Numerical Simulation of Groundwater Flow and Contaminant Transport in an Alluvial Aquifer

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ABSTRACT

A nitrate sampling program was conducted in the vicinity of a rural municipality to determine the source of nitrate contamination of the municipal groundwater supply. A finite-difference groundwater modeling program was also used to determine the direction of groundwater flow in the area. Results indicate that nitrate contaminated groundwater is directed preferentially towards the municipal wellfield by unique geologic features in the area.

ACKNOWLEDGMENTS

The author wishes to express thanks to the following individuals: the citizens in the Torrington area who participated in the nitrate sampling program, Ed Wells and George Baird of the Torrington Department of Public Works for their cooperation and assistance throughout the sampling program, and especially to David Foster for his input and guidance throughout my graduate studies.

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CHAPTER I

Introduction

The Wellhead Protection (WHP) Program

In June of 1986, Congress amended the Safe Drinking Water Act (SDWA) of 1974 to include section 1428 "State Programs To Establish Wellhead Protection Areas" (United States Statutes at Large, 1986). This amendment mandated for the first time specific provisions for the protection of groundwater resources used as public water supplies from the potential threat of contamination. The amendment empowers the United States Environmental Protection Agency (U.S. EPA) to be the lead regulatory agency and specifies the minimum duties to be carried out by the individual states to protect wellhead areas within their jurisdiction. These minimum duties are enumerated in part (a) of section 1428 and are summarized below:

Part (a):

1. specify the duties of state agencies, local governmental entities, and public water supply systems;
2. determine, for each wellhead, a wellhead protection area (WHPA) as defined in part (e);

3. identify potential anthropogenic sources of contamination within each wellhead protection area;
4. develop a program of technical and financial assistance, education, and training;
5. develop contingency plans for the location and provision of alternative drinking water supplies;
6. provide that consideration be given to all potential sources of contamination when locating future wells.

The definition of a wellhead protection area given in part (e) reads as follows: " ..."wellhead protection area" means the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield" (United States Statutes at Large, 1986). The State of Wyoming is currently in the process of considering the development of a comprehensive WHPA program.

Recognition of Groundwater Contamination in Torrington

The problem of nitrate contamination in the Town of Torrington groundwater supply was first observed in 1986 when, through routine sampling, it was found that nitrate levels had increased in several of the towns wells (Baker, 1989). The increase was slight and none of the wells were exceeding the EPA recommended maximum contaminant level (MCL) of 10 parts per million (ppm) Nitrate-Nitrogen (NO_3-N) (40 CFR 141.23). By the spring of 1988, however, several of the wells had shown a dramatic increase in the levels of nitrate and some were exceeding the 10 ppm NO_3-N limit. By November, 1988 all of the municipal wells were approaching the MCL. In accordance with EPA guidelines the town had developed a contingency plan to provide bottled water to pregnant women and infants under one year of age if the MCL was exceeded in the town's water supply. However, a more permanent solution to the problem was desirable. Developing a WHPA to protect the groundwater supply was deemed to be the most appropriate method towards achieving this goal.

Project Goals

This study is in response to an immediate threat of nitrate contamination to the municipal groundwater supply of Torrington, Wyoming. The goals of this report are:

1. Develop a sampling program in the Torrington area to monitor the levels of nitrate contamination;
2. Develop a database of technical information of aquifer properties for the purpose of simulating groundwater

flow using numerical modeling techniques;

3. Determine from the simulation the location of aquifer recharge areas, and the direction of groundwater flow and contaminant transport;
4. Identify potential sources of nitrate contamination within the area, and;
5. Develop management alternatives to mitigate the immediate threat to the municipal water supply.

This information can then be used to aid in the delineation of a wellhead protection area for the municipal groundwater supply of Torrington as specified by section 1428 parts a.2 and e of the 1986 amendments.

CHAPTER II

Literature Review

Toxicology of Nitrate

The toxicology of nitrate has been extensively studied and a definitive review of the voluminous literature is beyond the scope of this paper. The reader is referred to articles by authors such as Ridder and Oehme, 1974; Shirley, 1975 for a more comprehensive treatment. In the following paragraphs a brief review of the toxicological effects of nitrate ingestion by humans will be given.

Nitrate itself is essentially non-toxic to man but it can be reduced to nitrite in the gastrointestinal tract of human infants and by the microflora of the human mouth (Swann, 1975). The nitrite presents a direct toxic hazard, and has also been suspected for many years of forming carcinogenic N-nitroso compounds (nitrosamine) by reaction with amino compounds (Swann, 1975).

Clinically, acute nitrite poisoning is identified by the disease methemoglobinemia. The disease is characterized by drowsiness, increased respiration rates, the development of blue coloration of the skin tissue, and death (Ridder and Oehme, 1974). The characteristic discoloration of the skin is often the first symptom to appear in a victim.

Infants under 3 to 4 months are susceptible to nitrate due to the bacterial reduction of nitrate to nitrite in the upper digestive tract. This reduction occurs as a consequence of unique gastrointestinal features, principally elevated pH levels, that encourages the growth of these bacteria. The nitrite produced by these bacteria converts hemoglobin in the blood to methemoglobin which is unable to transport oxygen to the body tissues. The outcome is oxygen deprivation, or suffocation (Winston et al., 1971). The characteristic blue coloration of affected infants has resulted in the disease often being referred to as "blue-baby syndrome" (Atlas and Bartha, 1987).

The Nitrogen Cycle

Nitrogen is ubiquitous in the natural environment and is essential for plant and animal growth as it is incorporated in amino acids and proteins of all living organisms. In the broadest sense the nitrogen cycle describes the movement of nitrogen through all parts of the earths surface and the atmosphere. Figure 1 indicates how complex the nitrogen cycle is and why research often focuses on one aspect of the cycle (Bremner, 1967; Campbell and Lees, 1967; Keeney, 1983).

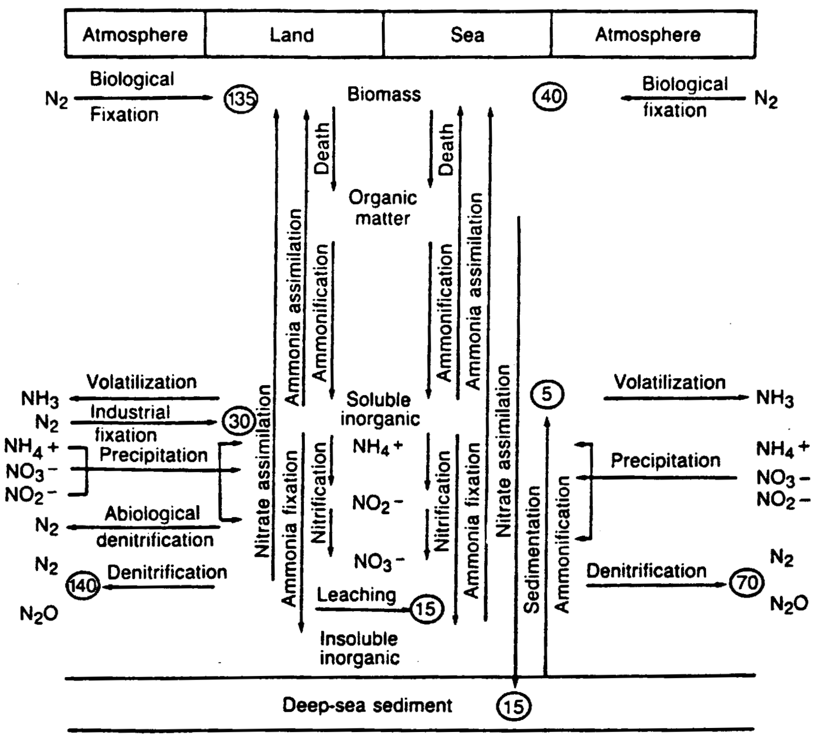

Figure 1. The Nitrogen Cycle (From Burns and Hardy, 1975).

As will be shown in Chapter III, the study area is located in a rural agricultural area and therefore a portion of the agricultural nitrogen cycle will be briefly discussed in order to provide an insight as to the behavior of nitrogen in this environment.

The Agricultural Nitrogen Cycle

The agricultural nitrogen cycle (Figure 2) has been extensively studied with the scope of investigations ranging in size from statewide groundwater investigations (Adelman et al., 1985; Hallberg, 1987a) to detailed studies of virtually all aspects of the cycle itself under almost every conceivable set of conditions (Hergert, 1986; Riha et al., 1986; Rosenberg et al., 1986).

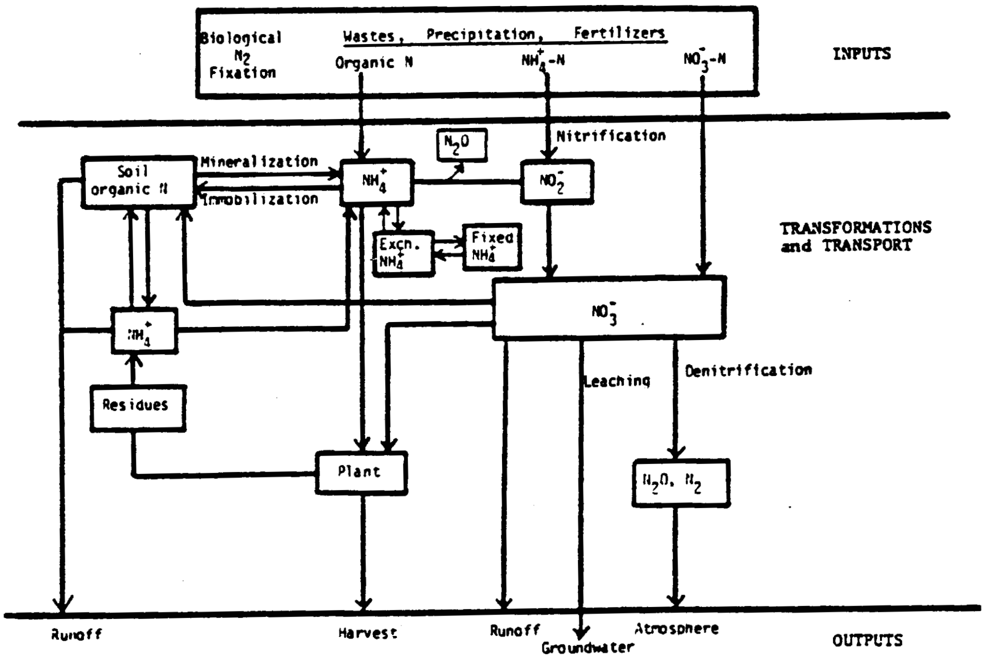

Figure 2. An Agricultural Nitrogen Cycle (From Keeney, 1983).

The intensive study of the agricultural nitrogen cycle in recent years has been prompted by increasing evidence that indicates excessive use of nitrogen fertilizer has a direct impact on shallow groundwater supplies (Baker and Johnson, 1981; Baker and Lafen, 1983; Keeney, 1986b; Halberg, 1987a). The threat to water quality of groundwater supplies by nitrogen is due to the transformation (nitrification) of applied nitrogen fertilizer to nitrate by microorganisms that thrive in soils. This transformation mobilizes the nitrogen which may then be readily leached into the groundwater system (Keeney, 1986a).

As the focus of this research is the nitrate contamination of a municipal groundwater supply, the pathway that leads to the mobilization and subsequent leaching of nitrate into the subsurface is of interest.

Nitrification and Movement of Nitrate in Groundwater

The soil nitrification process is illustrated in Figure 3. The conversion and mobilization of organic forms of nitrogen to nitrite and nitrate in the soil column is a biologically mediated process. The first step in the transformation of organic nitrogen to nitrate, ammoinium oxidation, is carried out in large part by Nitrosomonas bacteria. The second step, nitrite oxidation, is performed by Nitrobacter bacteria. In a strict chemical sense the reactions can be represented as follows:

1. $NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$

2. $NO_2^- + 0.5O_2 \rightarrow NO_3^-$

With the exception of minor transformations that occur in the atmosphere, this process is the only source of nitrate to the biosphere (Payne, 1981) and a sense of the dominance of these two bacteria over other species is shown in Table 1.

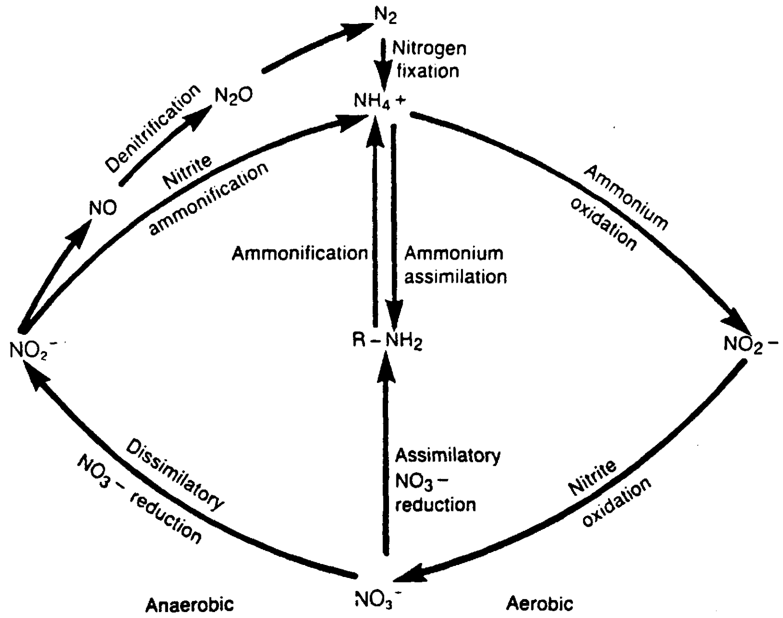

Figure 3. The Nitrification Process (From Atlas and Bartha, 1987).

Table 1. Nitrification Rates (From Focht and Verstreate, 1977).

Organism	Substrate	Product	Rate of formation (μgN/day/g dry cells)	Max. product accumulation (μgN/ml)
Arthrobacter (heterotroph)	NH_4^+	nitrite	375–9000	0.2–1
Arthrobacter (heterotroph)	NH_4^+	nitrate	250–650	2–4.5
Aspergillus (heterotroph)	HN_4^+	nitrate	1350	75
Nitrosomonas (autotroph)	NH_4^+	nitrite	1–30 million	2000–4000
Nitrobacter (autotroph)	NO_2^-	nitrate	5–70 million	2000–4000

Once formed, nitrate is highly mobile and is often found at greater concentrations in the soil solution than on soil particles and colloids (Bohn et al., 1979). This characteristic is due in large part to the anionic nature of both the nitrate ion and typical soil particles which, being of the same charge, tend to repel one another.

As a result in groundwater nitrate can essentially behave as a tracer (Thomas, 1970) and a knowledge of the movement of water through soil and groundwater systems enables the prediction of nitrate movement (MacGregor, et al., 1973). These characteristics provide the justification for utilizing a groundwater flow model as a first approximation for determining the movement of nitrate contaminants in aquifers which supply the Town of Torrington with drinking water.

Modeling

Numerous computer models exist for simulating the interaction of surface and ground waters (Schenk and Porter, 1989) and for simulating the flow of water in subsurface environments (McDonald and Harbaugh, 1984; Walton, 1989). For this investigation, the widely accepted model entitled "A Modular Three-Dimensional Finite-Difference Groundwater Flow Model" written by Michael G. McDonald and Arlen W. Harbaugh (MacDonald and Harbaugh, 1984) was used. The model consists of a main program and a series of subroutines or modules. The modules are composed of a series of packages with each package simulating a specific feature, such as flow from rivers or the pumping of wells, which may impact the hydrologic system. The modular nature of the program has resulted in it having become commonly known as "Modflow" and it will be referred to by this name in all future references.

Previous Groundwater Investigations

Numerous investigations with respect to groundwater and geology have been conducted in the area. Early investigations were concerned with determining the geology (Adams, 1902) and mineral resources found within the Goshen County area. The focus of a later investigation (Rapp et al., 1957) was the determination of the groundwater resources in the entire Goshen County area and an evaluation of the possibilities for developing these resources. The subject of the most recent investigations has been an evaluation of the hydrologic mass balance of the North Platte Irrigation District (Crist, 1975) and the evaluation of the impact of increased groundwater withdrawals upon the water quality and quantity in the alluvial aquifer of the North Platte Irrigation District (Herrmann, 1976).

The definitive report on the water resources in Goshen County is that of Rapp et al. (1957) mentioned above. The importance of this report lies in the fact that all subsequent investigations, i.e. Crist's and Herrmann's, utilized the geologic and hydrologic data developed by Rapp as the basis for their investigation.

The most significant difference between previous reports and this investigation is scale, or size, of the study area and its implications. Many of the assumptions regarding the relationship of the alluvial and terrace aquifers, while appropriate at the scale that Rapp and others were working, are not appropriate at the scale of this study. While the geologic and hydrologic data developed by Rapp is again used as the basis for this report, these data have been modified as the result of field observations. As will be shown in later chapters, these modifications become very significant to the problem of groundwater flow and nitrate contamination in the Torrington area.

CHAPTER III

DESCRIPTION OF STUDY AREA

Location

The study area is located in the east-central portion of Goshen County, Wyoming, within the high plains section of the Great Plains physiographic province of the western United States (Figure 4). The area extends for 10 miles along the valley of the North Platte River which flows eastward into Nebraska. Included within the boundaries of the area is the town of Torrington, Wyoming and its outlying rural population (Figure 5).

The topography is typical of alluvial valleys in eastern Wyoming and the western United States. Principle features include the currently active floodplain of the North Platte River located along the southern boundary of the area and a series of terraces sweeping away from the present channel (Figure 6). The terraces eventually grade into upland areas. Elevations range from 4075 ft. along the North Platte to 4250 ft. in the upland areas along the northern boundary of the site.

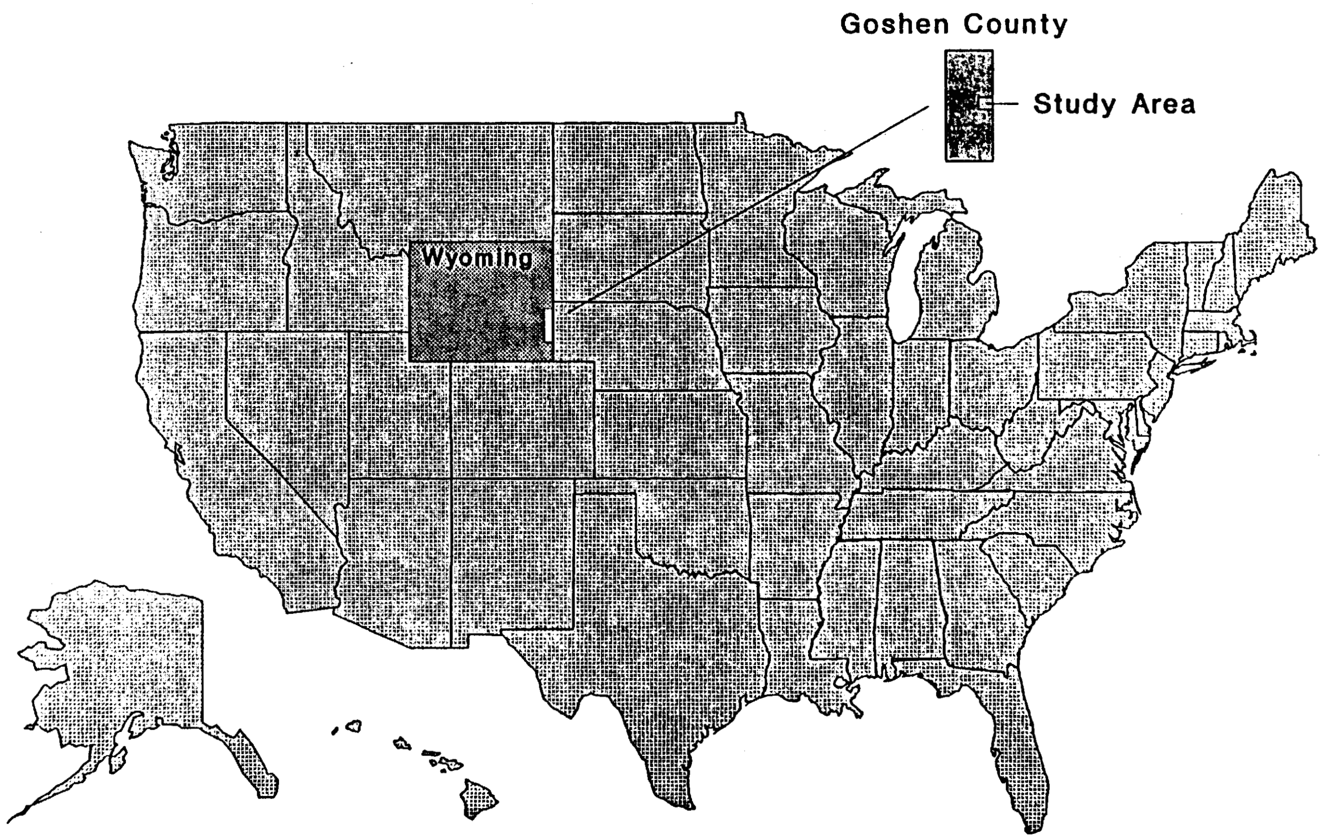

Figure 4. General Location of Study Area.

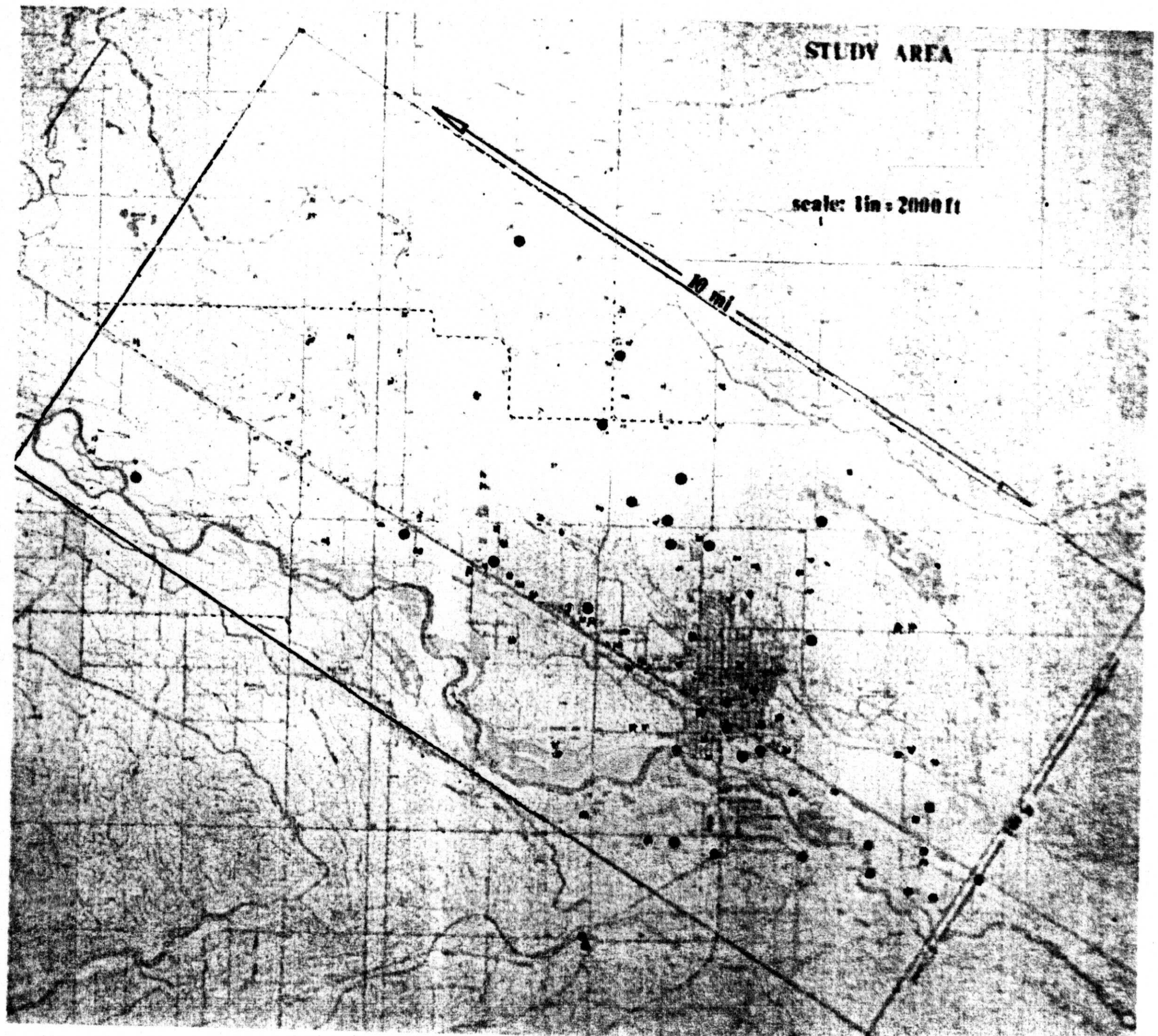

Figure 5. Study Area with Boundaries Delineated.

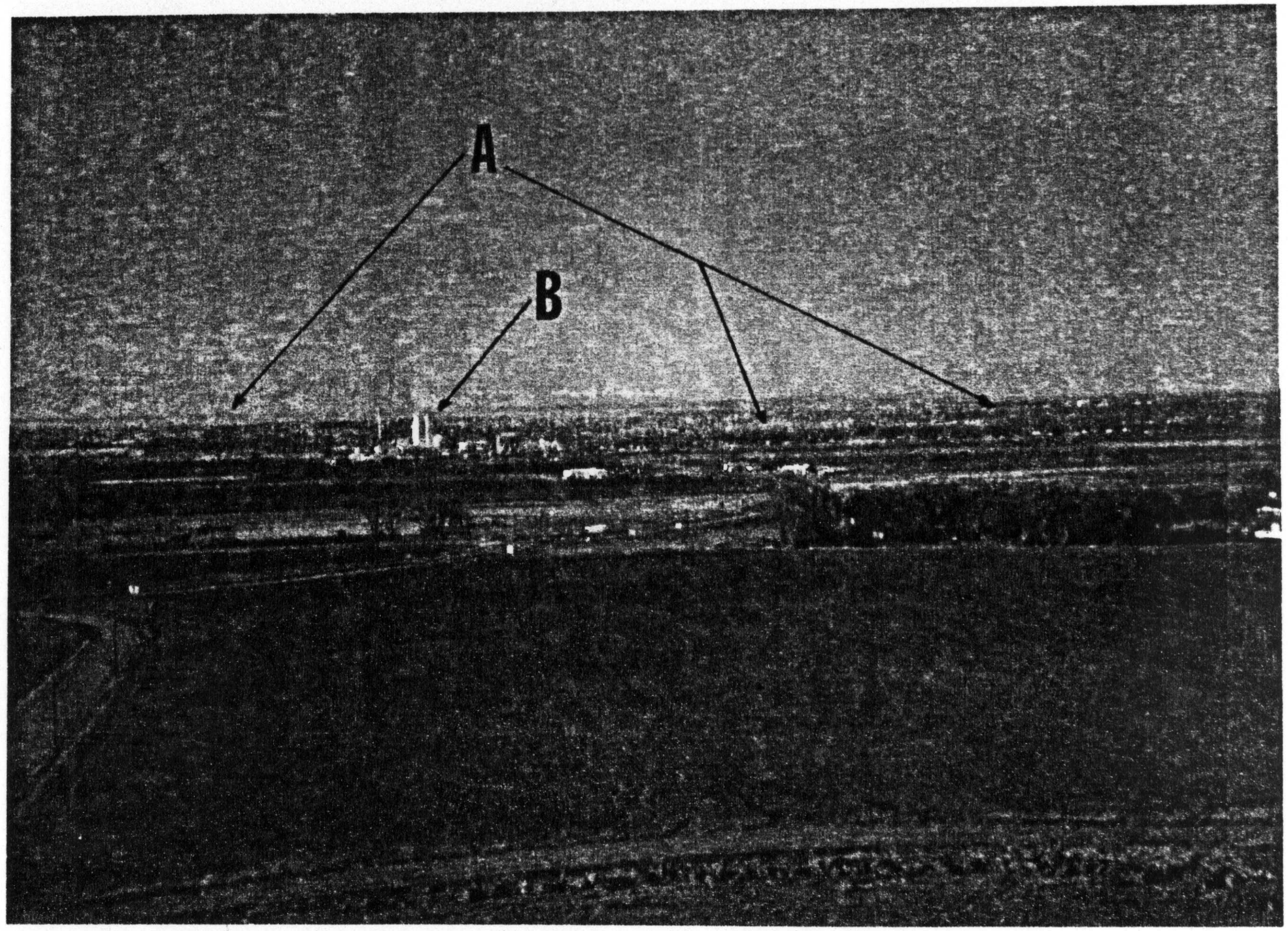

Figure 6. General Topography of the Study Area. View is from south of the Platte Valley looking north. Note North Platte channel as marked by vegetation (A) and Torrington's largest industry, Holly Sugar Co., (B).

Climate

The climate in the area is characterized as semi-arid with the annual average precipitation at Torrington being 13.36 inches as computed from the thirty year record prior to this study (Wyoming Water Research Center). The majority of this precipitation occurs within the period of April to July in the form of showers and thunderstorms.

Additional climatic characteristics include high rates of evaporation and large fluctuations in both daily and seasonal temperatures. The mean seasonal temperature in the area is 47.5° F and the growing season is approximately 150 days in length (Rapp et al., 1957).

This type of climate supports a variety of grasses and short shrubs in the upland areas away from the watercourses while large phreatophytes such as cottonwood densely populate the areas immediately adjacent to the watercourses (Figure 6). Intensive agricultural activities are supported by large irrigation diversions.

Industry

The principal industrial activities in the area are those associated with agriculture. Of the 32,000 acres included in the area, approximately 50% or 16,000 acres are under cultivation. The principal crops grown in the area include corn, soybeans and pinto beans, and sugar beets; smaller amounts of hay, alfalfa, and sorghum are also cultivated. While the majority of these crops are shipped out of the area for further processing, sugar beets are processed and refined at a large plant operated by Holly Sugar Co., Inc. in south Torrington, which is the towns single largest employer (Figure 6). Additional industrial activities include agrichemical and feedlot operations.

Geologic History

An extensive review of the geologic history of Goshen County is provided by Rapp et al. (1957). A brief summary of the history of the North Platte River and Rawhide Creek, which enters the Platte River west of the study area, is given here due to the relevant nature of this information to this study.

The North Platte River has existed for several million years, and, during middle Pliocene time (Appendix A), it was one of many river channels that meandered slowly across broad mudflats that existed in the area. Towards the end of Pliocene time, tectonic activity to the west resulted in increased erosive activity of the river, and the North Platte is thought to have established itself in essentially its present course at this time.

By middle Pleistocene time the river had cut through about 1100 feet of sedimentary material to a level approximately 200 feet above its current elevation. During late Pleistocene time, the Platte cut a channel nearly 200 feet below its current elevation.

During this time the Rawhide Creek tributary flowed through the area in a channel parallel to, and north of, the Platte River. This channel can be identified in the bedrock contour map of the area (Figure 7). A continuous ridge of bedrock separated the two channels in the study area.

After this erosional event, the valleys were refilled 180 ft. to the level of the highest, or third, terrace. The erosive power of the stream once again increased and the stream incised into and reworked parts of the third terrace to form the second terrace deposits. Further periods of erosion have resulted in the development of the deposits of the first terrace and the currently active floodplain of the river in recent times.

At some time during these events, the bedrock separating the two river channels was breached. The only breach mapped by Rapp et al. (1957) is located in the western part of the study area and is clearly evident when the bedrock contour map is viewed in three dimensions (Figure 8). This breach may reflect the position of Rawhide Creek as it shifted towards it current location west of the study area. However, it may also reflect a place where the main channel of the North Platte was captured by the Rawhide Creek tributary. The mechanisms for the capture of a main channel by a tributary are well documented by Ritter, 1978.

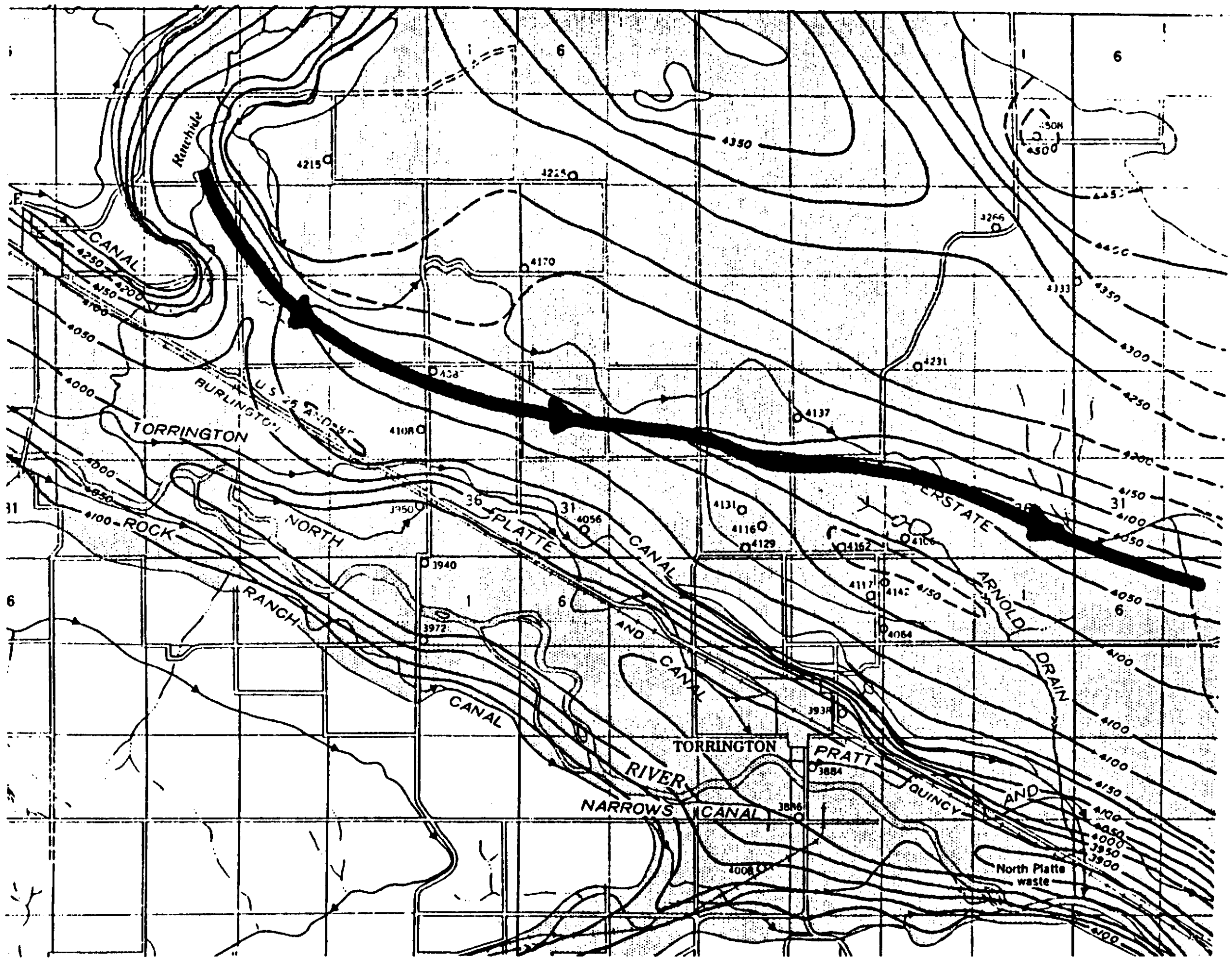

Figure 7. Bedrock Contour Map of the Study Area (Rapp et al., 1957). The previous channel of Rawhide Creek is indicated by the heavy black line.

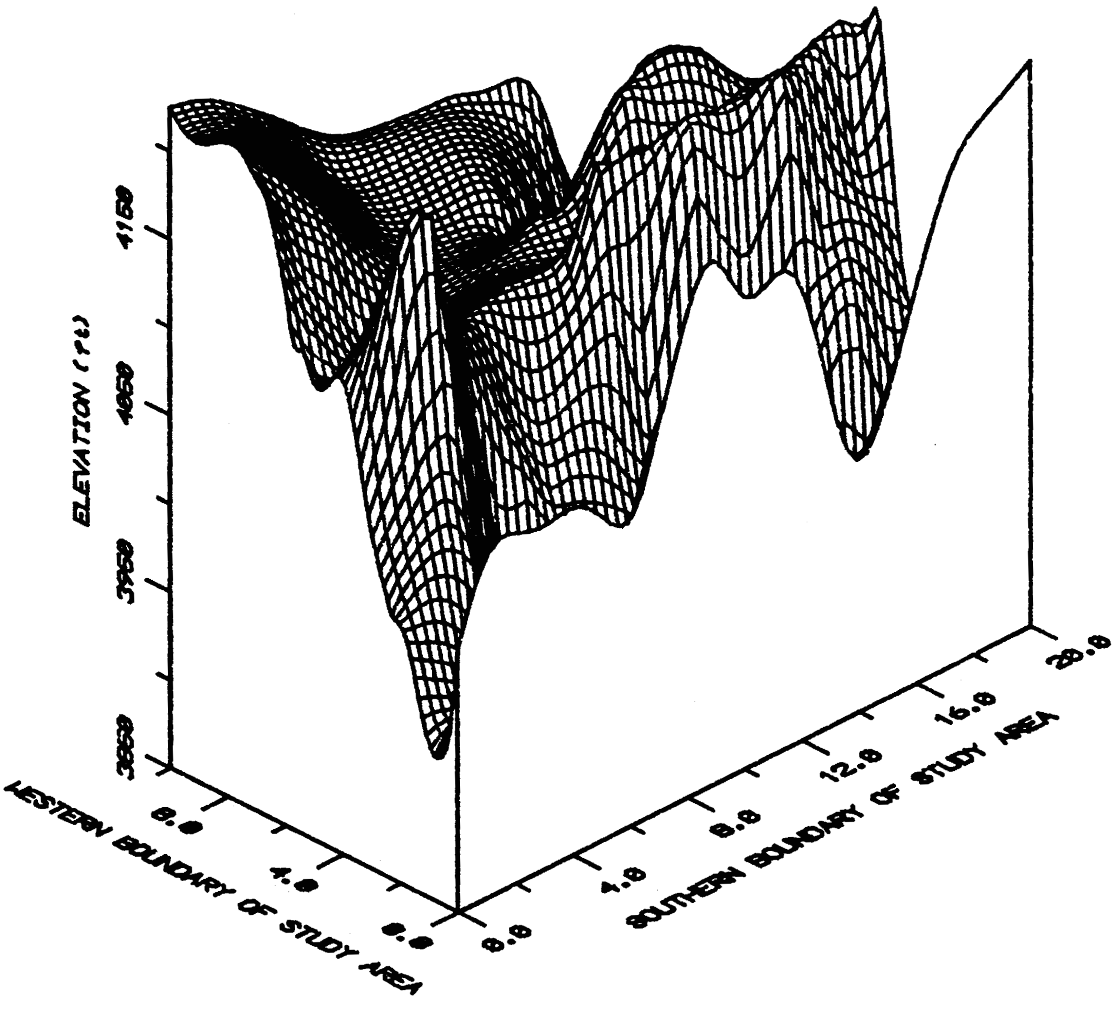

Figure 8. Computer Generated 3-D View of Bedrock Showing Breach. Data derived from Rapp et al., 1957. Arrow indicates location of large breach in the bedrock outcrop.

Regardless of origin, the most important consequence of this breach is that, where it occurs, a direct hydraulic connection exists between the deposits of the third terrace and those of the valley fill (Figure 9). Where the bedrock remains intact, it acts as a subsurface dam which hinders the movement of groundwater flow between these two deposits (Figure 10).

Geology of Study Area

As stated in Chapter II, a closer examination of the study area is warranted by the scale of the investigation. This examination reveals that the geologic mapping done by Rapp et al., (1957) may not be entirely correct. As a result, previous groundwater investigations which utilized this information may also be incorrect. Of particular interest to this investigation is the occurrence of a bedrock outcrop of the Brule Formation north of Torrington.

The geology of this area as mapped by Rapp et al., (1957) is shown in Figure 11 and a description of the geologic units is given in Table 2; the descriptions are those of Rapp et al. The representation of the Brule Formation north of Torrington given by Crist (1975) is similar (Figure 12); the outcrop is shown to be continuous through this area. Several lines of evidence suggest that this representation may not be correct.

A principle characteristic of the Brule formation is that, where it occurs at or near the land surface, it forms a

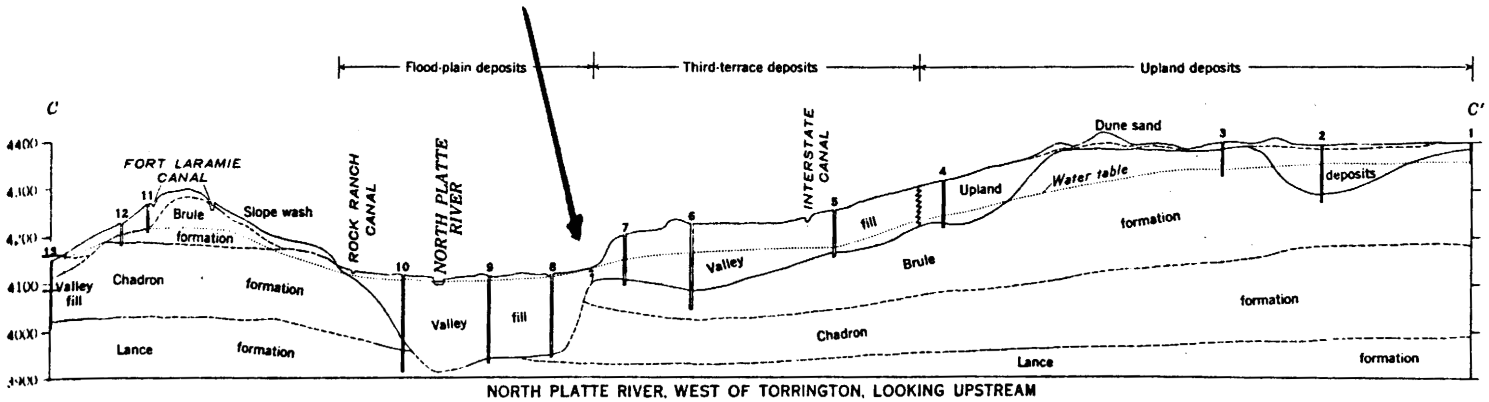

Figure 9. Cross Sectional View of Breach illustrating Hydraulic Connection between Deposits of the Third Terrace and Valley Fill (arrow). From Rapp et al., 1957.

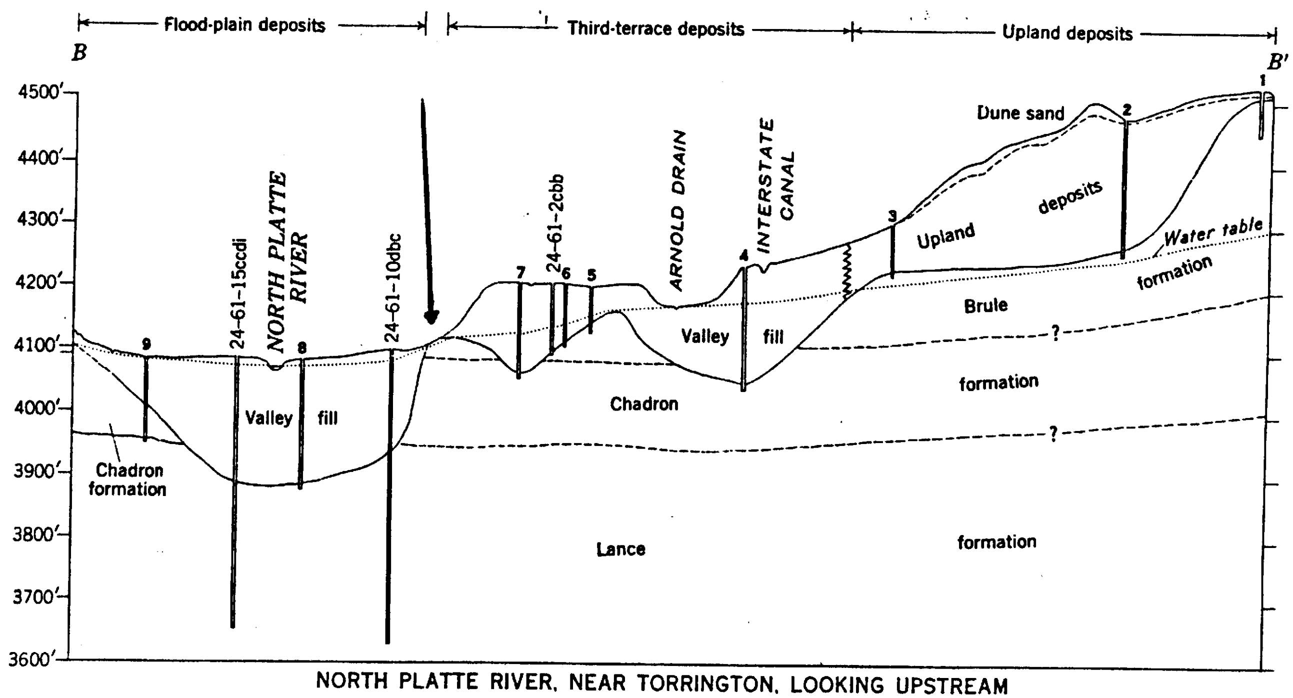

Figure 10. Cross Sectional View showing Bedrock acting as a Subsurface Dam (arrow). From Rapp et al., 1957.

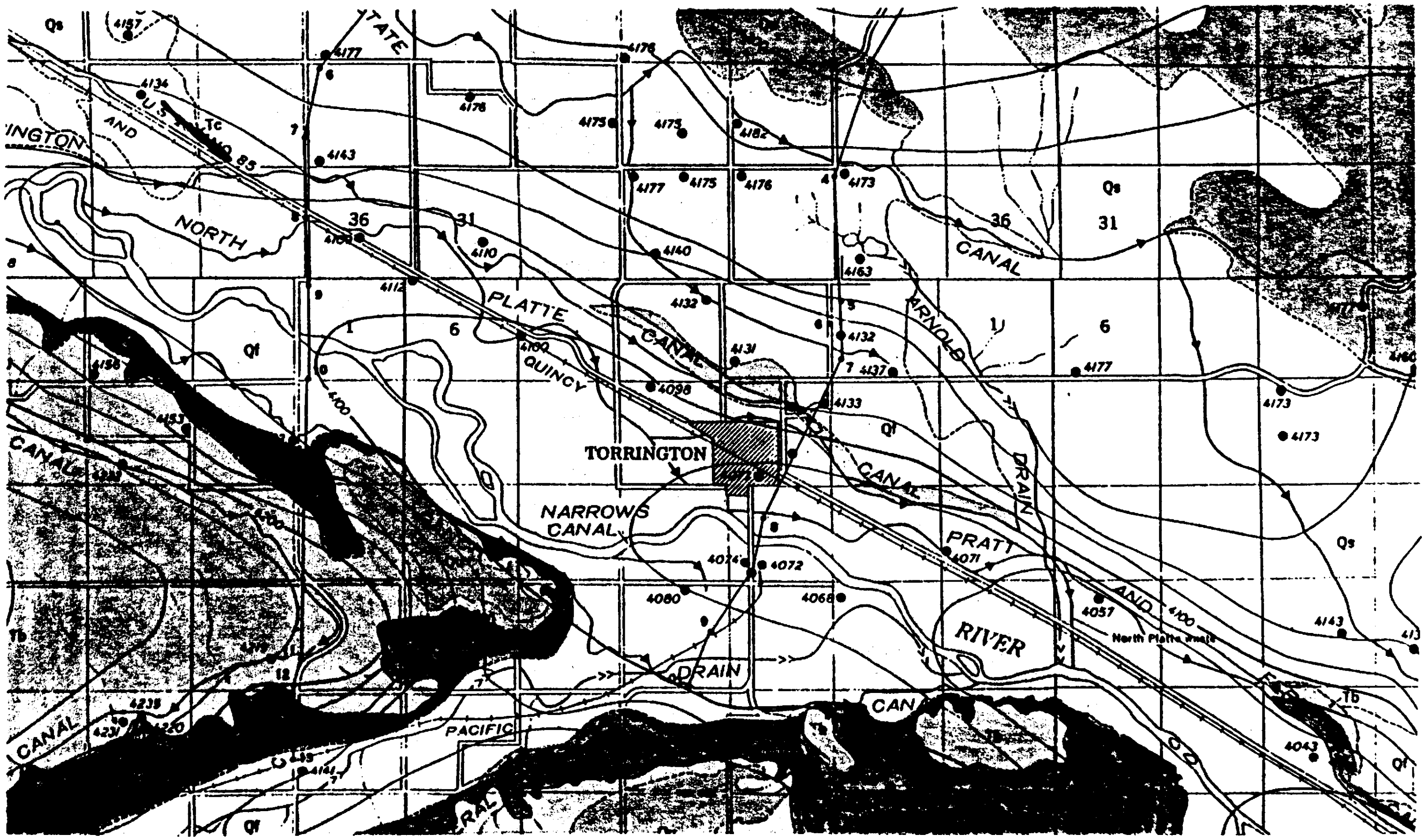

Figure 11. Geology of Study Site (From Rapp et al., 1957).

Table 2. Description of Geologic Units (From Rapp et al., 1957).

System	Series	Symbol	Unit	Description
QUATERNARY	*Recent*	Qs	Dune sand	*Fine-grained windblown sand; serves as excellent infiltration medium for recharge from precipitation*
QUATERNARY	*Pleistocene and Recent*	Qf	Valley fill	*Includes deposits beneath the third, second, and first terraces and the present flood plain. Sand and gravel containing lenses and beds of fine sand, silt, and clay, large chunks of siltstone, lenses of siltstone pebbles, and cobbles and boulders. Yields water to many domestic and stock, irrigation, municipal, and industrial wells*
QUATERNARY	*Pleistocene*	[illegible]	Upland deposits	*Sand and gravel containing lenses and beds of fine sand, silt, and clay, and lenses of siltstone pebbles. Some of these deposits in the northern part of the area would yield enough water for irrigation if a sufficient saturated thickness were reached. May include deposits of Pliocene age*
TERTIARY	*Oligocene*	Tb	Brule formation	*Moderately hard, brittle argillaceous siltstone. Yields small quantities of water to domestic and stock wells from fractures and from lenses of sandstone*
TERTIARY	*Oligocene*		Chadron formation	*Consists mainly of green, brown, red, or buff loosely to moderately cemented clay and silt that contains channel deposits of sandstone and conglomerate. Contains a lower unit consisting of variegated fluviatile deposits. Yields water under artesian pressure from coarse-grained channel deposits to many domestic and stock wells*

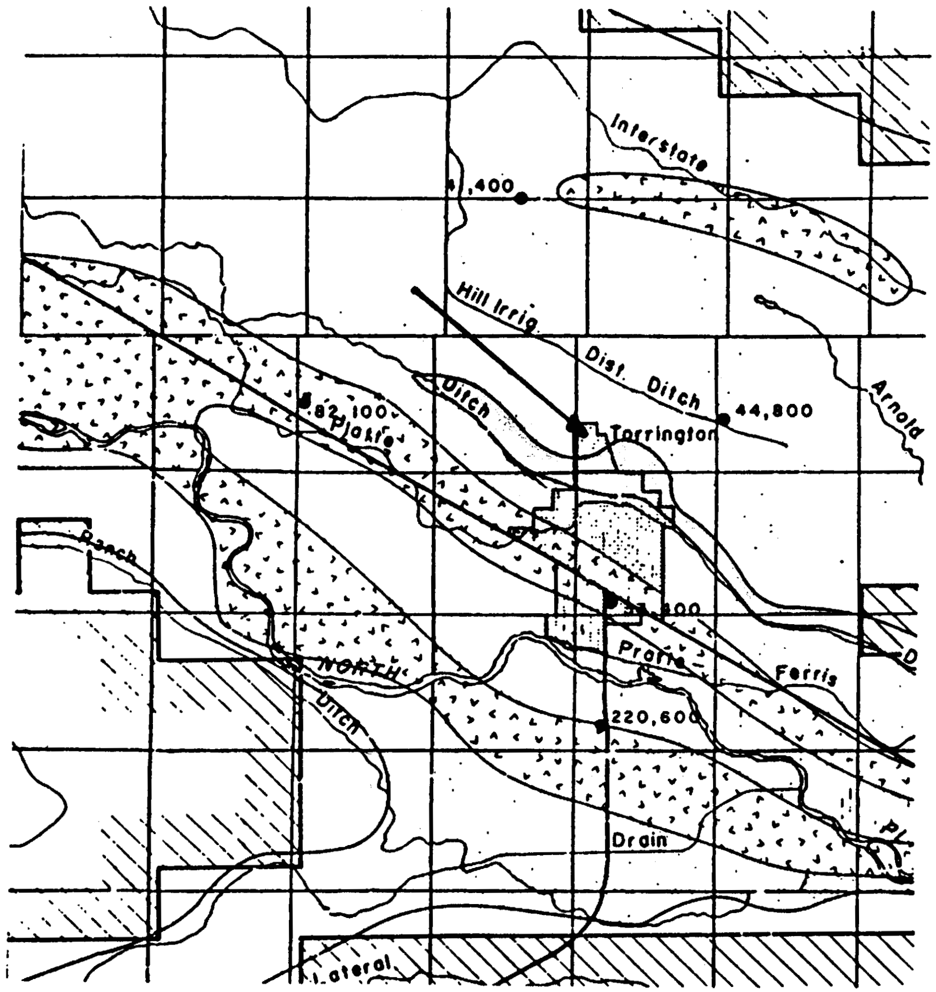

Figure 12. Geology of the Area (From Crist, 1975). Representation of Brule outcrop north of Torrington (arrow) is identical to that of Rapp et al., 1957.

distinctive ridge which appears as a well defined break in slope on a topographic map (Plate 1). However, where breaches in the Brule exist, as is the case west of Torrington, this sharp break in slope is not evident and the area is characterized by gentle slopes and gullies (Plate 1). The similarity between features found in this area and those found north of Torrington, where the Brule appears to be ill-defined, suggests that the Brule is not present at this location and that this area may mark the location of a previously unmapped breach.

Site investigation as recorded in Figures 13 through 18 tends to verify this conclusion; observation points for these Figures are shown on Plate 1. Figure 13 shows the Brule outcrop as it appears at the eastern end of the study area; the break in slope and coloration of the Brule is very distinct. Figure 14 shows the outcrop extending westward towards Torrington; a municipal water tank sits atop the ridge. In Figure 15, structures at the left hand side appear to be located in a depression, or gully, and the Brule seems to be pinching out in this area. Figure 16 clearly shows the gully in this area. While this feature is atypical for the Brule, it is quite consistent with the gully features that occur in the western part of the study area as mentioned above. Figure 17 marks the first location at which the Brule is once again clearly defined.

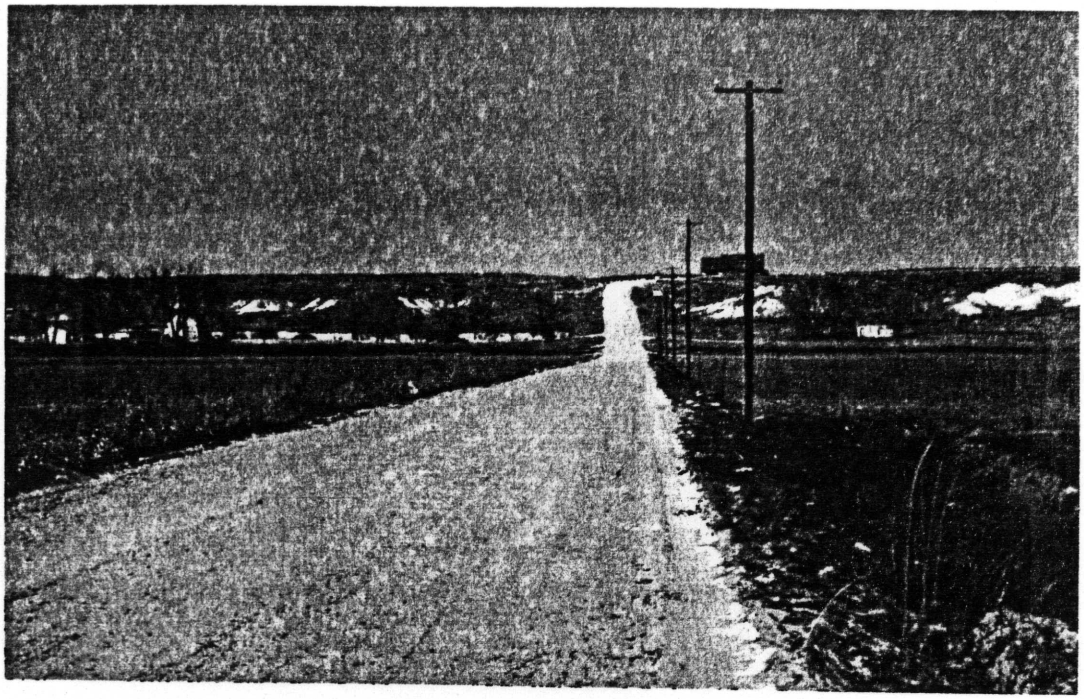

Figure 13. Brule Outcrop at East End of Study Area.

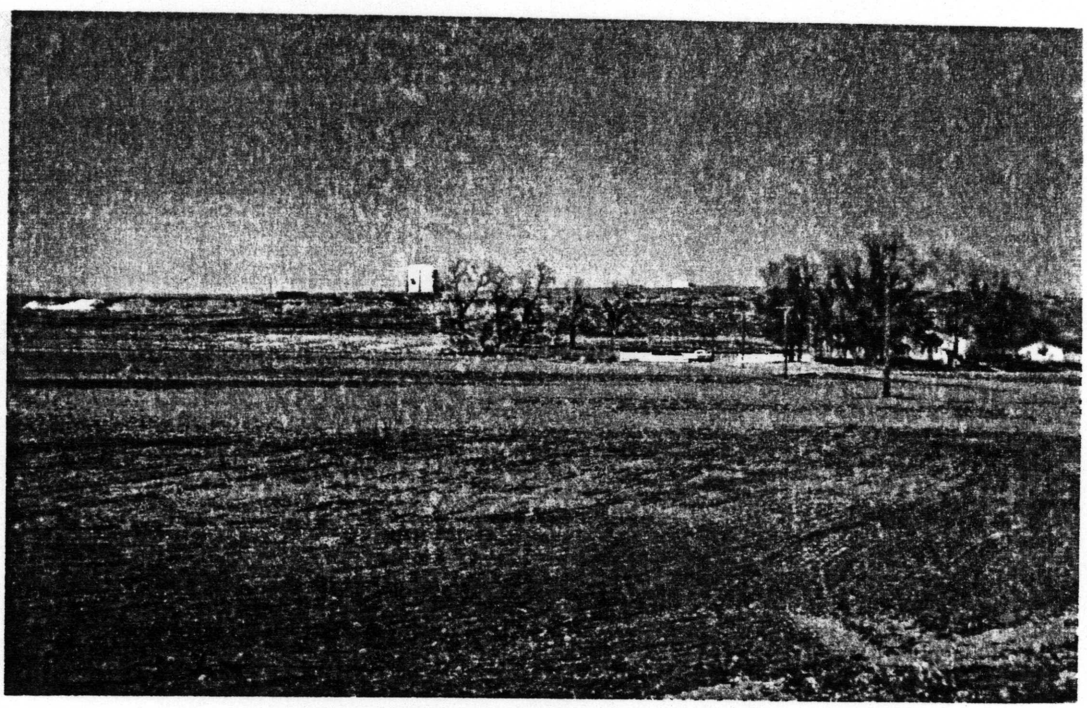

Figure 14. Brule Outcrop near Torrington.

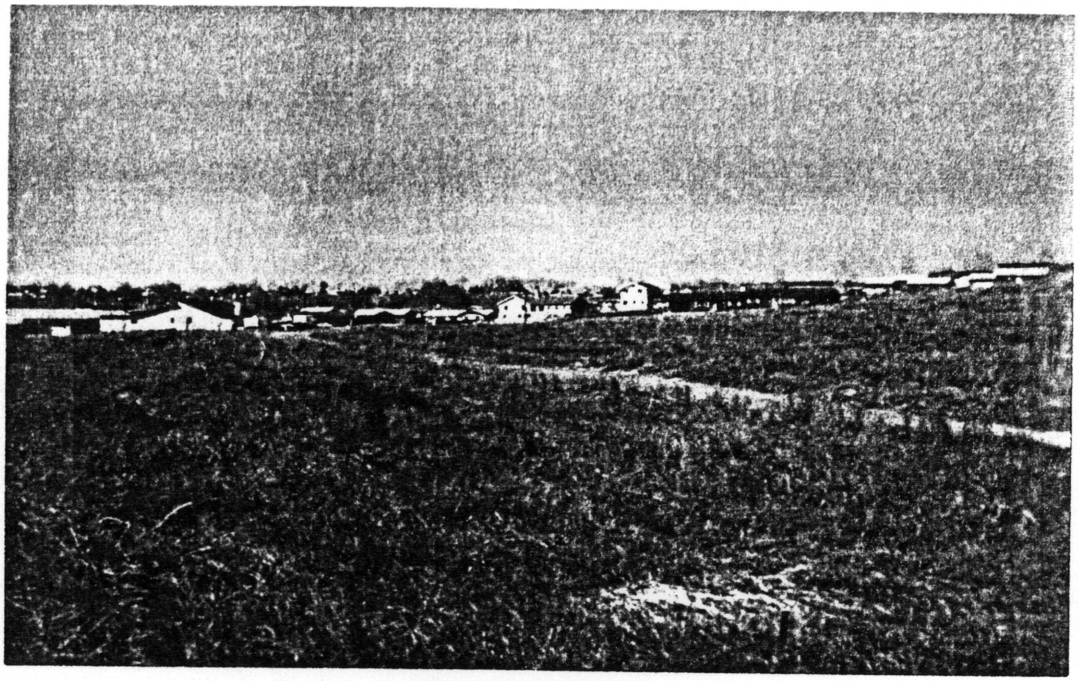

Figure 15. Brule Outcrop. Structures appear to be in a gully.

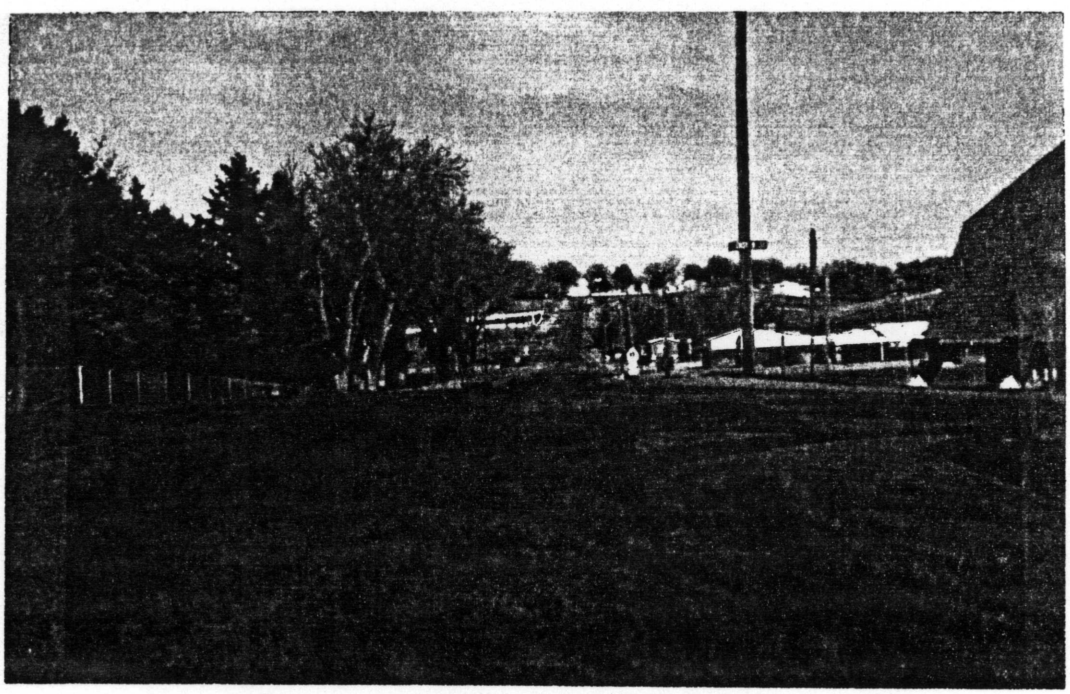

Figure 16. Breach in Brule Formation North of Torrington.

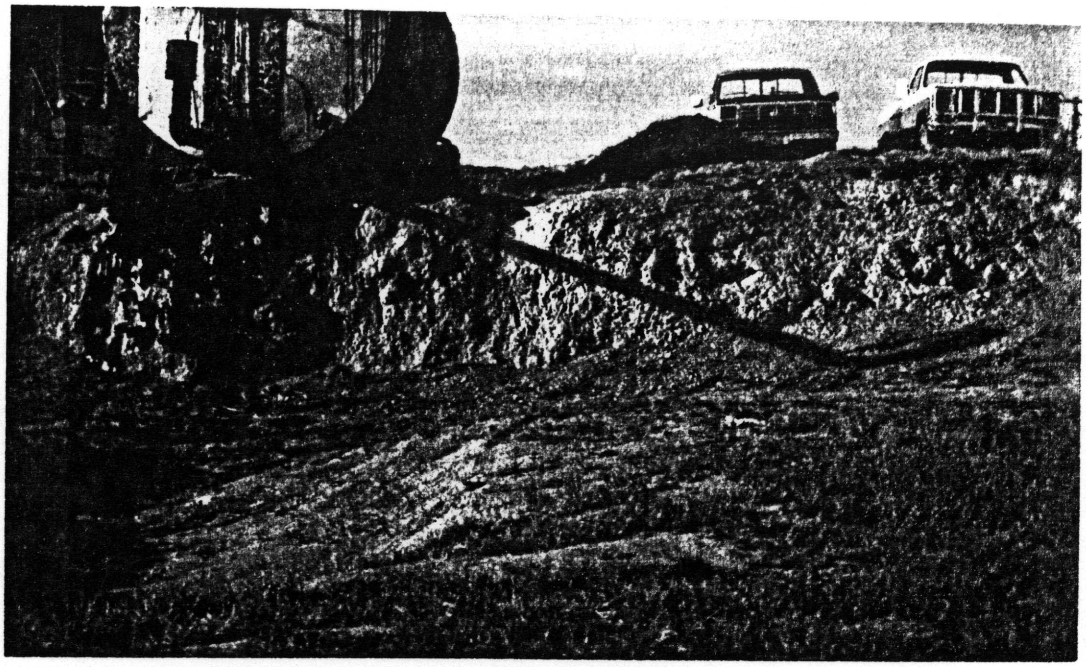

Figure 17. Brule Outcrop. First time it reappears on west side of town.

In figure 18, the Brule visible below the soil profile in the cut of an abandon quarry. The distinctive topography associated with the Brule is again evident.

The final line of evidence to support this conclusion is provided by logs of wells adjacent to the area in question (Figure 19 and Table 3). All of these wells are completed in sand and gravel deposits and reach depths of up to 151 ft. The presence of deposits of this depth adjacent to a bedrock outcrop is unlikely. Based on this evidence, the surface and bedrock geology of the area has been modified as shown in Figures 20 and 21.

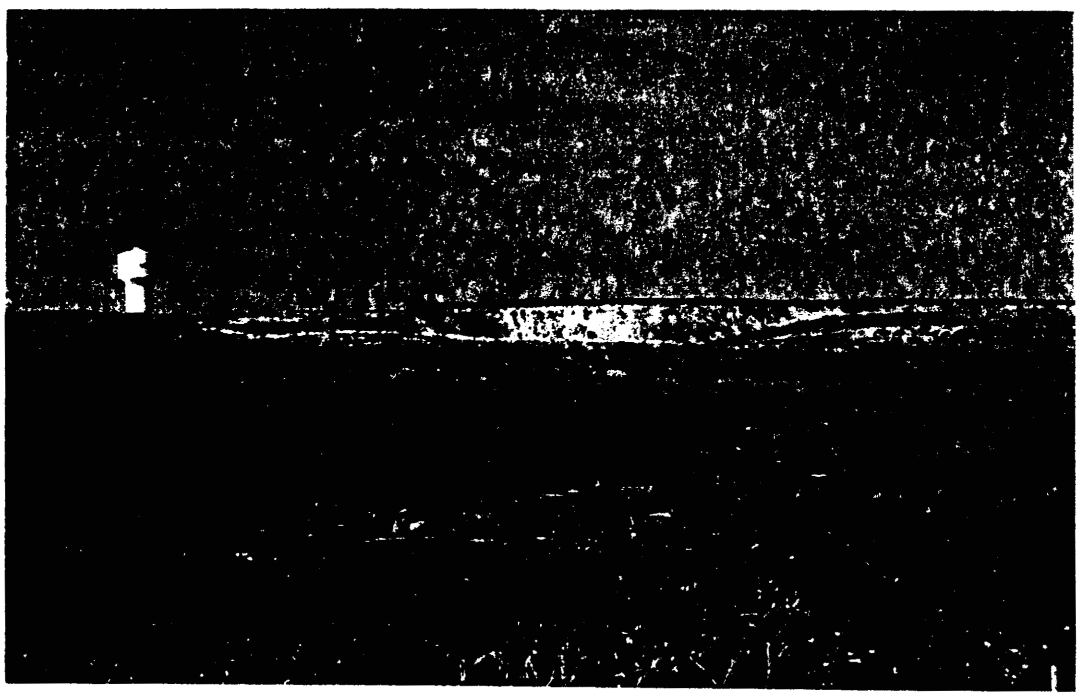

Figure 18. Brule Outcrop West of Torrington.

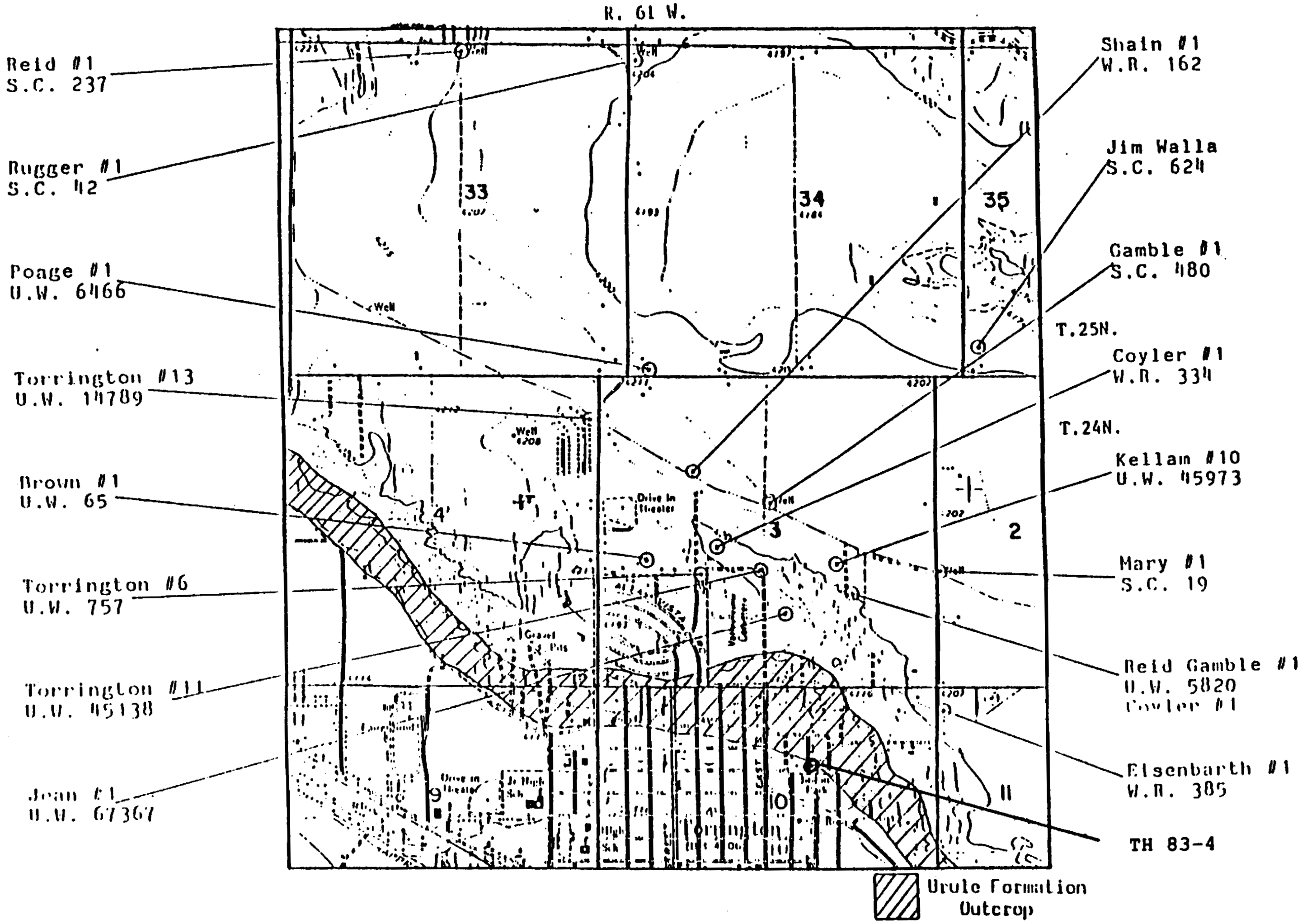

Figure 19. Location of Wells North of Torrington Completed in Sand and Gravel (Compiled from data supplied by Baker and Associates, 1983 and the Wyoming State Engineer's Office, 1984).

Table 3. Well Completion Data (Compiled from data supplied by Baker and Associates, 1983 and the Wyoming State Engineer's Office, 1984).

NAME OF WELL (OWNER)	LOCATION	PERMIT NO.	TOTAL DEPTH	DEPTH AT TIME OF COMPLETION	DEPTH TO WATER Sept. 1983	DEPTH TO WATER Sept. 1984
Mary #1 (Jim Gamble)	NWSW 2-24-61	S.C. 19	112 ft.	74 ft. (1940)	83 ft.	78.15 ft.
Gamble #1 (Jim Gamble)	SWNE 3-24-61	S.C. 480	137 ft.	70 ft. (1946)		84.92 ft.
Shain #1 (Dale Harris)	SENW 3-24-61	W.R. 162	170 ft.	69 ft. (1952)	93 ft.	85.7 ft.
Coyler #1 (Bob Fitch)	NESW 3-24-61	W.R. 334	100 ft.	73 ft. (1954)	85 ft.	80.02 ft.
#6 (City of Torrington)	NESW 3-24-61	U.W. 757	132 ft.	68 ft. (1962)	95 ft.	84.18 ft.
Brown #1 (Don Jones)	NWSW 3-24-61	U.W. 65	113 ft.	80 ft. (1958)	95 ft.	89.92 ft.
Kellam #10 (Dave Kellam)	NWSE 3-24-61	U.W. 45973	151 ft.	80 ft. (1979)	85 ft.	
Jean #1 (Dave Kellam)	NWSE 3-24-61	U.W. 67367	150 ft.	(1984)		75.90 ft.
Eisenbarth #1 (Bill Ring)	NWNW 11-24-61	W.R. 385	114 ft.	80 ft. (1955)	80.5 ft.	79.62 ft.
Poage #1 (Bill Poage)	SWSW 34-25-61	U.W. 6466	124 ft.	82 ft. (1970)	87 ft.	85.9 ft.
Reid #1 (Ken Morgheim)	NWNE 33-25-61	S.C. 237	92 ft.	36 ft. (1940)	40 ft.	
Rugger #1 (Verde Corp.)	NWNW 34-25-61	S.C. 42	90 ft.	31 ft. (1940)	31 ft.	
(Jim Walla)	SWSW 35-25-61	S.C. 624	84 ft.	22 ft. (1946)	22 ft.	
TH 83-4	SWNE 10-24-61		70 ft.	14.5 ft (1983)		

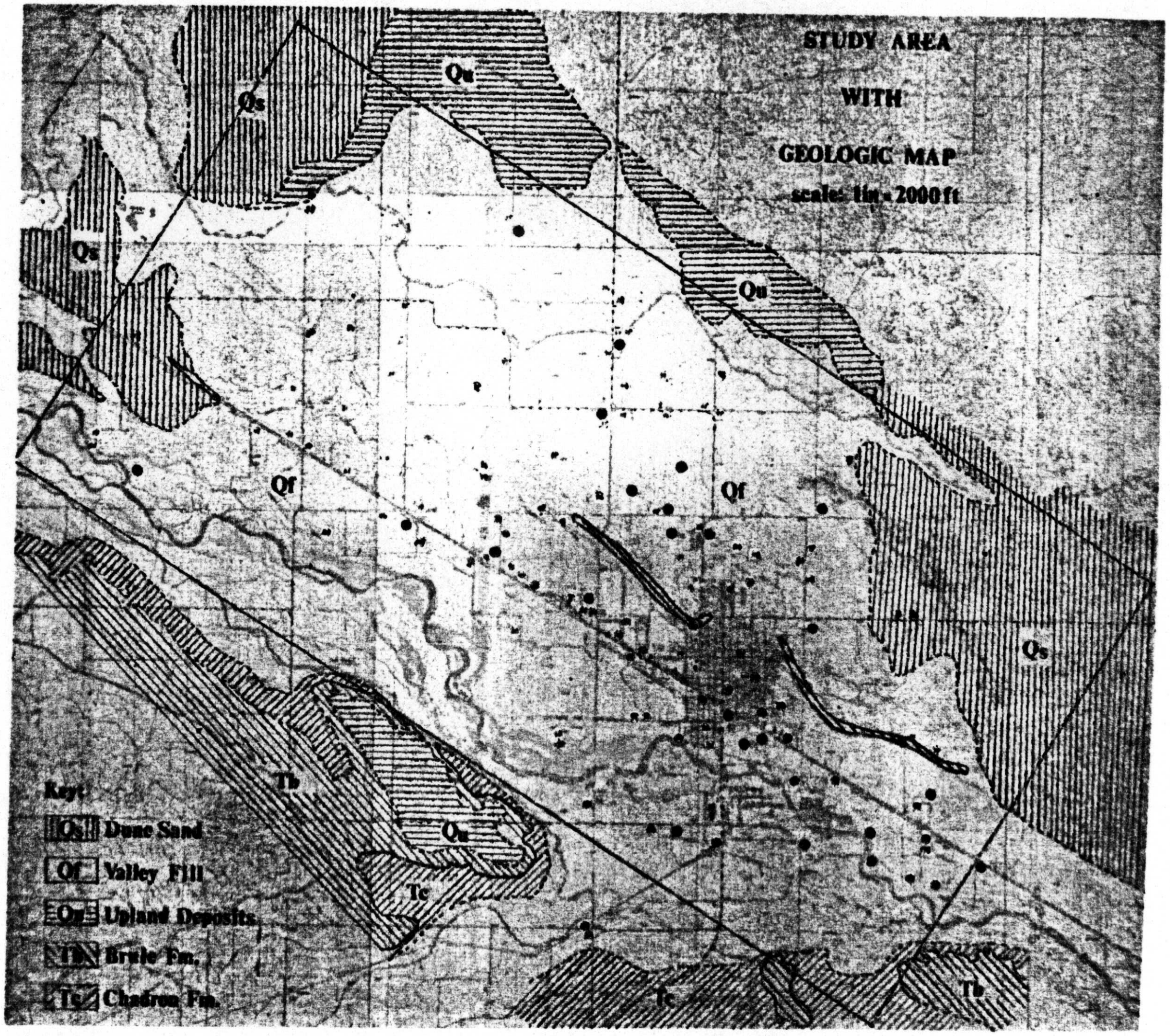

Figure 20. Modified Geologic Map showing Breach North of Torrington.

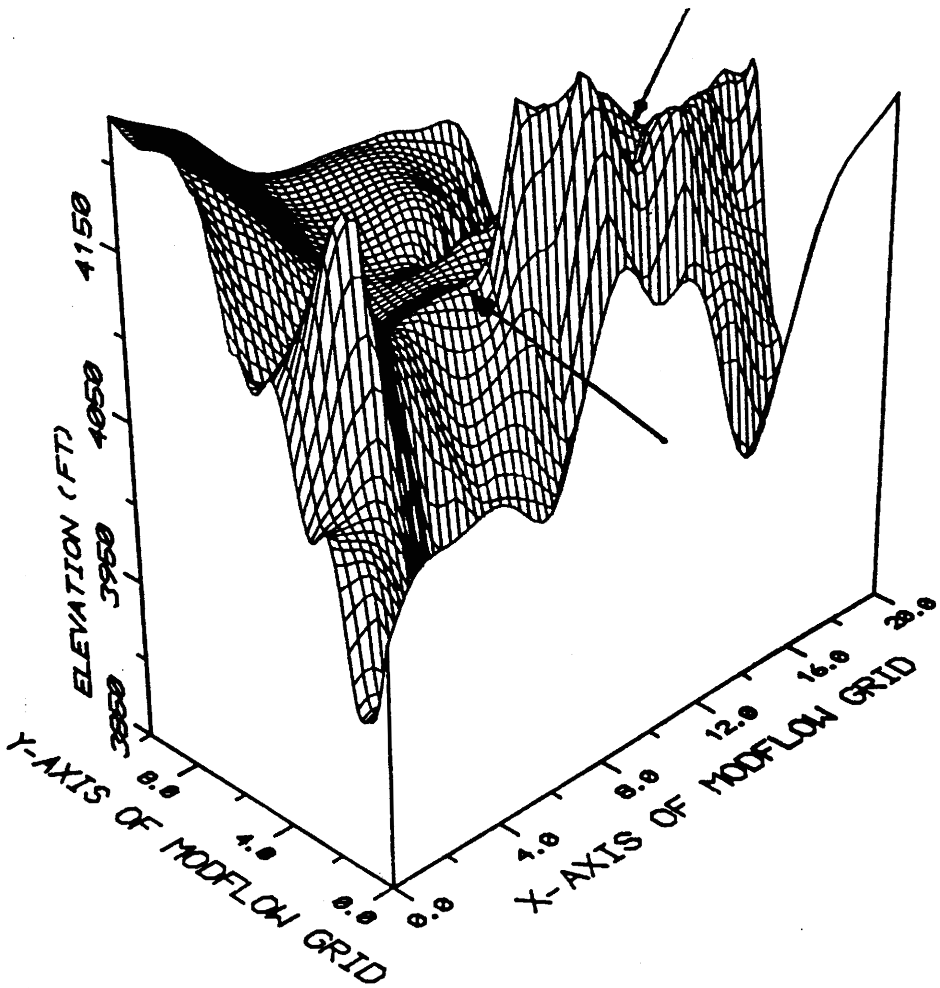

Figure 21. Modified Bedrock Geology.

Municipal Water Supply

The Town of Torrington obtains its water supply from eleven large capacity wells located throughout the town which penetrate both the valley fill and third terrace deposits. The wells are operated by an automated control system which cycles them into use based on demand. The wells discharge directly into the distribution system and as a result no form of water treatment, including chlorination, is used.

The wells are rated between 400 and 2000 gallons per minute (gpm) with the average discharge being roughly 700 gpm. Total pumping for the year 1989 was 1,079,566,000 gallons and 748,398,000 gallons in 1990 (Torrington Dept. of Public Works). The average daily per capita consumption was approximately 500 and 350 gallons per day per person in 1989 and 1990, respectively.

A comprehensive rate study for the Town of Torrington (Baker, 1983) indicates that historical water consumption during the summer months is approximately twice that consumed during the winter months.

Soils

The Soil Conservation Service has identified thirty-two soil mapping units in the study area (SCS, 1971). These have been reduced to two principal associations as shown in Figure 22. The principal differences in the associations

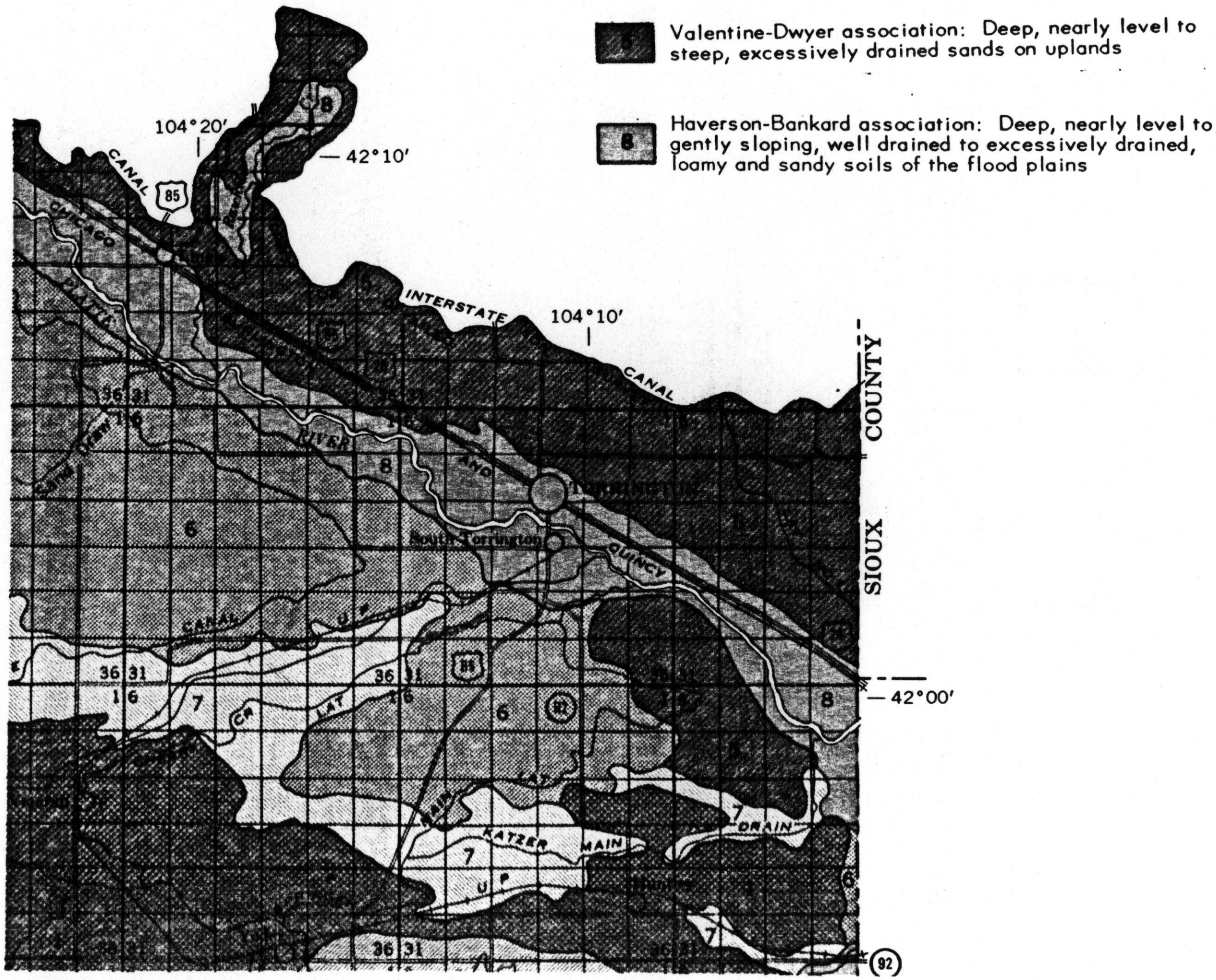

Figure 22. Soil Associations in the Study Area. From SCS, 1971.

are a function of the locations and parent material upon which they have developed. The Haverson-Bankard association soils developed on the floodplain and lower parts of terraces while the Valentine-Dwyer series soils developed on upper terrace surfaces, upland, and eolian material.

Both of the associations are recent in age and therefore classified as Entisols (SCS, 1971). Soils of the Valentine-Dwyer association are further classified as psamments (from Greek, psamm = sand) due to their sandy texture which reflects the nature of the parent material. Soils of the Haverson-Bankard association are further classified as fluvents in deference to the origin of the parent material from river (fluvial) deposition (Brady, 1974). A detailed description of the principle soils in these associations is given in Appendix B.

Surface Water Hydrology

Natural watercourses in the area include the North Platte River located along the southern boundary of the area and Arnold Drain located in the east-central part of the area. The North Platte River and its tributaries form a major drainage system throughout southeastern Wyoming while Arnold Drain serves as a local discharge point for irrigation return and underflow.

Three man-made canal systems exist in the area and include the Interstate Canal located along the northern boundary of the area, the Torrington Ditch and Platte Canal located in the central part of the study area, and their laterals. These canals serve as the principal source of irrigation water to support agricultural activities in the area. They also serve as a significant source of ground-water recharge when in operation during the irrigation season which runs from early May to late September. Crist (1975) estimated that up to 8800 acre-feet/month was lost from the Interstate Canal alone.

CHAPTER IV

NITRATE SAMPLING PROGRAM

Characteristics of Sampling Sites

Samples were collected at sites 1 through 66 (Figure 23 and Plate 1) during the initial sampling event conducted by the Torrington Dept. of Public Works in the Fall of 1989. These sites included the 11 municipal wells and two points within the distribution system, 51 domestic wells, the Interstate Canal and North Platte River. Domestic wells were selected essentially at random. However, because population density is greater west and northwest of Torrington, the majority of sites are in these areas. In order to provide greater control in the eastern part of the study area, 14 additional domestic wells, sites 67 through 80, were incorporated into the sampling program in the Spring of 1990. These 80 sites currently form the basis for the major biannual sampling events. These results were used to determine nitrate distribution in the study area (Chapter VI).

Twenty-six large capacity irrigation wells and the Interstate Canal, sites 81 through 107, were sampled in July of 1990. Because of intermittent operation, it can be difficult to consistently obtain samples from these sites. However, samples were obtained from 23 sites during a

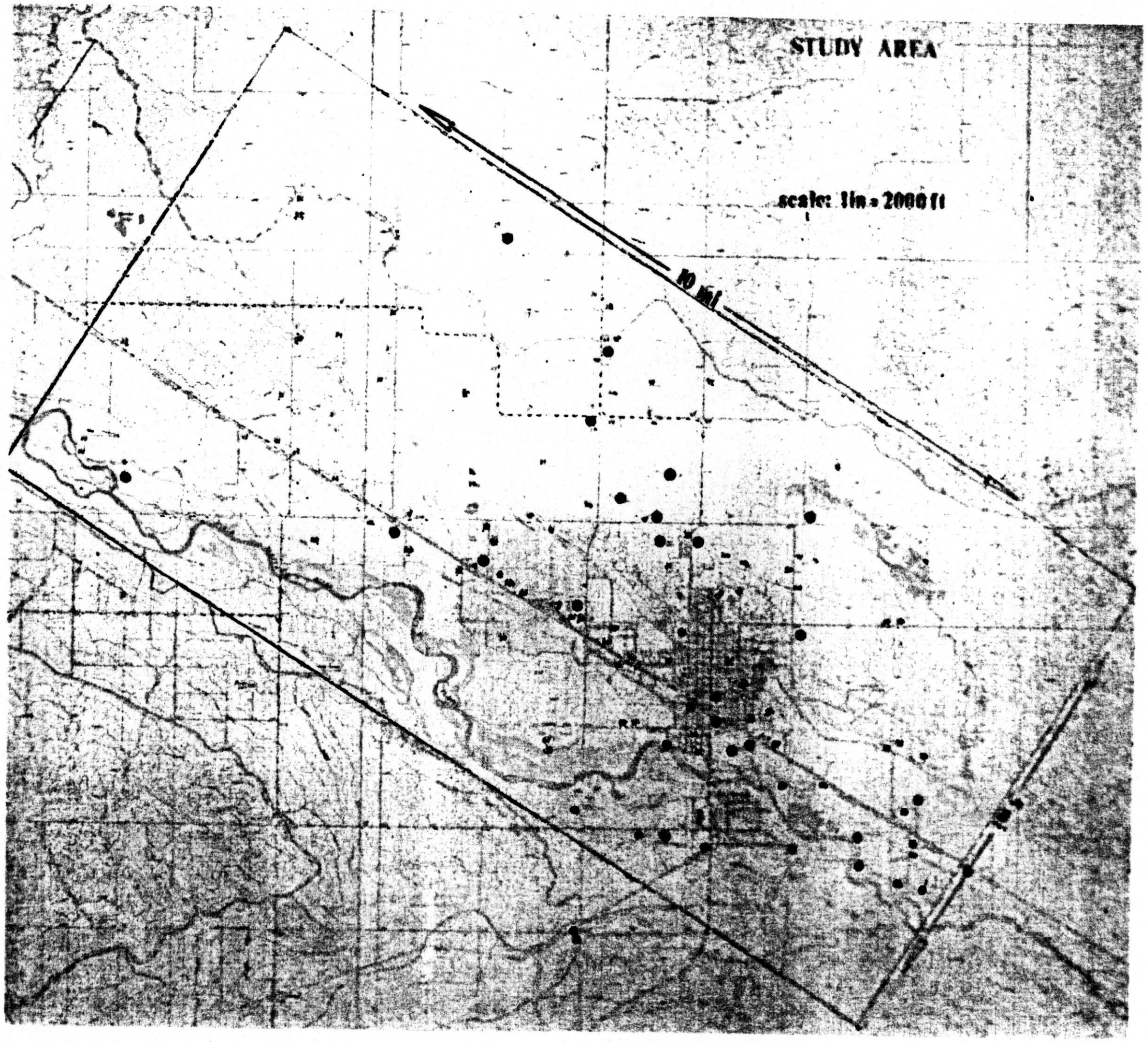

Figure 23. Location of Sample Sites shown in Yellow.

second sampling event conducted in August of 1990. Because of the limited number and distribution of these sites, plots of nitrate distribution throughout the study area were not generated from this data. However, these results were compared, on a well by well basis, with the results of the major sampling events to determine if anomalous conditions exist, as a result of extensive pumping, during the irrigation season.

A review of well completion records at the Wyoming State Engineer's Office provided a physical description of the sampling sites (Appendix C). However, because well permits, and consequently completion reports, were not required for domestic wells in Wyoming until 1969 little or no data is available on many of these wells.

Preparations for Sample Collection

Samples were collected in 250 ml polyethylene containers which were prepared in the following manner:

a. Rinsed several times in warm tap water;

b. Washed in warm soapy water using commercial dishwashing soap;

c. Rinsed several times in warm tap water;

d. Allowed to soak for 5 minutes in a 10% HCl acid bath;

e. Rinsed several times with distilled water and allowed to air dry.

General Collection Procedures

Every effort was made to purge 3 well volumes from the well prior to sample collection in accordance with EPA protocol. However, this was not possible in all instances. In spite of these deviations, which will be discussed in detail below, the following general procedures apply to all of the samples collected.

Samples were collected from a point as close to the well as possible in an effort to minimize the potential for additional contamination from the distribution system. The municipal, and many irrigation wells, were equipped with ports on the discharge line at the wellhead which provided for ready access (Figure 24).

Figure 24. Sample Port on an Irrigation Well. Sample ports on municipal wells are similar.

Domestic wells, however, were typically sealed to prevent bacteriological contamination (Figure 25) eliminating the possibility of collecting samples at the wellhead. Samples collected from this type of well were usually taken from an outside faucet (Figure 26) which was often located at some distance, up to 250 feet, from the wellhead.

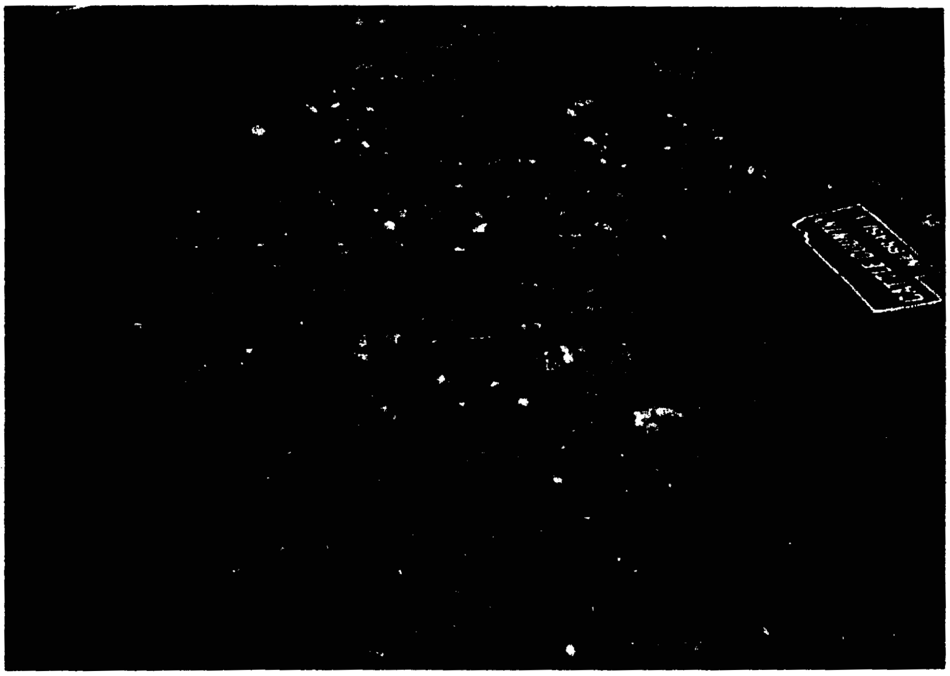

Figure 25. Sealed Domestic Well.

At each sampling point, the sample bottle was rinsed several times prior to final collection. The bottles were then labeled, recorded, and placed immediately upon ice where they remained until delivery to the laboratory. At the laboratory, the samples were refrigerated (2 to 5°C) until analyzed. No other form of preservation, such as acidification, was required.

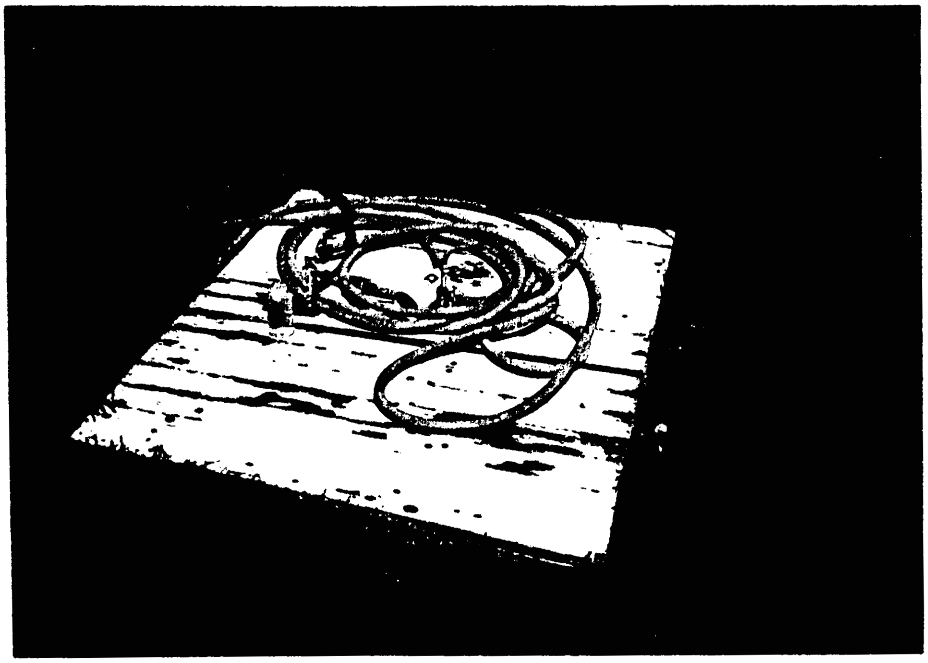

Figure 26. Typical Sampling Point for Domestic Wells.

Collection From Municipal Wells and Distribution System

As mentioned in Chapter III, the municipal wells are cycled into use by an automated control system. In most cases, the wells had been running for several hours prior to sample collection. In those instances when the wells were not in operation at the time of sample collection, they would be started by manually overriding the automated system from a control box located at the wellhead. Due to their large discharge rates these wells could be readily purged ensuring that formation water was being collected.

Sample collection from well 6 provided the exception to the above procedure. Due to water table decline in recent years, this well now penetrates very little saturated material. As a result, the capacity of the pump exceeds the ability of the aquifer to recharge the wellbore and the well may be "pumping air". Samples from this well were collected immediately upon start-up from any water that was produced. Samples obtained from the municipal distribution system were used to evaluate the effects of mixing within the system.

Collection From Domestic Wells

Several factors combined to result in an uncertainty that fresh formation water was being collected when sampling from domestic wells. With saturated depths of up to 100 feet, average diameters of six inches, and discharges at the sampling point of 5 gpm or less, several hours would have been required to properly purge some wells. Furthermore, during the initial sampling event of 10/30/89 carried out by the Torrington Dept. of Public Works, domestic wells were only allowed to run from 3 to 5 minutes prior to sample collection. It was determined that this procedure should be continued when sampling these wells in order to assure uniformity in the data collection procedure. Potential problems associated with this collection method could be more readily addressed as a separate issue.

Collection from Surface Waters

Grab samples were collected from the Interstate Canal and North Platte River at easily accessible locations where turbulent conditions prevailed and were used to provide an indication of the characteristics of aquifer recharge water.

Collection From Irrigation Wells

With only few exceptions, the irrigation wells were sampled after they had been running for many hours thereby ensuring that the water collected was truly formation water. Like the municipal wells, the irrigation wells that were not in operation at the time of sampling could be readily purged due to their large discharge rates.

Method of Analysis

As of 7/1/89, four analytical methods for the determination of nitrate in water samples were accepted by the EPA (40 CFR 141.23). These methods include the Colorimetric Brucine Method, the Manual Cadmium Reduction Method, the Automated Cadmium Reduction Method, and the Automated Hydrazine Reduction Method. In addition, it is anticipated that the Ion Chromatographic Method will soon be approved for use. A complete description of each method can be found in the various sections of the CFR as indicated in 40 CFR 141.23, the Annual Book of American Society for Testing and Materials (ASTM) Standards, part 31 Water, (ASTM 1989), or Standard Methods for the Analysis of Water and Wastewater (Standard Methods, 1989). The Wyoming Department of Agriculture Analytical Services Laboratory performed the analytical work reported in this study (Appendix D) using the Automated Cadmium Reduction Method.

The Cadmium Reduction Method is based upon the principle that nitrate is reduced almost quantitatively to nitrite in the presence of cadmium (Standard Methods, 4500-E, 1989). The amount of nitrite produced by the reduction is then determined by diazotizing with sulfanilamide and coupling with N-(1-naphthyl)-ethylenediamine dihydrochloride (Standard Methods, 1989). This process results in the formation of a highly colored azo dye. The absorbance of the dye is then measured colorimetrically with a spectrophotometer or a filter photometer operating at a wavelength of 543 nm. The absorbance measured is then plotted on a standard curve of absorbance versus nitrite concentration to determine the amount of nitrite in the sample.

The results reported represent the sum of the nitrate and nitrite concentrations (NO_3-N and NO_2-N/L) in the sample. To determine the nitrate concentration, a correction can be made by analyzing for nitrite only. This is accomplished by eliminating the reduction step and subtracting this value from the value obtained using the reduction method (Standard Methods, 1989).

The Cadmium Reduction method is extremely sensitive with an applicable range between 0.01 and 1.0 mg/l NO_3-N and is recommended for use when nitrate levels are below 0.1 mg/l. For nitrate levels above this range, dilutions can be made until the concentration falls within the applicable range and the true concentration is then determined by correcting for dilution.

Quality Control and Assurance

Quality control was approached in four different ways. Included within the sample series at the time of sample collection were the following quality control measures:

a. At least two blank samples consisting of distilled water randomly inserted in the sampling series;

b. Two quality control check samples prepared from concentrates obtained from the EPA Environmental Monitoring Systems Laboratory randomly inserted in the sampling series;

c. Two standards prepared in accordance with the Standard Methods for the Analysis of Water and Wastewater protocol (Standard Methods, 104-B, 1989);

d. Splits made of selected samples and randomly inserted in the sample series.

Although the quality control program was not extensive enough to allow for a rigorous statistical evaluation of the analytical results it did provide for a gross measure of laboratory performance. At the laboratory, each sample was analyzed twice. The results reported in this investigation (Appendix D) represent the mean value of the two analysis.

To independently verify results reported by the Analytical Services Laboratory, a seperate analysis was conducted on samples collected in the Fall of 1990 by Dr. George Vance and the author at the University of Wyoming using the Ion Chromatography Method. These results are given in Appendix

E. A statistical analysis (regression) performed on the data produced an R-squared value of 98.8 %. This value is particularly significant in light of the fact that 69 observations were used, and indicates that both methods of analysis are producing approximately the same results.

Sources of Error

Three principle sources of error can be identified. In general terms, these are associated with improper or inadequate preparation of the sample bottles, improper collection techniques, and laboratory error.

Inadequate preparation of the bottles would result in the presence of trace amounts of residual contamination in the sample bottles. Rinsing of the sample bottles several times prior to final collection should have minimized this problem, and several splits taken in "virgin" containers suggest that this was not a significant source of error.

As previously stated, there was some concern about the methods used to collect samples from the domestic wells because of incomplete purging prior to sample collection. In an effort to address this issue, four studies were conducted to determine the variations in nitrate concentration as a function of time. The Ion Chromatography Method was used to conduct these studies; the results are discussed in Appendix F.

Several factors, either individually or in combination, may be a source of error in the analytical procedure used by

Analytical Services Laboratory. Examples of these factors include:

a. Any component, other than the nitrate-reagent complexes, that absorbs at the 543 nm wavelength;

b. Metal ions such as iron or copper which can lower reduction efficiency if present in concentrations greater than several milligrams per liter;

c. Suspended matter that could plug the reduction column;

d. Oil and grease which can coat the cadmium reaction surface and;

e. Residual chlorine which can oxidize the column.

As these are mostly groundwater samples, it is likely that the only significant source of interference would be the presence of elevated levels of metal ions. However, separate analysis to determine the types and concentration of metal ions was not performed as the town's water supply is not approaching any metal MCL's.

CHAPTER V

Modeling

Model Description

The two principal types of mathematical models that are capable of simulating groundwater flow are analytical and numerical models. While analytical models are easier to operate and generally require less data, they typically lack the ability to simulate complex interactions between surface and subsurface hydrologic parameters which may affect a groundwater system. Because numerical models possess the capability to simulate these complex interactions, they are often preferred over their analytical counterparts. Two types of numerical models are finite-difference and finite-element models. A review of the structure and use of each of the models is discussed in detail by Peck (1985).

As stated in Chapter II, the finite-difference groundwater flow model, commonly referred to as "Modflow", will be used in this investigation. The model, written by Michael G. McDonald and Arlen W. Harbaugh (McDonald and Harbaugh, 1984) and published by the United States Geological Survey (USGS), has become widely accepted in the scientific community. The model is capable of simulating a wide variety of situations including steady state and transient flow, confined or unconfined aquifer conditions, and three dimensional flow fields. The model consists of a main program which directs and controls the overall operation of the model and a series of modules which simulate specific hydrologic parameters such as recharge from streams or the pumping of wells which may have an impact on the aquifer.

In order to utilize the methods of finite-difference analysis, the modeled area must be divided into discrete elements in both space and time. This is accomplished by dividing the area into a series of cells and time into a series of increments known as time steps. The time steps are further grouped into stress periods. The stress periods reflect periods of time when the hydrologic parameters impacting the aquifer remain constant. For each cell and time step the partial differential equation which describes the flow of water through the cell (Equation 1) is replaced by a set of linear algebraic equations.

$$\begin{aligned} &\partial/\partial x[K_x\, \partial h/\partial x\ \Delta y\Delta z]\Delta x + \partial/\partial y[K_y\, \partial h/\partial y\ \Delta x\Delta z]\Delta y \\ &+ \partial/\partial z[K_z\, \partial h/\partial z\ \Delta x\Delta y]\Delta z = \Delta x\Delta y\Delta z\ S_s\partial h/\partial t + W \end{aligned} \qquad [1]$$

where

x,y, and z = cartesian coordinates aligned along the major axis of hydraulic conductivity Kx, Ky, and Kz,

h = the potentiometric head,

W = a volumetric flux which represents sources and/or sinks of water,

S_s = the specific yield of the aquifer material,

t = time.

The entire set of algebraic equations are solved simultaneously to yield the potentiometric head values at the specified locations (the center of the cell) and times (the end of the time step).

The series of linear algebraic equations can be solved by one of two techniques; the Strongly Implicit Procedure (SIP) or the Slice-Successive Overrelaxation (SSOR) method. The SIP solution technique is a matrix operation while SSOR is an iterative procedure. Both of the techniques utilize the backwards-difference method whereby the current head values are determined from the head values of the previous time step. For the first time step, head values are specified by the user. This procedure provides numerical stability for the model. For a complete description of the model refer to MacDonald and Harbaugh (1988) or Peck (1985).

The Torrington Study Site

In order to adapt the numerical model to this investigation the study area was divided into a series of cells using the grid system shown in Figure 27. The size of the modeled area (50 sq. mi.) was based upon preliminary estimates of the time of travel (TOT) of nitrate contaminants in the groundwater system and was thought to reflect a TOT

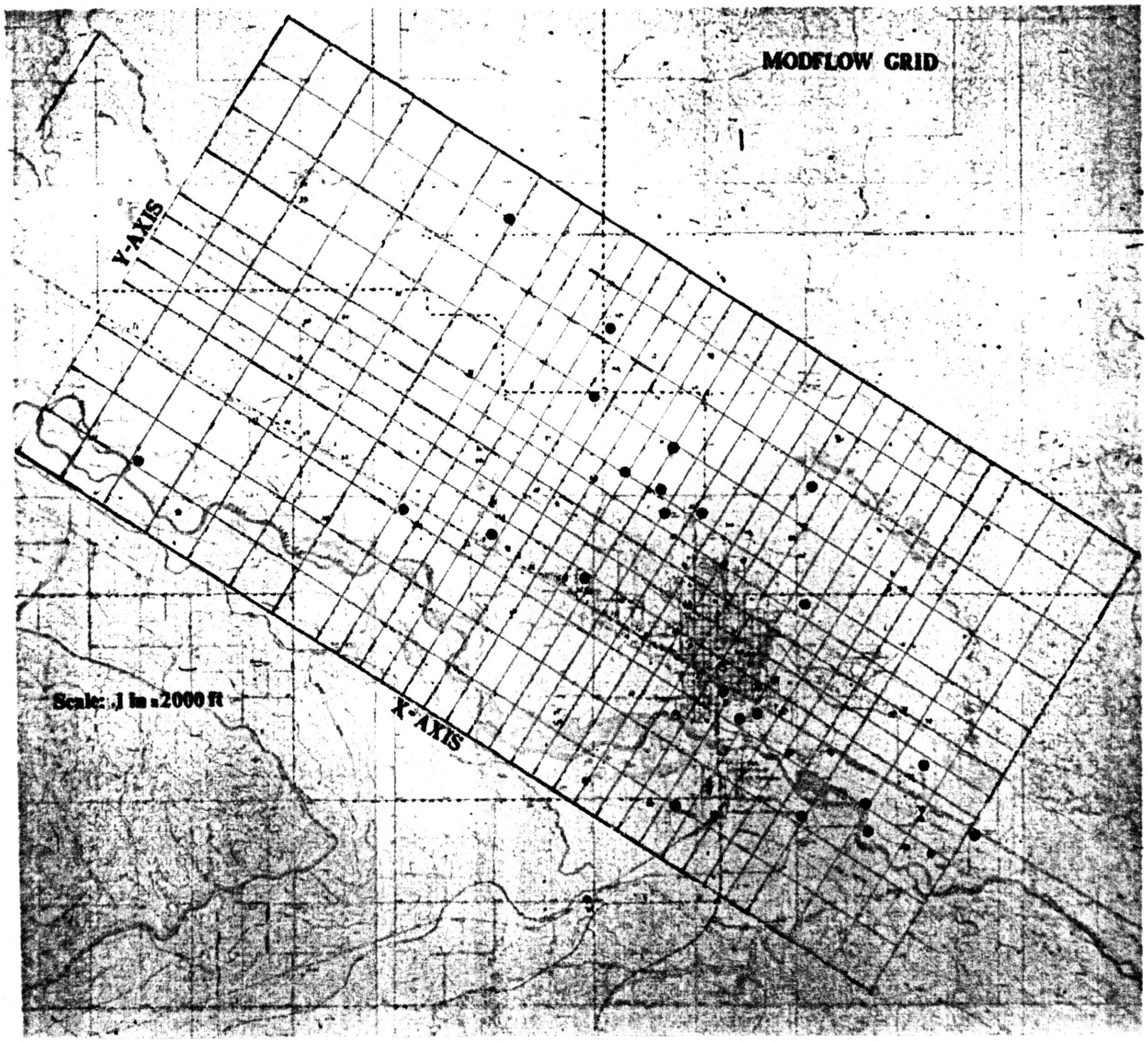

Figure 27. Grid System used to Delineate Cells.

between 15 and 25 years. The orientation of the grid system, approximately 30 degrees from north, was used to take advantage of natural hydrologic boundaries that exist in the study area. These boundary conditions will be discussed in greater detail in a later section.

The resulting model consists of a two dimensional array of 360 cells one layer deep. The largest grid cells are 2640 ft. by 2640 ft. and represent an area the size of a quarter section while the small grid cells are 1320 ft. by 1320 ft. and represent 1/16th of a section. The small cells were used in areas where the configuration of the potentiometric surface was of the greatest concern and also allowed for the accurate location of major physical features such as bedrock outcrops found within the area. The use of a single layer was determined to be an adequate representation of field conditions, because the hydraulic conductivity of the bedrock, 10^{-4} ft/d, is approximately seven orders of magnitude less than the conductivity of the alluvial material, 10^{+3} ft/d. It was, therefore, assumed that the bedrock acts as an impermeable lower boundary.

Flow Conditions

The elevation of the water table in the area is known to fluctuate seasonally and recent trends indicate that the water level in the area is declining annually (Ed Wells, Torrington Dept. of Public Works). The fluctuations indicate that water is moving into and out of storage in the aquifer and that transient conditions exist in the area.

Ideally a comprehensive study would simulate these conditions for the fifteen year time period from 1976 to 1991. The two additional reasons for simulating this extended time period are:

1. Initial head values were derived from the report of Crist (1975) which represents the most recent comprehensive data available on the elevation of the water table in the area and;
2. It is within this time period that a significant increase in the rate of groundwater withdrawal for irrigation purposes has occurred.

However, in order to develop this simulation, seasonal and yearly variations of the hydrologic parameters affecting the groundwater system for the entire 15 year period must be known in detail. Unfortunately, this information is unavailable. As a result, flow in the aquifer was simulated under steady state conditions.

It was determined, however, that a second simulation under transient conditions should also be conducted despite the lack of input data. The purpose of this simulation was to determine if any significant changes occur in the general configuration of the potentiometric surface when the effects of storage in the groundwater system are considered and to provide verification that a steady state simulation is appropriate. The results of both simulations will be discussed in Chapter VI.

Simulation Methods

The stress periods selected for use in this simulation correspond to conditions found during the summer and winter with each stress period being 182 days (26 weeks) in length. The principle difference between these stress periods are the number of pumping wells and the volume of recharge water entering the system. Summer conditions are characterized by the pumping of all of the wells in the area and groundwater recharge from seepage of the canals. During winter conditions only the municipal wells are in operation and because there is no flow in the canals during this period there is no subsurface recharge from this source.

For the steady state simulation each of the stress periods only need be considered once. That is, the simulation need only be a year in length. However, because a 15 year transient simulation was also to be performed the steady state simulation was allowed to run for 5 years, or ten stress periods, which is the limit imposed by the model. For the transient simulation, the output (head values) from the first five year increment were used as the starting values for the next five year increment. This procedure was performed twice in order to simulate the fifteen year period.

Model Calibration

The Modflow program has been used by previous investigators in other areas of Wyoming (Peck, 1985; Boelman, 1989; Wetstein, 1989). In these investigations, extensive monitoring networks were established to provide quantitative hydrologic data which could be used to establish aquifer characteristics and aid in model calibration.

This investigation differs from the previous studies in that an extensive monitoring network was not in place during the time of the investigation. Consequently, much of the data required for the calibration of the model is unknown. Because of the unknowns, many simplifying assumptions were made, making the task of calibrating the model more difficult. The difficulty arises in developing input parameters that were reasonable and justifiable.

Parameters required as input for some or all of the cells in the model grid for this simulation include:

1. Starting head values
2. Hydraulic conductivity of the aquifer material
3. Bedrock elevation
4. Boundary conditions
5. Pumping rate of wells
6. Rivers and canals
7. Drains
8. Evapotranspiration and recharge rates
9. The location of inactive cells

10. Specific storage (transient simulation)

The methods used to determine initial conditions for each of the above parameters are discussed below. The effects of modifying these initial conditions are discussed as part of a sensitivity analysis in Chapter VI.

Starting Heads. Starting heads were derived from the report of Crist 1975. The starting head value for each cell was determined by enlarging and then superimposing the potentiometric surface map developed by Crist over the grid system used for this simulation (Figure 28). Where an equipotential line passed through the center of a cell that value was used as the starting head for the cell. For cells that lay between equipotential lines a linear approximation was made to determine the starting head value. The starting head values determined in this manner were approximated to within 10 ft.

Hydraulic Conductivity. Six pump tests had been made in the flood plain and third terrace deposits (Rapp et al. 1957). These tests indicate that the hydraulic conductivity of the flood plain deposits range from 200 to 1200 cubic feet per day per square foot ($ft^3/d/ft^2$), or feet per day (ft/d), while the hydraulic conductivity of the deposits of the third terrace range from 300 to 800 ft/d. Initial values of hydraulic conductivity were assigned by determining which cells were located in the deposits of the floodplain and which are located in the deposits of the third

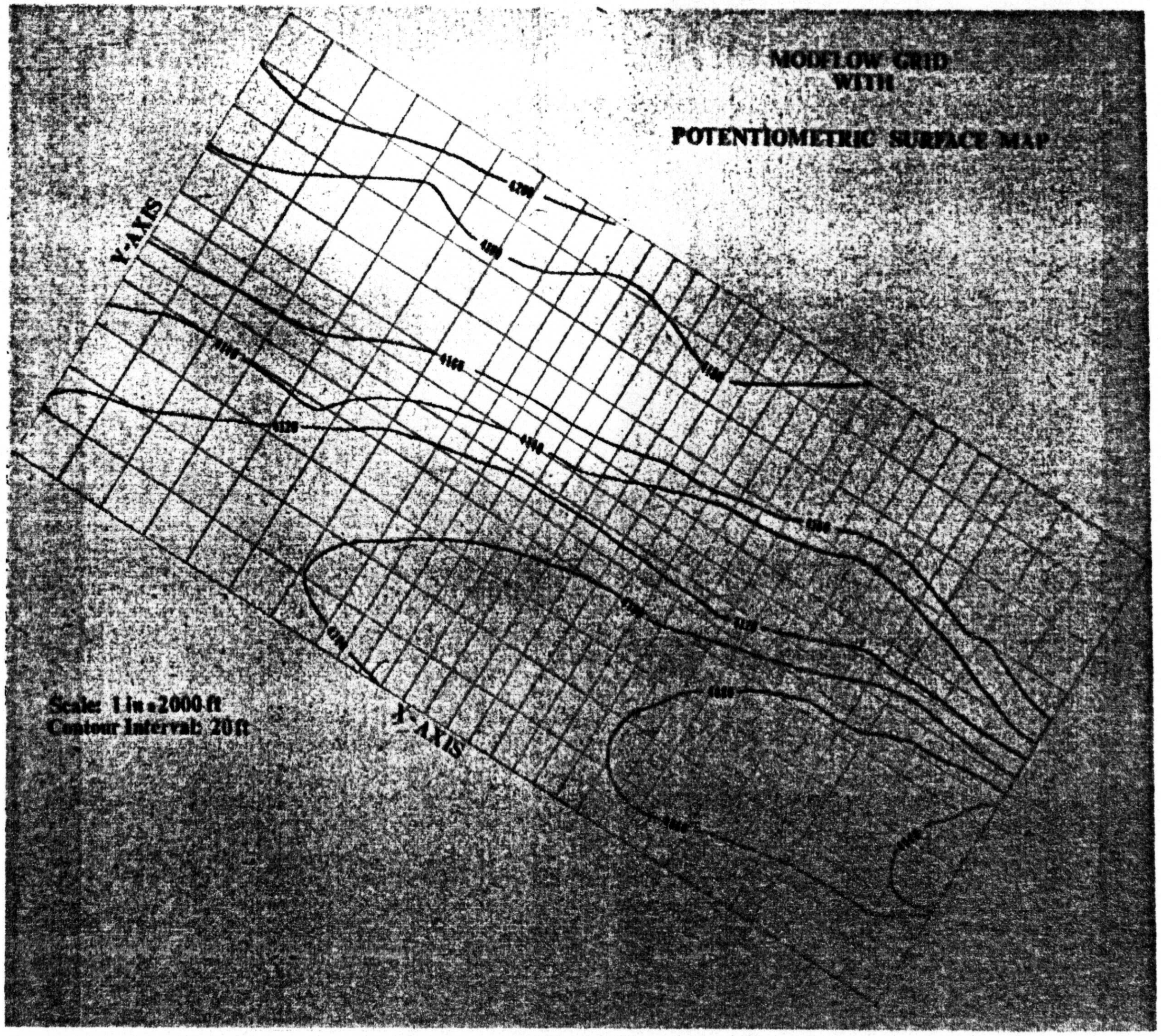

Figure 28. Modflow Grid with Potentiometric Surface Map.

terrace. All cells located north of the Brule outcrop were classified as third terrace while those south of the Brule were classified as flood plain deposits. A common value of hydraulic conductivity, within the range as determined by Rapp et al., was then assigned to each group of cells.

Bedrock Elevation. Bedrock elevation was determined from the bedrock map developed during this investigation (Figure 29). For cells in which a bedrock contour passes through the center of the cell, that value was assigned to the cell. For cells that lay between bedrock contours, a linear extrapolation method was used to determine the bedrock elevation for that cell in the same manner used to determine the initial head values. Bedrock elevations were calculated to within 25 ft.

Boundary conditions. As previously stated, the grid system used to delineate the study area was rotated approximately 30 degrees from the north in order to take advantage of naturally occurring boundary conditions. By orienting the model grid in this manner, the southern (southwestern) boundary of the area is located adjacent and parallel to an outcrop of the Brule and Chadron Formations (Figure 30). Because of the relatively low permeability of these materials, they are assumed to represent a natural no-flow boundary.

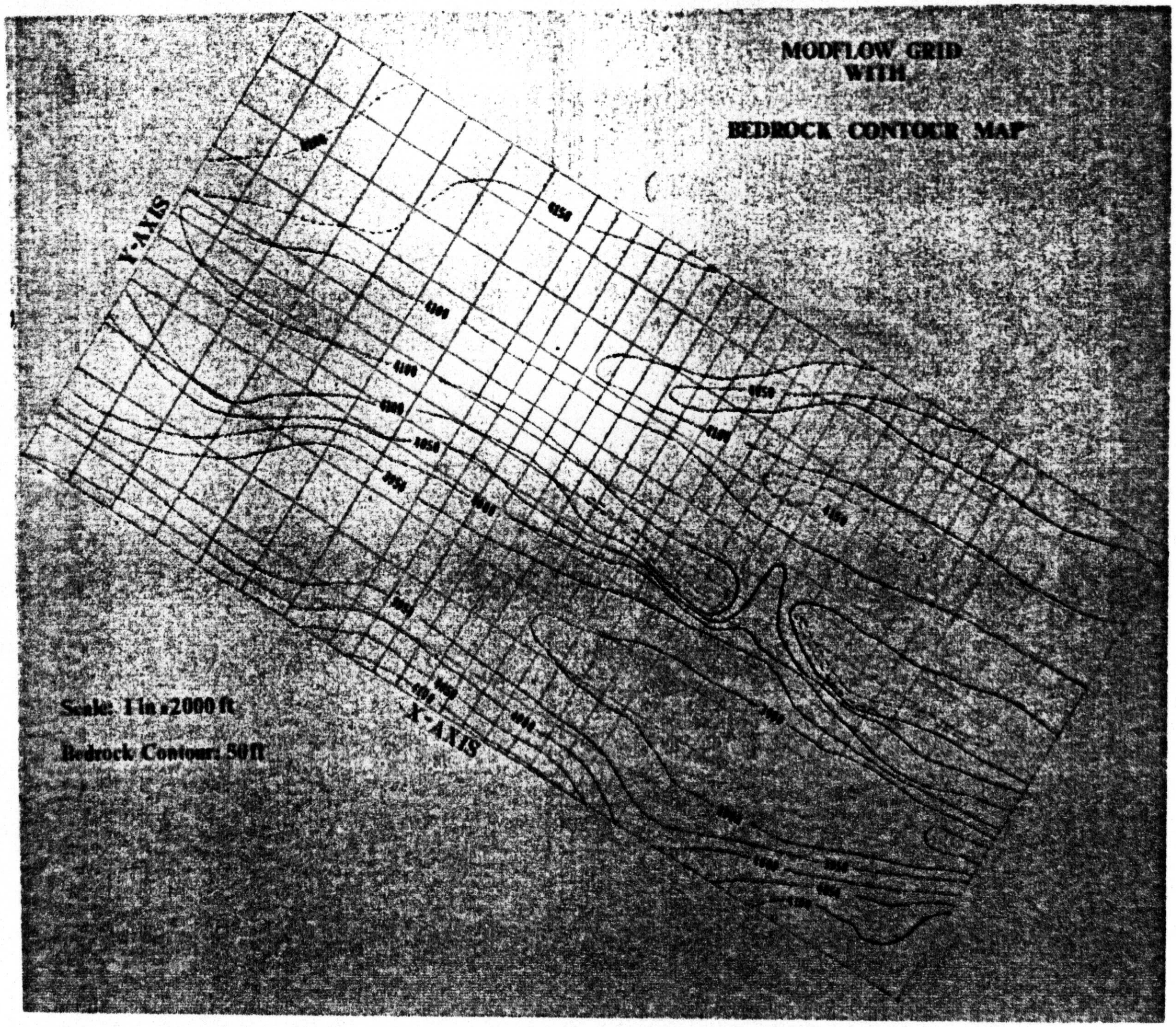

Figure 29. Modflow Grid with Bedrock Contour Map.

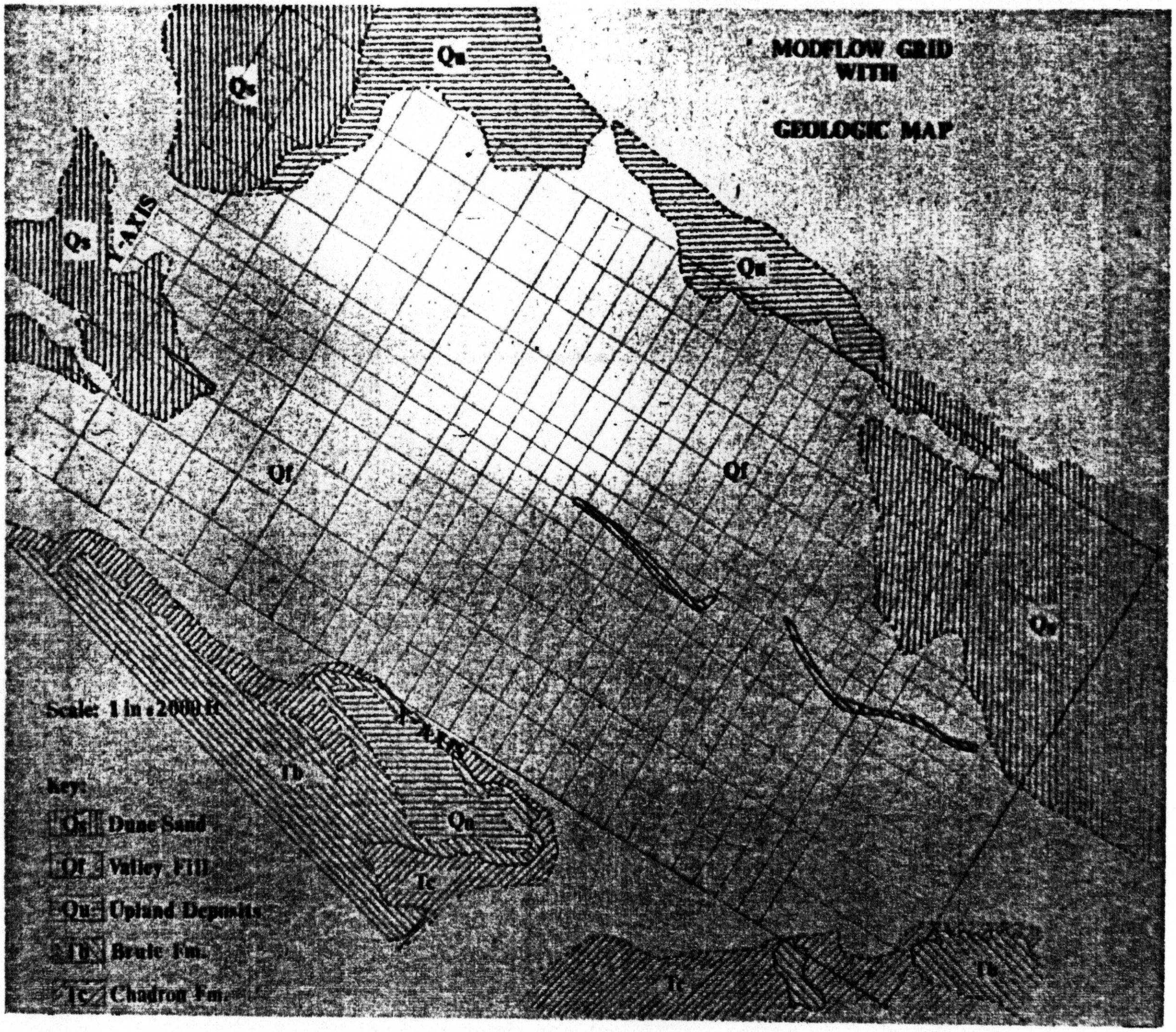

Figure 30. Modflow Grid with Geologic Map.

The northern and western boundaries of the study area are areas of recharge to the study site. Crist (1975) computed that the volume of water entering the area as underflow from the Rawhide Creek tributary just west of the study area to be on the order of 120 acre-feet per month (ac-ft/mo) and the volume of flow entering the area north of the Interstate Canal between Rawhide Creek and the Nebraska State Line to be 280 ac-ft/mo. In order to simulate this influx of water to the area, these boundaries were simulated as constant head boundaries with the initial head values being derived from the potentiometric surface map.
While this representation of flow may not entirely reflect conditions found at these boundaries, it was the best possible approximation available because of the limitations of the model.

Pumping wells. A severe limitation of the Modflow program is its lack of ability to simulate a large number of pumping wells. The maximum capacity of the program is 50 wells, far below the number of wells included in the sampling program and significantly less than the total number of wells known to exist in the area. This limitation was overcome in two ways. First, the impact on the aquifer of all low capacity wells, such as private domestic wells, was deemed to be insignificant when compared to that of the numerous large capacity irrigation and municipal wells. Secondly, many of the cells in the model grid contain more than one well. As a result the pumping capacity of these wells could be combined which allowed the 50 well limit to be, in effect, exceeded.

Wells included in the summer stress period include the 26 large capacity irrigation wells included in the nitrate sampling program, the 11 large capacity municipal wells, and 22 large capacity irrigation wells not included in the nitrate sampling program (Figure 31). The last 22 wells were identified and located from information derived from the United States Geologic Survey (USGS) Groundwater Site Inventory (GWSI) data base. Only the municipal wells are included in the winter stress period (Figure 32).

Because Modflow requires that the hydrologic parameters remain constant for the entire stress period, an average daily discharge for the wells had to be computed. For the irrigation wells, this was accomplished by assuming that the wells were operated for 24 hours one day a week at an average pumping rate of 1000 gpm. Based on this assumption, the total discharge for the 26 week (182 day) summer stress period was calculated. This total volume was then divided by the number of days in the stress period to determine the average daily discharge. The average daily discharge from the municipal wells was determined by dividing the total pumping over each stress period by 182. The pumping rate of the irrigation wells was further modified to account for

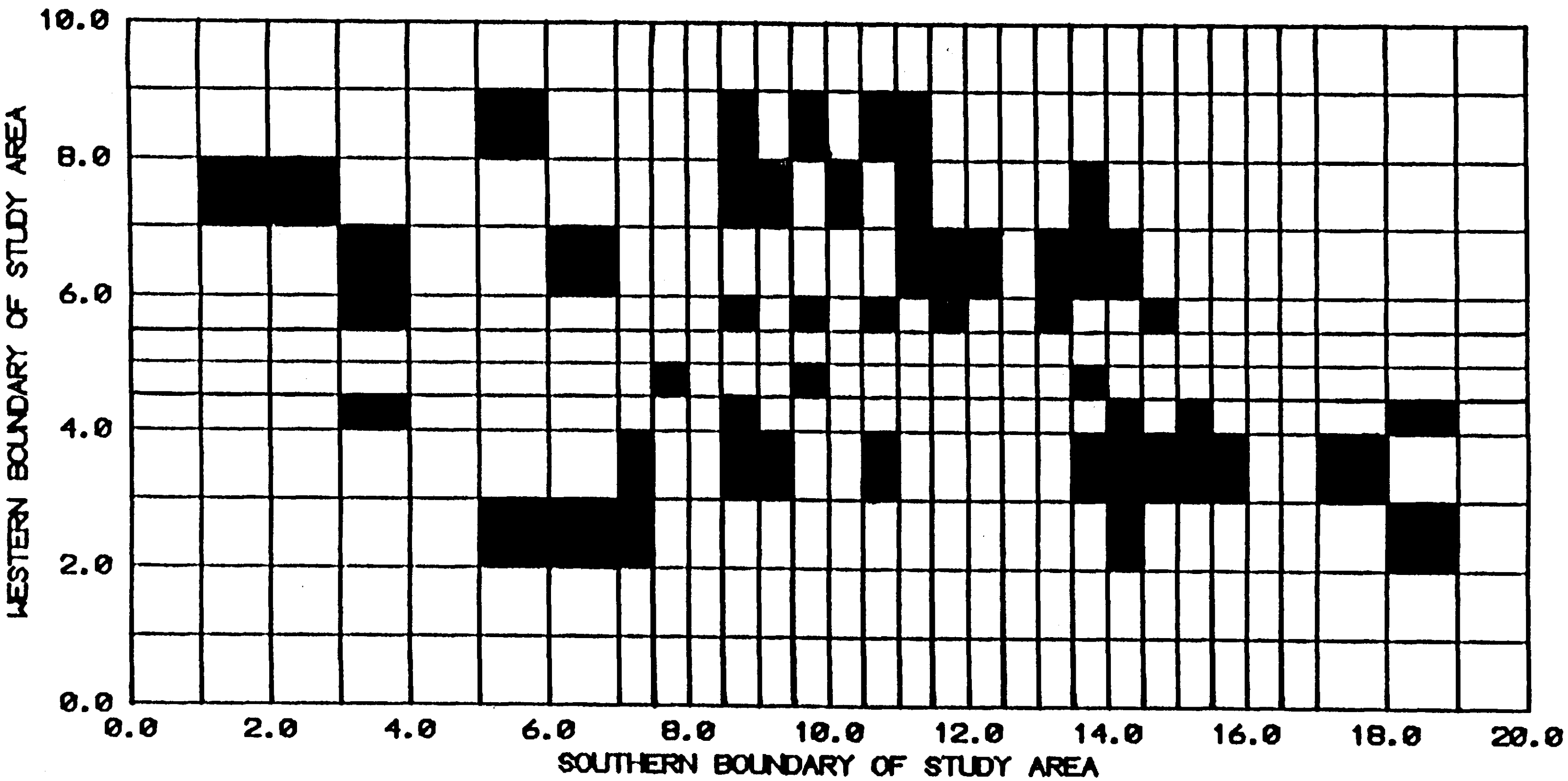

Figure 31. Location of Pumping Wells during the Summer Stress Period.

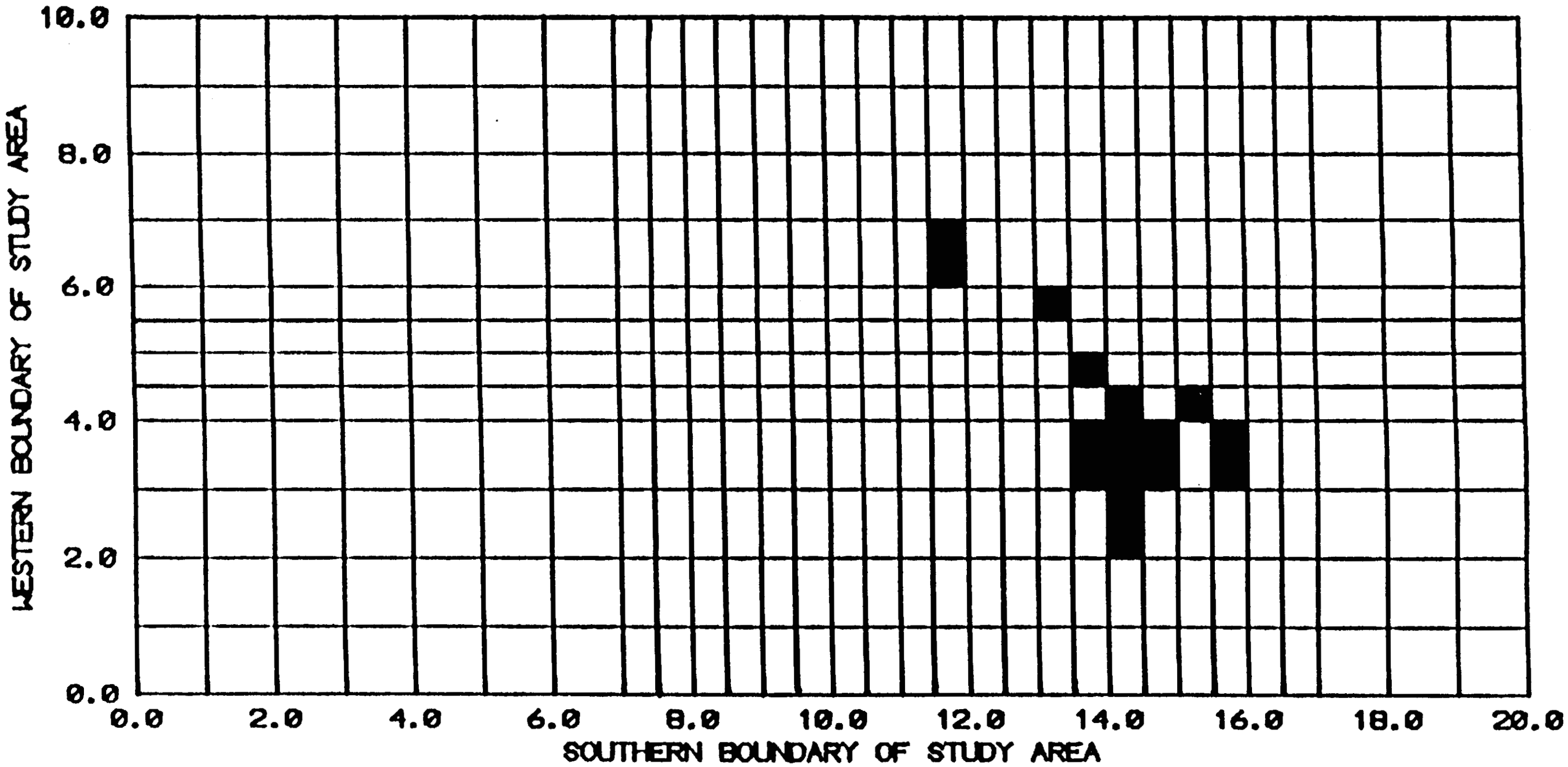

Figure 32. Location of Pumping Wells during the Winter Stress Period.

evapotranspiration losses. These modifications are discussed in the section on evapotranspiration and recharge.

Rivers and Canals. The location of the cells which contain a river or canal reach during the summer and winter stress periods are shown in Figures 33 and 34, respectively. As previously stated, the canals are only in operation during the summer months and, therefore, do not serve as a source of aquifer recharge during the winter stress period.

In order to simulate the effects of these surface water features on the aquifer, the three parameters of river stage, riverbed conductance, and riverbed elevation are required by the model. The general equation governing the interaction of a stream with the aquifer is given by equation (2) below:

$$QRIV = CRIV(HRIV - HAQ) \qquad [2]$$

where

QRIV = the volumetric flux

CRIV = the hydraulic conductance of the streambed material

HRIV = the head (stage) in the river

HAQ = the head in the aquifer

The direction of flow is determined by comparing the head in the cell with the elevation of the river bottom; the model makes this comparison prior to each iteration.

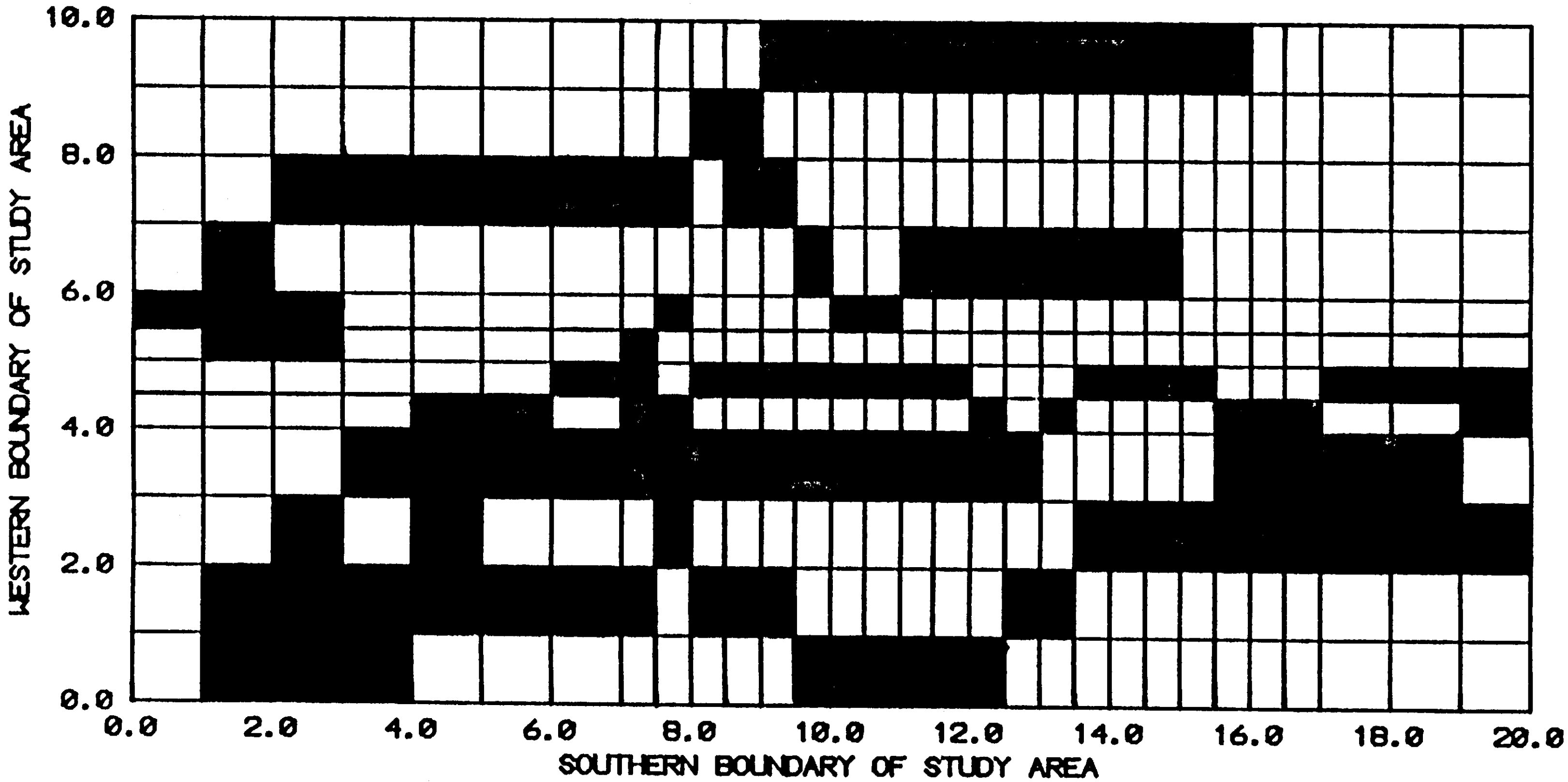

Figure 33. Location of River and Canal Cells during the Summer Stress Period.

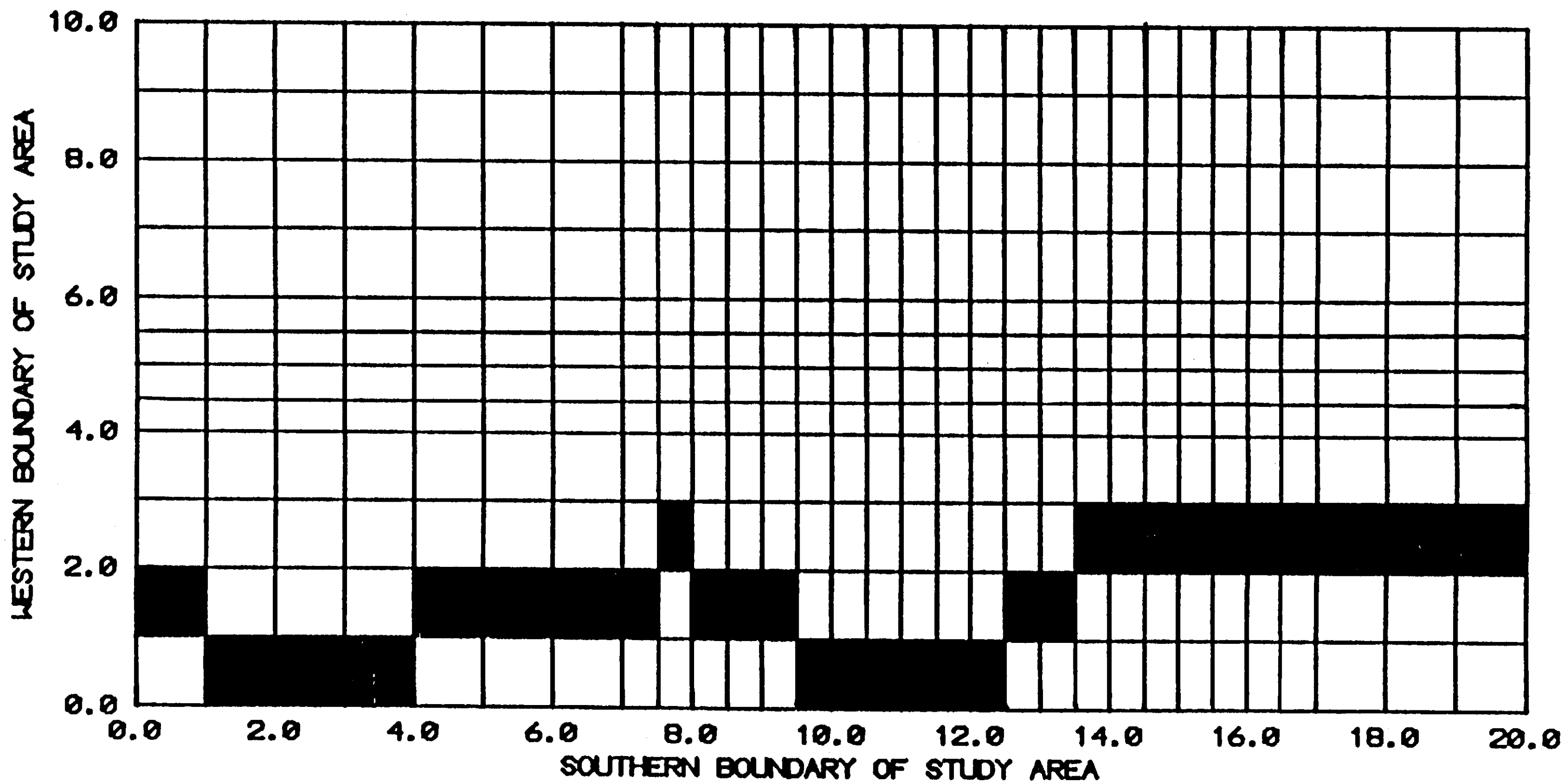

Figure 34. Location of River and Canal Cells during the Winter Stress Period.

Depending on the result of the comparison, equation (2) is modified into one of the following two forms:

$$QRIV = CRIV(HRIV - H) \qquad [3]$$

$$QRIV = CRIV(HRIV - RBOT) \qquad [4]$$

where

H = the head in the cell

RBOT = the elevation of the river bottom

all other terms are as above

Equation (3) describes the case where water is flowing towards the river while equation (4) describes the case where water is moving into the aquifer from the river channel.

The hydraulic conductance of the streambed is given as the product of length and width of the stream reach in the cell and hydraulic conductivity of the streambed material divided by the streambed thickness. The hydraulic conductance is computed by the user and input to the model as a single value.

While the length and width of a stream reach in a cell can be approximated from the grid system and topographic map, the hydraulic conductivity of the streambed material and streambed thickness are more difficult to obtain. Boelman (1989) found though extensive testing that the hydraulic conductivity of streambed material could be closely approximated by the hydraulic conductivity of the aquifer for a typical Wyoming stream. This characteristic was used to estimate the hydraulic conductivity of the streambed material of all streams and canals in the area with the exception of the main channel of the Interstate Canal, which is concrete lined. Estimates of the hydraulic conductivity of the concrete liner reflect consideration of secondary, or fracture, permeability. Except for the main channel of the Interstate Canal, a readily identifiable streambed layer does not exist beneath any of the streams or canals in the area and the value of this parameter had to be assumed. During model calibration, these values, and hence the conductance term, were modified extensively.

The elevation of the stream bottom was derived from the topographic map of the area. The average stream bottom elevation in the cell was used.

A value for the final parameter required by the model, stream stage, also had to be assumed as there are no stream stage recorders in the study area. However, flow in the North Platte is strictly controlled by three upstream dams and variations in flow are not dramatic. Maximum depths of 15 and 5 ft were assumed for the summer and winter stress periods respectively. During calibration stream stage was varied below these maximum values. By limiting the maximum depth of the stream, the head available to move water from the stream into the aquifer is also limited (Equation 2).

Drains. The only drain found within the study area is Arnold Drain located in the east-central part of the study area. The location of cells occupied by this drain during both the summer and winter stress periods are shown in Figure 35. The data required to describe a drain are identical to the requirements needed to describe a river reach and the model simulates flow to or from the drain in the same manner used to simulate a river.

The length, width, and elevation of the drain bottom were determined from the grid system and topographic map of the area. The hydraulic conductivity of the drain bottom was assumed to be equivalent to the conductivity of the aquifer. The maximum values allowed for the drain stage were 15 and 5 ft during the summer and winter stress periods, respectively. As with the river reaches, the thickness of the drain bottom was unknown and as a result the conductance term was modified extensively during model calibration.

Evapotranspiration and Recharge. The Modflow program contains separate modules for evaluating the effects of evapotranspiration and recharge. In this simulation neither of these options were used because their effects could be accounted for in other modules.

As stated in Chapter II, the bulk of precipitation in the area occurs during the growing season. Crist (1975) found that even during the months of greatest precipitation

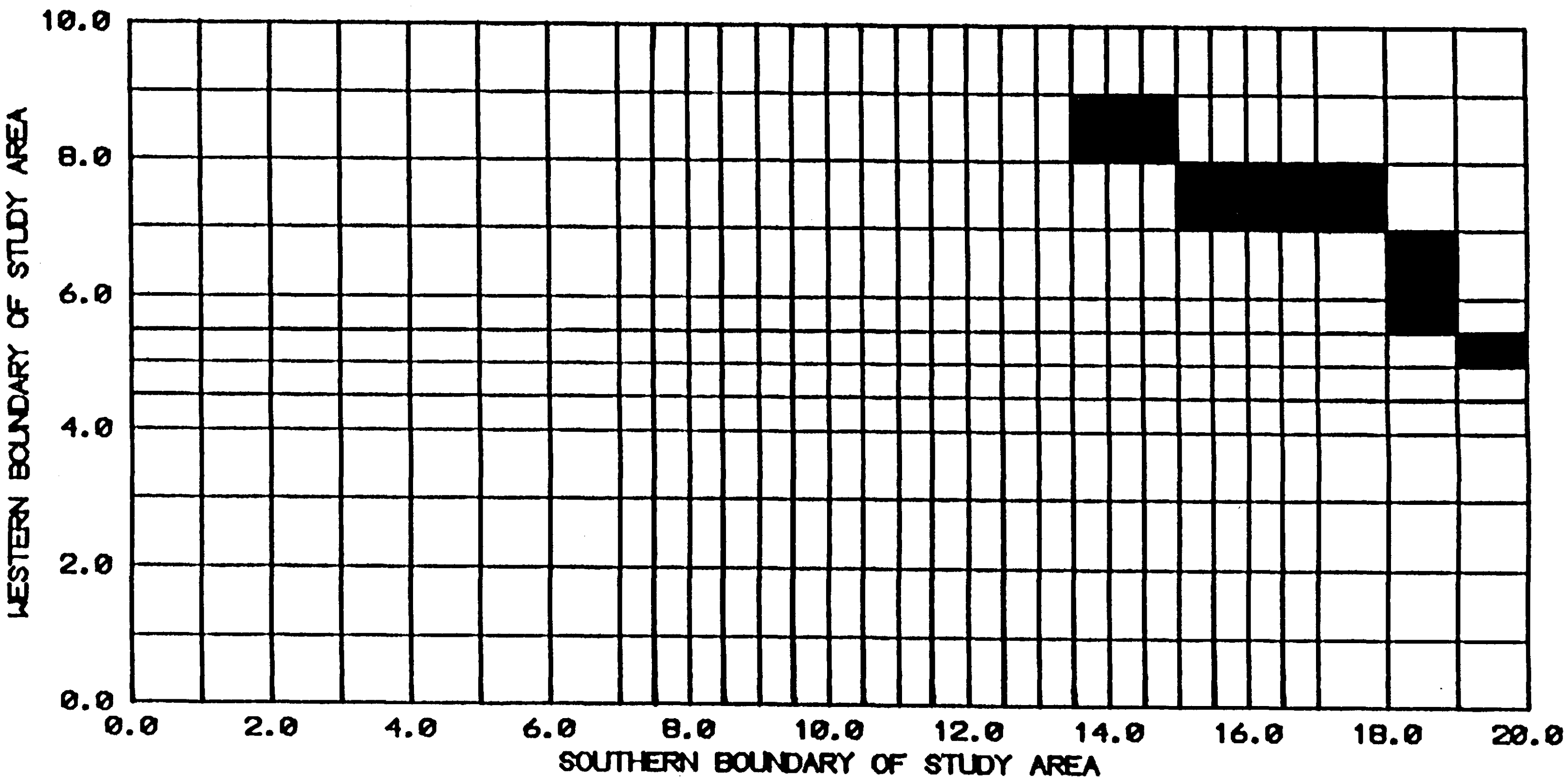

Figure 35. Location of Drains.

there was a net deficit between the effective precipitation and the consumptive use by crops. In effect, precipitation events were not a significant source of recharge to the aquifer in the study area.

Crist (1975) also determined that approximately 45 percent of surface water diversions for irrigation are lost to consumptive use during the growing season. If it is assumed that consumptive loss is similar for groundwater brought to the surface for irrigation, then approximately 55 percent of this is returned to the aquifer as recharge, or is in effect, water that is not removed from the groundwater system. This recharge can be accounted for by adjusting the pumping rates of irrigation wells downward by this amount during the summer stress period.

Inactive cells. In several cells north of Torrington, low permeability bedrock is exposed at or near the land surface. During the simulation these cells went dry due to their inability to transmit water. Because the model is incapable of reactivating a cell once it has gone dry, these cell are relegated to an inactive status (Figure 36) within the model.

Specific Storage. In order to simulate transient flow conditions, a value of specific storage must be assigned to the aquifer material. Rapp et al. (1957) found that the specific storage of the flood plain deposits is 0.235 and that of the third terrace deposits is 0.216.

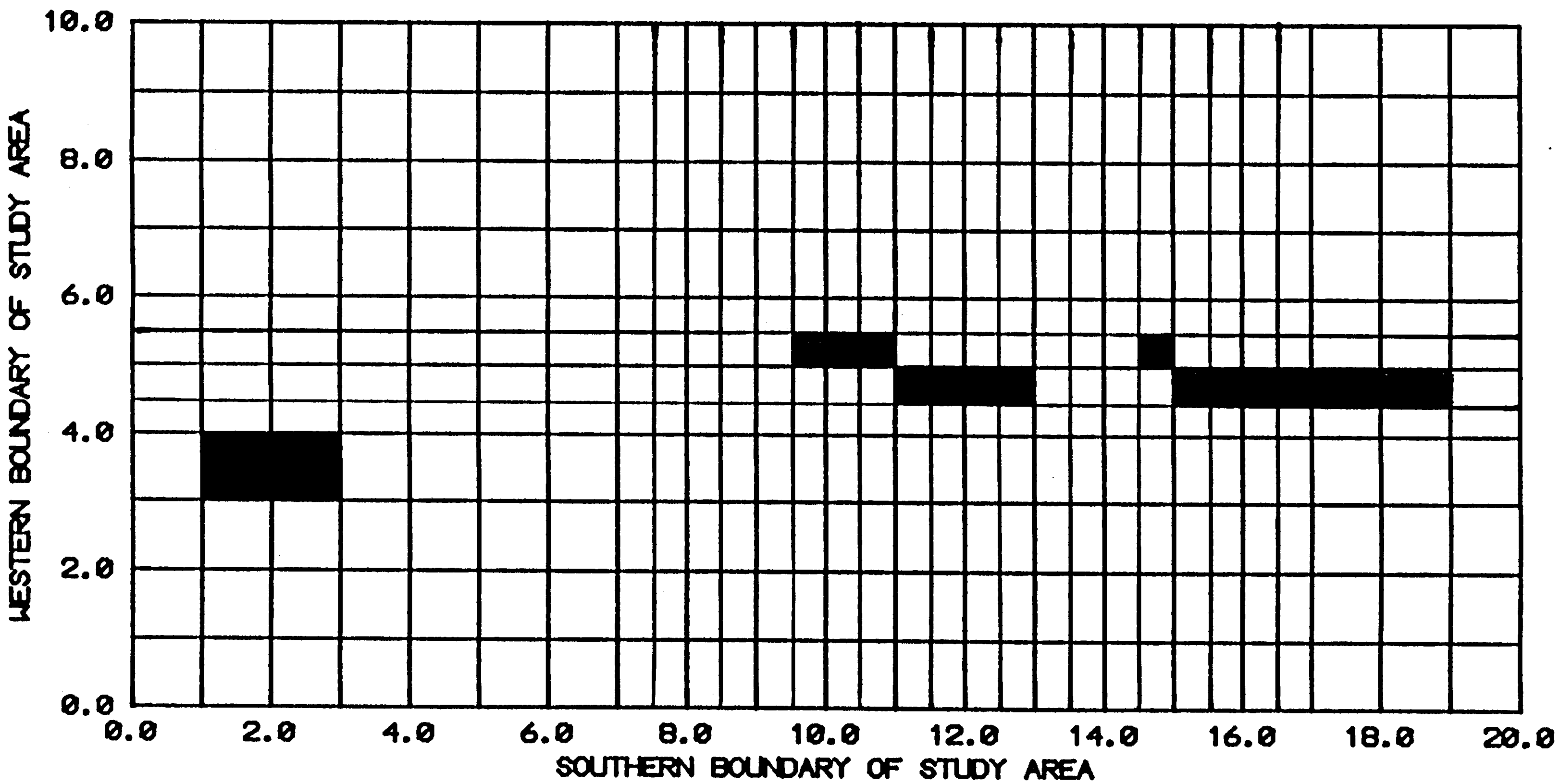

Figure 36. Modflow Grid showing Inactive Cells.

A uniform value of 0.23 was assigned to all cells in the model grid during transient simulation. This value was also utilized by Crist (1975). Because of the small variations in the range of values for this parameter, the value was not altered during the course of model calibration.

The model was deemed to be calibrated when the head values of the fifteen year simulation were within 5 to 7 ft of water level measurements made at ten irrigation wells on April 29, 1991. The large error was allowed as a result of the numerous assumptions made during the course of calibration and because the elevation of the top of the well casings were estimated from the topographic map rather than being sighted in using surveying techniques.

CHAPTER VI

Results and Discussion

Model Output

Head values predicted for each of the cells, as well as the x and y coordinates of the cell node, are recorded in a binary disk file by the Modflow program. The "Postmod" (post processing) package is utilized to convert this binary file into an American Standard Code for Information Interchange (ASCII) file which was then imported into Golden Software's three dimensional plotting package "Surfer" for further processing.

Four plots of the potentiometric surface were developed using the Surfer plotting program. These plots represent the configuration of the potentiometric surface at the end of the final two stress periods for both the steady state and transient flow simulations. They are discussed in detail below.

Plotting Method

Developing plots with the Surfer plotting program consists of the three step process of data entry, gridding, and plotting. The methods used in this investigation are discussed briefly.

Data entry involves inputting the x, y, and z output from Modflow into the Surfer spreadsheet. Three methods of creating a grid file are available in Surfer; the inverse distance, krieging, and minimum curvature methods. In order to determine which method to use, test runs were conducted using each method with data from an existing map. Results indicated that the minimum curvature method, with a maximum allowable error of 1% in conjunction with a tension factor of 0.002 in the plotting procedure, produced the closest match with the existing map. This method, and these settings, were used to produce all plots generated in this investigation.

Method of Interpretation

In order to interpret the plots and determine the direction of groundwater flow, the aquifer is assumed to be homogeneous and isotropic. This assumption is unlikely to reflect actual conditions found in the aquifer but the data required to justify any other assumption are unavailable at this time. Using this assumption, the direction of flow in the aquifer is perpendicular to the lines of equipotential.

Potentiometric Surface: Winter Stress Period

Figure 37 shows the configuration of the potentiometric surface following the final winter stress period of the steady state simulation. Elevations of the water table measured at ten locations in April 1991 are also shown. It should be noted that the measured elevations of the water table in the northern part of the study area, near the Interstate Canal, correspond poorly with predicted levels from the model. However, only after the measurements were obtained did it become known that the canal had been put in operation approximately two weeks earlier to fill a down-stream reservoir. Therefore, measurements in this vicinity are more likely to reflect conditions at the end of the summer rather than the beginning of the spring.

The results from the transient flow simulation of this stress period are given in Figure 38. It should be noted that while water levels in the area have declined over the past fifteen years, the simulation indicates that water levels are rising. This discrepancy is due to error in the mass balance. The consequences of this error become evident when aquifer storage is considered in the transient flow simulation.

In the steady state simulation, a net positive error of approximately 4% exists in the mass balance. That is, 4% more water is entering the system than leaving. In the transient flow simulation, this excess water accumulates in

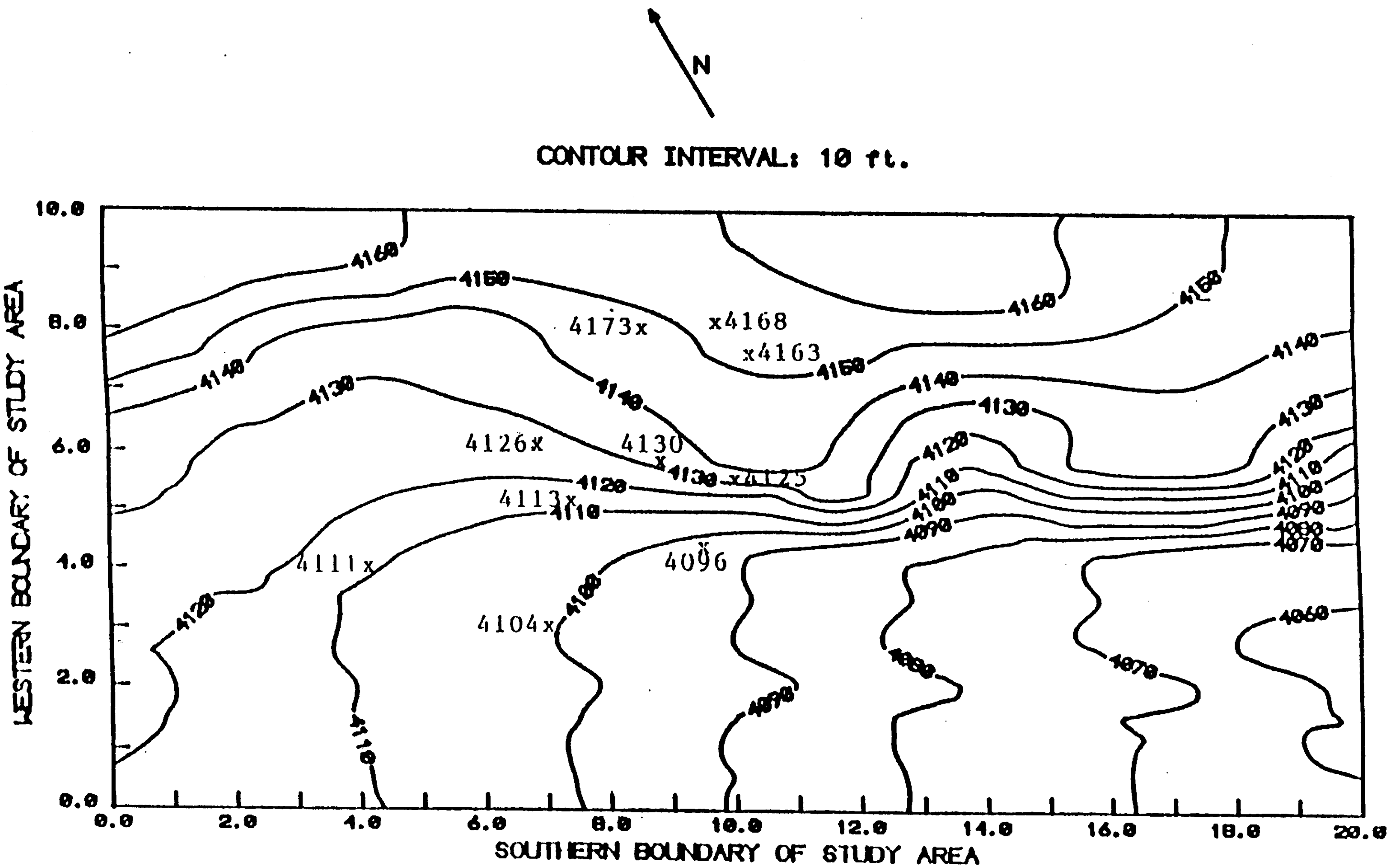

Figure 37. Configuration of the Potentiometric Surface from the Steady State Simulation: Winter Stress Period.

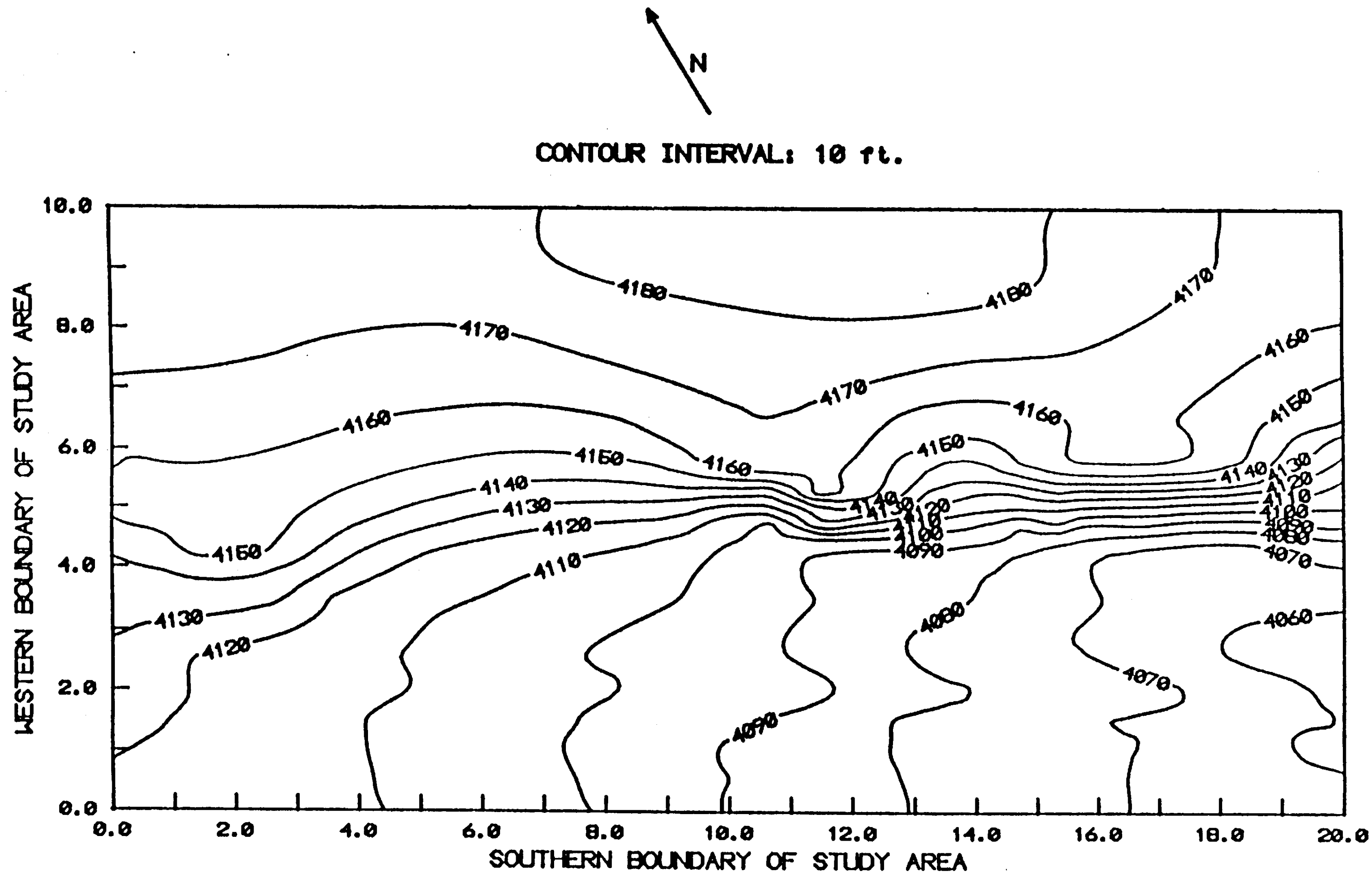

Figure 38. Configuration of the Potentiometric Surface from the Transient Flow Simulation: Winter Stress Period.

storage causing the water table to rise. For this investigation, however, the most important result of the transient flow simulation is that the general configuration of the potentiometric surface remained the same.

The single most important feature controlling the configuration of the potentiometric surface and the direction of flow in the aquifer at this time appears to be the presence of the bedrock outcrops that occur in the central and eastern parts of the study area. These outcrops can be identified by steep gradients, up to 120 ft/mi, in the potentiometric surface. The relationship between these gradients and the location of bedrock cells is shown in Figure 39.

During this time, recharge is derived from the upland areas to the north and northwest of the study area. As flow entering the area immediately north of the bedrock outcrops moves south and approaches the dams created by the outcrops, it appears to stagnate, as indicated by the modest gradients present in these areas, and to be diverted laterally toward the breaches in the bedrock (Figure 40). At the breaches, groundwater moves unhindered from the third terrace into the floodplain aquifer; the breaches apparently act as spillways between the two aquifers.

In the extreme northeastern part of the area, flow is directed toward Arnold Drain. Flow entering the area from the northwest moves directly toward the Platte River through

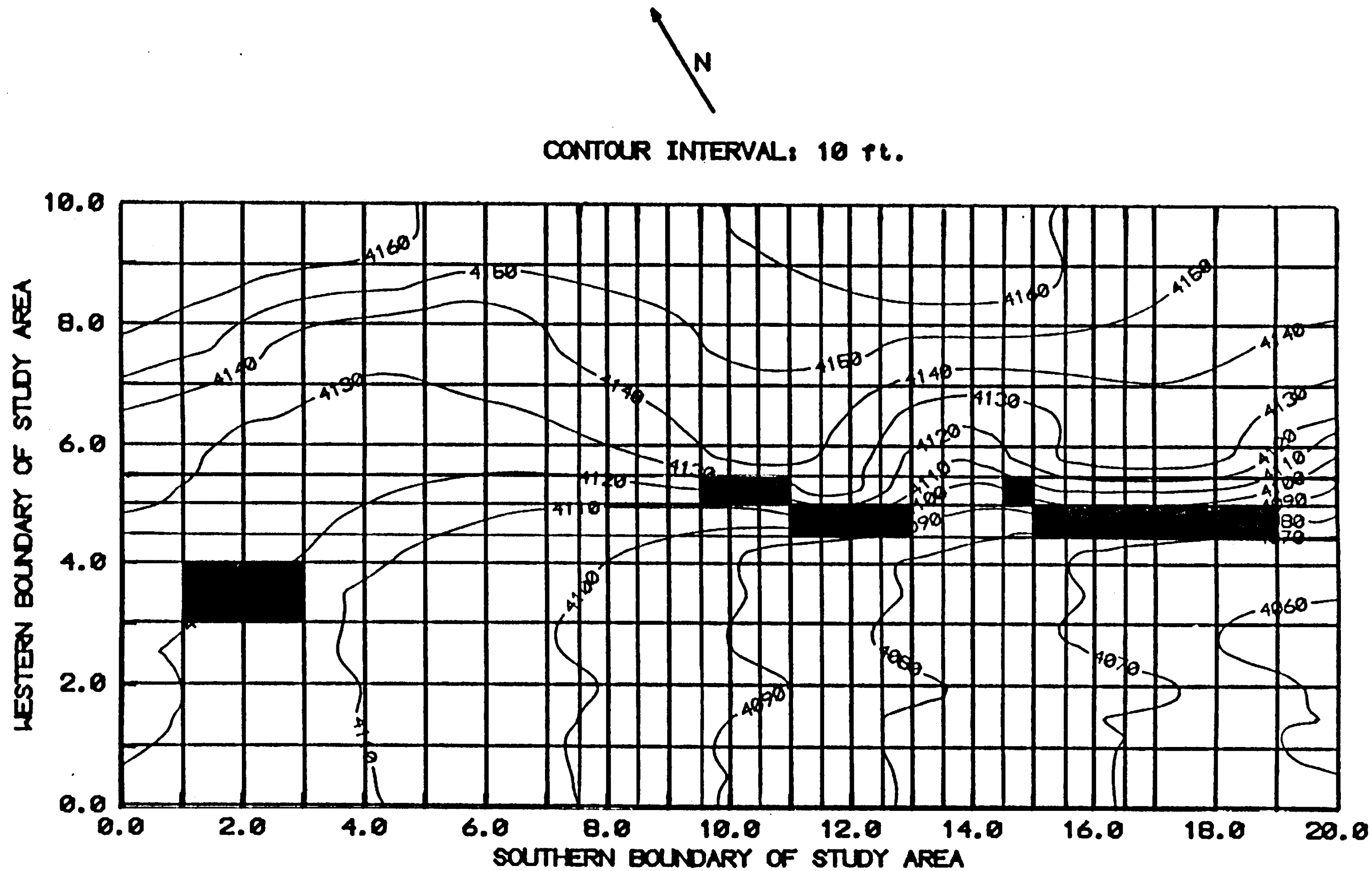

Figure 39. Relationship between Bedrock Cells and Steep Gradients in the Potentiometric Surface.

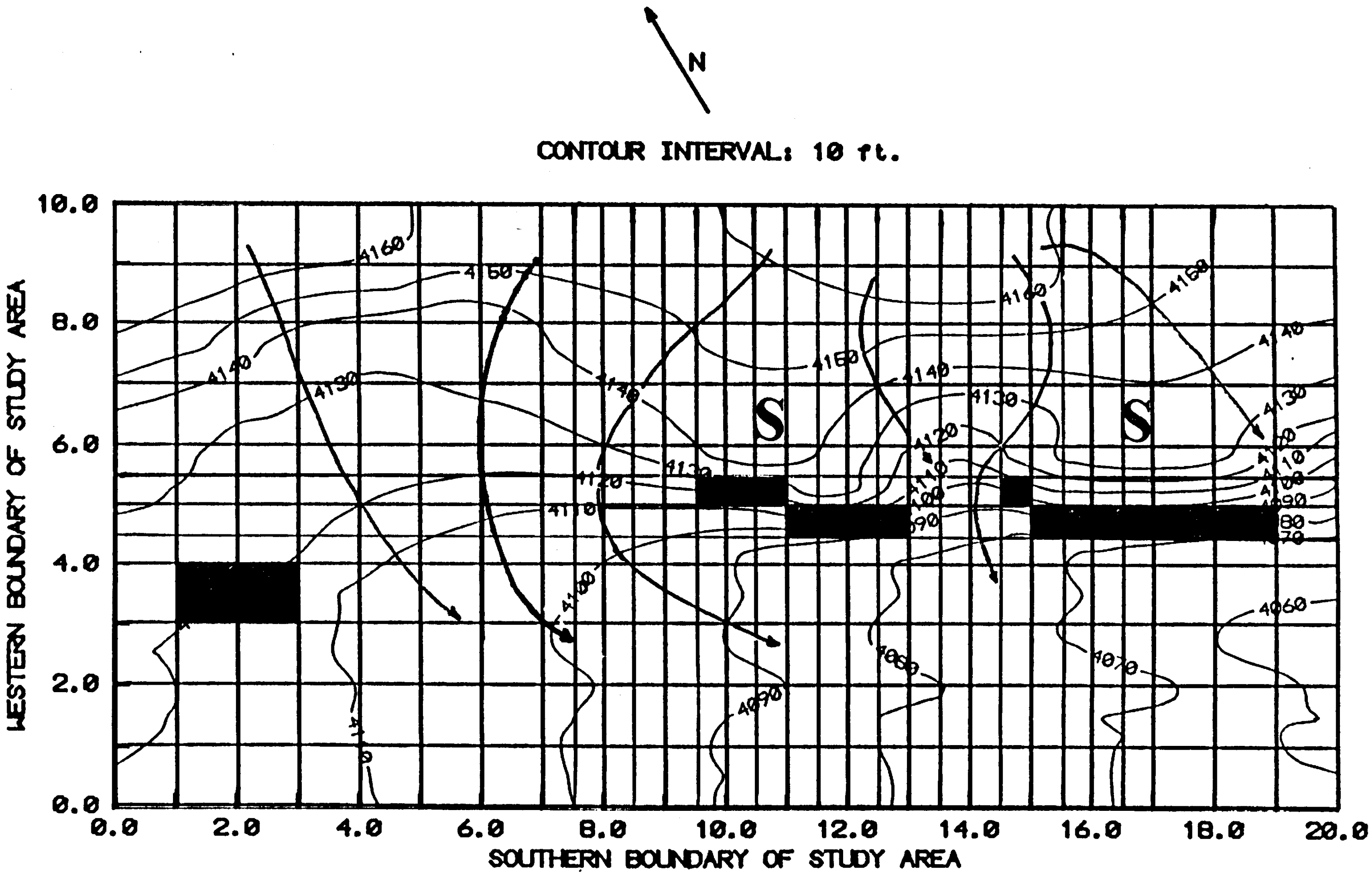

Figure 40. Areas of Stagnation (S) and Direction of Flow (arrows) in the Aquifer Following the Winter Stress Period.

the breach in the west-central part of the study area.

Previous investigations have shown the North Platte to be a gaining stream throughout the area during this stress period. This investigation indicates that the Platte is losing water to the aquifer during the winter months (Figure 41). This is likely to be the result of limited amounts of recharge reaching the floodplain aquifer from the deposits of the third terrace during this time period.

Potentiometric Surface: Summer Stress Period

A plot of the potentiometric surface at the end of the final summer stress period of the steady state simulation is shown in Figure 42. Measurements of the actual elevation of the water table at the end of this stress period are not available. However, as stated in the previous section, water levels measured in the vicinity of the Interstate Canal in the spring of 1990 may reflect conditions at the end of the summer stress period as the canal was serving as a source of recharge. Measurements taken within a few hundred feet of the canal are remarkably similar to the results predicted by the model. Nevertheless, further calibration of the model should be performed as more accurate data becomes available.

The corresponding plot from the transient flow simulation is shown in Figure 43. Again, although this simulation indicates that the water table has been rising over the past fifteen years, the most important feature is that the

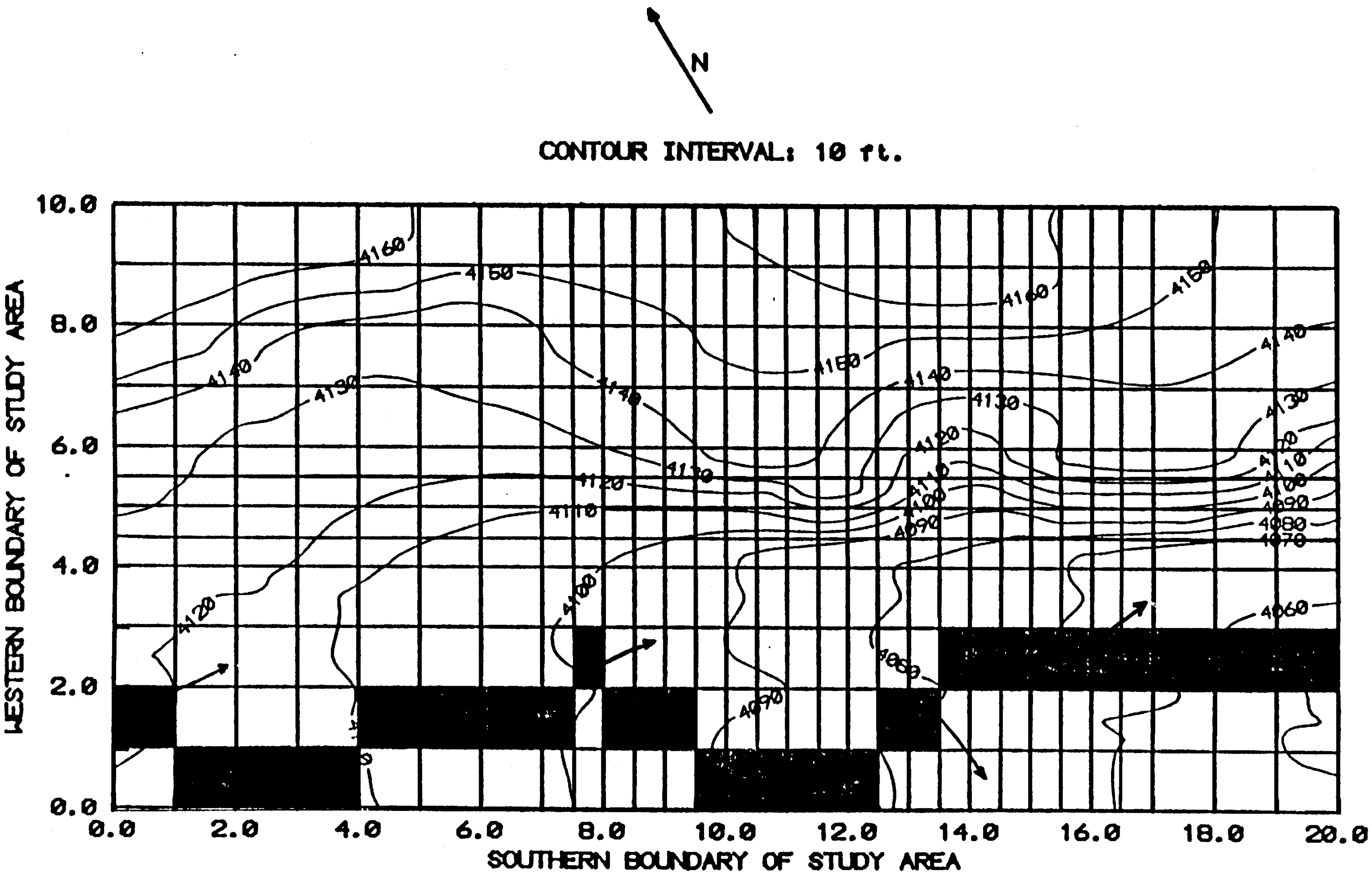

Figure 41. Platte River as a Losing Stream.

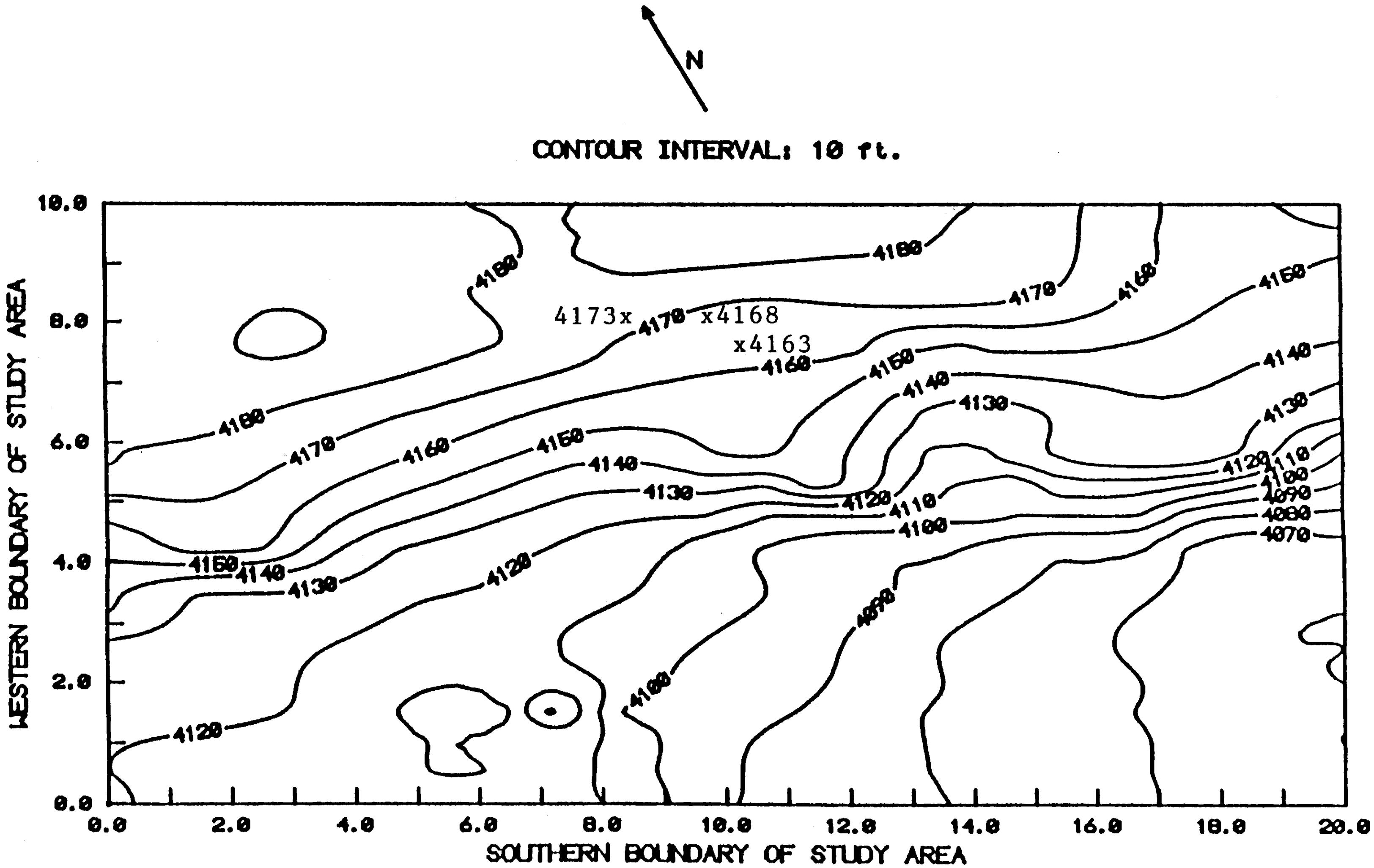

Figure 42. Configuration of the Potentiometric Surface from the Steady State Simulation: Summer Stress Period.

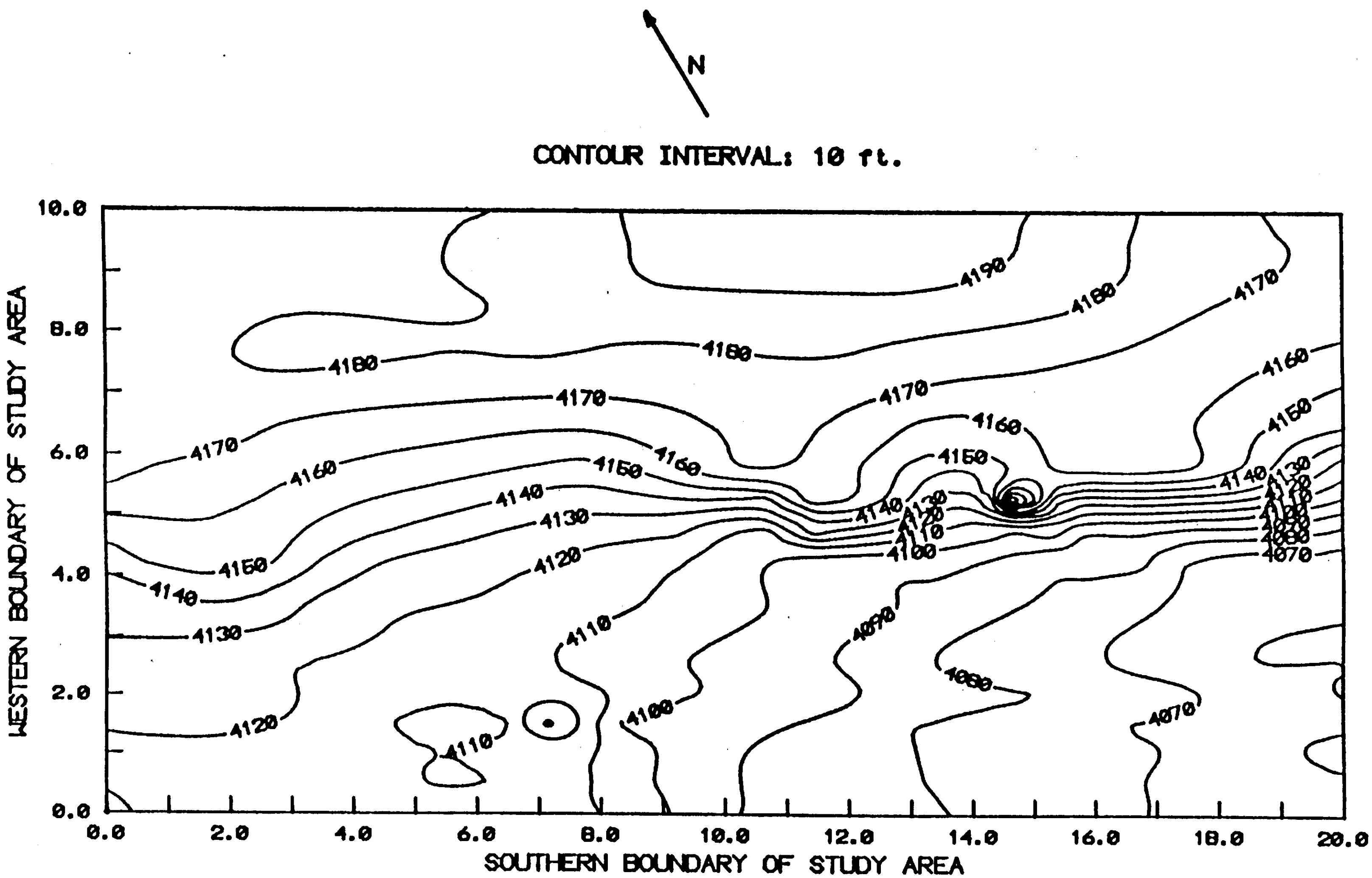

Figure 43. Configuration of the Potentiometric Surface from the Transient Flow Simulation: Summer Stress Period.

general configuration of the potentiometric surface remained constant.

The configuration of the potentiometric surface at the end of this stress period is similar to the previous stress period in several respects. Bedrock outcrops can again be identified by the extreme gradient which develops across them and the stagnation and lateral diversion of groundwater around these barriers toward the two breaches is still apparent (Figure 44). In addition, groundwater in the northeast part of the area continues to move toward Arnold Drain.

The most significant differences between the two stress periods are the increased elevation of the water table throughout the area and a change in the direction of flow toward the southeast in the central and western parts of the area during the summer. It is likely that both of these phenomena are due to extensive recharge to the groundwater system from irrigation canals and laterals, with the principal source of recharge being the Interstate Canal.

The large increases in the elevation of the water table during the summer are well documented by the Torrington Department of Public Works and occur despite extensive pumping that occurs during this period. In addition to these changes, the North Platte appears to be a gaining stream throughout the area during this time (Figure 45).

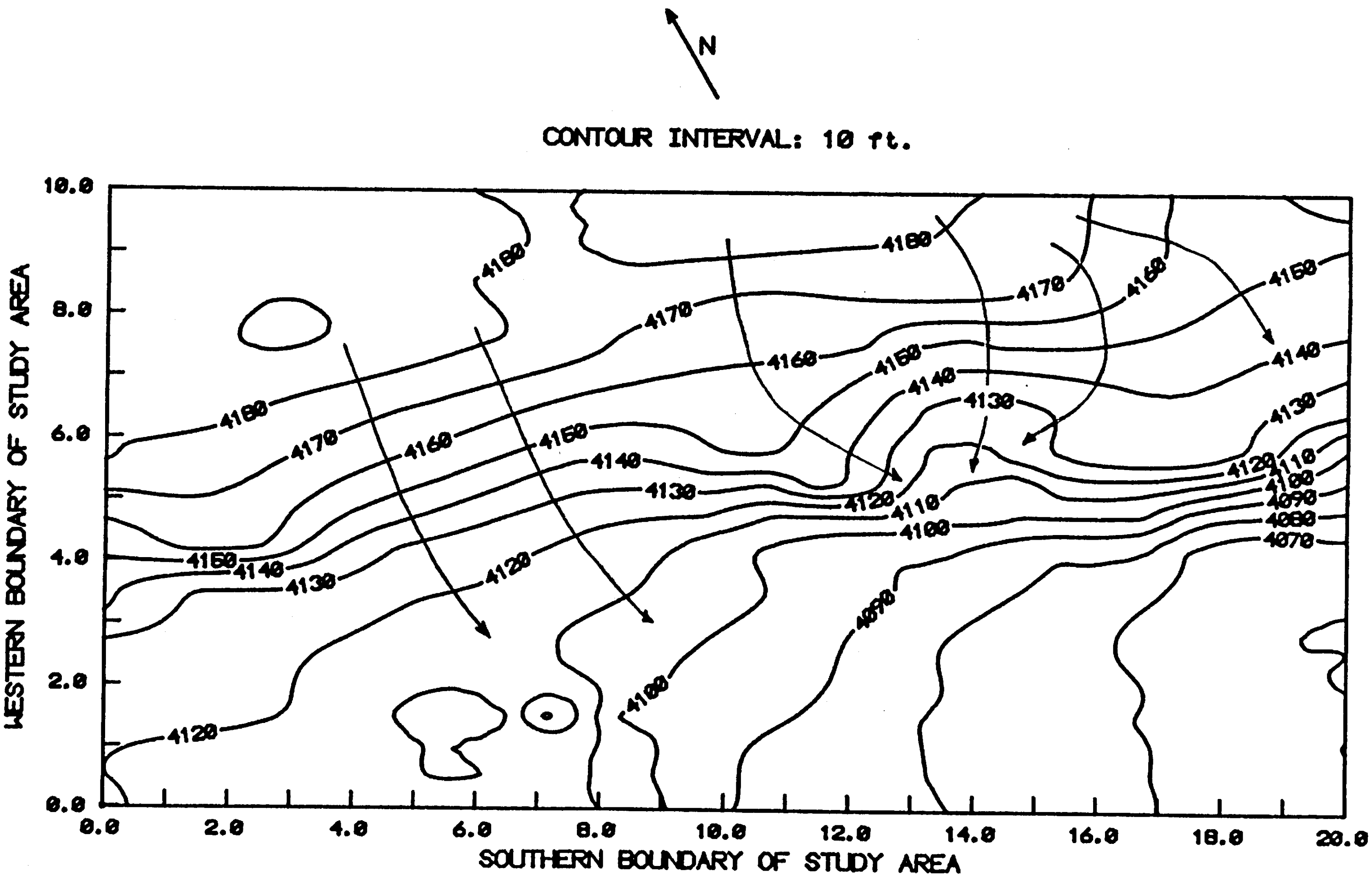

Figure 44. Direction of Groundwater Flow (arrows) during the Summer Stress Period.

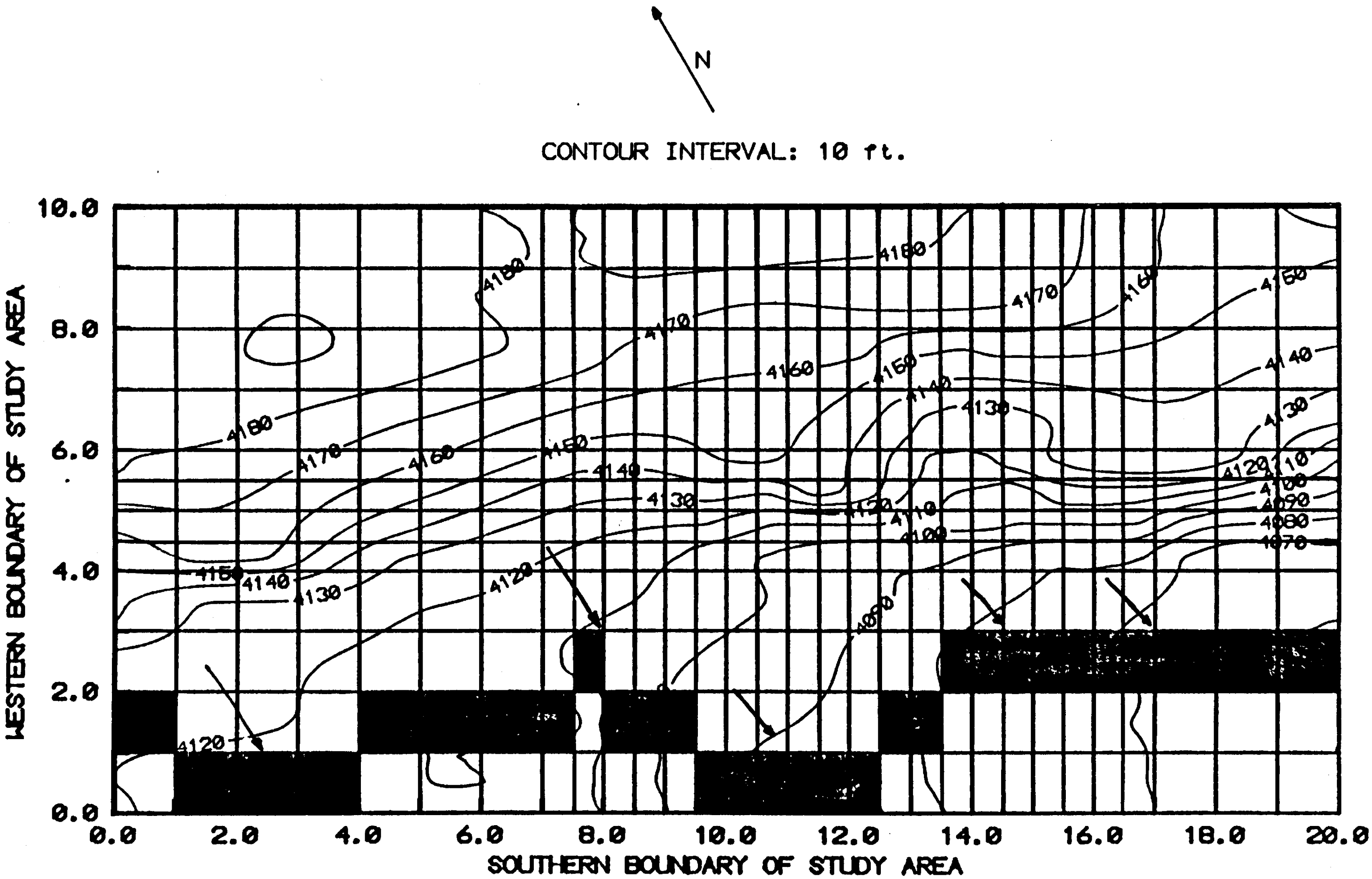

Figure 45. North Platte as a Gaining Stream.

The results of the simulation indicate that variations occur in the elevation of the water table as well as the direction of flow on a seasonal basis. Stagnation occurs behind the bedrock dams and groundwater flow is directed preferentially toward the breaches that occur in this dam where it can readily move from the third terrace to the floodplain aquifer. It appears that principal sources of recharge to the Town of Torrington municipal wellfield is water entering the floodplain aquifer from the third terrace through the breach that exists in the bedrock north of the town.

Sensitivity Analysis

As stated in Chapter V, input values of hydraulic conductivity, conductance of streams, canals, and drains, and the pumping rate of irrigation wells, were modified extensively during model calibration. With the exception of hydraulic conductivity, the error allowed in model calibration was greater than the effect of varying the input values. However, a sense for the relative effect of the modifications is given below.

The model was most sensitive to changes in each of the parameters in the order given above. During initial runs, hydraulic conductivities of 1200 and 800 ft/d were assigned to deposits of the floodplain and third terrace respectively. During subsequent runs, these values were adjusted downward to final values of 800 and 500 ft/d. This change, of less than one order of magnitude, resulted in a change in the elevation of the water table of 15 to 20 ft. In contrast to this, the value of conductance for the streams, canals, and drains was varied over several orders of magnitude and resulted in changes in the elevation of the water table of 5 ft. or less. The effect of varying the pumping rates of irrigation wells also resulted in changes of five feet or less in the cell containing the well.

Nitrate Sampling Program

The Surfer program was also used to generate contour maps of nitrate distribution in the study area. The results of the three major nitrate sampling events conducted in October 1989, May 1990, and October 1990 are shown in Figures 46, 47, and 48 respectively. In each figure, areas of low nitrate concentration, less than 5 mg/l, are shown in green while areas with nitrate concentrations above 5 mg/l are shown in red.

Several significant trends become apparent when the distribution of nitrates is analyzed in terms of the seasonal variations in the configuration of the potentiometric surface and the location of subsurface dams and breaches in the area. Potential sources of nitrate, both natural and anthropogenic, can be identified in many of the areas exhibiting elevated levels of nitrate contamination. The areas of low and high nitrate concentration are discussed separately.

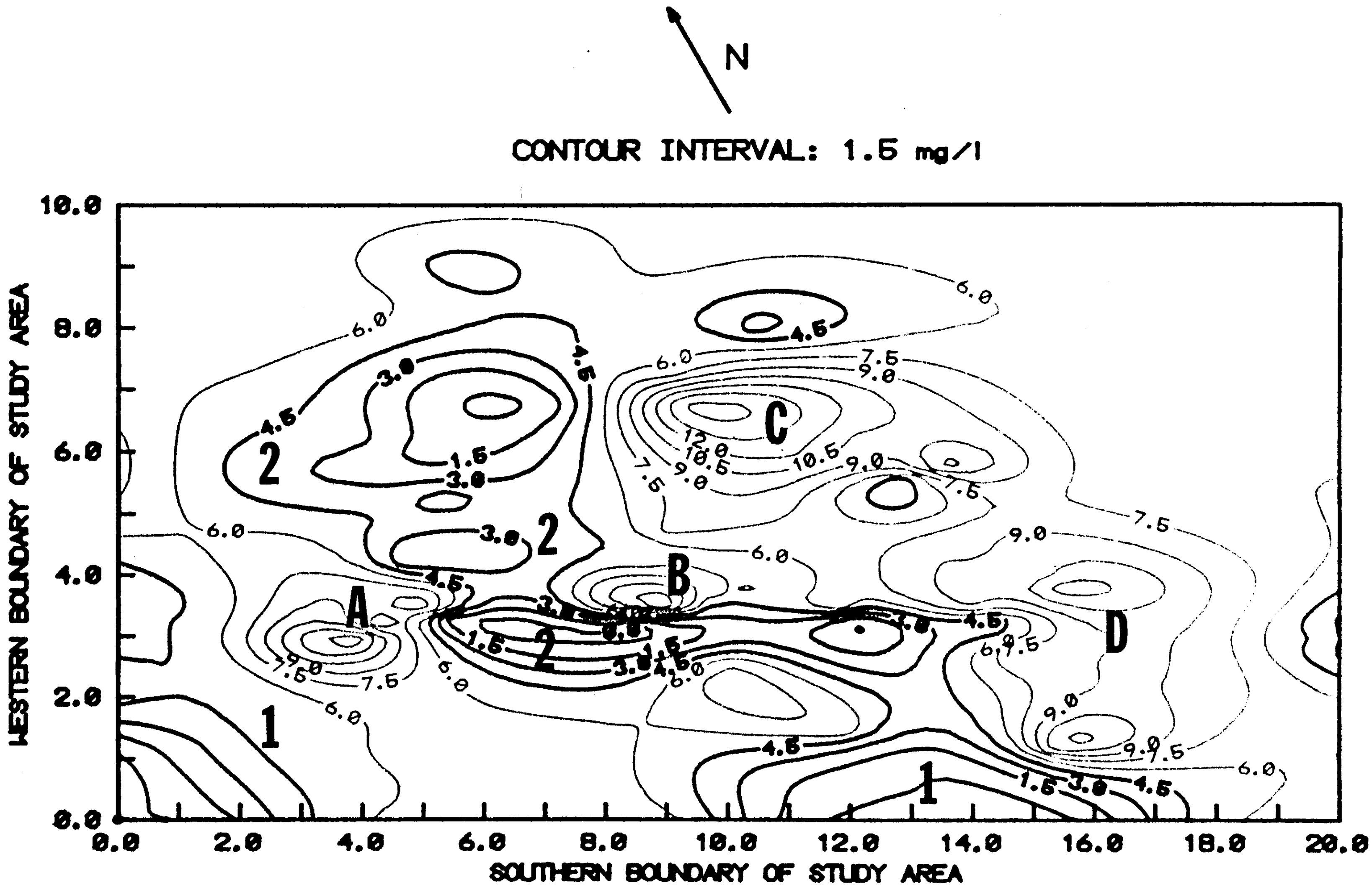

Figure 46. Distribution of Nitrate in the Fall of 1989.

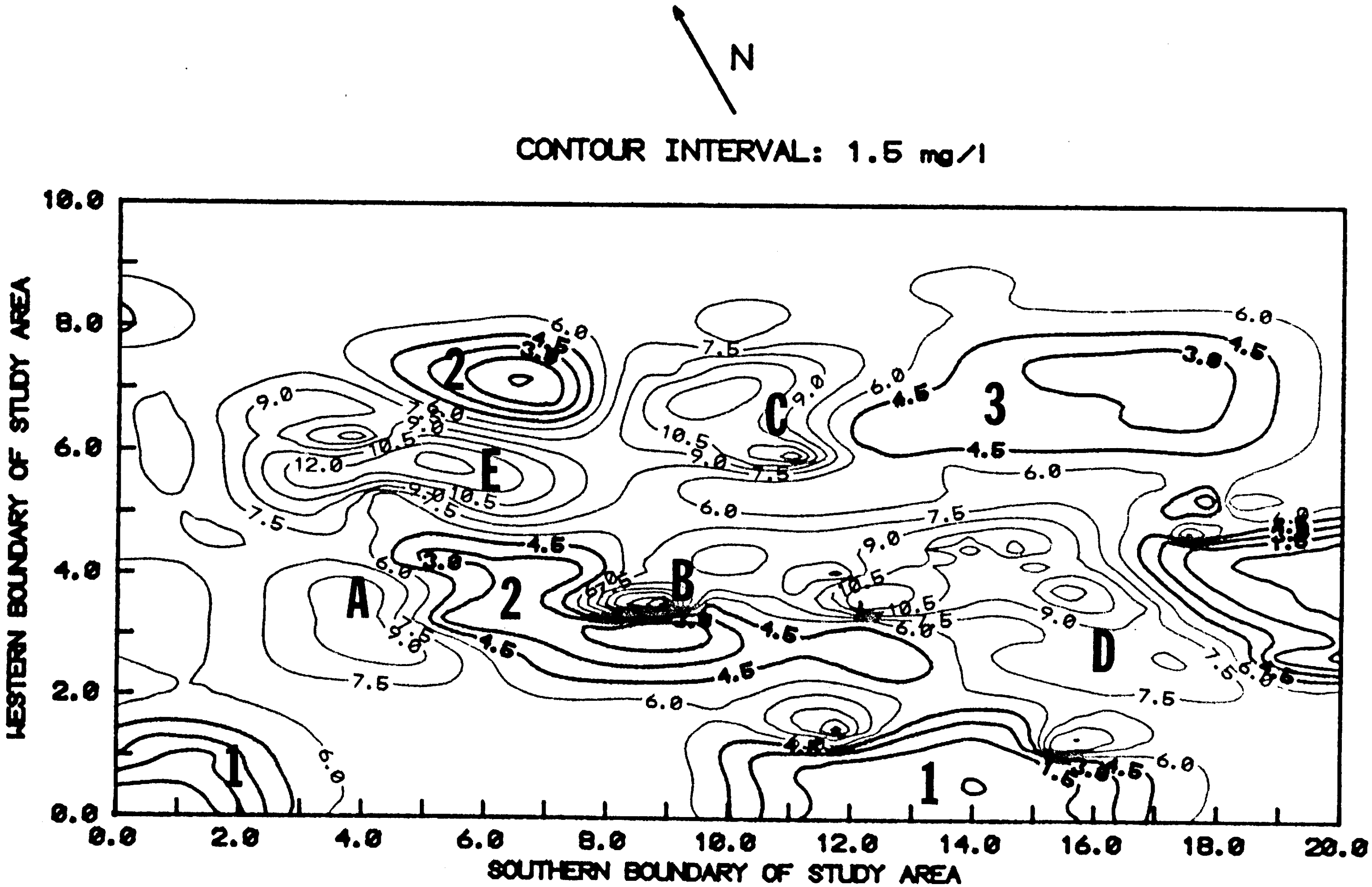

Figure 47. Distribution of Nitrate in the Spring of 1990.

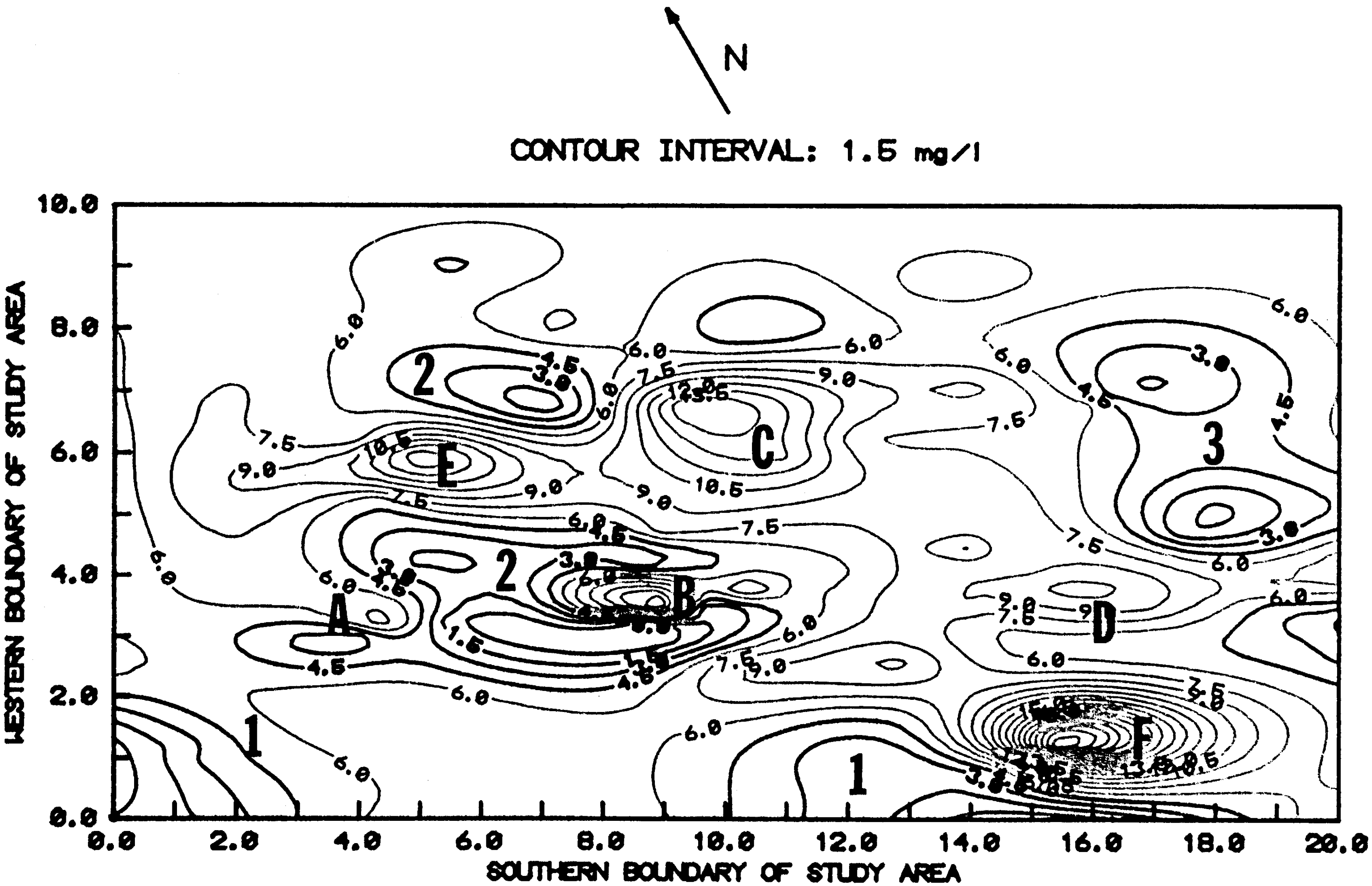

Figure 48. Distribution of Nitrate in the Fall of 1990.

Areas of Low Nitrate Concentration

For each of the sampling events, areas of low nitrate concentration are found along the southern boundary and the west-central part of the study area; locations 1 and 2 respectively on Figures 46-48. Low concentrations of nitrate found in the northeastern part of the study area in the sampling events conducted during 1990, location 3 on Figures 47 and 48, do not appear in 1989 because sampling sites had not been established in this area at that time.

Areas of low nitrate concentrations at location 1 may be the result of groundwater dilution by recharge derived from the North Platte. The Laramie Canal, located just south of the study area, may also be a source of recharge and dilution to these areas. However, because this canal is located in low permeability bedrock, the contribution from this source is likely to be small when compared to other potential sources. For this reason the canal was not included in the simulation, and the specific impact from this source is unknown.

At location 3 the size of the area of low nitrate concentration appears to expand and contract seasonally. This is likely to be a function of the variations in the direction of flow that occurs between the winter and summer stress periods. During the winter months, recharge is derived from the upland and dune sands to the north of this area. This water is likely to contain low concentration of nitrate as these lands are relatively unproductive and not as intensively cultivated as other areas. However, in the summer months when the direction of flow in the central and western parts of the area shifts to the southeast, nitrate laden waters beneath the most intensively cultivated and heavily fertilized parts of the third terrace displace the low nitrate waters toward the east.

In terms of aerial extent, the most significant area of consistently low levels of nitrate is location 2 in the west-central parts of the study area. Of particular interest is the relationship between the low levels of nitrate and the large breach in the bedrock found in this area. This relationship is best illustrated using the results of the Fall 1989 sampling event (Figure 49). The results from this sampling event suggest that where the flow of groundwater is unhindered by subsurface dams the aquifer system is capable, to some extent, of flushing itself. However, the results of the sampling conducted during 1990 indicates that there is a limit to this capability. While areas of low nitrate concentration are still present, they are not nearly as extensive as in 1989 and significant increases in the level of nitrate contamination have developed in large parts of this area. These increases may be due to cultural activities in the area. This and other areas of elevated levels of contamination are discussed in the following section.

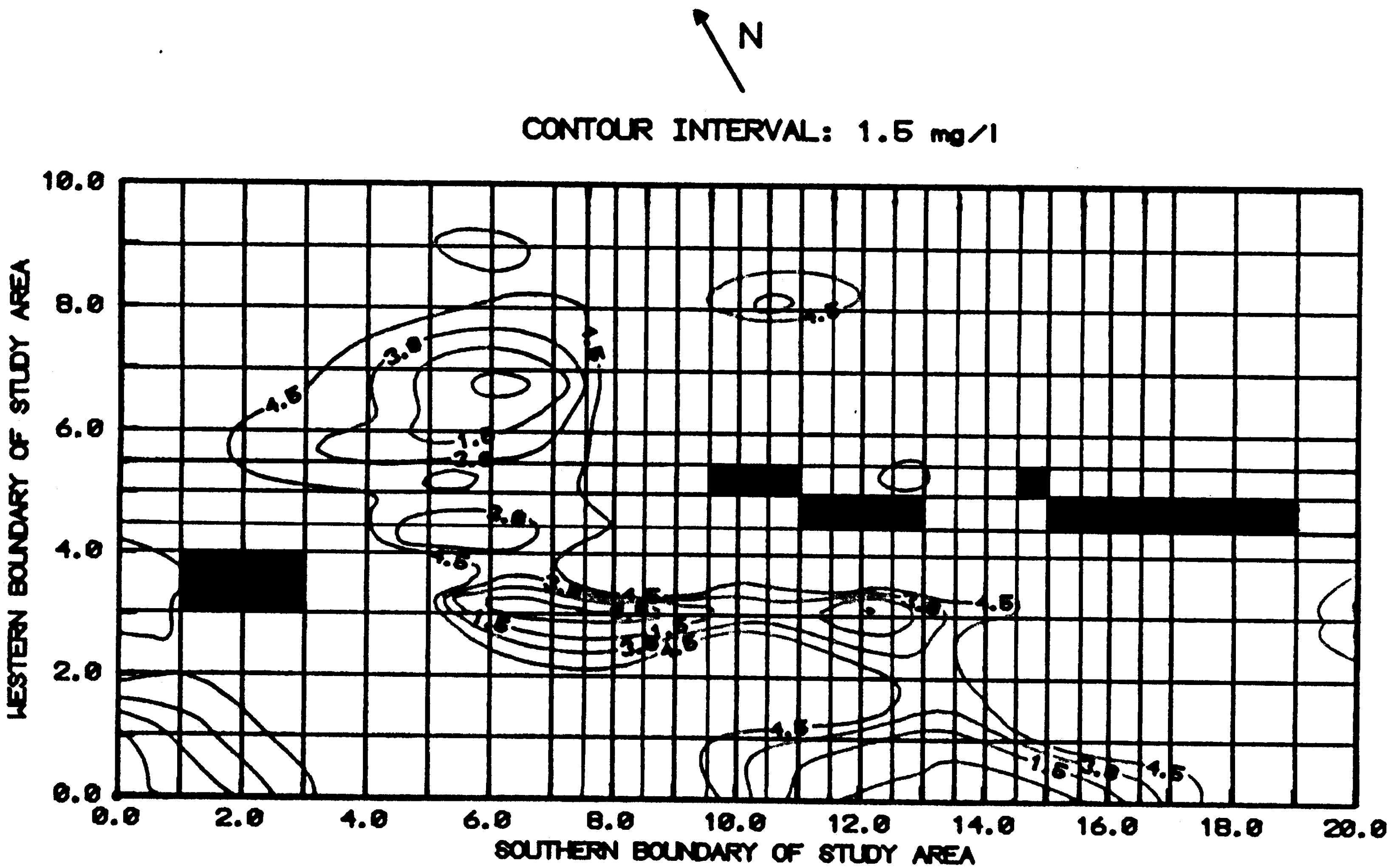

Figure 49. Relationship Between the Area of Low Nitrate Concentration and the Breach in the West-Central Part of the Study Area; 1989 Data.

Areas of High Nitrate Concentration

The results of the sampling conducted in the Fall of 1989 indicate the existence of four principal areas of elevated nitrate contamination (locations A, B, C, and D on Figure 46). Nitrate levels in each of these areas exceeds the MCL of 10.0 mg/l.

The results of sampling conducted in the Spring of 1990 indicates that the level of contamination at location A is diminishing. However, contaminant levels remained high at locations B, C and D, and a new location, E, developed to the west of C displacing the low nitrate levels recorded in the Fall of 1989.

Sampling conducted during the Fall of 1990 shows the continued decline of nitrate concentrations at location A to levels well below the MCL. Contaminant levels at locations B, C, and D, remained at levels observed throughout the course of sampling while contaminant levels at location E remained at levels first observed in the Spring of 1990. In addition to these sites, an area of extreme contamination, location F, appears in the southeastern part of the study area at this time.

Like the areas of low nitrate concentration, several significant trends become apparent when the location of areas of high nitrate concentration are evaluated in terms of the various features of the aquifer system. Each of the six areas of nitrate contamination are discussed below.

Location A is situated in the large breach that exists just to the east of the bedrock outcrop in the extreme western part of the study area. The steady decline in the level of nitrate found in this area, from 13.5 mg/l to less than 4.0 mg/l within a year, suggests that the elevated levels observed in the Fall of 1989 are the result of either a single event such as a spill or agricultural practices that no longer occur in this area. Furthermore, this decline also supports the hypothesis that in areas where groundwater flow between the two aquifers is unhindered by subsurface dams dilution can occur.

Location B is unique in the fact that the level and distribution of nitrate in this area remained essentially constant throughout the sampling program. Wells sampled in this area are located on or adjacent to property owned by the University of Wyoming and occupied by the Torrington Agricultural Experimental Station. Further investigation revealed that the soil type found at this location is unique to the entire study area. This soil, the Vetal Series, contains relatively large amounts of organic matter and is moderately to extremely permeable. While activities at the Experimental Station may be responsible for the elevated levels of nitrate, this unique soil may also be serving as a natural source of nitrate in this area.

Persistently elevated levels of nitrate at location C are not surprising when the proximity of a subsurface dam in this area is taken into account. The results of the 1989 sampling event are used to illustrate the relationship between this area of contamination and the location of bedrock cells (Figure 50). In each of the sampling events, contamination reaches its maximum level in the area of stagnation formed in the groundwater system behind this dam (Figure 51). Nitrate is most likely derived from the intensive agricultural activities that occur in this area. Because flow is directed from this area toward the breach in the bedrock north of Torrington, this area is probably one of the most important in terms of the impact to the municipal groundwater supply. It should be noted that here, as at location A, the concentration of nitrate diminishes as groundwater passes through the breach north of Torrington. This may again indicate that, where large volumes of water can pass easily through the aquifer, the system is capable of diluting itself to a certain extent.

Elevated levels of nitrate at location D are centered around wells located immediately downgradient from the town itself. Because contaminant levels at these locations exceed the levels entering the municipal wellfield from the third terrace, the town must also be contributing to the nitrate contamination problem. Excessive use of lawn fertilizer is likely to be the principal source of nitrate within the city limits. Overwatering can readily leach the fertilizer into the groundwater system.

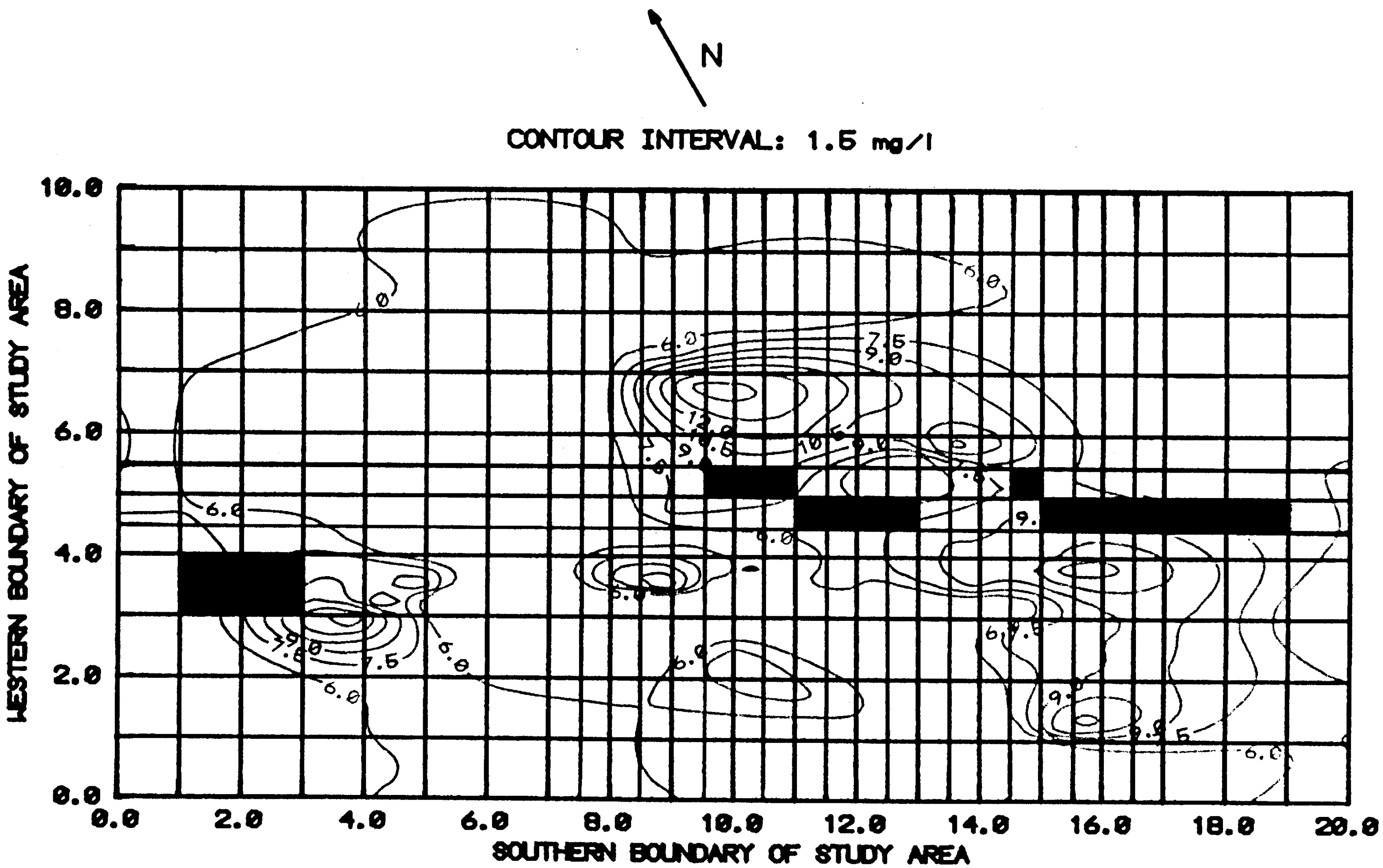

Figure 50. Relationship Between Subsurface Dams and High Nitrate Concentrations North of Torrington; 1989 Data.

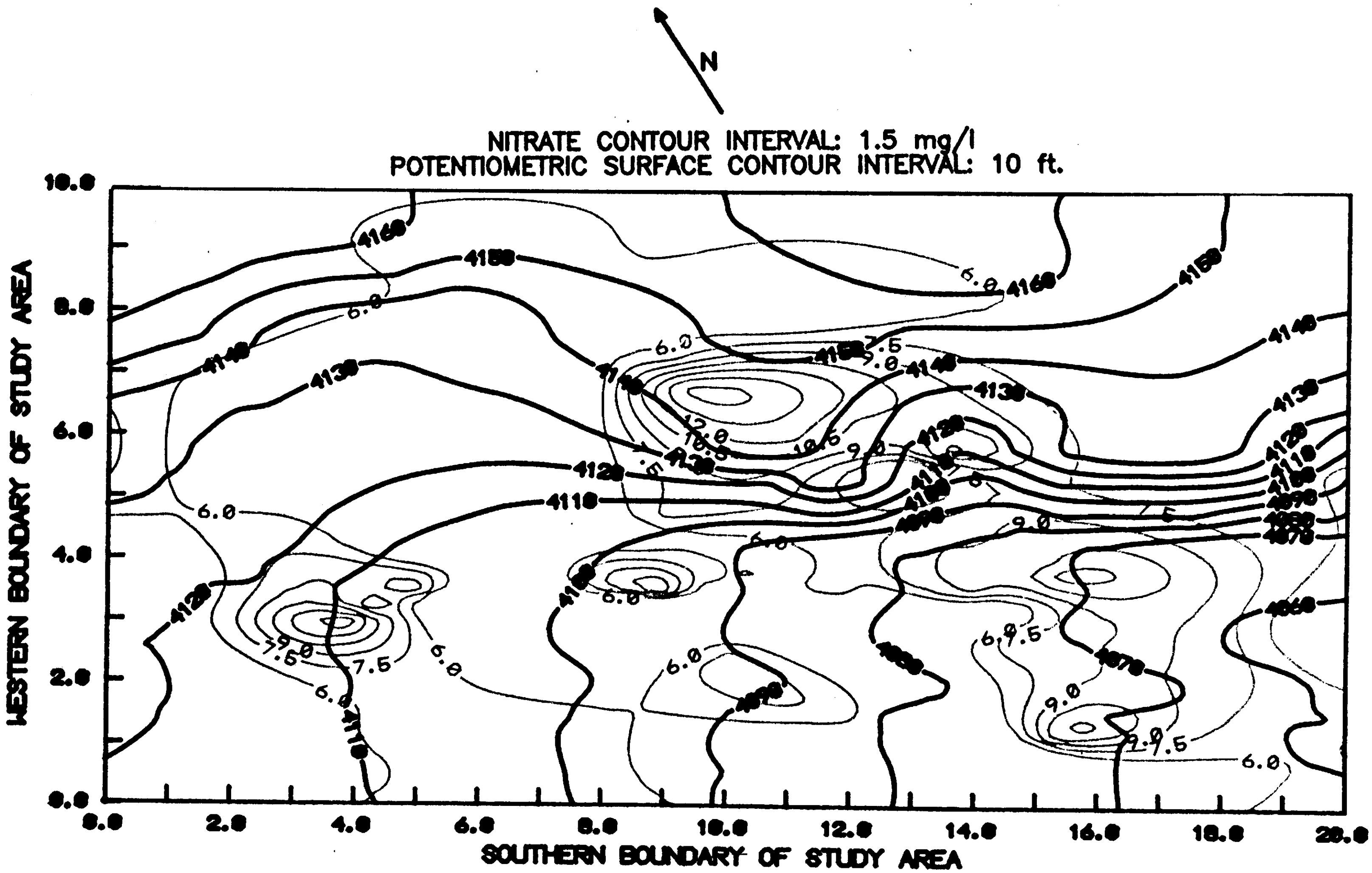

Figure 51. Location of Maximum Level of Nitrate Contamination in the Area of Stagnation; 1989 Data. The results of 1990 sampling are similar.

There is no immediately apparent reason for the development of a large area of elevated contaminant levels at location E in 1990. Although this area is intensively cultivated and a large feedlot operation exists in this area, the feedlot has been in operation for many years. If it were a continual source of contamination it should also have been detected during the 1989 sampling event. It is likely that the source of contamination in this area will only be determined through further sampling and investigation.

The sudden appearance of extreme contamination at location F in the fall of 1990 is particularly interesting in light of commercial activity in this area. The "bulls-eye" of the concentration contours is centered around a sampled well located approximately 300 ft. downgradient from an industrial tank farm storing anhydrous ammonia (Figure 52). The immediate interpretation is that some type of spill or leak has occurred at the facility in the recent past which is now appearing in downgradient wells. However, caution must be exercised in drawing this conclusion as these results are based on a one time sampling event at one location.

Result of Irrigation Well Sampling

As stated in Chapter IV, samples collected from 26 irrigation wells during July and August of 1990 were used to determine if nitrate levels (Appendix D) at these sites during this time were consistent with levels predicted by the Spring and Fall sampling events. Although inconsistencies exist, irrigation wells which showed either

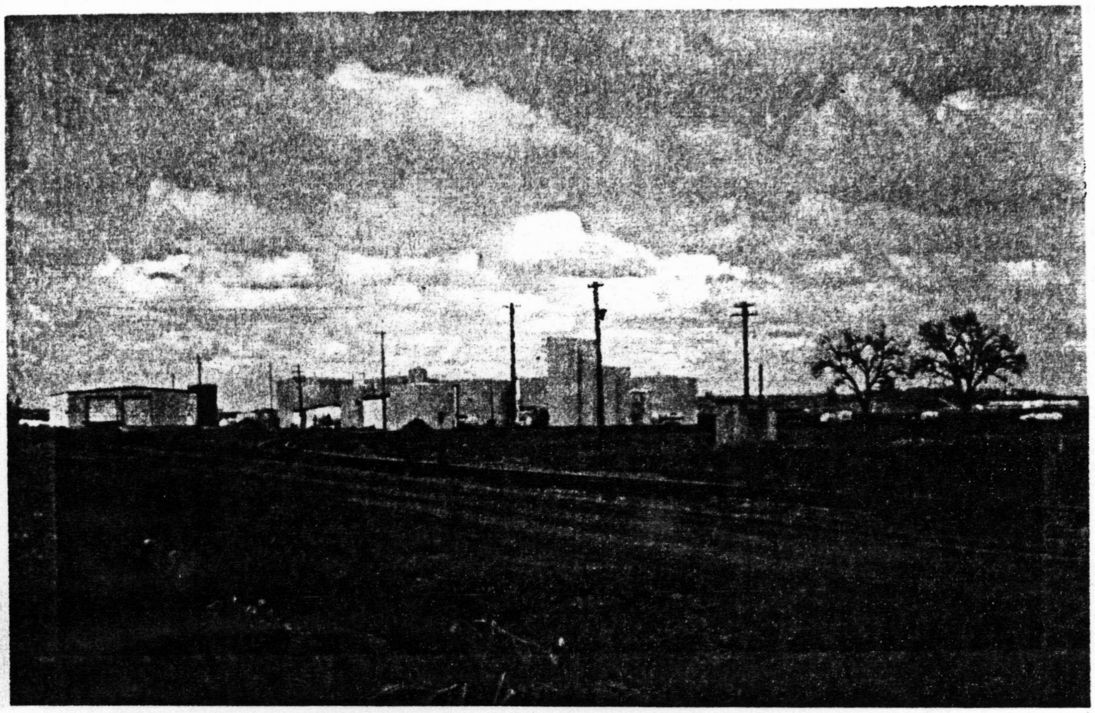

Figure 52. Tank Farm Storing Anhydrous Ammonia. Wellhouse of sampled well in foreground; view is toward the west.

consistently low or high levels of nitrate contamination are generally found within the areas of low and high nitrate concentrations predicted by the sampling events conducted in the Spring and Fall of 1990.

For example, wells 81, 85, 92, and 93 which are located between the Interstate Canal and the large breach in the west-central part of the study area (Plate 1) have nitrate levels below 5.0 mg/l, and all fall within the area(s) of low nitrate concentration (Figure 53). Wells 82, 83 and 98, which also have nitrate levels of less than 5.0 mg/l, are located near the Interstate Canal which probably serves as a significant source of recharge to these wells. Nitrate levels in wells 86, 88, 89, 90, 94, 100, 101, 102, 103, 104 where consistently above 5.0 mg/l and fell within the areas with nitrate concentrations above 5.0 mg/l as predicted by the Spring and Fall sampling events.

The results from wells 106 and 107 are inconsistent with the nitrate levels predicted by the Spring and Fall sampling events. While each of these wells had nitrate levels above 5.0 mg/l they are located in areas of low nitrate concentration.

The remaining wells (84, 87, 91, 96, 97, 99, and 105) displayed large variations in the results obtained between the one month sampling interval. Because of these variations these wells did not fall consistently in either the low of high nitrate areas. These result indicates that nitrate distribution predicted by the Spring and Fall sampling events generally reflect nitrate distribution throughout the year.

Modflow as a Contaminant Transport Model

While Modflow is not designed to be a contaminant transport model, the results of this investigation suggest that for conservative ions in a groundwater system it may serve as an adequate transport model.

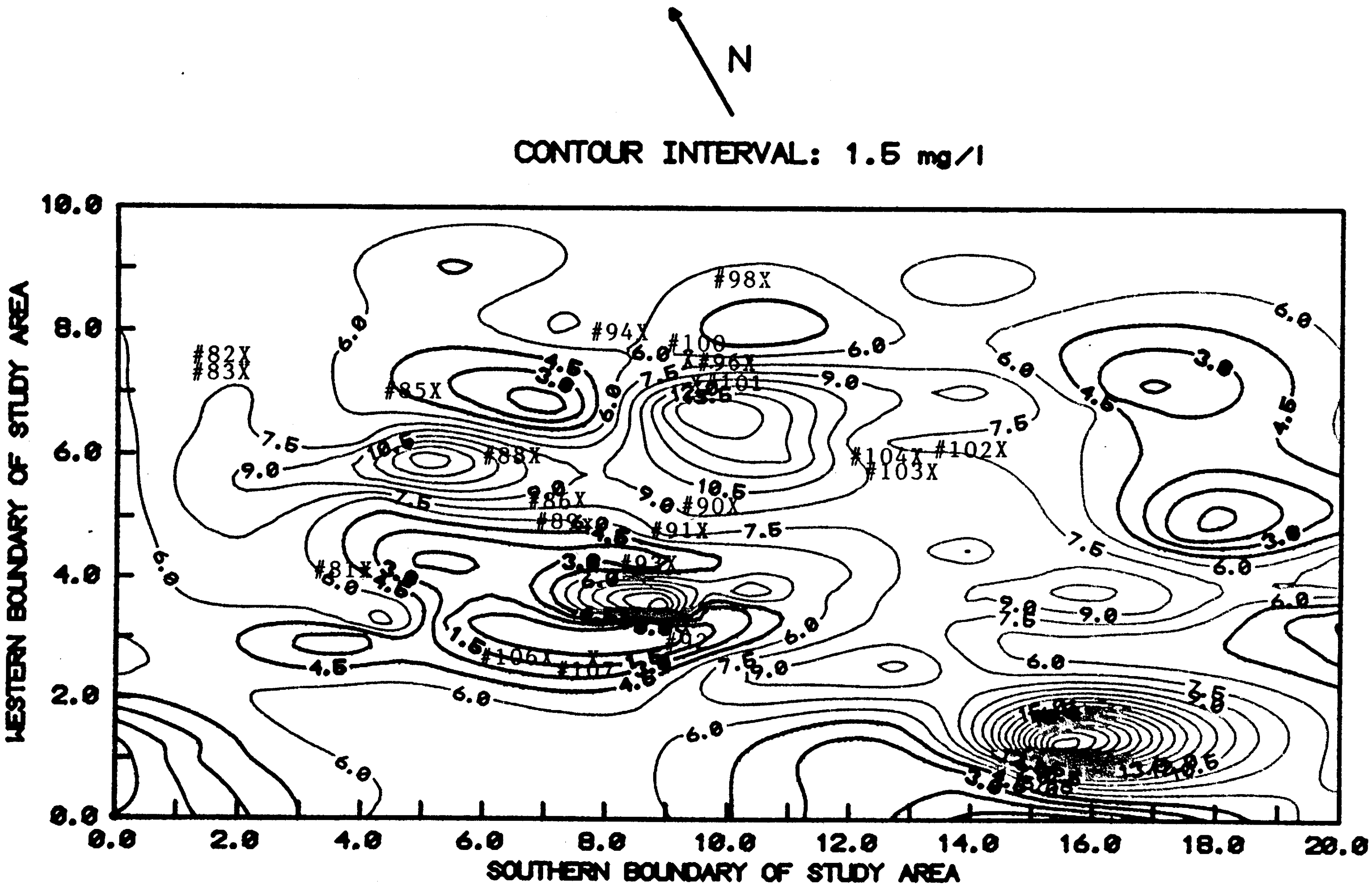

Figure 53. Location of Irrigation Wells sampled in the Summer of 1990. Nitrate levels are given in Appendix D.

Figure 54 shows the results of the 1989 sampling event superimposed on the potentiometric surface map for this stress period. In each area of elevated nitrate contamination the concentration of nitrate decreases from a central maximum in the direction of groundwater flow. This decrease continues indefinitely or until another area of contamination is encountered.

The results of the 1990 sampling events show a similar relationship. Because the Surfer program is designed to generate contour maps, elevated nitrate concentrations also appear upgradient of the maximum.

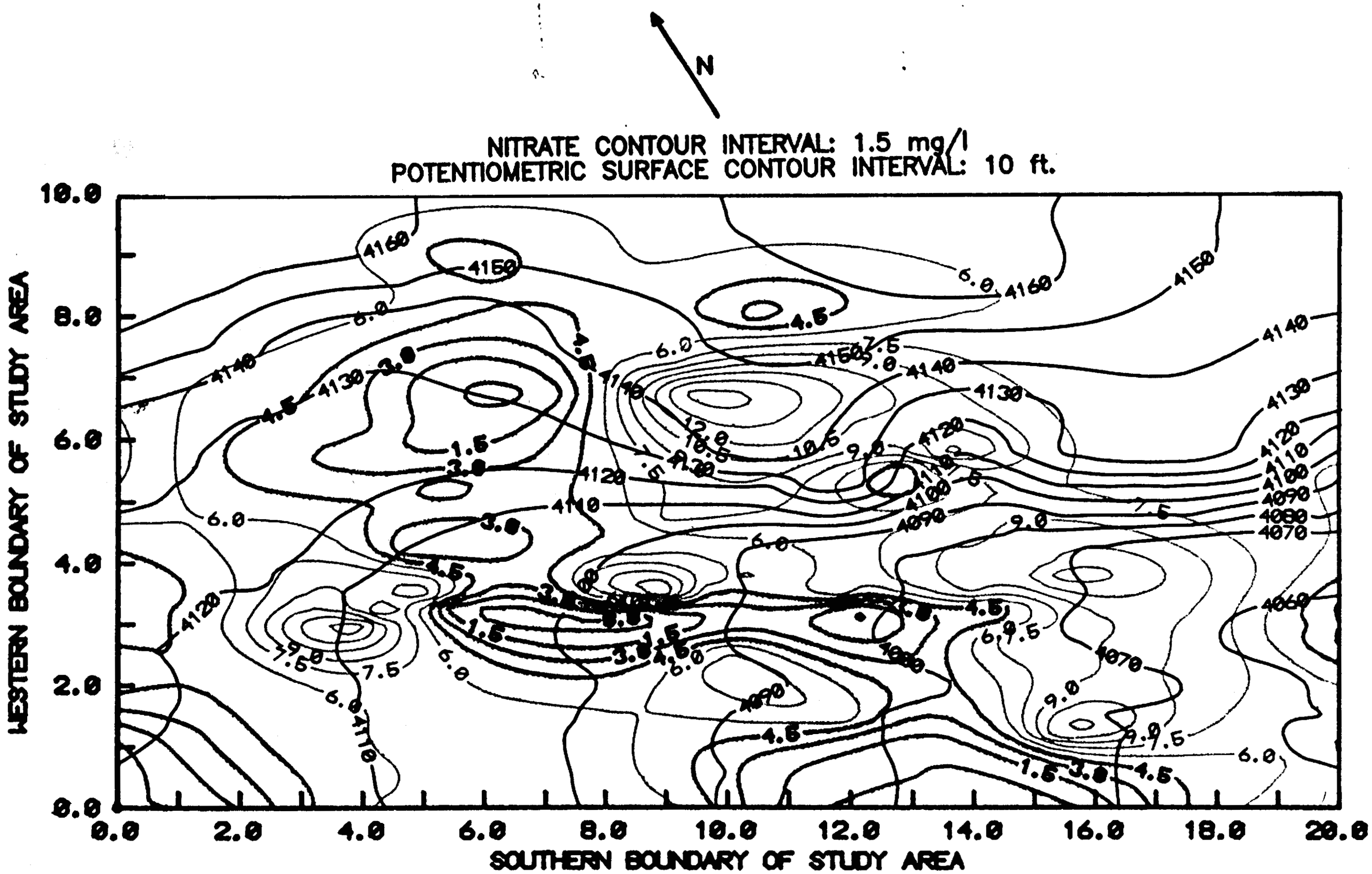

Figure 54. Results of the 1989 Sampling Event Superimposed on the Potentiometric Surface for this Stress Period. Nitrate concentrations decrease in the direction of flow.

CHAPTER VII

Conclusions and Recommendations

Conclusions

Site investigation indicates that the bedrock outcrop north of Torrington is not continuous and a previously unmapped breach exists in this outcrop immediately north of the town. When the effects of the bedrock outcrop and breaches are considered in the groundwater flow simulation, the configuration of the potentiometric surface is significantly different from that previously reported.

In areas where bedrock dams exist, the flow of groundwater between the third terrace and floodplain aquifers is stagnated and diverted toward one of the breaches where a direct hydraulic connection exists between the two aquifers. In these areas, groundwater moves readily from the third terrace to the floodplain aquifer. Groundwater beneath the most heavily cultivated and fertilized parts of the third terrace is directed toward the breach north of Torrington and eventually into the municipal well field area.

Seasonal variations occur in the direction of flow in parts of the third terrace. These variations occur in response to external hydrologic parameters affecting the aquifer. These parameters also vary seasonally.

The North Platte River appears to be a losing stream during the winter months. However, it is a gaining stream during the summer months when the elevation of the water table rises substantially.

The general configuration of the potentiometric surface during each of the stress periods is believed to be accurate despite the lack of a substantial amount of field data to verify these results. During model calibration, when the parameters impacting the aquifer were being varied widely, the general configuration of the surface remained constant.

Nitrate contamination of the municipal water supply of Torrington is due to the unique geologic features and cultural activities that occur in the area. When the results of the nitrate sampling program are evaluated in terms of the characteristics of the groundwater system, several significant trends become apparent.

The persistence and fate of nitrate in the groundwater system is determined by the particular properties of the aquifer(s) in the vicinity of the source. In areas where the flow of groundwater is hindered by the presence of subsurface dams, contaminant levels rise dramatically and persist for extended periods of time. In areas where groundwater flow is unhindered the aquifer(s) appear to be able to dilute themselves to lower levels of contaminants as long as the rate of input remains below some upper limiting level.

While nitrate contamination in some areas may be due to natural phenomena, the majority of the problem appears to be derived from agricultural and urban fertilization and irrigation practices, feedlot operations, and chemical storage facilities.

The immediate problem in Torrington appears to be the result of the flushing of the areas of highest contaminant levels in the third terrace into the municipal wellfield as well as contamination originating from the city itself.

The concentration of nitrate in the aquifer appears to diminish in the direction of flow. This indicates that it may be appropriate to use the Modflow program as a first approximation of the movement of conservative ions such as nitrate in a groundwater system. In this case, the use of additional contaminant transport models may not be required. The result of this would be to expedite groundwater investigations and reduce overall costs.

Recommendations for Remediation

Numerous processes are available which effectively remove nitrate contamination from water (Bouwer, 1990). However, when economic factors and technical problems are taken into consideration, the number of viable options available to the Town of Torrington becomes extremely limited.

For example, although reverse osmosis is an excellent method for removing nitrates from water, the enormous costs of this type of a system precludes its use in a community with limited economic resources. Currently, available ion exchange resins are generally incompatible with the high sulfate waters found in the area. Treating the water in a treatment plant designed for surface water would negate all of the benefits derived from using groundwater. Although rights to North Platte River water can be obtained, the costs of purchasing and treating the water are likely to be prohibitive.

In light of these problems, only two viable options are suggested. These include the relocation of wells to areas with persistently low levels of nitrate contamination and/or the initiation of management programs designed to monitor and limit the amount of nitrate entering the groundwater system. These management programs should be established in both the rural and urban areas as activities in both of these areas contribute to the problem of nitrate contamination.

If the town should decide to relocate wells, the two most promising sites are in the west-central and extreme northeastern parts of the study area. Regardless of the site selected, a wellhead protection area must be established around the well, or wells, to ensure they remain free from contamination in the future. Of these two sites, the northeast may be the better candidate for development.

Because the northeastern parts of the study area are relatively uninhabited, it may be easier to restrict land use here than in the more densely populated and intensively cultivated west-central area. Furthermore, the water from wells located in the northeast could be gravity fed into the upper zone of the municipal distribution system eliminating the need for booster stations which would be required for wells located in the west-central part of the area. One possible drawback to locating wells in the northeast is the potential impact of extensive groundwater withdrawals upon water levels in Arnold Drain which is likely to be considered a wetland.

The remediation alternative most likely to produce the greatest long term benefit is the development of a management program to control the amount of nitrate entering the groundwater system in areas that serve to recharge the municipal wellfield. To accomplish this the rates of fertilizer application must be reduced. The management program should include the agricultural areas to the north of Torrington as well as the town itself. Programs such as this have been implemented in other parts of the United States where nitrate contamination has become a problem (Ferguson et al., 1990; Logan, 1990; Yanggen and Born, 1990).

While the agricultural community may resist any further regulation of its activities, both cost and health benefits may be realized by reducing the amount of fertilizer being used. Cost benefits would be derived from the reduced fertilizer purchases as well as reduced fuel and maintenance costs of application equipment. The health benefits would be realized by the children of farming families who are currently consuming water which contains some of the highest nitrate levels found in the area. An educational program which discusses these benefits may be sufficient to convince the agricultural community to modify its current fertilization practices.

Within the city limits, a program to voluntarily reduce the amounts of fertilizer applied to lawns can be initiated. If a voluntary program fails to produce the desired results, more stringent regulation of the use of fertilizer may be required to protect the groundwater resource.

Recommendations for Additional Research

Additional research should be conducted in this area in order to verify, modify, or refute the conclusions arrived at during this preliminary investigation. These conclusions are believed to be logical and defensible in light of the information currently available. However, it must be kept in mind that these conclusions are based on a single year of sampling. In most groundwater systems this is an extremely insignificant length of time.

It is suggested that additional research be directed toward the seven following areas:

1. Continuation of the nitrate sampling program.

If possible the sampling program should be expanded to include areas where little data is currently available and to more closely monitor potential point sources. Additional data is likely to provide further insight in the behavior of nitrate in this system. Furthermore, should conservation or remediation programs be established in this area, the results of continued sampling can be used to evaluate their effectiveness. Sample collection at wells 3, 7, 14, 26, 28, 29, 50, 67, 68, 73, and 74 has been, or should be, discontinued for one of the following reasons:

- they are located outside the study area;
- they are no longer in operation;
- they are completed in an aquifer other than the alluvial aquifer;
- sampling has been terminated at the well owner's request.

2. Conduct a geophysical investigation north of Torrington to verify the existence of a breach in this area.
3. Develop a more accurate database on aquifer properties and the parameters affecting the aquifer system. This may include, but is not limited to, such items as a more accurate

determination of pumping and streambed seepage rates in the area. This information can be used to refine the numerical simulation. Furthermore, additional sites at which water levels can be measured should be established in order to verify these revisions.

4. Conduct soil column studies to determine the nitrate leaching characteristics of soils in the area. The focus of this study should be aimed at determining if the soil found in the vicinity of the University of Wyomings' Agricultural Experimental Station is a natural source of nitrate. This can be accomplished by comparing the nitrate leaching characteristics of this soil with more common soils.
5. Conduct nitrogen isotope studies in conjunction with the leaching study mentioned above. While the leaching study can quantify the amount of nitrate being removed from the soil, this study may be able to determine if the nitrate is derived from natural or artificial sources.
6. Initiate a comprehensive crop monitoring program for the purpose of evaluating possible correlations between the type of crops grown

in an area and the levels of nitrate found in these areas. While such a program currently exists under the direction of the Soil Conservation Service, reporting is voluntary and results in a spotty pattern which makes the data virtually useless.

7. Conduct additional modeling to evaluate the impact of a well relocation program prior to the initiation of any such program.

APPENDIX A

GEOLOGIC TIME SCALE

Geologic Time Scale

Eon	Era	Period		Epoch	Time (Millions of years)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01
				Pleistocene	1.6
		Tertiary	Neogene	Pliocene	5.3
				Miocene	23.7
			Palaeogene	Oligocene	36.6
				Eocene	57.8
				Paleocene	66.4
	Mesozoic	Cretaceous		late Cretaceous	97.5
				early Cretaceous	144
		Jurassic		late Jurassic	163
				middle Jurassic	187
				early Jurassic	208
		Triassic			245
	Palaeozoic	Permian			286
		Carboniferous		Pennsylvanian	320
				Mississippian	360
		Devonian			408
		Silurian			438
		Ordovician			505
		Cambrian			570
Proterozoic	Precambrian				
Archaean					4,600

APPENDIX B

DESCRIPTION OF SOILS IN THE STUDY AREA

LOCATION HAVERSON

CO+MT NE NM SD UT WY

Established Series
GB 6/85

HAVERSON SERIES

The Haverson series consists of deep, well drained soils that formed in alluvium from mixed sources. Haverson soils are on floodplains and low terraces and have slopes of 0 to 9 percent. The mean annual precipitation is about 16 inches and the mean annual temperature is about 52 degrees F.

TAXONOMIC CLASS: Fine-loamy, mixed (calcareous), mesic Ustic Torrifluvents

TYPICAL PEDON: Haverson loam, grassland. (Colors are for dry soil unless otherwise noted.)

A--0 to 6 inches; light brownish gray (10YR 6/2) loam, dark grayish brown (10YR 4/2) moist; moderate very fine granular structure; soft, very friable; calcareous; moderately alkaline (pH 8.2); clear smooth boundary. (4 to 8 inches thick)

C--6 to 60 inches; light brownish gray (10YR 6/2) loam stratified with thin lenses of clay loam and fine sandy loam, dark grayish brown (10YR 4/2) moist; weighted average texture approximately a loam; massive; slightly hard, very friable; a very small inconsistent amount of secondary calcium carbonate as soft concretions; calcareous; moderately alkaline (pH 8.2)

TYPE LOCATION: Prowers County, Colorado; approximately 0.8 mile south and 0.1 mile east of NW corner sec. 29, T. 22 S. R. 45 W.

RANGE IN CHARACTERISTICS: Organic carbon ranges from .6 to 1.5 percent in the surface horizon but decreases irregularly with depth. The control section is stratified with strata ranging from sandy loam to clay loam, but averaging approximately loam. On a weighted average basis clay ranges from 18 to 35 percent, silt from 10 to 50 percent, and sand from 20 to 60 percent with more than 15 percent but less than 35 percent being fine or coarser sand. Rock fragments are generally less than 5 percent and range from 0 to 20 percent. Some visible calcium carbonate may occur at any depth in these soils, but it is not concentrated into any consistent horizon of accumulation. Mean annual soil temperature ranges from 47 to 58 degrees F. and mean summer soil temperature ranges from 59 to 78 degrees F. This soil is not dry in all parts of the moisture control section for more than one-half the time the soil temperature is above 41 degrees F. (240 to 250 days) and is not dry for 45 consecutive days following July 15. The A horizon has hue of 2.5Y or 10YR, value of 5 or 6 dry, 3 through 5 moist and chroma of 2 or 3. When the value of the surface horizon is as dark as 5 dry and 3 moist, the horizon is thin enough so that if mixed to 7 inches it is too light colored or contains too little organic carbon to qualify as a mollic epipedon or are finely statified. The A horizon usually has granular primary structure but it has subangular blocky structure in some pedons. It is soft or slightly hard. It is neutral through moderately alkaline.

The C horizon has hue of 2.5Y through 7.5YR value of 5 or 6 dry, 4 or 5 moist and chroma of 2 or 3. It is mildly alkaline to strongly alkaline. It has from less than 1 to about 15 percent calcium carbonate equivalent which differs erratically from stratum to stratum.

COMPETING SERIES: These are the Barnum, Haverdad, Hysham, Navacity (T), Panitchen, San Mateo and Tropic (T) soils. Barnum soils have lithochromic hue of 5YR or redder. Hysham soils are very strongly alkaline and have a very hard or extremely hard Bw horizon. Haverdad soils receive over one-half of their precipitation during April to June and are dry in all parts for at least 60 consecutive days before July 15 to October 25 and for at least 90 consecutive days during this period. Navacity (T) soils are not clearly differentiated, overlapping in clay in the particle size control section. Panitchen soils are dry in the moisture control section for 15 consecutive days from May 15 to July 15 when the soil temperature at 20 inches is greater than 41 degrees F. It is not dry in all parts of the moisture control section for at least 45 consecutive days following the summer solstice to October 20, and for at least 90 cummulative days during that period. Tropic (T) soils have 15 to 40 percent calcium carbonate equivalent in the C horizon. San Mateo soils are dry in all parts for 30 consecutive days from May 15 to July 1 and are dry in all parts for 45 consecutive days from July 15 to October 25.

GEOGRAPHIC SETTING: The Haverson soils are on floodplains and low terraces of major rivers. Slope is 0 to 9 percent. The soils formed in highly statified, calcareous, recent alluvium derived from mixed sources. At the type location the average annual precipitation is 16 inches with peak periods of precipitation occuring during the early spring and summer. The average annual temperature is 52 degrees F. and the average summer temperature is 77 degrees F. The frost-free season is 125 to 180 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Bankard and Glenberg soils. Bankard and Glenberg soils have less than 18 percent clay in the series control section.

DRAINAGE AND PERMEABILITY: Well drained; slow runoff; moderate permeability.

USE AND VEGETATION: These soils are used as native pastureland, dry farm land or irrigated cropland. Native vegetation is mixed grasses, cottonwoods and brush.

DISTRIBUTION AND EXTENT: Eastern Colorado and Wyoming, northestern New Mexico and adjacent states. This soil is of large extent.

REMARKS: Differentation from Navacity (T) needs further study.

National Cooperative Soil Survey
U.S.A.

LOCATION BANKARD

CO+KS MT NE NM SD UT WY

Established Series
Rev. AJC/GB
6/86

BANKARD SERIES

The Bankard series consists of deep, well to somewhat excessively drained soils that formed in alluvium from a variety of rocks. Bankard soils are on flood plains and low terraces and have slopes of 0 to 6 percent. The mean annual precipitation is about 14 inches and the mean annual temperature is about 48 degrees F.

TAXONOMIC CLASS: Sandy, mixed, mesic Ustic Torrifluvents

TYPICAL PEDON: Bankard loamy sand - grassland. (Colors are for dry soil unless otherwise noted.)

A--0 to 5 inches; light brownish gray (2.5Y 6/2) loamy fine sand, grayish brown (2.5Y 5/2) moist; weak fine granular structure; soft, very friable; calcareous; moderately alkaline (pH. 8.0); clear smooth boundary. (4 to 8 inches thick)

C--5 to 60 inches; light yellowish brown (2.5Y 6/3) loamy very fine sand stratified with thin layers of sand, sandy loam, and loam, light olive brown (2.5Y 5/3) moist; the weighted average texture is loamy fine sand; single grained; soft, very friable, calcareous; moderately alkaline (pH 8.2).

TYPE LOCATION: Morgan County, Colorado; 100 feet south and 210 feet east of the northwest corner of Sec. 30, T. 4 N., R. 56 W.

RANGE IN CHARACTERISTICS: The soils are typically calcareous throughout but are noncalcareous in the upper few inches in some pedons. Organic carbon in the A horizon ranges from .6 to 1.5 percent and decreases irregularly with increasing depth. The control section is variable in texture due to the stratification, but loamy fine sand predominates above 40 inches. Rock fragments range from 0 to 15 percent, but are typically less than 5 percent. Weak accumulations of secondary carbonate as soft concretions or seams is present in some pedons. Mean annual soil temperature ranges from 47 to 58 degrees F., and mean summer soil temperature ranges from 60 to 78 degrees F. In some pedons, gravel ranges from 0 to 35 percent below depths of 40 inches. The moisture control section is moist in some or all parts for as long as 60 consecutive days when the soil temperature at 20 inches is 41 degrees F., which occurs in April.

The A horizon has hue of 2.5Y through 5YR, value of 5 or 6 dry, 3 through 5 moist, and chroma of 2 through 6. Typically the horizon has granular or crumb structure but is subangular blocky in some pedons. It is soft or slightly hard and is mildly alkaline or moderately alkaline.

The C horizon has hue of 2.5Y through 5YR. It is mildly alkaline to strongly alkaline. Calcium carbonate equivalent ranges from less than 1 to 10 percent depending upon character of individual strata, but there is no distinct continuous horizon of calcium carbonate accumulation.

COMPETING SERIES: These are the Draknab, Dwyer, and Ellicott series. Draknab soils are never moist in some or all parts for as long as 60 consecutive days when the soil at 20 inches is 41 degrees or more. Dwyer soils have uniform texture in which organic carbon decreases uniformly with depth. Ellicott soils are noncalcareous and contain a high proportion of medium and coarse angular granite sand and fine and very fine angular granite gravel.

GEOGRAPHIC SETTING: These soils are on flood plains and low terraces. Slope gradients range from 0 to about 6 percent. The soils formed in calcareous highly stratified but predominantly coarse textured recent alluvium derived from a variety of rocks. At the type location, the aveage annual temperature ranges from 48 to 51 degrees F., the average summer temperature is 70 degrees F., and the average annual precipitation is 10 to 14 inches with peak periods of precipitation in the spring and early summer.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Glenberg and Haverson soils. Glenberg soils have a coarse-loamy control section. Haverson soils have a fine-loamy control section.

DRAINAGE AND PERMEABILITY: Well to somewhat excessively drained; slow or very slow runoff; rapid or very rapid permeability.

USE AND VEGETATION: These soils are used chiefly as native pastureland; however, they are tilled in some localities. Native vegetation consists of scattered cottonwood, grass, and brush.

DISTRIBUTION AND EXTENT: The flood plains and low terraces of the major streams in Colorado, Kansas, Wyoming, New Mexico, and parts of Montana, South Dakota, Nebraska, and eastern Utah.

SERIES ESTABLISHED: Red Willow County, Nebraska, 1965.

National Cooperative Soil Survey
U.S.A.

LOCATION VALENTINE

NE+CO KS MT NM SD TX WY

Established Series
Rev. MAP-MLD
2/90

VALENTINE SERIES

The Valentine series consists of very deep, excessively drained, rapidly permeable soils formed in eolian sands. These upland soils have slopes ranging from 0 to 60 percent. Mean annual temperature is about 51 degrees F, and mean annual precipitation is about 20 inches.

TAXONOMIC CLASS: Mixed, mesic Typic Ustipsamments

TYPICAL PEDON: Valentine fine sand - on an 8 percent convex northwest-facing slope in rangeland. When described the soil was moist throughout. (Colors are for dry soil unless otherwise stated.)

A--0to 5 inches; grayish brown (10YR 5/2) fine sand, dark grayish brown (10YR 4/2) moist; weak fine granular structure parting to single grained; loose; slightly acid; abrupt smooth boundary. (2 to 9 inches thick)

AC--5 to 9 inches; brown (10YR 5/3) fine sand, grayish brown (10YR 5/2) moist; weak, coarse prismatic structure parting to single grained; loose; slightly acid; clear smooth boundary. (0 to 8 inches thick)

C1--9 to 17 inches; pale brown (10YR 6/3) fine sand, pale brown (10YR 6/3) moist; weak coarse prismatic structure parting to single grained; loose; slightly acid; gradual smooth boundary. (0 to 12 inches thick)

C2--17 to 60 inches; very pale brown (10YR 7/3) fine sand, pale brown (10YR 6/3) moist, single grained, loose; neutral.

TYPE LOCATION: Logan County, Nebraska; about 12 1/2 miles north of Stapleton, Nebraska; 1060 feet north and 530 feet west of the center of sec. 36, T.20 N., R. 28 W.

RANGE IN CHARACTERISTICS: Texture of the profile typically is fine sand or loamy fine sand, but includes sand and loamy sand having less than 35 percent medium sand and less than 10 percent coarse or very coarse sand. The soil is medium acid or neutral throughout the profile.

The A horizon has hue of 10YR, value of 4 through 6 and 3 through 5 moist, and chroma of 2 or 3.

Where present, the AC horizon has hue of 10YR, value of 5 through 7 and 4 through 6 moist, and chroma of 2 or 3.

The C horizon has hue of 10YR, value of 6 or 7 and 5 or 6 moist, and chroma of 2 through 4. In some pedons, dark colored loamy textured strata ranging from 1/8 to 2 inches in thickness are below depths of 20 inches. When Valentine soils are associated with clayey soils, clayey substratum phases are recognized at 40 to 60 inches.

COMPETING SERIES: These are the Duda, McKelvie, Roysa, Simeon, and Tonalea series in the same family. A similar soil is Valent. Duda and Tonalea soils have weakly cemented sandstone between a depth of 20 to 40 inches. McKelvie soils have sandstone fragments in their sola. Royosa soils have drier climate with less than 16 inches mean annual precipitation. Simeon soils have a control section of loamy coarse sand, loamy sand, sand or coarse sand and it contains more than 35 percent medium and coarse sand and less than 50 percent fine or very fine sand, and up to 15 percent by volume of gravel. Valent soils have a drier climate.

GEOGRAPHIC SETTING: Valentine soils are on nearly level to slightly hummocky to steep, hilly uplands. Slope gradient ranges from 0 to 60 percent. Relief ranges from 1 to over 100 feet. Soils formed in eolian sands. The mean temperature ranges from 47 to 59 degrees F, and mean annual precipitation ranges from about 16 to 25 inches.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the competing Duda and Simeon soils and the Doger, Dunday, Els, Elsmere, Gannett, Hersh, Loup, Ord, Ovina, and Tryon soils. Duda soils occur below Valentine soils. Simeon soils occur on nearly level to steep slopes below areas of Valentine soils. Doger and Dunday soils have mollic epipedons and occur on nearly level to strongly sloping areas below Valentine. The somewhat poorly drained Els, Elsmere, Ord, Ovina, and the poorly or very poorly drained Gannett, Loup, and Tryon soils occur in sandhill valleys and along bottom lands. Hersh soils have a coarse-loamy control section and occur below areas of Valentine.

DRAINAGE AND PERMEABILITY: Excessively drained. Runoff is slow or very slow because of rapid infiltration; permeability is rapid. Capacity to hold water is low.

USE AND VEGETATION: These soils are dominantly in native grass and used for grazing or hay. The main grasses are prairie sandreed, little bluestem, sand bluestem, switchgrass, sand lovegrass, needleandthread, blue grama and hairy grama. Some of these soils have been cultivated but unless irrigated, have been returned to grass.

DISTRIBUTION AND EXTENT: Principally north-central Nebraska, but also extending into South Dakota and Kansas. The series is of large extent. Estimated acreage is over 5,000,000 acres.

SERIES ESTABLISHED: Reconnaissance Survey of Western Nebraska, 1911.

REMARKS: The Valentine soils are classified as Regosol in the former system. They presently include much of the area formerly mapped as Dune sand.

ADDITIONAL DATA: Samples No. S54-Neb-16-1 and 2; MSL No. 2440-2444 and 2445-2449, as published in Soil Survey Investigations No. 5.

National Cooperative Soil Survey
U.S.A.

LOCATION DWYER

WY+CO KS MT NE SD

Established Series
Rev. PSD
1/83

DWYER SERIES

The Dwyer series consists of deep, excessively drained soils that formed in eolian sand. Dwyer soils are on dune-like forms frequently on or near the edges of alluvial terraces and have slopes of 0 to 25 percent. The mean annual precipitation is about 14 inches, and the mean annual temperature is about 48 degrees F.

TAXONOMIC CLASS: Mixed, mesic Ustic Torripsamments

TYPICAL PEDON: Dwyer fine sand - grassland. (Colors are for dry soil unless otherwise stated.)

A1--0 to 6 inches; pale brown (10YR 6/3) fine sand, dark grayish brown (10YR 4/2) moist; single grained; loose; calcareous; moderately alkaline (pH 8.0); gradual smooth boundary. (4 to 8 inches thick)

C--6 to 60 inches; very pale brown (10YR 7/3) fine sand, grayish brown (10YR 5/2) moist; single grained; loose; calcareous; moderately alkaline (pH 8.2).

TYPE LOCATION: Goshen County, Wyoming; approximately 200 feet south and 100 feet west of NE corner of SE1/4, NE1/4 of sec. 26, T. 22 N., R. 61 W.

RANGE IN CHARACTERISTICS: Typically, this soil is calcareous throughout but is leached in the upper part of the series control section in some pedons. The control section is sand, loamy sand, fine sand, or loamy fine sand. Coarse fragments range from 0 to 15 percent but are commonly less than 3 percent. These soils may have a weak and inconsistent accumualation of secondary calcium carbonate at any depth but are not considered to have a continuous Bk horizon. The soil is dry in the moisture control section more than half the time cumulative that the soil temperature at a depth of 20 inches is 41 degrees F. and is never moist in some or all parts for as long as 60 consecutive days when the soil temperature at a depth of 20 inches is 41 degrees F., which occurs about April 21-27, but is dry in all parts of the moisture control section for at least 60 consecutive days from July 15 to October 25 and for at least 90 cumulative days during this period. The mean annual soil temperature is 47 to 53 degrees F., and the soil temperature at a depth of 20 inches is 41 degrees F. or more for 175 to 192 days. Bedrock is deeper than 60 inches.

The A horizon has hue of 2.5Y or 10YR, value of 5 through 7 dry, 3 through 5 moist, and chroma of 2 or 3. The horizon is usually mildly alkaline through strongly alkaline but is slightly acid or neutral in some pedons. It is soft to loose. An AC horizon of loamy fine sand or fine sand is in some pedons.

The C horizon has hue of 2.5Y through 7.5YR, value of 5 through 7 dry, 3 through 5 moist, and chroma of 2 through 4. It is moderately alkaline or strongly alkaline and may contain few small carbonate concretions or seams of calcium carbonate erratically at any depth.

COMPETING SERIES: These are the Curtis Siding, Orpha, Mespun, Tullock, Valent, and Wigton series. Curtis Siding soils have greater than 15 percent coarse fragments in the control section. Orpha soils are noncalcareous above a depth of 30 inches. Mespun soils have a control section that dominantly has hue of 5YR and has chroma of 4 through 8. Tullock soils have a paralithic contact between 20 and 40 inches. Valent and Wigton soils are moist in some or all parts for 60 consecutive days following July 15 and are moist in some parts for at least 90 cumulative days when the soil temperature at a depth of 20 inches is 41 degrees F. or more and also have soil temperatures warmer than 41 degrees F. for 195 to 210 days or more. Wigton soils also have a dry consistence of hard or very hard.

GEOGRAPHIC SETTING: Dwyer soils are on dune-like forms frequently on or near the edges of alluvial terraces. Slopes are irregular, ranging from 0 to 25 percent. Elevation ranges from 3,500 to 5,600 feet. Dwyer soils formed in eolian sand. At the type location average annual precipitation is 14 inches with about half of the precipitation occurring in April, May, and June. The mean annual precipitation ranges from 10 to 16 inches. The mean annual temperature is 48 degrees F., and the mean summer temperature is 68 degrees F. The frost-free season is 110 to 130 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the competing Orpha soils and the Draknab and Hiland soils. Draknab soils have a stratified control section in which organic matter decreases irregularly with increasing depth. Hiland soils have a sandy loam control section and argillic horizons.

DRAINAGE AND PERMEABILITY: Excessively drained; very slow to medium runoff depending on slope and compaction; rapid permeability.

USE AND VEGETATION: Used principally as native pastureland. Native vegetation is short and tall grasses and sage.

DISTRIBUTION AND EXTENT: Wyoming, Nebraska, South Dakota, and Colorado. The soil has moderate extent.

SERIES ESTABLISHED: Wheatland Area, Wyoming: 1926.

National Cooperative Soil Survey
U.S.A.

APPENDIX C

DESCRIPTION OF SAMPLE SITES

ATER T/YR)	TOP OF SCREEN(FT)	SCREENED INTERVAL(FT)	CASING TYPE	DIAMETER(IN)	DISCHARGE(GPM)	USE	DRILL LOG(Y/N)
	65	60	NR**	8	20	D****	N
	NR	30	STL***	18	750	M	Y
	40	20	STL	5.5	50	D	Y
	NR	NR	NR	5	20	D	N
	NR	NR	NR	NR	NR	D	N
	53	15	STL	16	900	M	Y
	117	20	PLA	8	6	D	Y
	NR	NR	NR	NR	NR	NR	N
	106	17	PVC	5	25	D	Y
	20	26	STL	5.5	15	D	Y
	NR	NR	NR	6	NR	D	N
	NR	NR	NR	NR	NR	D	N
	40	20	PLA	5	9	D	Y
	NR	NR	STL	6	5	D	N
	50	10	STL	8	50	D	Y
	40	10	PLA	6	25	D	Y
	124	16	STL	5.5	20	D	Y
	17	63	PLA	6	20	D	Y
	NR	NR	NR	NR	NR	D	N
	115	60	STL	16	2000	M	Y
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	6	NR	D	N
	NR	NR	NR	6	25	D	Y
	NR	NR	NR	6	NR	D	N
	102	15	STL	36	NR	M	Y
	280	100	PLA	4.5	10	D	Y
	25	40	STL	16	1000	M	Y
	NR	NR	NR	NR	6	D	N
	NR	NR	STL	4	5	D	N
	NR	NR	NR	NR	NR	D	N
	40	60	STL	6	18	D	Y
	52	20	NR	5	NR	D	N
	NR	NR	NR	NR	NR	D	N
	70	20	PLA	5	20	D	Y
	NR	NR	STL	5	35	D	Y
	NR	30	STL	16	521	M	Y
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N

information was supplied by the well owner.

ATER T/YR)	TOP OF SCREEN(FT)	SCREENED INTERVAL(FT)	CASING TYPE	DIAMETER(IN)	DISCHARGE(GPM)	USE	DRILL LOG(Y/N)
	35	40	STL	16	1400	IR	Y
	30	7	STL	4.5	5	D	Y
	60	40	STL	16	1000	M	Y
	65	60	STL	16	1000	M	Y
	NR	NR	PLA	8	5	D	N
	60	20	PLA	5	15	D	Y
	140	30	PLA	5	8	D	Y
	NA	NA	NA	NA	NA	M	N
	135	18	STL	5.5	10	D	Y
	NR	NR	NR	18	300	D	N
	55	20	PLA	5	4	D	Y
	NR	NR	NR	NR	NR	IR	N
	80	50	STL	30	1200	M	Y
	70	10	PVC	6	18	D	Y
	20	20	STL	4	20	D	Y
	20	20	STL	4	20	D	Y
	40	20	PLA	5	5	D	Y
	NR	NR	CON	48	1000	M	N
	NR	NR	NR	NR	NR	D	N
	80	20	STL	5	10	IN	Y
	NA	NA	NA	NA	NA	NA	N
	56	10	PVC	6	35	D	Y
	NR	NR	CON	48	750	M	N
	NR	NR	NR	NR	NR	D	N
	NA	NA	NA	NA	NA	M	N
	NR	NR	NR	NR	NR	IR	N
	NR	NR	NR	NR	NR	D	N
	NA	NA	NA	NA	NA	IR	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N
	97	103	PLA	5	19	D	Y
	40	20	PVC	5	20	D	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	NR	NR	D	N
	NR	NR	NR	5.5	NR	D	Y
	69	40	NR	26	450	IR	Y
	NR	NR	NR	20	1454	IR	N
	NR	NR	STL	30	950	IR	Y

ATER /YR)	TOP OF SCREEN(FT)	SCREENED INTERVAL(FT)	CASING TYPE	DIAMETER(IN)	DISCHARGE(GPM)	USE	DRILL LOG(Y/N)
	80	40	STL	13	400	IR	Y
	NR	NR	STL	18	1500	IR	Y
	NR	NR	STL	18	1200	IR	Y
	41	82	STL	28	1110	IR	Y
	80	40	STL	16	1000	IR	Y
	40	40	STL	16	1000	IR	Y
	26	39	NR	16	1200	IR	Y
	NR	NR	NR	32	1800	IR	Y
	NR	NR	STL	18	1200	IR	Y
	50	30	STL	32	1500	IR	Y
	NR	NR	STL	18	860	IR	N
	NA	NA	NA	NA	NA	IR	N
	47	45	STL	24	1025	IR	Y
	NR	NR	STL	24	1500	IR	Y
	46	40	STL	18	1225	IR	Y
	45	60	STL	24	975	IR	Y
	NR	NR	NR	NR	950	IR	N
	NR	NR	NR	NR	950	IR	N
	NR	NR	STL	24	1150	IR	Y
	NR	NR	STL	30	1200	IR	Y
	NR	NR	STL	30	1200	IR	Y
	30	30	NR	25	1800	IR	Y
	15	20	STL	18	1800	IR	Y
	45	10	STL	30	1500	IR	Y

APPENDIX D

RESULTS OF THE NITRATE SAMPLING PROGRAM

WELL I.D. #	DATE	NH4-N (mg/l)	NO3+NO2-N (mg/l)	NO2-N (mg/l)
1	10/30/89	<0.3	3.6	<0.1
1	5/22/90	<0.3	4.2	<0.1
1	10/30/90	N/A*	5.2	N/A
1	5/22/91	N/A	5.6	N/A
2	10/30/89	<0.3	9.2	<0.1
2	5/22/90	<0.3	9.1	<0.1
2	7/02/90	N/A	7.8	N/A
2	7/10/90	N/A	5.7	N/A
2	10/30/90	N/A	9.0	N/A
2	5/22/91	N/A	7.2	N/A
3	10/30/89	<0.3	9.7	<0.1
3	5/22/90	<0.3	11.7	<0.1
3	10/30/90	N/A	7.5	N/A
4	10/30/89	<0.3	3.9	<0.1
4	5/22/90	<0.3	2.6	<0.1
4	10/30/90	N/A	5.7	N/A
5	10/30/89	<0.3	6.8	.6
5	5/22/90	N/A	8.2	N/A
5	10/30/90	N/A	8.4	N/A
6	10/30/89	<0.3	13.0	0.2
6	5/22/90	<0.3	13.5	<0.1
6	7/02/90	N/A	12.1	N/A
6	7/10/90	N/A	12.8	N/A
6	10/30/90	N/A	11.0	N/A
7	10/30/89	<0.3	6.3	<0.1
7	5/22/90	<0.3	7.9	<0.1
7	10/30/90	N/A	6.2	N/A
8	10/30/89	<0.3	6.2	<0.1
8	5/22/90	N/A	9.7	N/A
8	10/30/90	N/A	10.0	N/A
9	10/30/89	<0.3	5.3	<0.1
9	5/22/90	N/A	5.6	N/A
9	10/30/90	N/A	4.5	N/A
10	10/30/89	<0.3	6.3	<0.1
10	5/22/90	<0.3	4.5	<0.1
10	10/30/90	N/A	5.5	N/A
11	10/30/89	<0.3	2.6	<0.1
11	5/22/90	<0.3	4.0	<0.1
11	10/30/90	N/A	5.8	N/A
12	10/30/89	<0.3	4.6	<0.1
12	5/22/90	N/A	14.4	N/A
12	10/30/90	N/A	7.2	N/A

* N/A = Not analyzed

WELL I.D. #	DATE	NH4-N (mg/l)	NO3+NO2-N (mg/l)	NO2-N (mg/l)
13	10/30/89	<0.3	6.9	<0.1
13	5/22/90	<0.3	9.5	<0.1
13	10/30/90	N/A	6.2	N/A
14	10/30/89	<0.3	12.3	<0.1
14	5/22/90	N/A	11.8	N/A
14	10/30/90	N/A	12.0	N/A
15	10/30/89	<0.3	9.0	<0.1
15	5/22/90	N/A	8.2	N/A
15	10/30/90	N/A	5.4	N/A
16	10/30/89	<0.3	<0.1	<0.1
16	5/22/90	<0.3	4.8	<0.1
16	10/30/90	N/A	N/A	N/A
17	10/30/89	0.3	4.0	<0.1
17	5/22/90	N/A	5.9	N/A
17	10/30/90	N/A	7.7	N/A
18	10/30/89	<0.3	13.0	<0.1
18	5/22/90	<0.3	21.5	<0.1
18	10/30/90	N/A	17.0	N/A
19	10/30/89	0.3	2.9	<0.1
19	5/22/90	<0.3	3.3	<0.1
19	10/30/90	N/A	2.4	N/A
20	10/30/89	<0.3	10.3	<0.1
20	5/22/90	<0.3	3.9	<0.1
20	7/02/90	N/A	5.2	N/A
20	7/10/90	N/A	5.7	N/A
20	10/30/90	N/A	8.3	N/A
21	10/30/89	<0.3	0.9	<0.1
21	5/22/90	<0.3	13.5	<0.1
21	10/30/90	N/A	16.0	N/A
22	10/30/89	<0.3	0.7	<0.1
22	5/22/90	N/A	1.6	N/A
22	10/30/90	N/A	3.3	N/A
23	10/30/89	<0.3	4.2	<0.1
23	5/22/90	N/A	2.4	N/A
23	10/30/90	N/A	2.7	N/A
24	10/30/89	<0.3	2.4	0.1
24	5/22/90	<0.3	1.5	<0.1
24	10/30/90	N/A	16.0	N/A
25	10/30/89	<0.3	3.4	0.4
25	5/22/90	<0.3	6.9	<0.1
25	7/02/90	N/A	7.3	N/A
25	7/10/90	N/A	7.9	N/A
25	10/30/90	N/A	6.4	N/A
26	10/30/89	<0.3	30.3	<0.1
26	5/22/90	N/A	27.7	N/A
26	10/30/90	N/A	26.0	N/A

WELL I.D. #	DATE	NH4-N (mg/l)	NO3+NO2-N (mg/l)	NO2-N (mg/l)
27	10/30/89	<0.3	9.8	<0.1
27	5/22/90	<0.3	8.2	<0.1
27	7/02/90	N/A	9.2	N/A
27	7/10/90	N/A	6.4	N/A
27	10/30/90	N/A	8.3	N/A
28	10/30/89	<0.3	8.5	<0.1
28	5/22/90	N/A	4.6	N/A
28	10/30/90	N/A	7.0	N/A
29	10/30/89	<0.3	3.4	0.4
29	5/22/90	N/A	7.0	N/A
29	10/30/90	N/A	4.1	N/A
30	10/30/89	<0.3	8.0	<0.1
30	5/22/90	<0.3	3.9	<0.1
30	10/30/90	N/A	8.7	N/A
31	10/30/89	<0.3	1.0	,0.1
31	5/22/90	<0.3	1.6	<0.1
31	10/30/90	N/A	1.1	N/A
32	10/30/89	<0.3	3.4	<0.1
32	5/22/90	N/A	5.5	N/A
32	10/30/90	N/A	2.2	N/A
33	10/30/89	<0.3	4.4	0.2
33	5/22/90	N/A	5.8	N/A
33	10/30/90	N/A	5.5	N/A
34	10/30/89	<0.3	5.5	0.4
34	5/22/90	<0.3	8.1	<0.1
34	10/30/90	N/A	8.3	N/A
35	10/30/89	<0.3	6.4	,0.1
35	5/22/90	<0.3	6.6	<0.1
35	10/30/90	N/A	N/A	N/A
36	10/30/89	<0.3	9.5	<0.1
36	5/22/90	<0.3	9.5	<0.1
36	7/02/90	N/A	8.5	N/A
36	7/10/90	N/A	6.4	N/A
36	10/30/90	N/A	9.1	N/A
37	10/30/89	<0.3	15.0	<0.1
37	5/22/90	<0.3	13.0	<0.1
37	10/30/90	N/A	16.0	N/A
38	10/30/89	<0.3	5.0	<0.1
38	5/22/90	<0.3	7.5	<0.1
38	10/30/90	N/A	1.4	N/A
39	10/30/89	<0.3	4.2	<0.1
39	5/22/90	N/A	7.0	N/A
39	10/30/90	N/A	N/A	N/A
40	10/30/89	<0.3	6.1	,0.1
40	5/22/90	<0.3	2.5	<0.1
40	10/30/90	N/A	3.4	N/A

WELL I.D. #	DATE	NH4-N (mg/l)	NO3+NO2-N (mg/l)	NO2-N (mg/l)
41	10/30/89	1.7	8.5	<0.1
41	5/22/90	<0.3	8.3	<0.1
41	7/10/90	N/A	7.7	N/A
41	10/30/90	N/A	6.0	N/A
42	10/30/89	<0.3	12.5	<0.1
42	5/22/90	<0.3	6.5	<0.1
42	7/02/90	N/A	11.3	N/A
42	7/10/90	N/A	7.9	N/A
42	10/30/90	N/A	8.3	N/A
43	10/30/89	<0.3	15.5	<0.1
43	5/22/90	N/A	9.7	N/A
43	10/30/90	N/A	1.4	N/A
44	10/30/89	<0.3	6.0	<0.1
44	5/22/90	<0.3	9.1	<0.1
44	10/30/90	N/A	7.9	N/A
45	10/30/89	<0.3	12.5	<0.1
45	5/22/90	<0.3	17.0	<0.1
45	10/30/90	N/A	14.0	N/A
46	10/30/89	<0.3	9.9	<0.1
46	5/22/90	<0.3	9.0	<0.1
46	10/30/90	N/A	8.9	N/A
47	10/30/89	<0.3	0.4	<0.1
47	5/22/90	<0.3	1.2	<0.1
47	10/30/90	N/A	0.52	N/A
48	10/30/89	<0.3	13.5	<0.1
48	5/22/90	<0.3	14.5	<0.1
48	10/30/90	N/A	32.0	N/A
49	10/30/89	<0.3	8.0	<0.1
49	5/22/90	N/A	7.2	N/A
49	10/30/90	N/A	8.3	N/A
50	10/30/89	<0.3	9.5	<0.1
50	10/30/90	N/A	N/A	N/A
51	10/30/89	<0.3	2.7	<0.1
51	5/22/90	<0.3	5.5	<0.1
51	7/10/90	N/A	4.5	N/A
51	10/30/90	N/A	N/A	N/A
52	10/30/89	<0.3	1.1	<0.1
52	5/22/90	<0.3	2.1	<0.1
52	10/30/90	N/A	<0.2	N/A
53	10/30/89	<0.3	2.3	<0.1
53	5/22/90	N/A	3.0	N/A
53	10/30/90	N/A	1.9	N/A
54	10/30/89	N/A	N/A	N/A
54	5/22/90	N/A	0.3	N/A
54	10/30/90	N/A	2.9	N/A

WELL I.D. #	DATE	NH4-N (mg/l)	NO3+NO2-N (mg/l)	NO2-N (mg/l)
55	10/30/89	<0.3	<0.1	<0.1
55	5/22/90	N/A	1.1	N/A
55	10/30/90	N/A	2.1	N/A
56	10/30/89	<0.3	9.8	<0.1
56	5/22/90	<0.3	14.5	<0.1
56	7/02/90	N/A	9.3	N/A
56	7/10/90	N/A	7.9	N/A
56	10/30/90	N/A	8.8	N/A
57	10/30/89	<0.3	8.0	<0.1
57	5/22/90	N/A	6.1	N/A
57	10/30/90	N/A	7.0	N/A
58	10/30/89	<0.3	10.5	<0.1
58	5/22/90	N/A	9.7	N/A
58	10/30/90	N/A	9.7	N/A
59	10/30/89	<0.3	0.7	<0.1
59	5/22/90	<0.3	1.3	<0.1
59	10/30/90	N/A	1.5	N/A
60	10/30/89	<0.3	4.3	<0.1
60	5/22/90	<0.3	6.2	<0.1
60	10/30/90	N/A	5.9	N/A
61	10/30/89	<0.3	8.0	<0.1
61	5/22/90	<0.3	6.5	<0.1
61	7/10/90	N/A	7.7	N/A
61	10/30/90	N/A	5.5	N/A
62	10/30/89	<0.3	<0.1	<0.1
62	5/22/90	<0.3	1.4	<0.1
62	10/30/90	N/A	<0.2	N/A
63	10/30/89	<0.3	9.5	<0.1
63	5/22/90	N/A	7.2	N/A
63	10/30/90	N/A	8.7	N/A
64	10/30/89	<0.3	7.5	<0.1
64	5/22/90	N/A	13.5	N/A
64	10/30/90	N/A	N/A	N/A
65	10/30/89	<0.3	2.2	<0.1
65	5/22/90	<0.3	3.9	<0.1
65	10/30/90	N/A	3.4	N/A
66	10/30/89	<0.3	0.3	<0.1
66	10/30/90	N/A	N/A	N/A
67	5/22/90	<0.3	13.5	<0.1
67	10/30/90	N/A	0.3	N/A
68	5/22/90	<0.3	7.1	<0.1
68	10/30/90	N/A	<0.2	N/A
69	5/22/90	<0.3	3.4	<0.1
69	10/30/90	N/A	6.1	N/A
70	5/22/90	<0.3	2.7	<0.1
70	10/30/90	N/A	1.7	N/A

WELL I.D. #	DATE	NH4-N (mg/l)	NO3+NO2-N (mg/l)	NO2-N (mg/l)
71	5/22/90	<0.3	<0.1	<0.1
71	10/30/90	N/A	6.9	N/A
72	5/22/90	<0.3	10.0	<0.1
72	10/30/90	N/A	<0.2	N/A
73	5/22/90	<0.3	<0.1	<0.1
73	10/30/90	N/A	<0.2	N/A
74	5/22/90	<0.3	10.0	<0.1
74	10/30/90	N/A	<0.2	N/A
75	5/22/90	<0.3	<0.1	<0.1
75	10/30/90	N/A	7.3	N/A
76	5/22/90	<0.3	<0.1	<0.1
76	10/30/90	N/A	3.7	N/A
77	5/22/90	<0.3	<0.1	<0.1
77	10/30/90	N/A	3.8	N/A
78	5/22/90	<0.3	5.0	<0.1
78	10/30/90	N/A	8.9	N/A
79	5/22/90	<0.3	4.0	<0.1
79	10/30/90	N/A	9.6	N/A
80	5/22/90	<0.3	3.4	<0.1
80	10/30/90	N/A	8.1	N/A
81	7/10/90	N/A	4.9	N/A
81	8/30/90	N/A	<0.2	N/A
82	7/10/90	N/A	2.6	N/A
82	8/30/90	N/A	2.0	N/A
83	7/10/90	N/A	3.8	N/A
83	8/30/90	N/A	1.1	N/A
84	7/10/90	N/A	1.8	N/A
84	8/30/90	N/A	7.8	N/A
85	7/10/90	N/A	1.1	N/A
85	8/30/90	N/A	1.8	N/A
86	7/10/90	N/A	8.9	N/A
86	8/30/90	N/A	12.3	N/A
87	7/10/90	N/A	9.1	N/A
87	8/30/90	N/A	N/A	N/A
88	7/10/90	N/A	5.9	N/A
88	8/30/90	N/A	5.6	N/A
89	7/10/90	N/A	7.7	N/A
89	8/30/90	N/A	8.8	N/A
90	7/10/90	N/A	6.9	N/A
90	8/30/90	N/A	8.9	N/A
91	7/10/90	N/A	9.1	N/A
91	8/30/90	N/A	N/A	N/A
92	7/10/90	N/A	2.4	N/A
92	8/30/90	N/A	2.9	N/A
93	7/10/90	N/A	2.5	N/A
93	8/30/90	N/A	3.9	N/A

WELL I.D. #	DATE	NH4-N (mg/l)	NO3+NO2-N (mg/l)	NO2-N (mg/l)
94	7/10/90	N/A	7.9	N/A
94	8/30/90	N/A	7.8	N/A
95	7/10/90	N/A	6.6	N/A
95	8/30/90	N/A	0.25	N/A
96	7/10/90	N/A	4.1	N/A
96	8/30/90	N/A	N/A	N/A
97	7/10/90	N/A	5.4	N/A
97	8/30/90	N/A	10.5	N/A
98	7/10/90	N/A	2.4	N/A
98	8/30/90	N/A	2.1	N/A
99	7/10/90	N/A	7.4	N/A
99	8/30/90	N/A	.67	N/A
100	7/10/90	N/A	23.1	N/A
100	8/30/90	N/A	10.3	N/A
101	7/10/90	N/A	6.2	N/A
101	8/30/90	N/A	8.6	N/A
102	7/10/90	N/A	8.7	N/A
102	8/30/90	N/A	9.5	N/A
103	7/10/90	N/A	9.1	N/A
103	8/30/90	N/A	12.0	N/A
104	7/10/90	N/A	14.3	N/A
104	8/30/90	N/A	16.0	N/A
105	7/10/90	N/A	0.1	N/A
105	8/30/90	N/A	7.3	N/A
106	7/10/90	N/A	6.8	N/A
106	8/30/90	N/A	6.8	N/A
107	7/10/90	N/A	5.8	N/A
107	8/30/90	N/A	5.5	N/A

APPENDIX E

QUALITY ASSURANCE PROGRAM
RESULTS FROM ION CHROMATOGRAPHY STUDY

WELL #	F^- (ppm)	Cl^- (ppm)	NO_3^- (ppm)	SO_4^- (ppm)
1	0.74	14.41	4.50	215.84
2	0.77	25.37	8.96	247.72
3	1.16	21.36	7.18	250.03
4	0.66	15.18	5.26	202.93
5	0.66	16.07	8.19	219.67
6	0.69	16.98	10.61	201.43
7	0.67	14.46	5.85	178.73
8	0.87	17.86	10.76	213.87
9	0.70	14.81	4.06	196.25
10	1.11	36.07	4.95	243.98
11	0.84	15.80	5.25	233.72
11	0.72	15.41	5.19	228.44
12	0.99	24.21	6.86	262.40
13	0.78	18.93	5.91	237.24
14	0.73	8.83	12.55	21.43
15	0.84	25.00	4.98	289.14
16		11.53		
17	0.79	58.43	7.54	139.70
18	0.86	22.33	18.28	214.47
18	0.62	12.21	9.60	122.86
19	0.86	19.53	2.36	230.63
20	0.76	23.55	8.18	243.41
20	0.76	23.94	8.08	244.23
21	0.75	23.03	17.34	240.68
22	1.02	41.43	2.82	316.84
23	1.01	21.45	2.44	236.69
24	0.80	16.12	1.44	205.13
25	0.74	18.37	6.00	230.04
26	0.71	68.34	26.63	56.30
27	0.77	19.55	8.31	231.19
28	0.90	8.84	6.51	80.63
28	0.90	8.85	6.51	80.37
29	0.61	16.66	3.69	155.82

WELL #	F^- (ppm)	Cl^- (ppm)	NO_3^- (ppm)	SO_4^- (ppm)
30	0.85	17.23	8.41	261.35
31	0.74	15.07	1.20	199.01
32	0.90	15.26	2.06	207.79
33	0.89	14.62	5.01	205.89
34	0.72	25.40	8.08	210.94
35		11.54	5.29	
36	0.79	21.84	9.06	249.70
37	0.67	148.88	17.46	225.53
38	0.97	28.90	2.96	176.67
38	1.00	32.29	3.16	208.20
39				
40	0.96	15.83	1.52	216.64
41	0.79	20.24	5.62	219.15
42	0.72	21.80	8.11	273.15
42	0.74	21.20	8.19	249.90
43	0.76	27.46	1.28	173.18
44	0.90	25.49	7.77	221.27
45	0.72	19.37	15.45	245.86
46	0.76	24.57	8.38	241.51
47	0.69	14.67	0.77	210.33
48	0.99	43.46	31.44	377.41
49	0.70	15.10	8.44	220.22
50	0.64		0.89	
51		11.54		
52	0.86	15.90	1.57	205.52
53	0.86	15.89	1.64	214.20
54	0.75	16.54	1.74	218.87
55	0.94	16.61	0.81	228.14
56	0.77	25.64	8.87	253.23
57	0.79	16.14	6.78	219.96
58	0.74	21.33	9.54	218.91
59	0.75	17.46	1.50	215.96
60	0.85	14.65	5.64	205.34

WELL #	F^- (ppm)	Cl^- (ppm)	NO_3^- (ppm)	SO_4^- (ppm)
61			5.29	
62	0.85	18.17	0.46	256.80
63	0.78	25.83	8.89	255.85
64	0.65	11.57	0.89	
65	0.67	11.63	3.09	170.08
66				
67	1.95	8.85		19.47
67	1.99	8.74	0.53	16.17
68	1.13	25.32	0.46	140.08
69	0.71	14.79	5.86	227.94
70	1.04	13.55	1.57	199.45
71	0.97	16.78	6.60	242.87
72	2.54	16.00		0.57
73	1.63	8.74		
74	0.84	8.56		3.38
75	0.81	14.56	7.23	182.71
75	0.82	14.68	7.30	184.45
76	1.02	16.05	3.79	202.32
77	0.78	13.53	3.57	168.09
78	0.83	17.57	9.38	191.06
79	0.75	16.00	10.25	205.31
80	0.90	17.00	8.39	175.05
80	0.88	16.89	8.27	171.89

APPENDIX F

TIME STUDY ANALISIS

As stated in Chapter V, there was some concern about the accuracy of results from samples collected from domestic wells because these wells may not have been properly purged. In order to address this issue four time studies were conducted in the Fall of 1990. The purpose of the studies was to evaluate variations in nitrate concentration with time.

Three domestic wells that had shown consistently high nitrate levels were selected. A municipal well was also included for comparative purposes. Samples were collected from each of the wells every fifteen minutes for a period of two hours, This ensured that the well(s) had been properly purged. Unfortunately, the results of these studies (Figures 55-58) prove largely inconclusive as no consistent pattern is observed.

Figures 55 through 57 represent the results from the domestic wells. Results from well #26 (Figure 55) indicates that the level of nitrate contamination rises dramatically during the first few minutes of operation. This suggests that results from samples collected within the first 3 to 5 minutes of start-up predict erroneously low levels of nitrate contamination in the aquifer. However, the results of samples collected from well #67 (Figure 56) indicate that just the opposite trend is occurring; nitrate levels decrease dramatically within the first minutes of operation. Results from well #45 (Figure 57) indicate that nitrate levels after 2 hours of sampling are approximately the same levels as at start-up. Samples collected from well #2, a municipal well (Figure 58), shows an early initial rise followed by a return to initial levels at the end of 2 hours.

Because of the large variability in the results produced by these studies, it is difficult to determine, at this time, the true effect of improperly purging these wells prior to sample collection. Additional studies of this type may be warranted and produce a statistically significant trend.

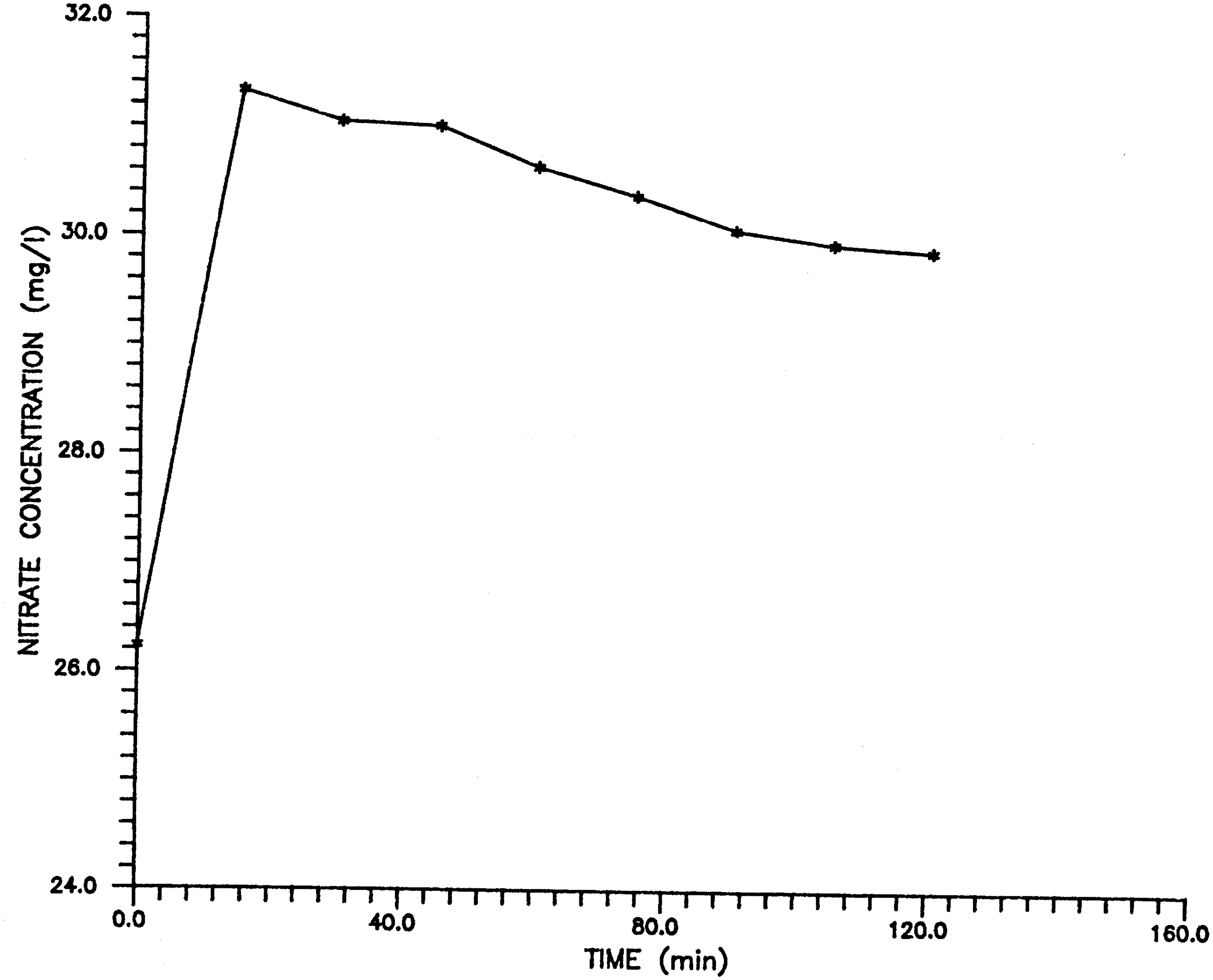

Figure 55. Variations in Nitrate Concentration with Time for Well #26.

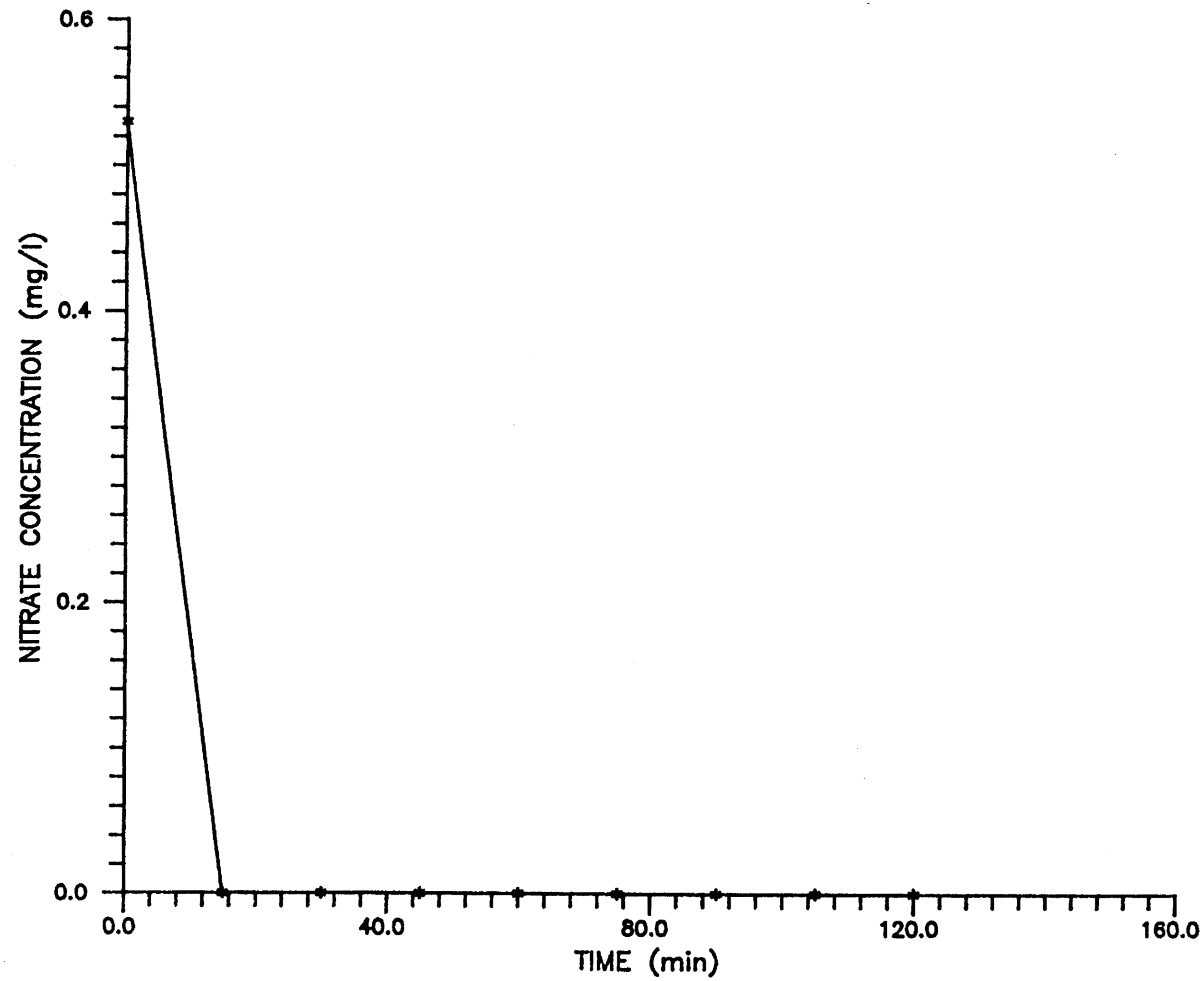

Figure 56. Variations in Nitrate Concentration with Time for Well #67.

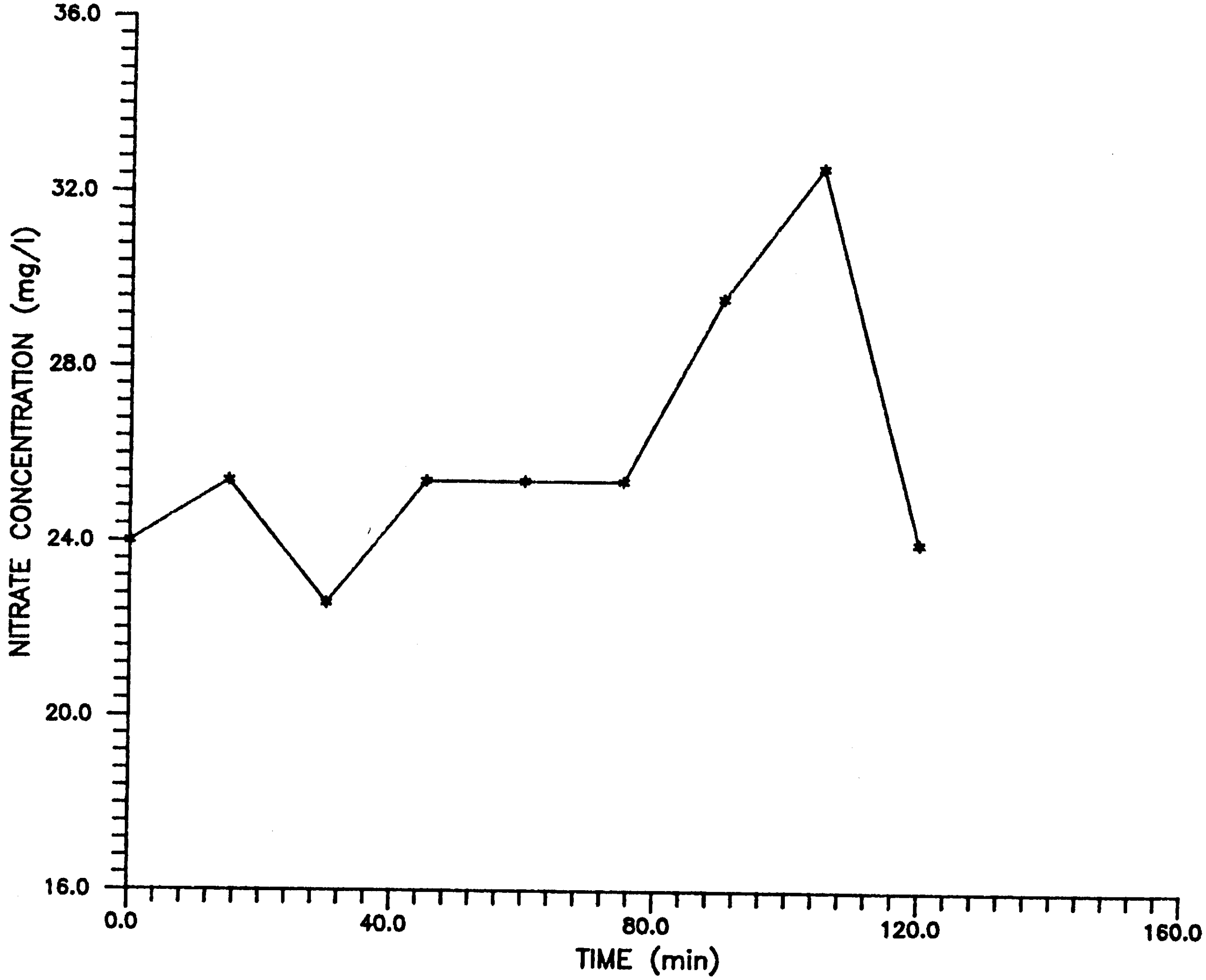

Figure 57. Variations in Nitrate Concentration with Time for Well #45.

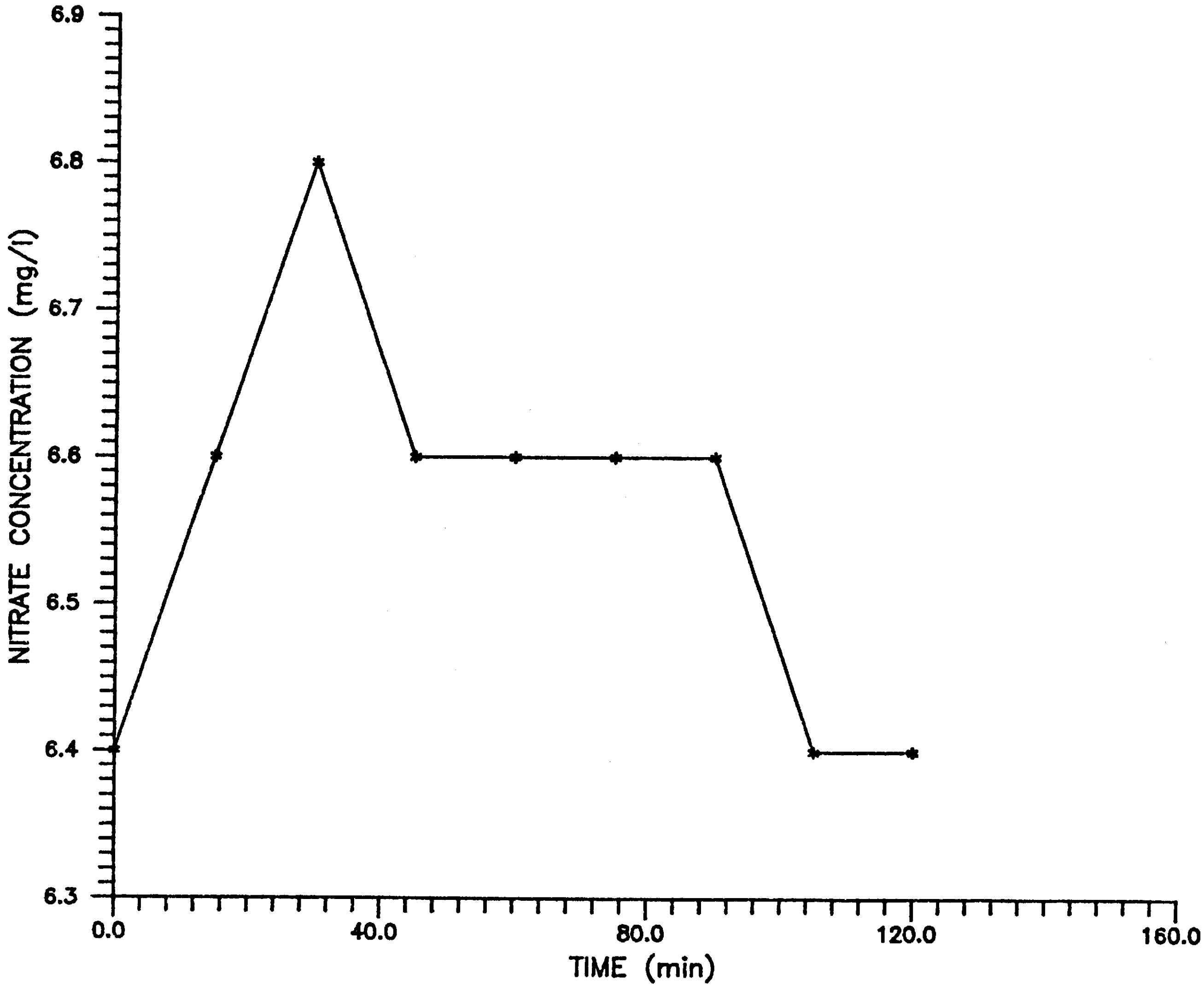

Figure 58. Variations in Nitrate Concentration with Time for Well #2.

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PLATE 1

Topographic Map of Study Area