81	3301.19	101	32	29	35	21	10
3	Offsite	06-44-7	D. Cottle	6/14/93	5	3516.00	3516.00	256.67	3259.33	101	37	26	35	17	19
4	Offsite	06-44-7	W. Hart	6/14/93	5	3509.00	3509.00	255.88	3253.12	101	37	10	35	17	25
5	Offsite	06-43-9	A. Klinke	6/17/93	5	3527.00	3527.00	252.53	3274.47	101	37	33	35	15	45
6	Offsite	06-44-6	L. Cockrell	6/17/93	5	3520.00	3520.00	329.43	3190.57	101	32	1	35	17	44
7	Offsite	06-44-8	D. Gabel (N)	6/15/93	5	3507.00	3507.00	308.13	3198.87	101	32	45	35	16	48
8	Offsite	06-44-9	G. Gideon	5/13/93	5	3491.00	3491.00	296.23	3194.77	101	32	10	35	16	44
9	Offsite	06-44-8	P. Smith	6/14/93	5	3486.00	3486.00	218.99	3267.01	101	34	13	35	15	2
10	Offsite	06-44-8	D. Vance	6/15/93	5	3461.00	3461.00	202.36	3258.64	101	33	14	35	15	7
11	Offsite	06-52-2	F. Wink	10/13/92	5	3472.00	3472.00	210.22	3261.78	101	33	20	35	14	50
12	Offsite	06-52-3	T. Bradshaw	6/15/93	5	3477.00	3477.00	228.66	3248.34	101	32	22	35	14	41
13	Offsite	06-44-9	D. Gabel (S)	3/31/93	5	3461.00	3461.00	220.75	3240.25	101	32	21	35	15	14
14	Offsite	06-43-6	C. Wink	10/12/92	5	3575.00	3575.00	295.46	3279.54	101	38	14	35	19	45
15	Offsite	06-44-2	E. Pratt	10/12/92	5	3522.00	3522.00	210.72	3311.28	101	32	52	35	21	12
16	OW-WR-19	PM-19	DOE	10/8/92	5	3539.46	3540.97	232.33	3308.64	101	33	19	35	19	51
17	OW-WR-20	PM-20	DOE	10/7/92	5	3537.93	3540.43	269.11	3271.32	101	33	12	35	18	27
18	PM-101	MW11-1	Battelle	7/14/92	4	3545.00	3548.6	275.52	3273.08	101	33	57	35	18	39
19	PM-102	MW11-2	Battelle	7/14/92	4	3545.00	3548.33	275.34	3272.99	101	33	59	35	18	37
20	PM-103	MW11-3	Battelle	7/14/92	4	3545.00	3548.44	275.32	3273.12	101	33	59	35	18	39
21	PM-104	MW11-4	Battelle	7/14/92	4	3545.00	3548.83	275.86	3297.97	101	33	57	35	18	37
22	PTX06-1001A		DOE	1/7/93	1	3535.00	3535.00	243.00	3292.00	101	33	1	35	19	2
23	PTX06-1002A		DOE	1/24/93	7	3538.00	3538.00	248.50	3289.50	101	33	1	35	19	2
24	PTX06-1003		DOE	11/17/93	2	3535.00	3535.00	259.30	3275.70	101	32	58	35	18	47
25	PTX06-1004		DOE	1/7/93	1	3534.00	3534.00	262.00	3272.00	101	33	6	35	18	30
26	PTX06-1005		DOE	1/7/93	1	3533.00	3533.00	271.00	3262.00	101	33	12	35	18	21
27	PTX06-1006		DOE	1/7/93	1	3543.00	3543.00	270.00	3273.00	101	33	46	35	18	33
28	PTX06-1007		DOE	1/23/93	7	3542.00	3542.00	268.00	3274.00	101	33	46	35	18	33

Table 1 (cont.)

	Well I.D.	Alternate I.D.	Owner/ Operator	Water-level measurement Date	Water-level measurement Source	Land-surface elevation (ft)	Reference elevation (ft)	Static water level (ft)	Water-level elevation (ft)	Well location Longitude	Well location Latitude
29	PTX06-1008		DOE	1/7/93	1	3544.00	3544.00	266.00	3278.00	101 33 19	35 18 53
30	PTX06-1010		DOE	1/7/93	1	3541.00	3541.00	266.60	3274.40	101 33 12	35 18 39
31	PTX06-1011		DOE	1/7/93	1	3540.00	3540.00	270.15	3269.85	101 33 22	35 18 31
32	PTX08-0001 OW-WR-38	PM-38	DOE	10/6/92	5	3518.10	3520.18	206.90	3313.28	101 33 2	35 19 55
33	PTX08-1001		DOE	2/8/93	3	3515.00	3515.00	212.80	3302.20	101 33 19	35 19 26
34	PTX08-1002		DOE	2/8/93	3	3510.00	3510.00	209.58	3300.42	101 33 05	35 19 30
35	PTX08-1003		DOE	10/7/92	7	3547.00	3547.00	297.10	3249.90	101 34 08	35 18 59
36	PTX08-1005		DOE	10/13/92	7	3540.00	3540.00	274.00	3266.00	101 34 11	35 18 24
37	PTX08-1007		DOE	1/93	7	3545.00	3545.00	280.00	3265.00	101 33 31	35 18 47
38	PTX08-1010		DOE	9/16/92	7	3519.00	3519.00	218.00	3301.00	101 32 54	35 21 09
39	PTX09-0004 OW-WR-45	PM-45	DOE	10/6/92	5	3544.10	3546.10	257.73	3288.37	101 33 26	35 18 56
40	PTX10-0002 OW-WR-44	PM-44	DOE	10/6/92	5	3542.16	3542.16	267.34	3274.82	101 34 36	35 19 02
41	PTX10-1007	PM-107	DOE	1/7/93	1	3542.00	3542.00	277.00	3265.00	101 34 26	35 19 6
42	PTX10-1008	PM-108	DOE	1/7/93	1	3542.00	3542.00	277.00	3265.00	101 34 26	35 19 2
43	PTX10-1013 PTX09-0013	PM-109	DOE	1/7/93	1	3543.00	3543.00	252.10	3290.90	101 33 16	35 18 57
44	PTX10-1014 PTX09-0014	PM-110	DOE	1/7/93	1	3543.00	3543.00	252.80	3290.20	101 33 16	35 18 56

Measurement notes:
1. U.S. Army Corp of Engineers Pantex map dated January 7, 1993
2. U.S. Army Corp of Engineers, received by BEG 11/17/92
3. U.S. Army Corp of Engineers, received by BEG after 2/8/93
4. Battelle measurement, static water level corrected for well deviation
5. BEG measurement
6. BEG determination, geophysical log of Ogallala monitoring well
7. Original static water level at time of well completion

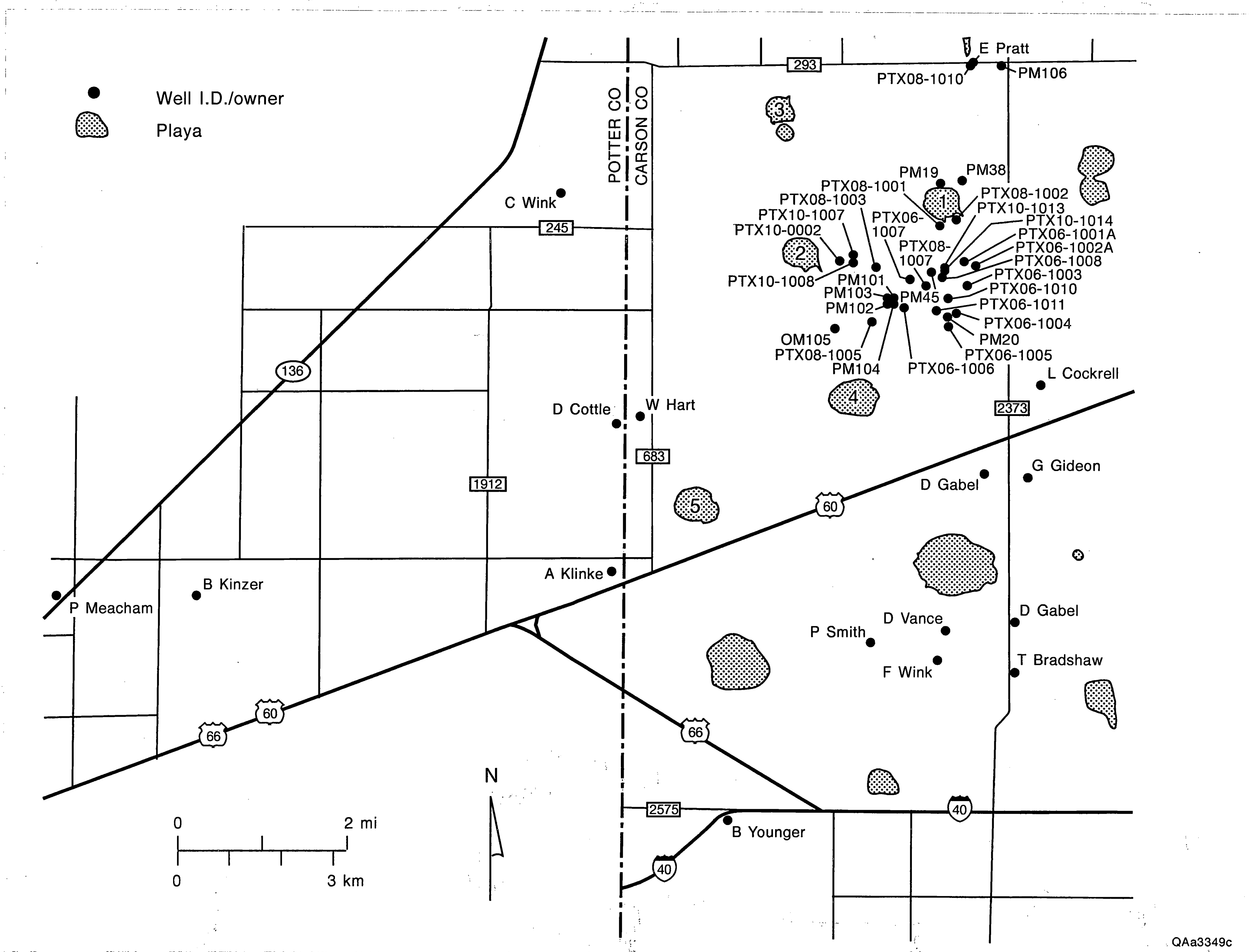

Figure 1. Location map of known perched aquifer(s) monitoring and domestic wells in the area of the Pantex Plant. Owners of domestic wells located outside the Pantex Plant boundary are indicated.

These water-level elevations are then contoured in map view to illustrate the potentiometric surface of the perched aquifer(s) in the area of the Pantex Plant.

Where neutron and density porosity profiles are run in combination, geophysical logs were also used to identify zones of saturation above the main Ogallala aquifer. The two wells where these were available were OM-105 and PM-106 (formerly BEG/PTX no. 2 and BEG/PTX no. 3). The use of these logs to identify zones of saturation within an unsaturated section is based on the neutron log response to gas-filled pore space (in this case the gas is normal atmosphere). In a typical saturated section, the density and neutron profiles will track within 1 to 3 percent porosity of each other. In a gas-filled (or unsaturated) section, however, there is a significant reduction in the volume of water filling the pore space and therefore a reduction in hydrogen atoms—which is what the neutron log is measuring. Therefore, in unsaturated sections there is a significant reduction in neutron porosity response, often as much as 30 to 40 percent. In practice, when the neutron porosity track on a log is more than 4 or 5 percent less than the density porosity track, a gas effect or unsaturated condition is indicated.

Samples of ground water have been collected from 8 perched aquifer wells (6 onsite monitoring wells and 2 offsite domestic wells) and 18 Ogallala aquifer wells (6 onsite monitoring wells, 4 onsite production wells, 4 offsite domestic wells, and 4 offsite wells for livestock). The samples were analyzed for stable isotopes of hydrogen, boron, carbon (both organic and inorganic), nitrogen, oxygen, and sulfur; for the radionuclides tritium (indicative of post-1952 water) and carbon-14; and for cations, anions, and other parameters. These chemical constituents are potentially useful in identifying (characterizing) discrete aquifers where ground waters reflect geochemically distinct sources of recharge. Such sources could indicate different land-use practices (e.g., cultivation versus grazing), contamination (such as that found in the vicinity of playa 1 at the Pantex Plant), or natural spatial variability. Stable isotopes have been shown elsewhere to be sensitive indicators of mixing of different waters (Whelan, 1987). It is also plausible that, where perched aquifer(s) with distinct chemistries merge, stable isotopic compositions would be intermediate between the end-member values.

THE EXTENT OF PERCHED AQUIFER(S)

Potentiometric Surface

Figure 1 depicts all of the monitoring and domestic wells known to be producing from the perched aquifer(s). In addition, several new Ogallala aquifer water-level measurements in the Sevenmile Basin area are mapped. Not only has the data base of water-level elevations for the perched and Ogallala aquifers in the region of the Pantex Plant significantly increased from previous studies (Mullican and Fryar, 1992), but this data base will continue to expand as more monitoring wells are completed and more landowners are contacted. Clearly, the most significant increase in data in figures 1 and 2a of this report, relative to figure 2 (included in this report as fig. 2b) in Mullican and Fryar (1992), occurs south of playa 1 in the Zone 12 South area.

The potentiometric surface of the perched aquifer(s) and the southern portion of the Ogallala aquifer, as currently mapped, are illustrated in figure 2a. An understanding of how playas act as focal points of recharge resulting in localized ground-water mounds was used to interpolate some of the contours in areas with sparse data. Although there are several factors that may control the formation and development of a perched aquifer(s) above the regional Ogallala aquifer, three of these factors clearly exhibit the most influence. These factors are location and rate of recharge, horizontal hydaulic conductivity of the perched aquifer(s), and presence and vertical conductance (vertical hydraulic conductivity) of the perching layer.

Although a detailed discussion of the controls and rates of recharge based on BEG investigation is beyond the scope of this report, a few summary statements are justified. First, based on both physical and chemical data, the overwhelming majority of recharge is focused in the floors and immediately surrounding sediments of the numerous playa lakes (ephemeral lakes) present throughout the area. Negligible recharge is observed in interplaya areas. Second, previously reported regional, mass-balance recharge calculations have grossly underestimated the actual rate of recharge through these playa lakes.

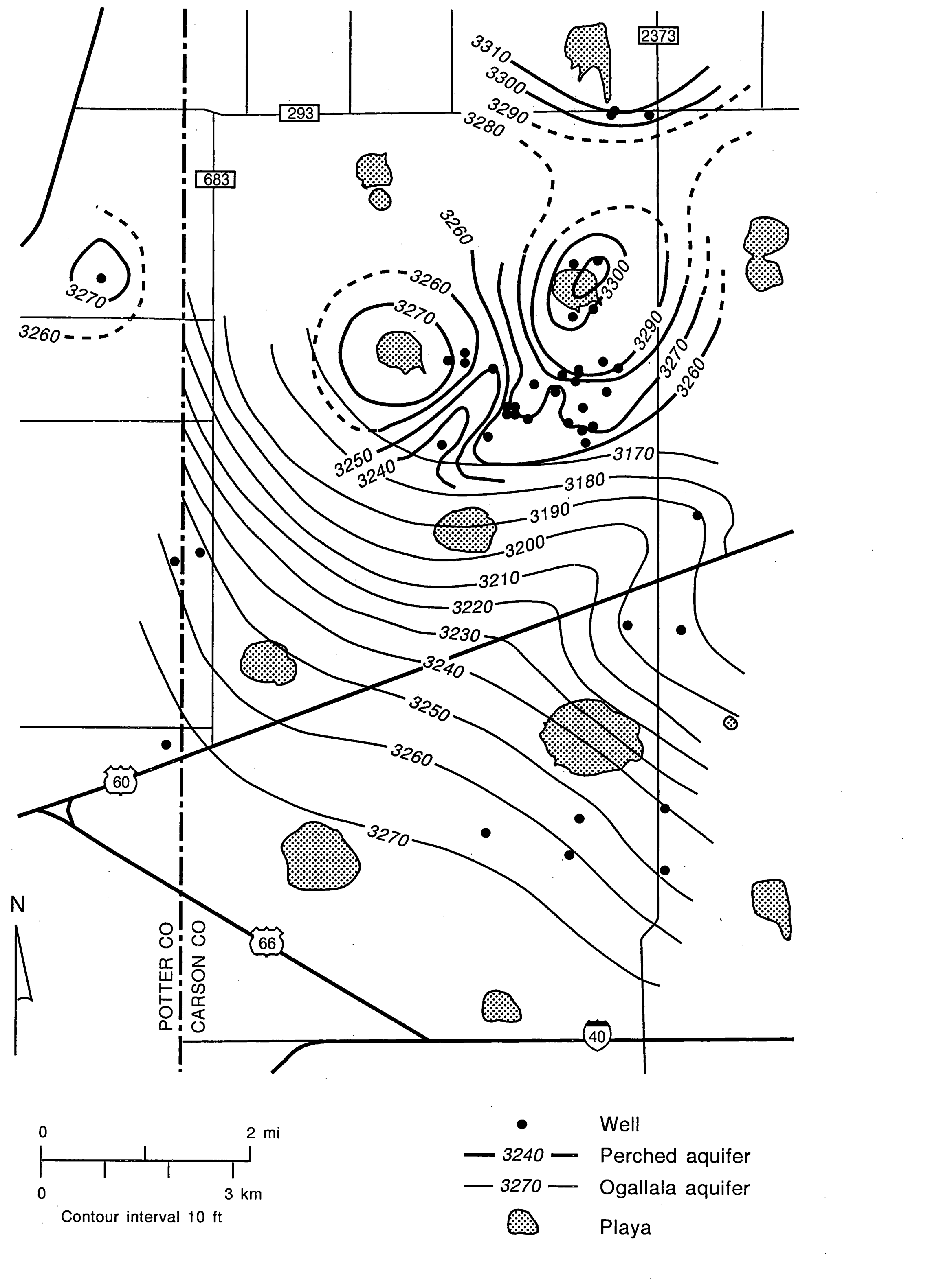

Figure 2. (a) Potentiometric-surface map of the perched aquifer(s) in the area of the Pantex Plant and the Ogallala aquifer in the Sevenmile Basin area. Contouring is based both on known water-level elevations and on ground-water flow models of the perched aquifer(s). (b) Potentiometric-surface map of the perched aquifer from Mullican and Fryar (1992, their fig. 2).

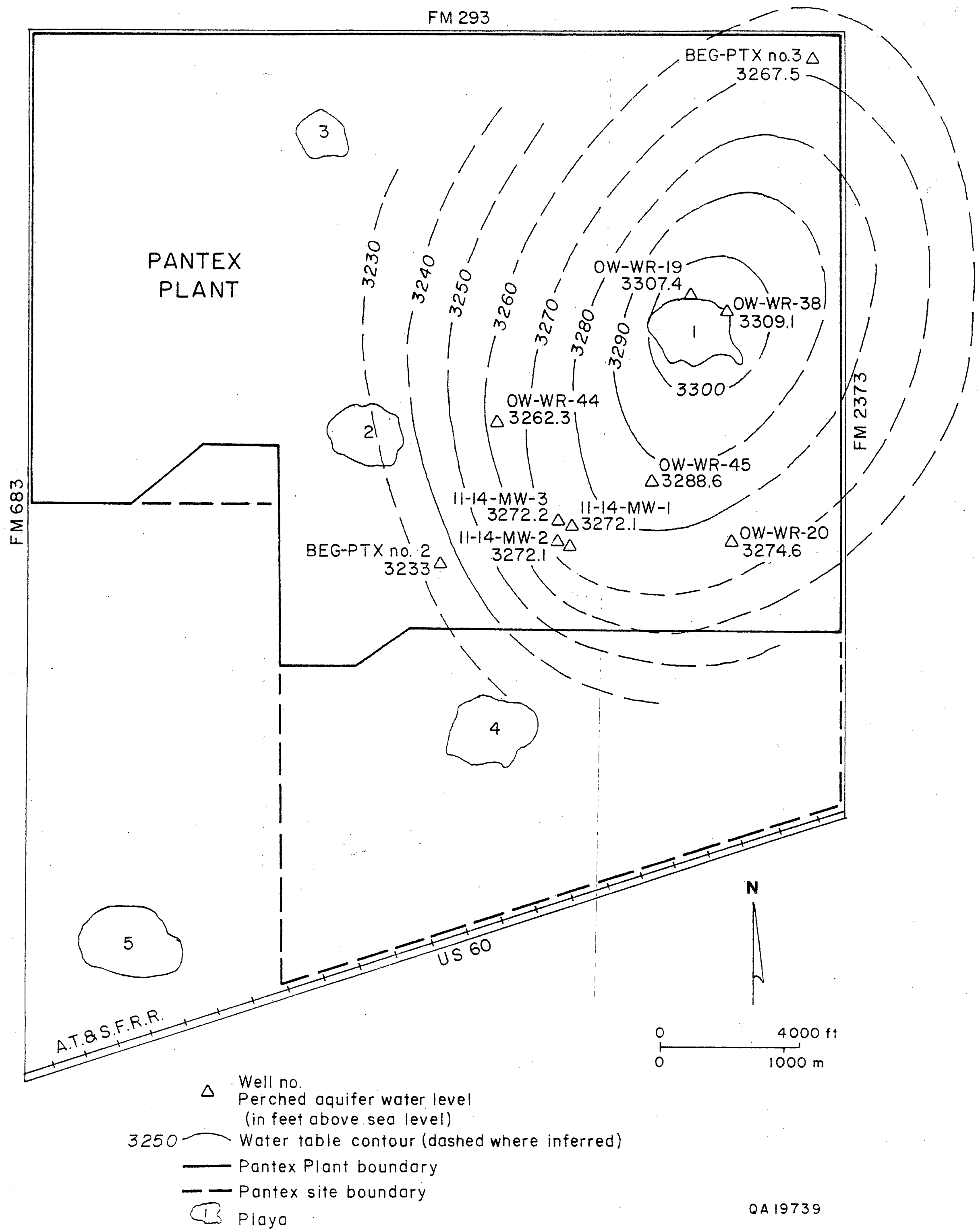

Figure 2. Cont.

Turin and others (1992), for example, provide a table compiling reported recharge rates calculated for the Ogallala aquifer from 11 different studies dating back to Theis (1937). These recharge rates, most of which were based on regional averages, range from 0.075 to 8 cm/yr. On a regional mass-balance approach, currently available data seem to indicate that about 1 cm/yr is appropriate. It must be clear, however, that this value of 1 cm/yr is based on a uniform regional application of recharge to the Ogallala aquifer. In a system in which preferential flow influences or controls recharge, as is the case with focused recharge in the playa lakes, regionally averaged recharge rates may underestimate actual rates at the point of recharge by over an order of magnitude (Gee and Hillel, 1988). Modeling of ground-water flow in the perched aquifer(s) in the area of the Pantex Plant, for example, indicates that, on the basis of the ratio between surface area of playa lakes versus total surface area, recharge rates in these playa lakes will be between 30 and 50 cm/yr. Thus, the focused nature and rates of recharge through the playa lakes are primary controlling factors in perched aquifer(s) development.

Because of the focused nature of recharge, mounding of ground water may occur. The vertical extent of mound development is dependent, all other factors being equal, on the hydraulic conductivity of the aquifer. The lower the hydraulic conductivity of an aquifer, the greater the vertical mound development, and, conversely, the higher the hydraulic conductivity, the lower the vertical mound development. Typically, the hydraulic conductivity of the Ogallala aquifer is so high that no mound development is evident, even in monitoring wells immediately adjacent to the playas, because of the aquifer's capacity to conduct recharging water away from the point of recharge faster than the rate of recharge. In the Pantex Plant area, however, sediments saturated above the Ogallala aquifer have much lower hydraulic conductivities and therefore significant mound development is observed.

The third factor, and perhaps the most critical factor controlling the development and extent of perched aquifer(s), is the presence of a stratigraphic unit(s) that has a vertical conductance (vertical hydraulic conductivity) or ability to transmit water which is less than the rate of recharge. Regardless of how high the rate of recharge is, if no layer with relatively lower vertical conductance is encountered, no perched aquifer(s) will develop. Another important element of this factor controlling perched aquifer(s) development is that even when these perching layers are present, they are not impermeable to ground-water flow. Modeling results along this line indicate that perhaps as much as 80 percent of the water perched above the low vertical conductance perching layer will actually move through the perching layer before traveling 2,600 ft laterally.

An understanding of these three factors that control perched aquifer(s) development can then be used to assist in contouring the potentiometric surface in areas of sparse data as long as it is at least known that a perched zone is present. Since recharge rates are "relatively" uniform from playa to playa and horizontal hydraulic conductivity only impacts vertical mound development, the most important variable to perched aquifer(s) formation is the presence of a perching layer. It is now clear that there is not a continuous perched aquifer underlying the Pantex Plant, since there have been areas investigated where no perched aquifer(s) were encountered.

Initial water-level measurements collected south of Sevenmile Basin (including water levels measured by BEG staff and water levels reported by well owners) were thought to indicate the presence of a perched aquifer(s) in the area. Chemical data such as high tritium levels in the P. Smith well (42.7 tritium units [TU]) also supported the initial hypothesis that this was an area of perched ground water. However, recently measured static water levels in several additional wells indicate that wells in this area probably produce from the main Ogallala aquifer where it is shallow (less than 200 ft below land surface) to the south of the Pantex Plant.

Figure 2a illustrates both the perched aquifer(s) potentiometric surface throughout the region of the Pantex Plant and the Ogallala aquifer potentiometric surface to the south of Zone 12. It is important to note that there is only one monitoring well, OM-105, at which sufficient data exist to illustrate the vertical relationship between these two surfaces. Figure 3 is a composite geophysical log from OM-105 illustrating gamma-ray, SP, caliper, resistivity, neutron, density, and tension profiles. Using the track illustrating neutron porosity and density porosity, the presence of multiple layers with saturated conditions is clearly demonstrated by the absence of crossover between the two profiles. As discussed above, the presence of crossover, where the neutron profile extends

Figure 3
See Separate File

approximately 3 percent or greater to the right of (less than) the density profile, indicates the presence of gas, in this case normal atmosphere. Thus, the combination of these two log profiles can be used to document unsaturated conditions. The top of the Ogallala aquifer in this well was encountered at a depth of 372.5 ft, whereas a separate saturated section that correlates with the perched aquifer extending from playa 1 is present from 308 to 320 ft. Thus, in this well there is 52.5 ft of unsaturated sediments separating the perched aquifer from the Ogallala aquifer. Another thin, fine-grained, saturated section is also present in this well, based on neutron-density crossover, at 111 to 118 ft below land surface. Multiple saturated zones above the Ogallala aquifer were also recorded on geophysical logs from PM-106 (formerly BEG/PTX no. 3), located in the northeast corner of the Pantex Plant.

On figure 2a, the potentiometric surfaces of both the perched and Ogallala aquifers are overlaid at OM-105 to illustrate that the directions of ground-water flow are different within the two units intersecting this well. Within the perched aquifer at OM-105, ground-water flow appears to be from the northeast to the southwest, whereas flow in the Ogallala aquifer is from the southwest to the northeast.

Although data between the southern boundary of Zone 12 and the northern edge of Sevenmile Basin are lacking, historical evidence of the presence of numerous shallow domestic wells in this area prior to the establishment of the Pantex Plant makes the determination of the southern boundary of the perched aquifer difficult. Did these historical wells produce from a perched aquifer hydrologically connected to playa 1, from separate perched aquifer(s), or from the regional Ogallala aquifer? It seems clear, however, that the perched aquifer located under and primarily recharged by playa 1 extends to the south as far as the southern end of Zone 12 and to the north at least as far as the E. Pratt domestic well.

Extending the perched aquifer to the east of the area mapped in figure 2a is problematic because of the absence of data in the area east of Farm to Market (FM) road 2373 at the east boundary of the Pantex Plant. If it is necessary to demonstrate that any current (but not located and measured) or future domestic wells located to the east of the Pantex Plant will not be affected by plant activities, additional data (either monitoring wells producing from the perched aquifer or test wells that clearly document the absence of a perched aquifer) will be required.

There are also two clearly documented zones of perched ground water above the Ogallala aquifer immediately adjacent to the Pantex Plant (fig. 2a). The first is recognized from water levels measured in three wells (E. Pratt well, north of the plant, and PM-106 and PTX08-1010, within the plant) that indicate the presence locally of a potentiometric surface with a north-to-south hydrologic gradient, a reversal from the south-to-north hydrologic gradient observed just north of playa 1. From these data we infer that this area may be in hydrologic continuity with the perched aquifer underlying a majority of the plant.

The second area of known perched ground water off the Pantex Plant, in contrast to the area identified north of the plant, appears to be hydrologically isolated from the main perched aquifer proximal to playa 1. This area is currently restricted (by data availability) to the C. Wink property to the west of the plant. Evidence of discontinuous perched ground water is based on monitoring well PTX 08-1011A, which was drilled in 1992 between the C. Wink property and the perched aquifer proximal to playa 1. Well PTX 08-1011A was drilled with air and did not encounter any saturated section or fine-grained zone at the anticipated depth for a perched zone but did encounter the Ogallala aquifer as expected.

Geochemistry

Differentiating perched from Ogallala ground waters at the Pantex Plant is also possible on the basis of radionuclide levels. Levels of tritium in perched ground water onsite range from 0.4 to 14.5 TU, whereas tritium in the Ogallala aquifer onsite ranges from 0 to 0.47 TU. Carbon-14 in perched ground water onsite ranges between 62.6 and 109.4 pmc (percent modern carbon); in Ogallala ground water onsite, carbon-14 ranges between 23.9 and 44.5 pmc. South of the Pantex Plant in the Sevenmile Basin area, the radionuclide signature of Ogallala aquifer water much more closely resembles the perched aquifer(s) than the Ogallala aquifer in the plant area. This is to be expected, however, when the shallow nature of the Ogallala aquifer and thus shorter travel times in the Sevenmile Basin area are considered. In addition, levels of carbon-14 and TDS (total dissolved solids) in perched ground water decline away from the center of playa 1. Perched TDS levels range from 696 mg/L in well PM-38 to 280 mg/L in well PM-106.

To date, geochemical analyses have not identified separation of perched aquifer(s) with the possible exception of the perched aquifer on the C. Wink property. The major-ion composition of ground water in the study area is relatively uniform (calcium bicarbonate or mixed-cation bicarbonate). Major-ion analyses, however, support the distinct nature of the perched aquifer on the C. Wink property. Na and Cl concentrations are lower by a factor of approximately 2 to 3 than in other perched wells (5.9 mg/L Na and 3.23 mg/L Cl versus 13.0 to 60.2 mg/L Na and 9.44 to 45.8 mg/L Cl elsewhere). However, no systematic spatial variability in the stable isotopic composition of perched ground water is evident. With the exception of well PM-20, which has exhibited high-explosive contamination, levels of nitrogen-15 and organic carbon-13 are relatively uniform in both perched and Ogallala ground waters. Nitrogen-15 and organic carbon-13 for PM-20 are 7.95‰ and –12.63‰, respectively, versus ranges for other wells of 13.19 to 19.46‰ for nitrogen-15 and –13.78 to –19.94‰ for organic carbon-13. Although some analyses are pending, the distribution of perched-aquifer wells, especially offsite, may be too sparse to permit better geochemical resolution of the question of aquifer continuity. Alternatively, contaminants at the Pantex Plant may not yet have moved far enough laterally for mixing to occur.

CONCLUSIONS

1. The areal extent of the perched aquifer centered under playa 1 appears to be confined to the plant boundary to the south and west and is to some extent continuous with perched ground water to the north. There is no known data to document the presence or absence of perched aquifer(s) to the east of the plant.

2. There are three primary factors controlling the development of perched aquifer(s): focused recharge, hydraulic conductivity, and vertical conductance. The most important of these three is the vertical conductance of any potential perching layer. If the recharge rate exceeds the vertical conductance for a particular layer, a perched zone will develop. Conversely, if no zones with a vertical conductance lower than the rate of recharge are encountered, no perched aquifer(s) will develop, regardless of how high the recharge rates may be.

3. Radionuclides (tritium and carbon-14) indicate that perched ground water at the Pantex Plant is significantly younger the Ogallala ground water due to the shorter travel distance and thus shorter travel times.

REFERENCES

Gee, G. W., and Hillel, D., 1988, Groundwater recharge in arid regions: review and critique of estimation methods: Hydrological Proceedings, v. 2, p. 255–266.

Mullican, W. F., III, and Fryar, A. E., 1992, Hydrogeology of a perched aquifer in the Pantex Plant region: The University of Texas at Austin, Bureau of Economic Geology, report prepared for the U.S. Department of Energy under subgrant to DOE grant no. DE-FG04-90AL65847, 12 p.

North American Commission on Stratigraphic Nomenclature, 1983, North American stratigraphic code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841–875.

Theis, C. V., 1937, Amount of ground-water recharge in the Southern High Plains: Geophysical Union Transactions, 18th Annual Meeting, p. 564–568.

Turin, H. J., Triay, I. R., Hansen, W. R., and Wenzel, W. J., 1992, Potential Ogallala aquifer impacts of a hypothetical plutonium dispersal accident in Zone 4 of the Pantex Plant: Los Alamos National Laboratory, Contract Report, 32 p.

Whelan, J. A., 1987, Stable isotope hydrology, *in* Kyser, T. K., ed., Stable isotope geochemistry of low-temperature processes: Mineralogical Association of Canada, Short Course Handbook, v. 13, p. 129–161.