EVALUATING BMPS TO CONTROL NITRATE CONTAMINATION IN GROUND WATER

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Executive Summary

A non-point source pollution assessment study, conducted by the Oklahoma Conservation Commission, identified several alluvial and terrace aquifers in Oklahoma having elevated levels of nitrate. To address this issue, a pilot project was proposed to be conducted in Tipton, Oklahoma, where agricultural activities were believed to be a major contributor of nitrates to ground water. The Town of Tipton municipal wells, which draw water from the Tillman terrace aquifer, showed elevated nitrate-N concentrations over the past two decades. The aim of the project was to delineate a wellhead protection area (WHPA) around the municipal wells and implement appropriate best management practices (BMPs) to the agricultural fields within the WHPA to reduce the nitrate loading to ground water.

The WHPAs for the Tipton municipal wells were delineated based on ten-year time-of-travel (T-O-T) criteria using three different procedures. In the first procedure, T-O-T (Fabian and Summers, 1990), a semi-analytical model was used. This approach did not consider the effect of neighboring wells and the seasonal variation in pumping. Based on this WHPA, four monitoring wells were drilled to monitor the ground water quality. In the second procedure, the flow portion of a numerical ground water flow and transport model, USGS-MOC (Konikow and Bredehoeft, 1978), was used. The effect of the nearby irrigation wells and their seasonal variation in pumping were considered in the second delineation process. The WHPA delineated in this process extended up to 16 square miles, which included the capture zones of municipal and irrigation wells. In the third process, both flow and transport parts of USGS-MOC were used to delineate a ten-year time-related capture zone, which extended up to 300 ac for each municipal well. For this study the 16 square mile area was considered as the study area.

A land use survey was conducted in the study area showing alfalfa, cotton and wheat as the major crops in the study area. The land use in this area changes frequently due to crop rotation.

Deep-core soil sampling was conducted in the study area during 1992 and 1993. Sampling was done on a grid basis in the chosen representative fields of irrigated and dryland alfalfa, cotton and wheat. A 500 ft grid was used for sampling during 1992 and in 1993 a 1000 ft grid was used. All the samples were analyzed for nitrate-N. In general, the soil nitrate-N profiles obtained from the deep-core sampling in 1993 had lower nitrate concentration than in 1992. All the surface layers in 1992 had higher nitrate concentration than in 1993. The cultural and irrigation practices in these fields were not changed from 1992 to 1993. Thus, for the nitrate-N concentration reduction in the soil profiles during 1993 may be attributed to changes in crop, sampling time, or leaching.

In addition to the deep-core sampling, standard surface (0 - 6") and subsurface (6 - 24") soil sampling was conducted during 1992 and 1993 in the study area. The samples were analyzed for pH, nitrate-N, and extractable P and K. The surface samples showed no change from 1992 to 1993 except in the wheat fields where it increased marginally. In both

the years, the subsurface samples showed higher nitrate-N concentrations than the surface samples, indicating nitrate accumulations. In 1992, alfalfa and wheat fields showed higher subsurface nitrate concentrations than the cotton fields, and in 1993 cotton and wheat fields showed high subsurface nitrate concentrations.

Starting from January 1992 until March 1994, monthly ground water samples were taken by the Oklahoma Water Resources Board (OWRB) from the four monitoring wells and were analyzed for chloride, nitrate-N, pH, total dissolved solids (TDS), and electical conductivity (EC). From October 1992 onwards, similar sampling and analysis were conducted for the two municipal wells. In addition to water sampling, the water table elevation was also monitored. The water table elevations at the monitoring and municipal wells showed no appreciable difference from each other during the sampling period except for one monitoring well, the reason for which could be attributed to local effects. Both municipal wells showed higher nitrate-N and TDS concentration than the monitoring wells. Since the monitoring wells are screened at a shallower depth than the municipal wells, there is a possibility of physical or chemical stratification with lower salt and nitrate concentration in the top portion than the bottom portion of the aquifer.

The project overview and current results were presented to the residents of Tipton during a public meeting conducted in June 1993. In addition, a water quality perception survey was conducted in the Town of Tipton. Seven irrigation pumps of individual growers were tested to determine the system characteristics of the wells.

Based on the soil and ground water sampling results, no conclusions could be drawn on the effectiveness of BMPs in reducing in nitrate concentration in the ground water over the two year period. This duration proved to be too short a time to notice any appreciable change in the ground water quality. The available level of technology, data, and time were not sufficient to draw any conclusion at present.

The difference between monitoring wells, which are screened in the upper part of the aquifer, and the municipal wells, which are screened in the lower part of the aquifer suggest that most of the nitrate might be coming into the WHPA through lateral ground water flow. This brings into question the feasibility of using the WHPA delineated using the existing time-of-travel criteria to protect the municipal wells. The extent of WHPA should be such that the reduced load of nitrates within the WHPA should dilute the excess nitrate concentration coming from outside. The WHPA delineated for the Tipton municipal wells should be evaluated for its effectiveness under this criteria. This work and further evaluation of BMPs is currently in progress.

Acknowledgements

This has been a cooperative project involving many federal, state, and local agencies. We would like to acknowledge the Oklahoma Conservation Commission for oversight and management of the project. The Oklahoma Water Resources Board provided Tillman aquifer information, delineated the wellhead protection area for the municipal wells using T-O-T, collected ground water samples from the monitoring and municipal wells, and compiled ground water quality data. The United States Environmental Protection Agency, the Oklahoma Agricultural Experiment Station, and the United States Geological Survey - Oklahoma Water Resources Research Institute provided funding.

We would like to extend a special acknowledgement to the United States Department of Agriculture Agricultural Research Service National Water Quality and Watershed Laboratory in Durant, Oklahoma. They provided personnel and equipment to drill four water quality monitoring wells. Their support and cooperation was critical to the success of the water quality monitoring program. A special acknowledgement is also extended to the United States Department of Agriculture Soil Conservation Service Office at Clinton for conducting the deep-core soil sampling in 1992. In addition, we would like to thank the Town of Tipton for providing municipal well pumping data and water supply information.

The Tillman County Extension Center, the Altus Irrigation Research Station, and the Tillman County Conservation District served as a vital link with Tipton agricultural growers. They were responsible for the standard surface and subsurface soil sampling program, the deep-core sampling, conducting land use surveys, and obtaining detailed crop and field information.

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Background

The Section 319 Non-Point Source (NPS) Assessment Report identified several alluvial and terrace aquifers in Oklahoma having elevated levels of nitrate concentration. While the available evidence is not adequate to prove absolutely the sources of nitrate contamination, there is a strong concern that agricultural activities, especially the use of commercial fertilizers, contribute to the nitrates reaching alluvial aquifers (OCC, 1991).

To address this issue, a pilot project was proposed to implement agricultural best management practices (BMPs) in and around a well system drawing water from an alluvial terrace aquifer within Oklahoma and evaluate the effects of BMPs on the ground water quality. The Tillman Terrace aquifer near the Town of Tipton was chosen as the study area for this project. The description of the study area is given later in this report.

The tasks assigned to Oklahoma State University (OSU) were: (1) evaluate historical ground water nitrate data for the Tipton area, (2) develop and apply a procedure to estimate a nitrogen balance and evaluate the impact of BMPs in the Tipton wellhead protection area, (3) take soil core samples to estimate nitrogen in the soil profile, and (4) combine the soil sampling data with ground water monitoring data, taken by Oklahoma Water Resources Board (OWRB), to evaluate the effectiveness of BMP implementation in reducing nitrate loading to Tillman aquifer. During the period of the project, August 1991 to August 1994, a number of activities and analysis were carried out to fulfill these tasks.

Description of the Study Area

The Tipton study area, shown in Figure 1, is mainly agricultural with cotton, wheat and alfalfa as major crops. There are two municipal wells in Tipton, which serve as drinking water sources to approximately 1,500 residents in the town. In the past two decades the nitrate-N concentration of the water from those wells was found to be above the EPA drinking water standard of 10 mg/l (Figure 2a and 2b). Currently, to bring the municipal water to the EPA drinking water standard, the well water is blended with lake water from Frederick, about 25 miles from Tipton. In Figure 2b, the approximate well data are the estimated nitrate concentration of the municipal well water excluding the effect of the lake water.

A detailed description of the Tillman Terrace aquifer, given by Al-Sumait (1978), indicates that the aquifer was formed by Quaternary alluvial terrace and floodplain deposits. It is located in the western half of Tillman County, bounded on the north by floodplains, on the east by a bedrock outcrop, on the west by the North Fork of the Red River, and on the south by the Red River (Figure 3). The aquifer extends over 285 square miles with a maximum length (north to south) of 29 miles and a maximum width (east to west) of 13 miles. The bedrock is characterized by reddish-brown argillaceous siltstones intercalted with thin layers of gray and reddish-brown shale. The outcrop has a gentle dip to the southwest. The thickness of the terrace deposits varies with an approximate mean depth of 42 ft.

Wellhead Protection Area Delineation

USEPA (1987) recommended several criteria to delineate a wellhead protection area (WHPA). We chose to delineate the Tipton WHPA on the time-of-travel criteria. USEPA USGS/OWRRI project titled "Evaluating BMPs to Control Nitrate Contamination in Groundwater" (Project Number 08). The principal investigators are Daniel E. Storm, Michael D. Smolen, and Michael A. Kizer(1987) also states that the most effective mechanisms to reduce nitrate pollution from ground water is by diffusion and dilution. However, there is no standard time-of-travel criteria prescribed for nitrate pollution. For this project we decided to use a ten-year time-of-travel criteria to delineate WHPA for the Tipton municipal wells. The WHPA was delineated by three procedures using two different ground water models, T-O-T (Fabian and Summers, 1990) and USGS-MOC (Konikow and Bredehoeft, 1978).

WHPA Using T-O-T

Initially the wellhead protection area (WHPA) for the Tipton municipal wells was delineated based on a ten-year time-of-travel using T-O-T, a semi-analytical model. T-O-T delineates WHPA based on simple ground water hydraulics and if there are more than one well in a well-field, the interaction between them is ignored. Near the Tipton municipal wells there are several irrigation wells of which two of them have significant interaction with the municipal wells. Since T-O-T is a steady-state model, the seasonal variation in pumping rates was also ignored.

WHPA Using Flow Part of USGS-MOC

A second estimate of the WHPA was generated by using the flow portion of USGS-MOC, a numerical ground water flow and transport model. This process accounts for the interaction between the municipal and irrigation wells and also their seasonal variation in pumping rates. To meet the water supply to the town, the municipal well water is currently blended with the lake water from Frederick. The lake water constitutes about 50% of the total water supplied. The pumping rates for the municipal wells were assumed to be the sum of the amount of water actually pumped from the wells (obtained from pumping logs) and the amount of lake water added because this is the potential pumping rate for the wells if nitrate concentration is not limiting. The pumping rates for the irrigation wells were calculated based on crop water requirements recommended by Oklahoma Cooperative Extension Service. The pumping rates from the municipal and irrigation wells are shown in Figure 4.

In this process the WHPA delineation was based on ground water hydraulics and a ten-year time-of-travel. The ground water flow system was simulated for ten years and the zone of contribution to the municipal and the irrigation wells was delineated based on the water table contour map resulting at the end of the simulation period. The ten-year time-of-travel was marked on the upstream side of the zone of contribution. The WHPA thus delineated extended approximately to about 16 square miles (Figure 5). This included the combined capture zone for the irrigation and the municipal wells. Since USGS-MOC does not have a particle tracking component, individual capture zones could not be separated by only considering the water table contours. The details of the delineation process is presented by Ramanarayanan et al. (1992) given in Appendix A.

WHPA Using Flow and Transport Part of MOC

The time-related capture zones for the Tipton municipal wells were delineated using the flow and transport parts of USGS-MOC by adopting a different approach in the delineation process. The aquifer was discretized into square cells of 660 ft on a side. The delineation was conducted on a *cell-by-cell* basis. Each cell that could potentially be included in the capture zone was tagged with a constant source of contaminant. If contaminant from a cell reached one of the municipal wells within the ten-year simulation period, the cell was included in the capture zone, and any cell that did not contribute contaminant to the municipal wells in ten years was excluded. A longitudinal dispersivity of 75 ft and a transverse dispersivity of 0.3 times the longitudinal dispersivity was assumed for the transport process. The interaction between wells and their seasonal variation in pumping rates were also considered. The WHPA for the municipal wells delineated by this procedure extended up to about 300 ac for each well (Figure 6). Although this is a much smaller area than the WHPA delineated previously, all the project activities were conducted within the 16 square mile area around the Tipton municipal wells.

Land Use Survey

A land use (crop) survey in the 16 square mile area was completed in December 1992. The summary of the land use in the study area is presented in Table 1 and the land use map is shown in Figure 7. Due to the crop rotation adopted by the growers, the land use in this area changes frequently. The most popular crop rotation is cotton-wheat, however, cotton-alfalfa rotation is also adopted by some growers.

Table 1. Summary of land use survey conducted in the 16 square mile study area.

Crop	Area (acres)	Percent Coverage
Wheat - Irrigated	202	2.0
Wheat - Dry	2005	20.0
Cotton - Irrigated	1129	11.3
Cotton - Dry	3251	32.4
Alfalfa - Irrigated	146	1.5
Alfalfa - Dry	515	5.1
Peanut	187	1.9
Grass	284	2.8
Fallow	1239	12.4
CRP	231	2.3
Other	340	3.4
Town of Tipton	508	5.1

Deep-Core Soil Sampling

Deep-core soil sampling was conducted on a grid basis in the study area during 1992 and 1993. Since detailed sampling of the entire study area was not feasible, representative fields (Fields 1 through 8 shown in Figures 8 and 10) were chosen for sampling. Irrigated and dryland fields of cotton, wheat and alfalfa were chosen based on major crops and irrigation. Table 2 shows the time of sampling and the land use in each field during deep-core sampling in 1992 and 1993.

At each sampling location soil samples were taken at 1 ft depth increments to a depth of 10 ft using a deep-core soil sampler. The samples were air dried, ground, sieved through a 2.0 mm sieve, and the fractions finer than 2 mm were used for further analysis. Nitrate was extracted from the soil samples by shaking 2 g of sample with 20 ml of 2M KCl for 1 hour and filtered through Whatman No. 42 filter paper. The extracts were analyzed using the Cadmium reduction method as described by Keeney and Nelson (1982).

1992 Sampling

Deep core soils sampling was carried out as described above during the spring and summer of 1992. A grid spacing of 500 ft was adopted. The sampling locations are shown in Figure 8. Figures 9a through 9d show the nitrate-N concentration distribution at selected depths in the northern half of Section 2, where most of the sampling was conducted. A geostatistical analysis (semi-variogram) showed no significant spatial structure to the distribution of nitrate-N concentration (Ramanarayanan et al., 1993). So the nitrate-N concentrations obtained on a grid basis could be treated as random samples collected across the fields. The details of the nitrate-N distribution analysis is presented in Appendix B and the soil nitrate-N concentration data are presented in Appendix C.

1993 Sampling

The 1992 deep-core sampling showed that soil nitrate-N concentration is highly variable in space. Since soil nitrate is also highly variable with time, knowing the spatial characteristics at one instant may not be very helpful in terms of fertilizer recommendations and other decision making at a later instant. Therefore, considering a central value of soil nitrate-N concentration of a field (mean or median) for a decision making, may not impose a higher level of error than considering the spatial characteristics. For the 1993 sampling we therefore, decided to increase the grid size to 1000 ft which is sufficient to obtain a central value of soil nitrate-N concentration of a particular field.

During the second week of March 1993, deep core samples were taken from sections 1 and 2, except from the wheat fields. Fields 6 and 7 in Section 36 were not sampled because land preparation was going on in those fields, and sampling those fields at a later date did not materialize due conflicts with the cropping dates. During the last week of June, soil samples from the wheat fields of sections 1 and 2 were collected. Figure 10 shows the 1993 sampling locations. The soil nitrate concentrations at 1, 3, 6, 9 ft in the northern half of section 2 are shown in Figures 11a through 11d and the entire data are presented in Appendix C.

Inferences

Figures 12a through 12h show the mean soil nitrate-N profiles in the representative fields sampled during 1992 and 1993. Tables 3 and 4 show the mean and range of nitrate-N found concentration at selected depths during 1992 and 1993 deep-core sampling. Soil nitrate-N profiles for Fields 6 and 7 during 1993 were not presented because they were not sampled in that year. In general all the fields showed lower nitrate-N concentration profiles in 1993 than 1992.

Field 1 changed from irrigated cotton in 1992 to irrigated wheat in 1993. Figure 12a shows that there is a notable decrease in nitrate-N concentration in the entire profile. The reason for this may be attributed to the change in crop, sampling times and climatic influences. Field 2, which remained in irrigated wheat over the two years showed higher nitrate-N concentration at the surface layers in 1992 than in 1993. The rest of the profile did not show any prominent difference in nitrate-N concentration. Figure 12c shows that there is a pronounced reduction in the nitrate-N concentration from 1992 to 1993 through out the profile in Field 3. Since the crop in this field did not change the difference in nitrate profiles may be attributed to climatic influences.

The comparison of 1992 and 1993 soil nitrate-N profiles of Fields 4, 5 and 8 shows prominent reduction in nitrate concentration at the surface layers in 1993. Figures 12d, 12e and 12h show that the 1993 soil nitrate-N profiles in Fields 4, 5 and 8 show a marginal decrease in nitrate concentration in the lower layers also. Field 4 and 5 remained in the same land use in 1992 and 1993 (dryland wheat and feeding area respectively), however, Field 8 changed from irrigated alfalfa in 1992 to irrigated cotton in 1993.

Table 2. Sampling time and land use of the deep-core sampled fields.

Field Number	1992		1993	
	Sampling Time	Land Use	Sampling Time	Land Use
1	Spring	Irrigated Cotton	Summer	Irrigated Wheat
2	Summer	Irrigated Wheat	Summer	Irrigated Wheat
3	Spring	Irrigated Cotton	Spring	Irrigated Cotton
4	Summer	Dryland Wheat	Summer	Dryland Wheat
5	Spring	Feeding Area	Spring	Feeding Area
6	Spring	Dryland Cotton	-	-
7	Spring	Dryland Alfalfa	-	-
8	Summer	Irrigated Alfalfa	Spring	Irrigated Cotton

Table 3. Summary of soil nitrate-N profiles in the deep-core sampled fields in 1992.

Field Number	Crop	Depth (ft)	Mean (mg/kg)	Maximum (mg/kg)	Minimum (mg/kg)	Number of Samples
1	Irrigated Cotton	1	18	44	9	15
		2	11	19	5	15
		3	10	19	3	15
		4	10	18	4	15
		5	10	19	5	15
		6	8	16	4	15
		7	8	20	3	15
		8	9	18	2	15
		9	13	56	4	15
		10	10	21	3	11
2	Irrigated Wheat	1	13	20	7	4
		2	3	6	1	4
		3	3	6	1	4
		4	2	4	1	4
		5	2	4	1	4
		6	2	2	1	4
		7	2	2	1	4
		8	2	2	1	4
		9	2	2	1	3
		10	2	2	1	3
3	Irrigated Cotton	1	21	71	4	19
		2	14	65	3	19
		3	14	49	2	19
		4	14	50	1	19
		5	15	48	1	19
		6	18	77	3	19
		7	17	78	2	19
		8	17	65	4	19
		9	15	51	3	19
		10	16	55	2	16
4	Dryland Wheat	1	57	75	28	6
		2	11	15	7	6
		3	6	11	4	6
		4	6	8	3	6
		5	4	6	2	6
		6	3	5	2	6
		7	7	19	2	6
		8	7	11	3	6
		9	9	15	4	6
		10	11	17	3	5

Table 3 (continued)

Field Number	Crop	Depth (ft)	Mean (mg/kg)	Maximum (mg/kg)	Minimum (mg/kg)	Number of Samples
5	Feeding Area	1	183	360	6	2
		2	42	81	3	2
		3	61	119	2	2
		4	54	106	2	2
		5	52	98	7	2
		6	32	60	4	2
		7	28	51	4	2
		8	21	35	6	2
		9	25	26	24	2
		10	31	39	23	2
6	Dryland Cotton	1	22	35	13	10
		2	11	15	7	10
		3	8	11	5	10
		4	10	24	4	10
		5	23	144	4	10
		6	25	165	2	10
		7	37	163	3	10
		8	41	278	5	10
		9	31	189	5	10
		10	19	52	5	10
7	Dryland Alfalfa	1	25	56	8	5
		2	7	11	4	5
		3	7	9	5	5
		4	5	7	4	5
		5	5	6	4	5
		6	4	6	3	5
		7	3	4	2	5
		8	4	7	2	5
		9	3	4	1	4
		10	5	10	3	4
8	Irrigated Alfalfa	1	77	221	15	10
		2	16	26	7	10
		3	12	17	3	10
		4	11	14	8	10
		5	11	18	7	10
		6	7	12	4	10
		7	7	11	3	10
		8	8	18	1	10
		9	7	17	4	10
		10	8	22	3	9

Table 4. Summary of soil nitrate-N profiles in the deep-core sampled fields during 1993.

Field Number	Crop	Depth (ft)	Mean (mg/kg)	Maximum (mg/kg)	Minimum (mg/kg)	Number of Samples
1	Irrigated Wheat	1	2	4	0	3
		2	1	2	1	3
		3	1	2	1	3
		4	1	3	1	3
		5	2	2	1	3
		6	1	2	1	3
		7	1	1	0	3
		8	1	1	1	3
		9	1	1	1	3
		10	1	1	1	3
2	Irrigated Wheat	1	4	7	1	2
		2	3	4	2	2
		3	3	4	2	2
		4	4	4	4	2
		5	2	3	1	2
		6	2	2	1	2
		7	2	2	1	2
		8	1	2	1	2
		9	2	2	1	2
		10	2	3	2	2
3	Irrigated Cotton	1	4	7	2	6
		2	3	4	2	6
		3	3	3	2	6
		4	2	2	1	6
		5	2	4	2	6
		6	2	4	1	6
		7	3	7	1	6
		8	3	12	1	6
		9	3	11	1	6
		10	3	8	1	6
4	Dryland Wheat	1	2	2	1	2
		2	1	1	1	2
		3	1	2	1	2
		4	2	4	1	2
		5	1	2	1	2
		6	1	2	1	2
		7	2	2	1	2
		8	1	2	1	2
		9	3	4	2	2
		10	4	5	3	2

Table 4 (continued)

Field Number	Crop	Depth (ft)	Mean (mg/kg)	Maximum (mg/kg)	Minimum (mg/kg)	Number of Samples
5	Feeding Area	1	15	15	15	1
		2	5	5	5	1
		3	2	2	2	1
		4	2	2	2	1
		5	2	2	2	1
		6	2	2	2	1
		7	2	2	2	1
		8	1	1	1	1
		9	1	1	1	1
		10	1	1	1	1
6	Dryland Cotton		NOT SAMPLED IN 1993			
7	Dryland Alfalfa		NOT SAMPLED IN 1993			
8	Irrigated Cotton	1	6	8	3	3
		2	4	5	2	3
		3	3	4	1	3
		4	2	3	1	3
		5	5	8	1	3
		6	5	10	2	3
		7	3	5	2	3
		8	3	4	2	3
		9	3	5	2	3
		10	2	2	2	3

Standard Soil Sampling

In addition to the deep-core sampling, standard soil sampling for nutrient analysis was carried out in 1992 and 1993 on all fields within the 16 square mile study area. The first sampling was initiated in December 1992 and completed in March 1993, and the second sampling was conducted in Fall 1993. The soil samples were sent to OSU Agronomic Services Laboratory for analyzing pH, nitrate-N, and extractable P and K. In addition to the surface nutrient contents, subsurface nitrate content in the fields were also analyzed. The results of the sampling were used to develop nutrient management plans for the local producers. The summaries for 1992 and 1993 standard surface and subsurface soil sampling results are given in Tables 5 and 6.

The results of the soil sampling show that the soil in the area is slightly acidic to alkaline, with high amounts of extractable P and K. The surface samples showed no change in the nitrate-N content except in the wheat fields where it got increased. In both the years, the subsurface samples showed higher nitrate-N concentrations than the surface samples, indicating nitrate movement in the downward in the profile. In 1992, alfalfa and wheat fields showed higher subsurface nitrate concentrations than the cotton fields, and in 1993, cotton and wheat fields showed high subsurface nitrate concentrations.

Table 5. Summary of standard soil sampling conducted during 1992 in the study area.

Crop (# samples)	pH			N (lb/ac)			P (lb/ac)			K (lb/ac)		
	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low
Cotton (54)												
Top[¶]	7.7	7.9	5.5	4	20	1	61	117	21	445	787	296
Sub[§]				16	21	2						
Wheat (17)												
Top	6.3	7.4	5.0	4	21	0	70	104	25	454	686	289
Sub				32	45	15						
Alfalfa (7)												
Top	6.7	7.4	6.0	6	15	2	58	78	41	364	410	305
Sub				29	45	10						
Sorghum (5)												
Top	6.7	7.1	6.4	4	5	1	73	103	45	484	589	266
Sub				3	8	0						
Peanuts (3)												
Top	7.3	7.5	7.0	3	4	1	48	67	12	228	309	105
Sub				5	8	2						
Cantaloupe (2)												
Top	8.0	8.3	7.6	2	3	1	77	95	60	546	548	544
Sudan (1)												
Top	6.4	.	.	1	1	1	42	42	42	234	234	234
Grass (1)												
Top	6.2	.	.	3	3	3	41	41	41	357	357	357

¶ 0 to 6" § 6 to 24"

Table 6. Summary of standard soil sampling conducted during 1993 in the study area.

Crop (# samples)	pH			N (lb/ac)			P (lb/ac)			K (lb/ac)		
	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low
Cotton (38)												
Top[¶]	6.7	8.0	5.5	8	23	2	50	100	15	338	618	186
Sub[§]				18	43	5						
Wheat (31)												
Top	6.6	8.0	5.8	14	38	2	62	130	23	406	641	204
Sub				24	45	5						
Alfalfa (2)												
Top	7.2	6.8	5.1	8	10	5	28	29	27	200	237	162
Sub				20	27	13						
Sorghum (2)												
Top	5.9	6.8	5.1	6	7	4	87	89	84	576	625	526
Sub				15	16	13						
Peanuts (3)												
Top	7.6	7.9	7.4	8	13	5	58	68	49	244	255	230
Sub				5	8	2						
Cantaloupe (1)												
Top	7.7	7.7	7.7	14	14	14	56	56	56	523	523	523
Fallow (1)												
Top	6.4	6.4	6.4	11	14	14	41	41	41	290	290	290
Grass (1)												
Top	7.5	7.5	7.5	13	14	14	110	110	110	501	501	501

[¶] 0 to 6" [§] 6 to 24"

Water Quality Monitoring

Four monitoring wells (Figure 1) were drilled in the study area in Fall 1991 by the USDA-ARS Water Quality Laboratory in Durant, Oklahoma. Starting from January 1992, ground water in the study area was sampled every month from these monitoring wells. The water samples were analyzed for chloride, total dissolved solids, nitrate-N, pH and EC. The sampling was carried out by OWRB and analyzed by the State Environmental Laboratory Service of the Oklahoma State Department of Health. Starting from October 1992, water samples from the two municipal wells were also collected and tested along with monitoring well samples. The water quality analysis data are given in Appendix D. Table 7 shows the well depth, screen interval and casing depth of the monitoring wells. This information is not available for the municipal wells. However, according to the local sources, the municipal wells are screened below 40 ft to the bottom of the aquifer (about 50 ft).

Water Table Elevation

Figure 13 shows the water table elevations recorded from the monitoring wells and municipal wells during the sampling period. Monitoring results show that there is no significant difference between the water table elevations recorded from the municipal and monitoring wells except in monitoring well 3. The ground elevation of monitoring well 3 itself is significantly higher than the rest of the wells and also the water table was nearer to the surface. This high water table observed in monitoring well 3 may be due to the mounding effect created by a drain field of a residential septic tank located nearby.

Table 7. Tipton Monitoring and Municipal wells information.

Well	Date Drilled	Well Depth (ft)	Screen Interval (ft)	Cased up to (ft)
Monitoring Well 1	11/14/91	40.0	20 to 30	30.4
Monitoring Well 2	11/13/91	48.0	20 to 30	30.0
Monitoring Well 3	11/18/91	25.5	15.25 to 25.25	25.25
Monitoring Well 4	11/19/91	50.0	32 to 42	47.0
Municipal. Well 1	******************* Details Not Available *****************			
Municipal. Well 2	******************* Details Not Available *****************			

Nitrate-N Concentration

The nitrate-N concentrations in the monthly water samples collected from the monitoring and municipal wells are shown in Figure 14. Monitoring wells 1, 2 and 4 showed mean nitrate-N concentrations lower than 5 mg/l. Monitoring well 3 showed mean nitrate-N concentration of 16 mg/l during the monitoring period. It was found that a domestic septic system nearby is a possible source of nitrate in that monitoring well. Municipal well 1 (north well) samples had a mean nitrate-N concentration of 18 mg/l, with a high of 28 mg/l. Municipal well 2 (south well) showed a mean nitrate-N concentration of 7 mg/l. The samples from this well showed nitrate-N concentrations less than 10 mg/l.

Total Dissolved Solids (TDS)

Figure 15 shows the TDS in the water samples from the monitoring and municipal wells. The TDS from the monitoring wells are not significantly different from each other. However, the TDS from both the municipal wells were significantly higher than that of the monitoring wells.

Inferences

From the above observations the following inferences were drawn:

1. The monitoring and municipal wells might have different source of water. The monitoring wells, which are screened in the shallow portion of the aquifer show lower concentration of nitrate-N than the municipal wells which are probably screened in the deeper portion. The difference in TDS between the municipal and monitoring wells suggest they may have different geologic influences.

2. There may be physical or chemical stratification in the aquifer: lower salt and nitrate concentrations in the top portion and higher concentrations in the bottom portion. If this is the case, then agricultural activities in the vicinity of the municipal wells may not be the source of nitrates in the aquifer, but parent material of the aquifer or sources from outside the study area may be the source. Existing literature on the Tillman Terrace aquifer (Al-Sumait, 1978; Kent and Naney, 1978) show that the aquifer is fairly uniform throughout its depth and the presence of local clay lenses in the Tipton area is not known. This leads to the possibility that the aquifer might be chemically stratified.
3. Nitrate-N concentrations from June 1993 to August 1993 in the municipal well decreased significantly. This is a period of high pumping where the water table might be lowered and water from the top portion of the aquifer could be pumped due to a deep cone of depression. In such a situation water from the top portion of the aquifer having lower concentration of nitrate would have been pumped by the municipal well. This might be the reason for the lower concentration during this period. However, the water table elevations and the TDS concentrations recorded during this period do not support this.
4. Most of the nitrate might be coming into the WHPA through lateral ground water flow. This brings into question the feasibility of the WHPA delineated using the existing procedures and criteria of delineation.

Water Quality Survey and Public Meeting

A water quality survey questionnaire was sent to the residents of the Town of Tipton to determine the chemical management practices being used for lawn and garden care, domestic water source, location of septic systems, perception of the water quality problems and other issues related to the project. In addition, a public meeting was organized in June 1993, and the project overview and current results were presented to the public. However, the turnout for the meeting was low.

Irrigation Pumps Testing

Testing of irrigation wells was proposed at the initial grower's meeting to determine the system characteristcis of wells in the study area. This also proved to be a benefit for the growers in the study area. There are a number of irrigation wells in the study area and wells A through E, listed below were the only ones for which arrangements could be made for pump testing. Performance evaluations were conducted in August 1993 on these five wells and two other additional wells outside the study area the owner of which had some dryland within the study area. Wells B, C, D and E all fed into a single center pivot irrigation system. Wells F and G, feeding a gated pipe surface irrigation system, are approximately 6 miles south of the intersection of Hwy 5 and Hwy 5C at Tipton. The system characteristics of the wells were tested at 505 gpm and 23 psi pressure at the pivot point. The summary of the pump tests are presented in Table 8.

Wells B through G are quite typical of the irrigation wells in the area. They are shallow, small diameter, relatively low yielding wells which can serve only a limited acreage unless the output of several wells can be combined. Well A is a fairly large capacity well for the area and by itself is a marginal water supply for the full-circle pivot system it serves. It is also the closest of the wells tested to the municipal wells.

Table 8. Summary of irrigation pumps test results.

No.	Location	Casing Size (in)	Column pipe (in)	Delivery (GPM)	Pressure (psi)	Water Depth (ft)
A	SE ¼, Sec. 26, T1N, R19W	12	8	405	49	-[1]
B	NW¼, Sec. 25, T1N, R19W	6	4	-[2]	-[3]	40
C	NW¼, Sec. 25, T1N, R19W	6	4	48	-[3]	32
D	NW¼, Sec. 25, T1N, R19W	6	4	90	-[3]	35
E	NW¼, Sec. 25, T1N, R19W	6	4	100	-[3]	28
F	NW¼, Sec. 12, T2S, R19W	6	4	140	-[3]	-[1]
G	NW¼, Sec. 12, T2S, R19W	6	4	170	-[3]	36

[1] No access port
[2] No suitable meter location
[3] No pressure gauge or port

Summary and Conclusions

The soil nitrate concentration in the study area is highly variable over space and time. The deep-core sampling conducted in 1992 with a grid size of 500 ft did not show any spatial characteristics of soil nitrate concentration in the area. Spatial characteristics are important to assess the distribution of a variable in a given area and sometimes it is important to estimate the distribution outside the sample area. In our case the soil nitrate-N concentration is the variable of interest. Since this is found to be highly variable over time and space, knowing the spatial characteristics may not be very helpful in terms of fertilizer recommendations and other decisions. Thus, considering a central value of soil nitrate-N concentration of a field (mean or median) for decision making may not impose a higher level of error than considering the spatial characteristics. However, there is no supporting research for this.

In general, the soil nitrate-N profiles obtained from the deep-core sampling in 1993 show lower nitrate concentration than in 1992. All the surface layers in 1992 have higher nitrate concentration than in 1993. The cultural and irrigation practices in these fields were not changed from 1992 to 1993. So the reason for the nitrate-N concentration reduction in the soil profiles during 1993 may be attributed to the change in crop, change in sampling time, or climatic influences.

The nitrate and TDS concentrations of the water samples suggest that the monitoring and municipal wells might have a different sources of water. The aquifer might be physically or chemically stratified with the top portion having lower nitrate-N concentration than the bottom portion. In such a case agricultural activities around the Town of Tipton may not be the reason for high nitrate concentration in the ground water. Sources could be from outside the study area or it may be due to the parent material of the aquifer.

Based on the soil and ground water sampling results, no conclusions could be drawn on the effectiveness of BMPs in reducing in nitrate concentration in the ground water over the two years. This duration proved to be too short a time to notice any appreciable change in the ground water quality. The available level of technology, data, and time were not sufficient to draw any conclusion at present.

Nitrate pollution due to agricultural activities usually originate from large areas. Dilution and dispersion are the most effective mechanisms for reducing nitrate concentration in the ground water. Delineating WHPA and implementing BMPs will reduce the nitrate loading to the ground water from within the WHPA. But typically a considerable amount of nitrate might come into the WHPA through lateral ground water flow. The extent of WHPA should be such that the reduced load of nitrates within the WHPA should dilute the excess nitrate concentration coming from outside. The WHPA delineated for the Tipton municipal wells should be evaluated for its effectiveness under this criteria. This work is currently in progress.

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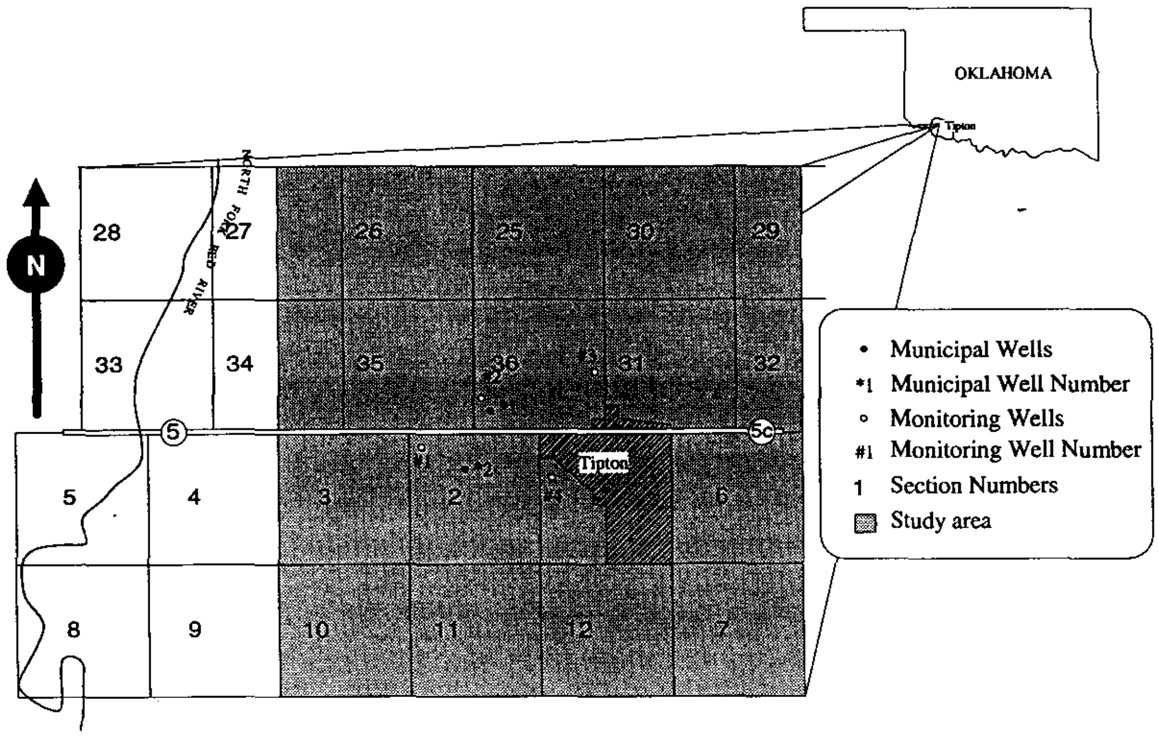

Figure 1. Location of the Tipton study area.

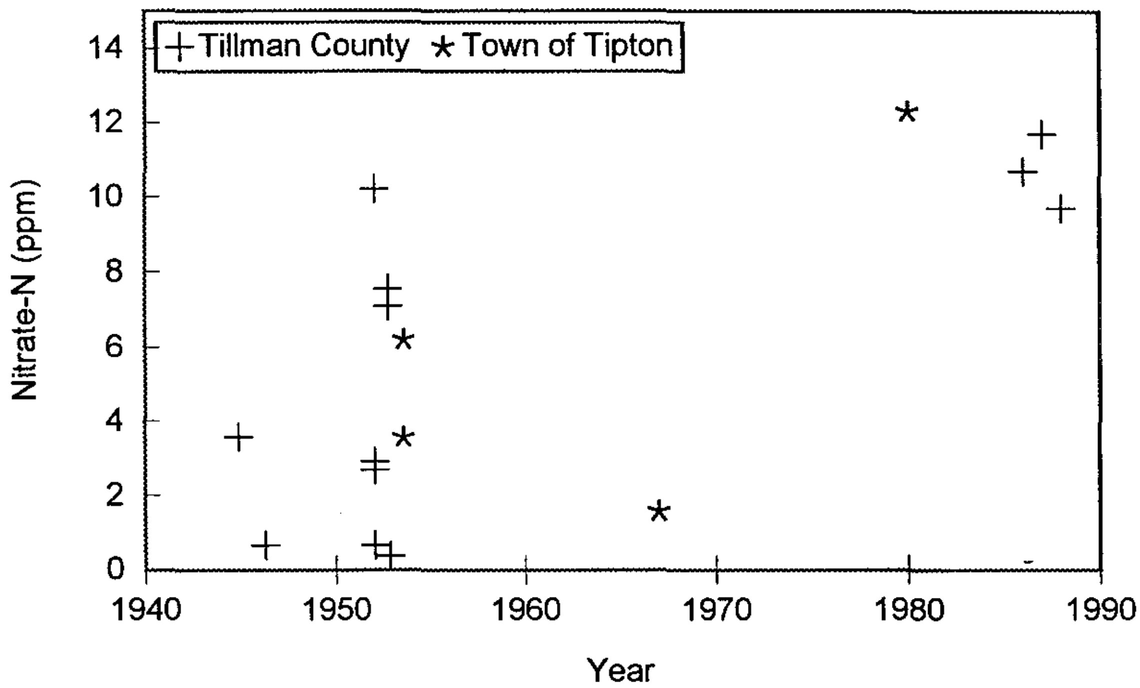

Figure 2a. Comparison of historic nitrate levels in Tillman County and Town of Tipton (OWRB, 1991).

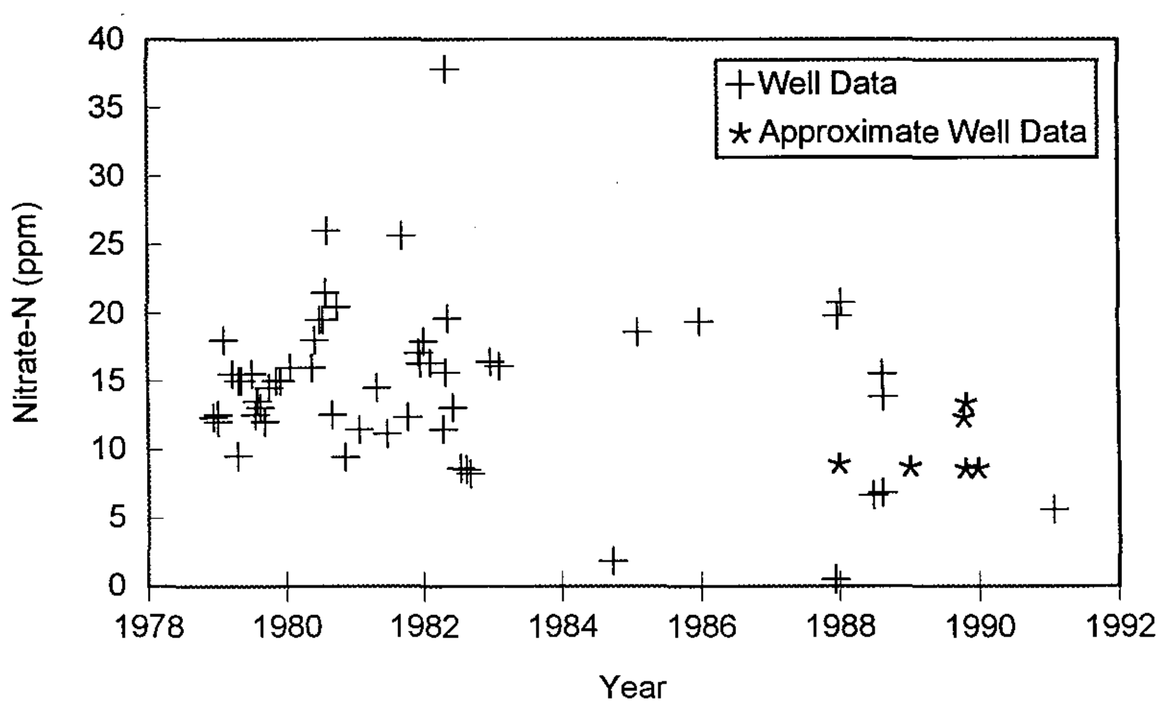

Figure 2b. Historic nitrate levels in Town of Tipton municipal wells (OSDH, 1991).

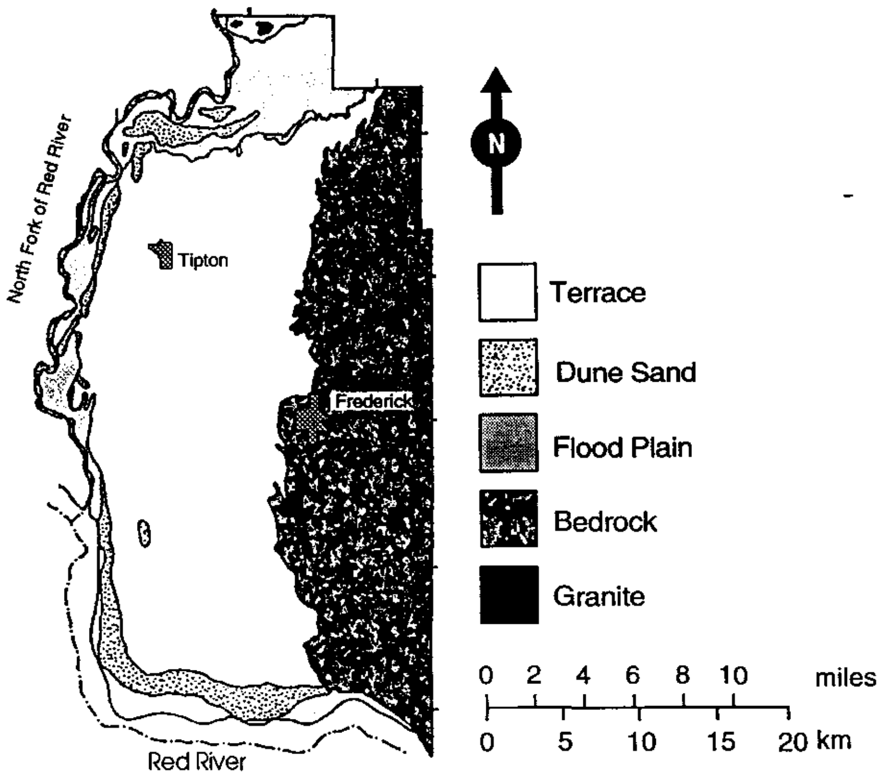

Figure 3. Tillman Terrace Aquifer (Al-Sumait, 1978).

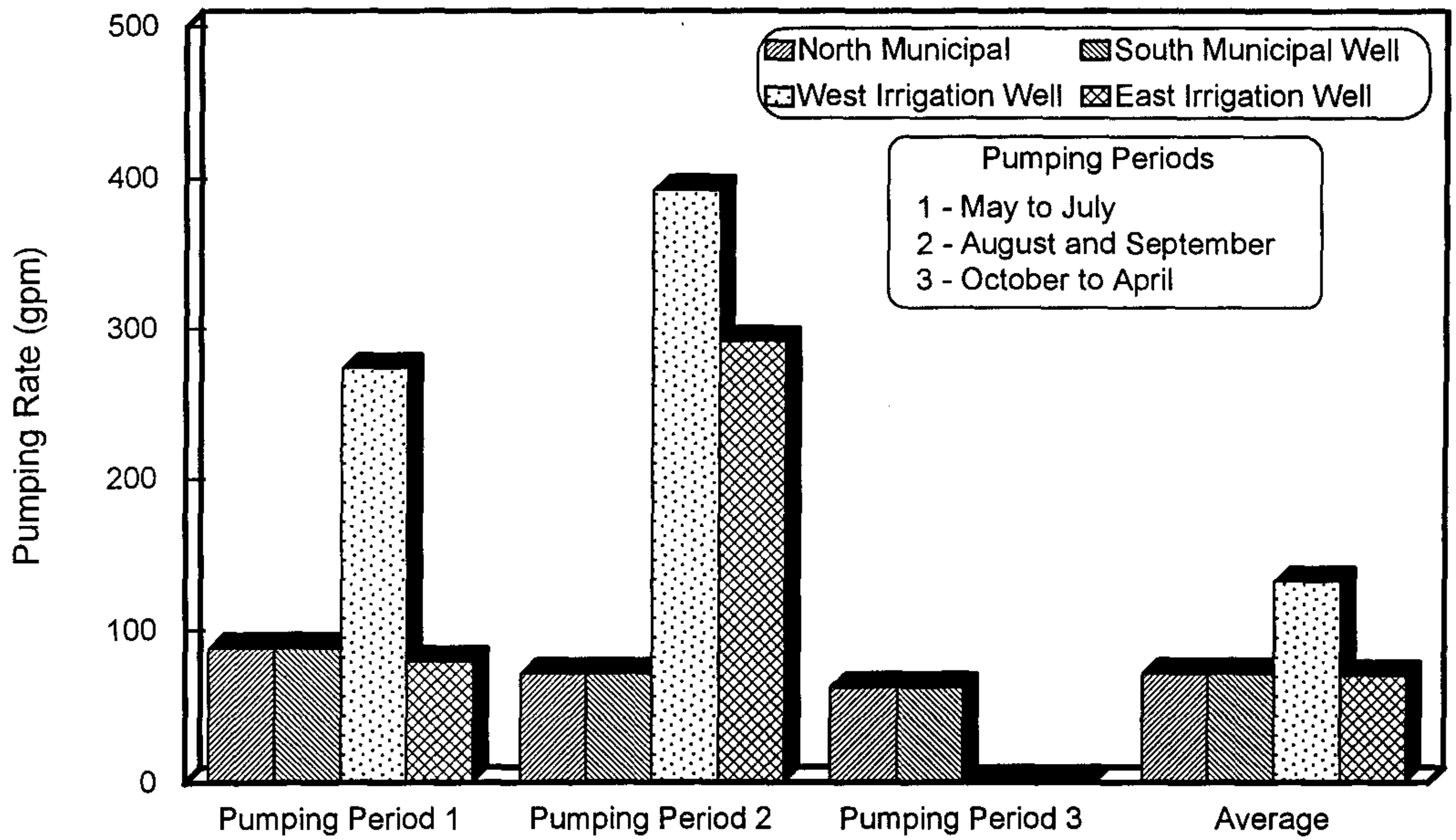

Figure 4. Pumping rates for the municipal and irrigation wells used in the WHPA delineation process

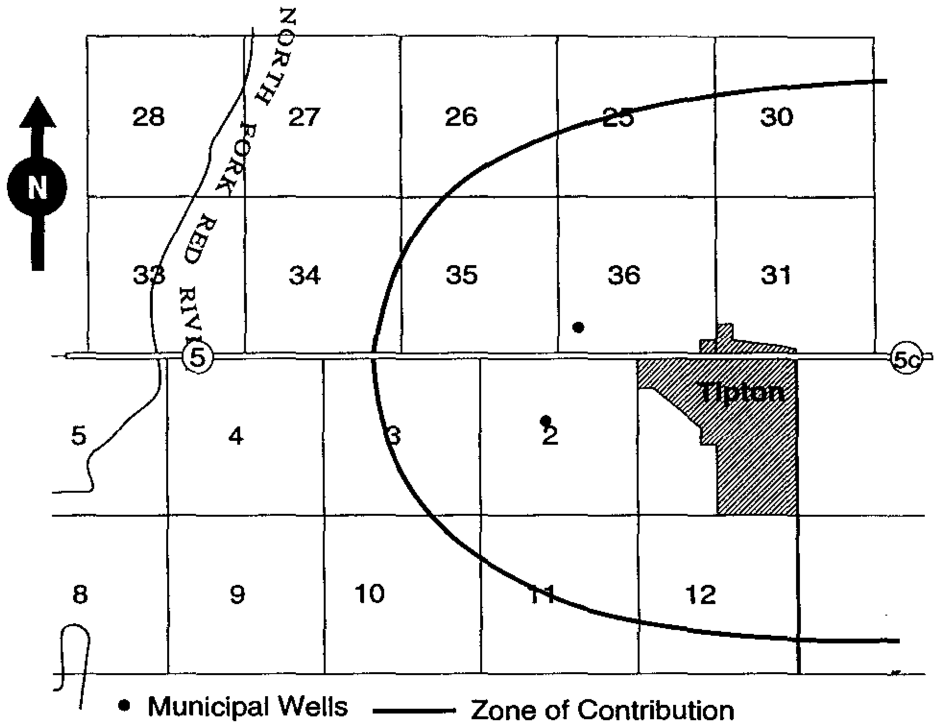

Figure 5. WHPA delineated using only the flow part of USGS-MOC

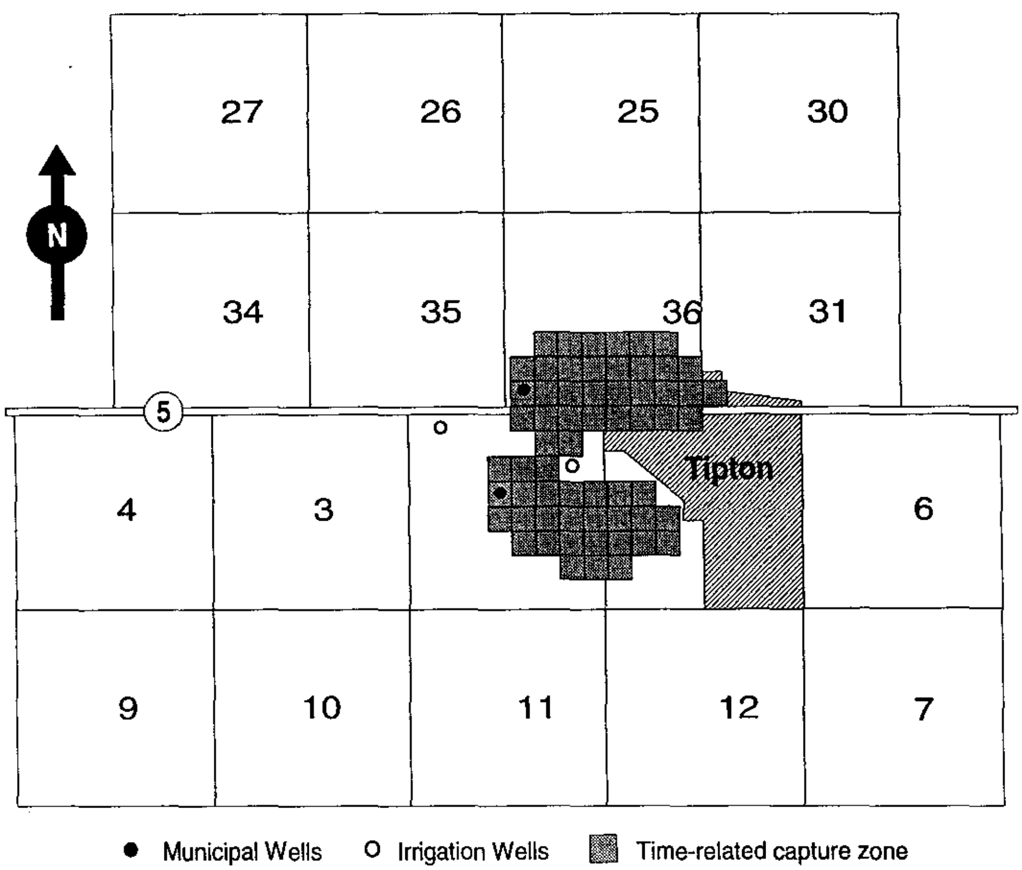

Figure 6. WHPA delineated using flow and transport parts of USGS-MOC

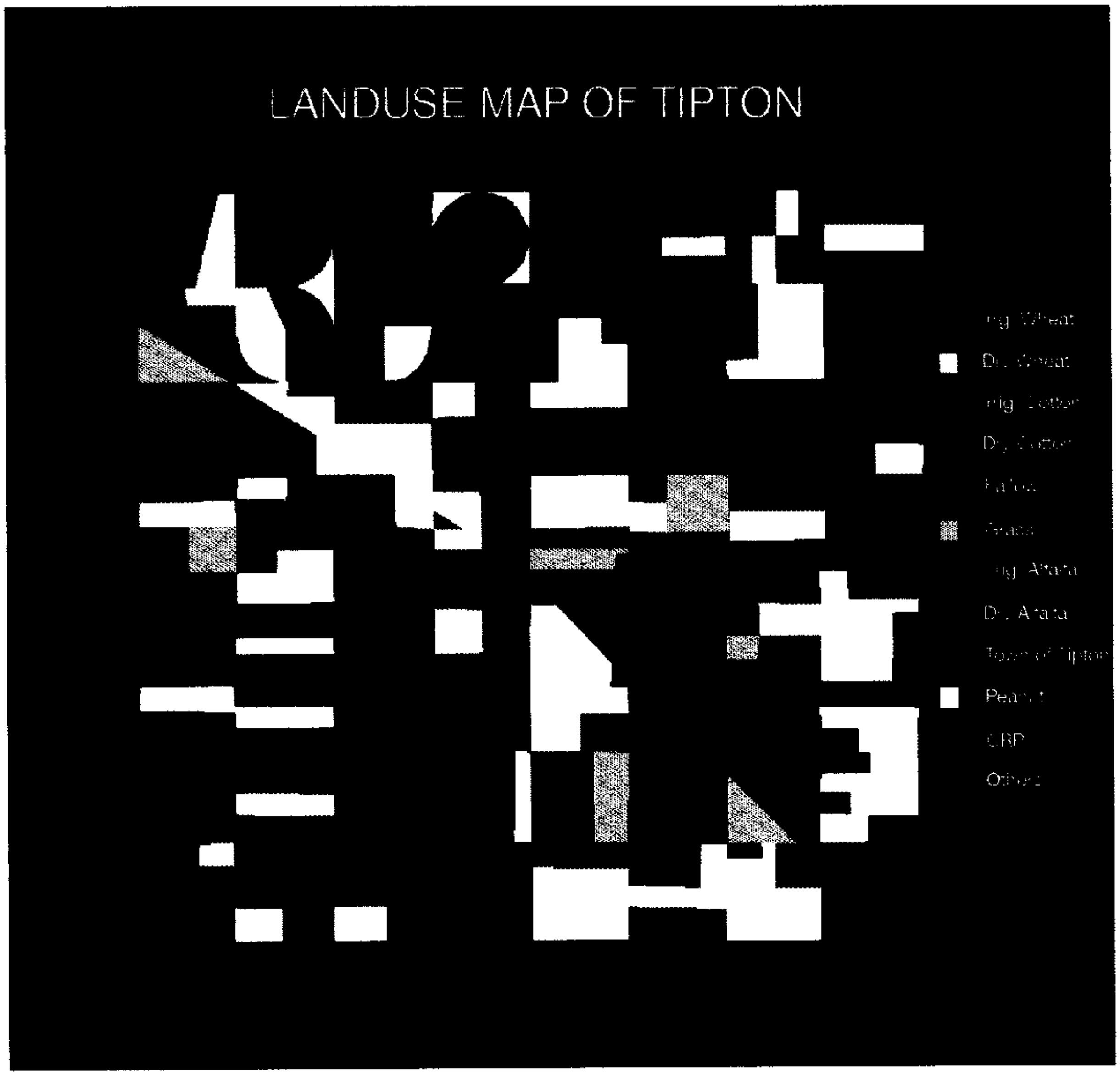

Figure 7. Land use map of the Tipton study area

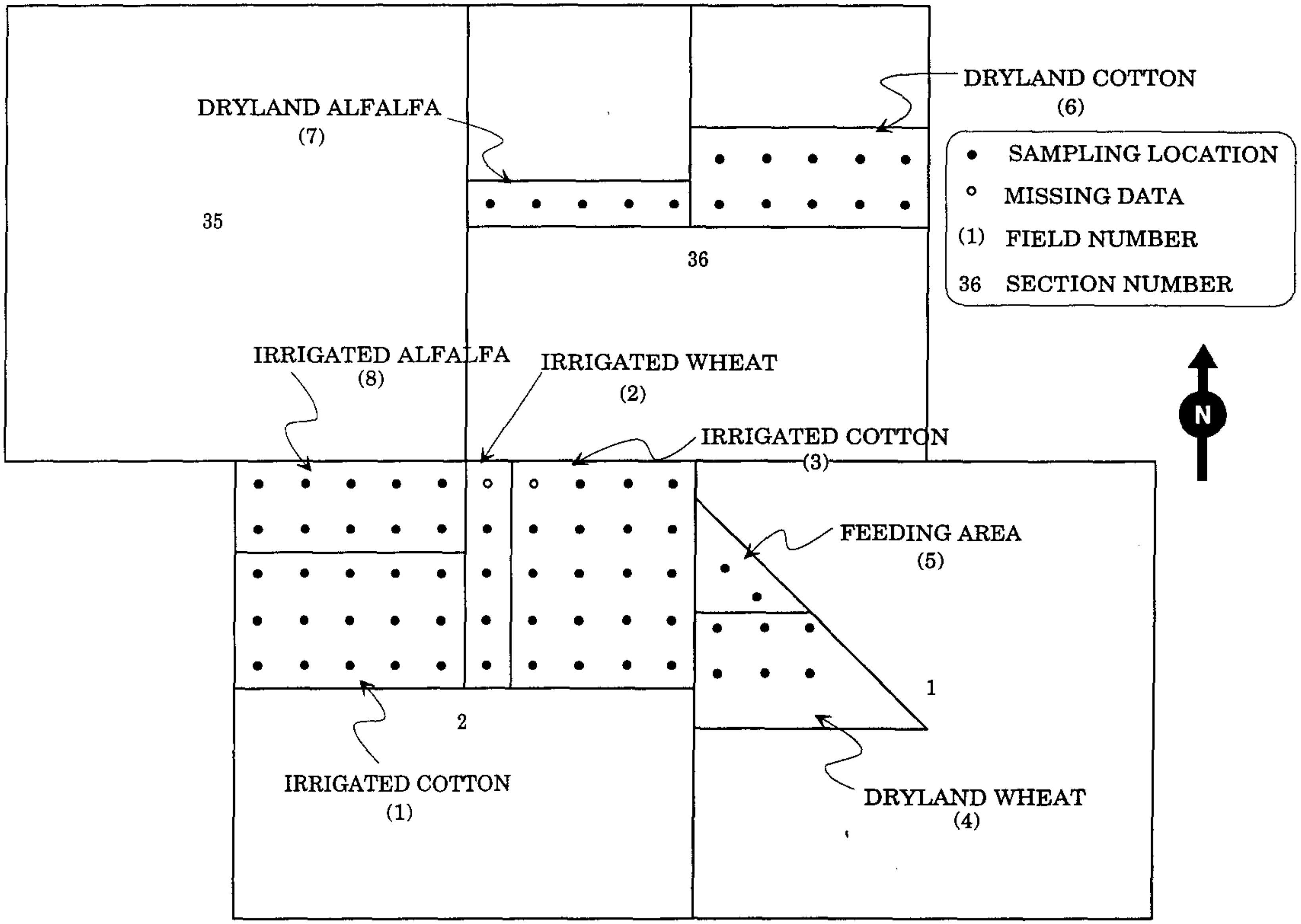

Figure 8. Deep-core soil sampling locations during 1992

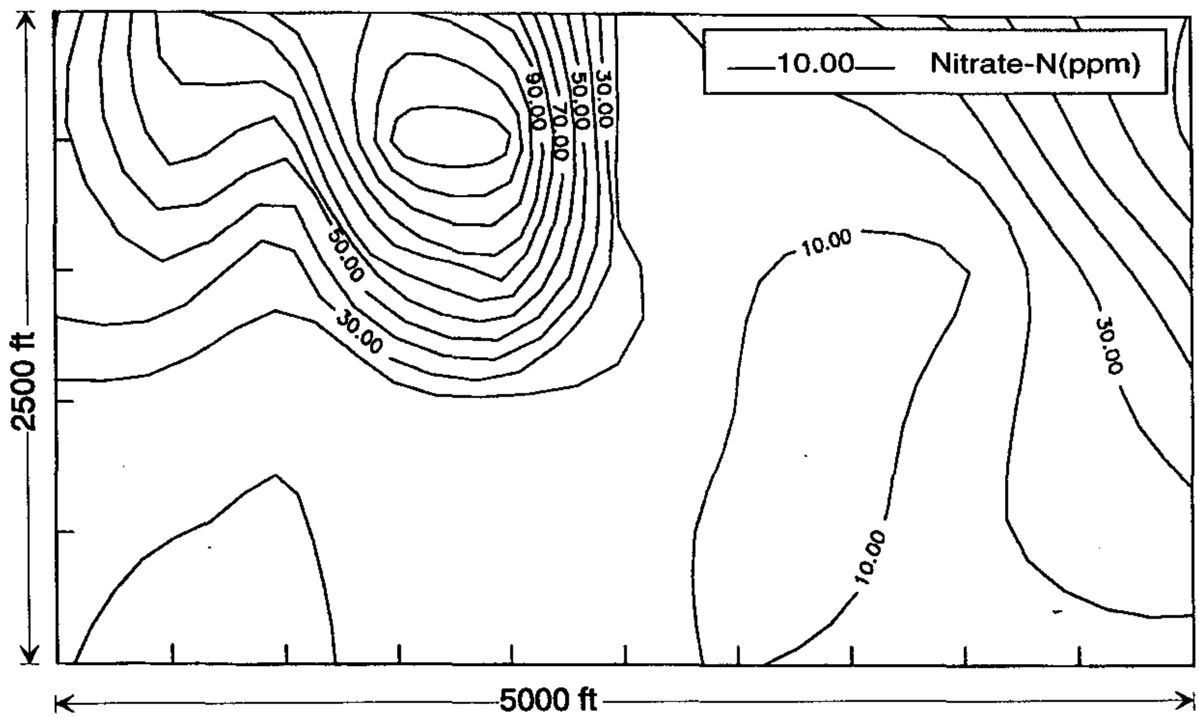

Figure 9a. Nitrate-N concentration distribution in 1992 at 1 ft depth in the northern half of Section 2

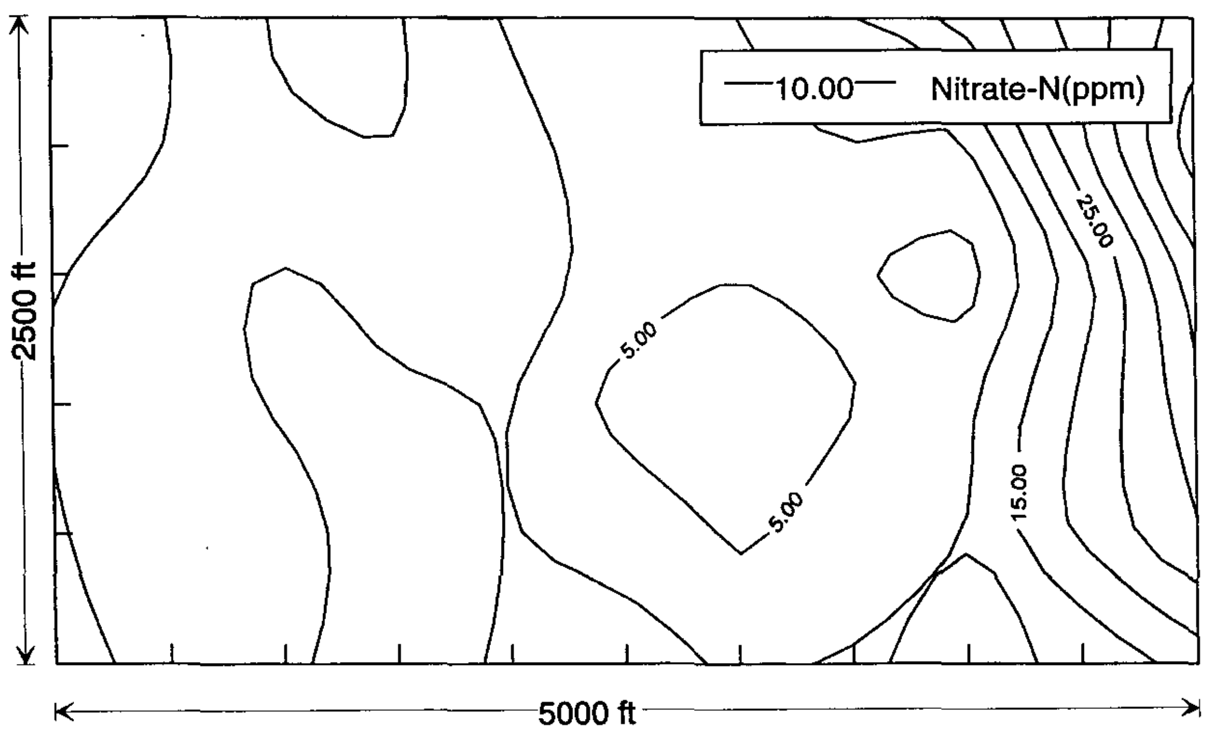

Figure 9b. Nitrate-N concentration distribution in 1992 at 3 ft depth in the northern half of Section 2

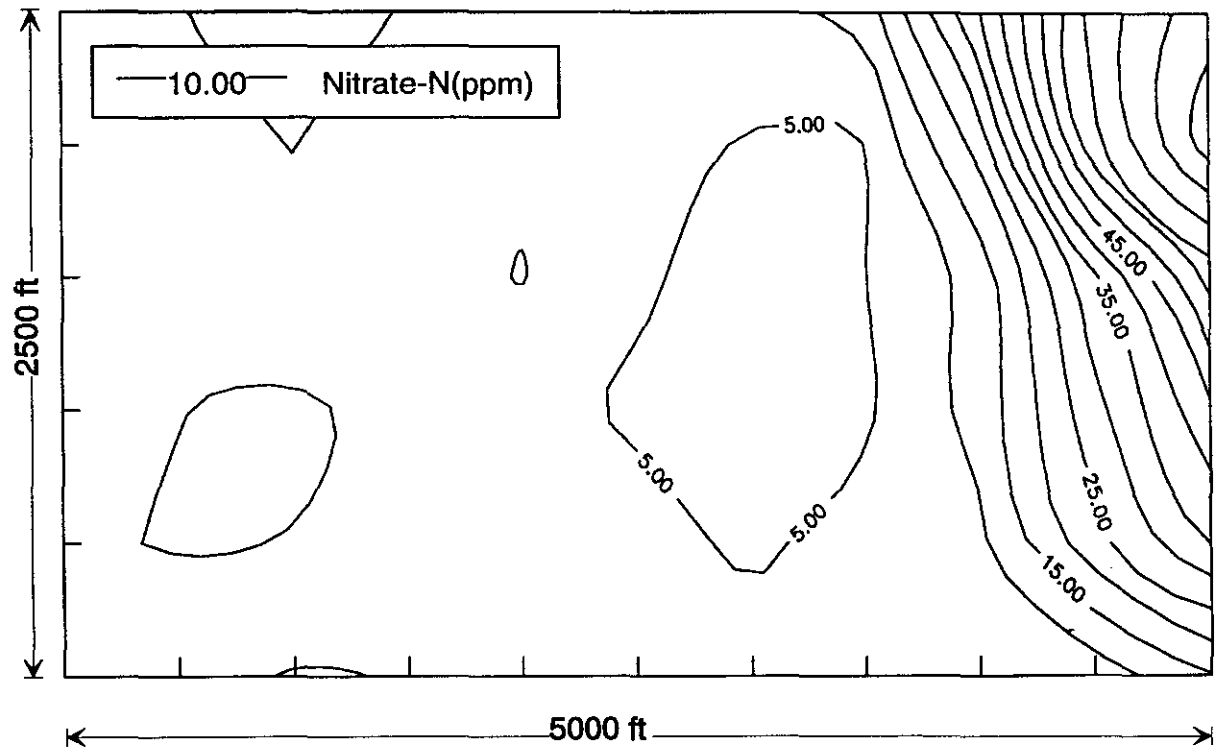

Figure 9c. Nitrate-N concentration distribution in 1992 at 6 ft depth in the northern half of Section 2

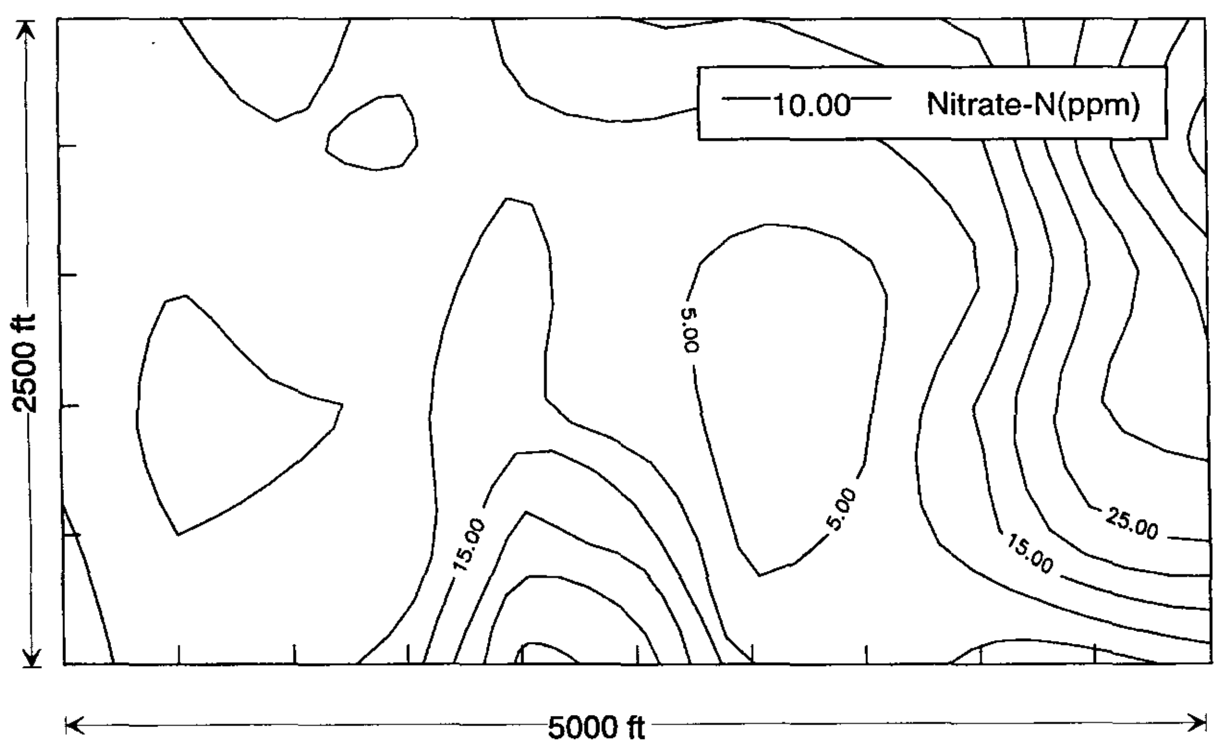

Figure 9d. Nitrate-N concentration distribution in 1992 at 9 ft depth in the northern half of Section 2

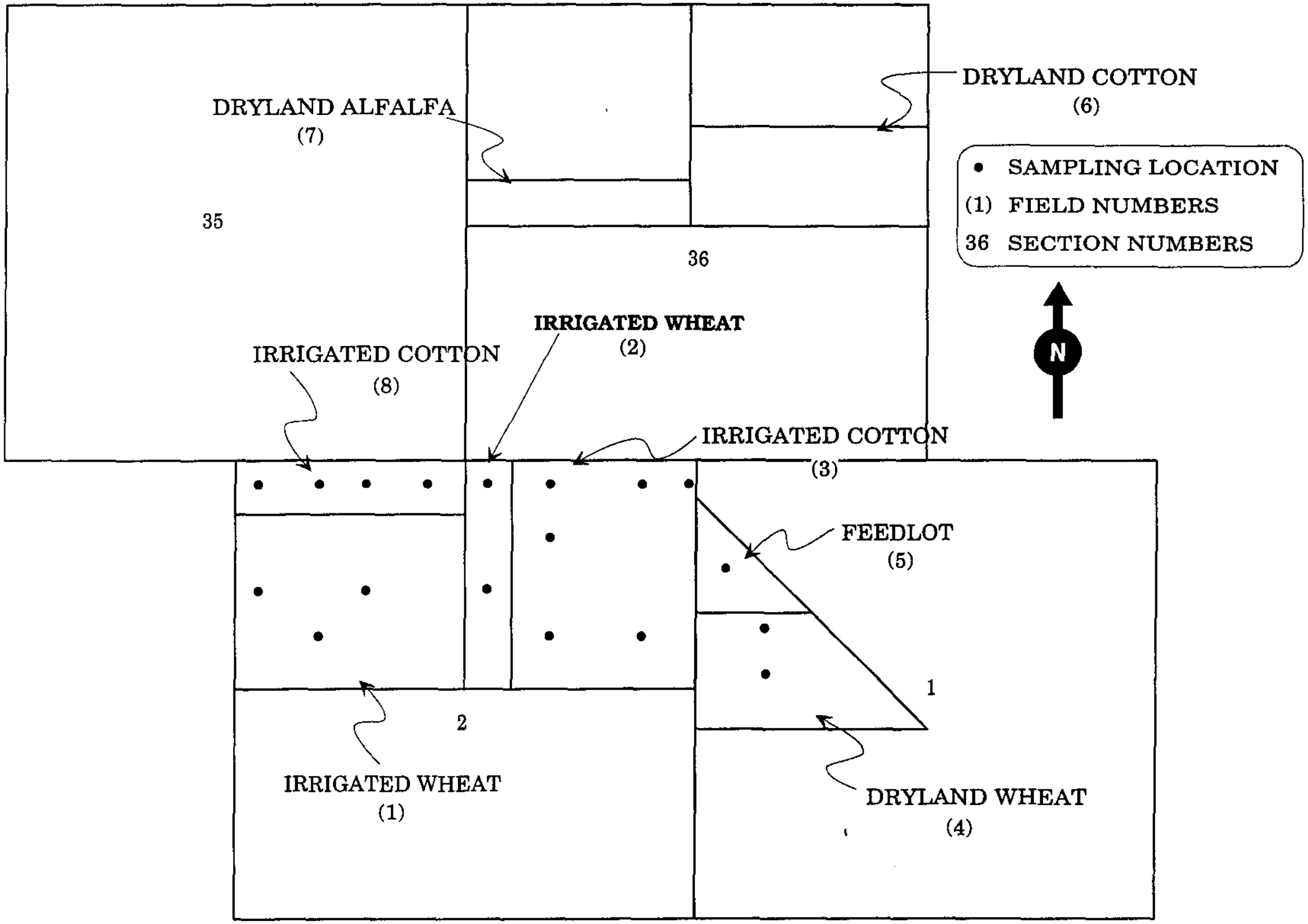

Figure 10. Deep-core soil sampling locations during 1993

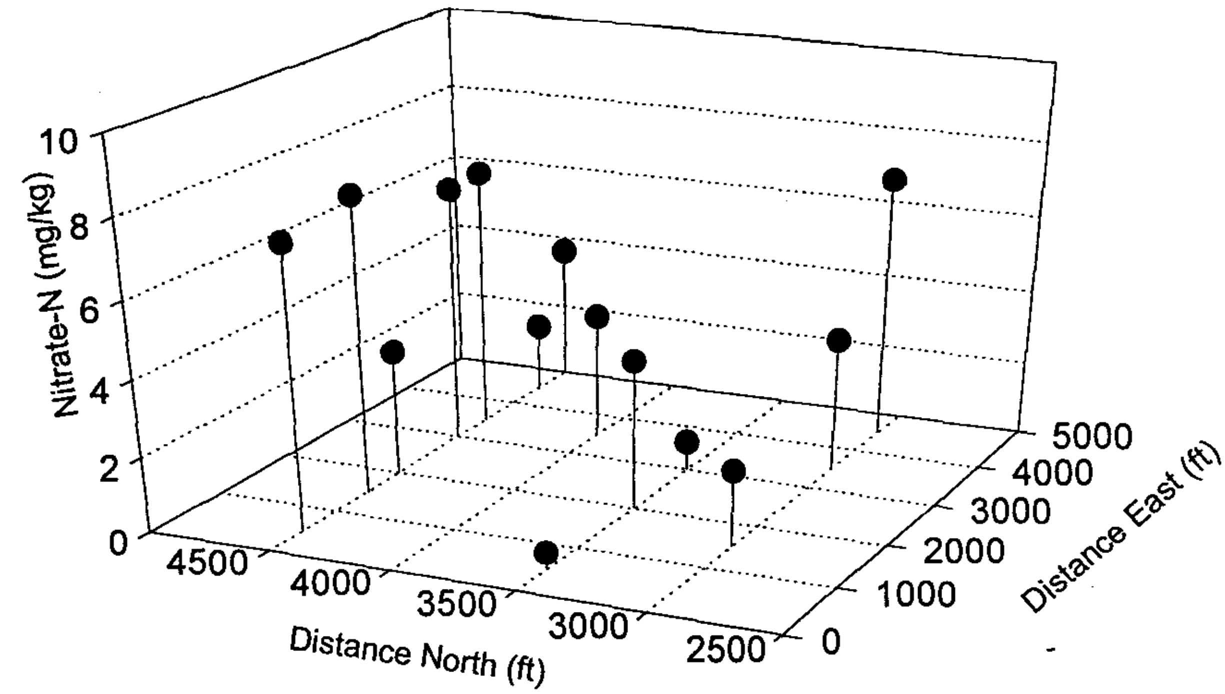

Figure 11a. Nitrate-N concentration in 1993 at 1 ft depth in the northern half of Section 2 (distances measured from SW corner of section)

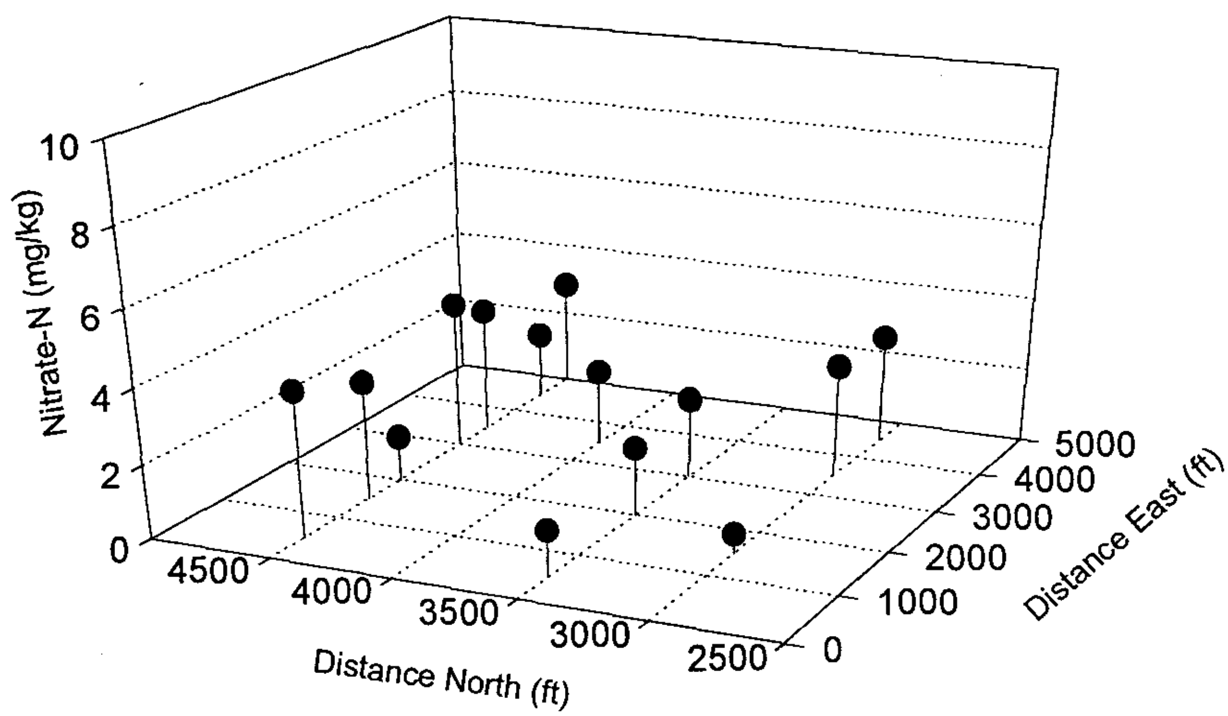

Figure 11b. Nitrate-N concentration in 1993 at 3 ft depth in the northern half of Section 2 (distances are measured from SW corner of section)

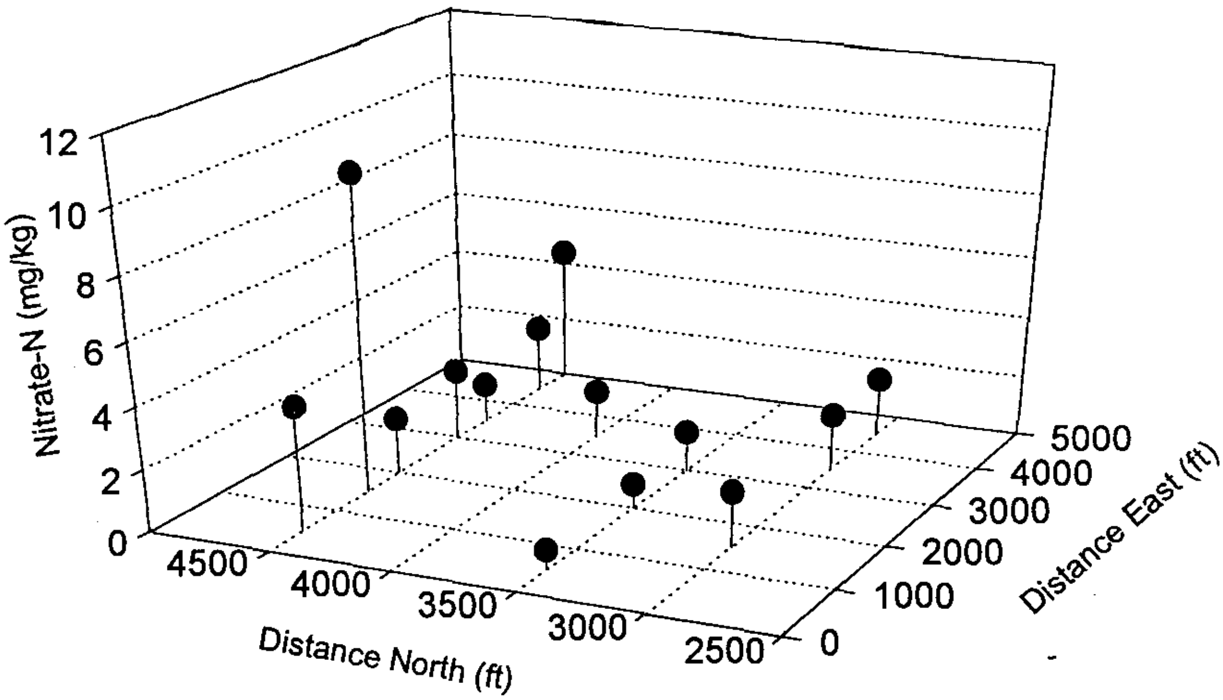

Figure 11c. Nitrate-N concentration in 1993 at 6 ft in northern half of Section 2 (distances from SW corner of the section)

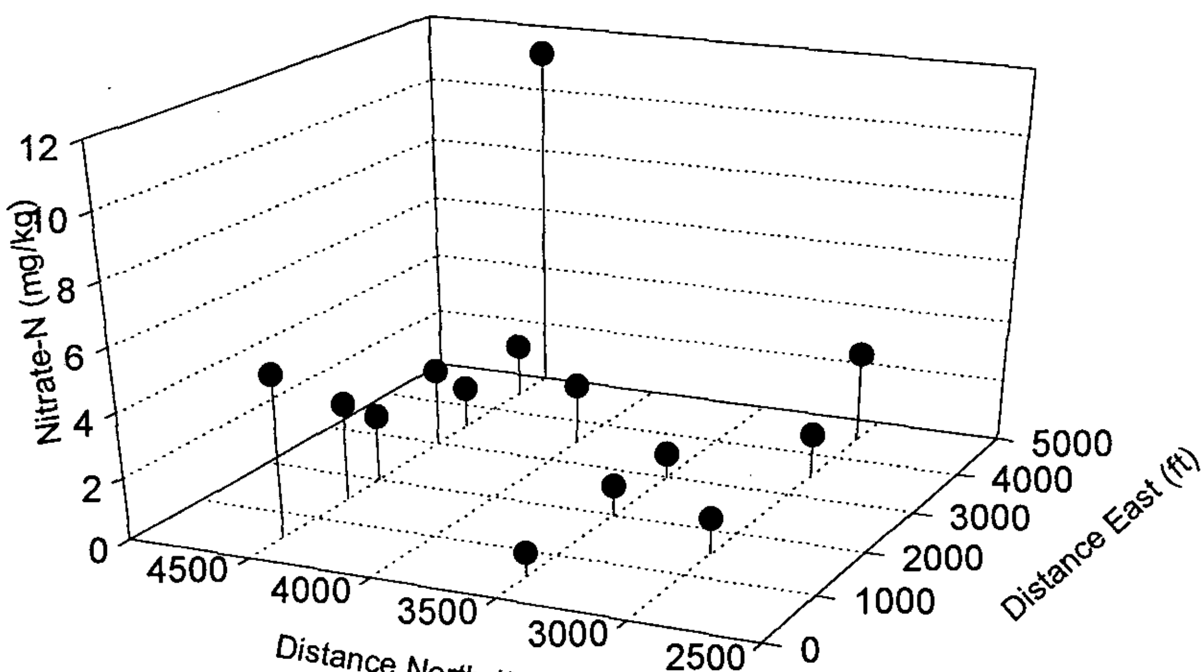

Figure 11d. Nitrate-N concentration in 1993 at 9 ft in northern half of Section 2 (distances from SW corner of the section)

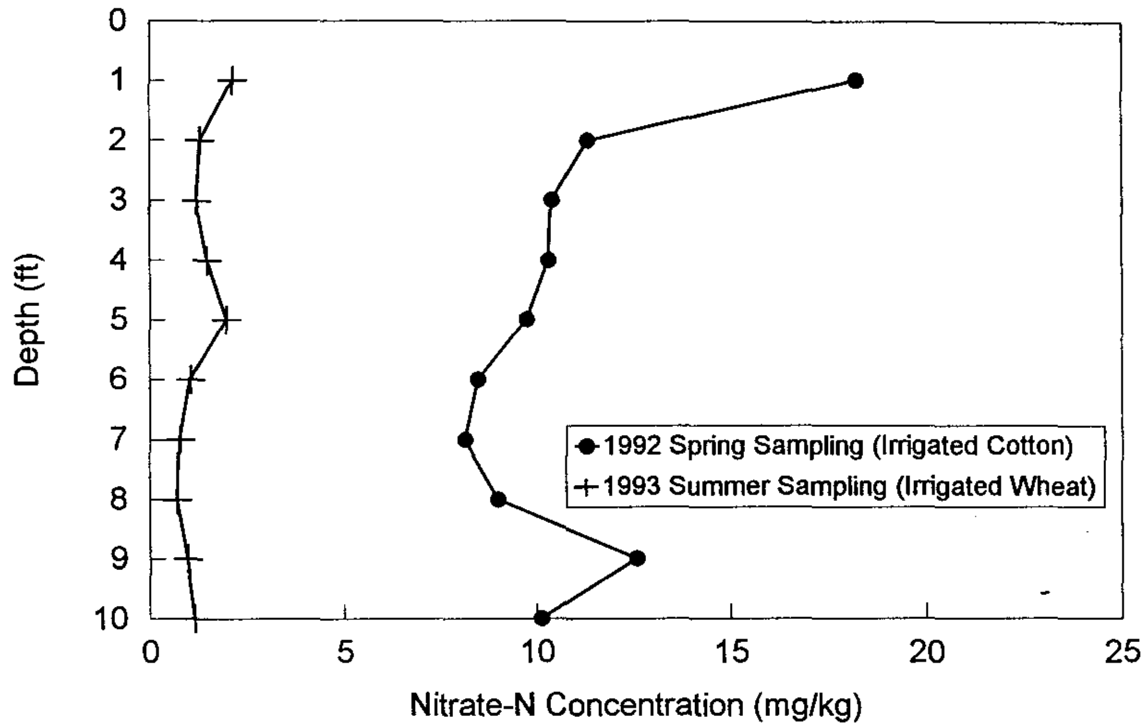

Figure 12a. Soil nitrate-N profiles in Field 1 during 1992 and 1993 sampling.

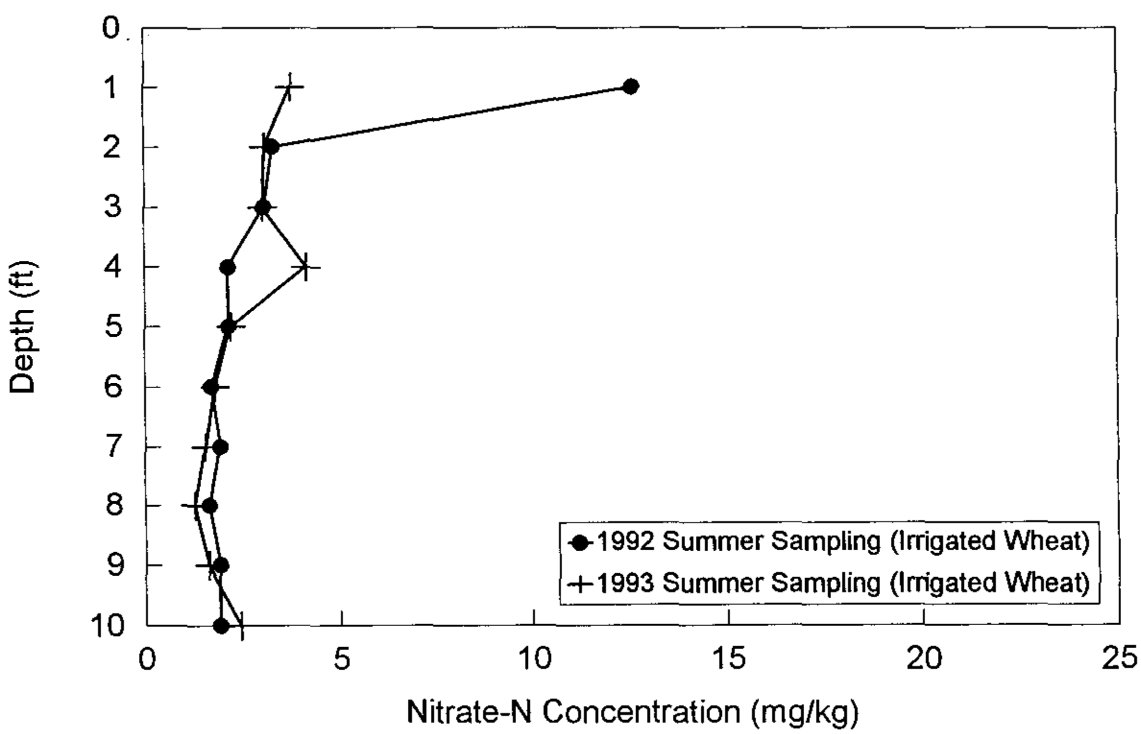

Figure 12b. Soil nitrate-N profiles in Field 2 during 1992 and 1993 sampling.

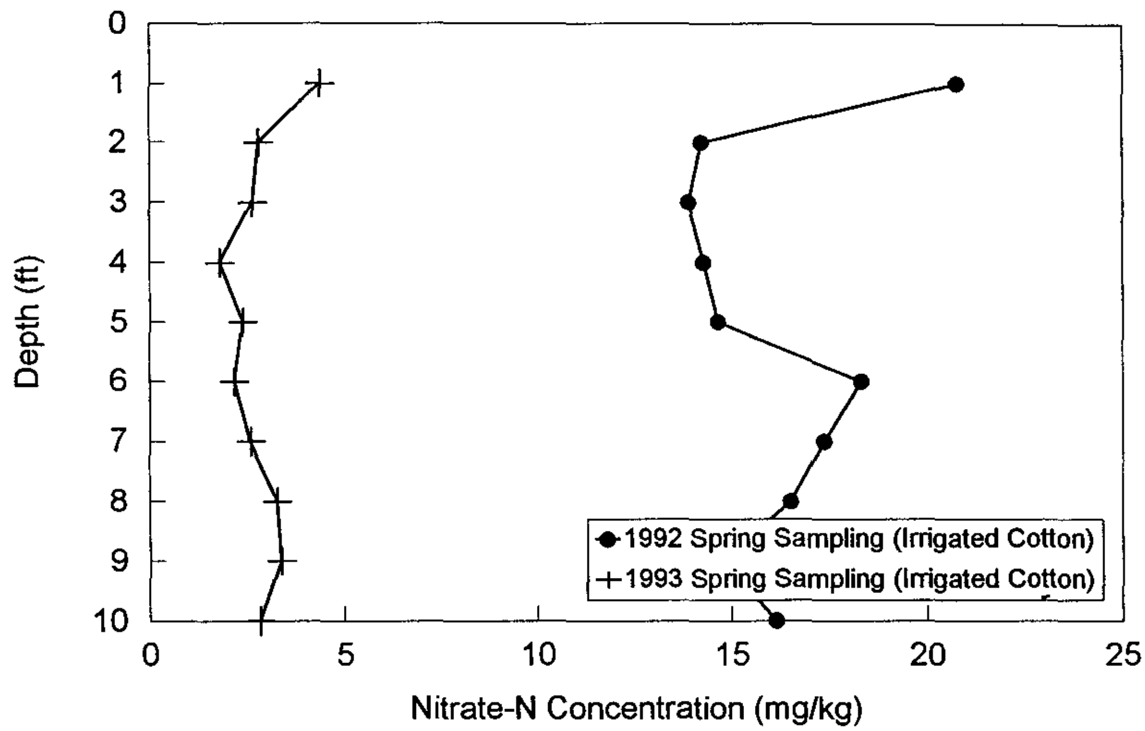

Figure 12c. Soil nitrate-N profiles in Field 3 during 1992 and 1993 sampling.

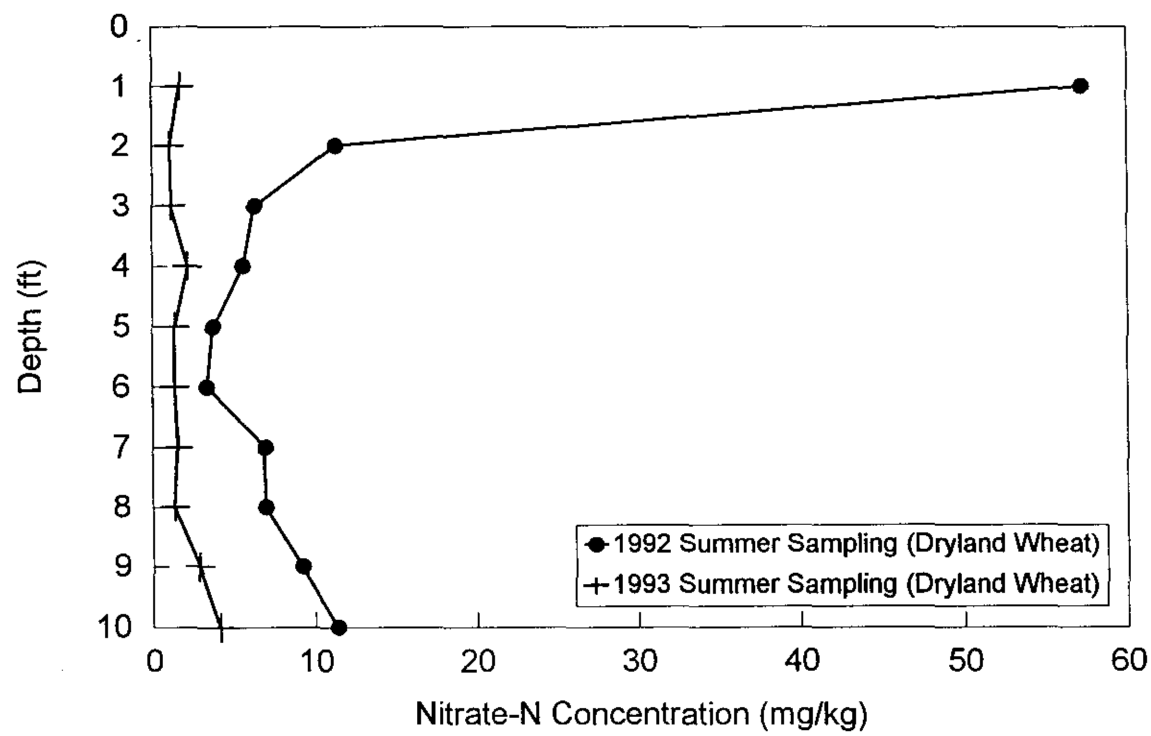

Figure 12d. Soil nitrate-N profiles in Field 4 during 1992 and 1993 sampling.

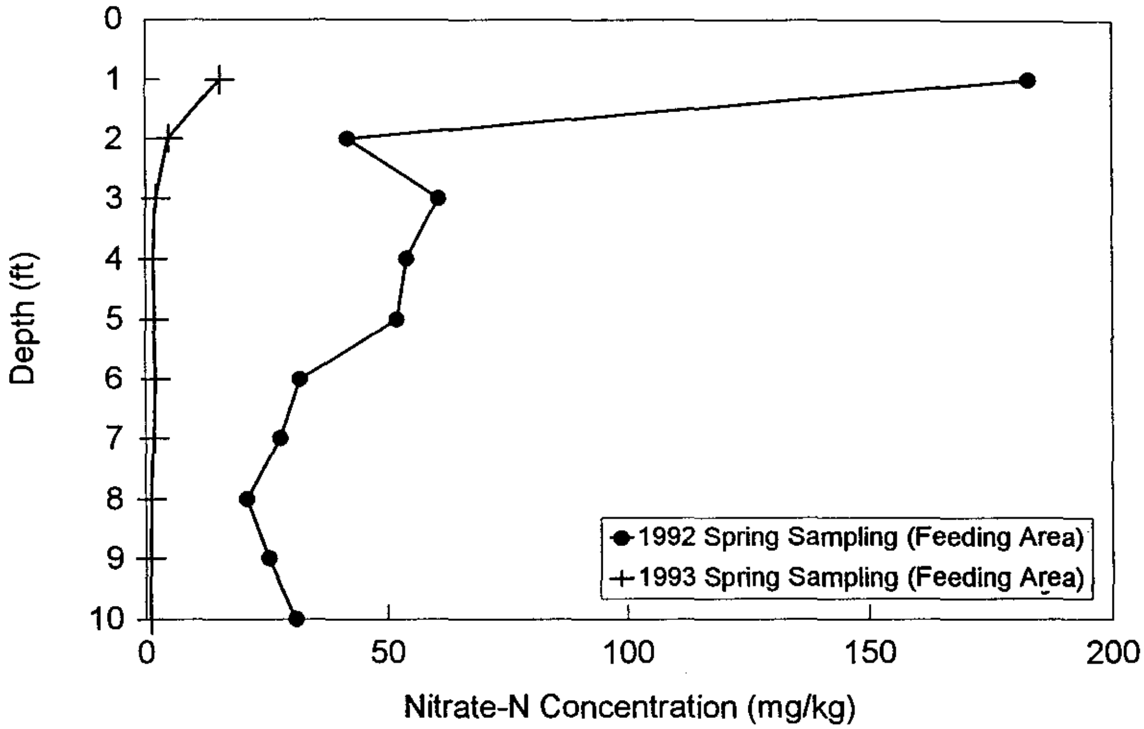

Figure 12e. Soil nitrate-N profiles in Field 5 during 1992 and 1993 sampling.

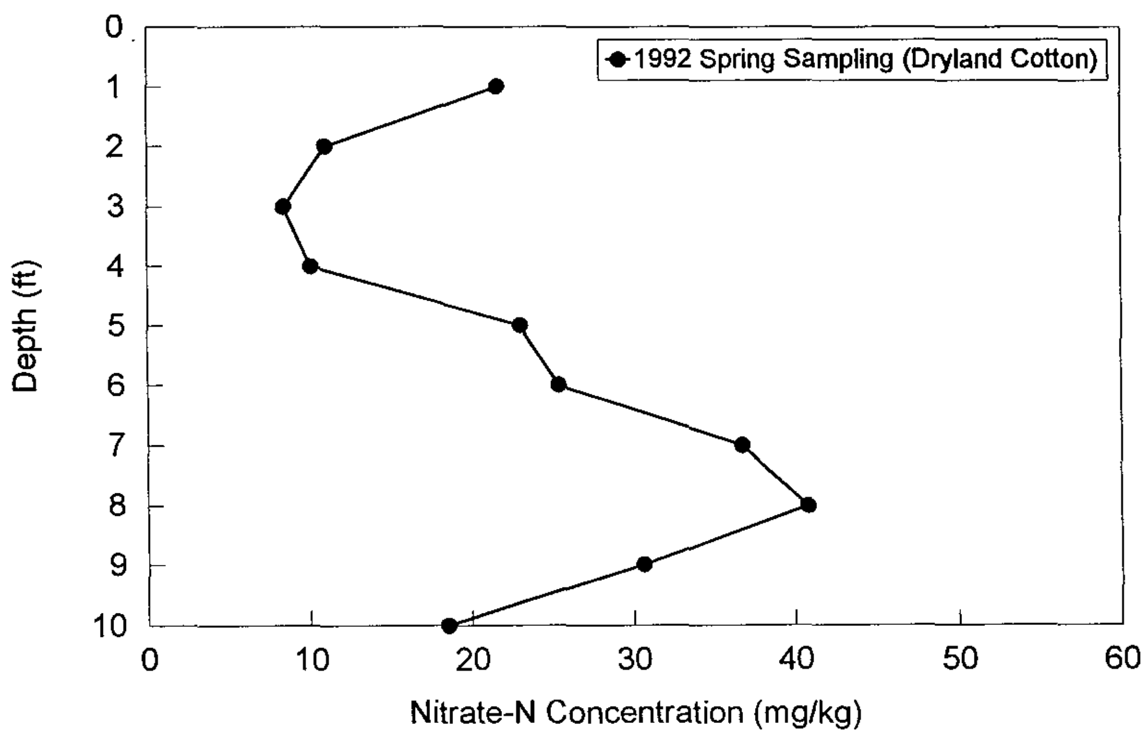

Figure 12f. Soil nitrate-N profiles in Field 6 during 1992 sampling.

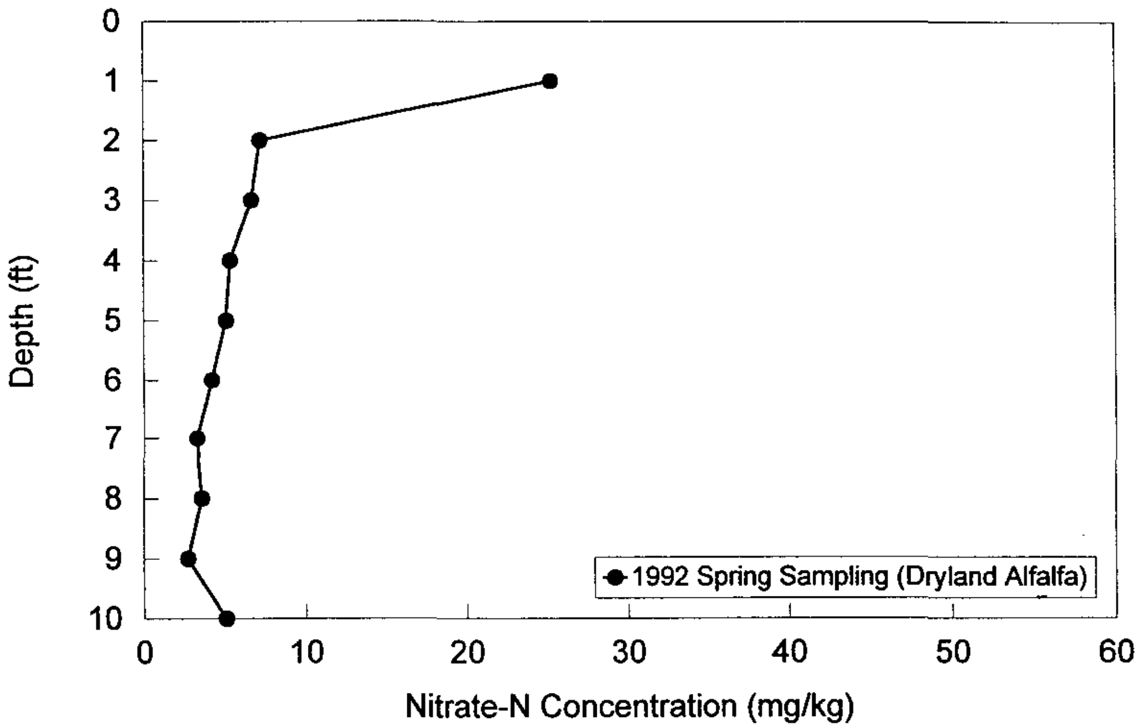

Figure 12g. Soil nitrate-N profiles in Field 7 during 1992 sampling

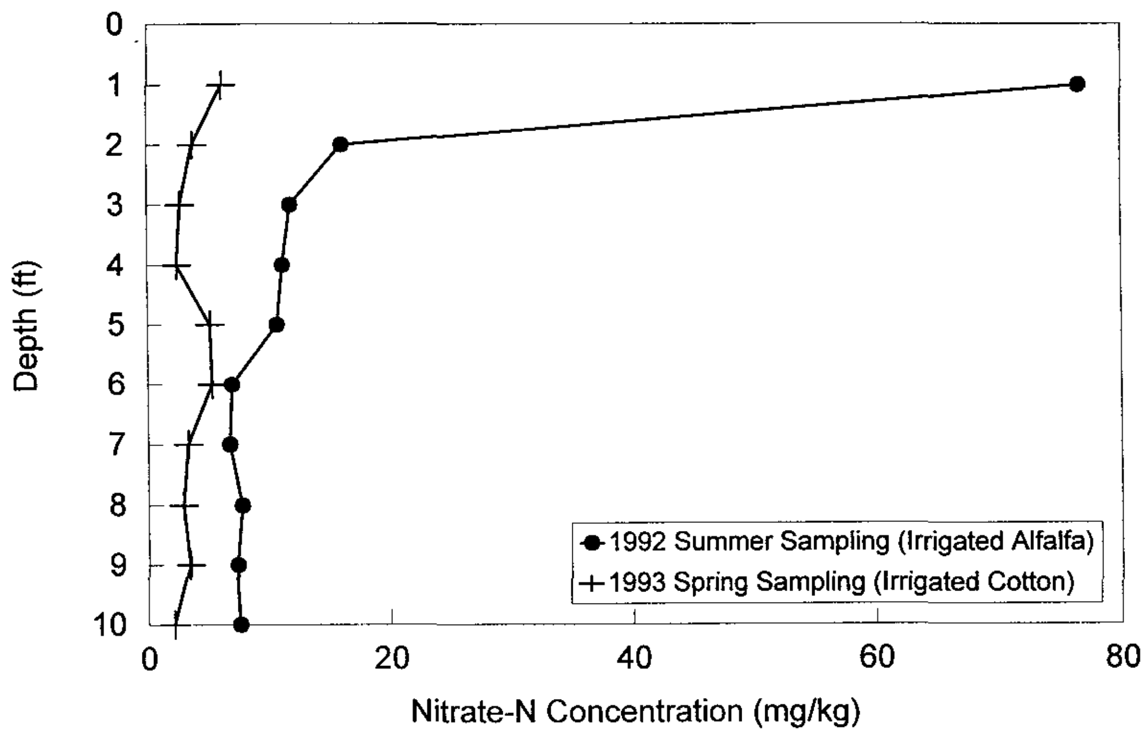

Figure 12h. Soil nitrate-N profiles in Field 8 during 1992 and 1993 sampling.

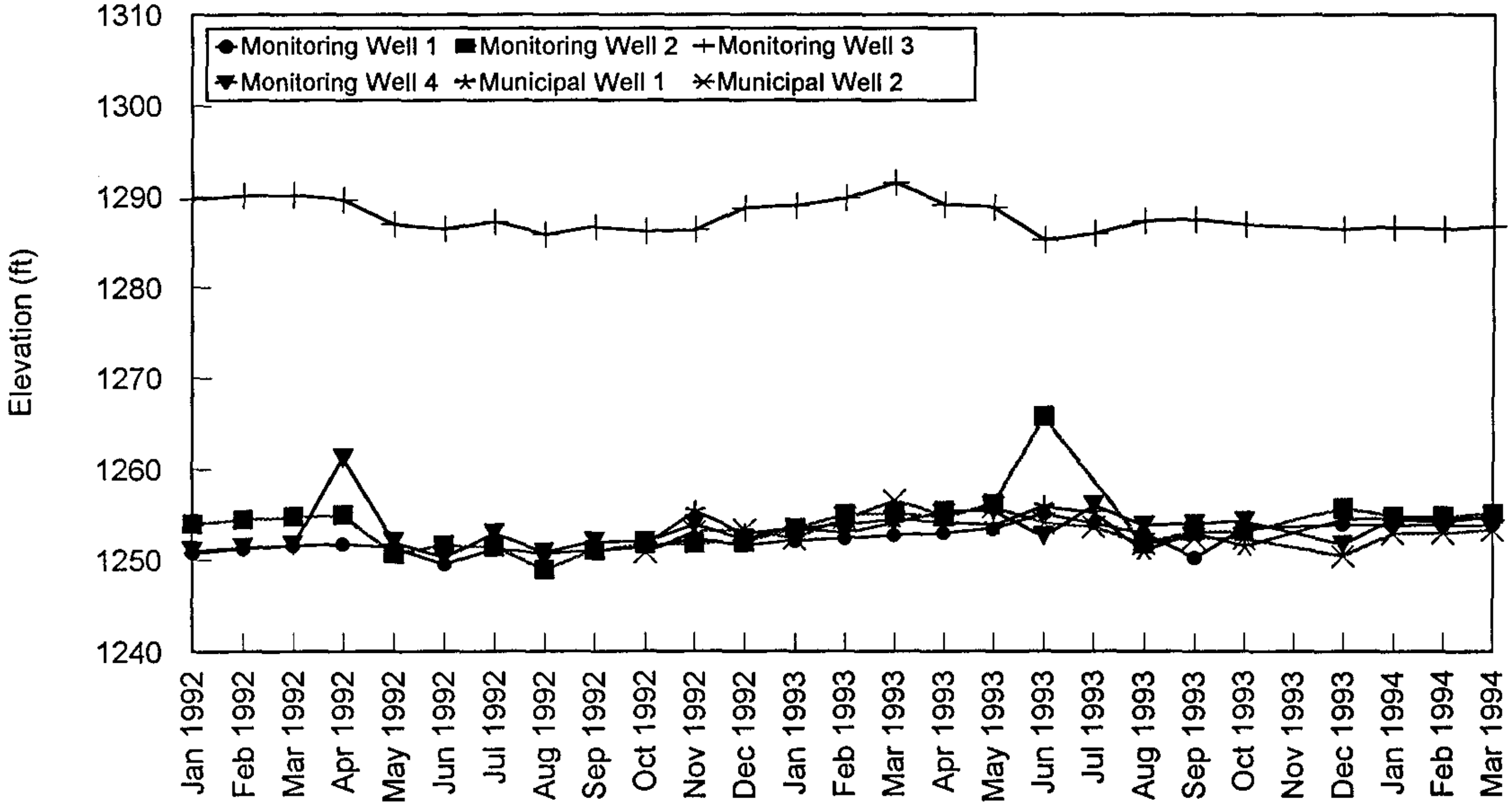

Figure 13. Monthly water table elevations recorded from the Tipton monitoring and municipal wells

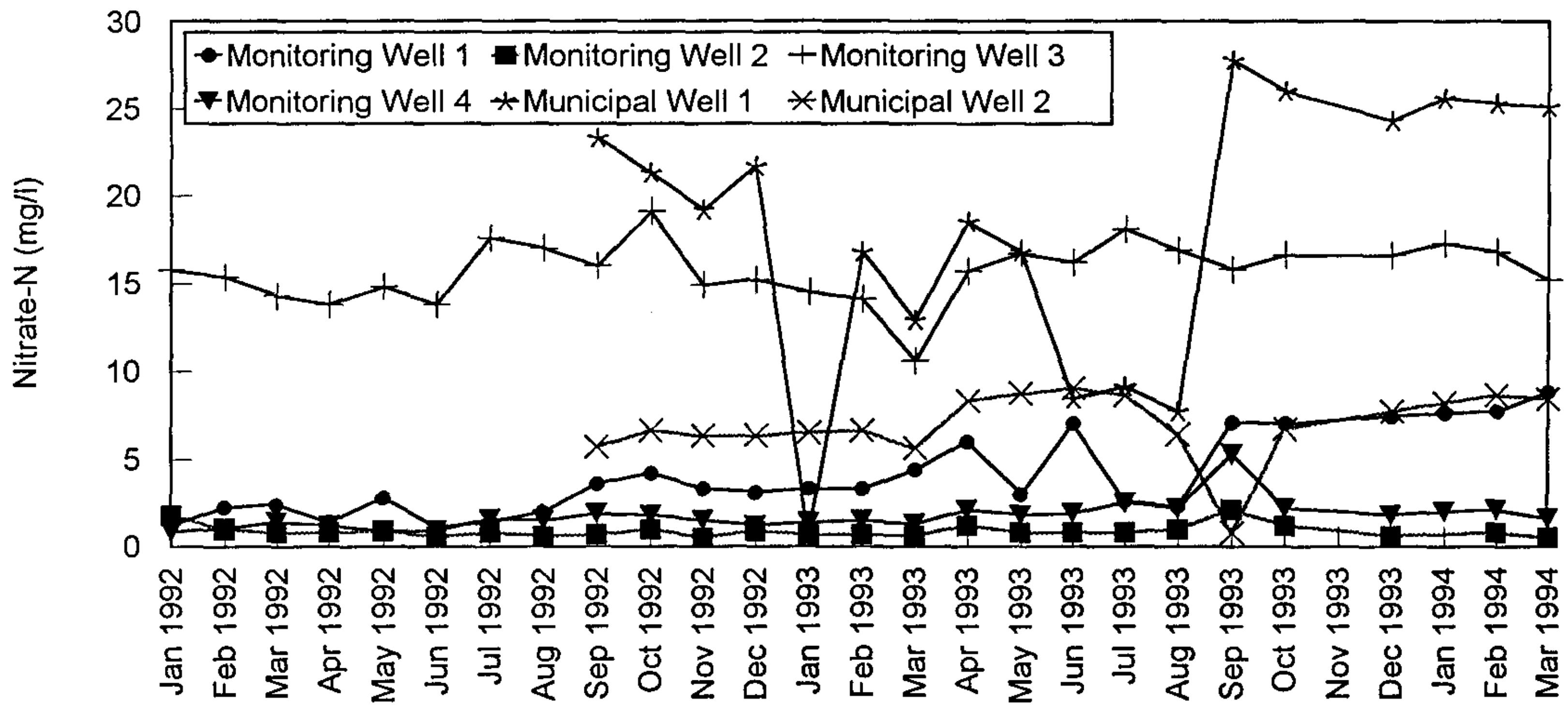

Figure 14. Nitrate-N concentrations observed in the monthly water samples from the Tipton monitoring and municipal wells

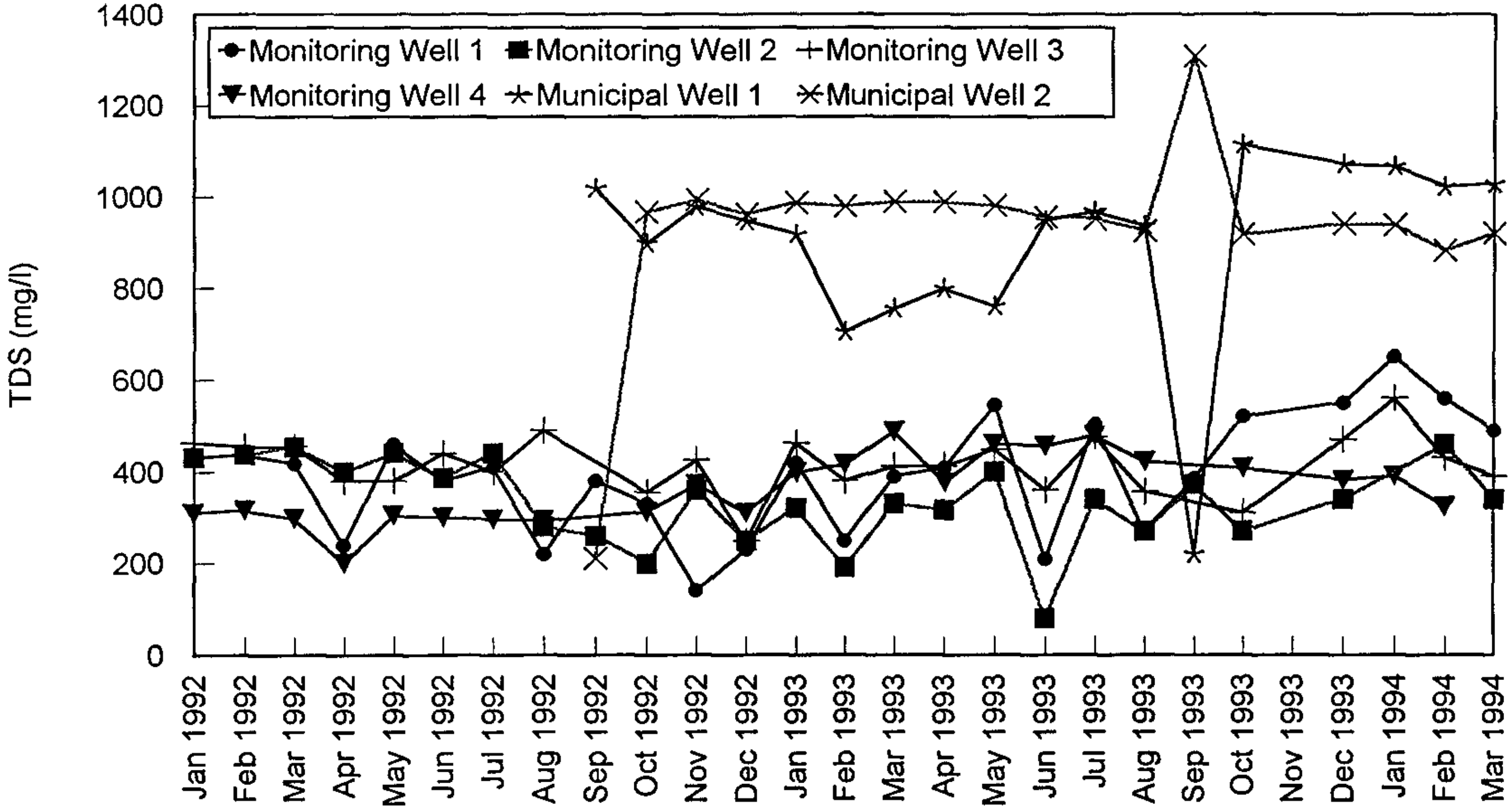

Figure 15. Monthly total dissolved solids (TDS) concentrations in the monthly water samples from the Tipton monitoring and municipal wells

APPENDIX - A

ASAE Paper No. 92-2036

Paper No. 922036
ASAE MEETING PRESENTATION

COMPARISON OF AN ANALYTICAL MODEL AND A NUMERICAL MODEL FOR DELINEATING WELLHEAD PROTECTION AREAS

by

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Daniel E. Storm, Assistant Professor
Michael D. Smolen, Associate Professor
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Stillwater, Oklahoma

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June 21-24, 1992

SUMMARY: Wellhead Protection Area (WHPA) was delineated for two municipal wells for the town of Tipton, Oklahoma using an analytical model, T-O-T and a numerical model, USGS-MOC. A well-field consisting of three irrigation wells and the municipal wells was considered for delineating the WHPA. The Zones of Contribution of the municipal and the irrigation wells within the well-field were found to overlap, indicating interactions between them. Temporal variations of pumping rates and hydrologic features in the system were incorporated into the numerical model. Comparison of the results of the models indicate that T-O-T under-estimated the WHPA when compared to USGS-MOC, due to the temporal variations of pumping rates and the hydrologic features.

KEYWORDS:

Wellhead, Time of Travel, Zone of Contribution, Up-gradient boundary, Down-gradient boundary.

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COMPARISON OF AN ANALYTICAL AND A NUMERICAL MODEL FOR DELINEATING WELLHEAD PROTECTION AREAS[1]

By

T. S. Ramanarayanan, D. E. Storm, M. D. Smolen, M. A. Kizer[2]

Introduction

Groundwater is an important source of drinking water as it constitutes a major portion of the world's freshwater (Bower, 1978). Non-point source pollution of groundwater systems has become an important concern in recent years as it poses a major problem. This led to the intensification of investigations on the causes and sources of pollution. In 1986 the Safe Drinking Water Act (SDWA) was amended to provide federal assistance to states to develop wellhead protection programs.

Wellhead protection is protecting the area surrounding a well or well-field, and thus this area is called as Wellhead Protection Area (WHPA). According to SDWA, WHPA is defined as the surface and subsurface surrounding a well or a well-field that supplies a public water system through which contaminants are likely to pass and eventually reach the water well or well-field (USEPA, 1987). Meyer (1990) stated three possible management objectives for WHPA; (a) Maintenance of remediation zone, (b) maintenance of attenuation zone and (c) maintenance of well-field management zone. Meyer also states that when there are many sources of contaminants in the WHPA, well-field management may be more practical.

Mapping of the area under the WHPA is referred to as delineating the WHPA (USEPA, 1987). According to USEPA (1987), there are several criteria to delineate WHPA, including time of travel, distance, drawdown and flow boundaries. Analytical methods are commonly used for delineation of WHPA since they are simple and require few details. Numerical methods, on the other hand are costly to adopt but are the least restrictive and can incorporate many complex hydrologic features. Also the temporal variations in the system can be included satisfactorily.

Analytical Method of Delineating WHPA

Flow boundaries are defined such that all points within the boundary contribute water to the well and the up-gradient boundary is determined by the Time of Travel (TOT). The down-gradient divide and the width of the WHPA, called the Zone of Contribution (ZOC), are determined by uniform flow equations (Fig. 1). The equations for uniform groundwater flow to

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[1]Paper No. PP3730 of the Agricultural Experiment Station, Oklahoma State University, Stillwater, Oklahoma. This research was supported in part by a grant from the USEPA and the Oklahoma Conservation Commission. The use of trade names in this publication does not imply endorsement by Oklahoma State University of the products named not criticism of similar products not mentioned.

[2]Graduate Research Assistant, Assistant Professor, Associate Professor and Assistant Professor, Agricultural Engineering Department, Oklahoma State University, Stillwater, OK 74078

a single pumping well system are utilized for determining the flow characteristics around a pumping well (USEPA, 1987). The down-gradient divide is calculated from the equation:

$$X_L = -\frac{Q}{2\pi Kbi} \tag{1}$$

where Q is the pumping rate of the well [L^3/T], K is the hydraulic conductivity of the area surrounding the well site [L/T], b is the length of the screened interval of the well [L], i is the hydraulic gradient [L/L], and X_L is the distance from the pumping well to the down-gradient divide [L]. The limit of the flow boundary, Y_L [L], is defined as (USEPA, 1987):

$$Y_L = \pm\frac{Q}{2Kbi} \tag{2}$$

The flow boundary defining the ZOC is given by (USEPA, 1987):

$$X = -\frac{Y}{\tan(Y/-X_L)} \tag{3}$$

where X and Y are points on the boundary of the ZOC.

Equations 1, 2 and 3 define the ZOC around a well. But the up-gradient boundary of the ZOC can extend to a very large distance. Therefore the up-gradient boundary of WHPA is estimated using time of travel criteria. TOT is estimated for the aquifer using the pore velocity equation which is the Darcian velocity divided by aquifer porosity. The pore velocity depends on (a) the regional water gradient and (b) the local gradient near the well due to pumping. Time of travel is calculated by (USEPA, 1987)

$$TOT = v_r t + v_p t \tag{4}$$

where v_r is the regional velocity [L/T], v_p is velocity near the well due to pumping [L/T], TOT is the distance the groundwater would have travelled in time t [L].

Based on the above equations, a computer model called "T-O-T" for delineating WHPA was developed by Fabian and Summers (1991). T-O-T is a menu-driven, user-friendly program for defining WHPA for a single pumping well. An iterative algorithm is used to calculate the time of travel. So the model can also be termed a semi-analytical model. The program uses USEPA recommended criteria and methods to delineate WHPA, assuming ideal uniform conditions. Hence it cannot include temporal variations of pumping rates and hydrologic features in the system which may have a significant impact on the WHPA. When the WHPA has to be delineated for multiple wells, individual WHPAs may be superimposed over each other on the base map.

Numerical Method of Delineating WHPA

Traditionally many numerical groundwater flow models were developed to characterize groundwater systems (Konikow and Bredehoeft, 1989; Prickett and Lonnquist 1971; Pinder and Bredehoeft 1968). USGS - Method of Characteristics (USGS-MOC) developed by Konikow and Bredehoeft (1989) is a widely used two-dimensional transport model. This model uses a groundwater flow algorithm developed by Pinder and Bredehoeft (1968). The flow portion of the model uses the Alternating Direct Implicit algorithm to solve the finite difference approximation of groundwater flow equations, and the transport portion uses Method of Characteristics.

To delineate WHPA, only the flow portion of the model is required. The temporal variations in pumping rates of the wells can be incorporated in the model. Also, hydrologic features such as rivers, can be included in USGS-MOC. In a steady system the ZOC will remain constant. But in an unsteady system the ZOC will change with time, and the simulations have to be carried out for 10 years, which is the standard time of travel criteria for delineating the up-gradient boundary of the WHPA (USEPA, 1987).

Description of the Study Area

Tipton, a small town in the southwestern part of Oklahoma, is located over the alluvial terrace deposits of the North Fork of the Red River. The aquifer is called the Tillman Terrace aquifer (Fig. 2), and a detailed description was given by Kent (1978) and Al-Sumait (1978). There are two municipal wells supplying drinking water to Tipton. Surrounding the municipal wells are three major irrigation wells which operate only during parts of the year. The pumping from these irrigation wells may influence the transport of contaminants to the municipal wells. In the past few decades the nitrate-nitrogen (NO_3-N) content in the two municipal wells were observed to exceed the EPA drinking water standards of 10 ppm (Fig. 3a and 3b). In such cases the reasons for the increase in the NO_3-N content in the groundwater is not only attributed to the agricultural activities but also to the domestic gardening and other activities in the urban areas (Johnson, 1991). This problem can be solved by delineating a WHPA around the wells and introducing best management practices for agricultural and other activities within the WHPA.

Input Parameters

Input parameters describing the groundwater system are listed and described briefly in this section. Al-Sumait (1978) and Kent (1978) modeled the Tillman aquifer using a two-dimensional groundwater flow model. Aquifer characteristics such as hydraulic conductivity, storage coefficient and recharge rates, determined by Al-Sumait (1978) were adopted for this study.

The water table map was prepared from the data collected by Oklahoma Water Resources Board in January 1992 (Fig. 4). From the map regional groundwater gradient was determined. The saturated thickness of the unconfined aquifer is approximately 15 m (50 ft) (Kent, 1978; Al-Sumait, 1978). From the results of pumping tests and calibration of computer model (Kent, 1978;

Al-Sumait, 1978), the hydraulic conductivity of the aquifer material was determined as 13.6 m/d (46 ft/d). The storage coefficient of 0.22 was determined from the storage coefficient map prepared by Al-Sumait (1978). The pumping rates for the municipal wells were estimated from the actual pumping rates (from May 1991 to January 1992) obtained from the town of Tipton. The average pumping time per day was assumed as ten hours. The pumping rates for the irrigation wells within the well-field were taken as 50% of the recommended irrigation requirement of the crop irrigated by the wells. The distribution of the pumping rates are shown in Fig. 5. The average recharge rates from the surface to the groundwater table was determined from the recharge map prepared by Al-Sumait (1978). The recharge rates for the irrigated fields within the study area was assumed to be 15% of the applied irrigation (Kent, 1978). Tables 1 and 2 show the input parameters used in T-O-T and in USGS-MOC.

Table 1: Input Parameters used in T-O-T and USGS-MOC

Parameter	T-O-T	USGS-MOC
Hydraulic Conductivity	13.81 m/d	13.81 m/d
Saturated Thickness	15 m	15 m
Aquifer Porosity	0.22	0.22
Storage Coefficient	0.22	0.22
Reg. Hydraulic. Gradient	0.004	0.004
Regional Recharge Rate	None	0.0017 m/d
Cropped Area Recharge Rate	None	15% of irrgn.

Table 2: Pumping Rates (m^3/d) of the Wells in the Well-field

	Municipal Wells		Irrigation Wells		
Period	1	2	1	2	3
Jul.-Sept. (92 days)	206	206	602	498	738
Oct.-Mar. (181 days)	165	165	-	-	-
Apr.-Jun. (92 days)	214	214	-	296	-
Average for the year	188	188	602	200	738

Results and Discussions

Using T-O-T the WHPAs for individual wells within the well-field were delineated and then superimposed to get the composite WHPA for the well-field (Fig. 6b). The pumping rates for the municipal wells were averaged over the whole year and maximum pumping rates were chosen for the irrigation wells (Table 2). The WHPAs for the individual wells in the well-field (Fig. 6a) show that the ZOCs of the irrigation wells overlap with the municipal wells. The ZOC for the well-field predicted by T-O-T extends up to 600 m (2000 ft) in the down-gradient direction. The width of the ZOC is 900 m (3000 ft) in the direction perpendicular to the direction of flow. The ten-year time of travel, delineated for the well-field extends up to 1200 m (4000 ft) up-gradient from the well-field. The WHPA delineated by T-O-T includes only a part of the town of Tipton.

In USGS-MOC, the pumping rates for the individual wells were incorporated with their temporal variations. Three time periods were chosen (Table 2) which were based on the cropping pattern in the area irrigated and the changes in the pumping rates of the municipal wells. The North Fork of the Red river, a hydrologic feature which could not be included in T-O-T, was included in USGS-MOC. Simulations were carried out for 10 years and a final water table map after ten years of pumping was prepared (Fig. 7). The ZOC for the well-field was determined based on the flow lines drawn on the water table map (Fig. 8). The ZOC delineated from the results of USGS-MOC, extends up to 1500 m (5000 ft) in the down-gradient direction with a width of about 4500 m (15,000 ft).

WHPA and ZOC delineated by T-O-T and USGS-MOC are shown Fig. 9. The inclusion of the temporal variations of the pumping rates in USGS-MOC, extended the WHPA down-gradient to about 300 m (1000 ft) farther than predicted by T-O-T. This can be attributed to the influence of the recharge from the North fork of the Red river which was included in USGS-MOC. Fig. 8 shows that a major portion of the town of Tipton is included in the WHPA delineated using USGS-MOC.

Conclusions and Recommendations

If there are wells with comparable pumping rates near the wells in question, it is necessary to include all the wells in the analysis as a well-field. T-O-T shows that the ZOCs for the irrigation wells and the municipal wells overlap. This indicates that pumping from the irrigation wells will influence the transport of contaminants to the municipal wells.

In areas where there are significant temporal variations in pumping and recharge rates and complex hydrologic features, a numerical model is recommended to delineate WHPA. When average uniform pumping rates were used in T-O-T, the extent of the WHPA was under-predicted, when compared to the results of USGS-MOC. The North Fork of the Red river which could not be included in T-O-T was found to influence recharge to the well-field.

Apart from introducing best management practices to the farming community, the urban community of Tipton may also be introduced to appropriate management practices for their domestic gardens. The WHPA delineated by using USGS-MOC included a major portion of the town of Tipton. So it can be concluded that the urban community also contribute to the contamination of the municipal wells.

Summary

The WHPA was delineated for two municipal wells located in the Tillman aquifer near Tipton, Oklahoma using an analytical model, T-O-T, and a numerical model, USGS-MOC. T-O-T does not have the provision to include temporal variations in the pumping rates of the wells and also complex hydrologic features. There are three major irrigation wells in the surroundings of the municipal wells. Pumping from these irrigation wells may influence the transport of contaminants to the municipal wells. Therefore for delineating the WHPA, a well-field including the irrigation wells was considered instead of the municipal wells alone.The pumping rates of the wells within the well-field had significant temporal variations (Fig. 5). The North Fork of the Red river, has some influence on the recharge to the well-field. Both of these features were included only in USGS-MOC. Due to these factors there is a major difference in the WHPA delineated by both the models. From the results of this study it is concluded that, all the interacting wells nearby the wells in question should be included as a well-field for delineating WHPA. Use of a numerical model is recommended in places where there are significant temporal variations in pumping rates and complex hydrologic features influencing the recharge to the wells.

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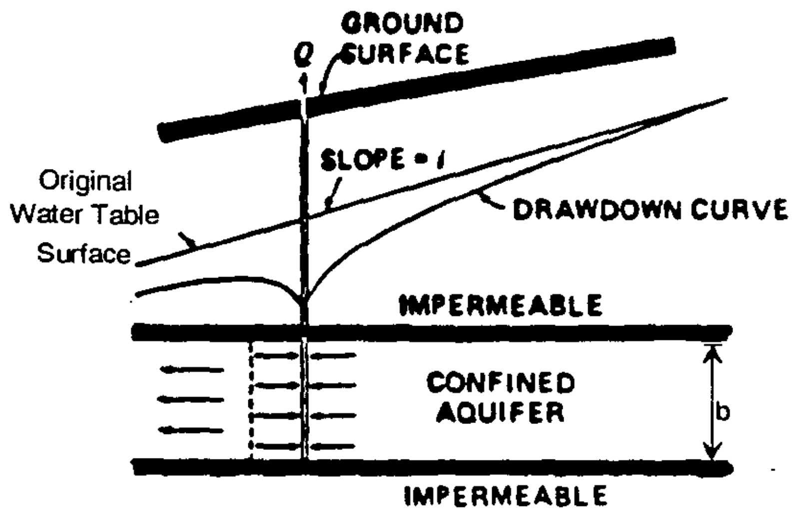
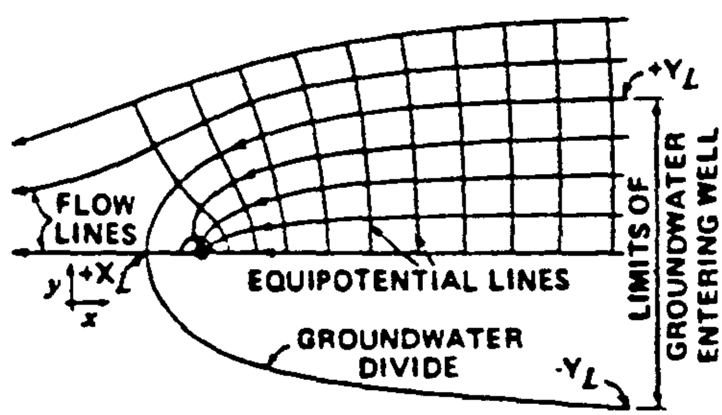
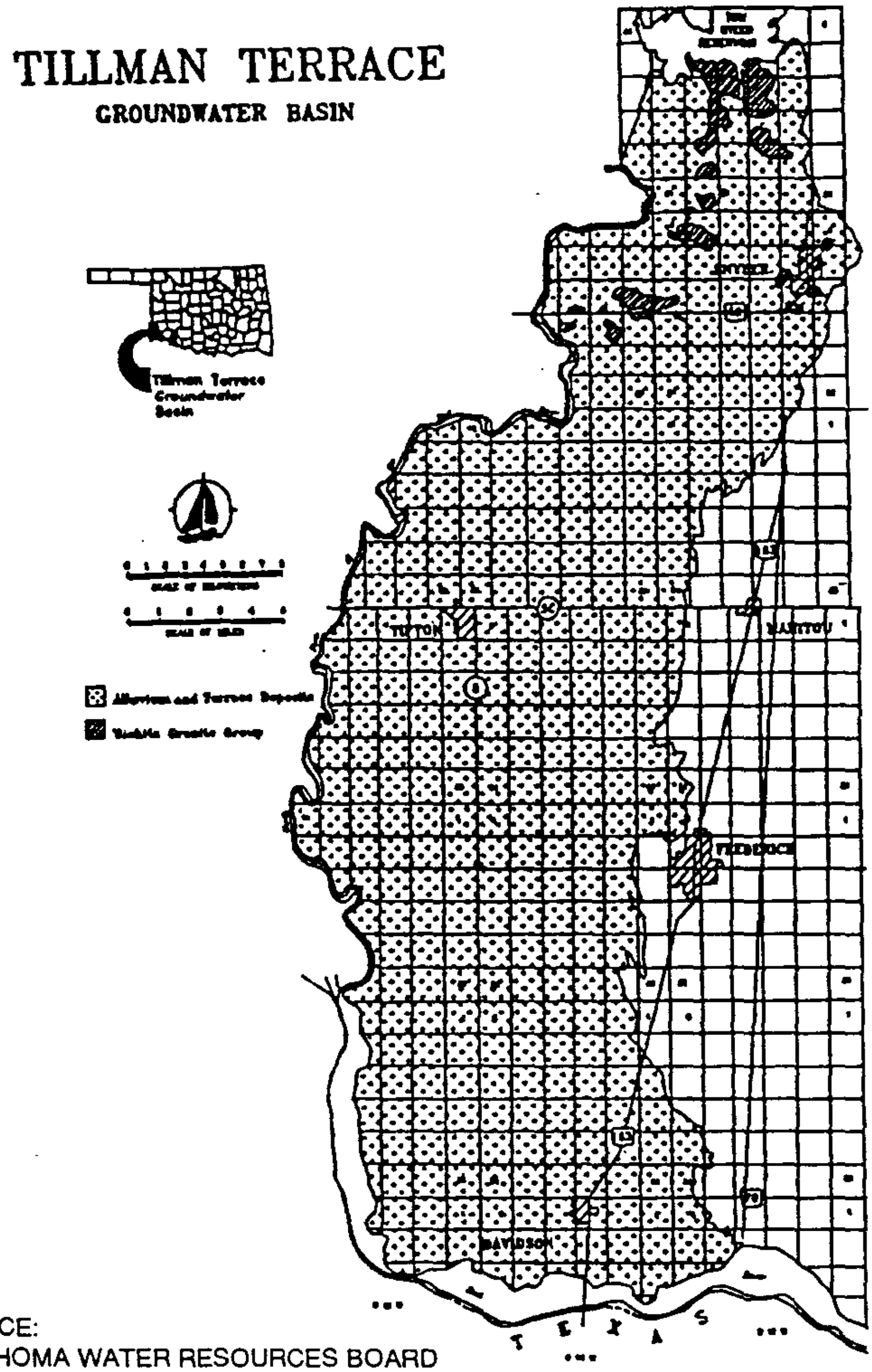


(a)



(b)

Fig. 1 Zone of Contribution for a Pumping Well (USEPA, 1987)



SOURCE:
OKLAHOMA WATER RESOURCES BOARD

Fig. 2 Map Showing the Tillman Terrace Aquifer

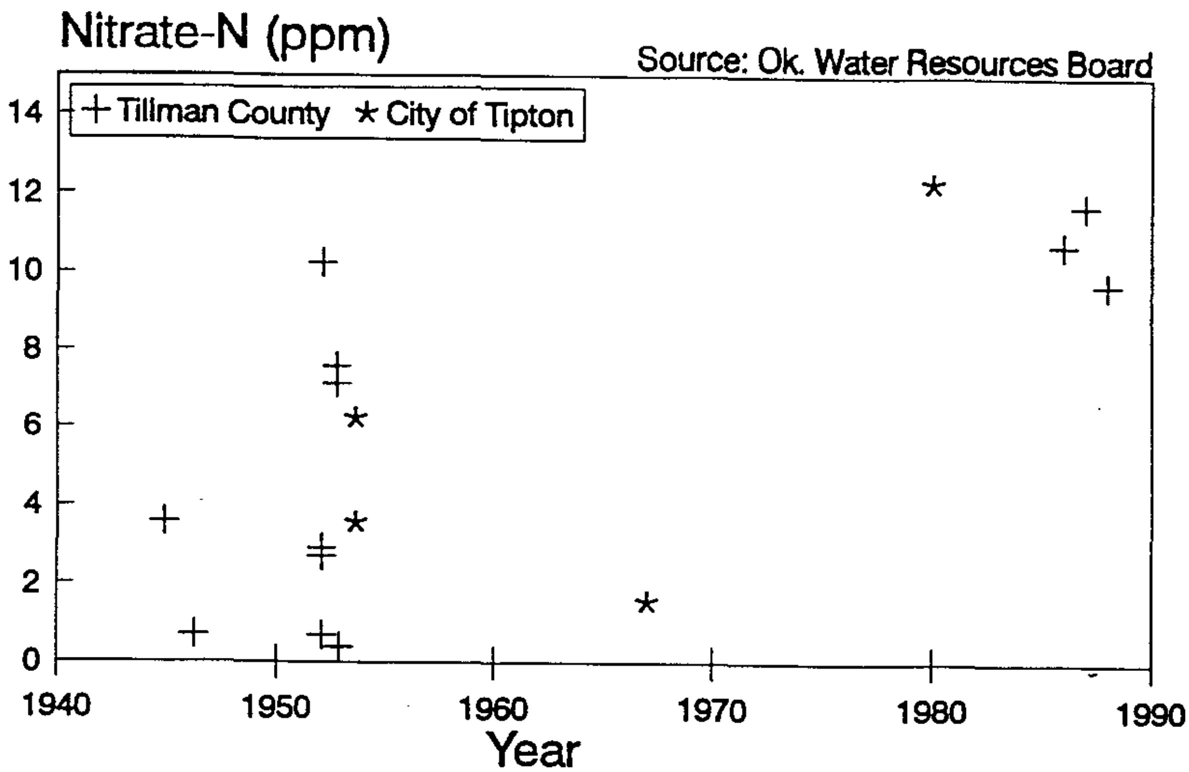


Fig. 3a: Historic Nitrate Levels in Tillman County, Oklahoma

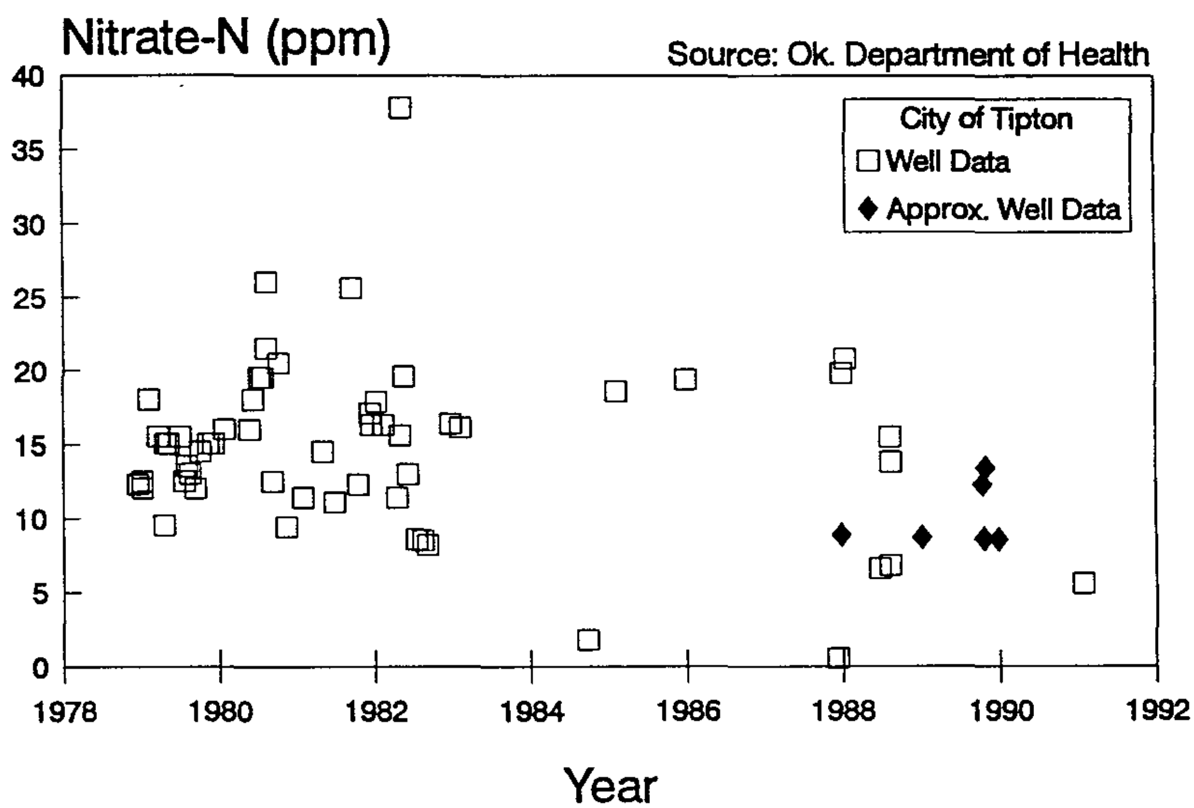
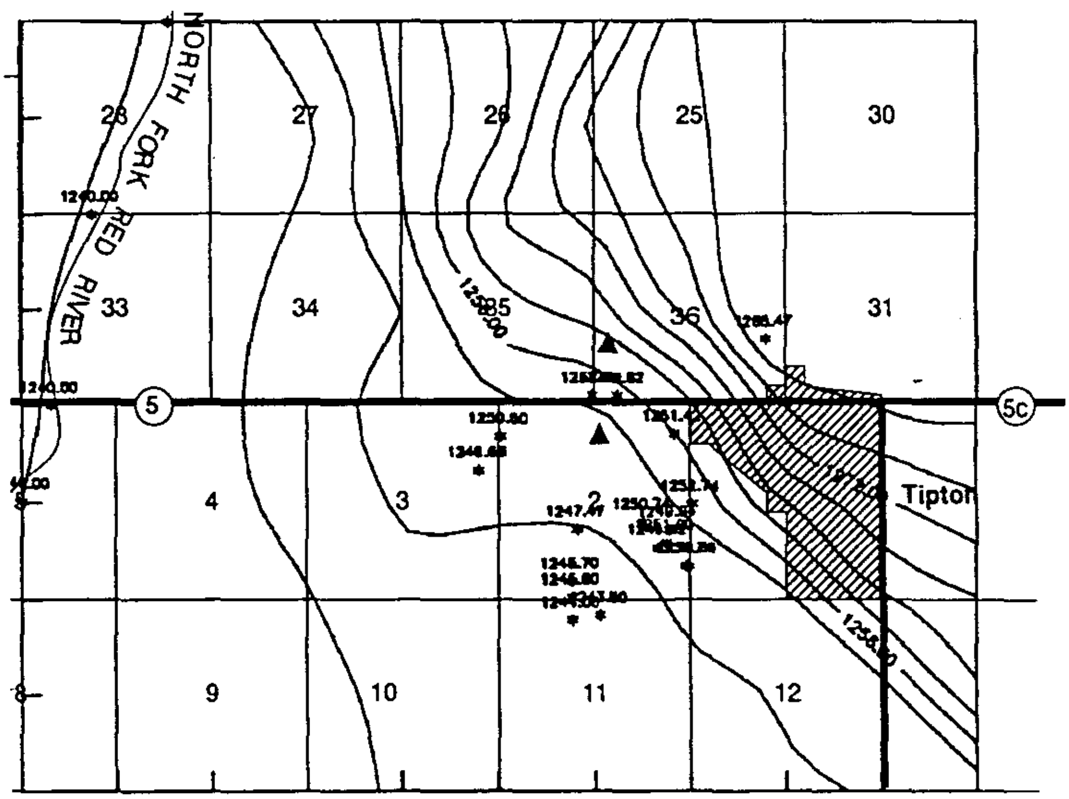


Fig. 3b: Historic Nitrate Levels in Municipal Wells, Tipton, Oklahoma



▲ Municipal Wells

Fig. 4: Water Table Map of the Study Area

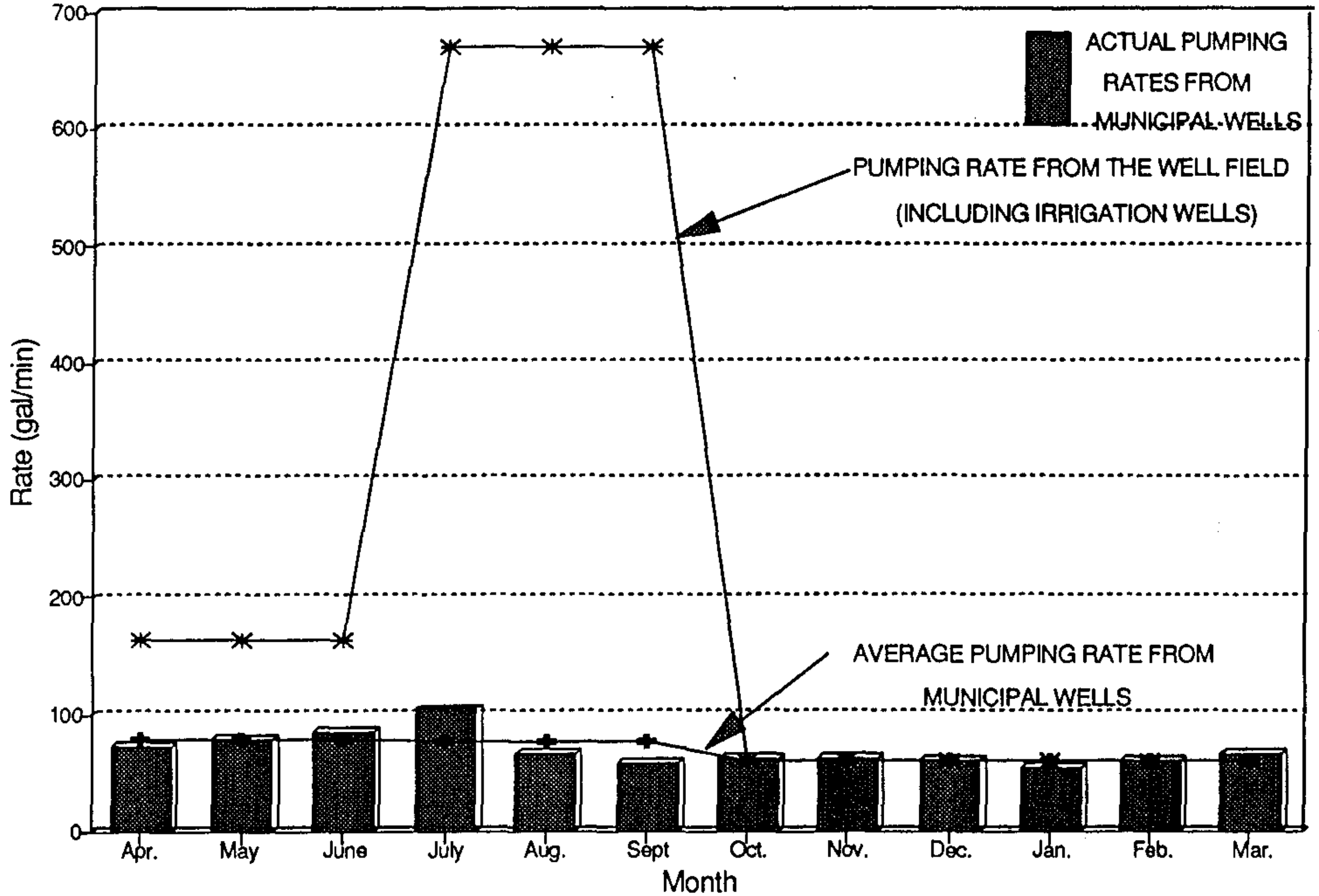


Fig. 5: Average Pumping Rates for Tipton Municipal Wells and Well-Field

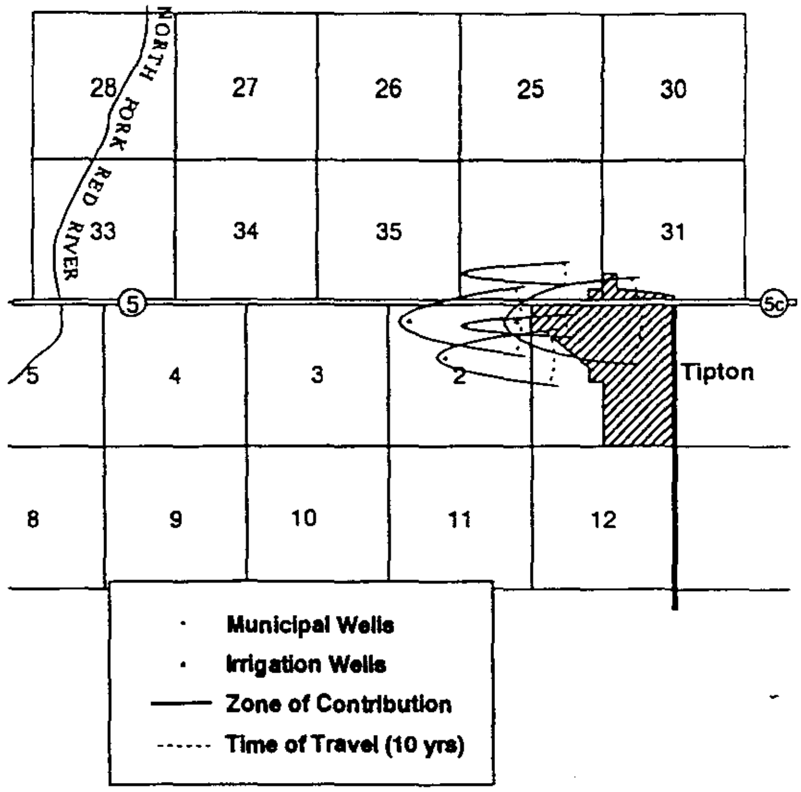


Fig. 6a: WHPA for Individual Wells Delineated by T-O-T

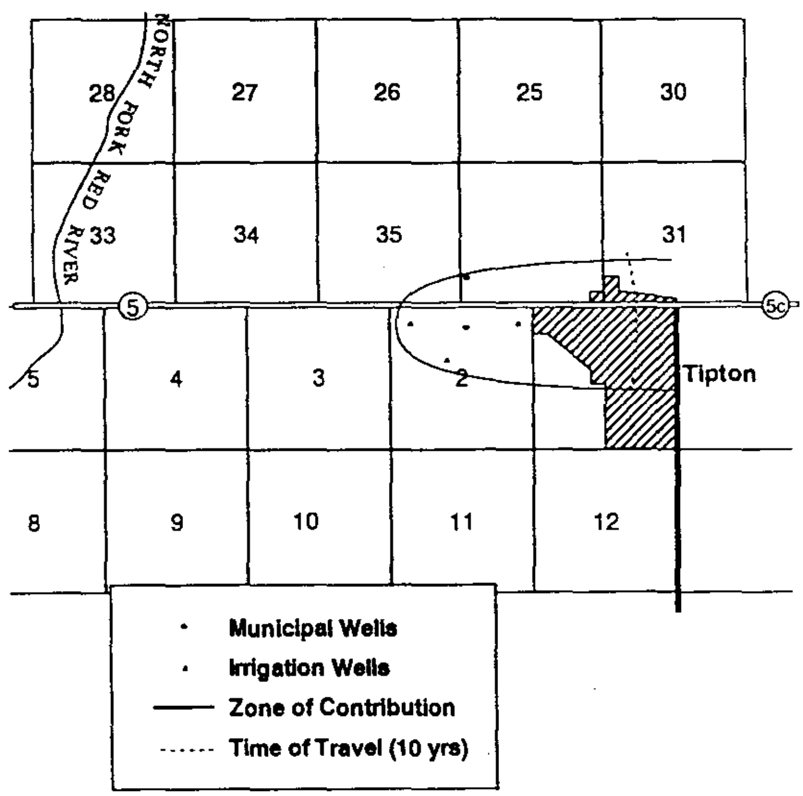


Fig. 6b: WHPA for Well-Field Drawn by Superimposing Individual WHPAs

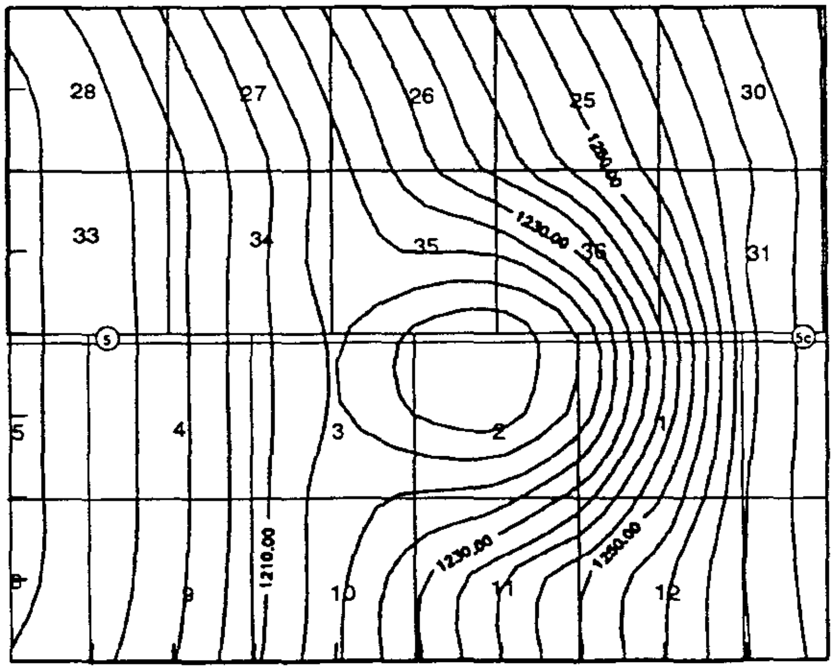


Fig. 7: Water Table Map After Pumping for Ten Years

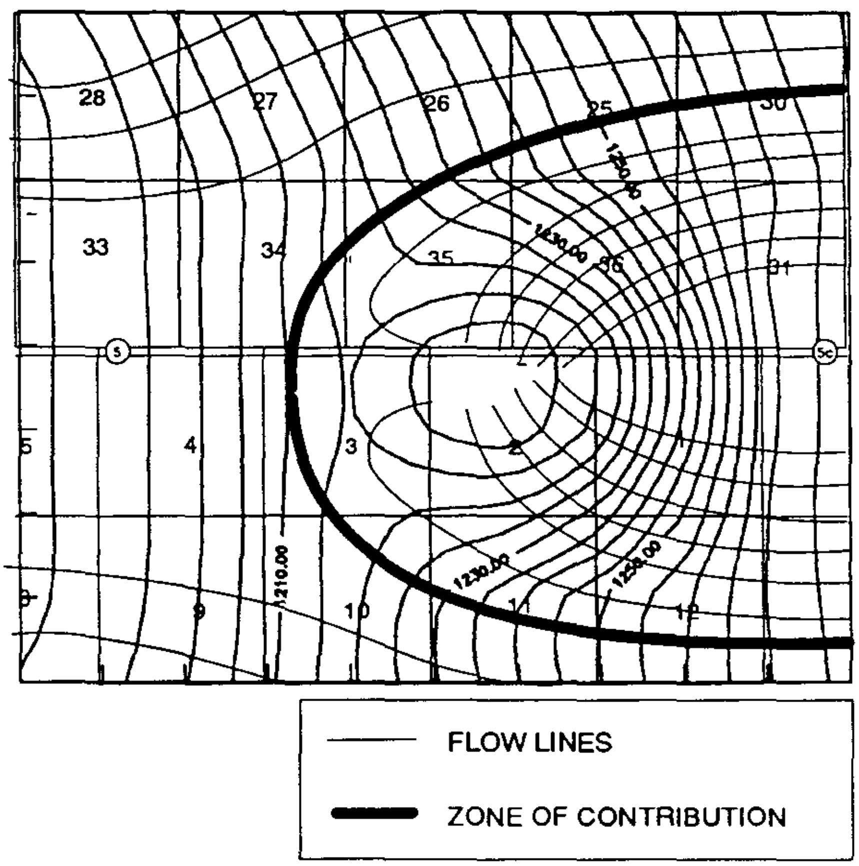


Fig. 8: Map Showing the Flow Lines and ZOC Delineated Using USGS-MOC

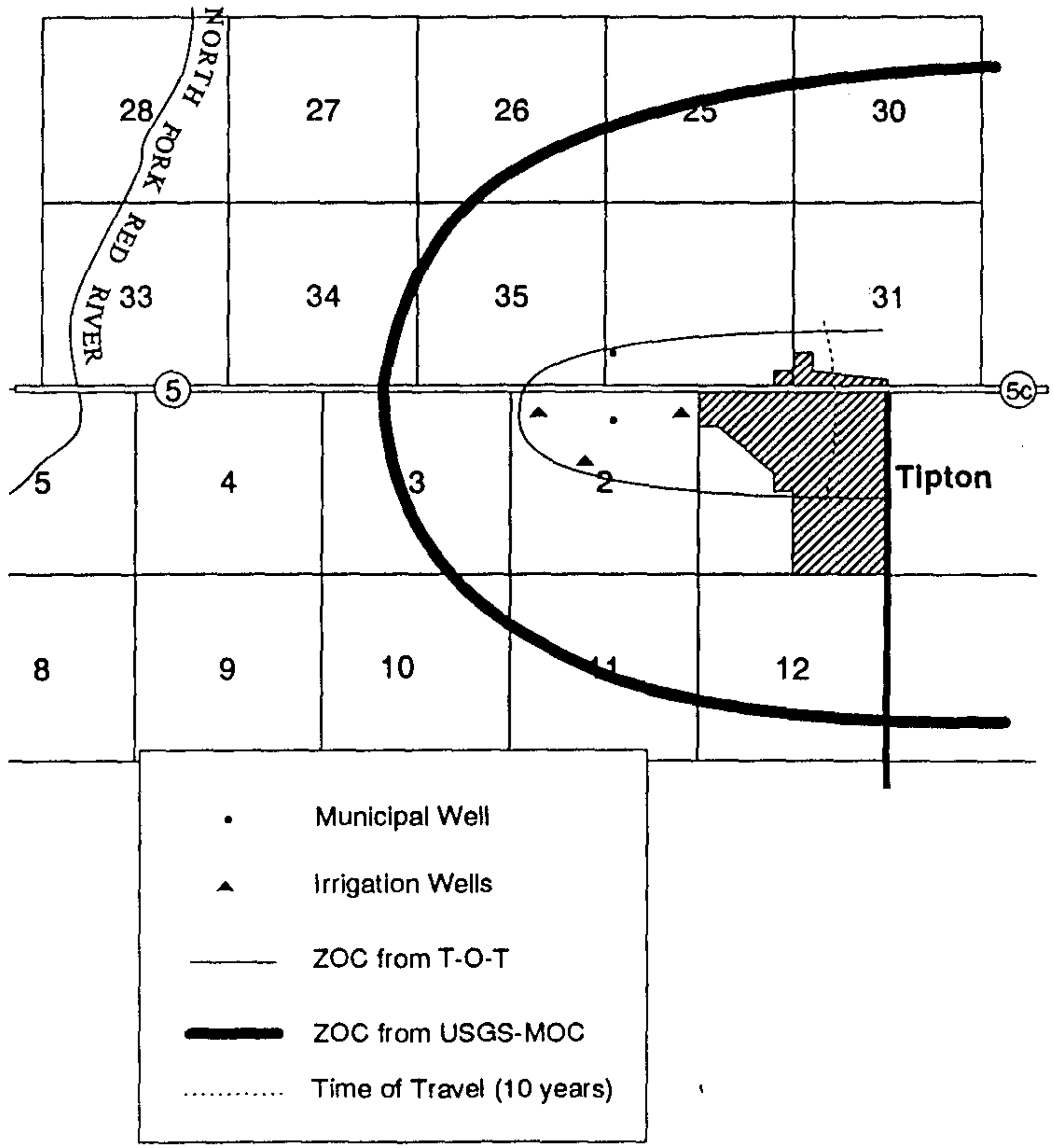


Fig. 9: Map Showing the ZOC Delineated Using T-O-T and USGS-MOC

APPENDIX - B

ASAE Paper No. 93-2086

Paper No. 932086
AN ASAE/CSAE MEETING PRESENTATION

SOIL NITRATE-N VARIABILITY AND DISTRIBUTION IN THE TIPTON WELLHEAD PROTECTION AREA

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SUMMARY: Spatial variability of soil profile NO_3-N present in selected fields within the Wellhead Protection Area (WHPA) of Tipton is studied. Representative irrigated and dry land fields of wheat, cotton and alfalfa along with a feedlot were sampled. Soils samples were taken at 0.3 m (1 ft) increments up to 3 m (10 ft) on a 150 m (500 ft) grid basis and were analyzed for NO_3-N using the modified Griess-Ilossvey method. The semivariogram and autocorrelation analysis showed no pronounced spatial relationships. Agricultural practices, fertility, and possibly water table fluctuations appear to be a major factor affecting the NO_3-N variability. The contour plots show high surface NO_3-N concentrations in irrigated alfalfa fields and high subsurface NO_3-N concentrations in irrigated cotton fields.

KEYWORDS: Nitrate, semivariogram, autocorrelation, correlogram, sampling

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Soil Nitrate-N Variability and Distribution in the Tipton Wellhead Protection Area[1]

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INTRODUCTION

Soil is a classical example of a physical feature exhibiting variability. The study of soil variability started when soils were first classified. In earlier years researchers like Reed and Rigney (1946) assumed that soil properties were independent with space, which is not true. Soil properties often exhibit spatial dependency. Researchers started analyzing variability over areas (Biggar and Nielsen, 1976), which were made on the basis of frequency distribution. But the knowledge of frequency alone does not provide all the information about the variability of the observation with respect to the neighboring observations (Vieira et al., 1981). Webster and Cuanalo (1975) analyzed the variations in clay, silt, pH, $CaCO_3$, color value and stoniness of three soil horizons across a Lower Jurassic outcrop of North Oxfordshire and used correlograms to describe the spatial dependency of these parameters. In that study the use of autocorrelation disclosed sampling intervals which had a repetitive nature and information on a minimum sampling density for which the observations remain correlated.

There is yet another popular method called geostatistics, to analyze spatial variability. This is an interpolation method introduced by Matheron (1963). This was initially developed from the Theory of Regionalized Variables (developed by Matheron and was later termed as geostatistics) for solving problems in mining and geology. Kriging interpolation is used to estimate unknown values within and beyond a site. Variogram construction is a necessity for kriging interpolation. Burgess and Webster (1980) applied semivariogram and kriging for analyzing data from a detailed soil survey in Central Wales and Northfolk. Vieira et al., (1981) studied the spatial variability of field-measured infiltration rate of a Yolo loam using 1280 measurements taken on nodes of a grid arrangement having 160 rows and 8 columns. The use of semivariograms in extrapolation and the use of autocorrelation for sampling schemes were presented.

Many researchers have recently used semivariograms and kriging to solve problems involving the analysis of variability in soils. However, few have studied the spatial variability of soil profile nitrogen. Studies which have examined the soil profile nitrogen characteristics are: (a) Spatial variability and correlation of soil nitrate and eight other related variables using geostatistics and cluster analysis in irrigated cotton field (Tabor et al., 1985), (b) Spatial variability of nitrate leaching characteristics in Gainesville, Florida (Flaig et al., 1986), (c) Spatial relationship of animal waste deposits in soils of grazing fields (West et al., 1989), (d)

[1]Research paper of the Agricultural Experimentation Station, Oklahoma State University, Stillwater, Oklahoma. This research was supported in part by a grant from USEPA and the Oklahoma Conservation Commission. The sampling for this study was conducted by the Soil Conservation Service and the Tillman County Extension Service. The use of trade names in this publication does not imply endorsement by Oklahoma State University of the products named, not criticism of similar products not mentioned.

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Spatial and temporal variability of NO_3-N and estimation of minimum number of samples required to estimate mean NO_3-N value within prescribed confidence intervals (Hergert et al., 1992), and (e) Spatial variability and Geostatistical analysis of soil nitrogen forms in a continuously cropped wheat field in Oklahoma (Guertal, 1993). Tabor et al., (1985) used 0.2 m (8 in) soil samples, Flaig et al., (1986) analyzed soil water sampled using soil lysimeters, Hergert et al., (1992) and Guertal (1993) used 1.2 m (4 ft) soil samples. To date the spatial variability of soil profile nitrogen below 1.2 m (4 ft) remains undocumented.

In this paper the spatial variability of soil profile NO_3-N present in selected fields within the Wellhead Protection Area (WHPA) of Tipton municipal wells is studied. WHPA was delineated for Municipal wells of Tipton by the Oklahoma Water resources Board and Ramanarayanan et al., (1992). Tipton, a small town in southwestern Oklahoma, has intensive cropping of cotton, wheat and alfalfa. Fig. 1 shows the WHPA delineated by Ramanarayanan et al., (1992). For many fields in the WHPA the water table fluctuates from approximately 3 m (10 ft) to 1.5 m (5 ft) below the ground level. The soils in the Tipton area are characterized as deep, nearly level to moderately steep, loamy and sandy soils that have a loamy subsoil. The selected fields are composed of Tipton fine sandy loam and Tipton loam soils with 1 - 3 percent slopes.

To study and characterize the nitrate status of different fields, sampling was conducted on a grid basis. Since analyzing the soils over the entire WHPA on a dense grid basis was not feasible, representative fields were selected based on irrigation and crops. Irrigated and dry land fields of wheat, cotton and alfalfa along with a feedlot were chosen to be the representative fields. The objective of this study is to evaluate the magnitude of spatial variation of soil nitrate levels over the representative fields.

THEORETICAL BACKGROUND

Regionalized Variables

A regionalized variable is distributed in space. Each observation (x_i) is associated with coordinates in three dimensions (x_u, x_v, x_w). A regionalized variable possess two characteristics, namely (a) a local random characteristic and (b) a general spatial characteristic. For an analysis of a spatially distributed variable, an assumption that must be considered is whether the variables are stationary of order two. That is, the variables must be stationary with respect to their mean and variance.

Let $Z(x_i)$ be a random variable at x_i, and Z(x) be a random function. The random function is said to be stationary of order two if the expected value of Z(x) is stationary all over the field of interest such that:

$$E\left[Z(x)\right] = m, \qquad for\ all\ x \tag{1}$$

In addition the spatial covariance must be stationary for each pair of random variables [$Z(x_i)$, $Z(x_{i+h})$] over the field of interest such that:

$$c(h) = E\left[Z(x_i) \cdot Z(x_{i+h})\right] - m^2, \qquad for\ all\ x \tag{2}$$

where h is a vector in three dimensional space. From the above expressions c(0) is the variance of $Z(x_i)$, $Var[Z(x_i)]$.

Semivariogram

Semivariogram construction is a useful tool for analyzing spatial variability and is needed for kriging interpolation. Journel and Huijbregts (1978) define the variogram as follows: if Z_x and Z_{x+h} are observations separated by a vector h, the variability between these quantities is characterized by the variogram function 2γ (x,h). The variogram function is defined as the expectation of the random variable $[Z(x) - Z(x+h)]^2$ given as:

$$2\gamma(x,h) = E\left(\left[Z(x) - Z(x+h)\right]^2\right) \tag{3}$$

The semivariogram is half of the variogram, or γ [x(h)]. Journel and Huijbregts (1978) gave an estimator of a semivariogram, γ^* [x(h)] as half the arithmetic mean of the squared differences between two experimental measurements, Z(x) and Z(x+h). If h = 0 then 2γ [x(h)] should equal zero. The expression for calculating γ^* [x(h)] is given by:

$$\gamma^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z_{(i+h)} - Z_i\right]^2 \tag{4}$$

where N(h) is the number of experimental pairs separated by h. A plot of γ^* [x(h)] versus h is called a semivariogram. Computer software developed for calculating and plotting semivariograms is presented by Englund and Sparks (1988).

Although theoretically γ^* [x(h)] should equal zero when h = 0, researchers in the past often estimated a positive value as h approached zero (Burgess and Webster, 1980; Vieira et al., 1981). They have termed this value as a *nugget*, which is random error. In a typical variogram, as h increases γ^* [x(h)] also increases and reaches approximately a constant value called the *sill*. The distance after which the value of γ^* [(x(h)] becomes constant is called the *Range*. Measurements beyond the range do not have a spatial relationship. After calculating and plotting the variogram, a model can be fitted to the points to estimate the nugget, sill and range which can be used for kriging calculations (Journel and Huijbregts, 1978). An ideal semivariogram is presented in Fig. 2.

If the variogram shows no trend beyond the minimum grid spacing, that is, if it shows no sill value, then it has only purely nugget (random) effect. Journel and Huijbregts (1978), Burgess and Webster (1980), Vieira et al. (1981) and others have explained how a semivariogram is utilized in a kriging model. In this paper a semivariogram is used as a tool to determine the spatial relationship of NO_3-N concentrations at various depths.

Autocorrelation

Several researchers have made use of correlograms as a means of explaining the spatial variability (Webster and Cuanalo, 1975; Webster, 1978; Vieira et al., 1981). The autocorrelation of a spatial series at lag L is given by (Davis, 1973):

$$r_L = \frac{[(n-L)(\sum_{i=1}^{n-L} z_i \, z_{(i+L)}) - \sum_{i=1}^{n-L} z_i \sum_{i=1}^{n-L} z_{(i+L)}][(n-L)(n-L-1)]^{-1}}{[n \sum_{i=1}^{n} z_i^2 - (\sum_{i=1}^{n} z_i)^2][n(n-1)]^{-1}} \tag{5}$$

where r_L is the autocorrelation at lag L, n is the number of observations, z_i is the value of observation at i and z_{i+L} is the value of the observation at (i+L) . The lag L is the amount of offset between the two series being compared. If L = 0 then r_L = 1.

METHODOLOGY

Representative fields for sampling were selected within the WHPA of Tipton. Soils samples were taken during the spring and the summer of 1992. The fields that were sampled in the spring were irrigated cotton, irrigated alfalfa, and dry land cotton. In the beginning of spring 1992, the irrigated alfalfa crop was stripped by the farmer. In summer dry land wheat, feedlot, irrigated wheat, and dry land alfalfa fields were sampled. Sampling was carried out on a grid basis using a 150 m (500 ft) spacing. Fig. 3 shows the sampling locations.

Soils samples were taken at 0.3 m (1 ft) increments up to 3 m (10 ft) using a deep core sampler. The samples were bagged and transported in polyethylene bags. Then they were air dried, ground, sieved to pass through 2 mm sieve and the finer than 2 mm (0.08 inch) were used for further analysis. NO_3-N was extracted from the soil samples by shaking 2 g sample with 20 ml of 2M KCl for 1 hour. The extracts were analyzed for NO_3-N using the modified Griess-Ilossvey method (Keeney and Nelson, 1982).

The KCl extract was passed through a copperized cadmium column where the NO_3^- was converted to NO_2^-. Then NO_2^- was diazotized with sulfanilamide and coupled with N-(1-Naphthyl) ethylene-diamine dihydrochloride to form a pink solution. The intensity of the pink color in this solution is directly proportional to the NO_3-N content. The pink color intensity was determined by measuring the absorbance of the diazotized and coupled solution at 540 nm in a Hitachi spectrophotometer. Some of the samples were tested for NO_2-N content and showed insignificant amounts of NO_2-N and thus no corrections were made in the NO_3-N analysis for NO_2-N.

ANALYSIS AND DISCUSSION

The analysis in this paper were conducted for NO_3-N concentrations at 4 depths, namely 0 - 0.3 m (0 - 1 ft: surface), 0.9 - 1.2 m (3 - 4 ft: rooting depth of wheat), 1.8 - 2.1 m (6 - 7 ft: rooting depth of cotton and alfalfa), 2.7 - 3.0 m (9 - 10 ft: water table depth). From now on 0 - 0.3 m (1 - 2 ft), 0.9 - 1.2 m (3 - 4 ft), 1.8 - 2.1 m (6 - 7 ft) and 2.7 - 3.0 m (9 - 10 ft) will be referred as 1 ft, 3 ft, 6 ft and 9 ft, respectively. General statistics (mean, standard deviation, skewness and range) were determined for the four depths for each of the fields, and are presented in Table 1. Irrigated alfalfa and feed lot fields showed high concentrations of NO_3-N in the surface. The dry land cotton and wheat showed higher concentrations of NO_3-N than irrigated cotton and wheat, which may be due to crop rotation. However, nothing could be concluded from this in the absence of cropping history of the fields.

Semivariogram

Since there were not many samples for the dry land alfalfa, dry land cotton, dry land wheat and feedlot fields, the semivariogram analysis was carried out only for the fields in Section 2. The irrigated wheat field strip in Section 2 was not included in subsequent analysis because the sampling time differed from the other fields. Semivariograms were calculated in East-West and North-South directions. Plots of these semivariograms are shown in figures 4 and 5.

The semivariogram for North-South direction (1 ft samples) produced a semivariogram with a 'classic' shape, exhibiting a defined nugget, sill (3000 ppm^2) and range (600 m). East-West variograms of 1 ft, 3 ft and 9 ft NO_3-N concentrations and North-South variogram of 6 ft NO_3-N concentrations show a hole effect. When the variogram does not grow monotonically, it is said to display a hole effect (Journel and Huijbregts, 1978). The hole effect in these variograms occurs in the range of 300 m (1000 ft) to 750 m (2500 ft). Except for the North-South semivariogram for 1 ft samples, all the other variograms do not show pronounced spatial continuity. The North-South variograms of 3 ft, 6 ft and 9 ft showed only pure nugget effect.

Autocorrelation

The NO_3-N concentrations were then analyzed for spatial correlation using the samples in Section 2. In this study, autocorrelation was calculated along four rows (East-West direction) for NO_3-N concentrations at 1, 3, 6 and 9 ft. For the autocorrelation analysis the irrigated wheat strip was included because it was necessary to have no missing points for the autocorrelation analysis. For the same reason, autocorrelation for Row # 4 for 9 ft and Row # 5 were not calculated.

Autocorrletions were calculated using SYSTAT, a statistical software package developed by Wilkinson (1989). The correlograms are shown in figures 6 through 9. These correlograms shown no significant correlation among the samples. The 95% confidence intervals for r(h) at each lag were greater than the calculated correlation values which indicates the correlation coefficients are not significant. Therefore, a spatial relationship between the samples cannot be established.

Contour Plots

Contour plots were created for fields in Section 2. Kriging interpolation method was chosen to create the contour plots. Figures 10 through 13 show the NO_3-N concentration distributions at 1, 3, 6 and 9 ft. By looking at the contour plots a general idea about the spatial relationship and distribution of Nitrate-N concentrations at different depths over the field can be obtained. The 1 ft (surface) contour plot shows high concentrations of NO_3-N in the irrigated alfalfa fields. The subsurface (3, 6 and 9 ft) NO_3-N distributions showed higher concentrations along the eastern edge of the northeast irrigated cotton field.

CONCLUSIONS

An attempt was made to determine the spatial variability and distribution of soil profile NO_3-N content in fields within the WHPA of Tipton municipal wells. The general statistics show that the NO_3-N concentrations have a wide range at all depths in almost all the fields. The dry land fields of cotton and wheat showed higher mean NO_3-N concentrations. This may be due to the effect of the previous crop, but cannot be confirmed without examining the cropping history.

Except for the North-South semivariogram for 1 ft samples, all the other variograms do not show pronounced spatial continuity. There were not enough data points to indicate spatial relationship among the samples using semivariograms. Agricultural practices, fertility, and possibly water table fluctuations appeared to be a major factor affecting the NO_3-N variability. To get a better description of the spatial variability, it is recommended that sampling to be done on a finer grid. The hole effect found in some of the variograms may be due to the cross over of the semivariogram calculations from one crop or soil type to another.

At a 95% confidence interval, the autocorrelation analysis did not show spatial correlation. Few sampling points and high variance among the samples may be a few reasons for the correlograms to have insignificant correlation values.

Contour plots were presented to illustrate the distributions of NO_3-N concentrations at different depths. High NO_3-N concentrations in the surface samples of the irrigated alfalfa field were due to stripping and plowing of an alfalfa crop prior to sampling. There is a drainage channel on the eastern edge of Section 2, which may explain the high NO_3-N concentrations in the subsurface samples of the irrigated cotton field along the eastern edge. The high subsurface nitrate in irrigated cotton field may be due to the residual effect of the previous crop.

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Table 1: General Statistics of Nitrate-N Concentrations in the Sampled Fields

Field	Depth (ft)	Mean (μg/g)	SD[¶] (μg/g)	Skewness	Minimum (μg/g)	Maximum (μg/g)
Irr. Alfalfa	1	77	72.	1.02	15.	220.
	3	12	5.	-0.72	3.	17.
	6	7	2.	0.97	4.	12.
	9	7	4.	1.74	4.	17.
Irr. Cotton (NE Field)	1	21	18.	1.46	4.	71.
	3	14	12.	1.60	2.	49.
	6	18	21.	1.75	3.	79.
	9	15	14.	1.49	3.	52.
Irr. Cotton (NW Field)	1	18	10.	1.26	9.	45.
	3	10	5.	0.25	3.	19.
	6	8	4.	0.58	4.	16.
	9	13	13.	2.78	4.	56.
Irr. Wheat	1	13	6.	0.55	7.	20.
	3	3	3.	0.18	1.	6.
	6	2	0.	0.44	1.	2.
	9	2	1.	-0.63	1.	2.
Dry Alfalfa	1	25	20.	0.66	8.	56.
	3	7	2.	0.35	5.	9.
	6	4	1.	0.40	3.	6.
	9	3	1.	-0.75	1.	4.
Dry Cotton	1	22	7.	0.85	13.	35.
	3	8	2.	-0.12	5.	12.
	6	25	51.	2.42	2.	170.
	9	31	57.	2.50	5.	190.
Dry Wheat	1	57	18.	-0.55	28.	75.
	3	6	3.	0.60	4.	11.
	6	3	1.	0.46	2.	5.
	9	9	4.	0.23	4.	15.
Feed Lot[§]	1	180	250.	.	6.	360.
	3	61	83.	.	2.	120.
	6	32	40.	.	4.	60.
	9	25	1.	.	25.	26.

[¶] Standard Deviation

[§] Only two data points were available and thus skewness is undefined.

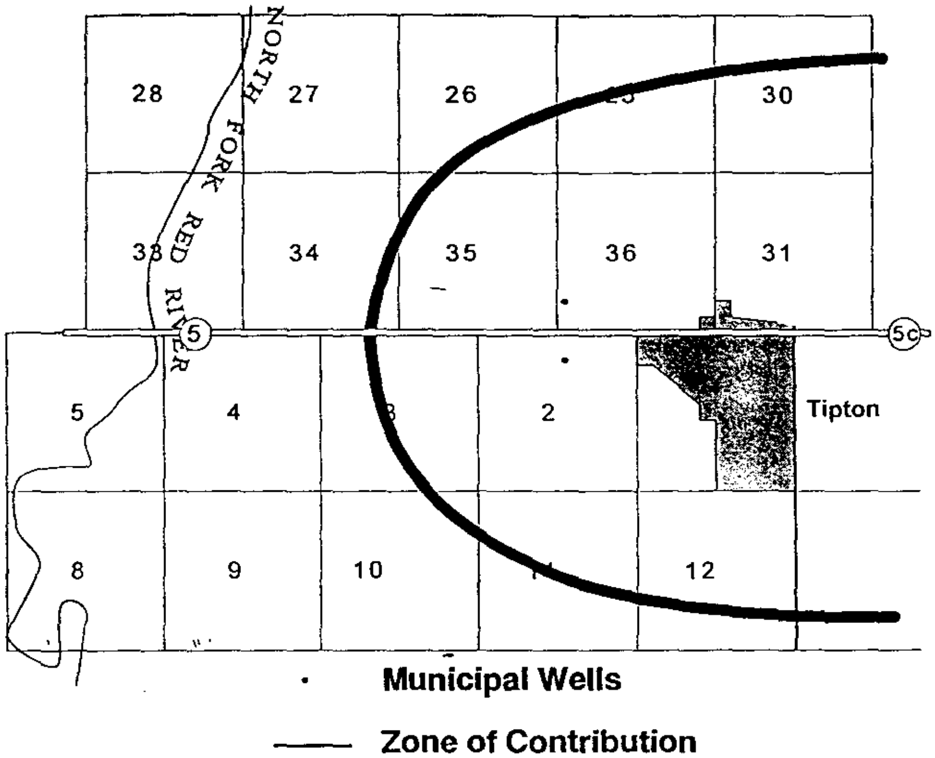

Fig. 1: Wellhead Protection Area for Tipton

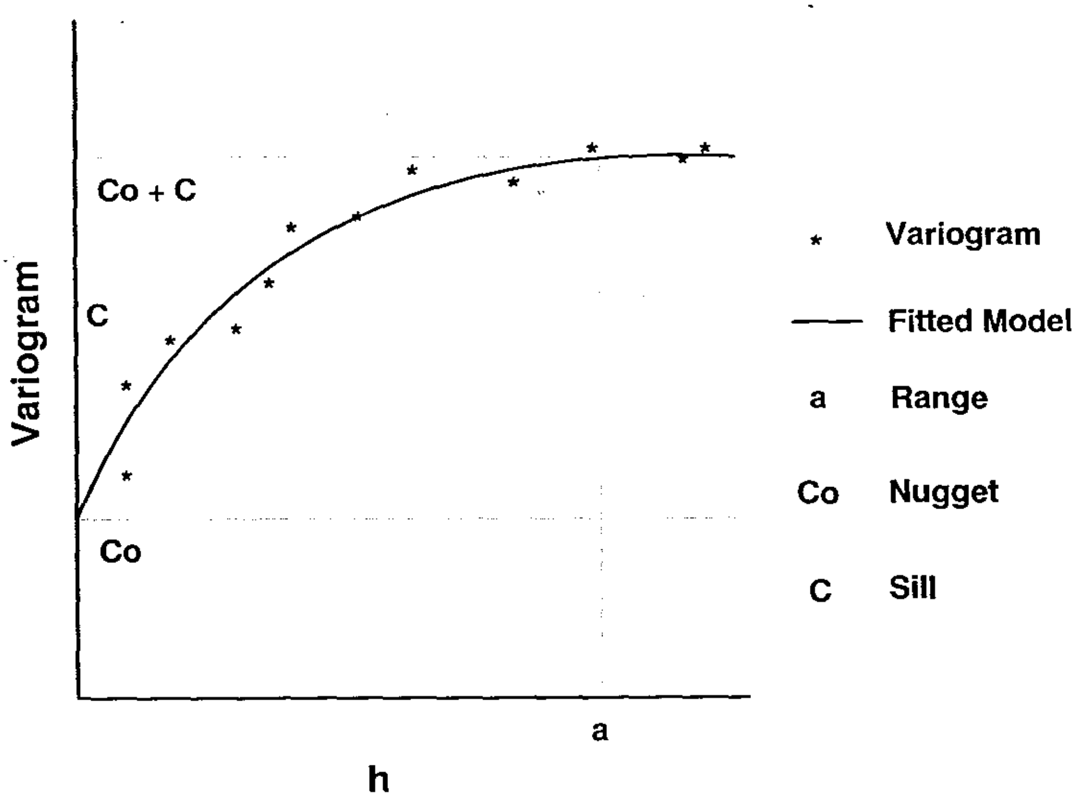

Fig. 2: Ideal Semivariogram

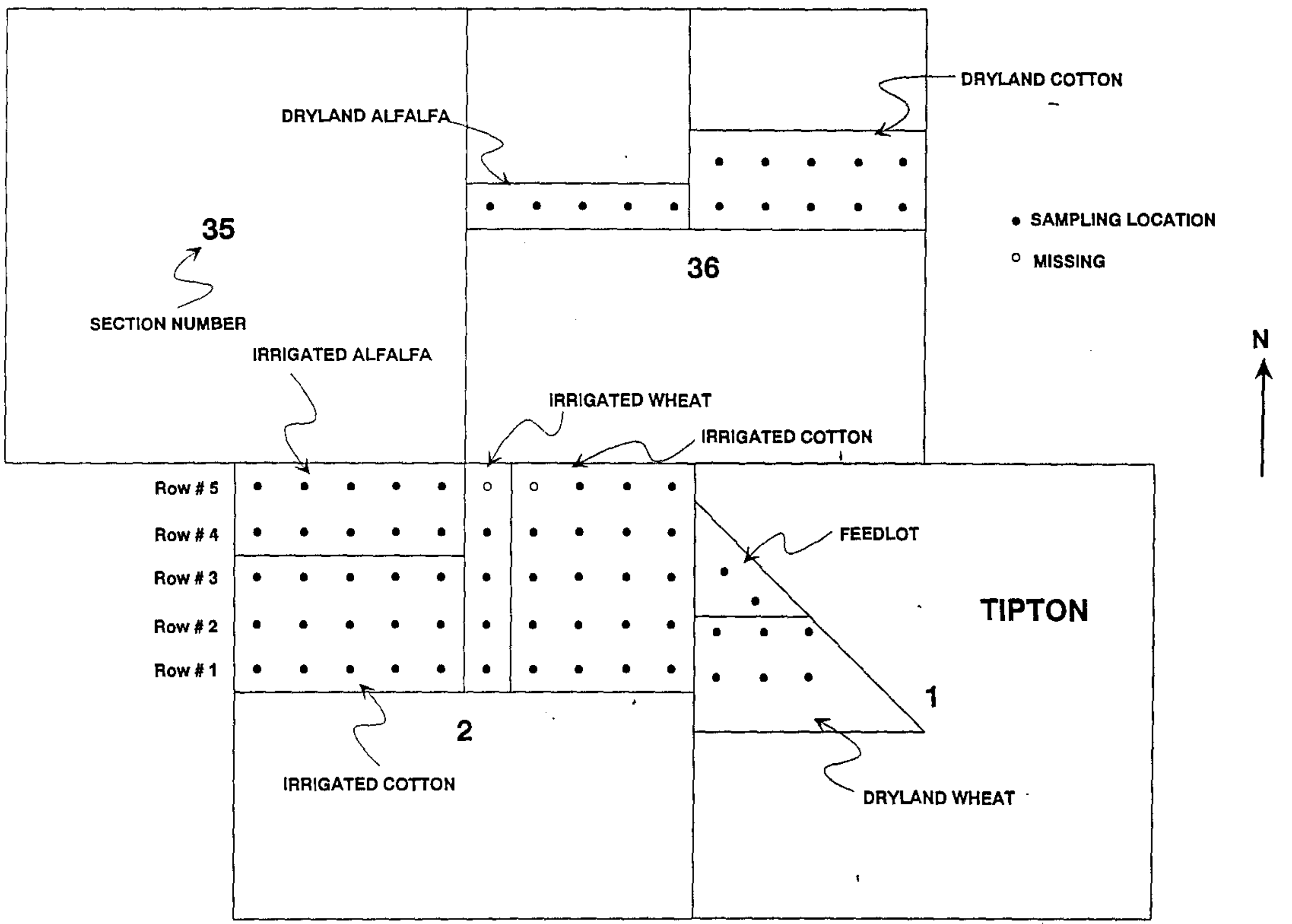

Fig. 3: Sampling Locations

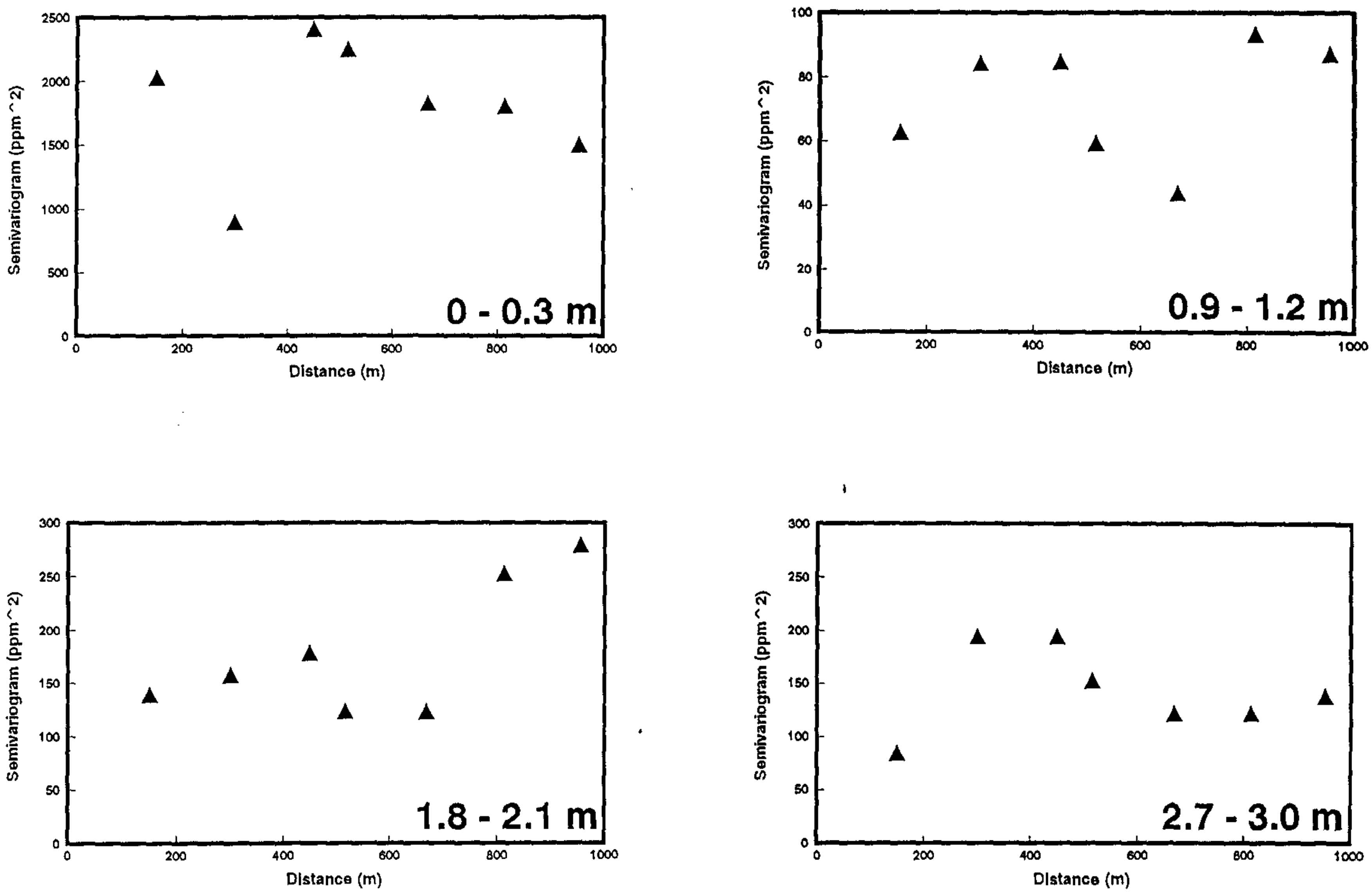

Fig. 4: East-West Semivariograms For Nitrate-N Concentrations at Different Depths

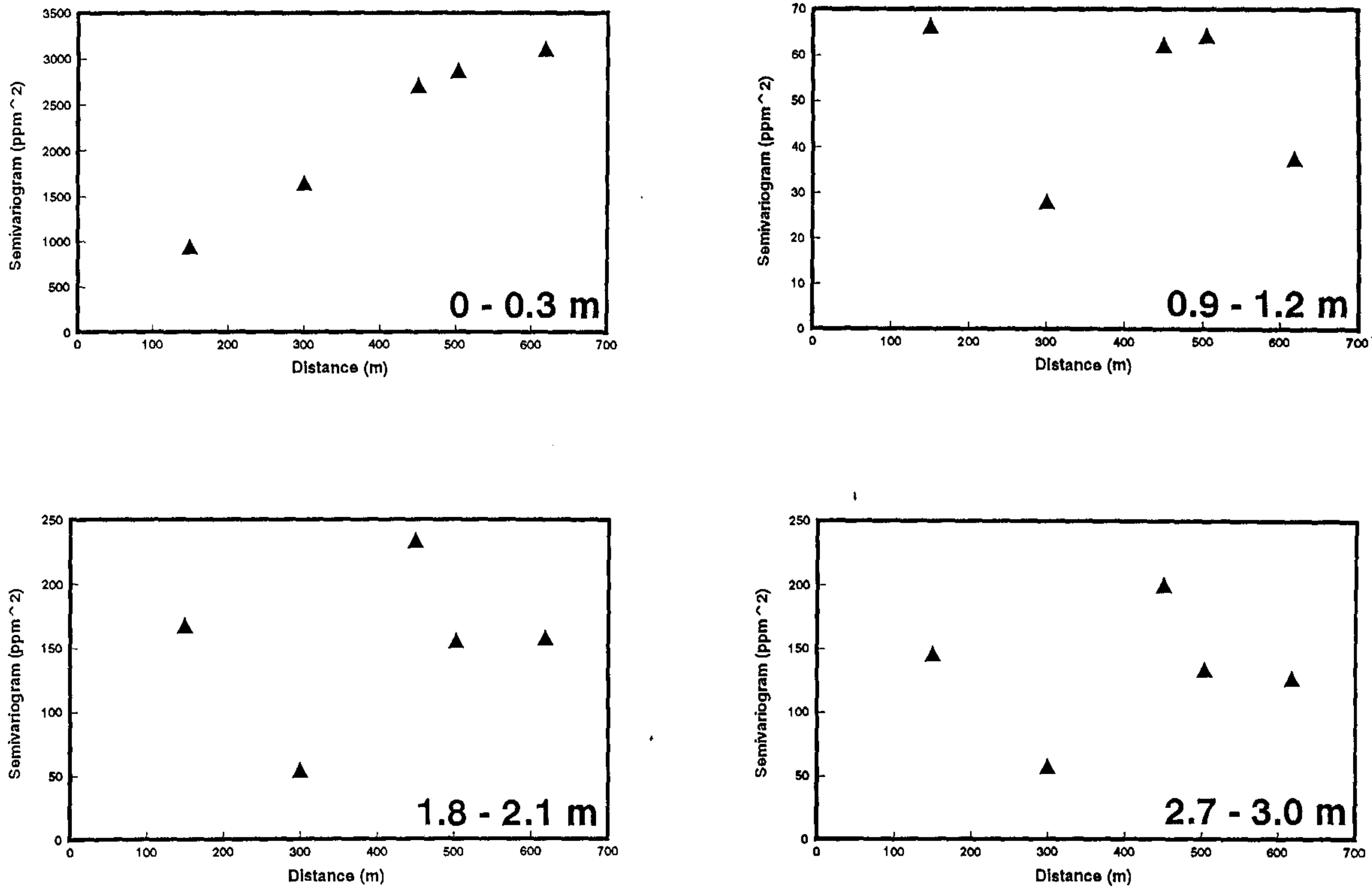

Fig. 5: North-South Semivariograms For Nitrate-N Concentrations at Different Depths

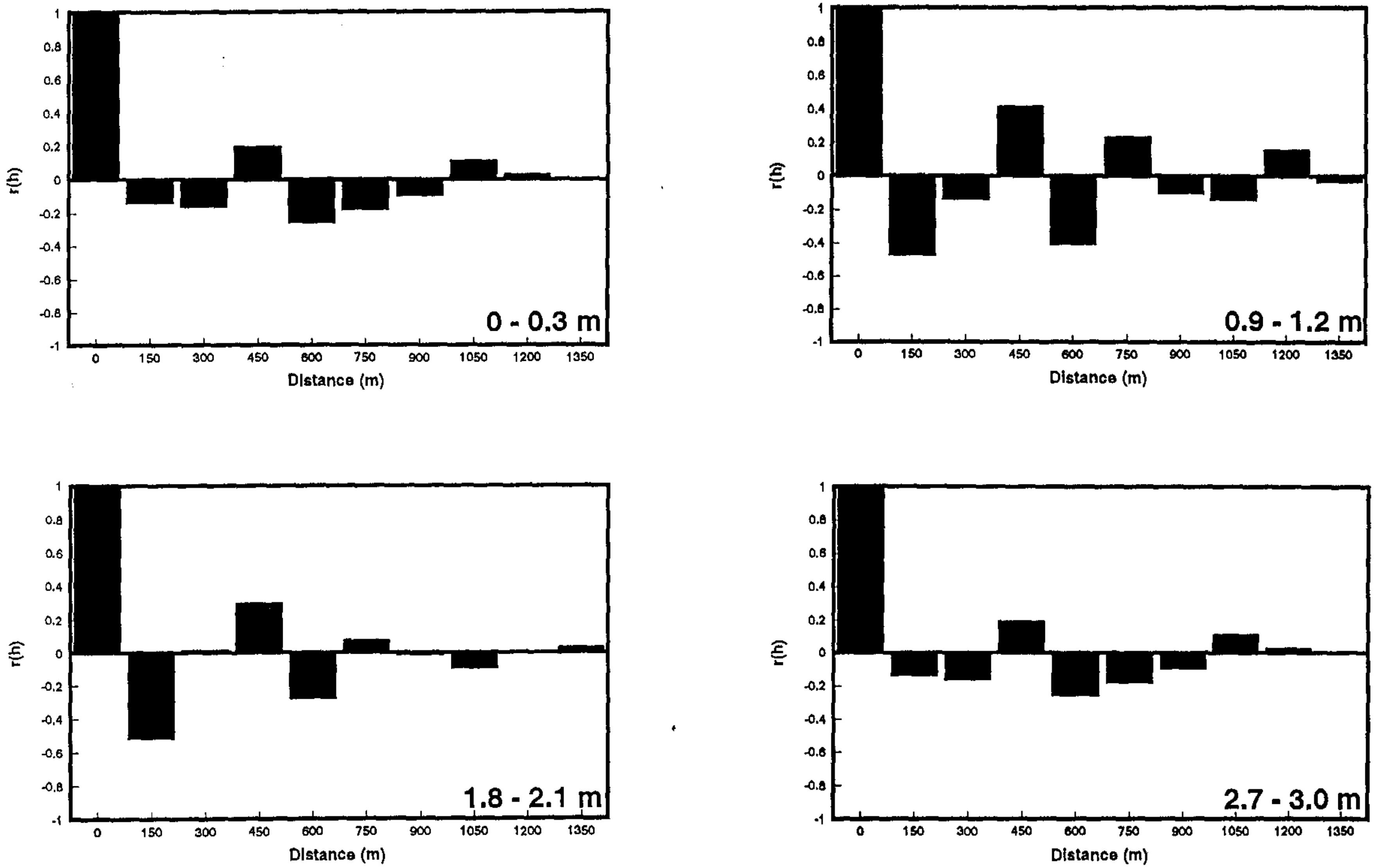

Fig. 6: Correlograms of Nitrate-N Concentrations at Different Depths in Row # 1

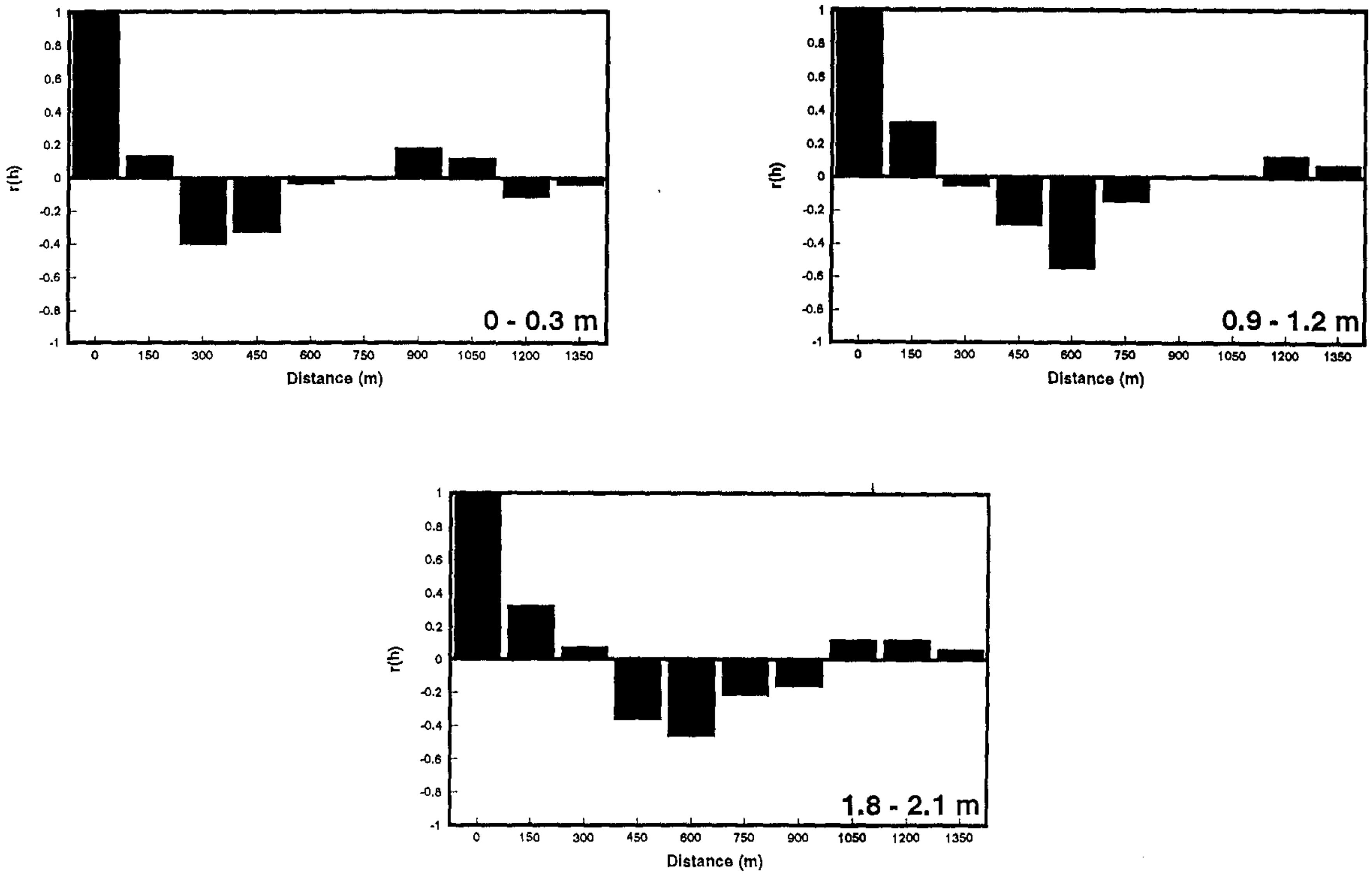

Fig. 7: Correlograms of Nitrate-N Concentrations at Different Depths in Row # 2

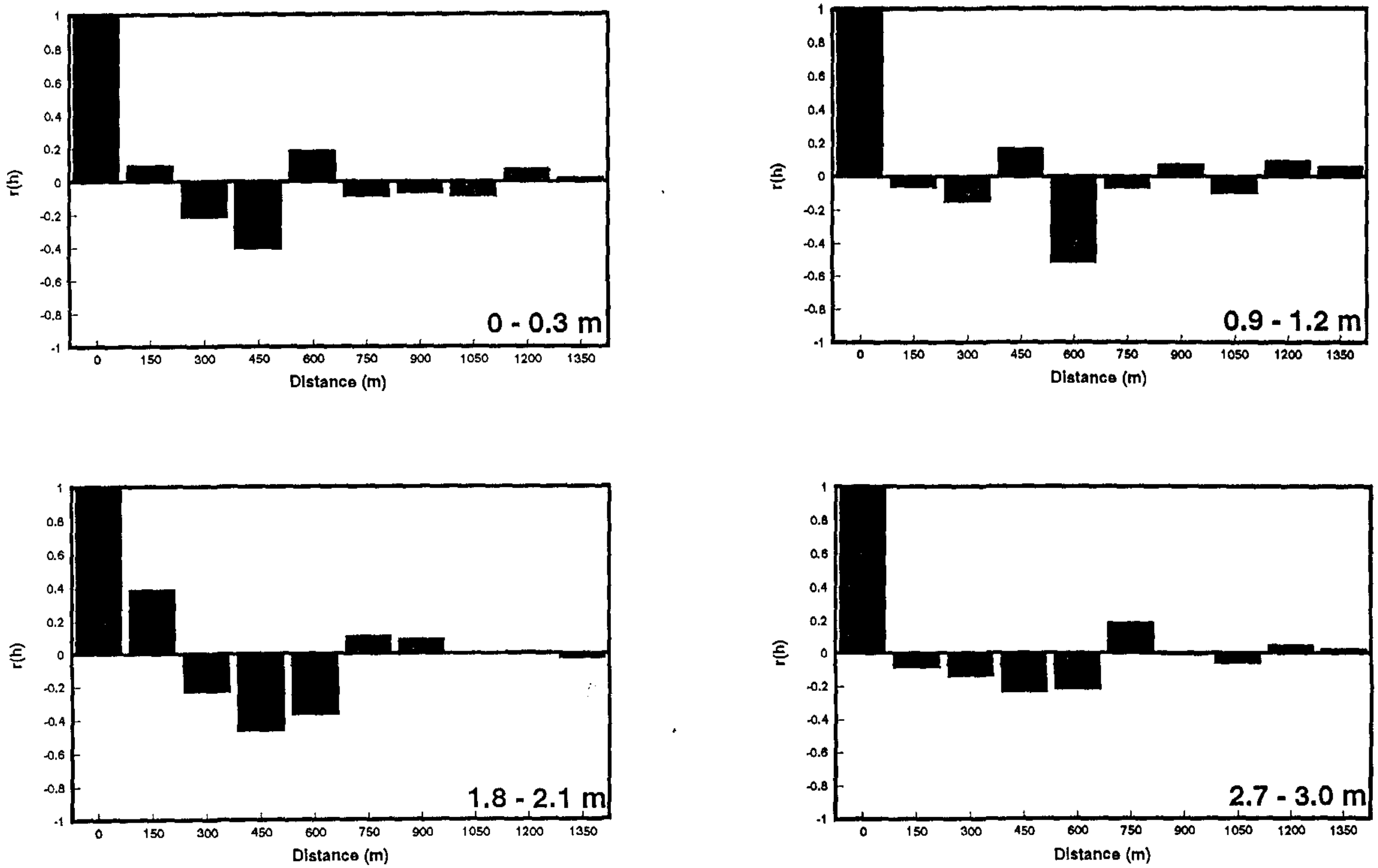

Fig. 8: Correlograms of Nitrate-N Concentrations at Different Depths in Row # 3

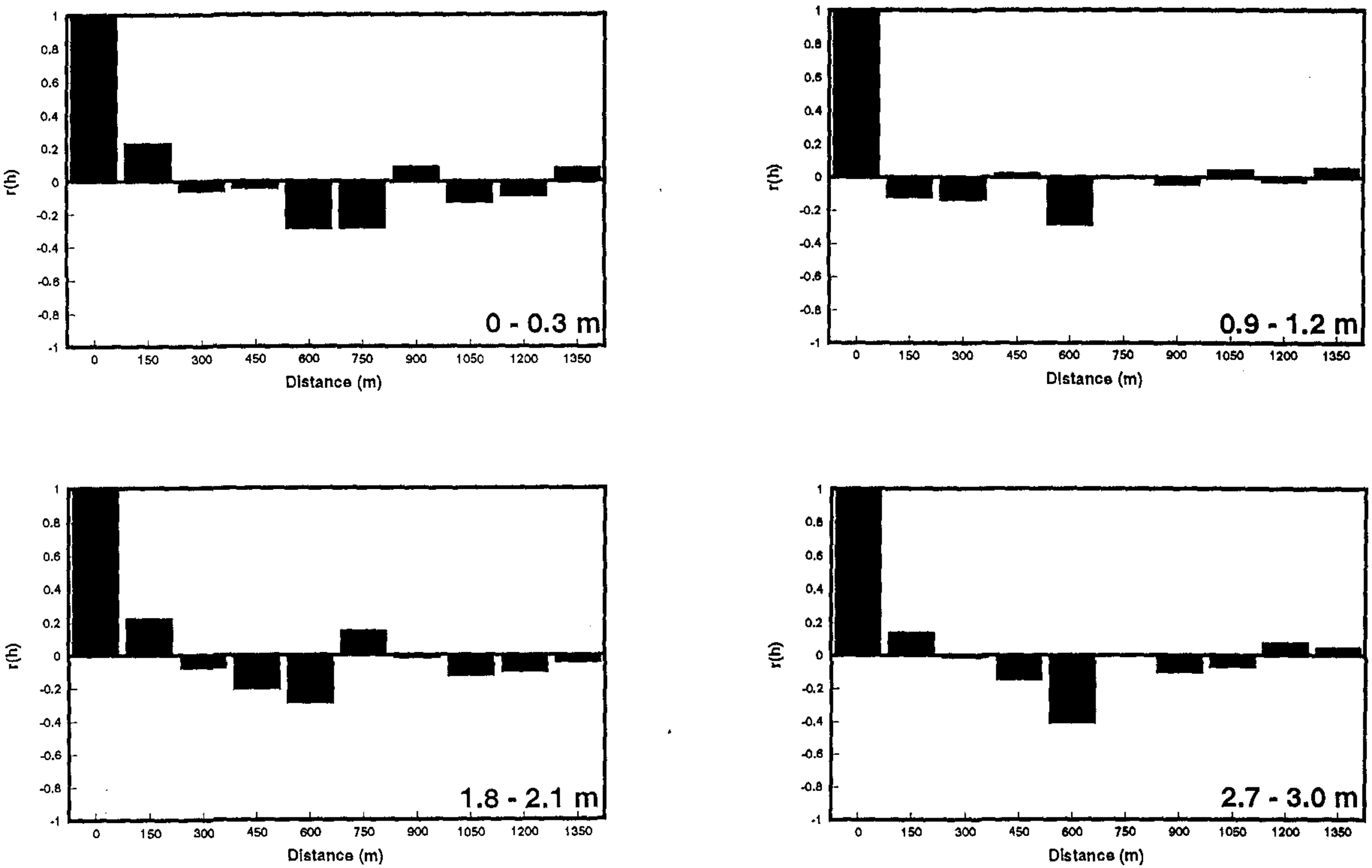

Fig. 9: Correlograms of Nitrate-N Concentrations at Different Depths in Row # 4

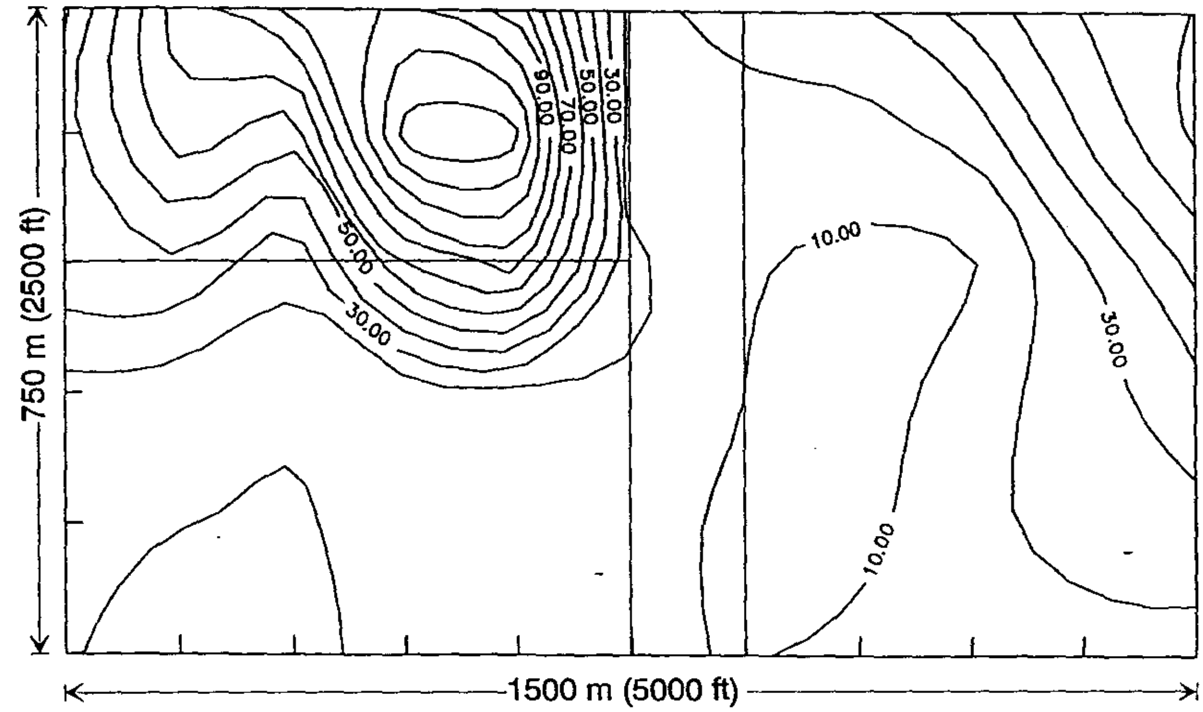

Fig. 10: Nitrate-N Concentration (ppm) distribution at 0.33m (1ft) Depth

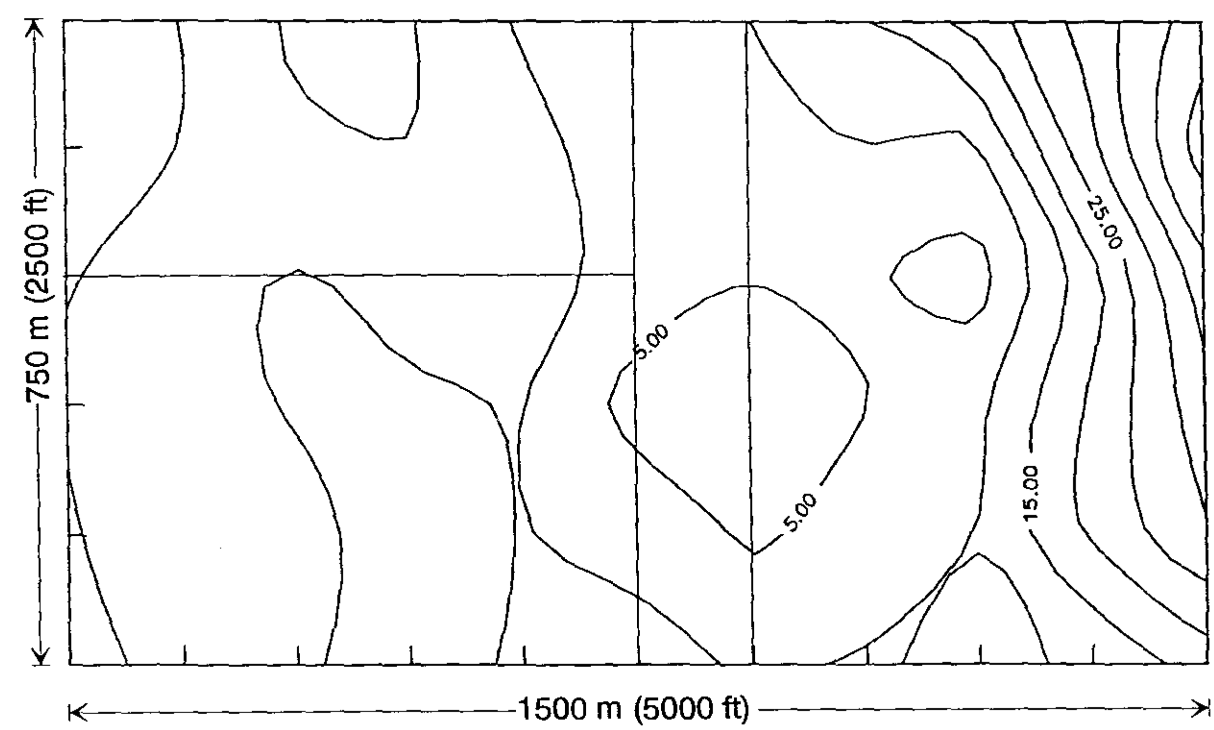

Fig. 11: Nitrate-N Concentration (ppm) distribution at 0.9 m (3ft) Depth

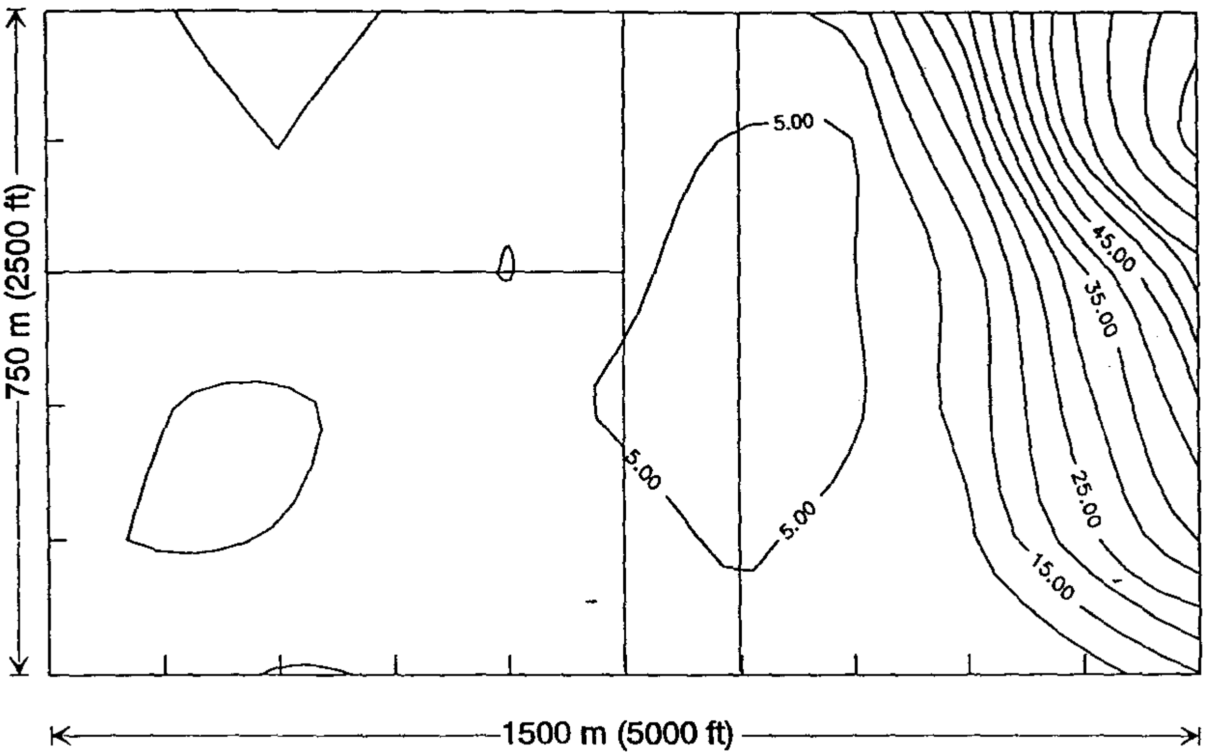

Fig. 12: Nitrate-N Concentration (ppm) distribution at 1.8 m (6ft) Depth

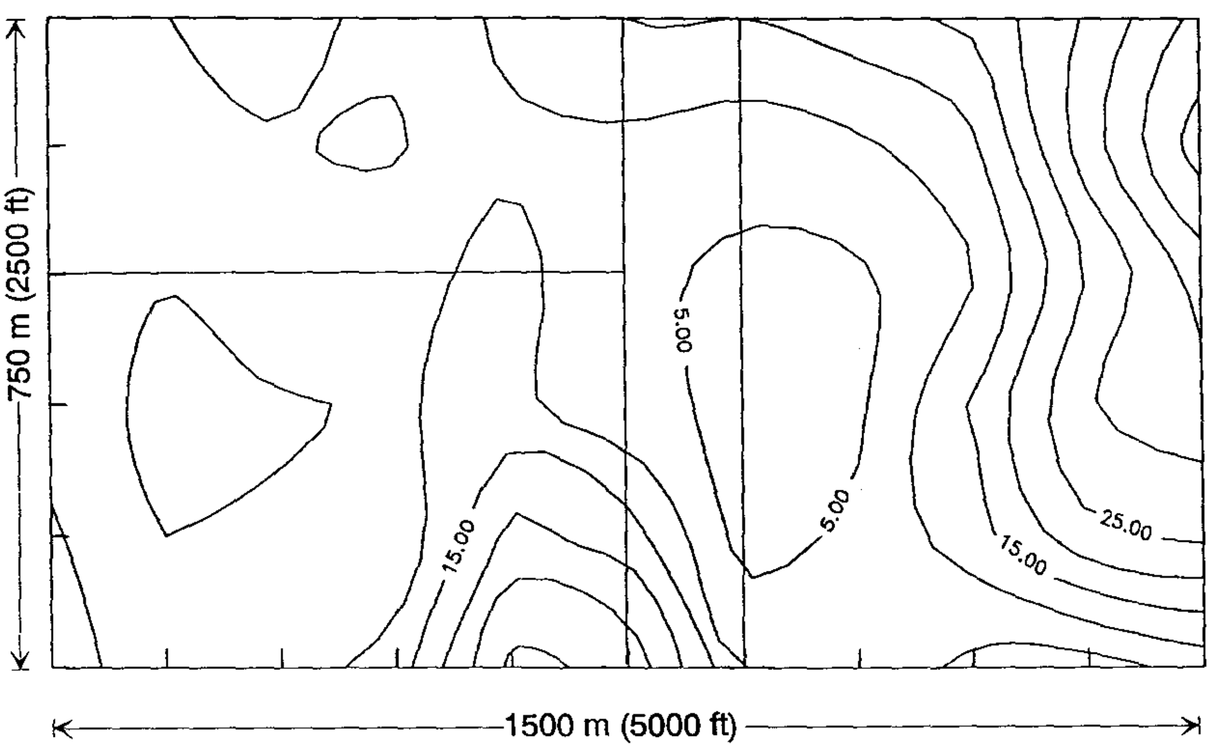

Fig. 13: Nitrate-N Concentration (ppm) distribution at 2.7 m (9ft) Depth

APPENDIX - C

Deep-Core Sampling Data

Table A3-1. Soil nitrate-N profiles obtained from the deep-core sampling conducted during 1992 (the distances are measured from the southwest corner of the sections)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
1	250	3700	1	75.1
1	250	3700	2	13.4
1	250	3700	3	11.2
1	250	3700	4	5.5
1	250	3700	5	6.4
1	250	3700	6	4.4
1	250	3700	7	19.2
1	250	3700	8	11.0
1	250	3700	9	8.8
1	250	4200	1	28.2
1	250	4200	2	6.6
1	250	4200	3	4.0
1	250	4200	4	2.6
1	250	4200	5	3.5
1	250	4200	6	3.1
1	250	4200	7	2.4
1	250	4200	8	3.1
1	250	4200	9	4.0
1	250	4200	10	2.9
1	290	4250	1	5.5
1	290	4250	2	2.9
1	290	4250	3	2.2
1	290	4250	4	2.0
1	290	4250	5	6.6
1	290	4250	6	4.0
1	290	4250	7	4.4
1	290	4250	8	6.4
1	290	4250	9	24.5
1	290	4250	10	38.6
1	540	3965	1	360.1
1	540	3965	2	80.8
1	540	3965	3	119.2
1	540	3965	4	106.2
1	540	3965	5	97.6
1	540	3965	6	59.9
1	540	3965	7	51.1
1	540	3965	8	35.5
1	540	3965	9	26.4
1	540	3965	10	23.4
1	750	3700	1	74.5
1	750	3700	2	11.7
1	750	3700	3	8.2
1	750	3700	4	2.9
1	750	3700	5	3.3
1	750	3700	6	3.1
1	750	3700	7	4.9
1	750	3700	8	8.2
1	750	3700	9	14.8
1	750	3700	10	16.7
1	750	4200	1	48.9
1	750	4200	2	7.9
1	750	4200	3	3.7
1	750	4200	4	8.2
1	750	4200	5	2.4
1	750	4200	6	2.2
1	750	4200	7	3.7
1	750	4200	8	4.0
1	750	4200	9	7.5
1	750	4200	10	14.1
1	1250	3700	1	63.0
1	1250	3700	2	13.7
1	1250	3700	3	7.1
1	1250	3700	4	7.1
1	1250	3700	5	4.4
1	1250	3700	6	5.1
1	1250	3700	7	7.9
1	1250	3700	8	11.0
1	1250	3700	9	12.6
1	1250	3700	10	13.2
1	1250	4200	1	53.7
1	1250	4200	2	14.5
1	1250	4200	3	3.7
1	1250	4200	4	7.3
1	1250	4200	5	2.4
1	1250	4200	6	2.2
1	1250	4200	7	3.3
1	1250	4200	8	4.4
1	1250	4200	9	7.5
1	1250	4200	10	9.9

Table A3-1. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	250	3000	1	15.2
2	250	3000	2	10.1
2	250	3000	3	7.7
2	250	3000	4	8.2
2	250	3000	5	6.2
2	250	3000	6	8.2
2	250	3000	7	4.6
2	250	3000	8	4.0
2	250	3000	9	4.4
2	250	3000	10	4.2
2	250	3500	1	10.6
2	250	3500	2	8.6
2	250	3500	3	12.6
2	250	3500	4	13.4
2	250	3500	5	17.2
2	250	3500	6	11.5
2	250	3500	7	8.2
2	250	3500	8	8.4
2	250	3500	9	5.5
2	250	4000	1	18.0
2	250	4000	2	13.8
2	250	4000	3	10.1
2	250	4000	4	10.3
2	250	4000	5	10.1
2	250	4000	6	6.0
2	250	4000	7	8.2
2	250	4000	8	14.5
2	250	4000	9	10.6
2	250	4000	10	8.6
2	250	4500	1	70.7
2	250	4500	2	14.8
2	250	4500	3	11.5
2	250	4500	4	13.7
2	250	4500	5	12.6
2	250	4500	6	7.5
2	250	4500	7	11.2
2	250	4500	8	12.1
2	250	4500	9	8.4

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	250	5000	1	15.4
2	250	5000	2	6.8
2	250	5000	3	4.2
2	250	5000	4	8.2
2	250	5000	5	8.2
2	250	5000	6	6.2
2	250	5000	7	4.2
2	250	5000	8	4.9
2	250	5000	9	7.1
2	250	5000	10	8.2
2	750	3000	1	44.5
2	750	3000	2	18.5
2	750	3000	3	17.4
2	750	3000	4	18.1
2	750	3000	5	5.3
2	750	3000	6	6.8
2	750	3000	7	5.5
2	750	3000	8	7.9
2	750	3000	9	10.4
2	750	3000	10	9.0
2	750	3500	1	8.8
2	750	3500	2	9.3
2	750	3500	3	13.9
2	750	3500	4	10.6
2	750	3500	5	18.5
2	750	3500	6	13.4
2	750	3500	7	6.6
2	750	3500	8	10.1
2	750	3500	9	17.8
2	750	3500	10	14.1
2	750	4000	1	26.7
2	750	4000	2	16.7
2	750	4000	3	12.2
2	750	4000	4	12.8
2	750	4000	5	7.4
2	750	4000	6	7.9
2	750	4000	7	9.2
2	750	4000	8	7.4
2	750	4000	9	10.2
2	750	4000	10	9.2

Table A3-1. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)	Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	750	4500	1	34.1	2	1250	4000	1	10.3
2	750	4500	2	10.6	2	1250	4000	2	5.5
2	750	4500	3	9.7	2	1250	4000	3	4.3
2	750	4500	4	9.9	2	1250	4000	4	4.1
2	750	4500	5	9.7	2	1250	4000	5	6.4
2	750	4500	6	6.4	2	1250	4000	6	6.1
2	750	4500	7	7.9	2	1250	4000	7	7.2
2	750	4500	8	17.8	2	1250	4000	8	4.3
2	750	4500	9	8.8	2	1250	4000	9	6.1
2	750	4500	10	7.7	2	1250	4000	10	3.3
2	750	5000	1	126.4	2	1250	4500	1	23.8
2	750	5000	2	18.3	2	1250	4500	2	15.6
2	750	5000	3	15.2	2	1250	4500	3	13.9
2	750	5000	4	11.7	2	1250	4500	4	9.3
2	750	5000	5	10.4	2	1250	4500	5	7.7
2	750	5000	6	4.4	2	1250	4500	6	6.0
2	750	5000	7	2.6	2	1250	4500	7	6.0
2	750	5000	8	1.1	2	1250	4500	8	5.5
2	750	5000	9	3.7	2	1250	4500	9	4.9
2	750	5000	10	2.6	2	1250	4500	10	6.2
2	1250	3000	1	8.6	2	1250	5000	1	48.7
2	1250	3000	2	4.9	2	1250	5000	2	26.0
2	1250	3000	3	7.1	2	1250	5000	3	16.7
2	1250	3000	4	7.1	2	1250	5000	4	12.8
2	1250	3000	5	6.6	2	1250	5000	5	6.6
2	1250	3000	6	4.0	2	1250	5000	6	3.7
2	1250	3000	7	3.3	2	1250	5000	7	4.2
2	1250	3000	8	2.2	2	1250	5000	8	4.6
2	1250	3000	9	4.2	2	1250	5000	9	4.2
2	1250	3000	10	4.0	2	1250	5000	10	4.9
2	1250	3500	1	24.2	2	1750	3000	1	10.4
2	1250	3500	2	17.8	2	1750	3000	2	5.7
2	1250	3500	3	7.9	2	1750	3000	3	3.3
2	1250	3500	4	11.0	2	1750	3000	4	3.7
2	1250	3500	5	14.1	2	1750	3000	5	5.3
2	1250	3500	6	13.7	2	1750	3000	6	5.1
2	1250	3500	7	17.6	2	1750	3000	7	5.5
2	1250	3500	8	14.5	2	1750	3000	8	5.7
2	1250	3500	9	5.3	2	1750	3000	9	10.6
					2	1750	3000	10	14.1

Table A3-1. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	1750	3500	1	9.7
2	1750	3500	2	14.8
2	1750	3500	3	11.7
2	1750	3500	4	14.8
2	1750	3500	5	12.1
2	1750	3500	6	3.7
2	1750	3500	7	7.1
2	1750	3500	8	12.1
2	1750	3500	9	10.6
2	1750	3500	10	15.9
2	1750	4000	1	25.6
2	1750	4000	2	11.9
2	1750	4000	3	15.0
2	1750	4000	4	11.7
2	1750	4000	5	12.1
2	1750	4000	6	10.6
2	1750	4000	7	7.5
2	1750	4000	8	8.4
2	1750	4000	9	16.7
2	1750	4000	10	20.7
2	1750	4500	1	220.9
2	1750	4500	2	16.5
2	1750	4500	3	11.0
2	1750	4500	4	12.6
2	1750	4500	5	16.5
2	1750	4500	6	9.0
2	1750	4500	7	6.2
2	1750	4500	8	4.2
2	1750	4500	9	5.5
2	1750	4500	10	6.4
2	1750	5000	1	169.2
2	1750	5000	2	26.0
2	1750	5000	3	16.5
2	1750	5000	4	11.7
2	1750	5000	5	9.3
2	1750	5000	6	7.5
2	1750	5000	7	4.9
2	1750	5000	8	3.1
2	1750	5000	9	5.5
2	1750	5000	10	5.1
2	2250	3000	1	17.4
2	2250	3000	2	17.2
2	2250	3000	3	18.7
2	2250	3000	4	17.4
2	2250	3000	5	11.7
2	2250	3000	6	15.6
2	2250	3000	7	19.8
2	2250	3000	8	18.3
2	2250	3000	9	55.7
2	2250	3500	1	19.8
2	2250	3500	2	5.1
2	2250	3500	3	6.2
2	2250	3500	4	5.3
2	2250	3500	5	5.7
2	2250	3500	6	7.5
2	2250	3500	7	4.0
2	2250	3500	8	5.1
2	2250	3500	9	5.1
2	2250	4000	1	23.6
2	2250	4000	2	10.1
2	2250	4000	3	7.9
2	2250	4000	4	6.4
2	2250	4000	5	7.5
2	2250	4000	6	7.3
2	2250	4000	7	7.9
2	2250	4000	8	12.3
2	2250	4000	9	15.4
2	2250	4000	10	8.4
2	2250	4500	1	39.4
2	2250	4500	2	18.1
2	2250	4500	3	15.9
2	2250	4500	4	12.1
2	2250	4500	5	18.1
2	2250	4500	6	12.3
2	2250	4500	7	10.6
2	2250	4500	8	9.7
2	2250	4500	9	7.7
2	2250	4500	10	5.3

Table A3-1. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	2250	5000	1	17.2
2	2250	5000	2	7.7
2	2250	5000	3	3.3
2	2250	5000	4	9.5
2	2250	5000	5	7.3
2	2250	5000	6	6.2
2	2250	5000	7	9.3
2	2250	5000	8	14.1
2	2250	5000	9	17.2
2	2250	5000	10	21.6
2	2750	3000	1	6.8
2	2750	3000	2	4.6
2	2750	3000	3	6.0
2	2750	3000	4	4.0
2	2750	3000	5	4.0
2	2750	3000	6	2.2
2	2750	3000	7	2.4
2	2750	3000	8	1.8
2	2750	3000	9	2.4
2	2750	3000	10	2.4
2	2750	3500	1	11.0
2	2750	3500	2	1.1
2	2750	3500	3	0.9
2	2750	3500	4	0.7
2	2750	3500	5	1.3
2	2750	3500	6	1.3
2	2750	3500	7	1.3
2	2750	3500	8	1.1
2	2750	4000	1	20.3
2	2750	4000	2	1.1
2	2750	4000	3	1.1
2	2750	4000	4	1.8
2	2750	4000	5	1.1
2	2750	4000	6	1.5
2	2750	4000	7	2.2
2	2750	4000	8	2.2
2	2750	4000	9	2.2
2	2750	4000	10	2.2
2	2750	4500	1	12.3
2	2750	4500	2	6.4
2	2750	4500	3	4.4
2	2750	4500	4	2.2
2	2750	4500	5	2.2
2	2750	4500	6	1.8
2	2750	4500	7	1.8
2	2750	4500	8	1.5
2	2750	4500	9	1.1
2	2750	4500	10	1.1
2	3250	3000	1	10.4
2	3250	3000	2	10.8
2	3250	3000	3	8.0
2	3250	3000	4	10.4
2	3250	3000	5	9.7
2	3250	3000	6	10.3
2	3250	3000	7	7.9
2	3250	3000	8	7.3
2	3250	3000	9	7.8
2	3250	3500	1	4.8
2	3250	3500	2	5.3
2	3250	3500	3	4.5
2	3250	3500	4	5.1
2	3250	3500	5	4.0
2	3250	3500	6	4.1
2	3250	3500	7	5.3
2	3250	3500	8	4.4
2	3250	3500	9	4.4
2	3250	3500	10	5.1
2	3250	4000	1	4.2
2	3250	4000	2	4.4
2	3250	4000	3	6.4
2	3250	4000	4	4.6
2	3250	4000	5	5.1
2	3250	4000	6	3.1
2	3250	4000	7	2.2
2	3250	4000	8	4.4
2	3250	4000	9	7.1
2	3250	4000	10	5.3

Table A3-1. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	3250	4500	1	9.7
2	3250	4500	2	11.5
2	3250	4500	3	9.5
2	3250	4500	4	9.0
2	3250	4500	5	8.8
2	3250	4500	6	6.4
2	3250	4500	7	2.9
2	3250	4500	8	4.9
2	3250	4500	9	5.6
2	3250	4500	10	4.9
2	3750	3000	1	12.9
2	3750	3000	2	9.4
2	3750	3000	3	12.2
2	3750	3000	4	10.9
2	3750	3000	5	8.1
2	3750	3000	6	7.7
2	3750	3000	7	8.6
2	3750	3000	8	8.0
2	3750	3000	9	8.5
2	3750	3500	1	4.6
2	3750	3500	2	4.1
2	3750	3500	3	4.1
2	3750	3500	4	4.2
2	3750	3500	5	5.7
2	3750	3500	6	5.2
2	3750	3500	7	5.4
2	3750	3500	8	4.9
2	3750	3500	9	4.3
2	3750	3500	10	2.4
2	3750	4000	1	9.3
2	3750	4000	2	6.2
2	3750	4000	3	4.6
2	3750	4000	4	7.3
2	3750	4000	5	7.9
2	3750	4000	6	5.3
2	3750	4000	7	6.2
2	3750	4000	8	4.0
2	3750	4000	9	3.5
2	3750	4000	10	5.5

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	3750	4500	1	9.7
2	3750	4500	2	5.3
2	3750	4500	3	2.6
2	3750	4500	4	8.6
2	3750	4500	5	8.8
2	3750	4500	6	5.7
2	3750	4500	7	8.2
2	3750	4500	8	7.7
2	3750	4500	9	2.9
2	3750	4500	10	3.3
2	3750	5000	1	27.1
2	3750	5000	2	8.6
2	3750	5000	3	15.4
2	3750	5000	4	9.3
2	3750	5000	5	8.6
2	3750	5000	6	7.1
2	3750	5000	7	15.2
2	3750	5000	8	17.4
2	3750	5000	9	18.1
2	3750	5000	10	16.3
2	4250	3000	1	17.6
2	4250	3000	2	7.5
2	4250	3000	3	6.6
2	4250	3000	4	7.4
2	4250	3000	5	7.8
2	4250	3000	6	6.3
2	4250	3000	7	6.2
2	4250	3000	8	8.4
2	4250	3000	9	4.4
2	4250	3000	10	3.7
2	4250	3500	1	29.6
2	4250	3500	2	21.3
2	4250	3500	3	18.8
2	4250	3500	4	15.0
2	4250	3500	5	17.8
2	4250	3500	6	19.3
2	4250	3500	7	33.0
2	4250	3500	8	39.6
2	4250	3500	9	33.6
2	4250	3500	10	32.4

Table A3-1. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	4250	4000	1	14.8
2	4250	4000	2	6.4
2	4250	4000	3	7.3
2	4250	4000	4	6.6
2	4250	4000	5	19.6
2	4250	4000	6	17.2
2	4250	4000	7	14.8
2	4250	4000	8	18.5
2	4250	4000	9	18.5
2	4250	4000	10	20.7
2	4250	4500	1	8.2
2	4250	4500	2	3.1
2	4250	4500	3	2.2
2	4250	4500	4	0.9
2	4250	4500	5	0.7
2	4250	4500	6	22.5
2	4250	4500	7	15.6
2	4250	4500	8	11.7
2	4250	4500	9	15.6
2	4250	4500	10	10.4
2	4250	5000	1	50.4
2	4250	5000	2	22.5
2	4250	5000	3	22.3
2	4250	5000	4	22.7
2	4250	5000	5	34.4
2	4250	5000	6	54.4
2	4250	5000	7	34.6
2	4250	5000	8	22.5
2	4250	5000	9	20.5
2	4250	5000	10	21.2
2	4750	3000	1	14.2
2	4750	3000	2	12.0
2	4750	3000	3	16.0
2	4750	3000	4	17.4
2	4750	3000	5	10.0
2	4750	3000	6	11.8
2	4750	3000	7	13.0
2	4750	3000	8	9.8
2	4750	3000	9	6.1
2	4750	3500	1	35.3
2	4750	3500	2	32.7
2	4750	3500	3	38.9
2	4750	3500	4	46.8
2	4750	3500	5	47.7
2	4750	3500	6	52.8
2	4750	3500	7	47.3
2	4750	3500	8	47.1
2	4750	3500	9	45.7
2	4750	3500	10	53.5
2	4750	4000	1	24.5
2	4750	4000	2	18.1
2	4750	4000	3	17.2
2	4750	4000	4	18.7
2	4750	4000	5	18.5
2	4750	4000	6	23.6
2	4750	4000	7	17.8
2	4750	4000	8	18.5
2	4750	4000	9	16.1
2	4750	4000	10	13.0
2	4750	4500	1	71.1
2	4750	4500	2	64.7
2	4750	4500	3	48.9
2	4750	4500	4	49.8
2	4750	4500	5	48.0
2	4750	4500	6	76.8
2	4750	4500	7	77.7
2	4750	4500	8	65.2
2	4750	4500	9	51.5
2	4750	4500	10	54.8
2	4750	5000	1	36.3
2	4750	5000	2	16.7
2	4750	5000	3	18.5
2	4750	5000	4	17.0
2	4750	5000	5	7.3
2	4750	5000	6	8.6
2	4750	5000	7	8.6
2	4750	5000	8	10.1
2	4750	5000	9	6.8
2	4750	5000	10	6.2

Table A3-1. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)	Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
36	500	2800	1	55.5	36	2500	2800	1	16.1
36	500	2800	2	9.7	36	2500	2800	2	5.5
36	500	2800	3	7.9	36	2500	2800	3	5.3
36	500	2800	4	7.5	36	2500	2800	4	4.4
36	500	2800	5	5.5	36	2500	2800	5	3.7
36	500	2800	6	5.5	36	2500	2800	6	3.5
36	500	2800	7	3.3	36	2500	2800	7	3.1
36	500	2800	8	3.7	36	2500	2800	8	2.2
36	500	2800	9	0.9	36	2500	2800	9	3.7
36	500	2800	10	3.3	36	2500	2800	10	2.9
36	1000	2800	1	36.6	36	2900	2900	1	34.8
36	1000	2800	2	11.0	36	2900	2900	2	11.7
36	1000	2800	3	9.3	36	2900	2900	3	9.7
36	1000	2800	4	4.9	36	2900	2900	4	11.9
36	1000	2800	5	5.3	36	2900	2900	5	22.7
36	1000	2800	6	5.3	36	2900	2900	6	43.8
36	1000	2800	7	4.4	36	2900	2900	7	163.0
36	1000	2800	8	6.6	36	2900	2900	8	278.0
36	1500	2800	1	10.1	36	2900	2900	9	189.0
36	1500	2800	2	4.4	36	2900	2900	10	52.2
36	1500	2800	3	4.6	36	2900	3400	1	18.9
36	1500	2800	4	4.2	36	2900	3400	2	12.1
36	1500	2800	5	5.7	36	2900	3400	3	6.6
36	1500	2800	6	3.3	36	2900	3400	4	6.2
36	1500	2800	7	3.1	36	2900	3400	5	6.6
36	1500	2800	8	2.9	36	2900	3400	6	6.6
36	1500	2800	9	3.5	36	2900	3400	7	6.4
36	1500	2800	10	4.0	36	2900	3400	8	7.3
36	2000	2800	1	7.9	36	2900	3400	9	9.9
36	2000	2800	2	5.3	36	3400	2900	1	18.5
36	2000	2800	3	6.2	36	3400	2900	2	7.5
36	2000	2800	4	5.7	36	3400	2900	3	5.7
36	2000	2800	5	5.1	36	3400	2900	4	4.9
36	2000	2800	6	3.3	36	3400	2900	5	7.5
36	2000	2800	7	2.4	36	3400	2900	6	6.0
36	2000	2800	8	2.4	36	3400	2900	7	9.9
36	2000	2800	9	2.6	36	3400	2900	8	5.5
36	2000	2800	10	10.1	36	3400	2900	9	9.5

Table A3-1. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
36	3400	3400	1	19.6
36	3400	3400	2	15.4
36	3400	3400	3	10.8
36	3400	3400	4	8.6
36	3400	3400	5	7.9
36	3400	3400	6	3.1
36	3400	3400	7	3.3
36	3400	3400	8	6.0
36	3400	3400	9	4.6
36	3400	3400	10	5.3
36	3900	2900	1	13.4
36	3900	2900	2	8.2
36	3900	2900	3	5.3
36	3900	2900	4	4.0
36	3900	2900	5	3.5
36	3900	2900	6	2.2
36	3900	2900	7	5.3
36	3900	2900	8	6.8
36	3900	2900	9	8.4
36	3900	3400	1	27.8
36	3900	3400	2	12.6
36	3900	3400	3	9.3
36	3900	3400	4	9.7
36	3900	3400	5	8.6
36	3900	3400	6	6.0
36	3900	3400	7	9.3
36	3900	3400	8	9.7
36	3900	3400	9	14.3
36	4400	2900	1	18.3
36	4400	2900	2	8.4
36	4400	2900	3	10.8
36	4400	2900	4	8.2
36	4400	2900	5	7.5
36	4400	2900	6	6.4
36	4400	2900	7	10.8
36	4400	2900	8	9.5
36	4400	2900	9	8.2
36	4400	2900	10	11.0
36	4400	3400	1	29.3
36	4400	3400	2	12.8
36	4400	3400	3	6.0
36	4400	3400	4	11.5
36	4400	3400	5	12.1
36	4400	3400	6	10.6
36	4400	3400	7	12.8
36	4400	3400	8	11.7
36	4400	3400	9	11.2
36	4400	3400	10	12.8
36	4900	2900	1	19.4
36	4900	2900	2	10.1
36	4900	2900	3	11.5
36	4900	2900	4	24.2
36	4900	2900	5	144.5
36	4900	2900	6	166.7
36	4900	2900	7	141.4
36	4900	2900	8	69.2
36	4900	2900	9	43.2
36	4900	2900	10	21.4
36	4900	3400	1	16.7
36	4900	3400	2	11.2
36	4900	3400	3	8.6
36	4900	3400	4	11.7
36	4900	3400	5	9.5
36	4900	3400	6	3.1
36	4900	3400	7	5.5
36	4900	3400	8	4.6
36	4900	3400	9	8.2
36	4900	3400	10	8.6

Table A3-2. Soil nitrate-N profiles obtained from the deep-core sampling conducted during 1993 (the distances are measured from the southwest corner of the sections)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)	Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
1	250	4750	1	15.4	2	500	4500	1	7.4
1	250	4750	2	4.9	2	500	4500	2	4.3
1	250	4750	3	2.2	2	500	4500	3	3.9
1	250	4750	4	1.7	2	500	4500	4	3.4
1	250	4750	5	1.9	2	500	4500	5	7.9
1	250	4750	6	2.2	2	500	4500	6	4.0
1	250	4750	7	1.8	2	500	4500	7	3.4
1	250	4750	8	1.3	2	500	4500	8	3.0
1	250	4750	9	1.1	2	500	4500	9	5.1
1	250	4750	10	1.2	2	500	4500	10	2.4
1	750	3500	1	2.2	2	1500	3000	1	2.0
1	750	3500	2	1.0	2	1500	3000	2	0.8
1	750	3500	3	0.6	2	1500	3000	3	0.5
1	750	3500	4	0.8	2	1500	3000	4	0.8
1	750	3500	5	1.2	2	1500	3000	5	2.3
1	750	3500	6	1.6	2	1500	3000	6	1.8
1	750	3500	7	2.2	2	1500	3000	7	1.3
1	750	3500	8	1.8	2	1500	3000	8	0.9
1	750	3500	9	1.9	2	1500	3000	9	1.1
1	750	3500	10	4.8	2	1500	3000	10	1.1
1	750	4500	1	1.3	2	1500	4500	1	7.8
1	750	4500	2	1.1	2	1500	4500	2	5.1
1	750	4500	3	1.7	2	1500	4500	3	3.2
1	750	4500	4	3.6	2	1500	4500	4	2.6
1	750	4500	5	1.5	2	1500	4500	5	6.2
1	750	4500	6	1.2	2	1500	4500	6	10.0
1	750	4500	7	0.8	2	1500	4500	7	4.5
1	750	4500	8	0.8	2	1500	4500	8	4.0
1	750	4500	9	3.8	2	1500	4500	9	3.1
1	750	4500	10	3.4	2	1500	4500	10	1.8
2	500	3500	1	0.5	2	2000	3500	1	3.9
2	500	3500	2	0.8	2	2000	3500	2	2.2
2	500	3500	3	1.2	2	2000	3500	3	1.8
2	500	3500	4	2.9	2	2000	3500	4	0.8
2	500	3500	5	1.2	2	2000	3500	5	2.4
2	500	3500	6	0.6	2	2000	3500	6	0.8
2	500	3500	7	0.4	2	2000	3500	7	0.6
2	500	3500	8	0.6	2	2000	3500	8	0.6
2	500	3500	9	0.8	2	2000	3500	9	1.0
2	500	3500	10	1.4	2	2000	3500	10	0.9

Table A3-2. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)	Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	2000	4500	1	3.3	2	3500	4000	1	3.4
2	2000	4500	2	1.9	2	3500	4000	2	2.5
2	2000	4500	3	1.2	2	3500	4000	3	2.0
2	2000	4500	4	1.3	2	3500	4000	4	1.2
2	2000	4500	5	1.2	2	3500	4000	5	1.7
2	2000	4500	6	1.8	2	3500	4000	6	1.5
2	2000	4500	7	2.0	2	3500	4000	7	1.3
2	2000	4500	8	1.7	2	3500	4000	8	1.2
2	2000	4500	9	2.1	2	3500	4000	9	1.9
2	2000	4500	10	2.2	2	3500	4000	10	3.4
2	3000	3500	1	0.8	2	3500	4500	1	6.9
2	3000	3500	2	1.8	2	3500	4500	2	3.1
2	3000	3500	3	2.2	2	3500	4500	3	3.3
2	3000	3500	4	4.4	2	3500	4500	4	2.2
2	3000	3500	5	1.0	2	3500	4500	5	2.0
2	3000	3500	6	1.3	2	3500	4500	6	1.3
2	3000	3500	7	1.4	2	3500	4500	7	1.4
2	3000	3500	8	1.0	2	3500	4500	8	1.2
2	3000	3500	9	0.8	2	3500	4500	9	1.3
2	3000	3500	10	1.6	2	3500	4500	10	0.9
2	3000	4500	1	6.8	2	4500	3000	1	7.0
2	3000	4500	2	4.3	2	4500	3000	2	3.8
2	3000	4500	3	3.9	2	4500	3000	3	2.9
2	3000	4500	4	3.9	2	4500	3000	4	2.3
2	3000	4500	5	3.4	2	4500	3000	5	3.8
2	3000	4500	6	2.3	2	4500	3000	6	1.9
2	3000	4500	7	1.7	2	4500	3000	7	2.5
2	3000	4500	8	1.5	2	4500	3000	8	2.2
2	3000	4500	9	2.5	2	4500	3000	9	2.9
2	3000	4500	10	3.3	2	4500	3000	10	2.3
2	3500	3000	1	3.6	2	4500	4500	1	1.8
2	3500	3000	2	2.0	2	4500	4500	2	2.1
2	3500	3000	3	3.0	2	4500	4500	3	1.8
2	3500	3000	4	1.8	2	4500	4500	4	1.4
2	3500	3000	5	2.0	2	4500	4500	5	1.7
2	3500	3000	6	1.8	2	4500	4500	6	2.1
2	3500	3000	7	1.1	2	4500	4500	7	1.8
2	3500	3000	8	1.2	2	4500	4500	8	1.8
2	3500	3000	9	1.4	2	4500	4500	9	1.7
2	3500	3000	10	0.8	2	4500	4500	10	1.2

Table A3-2. (contd . . .)

Section	Distance East (ft)	Distance North (ft)	Depth (ft)	NO3-N (ppm)
2	5000	4500	1	3.6
2	5000	4500	2	3.4
2	5000	4500	3	2.8
2	5000	4500	4	1.8
2	5000	4500	5	3.2
2	5000	4500	6	4.4
2	5000	4500	7	7.4
2	5000	4500	8	11.9
2	5000	4500	9	11.1
2	5000	4500	10	8.5

APPENDIX - D

Ground Water Quality Monitoring Data
(Source: Oklahoma Water Resources Board)

Table A4 - 1. Ground water quality monitoring data for nitrate-N (mg/l).

	Monitoring Wells				Municipal Wells	
Date	1	2	3	4	1	2
Jan. 92*	1.2	1.8	15.8	0.9		
Feb. 92*	2.3	1.0	15.4	1.1		
Mar. 92	2.4	0.8	14.3	1.4		
Apr. 92	1.4	0.8	13.8	1.2		
May. 92	2.8	0.9	14.8	0.9		
Jun. 92	1.1	0.6	13.8	0.9		
Jul. 92	1.4	0.8	17.6	1.6		
Aug. 92	2.0	0.6	17.0	1.5		
Sep. 92	3.6	0.7	16.0	1.9	23.3	5.7
Oct. 92	4.2	1.0	19.1	1.8	21.3	6.6
Nov. 92	3.3	0.5	14.9	1.5	19.2	6.3
Dec. 92	3.1	0.9	15.2	1.2	21.7	6.3
Jan. 93	3.3	0.7	14.5	1.4	0.6	6.5
Feb. 93	3.3	0.7	14.1	1.5	16.8	6.6
Mar. 93	4.4	0.6	10.6	1.3	12.9	5.6
Apr. 93	6.0	1.2	15.7	2.1	18.5	8.3
May. 93	3.0	0.8	16.7	1.8	16.8	8.7
Jun. 93	7.0	0.8	16.2	1.9	8.4	9.0
Jul. 93	2.6	0.8	18.1	2.5	9.1	8.6
Aug. 93	2.3	1.0	16.9	2.2	7.7	6.4
Sep. 93	7.1	2.1	15.8	5.3	27.8	0.8
Oct. 93	7.0	1.2	16.6	2.2	26.0	6.7
Nov. 93						
Dec. 93	7.4	0.6	16.6	1.8	24.3	7.7
Jan. 94	7.6		17.3	2.0	25.6	8.2
Feb. 94	7.7	0.8	16.8	2.1	25.3	8.6
Mar. 94	8.8	0.5	15.2	1.6	25.1	8.4

Statistics						
Mean	4.2	0.8	15.7	1.8	18.4	6.9
Variance	5.7	0.1	2.9	0.7	60.1	3.6
Maximum	8.8	2.1	19.1	5.3	27.8	9.0
Minimum	1.1	0.5	10.6	0.9	0.6	0.8

* Two samples were taken during these months and the mean is reported here

Table A4-1. Ground water quality monitoring data for total dissolved solids (mg/l).

	Monitoring Wells				Municipal Wells	
Date	1	2	3	4	1	2
Jan. 92*	431.0	431.0	463.0	310.0		
Feb. 92*	438.0	438.0	454.0	316.0		
Mar. 92	418.0	454.0	455.0	298.0		
Apr. 92	240.0	400.0	380.0	200.0		
May. 92	460.0	440.0	380.0	304.0		
Jun. 92	380.0	387.0	440.0	300.0		
Jul. 92	410.0	440.0	400.0	296.0		
Aug. 92	220.0	280.0	490.0	294.0		
Sep. 92	380.0	260.0			1019.0	211.0
Oct. 92	330.0	200.0	355.0	312.0	898.0	966.0
Nov. 92	140.0	360.0	425.0	372.0	978.0	993.0
Dec. 92	231.0	250.0	248.0	310.0	947.0	962.0
Jan. 93	420.0	320.0	462.0	398.0	917.0	987.0
Feb. 93	250.0	190.0	380.0	415.0	704.0	979.0
Mar. 93	390.0	330.0	412.0	488.0	755.0	989.0
Apr. 93	408.0	316.0	412.0	376.0	798.0	988.0
May. 93	545.0	400.0	448.0	460.0	760.0	980.0
Jun. 93	210.0	80.0	360.0	456.0	948.0	956.0
Jul. 93	504.0	340.0	476.0	478.0	967.0	952.0
Aug. 93	270.0	270.0	356.0	422.0	937.0	926.0
Sep. 93	386.0	372.0			220.0	1310.0
Oct. 93	520.0	270.0	310.0	408.0	1114.0	917.0
Nov. 93						
Dec. 93	550.0	340.0	470.0	382.0	1072.0	941.0
Jan. 94	650.0		560.0	390.0	1067.0	938.0
Feb. 94	560.0	460.0	430.0	324.0	1023.0	883.0
Mar. 94	490.0	340.0	390.0		1029.0	920.0

Statistics						
Mean	393.5	334.7	414.8	361.3	897.4	933.2
Variance	16255.7	8920.5	4201.4	5320.7	42215.9	40370.4
Maximum	650.0	460.0	560.0	488.0	1114.0	1310.0
Minimum	140.0	80.0	248.0	200.0	220.0	211.0

* Two samples were taken during these months and the mean is reported here

Table A4 - 3. Water table elevation data (ft).

Date	Monitoring Wells 1	2	3	4	Municipal Wells 1	2
Jan. 92*	1250.8	1254.0	1289.7	1251.0		
Feb. 92*	1251.2	1254.4	1290.1	1251.4		
Mar. 92	1251.5	1254.7	1290.1	1251.6		
Apr. 92	1251.7	1254.9	1289.6	1261.2		
May. 92	1251.3	1250.7	1286.9	1252.0		
Jun. 92	1249.5	1251.6	1286.4	1250.2		
Jul. 92	1251.2	1251.4	1287.2	1252.9		
Aug. 92	1250.7	1248.9	1285.8	1250.8		
Sep. 92	1251.0	1251.0	1286.6	1252.0		
Oct. 92	1251.3	1251.7	1286.1	1252.0	1251.6	1250.8
Nov. 92	1252.3	1251.8	1286.3	1253.9	1255.4	1253.1
Dec. 92	1251.6	1251.9	1288.7	1252.3	1252.9	1253.3
Jan. 93	1252.1	1253.5	1289.0	1253.5	1253.4	1252.3
Feb. 93	1252.4	1255.0	1289.8	1253.0		1254.6
Mar. 93	1252.7	1255.1	1291.5	1254.1	1254.5	1256.5
Apr. 93	1253.0	1254.7	1289.1	1255.4		1255.0
May. 93	1253.4	1256.2	1288.8	1255.4	1253.8	1255.8
Jun. 93	1255.1	1265.7	1285.2	1252.6	1255.9	1254.1
Jul. 93	1254.0		1285.9	1256.0	1255.2	1253.6
Aug. 93	1253.0	1251.8	1287.3	1253.8	1251.0	1251.8
Sep. 93	1250.2	1253.2	1287.5	1254.0	1253.0	1252.4
Oct. 93	1253.5	1253.1	1286.9	1254.3	1251.5	1252.4
Nov. 93						
Dec. 93	1253.9	1255.7	1286.4	1251.7	1254.5	1250.4
Jan. 94	1253.8	1254.8	1286.6	1254.4	1254.6	1252.9
Feb. 94	1253.8	1254.8	1286.4	1254.2	1254.6	1253.0
Mar. 94	1253.9	1255.1	1286.7	1254.8	1254.7	1253.3

Statistics						
Mean	1252.3	1253.8	1287.7	1253.4	1253.8	1253.3
Variance	2.0	9.6	2.8	4.9	2.3	2.6
Maximum	1255.1	1265.7	1291.5	1261.2	1255.9	1256.5
Minimum	1249.5	1248.9	1285.2	1250.2	1251.0	1250.4

* Two samples were taken during these months and the mean is reported here