IMPACTS OF WASTEWATER DISCHARGE TO FOUNTAIN CREEK ON NITRATE CONTAMINATION IN THE WIDEFIELD AQUIFER

by

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Resources Research Institute

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ABSTRACT

IMPACTS OF WASTEWATER DISCHARGE TO FOUNTAIN CREEK ON NITRATE CONTAMINATION IN THE WIDEFIELD AQUIFER

At the present time there is an indirect treated wastewater recharge system in existence in El Paso County, Colorado. The Colorado Springs sewage treatment plant discharges its effluent to Fountain Creek where it accounts for over half of the flow in the creek the majority of the time. Further downstream, Fountain Creek supplies the main source of recharge water to the north-west end of the Widefield aquifer. The city of Colorado Springs and three communities adjacent to the aquifer, Stratmoor Hills, Security, and Widefield, all use water from the Widefield aquifer for municipal supplies.

For the past 10 to 15 years, increasing nitrate concentrations have been noted in the Widefield aquifer. Currently the concentrations are approaching and occasionally exceeding the drinking water standard of 10 mg/l as N. The most significant nitrate increases have occurred near the area of recharge from Fountain Creek. Ammonium discharged from the sewage treatment plant is being converted to nitrate upon recharge to the aquifer.

To quantify future nitrate increases in the aquifer a predictive modeling effort was conducted using a two-dimensional finite element flow and transport code. Several simulations were run depicting:

1. Increases in flow from the Colorado Springs sewage treatment plant.
2. The effects of nitrogen removal from the sewage effluent.
3. Movement of the treatment plant's discharge point below the area of recharge.
4. Direct groundwater recharge of the effluent near the treatment plant.
5. Increased or decreased pumping rates by the Widefield aquifer water users.
6. Other potential contaminants from effluent recharge in addition to nitrates.

In general, increasing the amount of effluent discharge from Colorado Springs without any nitrogen removal may continue to produce increased concentrations of nitrate in the aquifer. The up-gradient portion of the aquifer near the area of recharge would be most greatly affected. Concentrations of nitrate in the Stratmoor Hills well field, the Pinello well field and the majority of the up-gradient Security wells could all experience nitrate increases above the drinking water standard. Nitrogen removal at the treatment plant could prevent and even reverse the high nitrate levels. Reducing the recharge ammonium concentration in Fountain Creek to 6 mg/l as N could drop the nitrate concentration in the aquifer to below 10 mg/l as N after about 2 years.

Moving the treatment plant's effluent discharge point could also reduce the nitrate levels, but would severely reduce the volume of the water in storage. Direct recharge to groundwater near the treatment plant may circumvent the supply problem but it would not necessarily solve the nitrate contamination problem, only move the source to a different place. Increasing or decreasing the pumping in the aquifer alone has little to no effect on the nitrate levels in the aquifer. Coupled with nitrogen removal from the treatment plant, increased pumping may help restore lower nitrate concentrations more quickly.

The most promising action to help prevent future nitrate increases in the Widefield aquifer, and even restore current conditions, would be to reduce the ammonium concentration in the area of recharge. This could be accomplished in one of two ways, either by nitrogen removal at the sewage treatment plant or by diluting the ammonium concentration with some other water supply.

No contaminants other than nitrate have been found in the Widefield aquifer at levels of concern. Other potential contaminants that are mobile, such as chloride and some detergents, would move in a similar fashion as nitrate. A moderately adsorbing chemical, such as chloroform, was also modeled and found to move at a significantly slower rate.

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CHAPTER 1

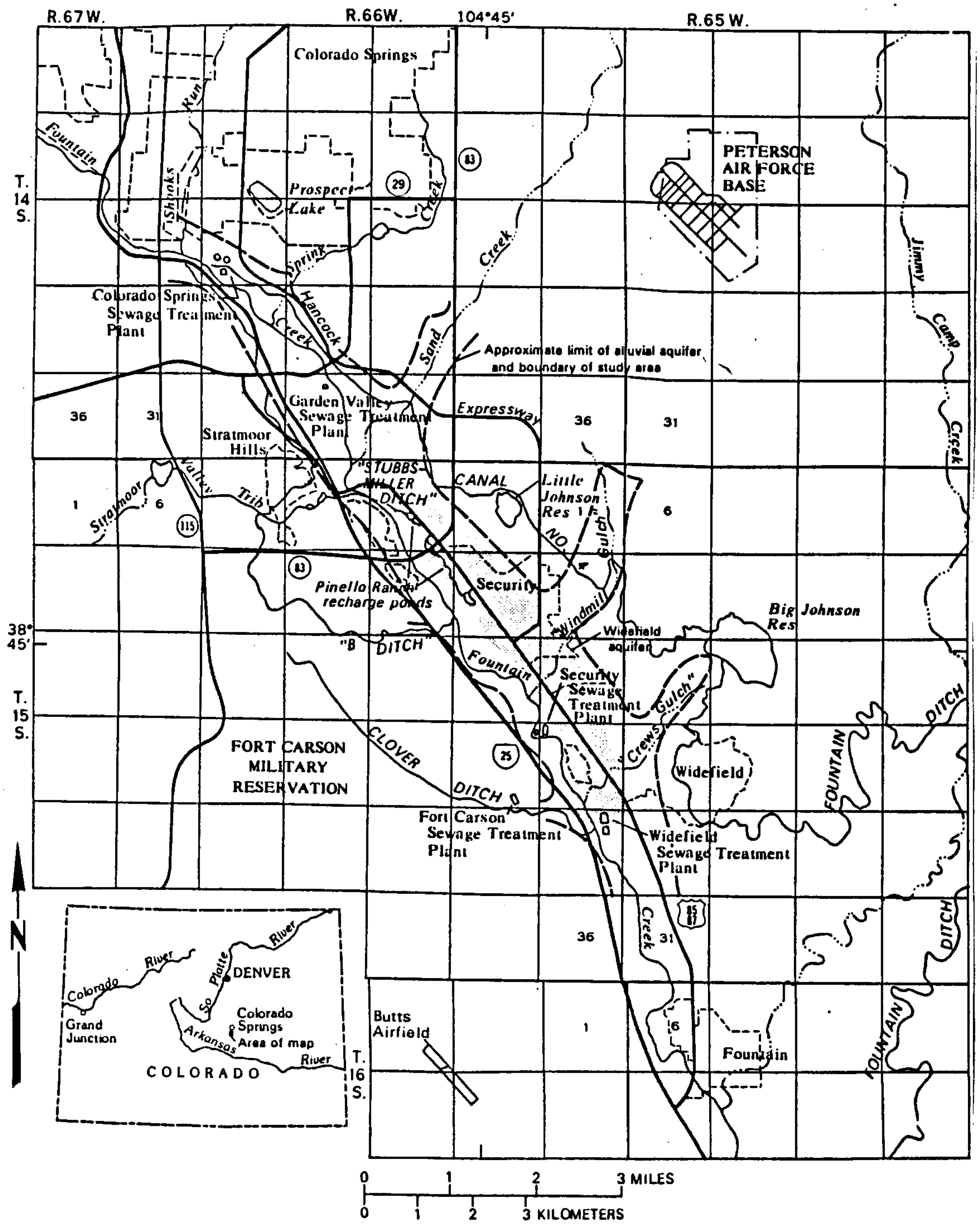
INTRODUCTION

1.1 Statement of the Problem

Water supply in the west has historically been plagued by quantity problems. In Colorado a complicated set of water laws has arisen in the form of the prior appropriation doctrine. Colorado has shown considerable growth over the past several decades - in particular the Colorado Springs area where the population doubled between 1950 and 1970 (Livingston et al, 1976b). Just south of Colorado Springs a nitrate contamination problem has been identified in the Widefield aquifer. The increase in nitrate may be in part the result of large discharges of sewage effluent from Colorado Springs into Fountain Creek. Over half of the water used by Colorado Springs (a total of about 70,000 acre-feet were used in 1986, personal communication, Maria Del Tor, City of Colorado Springs, 1987) was discharged to Fountain Creek in the form of treated sewage. Fountain Creek then flows south-east where it is recharged to the Widefield aquifer. An average of 36 million gallons per day (MGD) flows through the city's wastewater treatment plant according to the discharge permit for Colorado Springs. This effluent comprises the year round base flow in Fountain Creek. Without this constant supply, the flow in Fountain Creek would be reduced significantly.

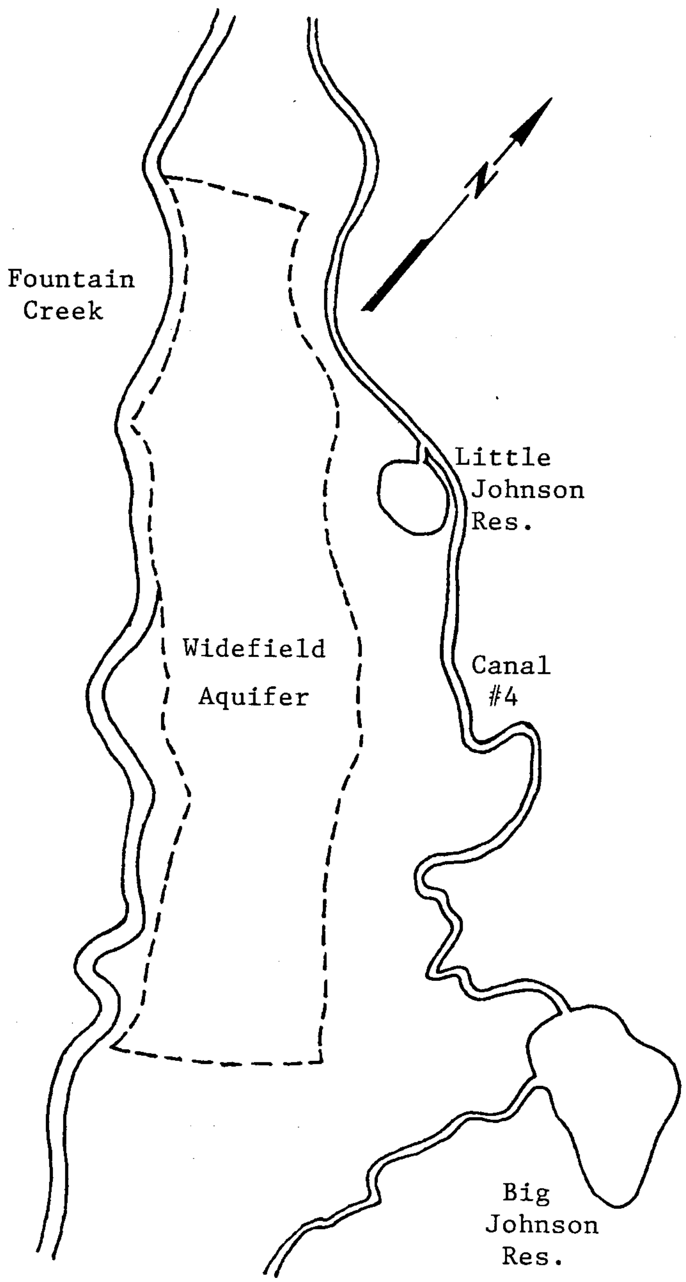
The study area (Figures 1 & 2) has been selected because three communities south of Colorado Springs in El Paso County rely on groundwater from the Widefield aquifer for their drinking water supply. These three communities are Stratmoor Hills, Security and Widefield. Stratmoor Hills lies just to the northwest of the aquifer and pumps an average of 630 acre-feet per year from three wells. The town of Security has thirteen wells actively pumping and Widefield has about the same number (W.W. Wheeler & Associates, 1986). The average annual pumping over the last ten years for Security is 1720 acre-feet and for Widefield is 1600 acre-feet. Many of these wells are used intermittently depending on the demand at particular times. There are fourteen wells located on the Pinello Ranch which are used for different purposes: irrigation, export to Security, and export to Colorado Springs. During 1986, 330 acre-feet were used for irrigation, 340 acre-feet were exported to Security and 1370 acre-feet were exported to Colorado Springs. It is interesting to note that ten years prior, in 1976, only 80 acre-feet were exported to Colorado Springs and 440 acre-feet to Security while 1120 acre-feet were used for irrigation. These water supplies pumped from the Widefield aquifer are then directly distributed, with the only treatment being chlorination at the pump for disinfection purposes (personal communication, Widefield Water and Security Sanitation, 1987).

The current problem under consideration is the increasing concentration of nitrate in the Widefield aquifer. Nitrate is regulated by the Safe Drinking Water Act of 1987 due to its toxicity to infants when ingested. The regulations state that the maximum concentration of nitrate shall be less than 10 mg/l as N. An extensive sampling effort



(Source: Edelmann and Cain, 1985)

Figure 1. Map showing Location of Study Area



----------- Widefield aquifer boundary

Scale: 1" equals 1 mile

Figure 2. Study Area Boundaries

was made in 1981 and 1982 by the USGS to quantify nitrogen in the aquifer. It was found that the concentration of nitrate in the aquifer ranged from 3 to 15 mg/l with an average of 7 mg/l as N.

1.2 Proposed Research to Quantify Problem

There currently exists an indirect wastewater recharge relationship between Colorado Springs' sewage treatment plant and the Widefield aquifer. Two-thirds of the water recharging the the aquifer enters from Fountain Creek as it crosses the north end of the aquifer. During most of the year, the effluent from the treatment plant comprises over half of the flow in Fountain Creek in this area of recharge to the aquifer (Edelmann and Cain, 1985). On the average, about 12% of the flow in Fountain Creek recharges the aquifer and half of this is actually from the treatment plant. This indirect wastewater recharge system does allow for some dillution of the effluent. Under existing conditions ammonium is diluted from about 20 mg/l as N in pure sewage effluent, down to about 10 mg/l as N once mixed in Fountian Creek. Questions have been raised about future contamination in the aquifer, such as the increase of nitrate levels and other contamiants. This study aims at exploring various choices that the Colorado Springs' sewage treatment plant could explore to prevent any further degradation of water quality in the Widefield aquifer.

The following alternatives were explored:

1) The "do nothing" alternative, continuing discharge practices to Fountain Creek with no changes. Future increases in water usage and subsequent increases of effluent discharges were included in this

alternative. As the amount of effluent increases relative to the base flow in Fountain Creek, the dilution potential is decreased. Concentrations of ammonium can increase in the area of recharge, potentially to a maximum of pure effluent.

2) Removal of contaminants at the treatment plant, specifically ammonium. Such a treatment scheme would be employed so that the ammoium concentration would be reduced significantly in the area of recharge.

3) Move the point of discharge below the recharge area. As well as monitoring the contaminant in this case, water levels must also be watched because this alternative would remove the major source of water to the aquifer.

4) Employ a direct groundwater recharge plan. Discharge the effluent to recharge ponds far upgradient from the Widefield aquifer to observe the contaminant removal capacity.

The question of altered pumping schemes by the water users themselves was also brought up. Both increased and decreased pumping can be tested for any beneficial effects on contamination in the aquifer.

Other than nitrates, there are only a few other wastewater components that are measurable in the Widefield aqufier. Most dissolved organic material, 70-90% (Cain and Edelmann, 1986), is filtered out of the groundwater upon recharge. There are some dissolved organic detergents which remain mobile in groundwater that can be detected, however, there is insufficient data to model them. Volatile organic compounds, such as trichloroethylene and tetrachloroethylene, can sometimes be found in secondary wastewater treatment plants. An adsorbing compound, such as ammonium or an organic will also be looked at to see the effects of adsorption on contamiant migration.

Nitrate contamination in the Widefield aquifer will remain the main focus of this study. Other questions about the effects of recharging treated wastewater may also be touched upon. To study the contamination in the aquifer, a predictive numerical modeling effort was proposed to determine the fate of contaminants, especially nitrate in the Widefield aquifer over time. The model is based on the Galerkin finite element method and was developed by Dr. James Warner, at Colorado State University. The model uses triangular elements over which it can solve both transient flow and transport. Aquifer properties may be spatially varied and aquifer stresses such as pumping and recharge can vary in time and space. There are data available to calibrate the model to existing conditions. After calibration, simulations were run to predict contaminant concentrations in the future.

CHAPTER 2

STUDY LOCATION

2.1 Literature Review: El Paso County

The water resources in Colorado have long been a focus of study. By the 1950's, the need for groundwater data and information was acknowledged with the publication of a series of groundwater basic data reports prepared by the Colorado Water Conservation Board in conjunction with the U.S. Geological Survey. At that time, the Widefield aquifer and the entire Fountain Valley alluvial aquifer already had extensively developed well fields. The basic data report compiled the location, owner or user, year of completion, characteristics of the well construction, hydrogeology, pump type, type of water use, depth to water, and well yields for 268 wells, of which 72 were in the Widefield aquifer. There are also actual well logs of 154 wells in the area, 32 of which are in the Widefield aquifer. Water levels for a few wells were recorded over several years (1954 - 1959), and there are also some chemical analyses dating from 1955. Pumping tests in Colorado were also published as a Colorado Water Conservation Board Groundwater Circular (Wilson, 1965). These basic data made it possible for this study to more accurately characterize the hydrogeology of the Widefield aquifer.

Subsequent water resource reports on the area contain more local details. The USGS conducted studies in cooperation with the

Southeastern Colorado Water Conservancy District, the El Paso County Board of Commissioners, the Pikes Peak Area Council of Governments, the City of Colorado Springs, and the US Air Force Academy (Klein and Bingham, 1975, Livingston et al, 1975, 1976a, 1976b). Community and regional water concerns were becoming issues of great importance in the early 1970's. Klein and Bingham with the USGS (1975) explored the quality of water in Fountain Creek, paying close attention to the dissolved oxygen depletion due to the sewage contributions. Fountain Creek was once described as a "clear stream which contained fish" but now, downstream of Colorado Springs it is "turbid, dark, odoriferous and devoid of aquatic insect and fish life" (Klein and Bingham, 1975). They determined that even though there is a high oxygen demand imposed by the sewage, through natural processes, Fountain Creek recovers from the biodegradable load imposed upon it.

Nitrates at this time were also noted to be high. Several sources were considered for the nitrate such as leaking sewage lagoons and canals, high nitrate fertilizers, and eroded bedrock, as well as the large amount of treated sewage effluent recharging the aquifer. Most well samples were below the drinking water standard with a mean of 5 mg/l as N. Figure 3 shows the approximate nitrate distribution for 1972. Nitrate concentrations were significantly greater in the southern portion of the aquifer, and were attributed to local recharge from sewage lagoons or over-application of commercial fertilizers.

These three USGS reports also cover demographics, general hydrology, surface water, flood frequency, groundwater, water quality,

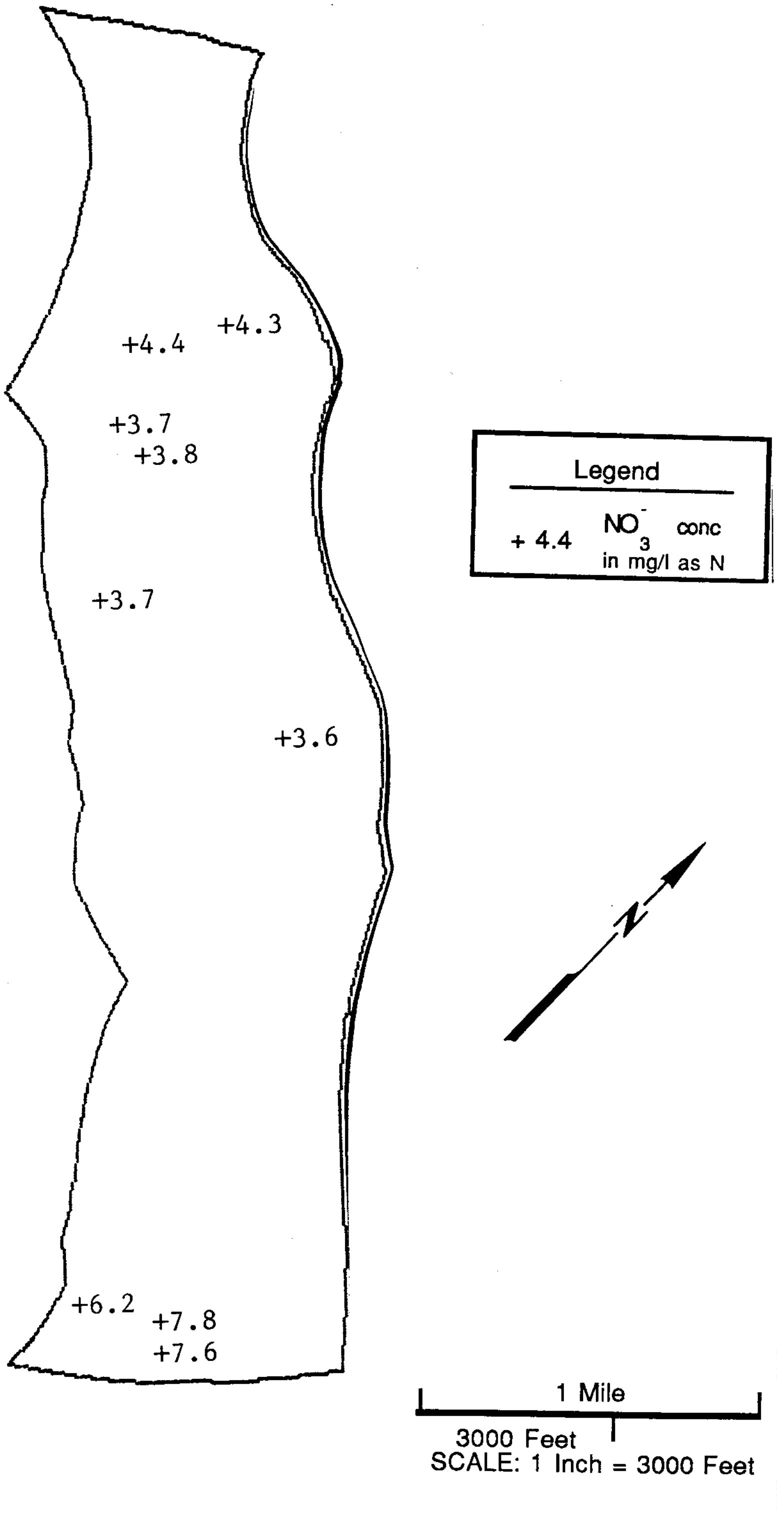


Figure 3. Nitrate Concentration Distribution for 1972 in the Widefield Aquifer

and water management. The aquifer material, the Broadway alluvium, was stated to have well yields as high as 1,340 GPM. Fluctuations of the water table throughout the year have not reflected any long term changes in storage and were considered negligible for long range planning. The hydraulic relationship between Fountain Creek and the Widefield aquifer was thoroughly explored. Fountain Creek recharges approximately 8,000 acre-feet per year to the northwest end of the aquifer. South of this recharge area, the aquifer tends to slowly lose water back to the creek across a discontinuous bedrock ridge. The other two major discharges from the aquifer are pumping and flow in the direction of the regional gradient.

Recent studies have been conducted concerning the water quality of the Widefield aquifer. Edelmann and Cain (1985) conducted a detailed study concerning water and nitrogen sources to the Widefield aquifer. This report contains recent (1981 - 1983) water quality data and current data are available for many of the wells. Edelmann and Cain point out that the concentration distribution in 1982 shows the highest nitrate concentrations in the north end and that the concentrations decrease down-gradient (Figure 4). This is opposite to the trend that was noted in 1972. The increase in the north end has been attributed to recharge containing high nitrogen concentrations from the Colorado Springs sewage treatment plant.

The nitrate contamination problem in the Widefield aquifer is a major water quality concern for El Paso County, Colorado. The increase in nitrate has been acknowledged for many years, and the possibility of continued increases should be better quantified for future use. Currently, most wells are pumping water which has nitrate concentrations

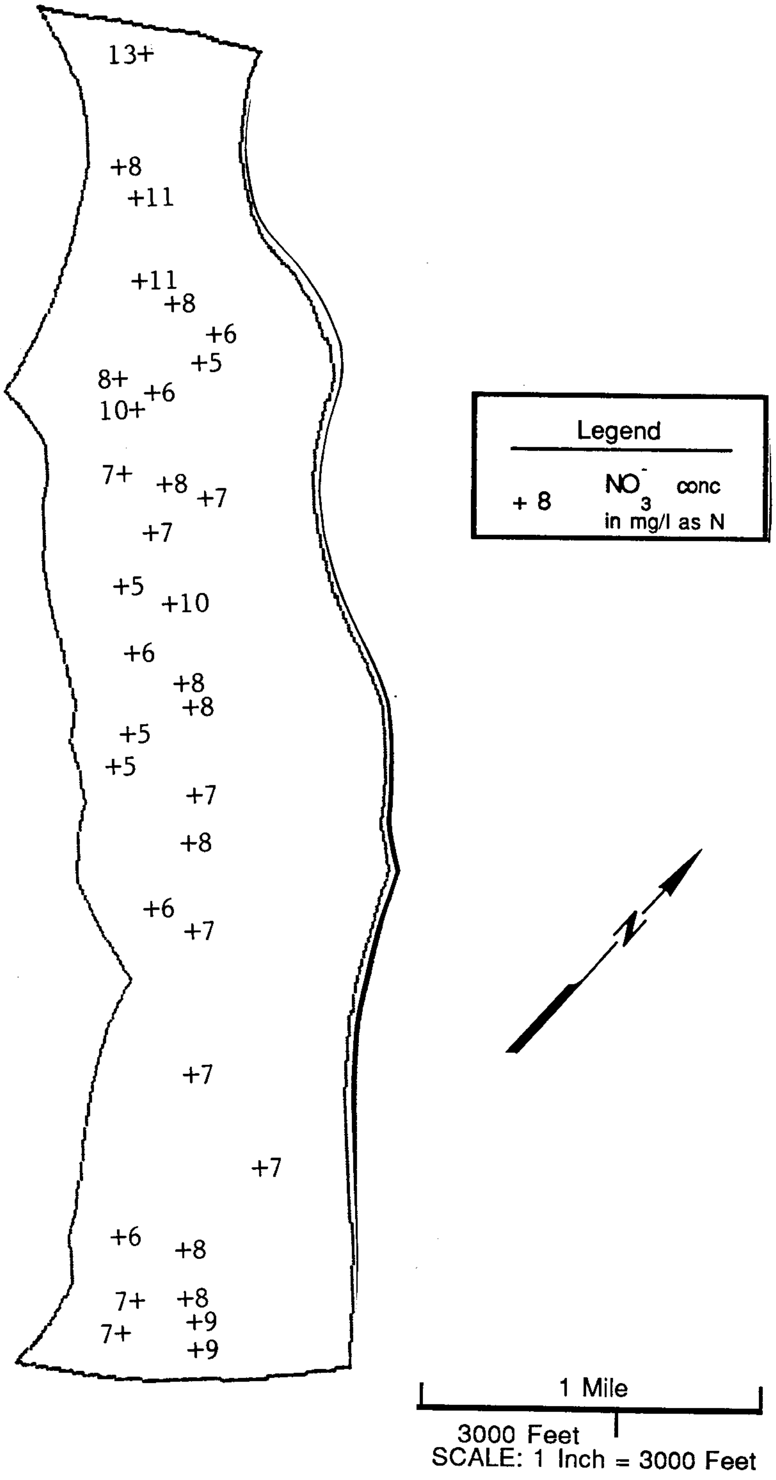


Figure 4. Nitrate Distribution for 1982

below or just below the drinking water standard of 10 mg/l as N. If it could be determined that the nitrate levels have reached a steady state then the future use of the aquifer could be managed more reliably. On the other hand, if changes in the boundary conditions, such as an increased nitrate source, were to cause a sharp increase of nitrate concentrations in the aquifer above the drinking water standard, then quick and possibly drastic action would be required. Management of large municipal water supplies such as the Widefield aquifer depends on being aware of potential problems in advance. A modeling study such as this will hopefully benefit the long range planning for the water resources in El Paso county.

2.2 General Hydrogeology

The Widefield aquifer consists of an ancient paleo-channel of Fountain Creek deeply incised into the Pierre Shale bedrock. The channel ranges from 10 to 100 feet thick, is about 4 1/2 miles long, and averages 3500 feet wide. The aquifer material is known as Broadway alluvium, and consists of yellowish-brown gravelly alluvium containing pebbles, cobbles, and boulders (Scott, 1973). Well yields are high, frequently over 750 GPM (Jenkins, 1961). Edelmann and Cain (1985) reported the following aquifer properties compiled in Table 1.

The Widefield aquifer is located just to the east of the current Fountain Creek channel from the north end of Security, Colorado to the south end of Widefield, Colorado (Figure 5) The western half of the aquifer lies under the Fountain Creek flood plain and has three active agricultural areas on it, the Pinello Ranch, the Venetucci Ranch, and the Camden Ranch. There are several industrial buildings located on the

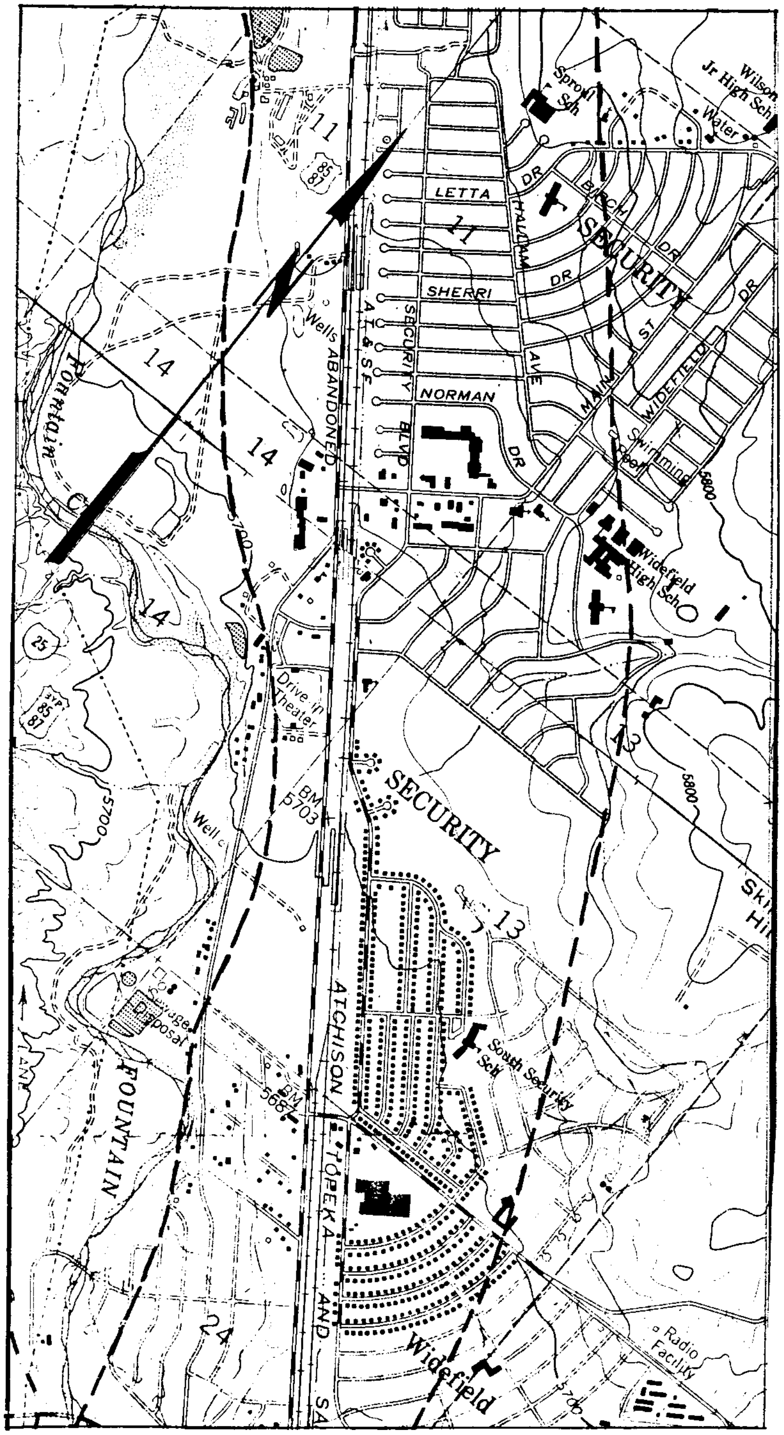
Table 1. Widefield aquifer properties.

PROPERTY	RANGE	MEAN
Saturated thickness	0 - 90 feet	30 - 35 feet
Storage	16,000-20,000 ac-ft	18,000 ac-ft
Hydraulic conductivity	670 - 1140 ft/day	830 ft/day
Specific yield	0.20 - 0.30	0.25
Seepage velocity	13 - 34 ft/day	20 ft/day

western side and the Sante Fe Railroad runs almost directly along the centerline of the aquifer. The eastern side of the aquifer has been extensively developed into the residential communities of Security and Widefield. The expansion primarily began in the 1950's with the introduction of Fort Carson. The current population of the area is greater than 30,000.

Fountain Creek itself drains about 85% of southwestern El Paso County. The watershed originates on the slopes of Pikes Peak, northwest of Colorado Springs. The mean annual discharge at Colorado Springs was 54 cfs in 1982. Below the city, at Security, the mean flow increased to 110 cfs (Edelmann and Cain, 1985). The increase in flow was due to the many inflows along the stream, most notably, Colorado Springs' wastewater treatment plant which contributed about 40 cfs. There are several tributaries, effluent discharges, and two main diversions along Fountain Creek in the study area. The major inflows and diversions in 1982 are listed in Table 2 (Edelmann and Cain, 1985).

The diversions from Fountain Creek may significantly affect the groundwater quality in the aquifer. Canal #4 is only about 200 yards downstream and on the same bank as the activated sludge outfall. Complete stream mixing has not occurred so most of the water in the



Base Map from USGS Colorado Springs, Cheyene Mountain and Elsmere, 1961, Interim revisions, 1975, Fountain, 1961 Interim revisions, 1976

Figure 5. Topographic Map Depicting Development on Top of the Widefield Aquifer

Table 2. Net Contributions to Fountain Creek

SITE	TYPE OF DISCHARGE	1982 AVERAGE FLOW (cfs)
Colorado Springs	Effluent Outfall	40
Canal #4	Diversion	15
Spring Creek	Tributary	2
Sand Creek	Tributary	<1
Stratmoor Valley	Tributary	<1
Stubbs- Miller Ditch	Diversion	1.6
B-Ditch Drain	Tributary	2
Windmill Gulch	Tributary	<1
Security	Effluent Outfall	1.7

canal is effluent. Canal #4 also receives the outfall from the trickling filter at Colorado Springs. The trickling filter is currently (fall 1986 - spring 1987) not in use, but when on line has about a 6 MGD capacity (9.3 cfs). In 1982 the average flow in the canal was about 15 cfs. The canal continues southeast and fills the two Johnson Reservoirs. Along its path, a significant amount of water leaks into the eolian deposits beneath it which in turn recharge the Widefield aquifer. The Stubbs-Miller Ditch diverts water directly to recharge ponds on the Pinello Ranch at the north end of the aquifer. The annual average flow to these ponds is approximately 1.5 cfs. All of these inflows and diversions combined have an impact on both Fountain Creek and the aquifer.

Fountain Creek interacts strongly with the Widefield aquifer. The main source of water which recharges the aquifer comes directly from the creek. At the north end, Fountain Creek cuts across the aquifer establishing an excellent hydraulic connection. South of this recharge area the aquifer and stream are only intermittently connected whereupon the aquifer tends to lose some water to the stream.

The aquifer is also fed via tributary and upgradient alluvium and water is removed by pumping and outflows. These contributions are listed for 1982 in Table 3 (Edelmann and Cain, 1985).

Because 1982 was a particularly wet year, the storage was slightly increased. In general, the storage in the aquifer does not change significantly from year to year. Good management practices for the last twelve years have kept the water levels from dropping significantly in any one area.

Table 3. Net Contributions to the Widefield Aquifer

NAME OF INFLOW	1982 AVERAGE CONTRIBUTION (gpm)	(%)
Fountain Creek Recharge	4900	66
Fountain Creek Alluvium	430	6
Sand Creek Alluvium	17	<1
Stratmoor Valley Tributary Alluvium	3	<1
B-Ditch Drain Alluvium	2	<1
Eolian Deposits (Canal #4)	570	8
Precipitation and Lawn Watering	620	8
Precipitation and Irrigation	740	10
Pinello Ranch Recharge Ponds	110	1
NAME OF OUTFLOW	**1982 AVERAGE LOSS (gpm)**	**(%)**
Loss to Fountain Creek	1400	23
Downgradient Flow	1500	24
Groundwater Pumpage	3300	53

2.3 Ammonium, Nitrate, and Nitrification in the Widefield aquifer

The state of Colorado has very strict regulations on ammonia due to its toxicity to fish. Ammonia (NH_3) exists in an equilibrium with the ammonium ion (NH_4^+). The concentration of each species found at any given time will be dependent on the pH and temperature of the water.

Several detailed tables of percent ammonia versus ammonium have been compiled as functions of both temperature and pH (Emerson et al, 1975). The 1981 and 1982 USGS data show that the pH in Fountain Creek below the sewage treatment plant did not exceed 8.0 and the temperature rarely exceeded 25 degrees C (Edelmann and Cain, 1985). Using these values as extreme conditions, 94% of the total ammonia would exist as the ammonium ion (Emerson et al, 1975).

The instream ammonia concentration limit for warm water aquatic life is 0.06 mg/l (Colorado Code of Regulations, 1982). Under the extreme conditions in Fountain Creek near the effluent outfall, the average instream total ammonia concentration, ie. both ammonia and ammonium combined, was about 10 mg/l in 1982 (Edelmann and Cain, 1985). This would yield 0.60 mg/l of ammonia - ten times the limit. However, it is important to note that Fountain Creek is one of two streams in Colorado not classified to support any aquatic life (Personal Communication, Dave Akers, Colo. Dept. of Health, 1986) and therefore has no ammonia limit. It is classified for public water supply and for agricultural uses (Colorado Code of Regulations, 1982). Further downstream, as Fountain Creek recharges the Widefield aquifer it carries the ammonia with it. The ammonium ion, upon entering the aquifer is adsorbed on the solid material and converted to nitrate. Allthough ammonia levels are not regulated by the State in Fountain Creek, nitrate levels are regulated in the drinking water pumped from the Widefield aquifer.

Nitrate concentrations in drinking water are regulated since nitrate is a health hazard to humans, especially young infants. Upon ingestion, the nitrate will be reconverted to nitrite in the stomach and may enter the blood. The nitrite tends to convert infant hemoglobin to methemoglobin, greatly reducing the oxygen carrying capacity of the blood (Shearer, 1972). The condition is known as methemoglobinemia or more commonly as "blue baby" syndrome. It may be fatal especially if the infant continues to ingest water with high concentrations of nitrates. Current drinking water regulations limit nitrate concentrations in drinking water to 10 mg/l as N, a level approached and sometimes exceeded in the Widefield aquifer.

2.4 Literature review: Wastewater reuse by groundwater recharge.

Reusing treated wastewater following groundwater recharge has been persued and studied in other states. In the San Francisco Bay area, wastewater with advanced treatment was injected to coastal aquifers to help prevent saltwater intrusion (Paul V. Roberts, et. al., 1978). During the initial stages of the project, careful monitoring was maintained to determine changes in quality as the injected water flowed through the aquifer. The water quality constituents associated with the wastewater, namely ammonium, trace elements and trace organics, moved slowly compared to the velocity of the injection water during the first 20 days. Adsorption was the main mechanism slowing the travel times. Dissolved oxygen concentrations dropped during a 25 foot passage through the aquifer from 8 mg/l to less than 1 mg/l. This decrease was attributed to both biodegradation of organic substrate and biological nitrification. It is important to note that the water injected had undergone extensive advanced treatment including flocculation, clarification, ammonia stripping, filtration, and carbon adsorption. Even with such treatment, the following constituents were detected in the groundwater due to the recharge: nitrate, Cd, Zn, Cu, Fe, Ag, chlorobenzene, dichlorobenzene, and chloroform.

Arizona has also developed projects with rapid infiltration of treated wastewater to groundwater. Several years of data from this project show similar nitrogen behavior patterns seen in the Widefield aquifer. Groundwater samples in the area of recharge contain no ammonium, but do contain increasing concentrations of nitrate (Bouwer and Rice, 1984). The water pumped from this recharge system did not meet drinking water standards, but could be used for unrestricted irrigation and primary contact recreation. In addition to nitrate, chloroform, 1,1,1-trichloroethane, tetrachloroethylene, dichlorobenzene were all detected. Two viruses, coxsackie and polio, were also found. Additional treatment would be required for potable use, specifically, treatment for refractory organics and potential nitrate problems.

The state of California has published a manual dealing with irrigation using reclaimed municipal wastewater (Pettygrove and Asano, 1985). Irrigation often leads to groundwater recharge and many potential contaminants were discussed in detail. The application of wastewater with high ammonium concentrations was noted to build up local populations of nitrifying bacteria. The actual amount of nitrate that is produced and remains in the groundwater is highly dependent on site specific conditions. Trace elements such as As, B, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Se, and Zn do not pose any harmful short-term effects, but may be a long-term problem if they accumulate in the soil. Bacterial entities, such as bacteria and viruses, are effectively removed by percolation through soils. They tend to be adsorbed onto the soil material. Their average survival time varies between one day and several months. Trace organics commonly found in sewage treatment plants were again listed. The most common compounds were chloroform, 1,1,1-trichloroethane, trichloroethylene, benzene, tetrachloroethylene, toluene, ethylbenzene, and dichlorobenzene. Of these common trace organics, chloroform is moderately mobile while the dichlorobenzenes are virtually immobile.

Specifically looking at the health effects of water reuse by groundwater recharge, several constituents were identified as potential contaminants (Nellor, 1980). The heavy metals Zn, Ba, Cr, Cd, and Pb, were detected beneath infiltration basins in one sewage reclamation project. However, the amounts were not significantly greater than the analysis of a clean sand. Trace organics that were found in sewage included benzene, chloroform, trichloroethylene, dichloromethane, acetone, and hexadecanoic acid. Several microorganisms were mentioned that could be of potential health problems: Giardia lamblia, roundworms, whipworms, tapeworms, Salmonella, Shigella, and the hepatitis A virus. All of these constituents may be of some health concerns and should be monitored closely, but it was still high nitrate concentrations that cause the greatest immeadiate problem.

Most of the literature indicates that nitrate contamination is the primary concern when recharging treated wastewater to a groundwater system. In general, wastewater reuse via groundwater recharge has many positive aspects especially for arid states where new water supplies are scarce. However, nitrate levels should be closely monitored near a wastewater recharge system that is intended to produce potable water.

CHAPTER 3

NITRIFICATION

3.1 Nitrogen transformations

The nitrogen contamination problem in the Widefield aquifer is much more complicated to model than a single species, conservative chemical tracer would be. Many questions quickly arise: What is involved in "nitrogen" contamination? What chemical forms are there? What physical processes affect it? What biological processes affect it? In the literature a number of terms are used to describe the various transformations of nitrogen. Alexander (1982) provided the following basic definitions.

nitrogen mineralization - Convertion of organic nitrogen forms, such as protein, to inorganic forms (NH_4^+) by any mechanism.

ammonification - The microbiological conversion of organic nitrogen to inorganic nitrogen.

nitrification - A microbiological conversion of ammonium to nitrite and then nitrate.

denitrification - The microbiological conversion of nitrate to N_2 gas and N_2O gas under anaerobic conditions.

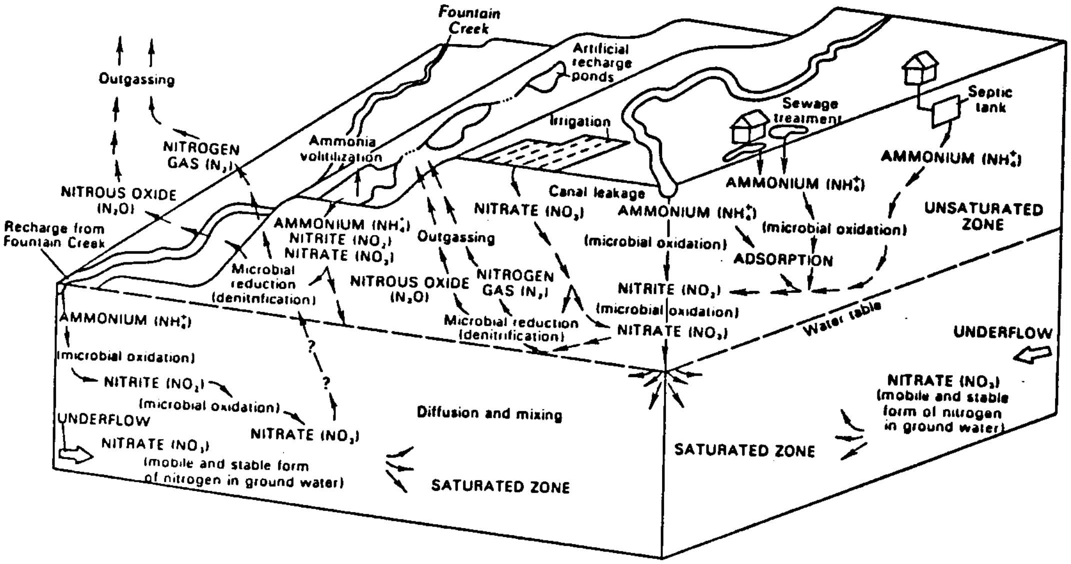
Nitrosomonas sp. and *Nitrobacter* sp. oxidize ammonium to nitrate in the following pathway:

$$NH_4^+ + 3/2\ O_2 \xrightarrow{\text{Nitrosomonas}} NO_2^- + 1/2\ O_2 \xrightarrow{\text{Nitrobacter}} NO_3^-$$

Just from these terms alone it becomes apparent that several chemical forms of nitrogen affect nitrogen contamination. In most soil-water systems, ammonium, nitrite, nitrate, and nitrogen gasses can all be found.

Nitrogen contamination and transport is complex in nature as shown in Figure 6. There has been extensive research conducted on nitrification since the early part of this century. Agricultural problems were originally the primary concern - specifically, how to retain nitrogen fertilizers in the soil for better crop utilization. A literature review provided much insight into the physics, chemistry, and biochemistry of nitrogen transformations and transport.

Because of the agricultural implications, early work was conducted to understand how the physical characteristics of soil affected nitrogen mineralization and nitrification. Early soil studies were usually conducted above the water table. These findings suggested that nitrification rates varied with soil properties. Soil pH, moisture content, and temperature were found to have pronounced effects on the patterns and rates observed for nitrification. The production of



(Source: Edelmann and Cain, 1985)

Figure 6. Possible Nitrogen Transformations Occuring in the Widefield Aquifer

nitrite is mediated by Nitrosomonas sp., while the conversion of nitrite to nitrate is mediated by Nitrobacter sp.; varying pH values affect the two bacteria differently.

Wastewater effluent has been addressed as a nitrogen contamination source in an extensive laboratory study by Preul and Schroepfer (1968). Column tests were performed under sterile conditions as well as under active microbiological conditions. With sterile conditions the effects of adsorption alone could be monitored. This particular experiment simulated a treated effluent having 25 mg/l of NH_4^+, and was run upflow to ensure saturated conditions through a sandy soil. As long as the ammonia was in the ionized form it was found to readily adsorb. Sand columns reached exhaustion, no longer able to adsorb any additional ammonium, after only four hours. Nitrate was also tested for adsorption on the sand; at pH values greater than 6.5 virtually no nitrate was found to adsorb. When the biological activity was allowed to remain in the soil samples, biological nitrification changed a portion of the influent ammonium to nitrite and then to nitrate. Initially adsorption was the dominant inhibitor of ammonium movement, but when the microbes acclimated to the supply of ammonium, nitrification became dominant. Dissolved oxygen appeared to be the limiting factor. Unsaturated columns exhibited even more nitrification at earlier times with most of the conversion to nitrate taking place within the first two feet from the influent surface.

3.2 Nitrogen movement in soil

Research has been conducted to mathematically model nitrogen transformations in soil. Mirsa, Nielsen and Biggar (1974a,b) set up and solved transport equations for ammonium including adsorption, biological conversion to nitrate, and subsequent biological denitrification to N_2 gas. They added terms to account for adsorption and biological action in the following manner:

$$\frac{\partial S_i}{\partial t} + \frac{\partial C_i}{\partial t} = D_i \frac{\partial^2 C_i}{\partial x^2} - v_i \frac{\partial C_i}{\partial x} + \phi_i \qquad (1)$$

Where:

S_i = amount of solute in adsorbed phase

C_i = amount of solute in free or non-adsorbed phase

ϕ_i = net time rate at which mass of solute i is produced due to a specific transformation

D_i = dispersion coefficient for solute i

v_i = average interstitial velocity of solution

A simple linear isotherm was used for reversible adsorption

$$S_i = R_i C_i \qquad (2)$$

Where:

R_i = a distribution coefficient for solute i between free and adsorbed phase. R_i is independent of concentration.

The adsorption of ammonium was incorporated into equation (1) using retarded values for D and v, and are shown in equation (3) as D_r and v_r. The transformation term ϕ was then expanded to include the three biological transformations:

$$NH_4^+ \longrightarrow NO_2^- \longrightarrow NO_3^- \longrightarrow N_2$$

Because the conversion of NO_2^- to NO_3^- is so rapid, the oxidation of NH_4^+ to NO_3^- was lumped into one step. First order reactions may be applicable when concentrations are low because the reaction rate is dependent on the amount of limiting substrate. The following equation would then describe the distribution of NH_4^+ from a single pulse:

$$\frac{\partial C_1}{\partial t} = D_{r1}\frac{\partial^2 C_1}{\partial x^2} - v_{r1}\frac{\partial C_1}{\partial x} - k_1 C_1 \qquad (3)$$

Where:

C_1 = concentration of NH_4^+

k_1 = first order reaction rate constant for NH_4^+ oxidation to NO_3^-

A similar equation would describe nitrate concentration distribution from a single pulse:

$$\frac{\partial C_2}{\partial t} = D_2\frac{\partial^2 C_2}{\partial x^2} - v_2\frac{\partial C_2}{\partial x} - k_2C_2 + k_1C_1 \quad (4)$$

Where:

C_1 = concentration of NH_4^+

k_1 = first order reaction rate constant for NH_4^+ oxidation to NO_3^-

C_2 = concentration of NO_3^-

k_2 = first order reaction rate constant for reduction of NO_3^- to N_2

Often, there is a large enough concentration of solute that the reaction rate becomes independent of concentration, and zero order reaction rates are applicable, considerably simplifying the equations. It is very important to emphasize that microbiological oxidation of NH_4^+ ions incorporates both adsorbed and non-adsorbed phases.

Nitrification also occurs in free-flowing stream systems. Nitrifiers usually are attached to the bottom of the stream sediment. Actual field data show both zero and first order nitrification rates occur (Lopez-Bernal, 1977), and similar to the subsurface systems, adequate dissolved oxygen tends to be the limiting factor. In all systems, groundwater, soil water, surface water, and sewage, there are predominant microbes from the family Nitrobacteraceae. Nitrosomonas europaea most commonly oxidizes ammonium to nitrite in soil, water and sewage, while Nitrobacter winogradskyi oxidized nitrite to nitrate in soil and water (Belser, 1979). The sources of available substrate for the bacteria regulate the population size. Sewage treatment plants contribute a continuous source of ammonium, enhancing the population. On the other hand fertilizer applications tend to be periodic so the mass of nitrifiers does not tend to build up. As the nitrifying population becomes large with adequate ammonium, the nitrification rate often becomes independent of the amount of substrate. In the Widefield aquifer a steady state system most likely exists. The population of nitrifiers has become sufficient to to nitrify the incomming ammonium supply.

Recent literature on nitrification affirms most of the earlier observations relating the physical properties of soil to reaction rates. Nitrification rates were found to be zero order and mainly dependent on pH, moisture content, temperature and influent ammonium concentrations

(Gilmour, 1984). Ammonium competition models are currently being used to determine the fate of nitrogen in soil systems (Riah, 1986). Several nitrogen transformations were considered: plant uptake, immobilization as soil organic matter, mineralization, adsorption and nitrification. A model was constructed combining those factors and was applied to agricultural problems where fertilizers were the main source of ammonium.

3.3 Nitrification model

The nitrification processes, in both soil and water, have been extensively researched since the turn of the century. The system is complex and several factors must be considered. Applying some of the above theory to an entire aquifer becomes most difficult. In the case of the Widefield aquifer, nitrification occurs in the area of recharge near Fountain Creek. A separate companion model was written to better quantify the relationship between the incomming ammonium and the observed nitrate in the aquifer (Figures 7 & 8). The program includes both nitrification of ammonium to nitrate and reversible adsorption. Nitrification is computed using the experimental ratio of 4.33 mg of oxygen which are required for every mg of nitrate produced (Wezernak and Gannon, 1967). Adsorbed or desorbed ammounts are calculated on the basis of a Freundlich isotherm. Freundlich isotherm values were taken from the literature for ammonium on a sandy material. The isotherm was relatively linear so the exponent was 1, and the coefficient Kd was 1.5 ml/gm (Preul and Schroepfer, 1968). A Freundllich isotherm relates the amount of chemical that is adsorbed expressed as a ratio of mass adsorbed to the mass of adsorbant, to the amount of chemical in solution

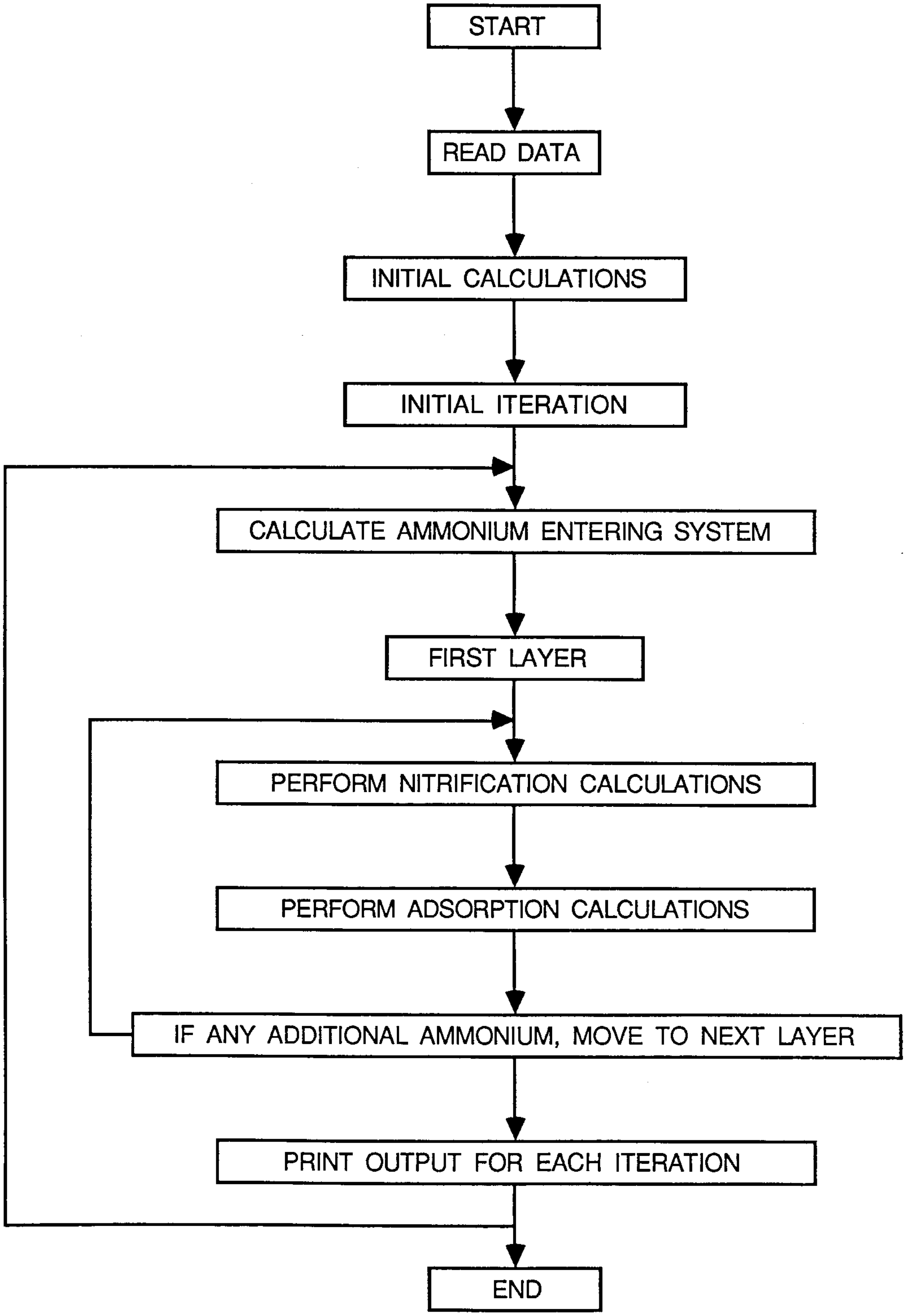
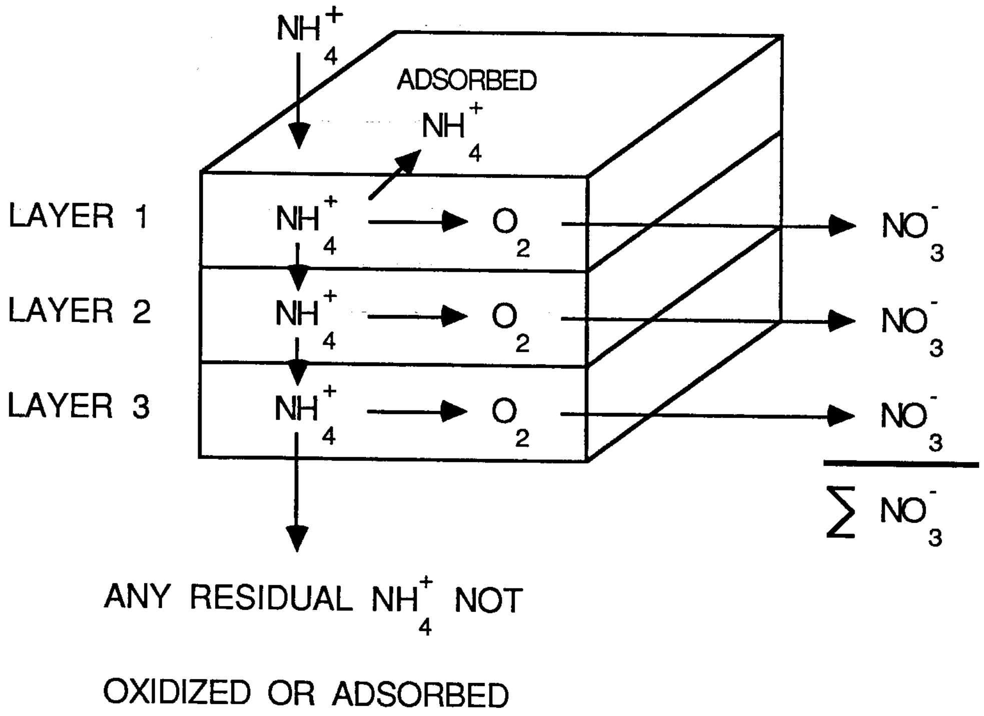


Figure 7. Flow Chart for Program NITRAD



Equation being solved in model:

$$NH_4^+ + 2\,O_2 \text{ --------> } NO_3^- + H_2O + 2\,H^+$$

Where from experimental data, 4.33 mg of O_2 are required to oxidize each mg of NH_4^+

Figure 8. Schematic Diagram for Program NITRAD

expressed as a concentration. The following equation shows the linear relationship between the adsorbed mass and that left in solution after equilibrium has been established at one particular temperature.

$$Ca = Kd * Cs$$

where:

Ca = amount of chemical adsorbed in mass adsorbed per mass dry weight of the adsorbent

Kd = Freundlich isotherm coefficient usually reported as ml/gm

Cs = amount of chemical in solution in mass per unit volume

It was first assumed that oxygen is the limiting factor in the nitrification process and it was also assumed that no denitrification occurs.

To explore the problem in the Widefield aquifer, this small scale model was applied to a representative column of aquifer material in the recharge area. A one square meter column was discretized into twenty layers, each three cm thick. The layers are thin because the nitrification process usually occurs in a very discrete area near the surface where oxygen is most plentiful. The maximum depth that ammonium travels was found to be about two feet from the influent surface. For each layer, values for the oxygen concentration and any previously adsorbed ammonium are required. The porosity, bulk density, and Freundlich isotherm values also need to be entered. Because this program was specifically written for the area including Colorado Springs and the Widefield aquifer, it will calculate the concentration of ammonium entering the recharge area given the flow and concentration of ammonium from the Colorado Spring's sewage treatment plant and the flow in Fountain Creek.

The model is capable of handling three basic situations:

(1) The stream/aquifer relationship which has not had any prior exposure to ammonium. In this case, both nitrification and adsorption would occur during the initial introduction of the sewage effluent to the aquifer material. Sewage discharge from Colorado Springs has been ongoing for many years, so this case does not pertain to the current problem.

(2) The stream/aquifer relationship that has been heavily contaminated with ammonium and continues to be subjected to recharge water with high concentrations of ammonium. The adsorptive capacity would probably be exhausted for a certain depth and only nitrification would occur. This case represents the current steady state situation seen in the area of recharge for the Widefield aquifer.

(3) Again a stream/aquifer system that has been heavily contaminated, but now has little or no additional ammonium entering. The nitrification process would still continue, desorbing the ammonium until all the ammonium had been removed from the depth of active nitrification. It was assumed that desorption occurs quickly, and a steady state nitrate production is reestablished based soley on the amount of incomming ammonium.

For each set of initial and boundary conditions, the model should be run to a steady state. During each iteration, the nitrification and adsorption are calculated sequentially for each layer. Beginning with the first layer, the recharge concentration of ammonium is subjected to nitrification limited by the available oxygen, and then any remaining ammonium in solution will either be adsorbed or moved to the next layer. The amount of ammonium nitrified is calculated first, then from the remaining ammonium in solution and the Freundlich isotherm values a maximum adsorbable amount of ammonium is calculated for that layer. If that maximum has not yet been reached then the remaining ammonium in solution will be adsorbed in that layer. If the maximum has been reached, the remaining ammonium will move to the next layer where again it will first be subjected to nitrification limited to the oxygen in that layer, and then to adsorption. After running the model to a steady state, concentrations for nitrate and remaining ammonium can be compared to observed values. A listing of the model, example data set, and computed output are given in Appendix A.

It was originally thought that the oxygen would limit the amount of nitrate produced. Subsurface oxygen concentrations are very difficult to quantify and were used as a calibration parameter. Nitrate and ammonium concentrations in the area of recharge were known both for the recharging water and in the groundwater. About 10-12 mg/l as N of ammonium was seen in the recharge water, while less than 1 mg/l as N was observed in the aquifer. Also in the aquifer in this area, about 9-11 mg/l as N of nitrate was noted (Edelmann and Cain, 1985). In order to produce this much nitrate, virually all the incomming ammonium had to be conservatively converted to nitrate. When oxygen was considered not to be limiting, the model produced results which closely matched the observed data. The model was run under the conditions described in the first situation, ie. with no previously adsorbed ammonium and a recharge water with a relatively high concentration of ammonium. Some ammonium appears to adsorb, but it was not quantitatively addressed. Desorption and subsequent nitrification runs were also made. Qualitatively it can be shown that adsorbed ammonium will serve as a supply for nitrification after the incomming ammonium supply has been stopped. However, quantitatively the model was not set up to answer questions that are time dependent.

From this small scale model it can be concluded that a conservative relationship may exist between the concentration of ammonium in the stream and the concentration of nitrate just inside the aquifer adjacent to the recharge area, ie. 10 mg/l as N of ammonium in Fountain Creek near the area of recharge represents 10 mg/l as N of nitrate in the aquifer at that boundary. Little ammonium is thought to be adsorbed on the aquifer material in the depth of active nitrification. Increases and decreases of ammonium at the recharge area will undoubtedly be affected by adsorption, but it is assumed that the effects are of short duration and an equilibrium between ammonium and nitrate is quickly reestablished. All of the observed ammonium in the area of recharge is converted to nitrate. With this relationship various scenarios involving the increases or decreases of ammonium in Fountain Creek were modeled to observe potential effects on the nitrate distribution in the aquifer.

CHAPTER 4

NUMERICAL MODEL

4.1 General Description of Model

This investigation used program CSU-GWTRAN, version FEM2D3.1, part of a groundwater modeling package developed at Colorado State University by Dr. James Warner. The program solves the flow equation and the transport equation sequentially for each time step. The solutions are based on the Galerkin finite element method with triangular elements and linear shape functions. Using finite elements irregular boundary areas may be accurately described. Aquifer parameters, such as porosity, saturated thickness, hydraulic conductivity, and initial concentrations may be heterogeneous over the model area to realistically match the field situation.

The flow equation being solved is the linearized Boussinesq equation (McWhorter and Sunada, 1977).

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W + \sum_{p=1}^{m} Q_p[d(x-x_p)d(y-y_p)]$$

Where: T = transmissivity, ft^2/day

h = potentiometric head, feet

S = storage coefficient

W = diffuse vertical recharge, ft/day

Q_p = point source or sink, ft/day

$d(x-x_p)d(y-y_p)$ = Dirac-Delta function

if $x \neq x_p$ or $y \neq y_p$, then function = 0

if $x = x_p$ and $y = y_p$, then function = 1

Regionally over the entire aquifer the average gradient is very small, being about 0.006. Local areas, particularly around wells may have some steep gradients but are not a significant influence. Horizontal flow is assumed with this equation, and except for local regions around wells, this appears to be the case in the Widefield aquifer.

The finite element model is segmented into a main program and 15 subroutines. The main program directs the execution in a sequential manner. The time increments are calculated and the subroutines for inputting, updating, and outputting data are called. The main program also calls the subroutines for integration of coefficient matrices, assembly and solution of equations, and mass balances for both flow and transport portions of the model.

The subroutines are incorporated as follow:

SUBROUTINE INPUT - loads all the data into the program needed to solve the problem - number of nodes, elements and boundary segments, boundary conditions, aquifer properties, initial potentiometric heads, initial chemical concentrations, and stresses on the aquifer.

SUBROUTINE UPDATE - allows for changes from the initially input stresses over the duration of the simulation, such as pumping rates and infiltration rates.

SUBROUTINE ELINTF - performs the integrations necessary to solve the flow equation.

SUBROUTINE MATFLOW - assembles and solves the flow equation using the point iterative successive over-relaxation (PISOR) technique.

SUBROUTINE MATSOL - assembles and solves the flow equation using Gaussian elimination.

SUBROUTINE WATBAL - calculates a water balance including all sources, sinks, and flows across the model boundaries.

SUBROUTINE ELINTT - performs the integrations necessary to solve the transport equation. To do this the groundwater velocities must first be determined from the calculated heads. The dispersion coefficients also need to be calculated from the dispersivity values. A minimum dispersivity is required in the model to insure stability.

SUBROUTINE MATCHEM - assembles and solves simultaneously the convection-dispersion equations using a block iterative Gaussian elimination technique.

SUBROUTINE CHEMBAL - calculates a chemical mass balance including all sources, sinks, flows across model boundaries, adsorbed and solution phases.

SUBROUTINE FLOWOUT - writes for designated times the potentiometric head map, a drawdown map, cumulative water balance, fluxes at nodes by node identification number, and fluxes at constant head nodes.

SUBROUTINE CHEMOUT - writes for designated times dissolved and adsorbed concentration maps, and a cumulative chemical mass balance.

SUBROUTINE OUTF - writes specified output parameters (head, concentrations, etc.) in compatible files for the input data set and various graphics packages.

SUBROUTINE MULT - multiplies a banded symmetric matrix by a vector; called by subroutines MATSOL, MATFLOW and MATCHEM.

SUBROUTINE UDU - solves a banded symmetric matrix equation by Gaussian elimination; called by MATSOL.

SUBROUTINE BSOLVE - solves a banded matrix by Gaussian elimination; called by MATCHEM.

More detailed discussions on the program and its development may be found in Warner (1981) and Warner and Walker (1986).

4.2 Main Data Sources

There is a vast supply of historical data available concerning the water resources of El Paso county. Pumping records have been kept by the individual water users as well as information from the previously cited USGS studies. In the early 1970's the Widefield aquifer water users realized that they needed to cooperate with one another to best utilize this water resource. The major users, Colorado Springs, Stratmoor Hills, the Pinello Ranch, the Venetucci Ranch, Security and Widefield, employed an engineering firm to monitor the aquifer for management reasons. Each user reports monthly pumpage by well to the consultant who in turn tabulates the total stresses on the aquifer. Records are also kept on diversion amounts to irrigation and recharge areas, and of water levels in various observation wells (personal communication, W.W. Wheeler and Associates, 1986). Chemical data came primarily from the USGS. Edelmann and Cain (1985) and Klein and Bingham

(1975) both reported nitrate concentrations from various wells in the Widefield aquifer.

4.3 Mesh Design

The finite element mesh consists of 369 node points and 640 elements (Figure 9). The boundaries were depicted to match the approximate extent of the region known as the Widefield aquifer contained within the Fountain Valley alluvium. The well field in this area contains 58 wells (Edelmann and Cain, 1985), 39 of which were significant stresses on the aquifer and were included in this study. The density of node points is greater along the well fields so that specific node points matched individual wells for more accurate pumping simulations. Table 4 contains the boundary conditions that were applied to the mesh as shown in Figure 9:

Table 4. Boundary Conditions for the Finite Element Mesh

Fountain Creek	Constant Head
Up Gradient Alluvium	Constant Head
Down Gradient Alluvium	Constant Head
Eastern Boundary Alluvium	Constant Flux
Western Boundary Alluvium	No Flow
Return Flow to the Creek	Constant Head

4.4 Input Data Used

The USGS estimated the water table for August 1982 (Edelmann and Cain, 1985). The average overall gradient along the Widefield aquifer was found to be 0.006. Water levels in several observation wells over the past 22 years have not varied much in an annual average sense. Therefore, the USGS estimates shown in Figure 10 are considered to be representative of the average water table.

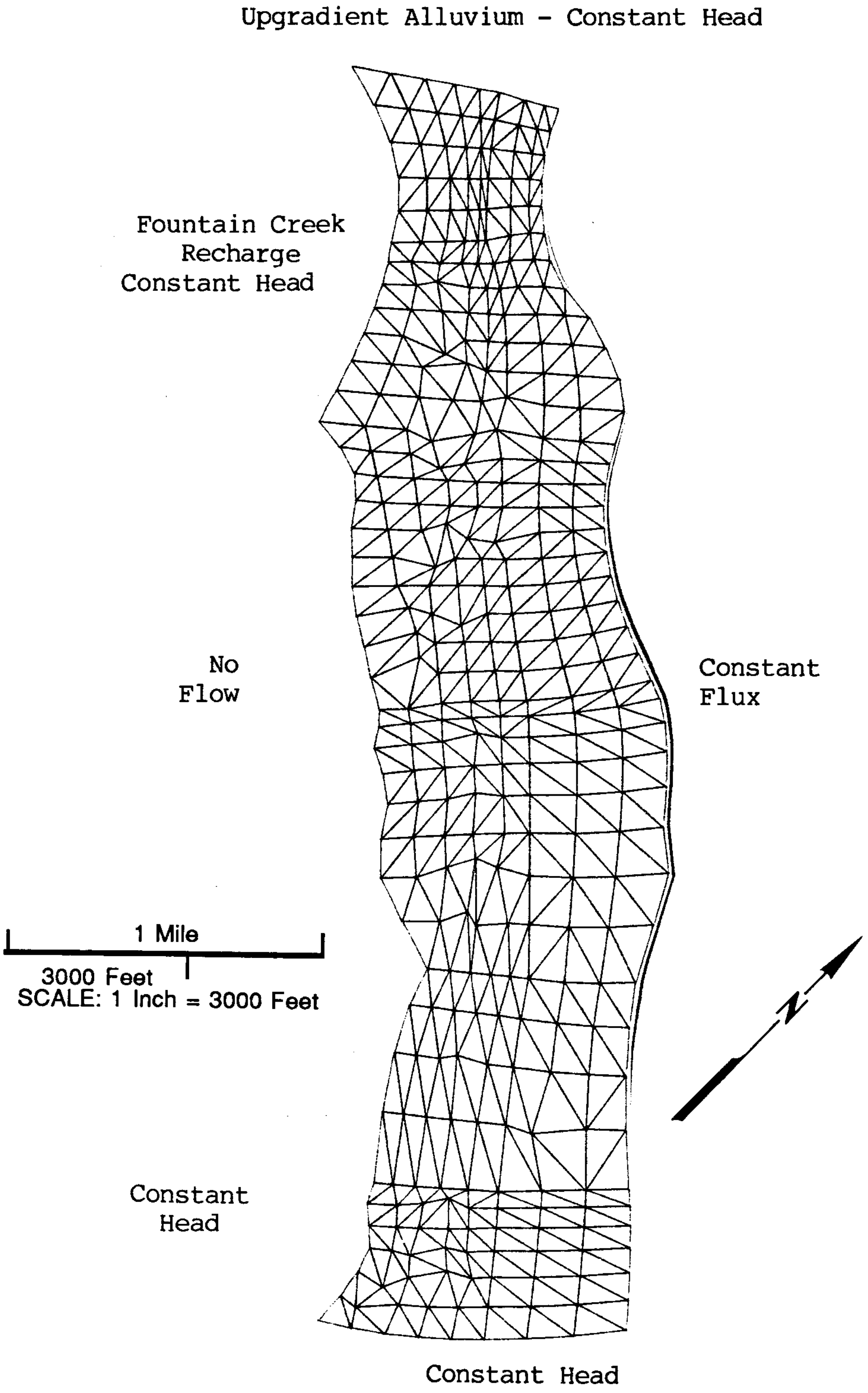


Figure 9. Finite Element Mesh and Boundary Conditions Used in the Model

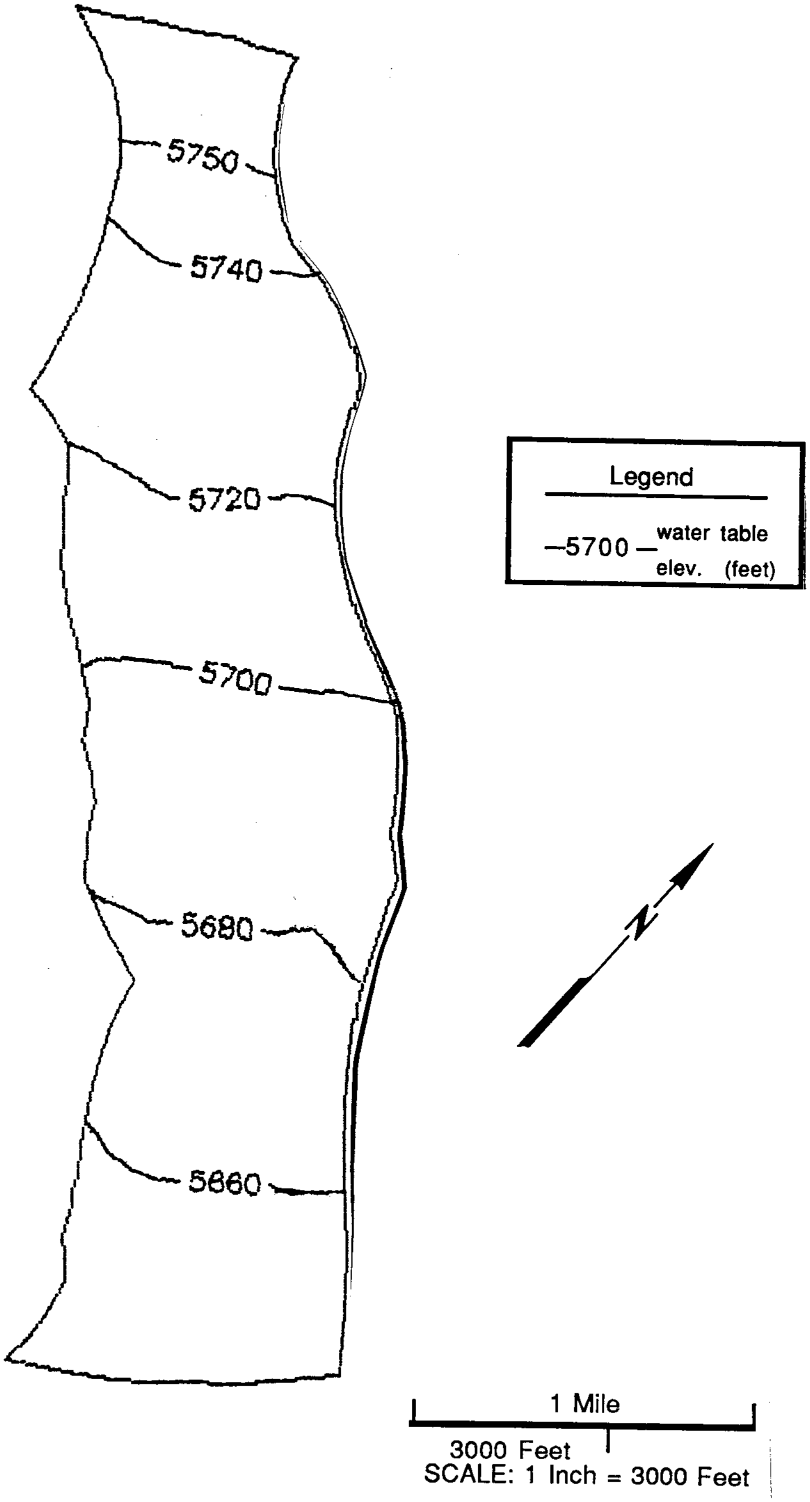


Figure 10. USGS Estimated Water Table for 1982

The pumping rates for the 39 wells were averaged over the year and assigned to the appropriate node points in gallons per minute (gpm). The data was compiled by W.W. Wheeler and Associates and verified by personal communications with the individual water users. The model was run using the 1986 pumping rates. These values may be considered average and probably represent future average pumping schemes, barring extreme drought. Table 5 lists the wells considered in this study and the average pumping rate for 1986. Figure 11 is an approximate location map for the wells.

Distributed recharge from precipitation alone is usually not significant due to the dry climate and evaporation potential. Total recharge from irrigation and precipitation can become significant and was included in this study. Table 6 shows the 6 sources of distributed recharge to the aquifer as identified by Edelmann and Cain (1985). Their locations are shown in Figure 12.

Existing nitrate concentration data were compiled onto two maps. Figures 3 and 4 show the nitrate distribution from data collected in 1972 (Klein and Bingham, 1975) and the nitrate data collected in 1982 (Edelmann and Cain, 1985). As mentioned before, in 1972 higher concentrations were seen in the south end of the aquifer, but by 1982 the concentrations increased over the entire aquifer, especially in the north end.

4.5 Calibration

Calibration of the model to match the available field data consists of two general procedures. The flow problem is calibrated by matching

Table 5. 1986 Average Pumping Rates for Wells in the Study Area (W.W. Wheeler and Associates, 1986)

WELL	1986 AVE PUMPING RATE (GPM)
Stratmoor Hills - 4	146
Stratmoor Hills - 5	23
Stratmoor Hills - 10	157
Pinello - 1	91
Pinello - 2	46
Pinello - 3	0
Pinello - 4	96
Pinello - 5	216
Pinello - 6	15
Pinello - 7	228
Pinello - 8	102
Pinello - 9	251
Pinello - 10	55
Pinello - 11	51
Pinello - 12	66
Pinello - 13	56
Pinello - 14	0
Security - 2	25
Security - 4	97
Security - 7	137
Security - 8	210
Security - 9	14
Security - 10	12
Security - 11	17
Security - 12	4
Security - 13	229
Security - 14	175
Security - 15	186
Security - 16	0
Security - 17	178
Ream - 1 (Security)	20
Ream - 2 (Security)	25
Widefield - 1	113
Widefield - 2	14
Widefield - 3	135
Widefield - 4	251
C - 36 (Widefield)	31
Venetucci - 1	0
Venetucci - 2	0

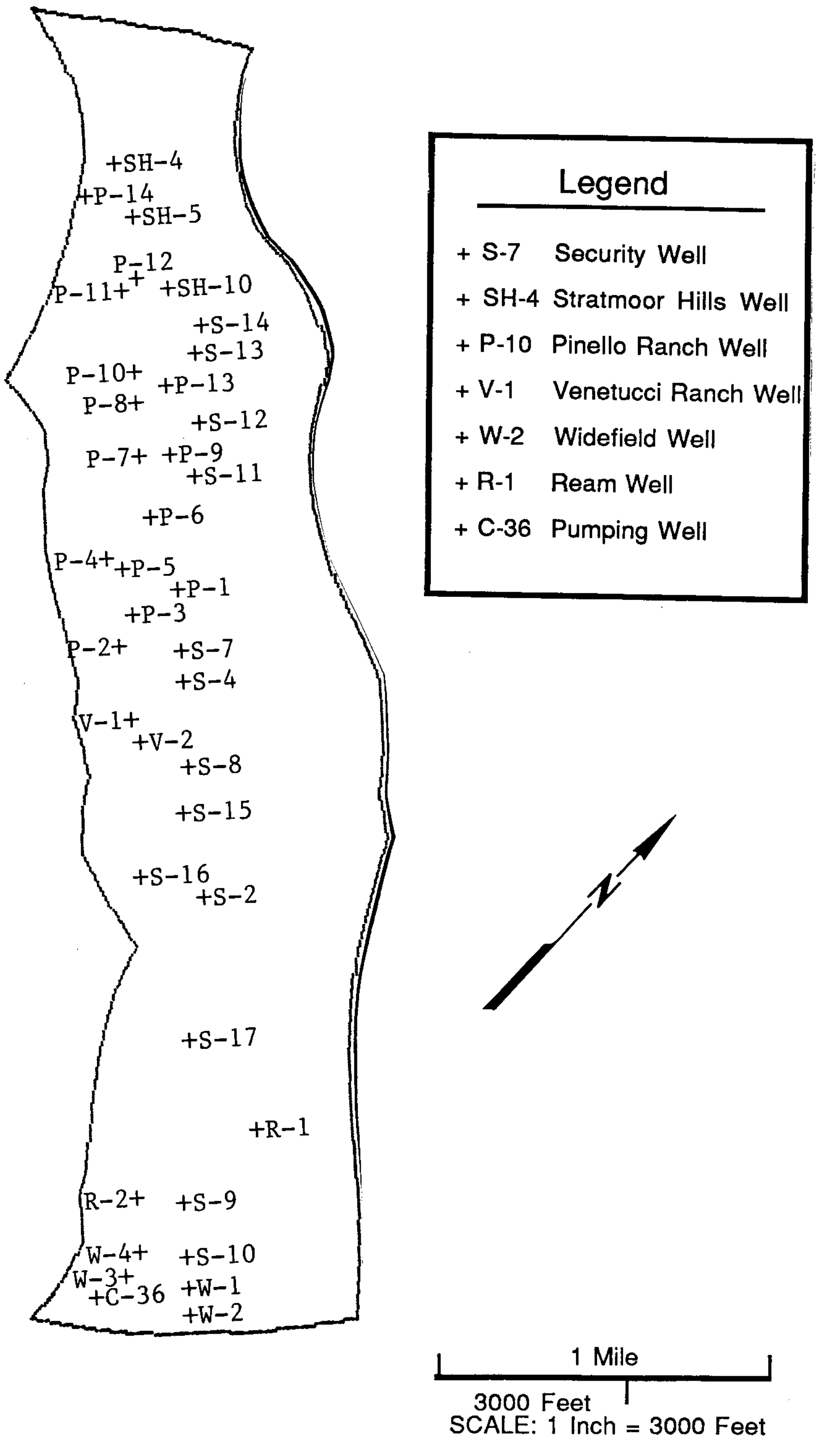


Figure 11. Location of the 39 Wells Included in this Study

Table 6. Distributed Recharge for the Widefield aquifer (Edelmann and Cain, 1985)

SOURCE	VOLUME OF WATER (AC-FT/DAY)	AREA (ACRES)	RECHARGE (FT/DAY)
Security lawn irrigation	2.39	299	0.0080
Widefield lawn irrigation	0.38	136	0.0028
Pinello Ranch irrigation	2.78	96	0.0290
Venetucci Ranch irrigation	0.22	159	0.0014
Camden Ranch irrigation	0.36	31	0.0108
Pinello recharge ponds	0.49	14	0.0342

the calculated potentiometric heads to field data for steady state and transient conditions. Subsequently the transport problem is calibrated to approximate the current solute concentrations. The head values to be used are from 1982 and are based on the USGS report by Edelmann and Cain (1985). The nitrate concentration values to be calibrated against are the 1982 - 1987 data, based on the USGS report by Edelmann and Cain (1985) and personal communications with Pat Edelmann (1987). Once the model has been calibrated to the field data, predicative simulation runs can be made under varying conditions.

There are several assumptions which have been incorporated into the modeling procedure. It is very important that these assumptions be kept in mind because they represent potential sources of error. It was assumed that the seasonal fluctuations of the water table could be ignored and an average annual water table was used. Pumping and recharge rates were averaged to yearly values also. Greater pumping rates actually occur in the summer due to the greater demand. Recharge is also probably higher in the spring and summer due to runoff, precipitation and irrigation. Since the details of the drawdown at

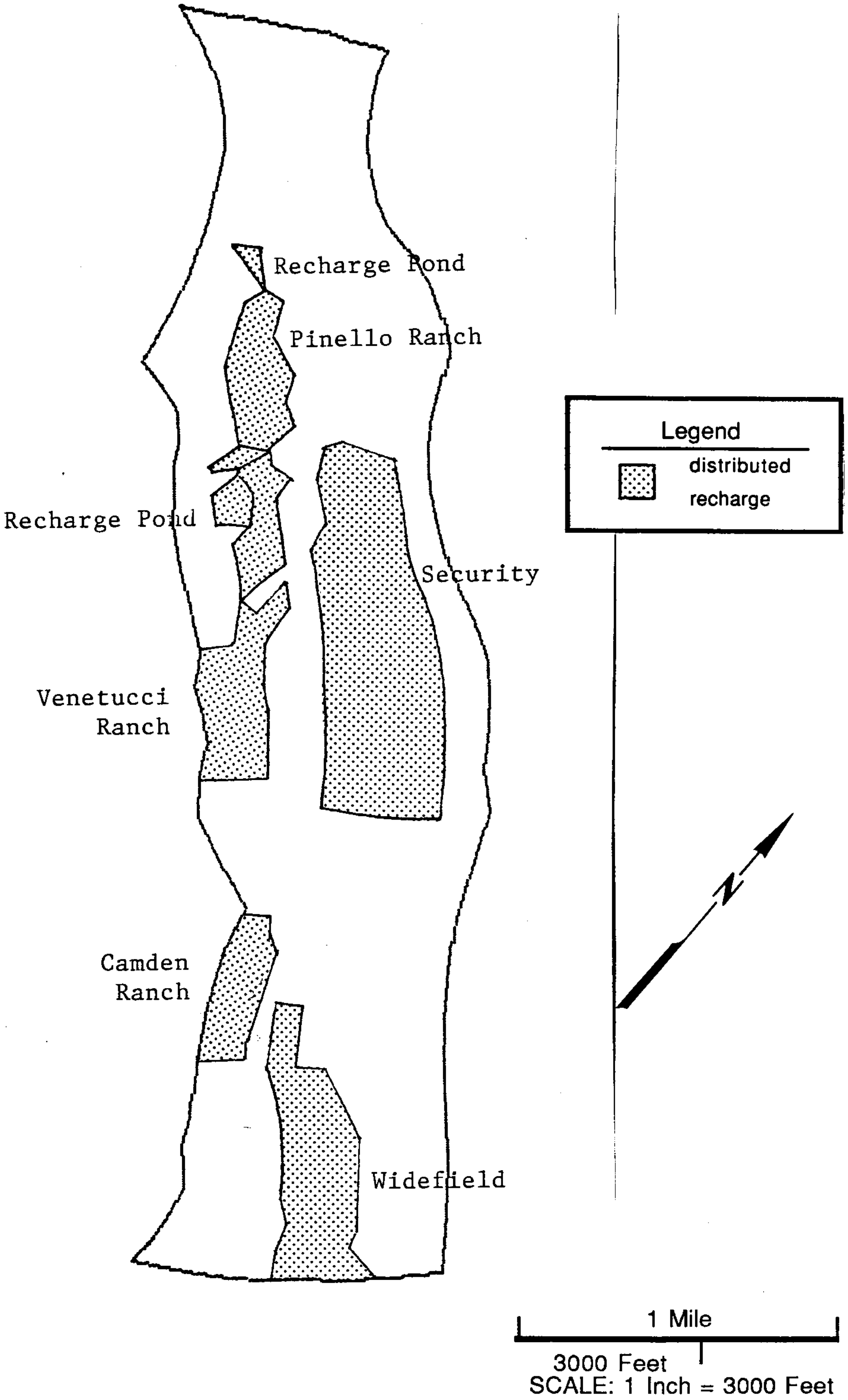


Figure 12. Locations of the Distributed Recharge Areas Included in this Study

various locations are not critical to the nitrate transport problem, yearly averages for the pumping and recharge are used.

Several assumptions were also made to solve the nitrate transport problem. Because nitrification is converting ammonium to nitrate in the immediate vicinity of recharge from Fountain Creek, a constant nitrate concentration was introduced into the model in this area. As demonstrated by the companion model it was assumed that the observed concentration of ammonium in Fountain Creek in the area of recharge reflects the concentration of nitrate entering the aquifer. Nitrate was assumed to be non-adsorptive and non-reactive. Edelmann and Cain (1985) found dissolved oxygen levels in the Widefield aquifer to be high enough that little denitrification probably occurs.

4.5.1 Flow Calibration

Results of the flow calibration were found to be quite satisfactory for nitrate transport simulations. Head values and transmissivities were adjusted until the water table closely matched a USGS prepared water table for August 1982 (Figure 10). The average error between the calibrated heads and the USGS heads at 61 node points on the contour lines was 4.5 feet. The percentages of flow calibration error are listed in Table 7. The maxumim error was 14 feet. During calibration the head values near the area of recharge were raised artificially high to produce the required recharge amount. Similarly, the heads along the downgradient boundary were lowered to maintain an appropriate discharge. Not including these boundaries, the overall calibrated water table gradient was the same as the USGS estimate of 0.006. The final calculated water table appears in Figure 13, and the saturated thicknesses are shown in Figure 14.

Table 7. Flow Calibration Error

PERCENT OF NODES WITH LESS THAN STATED ERROR AMOUNT	ERROR AMOUNT (feet)
36%	± 2
51%	± 4
70%	± 6
93%	± 8
100%	± 14

The boundary fluxes were the most important factor in the model calibration because it is these fluxes which bring contaminants into the aquifer and subsequently remove them. The USGS fluxes are the yearly average for 1982. The total error for inlows to the aquifer was 10% and the total error for outflows from the aquifer was less than 1%. The largest errors were seen in the Fountain Creek recharge, 14% error, and in the down gradient flow, 45% error. It is important to note that 1982 was a particularly wet year and the lower model calibrated recharge from Fountain Creek may be more realistic for long simulations. The fluxes, both calculated and the USGS values, are shown in Table 8. The USGS data show greater inflows for 1982, a particularly wet year. The model was run with a larger value for total pumpage than 1982 to be more realistic of future situations. The flow calibration is considered to be quite adequate to model nitrate transport.

4.5.2 Nitrate Calibration

The nitrate concentration distribution was calibrated to approximate current (1982-1987) observed nitrate concentrations in the

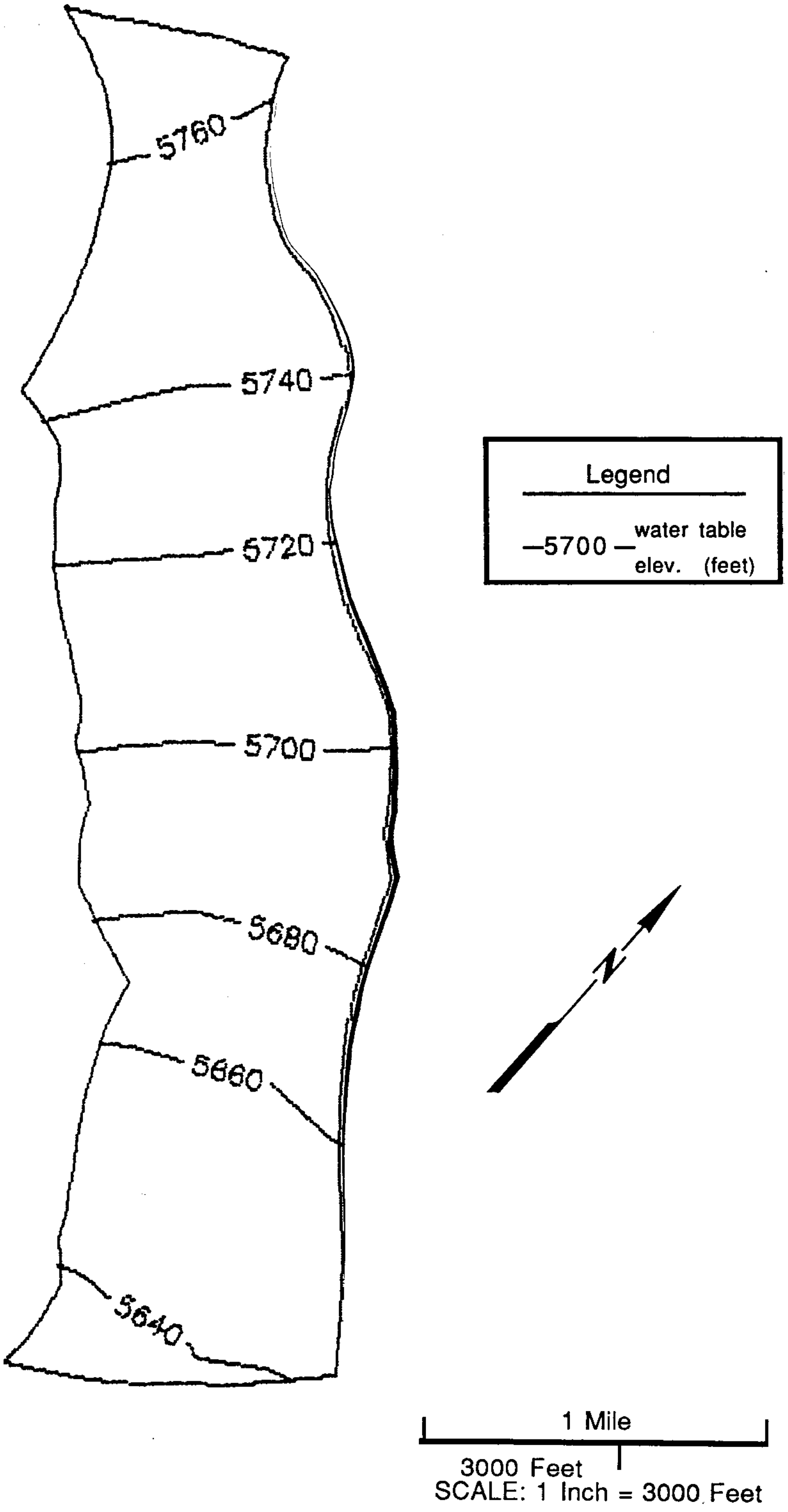


Figure 13. Calibrated Water Table

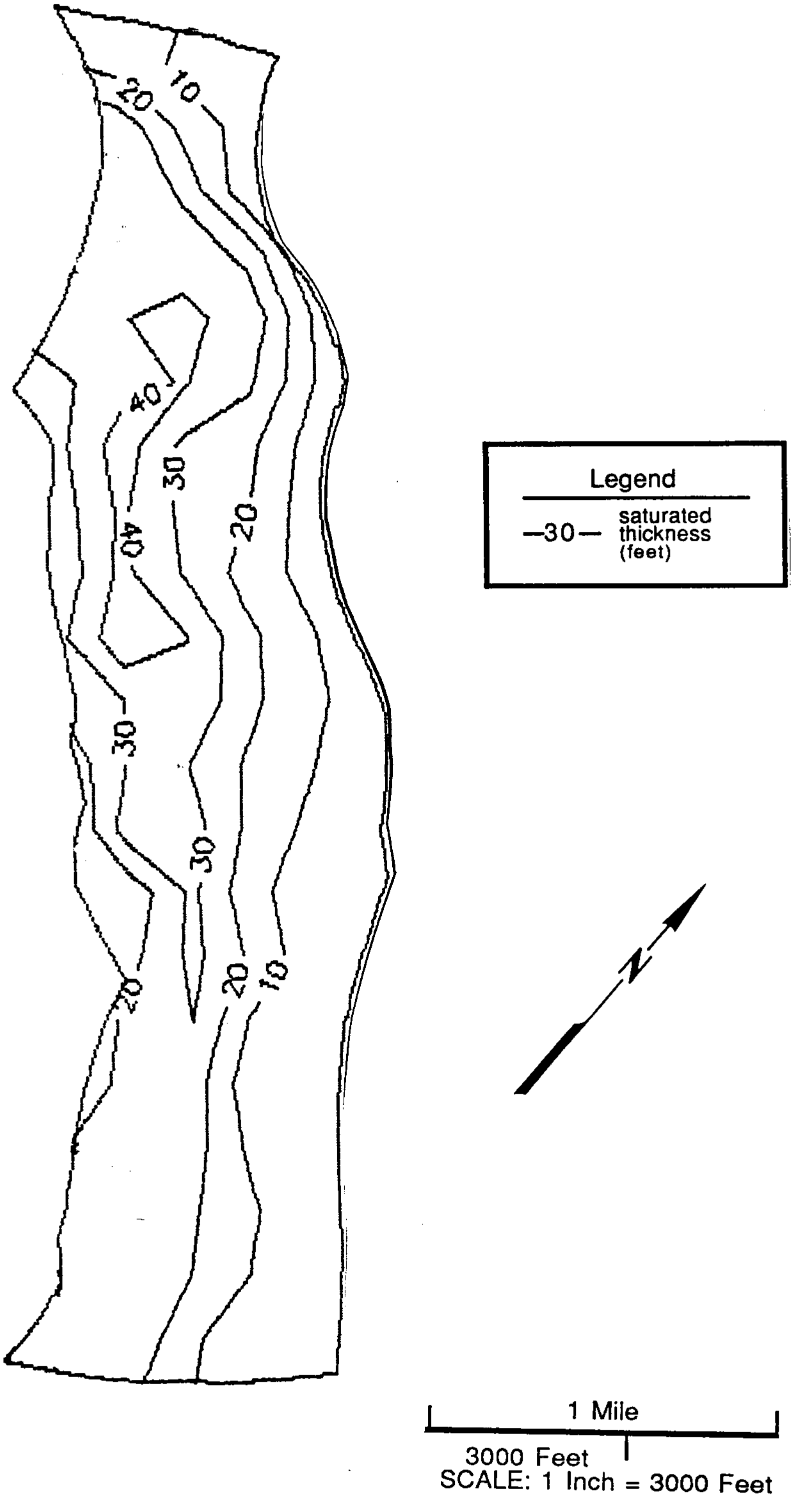


Figure 14. Saturated Thicknesses in the Widefield Aquifer

Table 8. Water Fluxes, USGS (1982) and Model Calibrated

NAME OF INFLOW	USGS FLUX (1982) (gpm)	MODEL FLUX (gpm)
Fountain Creek Recharge	4900	4200
Fountain Creek Alluvium	430	420
Eolian Deposits	570	580
Total distributed recharge	1100	1100
NAME OF OUTFLOW	**USGS FLUX (1982) (gpm)**	**MODEL FLUX (gpm)**
Loss to Fountain Creek	1400	1500
Downgradient flow	1500	820
Total pumpage	3300	3900

aquifer. Nitrate enters the aquifer primarily from three sources: Fountain Creek recharge, Fountain Creek alluvial recharge, and distributed recharge. The intial concentration over the entire aquifer was set to a background concentration (1.5 mg/l as N). Different input nitrate concentrations at the Fountain Creek Boundary were run with steady state flow until the change of concentration on the average was very small (less than 0.1 mg/l as N over 6 months). The resulting distribution was compared to the observed concentrations. The boundary conditions which produced the best match to the current distribution are shown in Table 9.

The model calibrated nitrate distribution is shown with the current observed nitrate data in Figure 15. The boundary coditions which produced such a close match are fairly realistic values. The concentration of ammonia and nitrate combined in Fountain Creek near the

Table 9. Nitrate Boundary Conditions for Calibrated Nitrate Distributions.

RECHARGE SOURCE	NITRATE CONCENTRATION
Fountain Creek recharge	10 mg/l as N
Fountain Creek alluvium	8 mg/l as N
Security lawn irrigation	8 mg/l as N
Widefield lawn irrigation	8 mg/l as N
Pinello Ranch irrigation	8 mg/l as N
Venetucci Ranch irrigation	8 mg/l as N
Camden Ranch irrigation	8 mg/l as N
Pinello Ranch recharge ponds	8 mg/l as N

area of recharge averaged 10 mg/l as N, and ranged from 5 to 14 mg/l as N for 1981 and 1982 (Edelmann and Cain, 1985). Wells in the upgradient alluvium tended to show higher concentrations of nitrate with an average of 9 mg/l as N. Because recharge from the alluvium is only one tenth of the recharge from Fountain Creek, no significant difference was seen if 6 mg/l as N or 8 mg/l as N was used at the Fountain Creek alluvium boundary. All the water that is involved in distributed recharge comes from either the Widefield aquifer or Fountain Creek itself. This recharge water allready has an initial nitrate concentration, and may pick up additional nitrate from fertilizers applied to crops and lawns.

Calibration of solute distributions is subject to many sources of error. The actual field data for 1982 shown in Figure 4 may vary significantly depending on the time of year, the type of analytical test, and the sample collecting procedure. To generate an exact duplicate of the observed nitrate distribution would not be possible. The procedure described above, using all the known nitrate sources with appropriate concentrations, did produce reasonable results. Using the 35 node points which represent the 39 wells used in this study, the

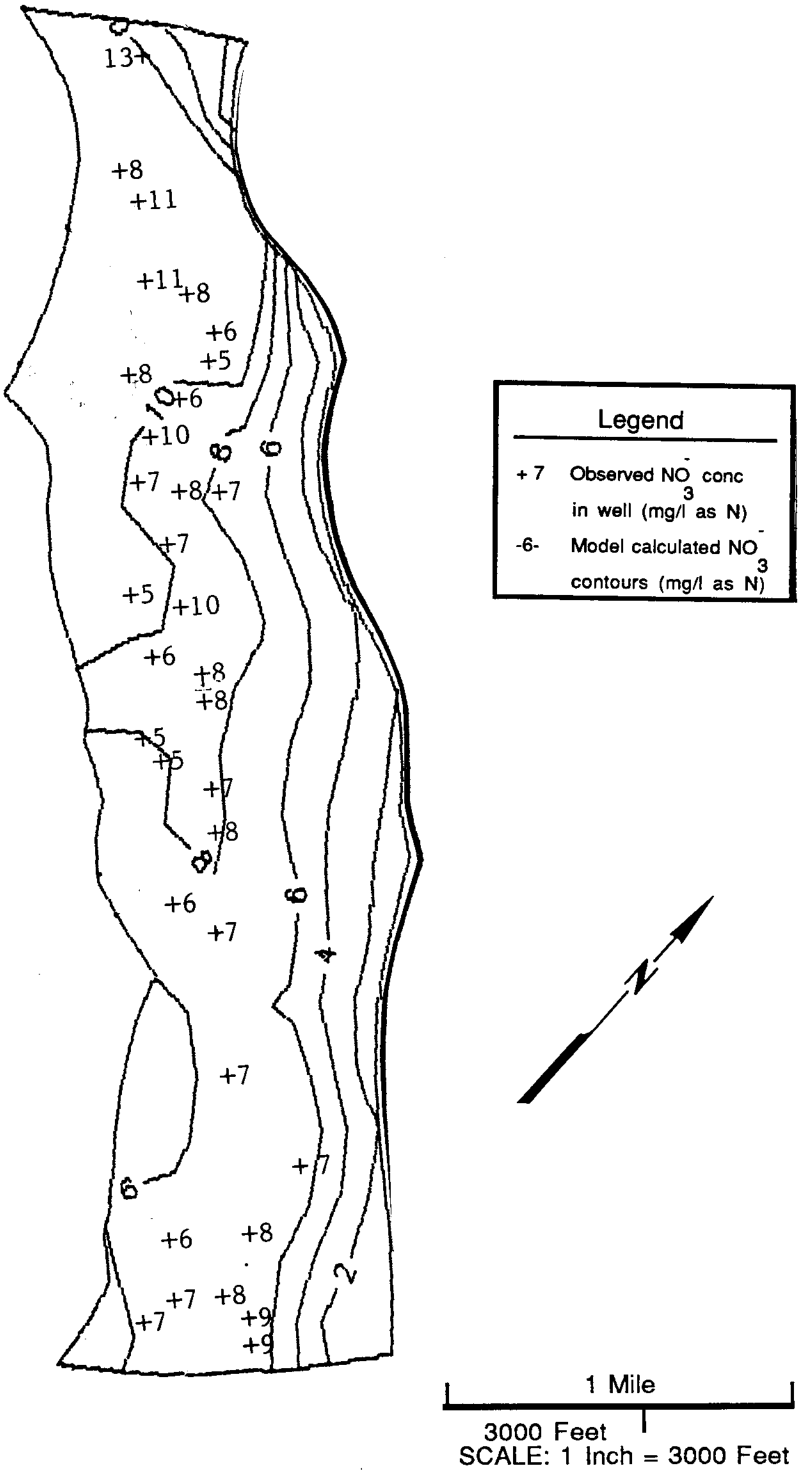


Figure 15. Calibrated Nitrate Distribution and Current (1982) Observed values

average error was 2 mg/l as N. The maximum error at any one well was 6 mg/l as N. As with the flow calibration the largest errors were encountered near the area of recharge. The percentages of nitrate calibration error are listed in Table 10.

The calibrated nitrate distribution and water table subsequently became the initial conditions for the predictive simulations.

Table 10. Nitrate Calibration Error

PERCENT OF NODES WITH LESS THAN STATED ERROR AMOUNT	ERROR AMOUNT (mg/l as N)
26%	± 1
66%	± 2
74%	± 3
89%	± 4
97%	± 5
100%	± 6

CHAPTER 5

SIMULATIONS

5.1 Potential nitrate increases if no changes are made in effluent discharge practices.

Using the calibrated water table and nitrate distribution, several simulations were run depicting increases in flow from the Colorado Springs sewage treatment plant. Increased flow from the plant would in turn increase the concentration of ammonium near the recharge area. Currently the sewage treatment plant is discharging about 30 MGD (46 cfs) which contains about 20 mg/l as N of ammonium. It was assumed that the ammonium concentration from the plant will remain the same and that the base flow in Fountain Creek contains no ammonium. The average base flow that was used for Fountain Creek was 40 cfs. The concentration of ammonium in the area of recharge after dilution in Fountain Creek was calculated with the following formula:

$$\text{Concentration in recharge area} = \frac{Q_{STP} * C_{STP}}{Q_{STP} + Q_{FC}}$$

Where:

Q_{STP} - Flow from the sewage treatment plant

Q_{FC} - Flow in Fountain Creek

C_{STP} - Concentration in the sewage effluent

If the population continues to grow at a rapid rate, then as many as 800,000 people may live in the Colorado Springs area by the year 2000 (Livingston, Klein & Bingham, 1976a). The amount of sewage produced from a population of this size could cause a nitrate concentration increase to about 16 mg/l as N in the area of recharge. Table 11 contains various ammonium concentrations that could recharge the aquifer under different flow conditions. As explained in the chapter on nitrification, an increased ammonium concentration in the recharge area represents an increased nitrate concentration entering the aquifer. Because of the small size of the study area and the rapid travel times in the aquifer, steady state conditions are achieved in about two years after changing boundary conditions. The system was very sensitive to even slight changes of the incoming nitrate concentrations. Four gradual nitrate concentration increases were tested simulating increased effluent discharges from the treatment plant. The author would like to caution the reader that the model predicted concentrations contain several assumptions and are only suggestive of possible outcomes.

Table 11. Various Ammonium Recharge Concentrations.

YEAR	POPULATION	Q of sewage MGD	Q of sewage cfs	Q in creek cfs	RECHARGE CONC mg/l
1986	265,700	30	46	40	11
1990	345,000	39	60	40	12
1995	530,000	60	93	40	14
2000	800,000	90	140	40	16
2000	800,000	90	140	20	18

A slight increase from 10 mg/l as N to 12 mg/l as N is shown in Figure 16. This could be the result of increasing the flow from the treatment plant to about 39 MGD. In the steady state nitrate

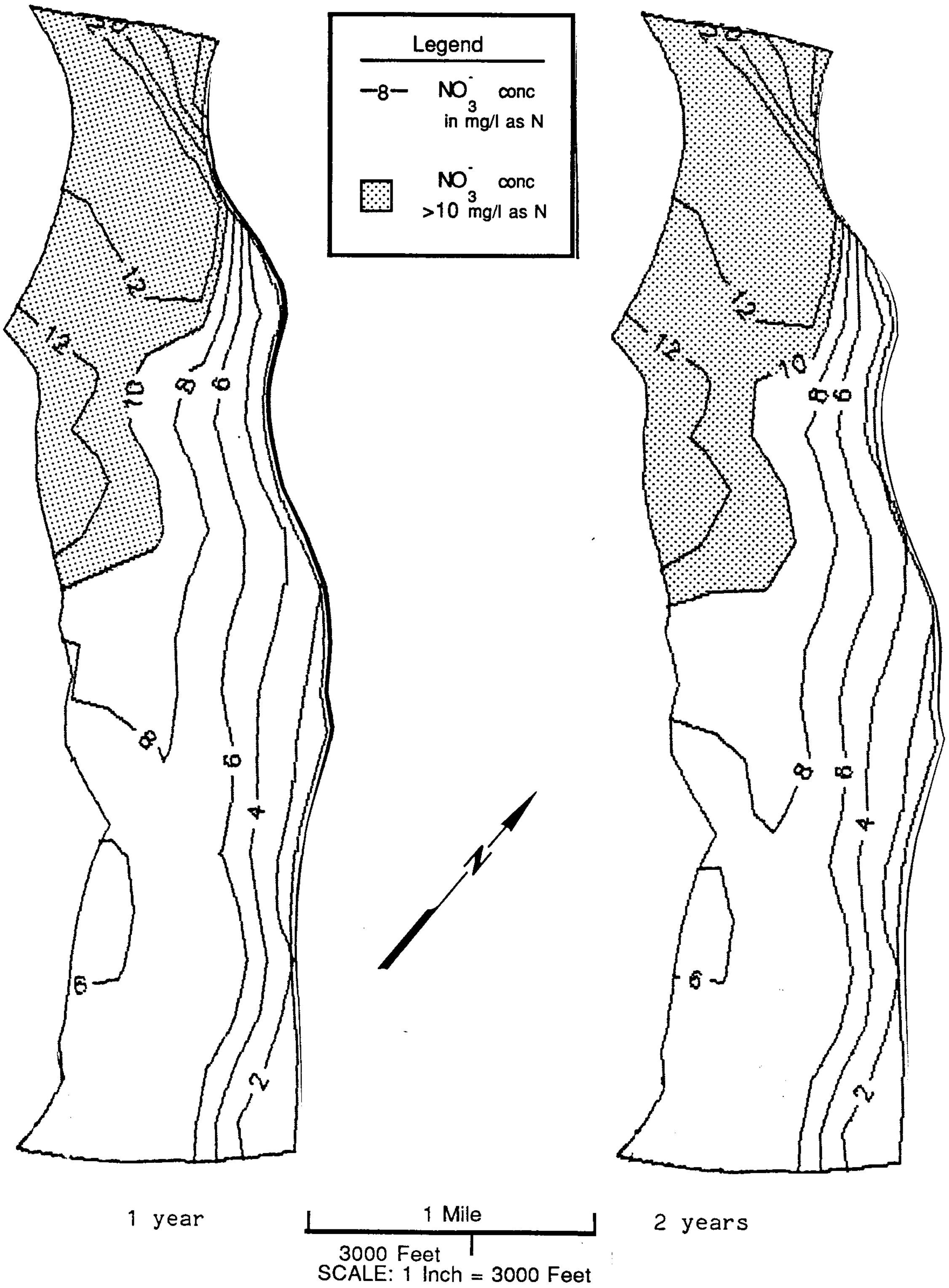


Figure 16. Nitrate Distribution with 12 mg/l as N Recharging from Fountain Creek

distibution at the end of two years, the 10 mg/l as N contour has moved down-gradient and now encompasses the majority of the Pinello well field. As mentioned earlier most of the water pumped from the Pinello wells is imported to Colorado Springs. In this case, the water could be diluted with other water supplies so the nitrates would probably not be a problem. The three Stratmoor Hills wells would appear to suffer the most with nitrate concentrations approaching 12 mg/l as N. The remainder of the aqufier seems to experience slight increases in concentrations, but in general remains below the drinking water standard. With the exception of the Stratmoor Hills wells, an annual average increase in the recharging ammonium concentration to 12 mg/l as N probably would not have a detrimental effect on the water quality in the Widefield aquifer.

If the sewage treatment plant increased flow to 60 MGD, the approximate maximum capacity of the plant, then the recharging concentration would again increase to 14 mg/l as N. Higher nitrate concentrations would continue to move down-gradient (Figure 17). After two years, the 10 mg/l as N contour covers all of the Pinello wells and over half of the Security wells in addition to the Stratmoor Hills wells. Concentrations continue to increase in the up-gradient part of the aquifer near the area of recharge. Although the down-gradient portion of the aquifer has not experienced any nitrate concentrations over the drinking water standard, concentrations around 8 mg/l as N are seen in several wells. An increase such as this on an annual basis begins to show signs of degrading the water quality.

To this point it was assumed that the average flow in Fountain Creek is 40 cfs. If this were to decrease to 20 cfs, the dilution

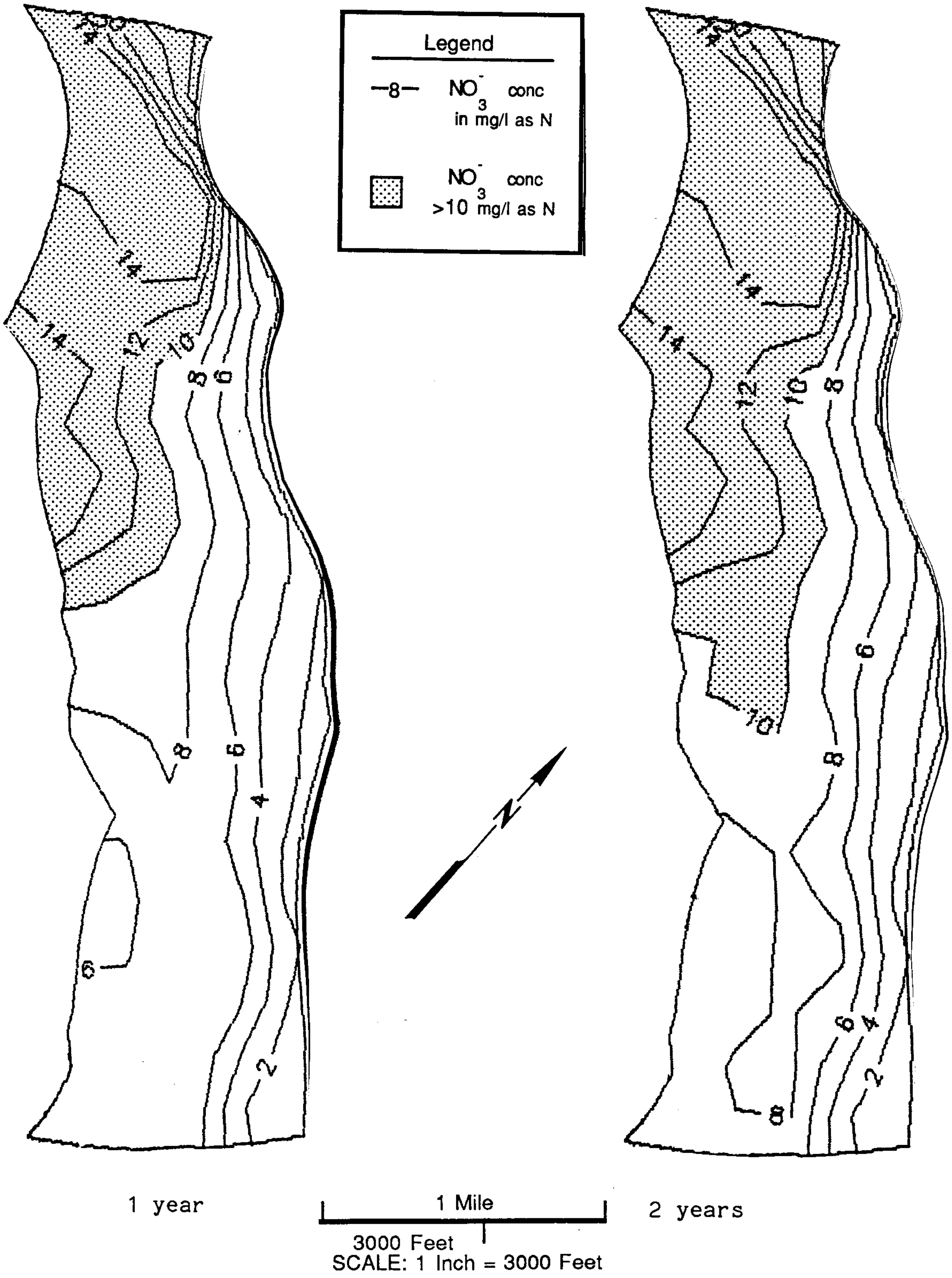


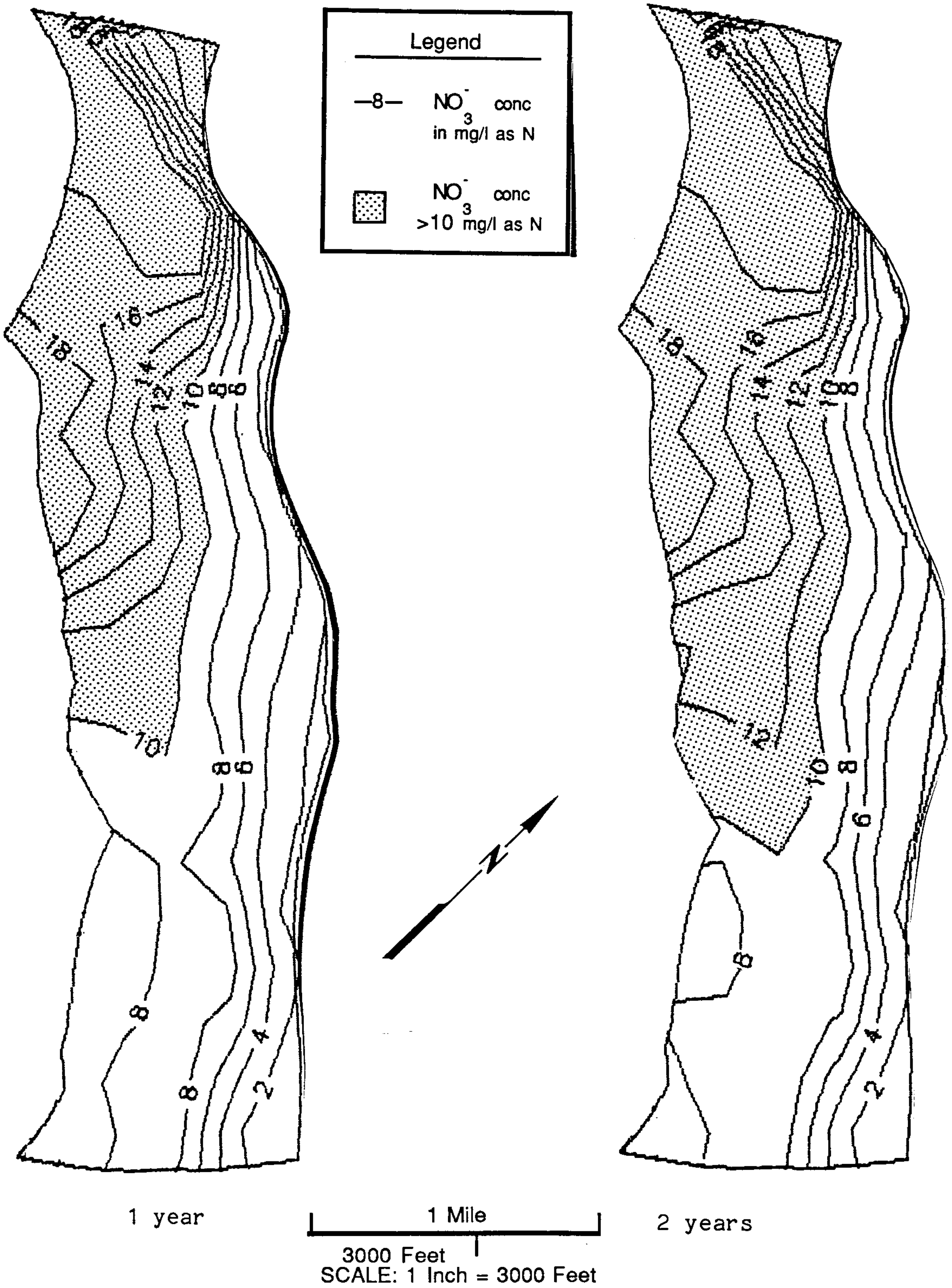
Figure 17. Nitrate Distribution with 14 mg/l as N Recharging from Fountain Creek

potential would accordingly be decreased and the ammonium concentration in the area of recharge would be near 18 mg/l as N. More than two-thirds of the aquifer could potentially be contaminated with nitrate concentrations over the drinking water standard (Figure 18). The Pinello wells, Stratmoor Hills wells and most of the up-gradient Security wells would then experience nitrate concentrations between 12 and 18 mg/l as N. This water would probably not be useable for consumption without some kind of treatment or dilution to reduce the nitrate concentration.

Figure 19 depicts an absolute worst case scenario. The recharge water contains 22 mg/l as N of ammonium representing a high concentration even for undiluted effluent. The steady state nitrate distribution shows serious degradation of the water quality. It appears that only the four Widefield wells near the down-gradient boundary would yield water having nitrate concentrations below the drinking water standard. These results do not favor the use of a recharge scheme for conventionally treated wastewater. Without any nitrogen removal prior to recharge, high nitrate concentrations are the most likely outcome.

5.2 Effects of nitrogen removal prior to discharge

It is important to know if the aquifer, once polluted, could be restored to safe drinking water levels. If Colorado Springs were to treat their wastewater to remove ammonium, the ammonium concentrations in the area of recharge would decrease significantly. An ideal situation is shown in Figure 20 where the recharging concentration has been reduced to 1 mg/l as N. Assuming that there is an insignificant



1 year

2 years

Figure 18. Nitrate Distribution with 18 mg/l as N Recharging from Fountain Creek

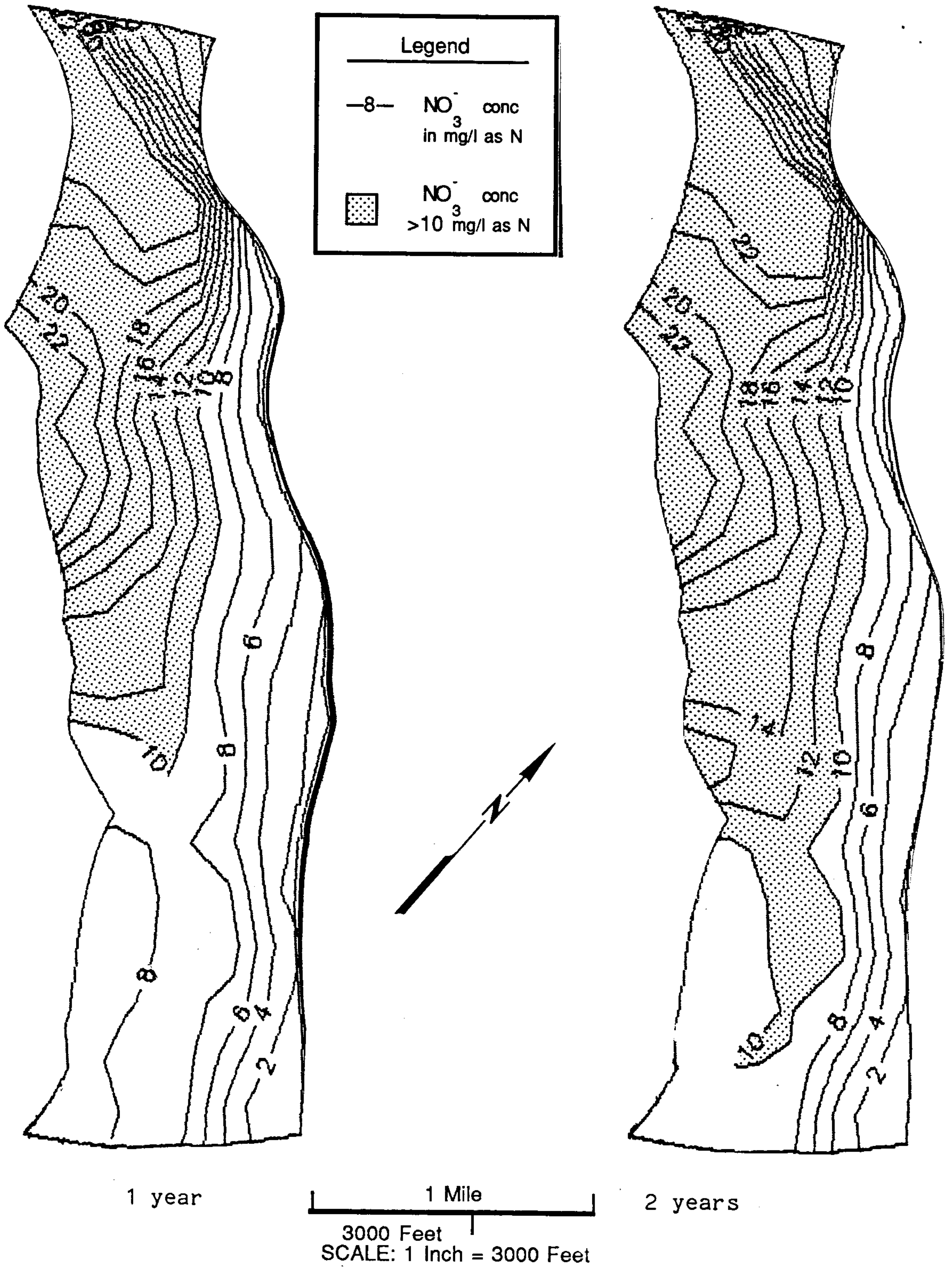


Figure 19. Nitrate Distribution with 22 mg/l as N Recharging from Fountain Creek

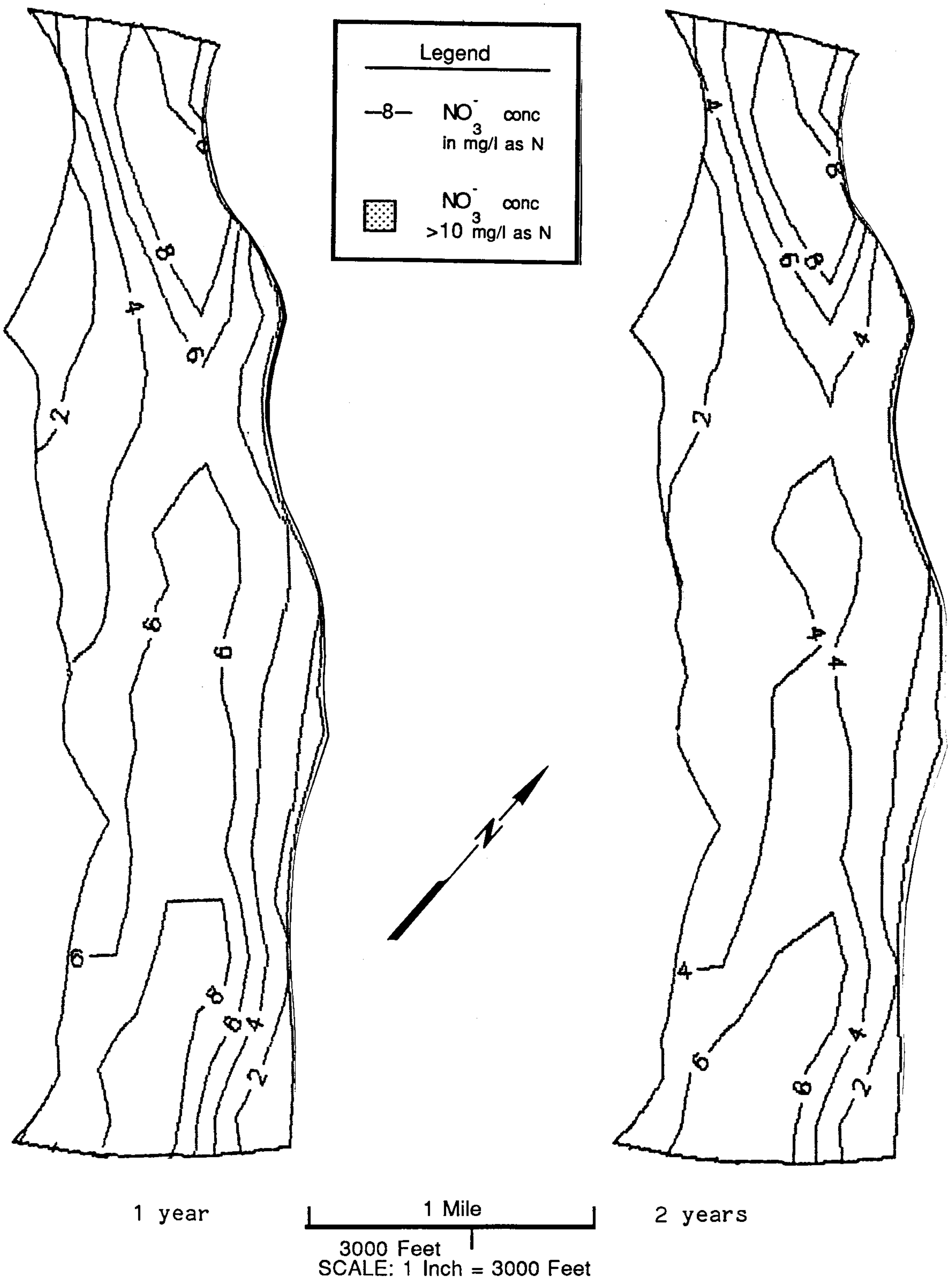
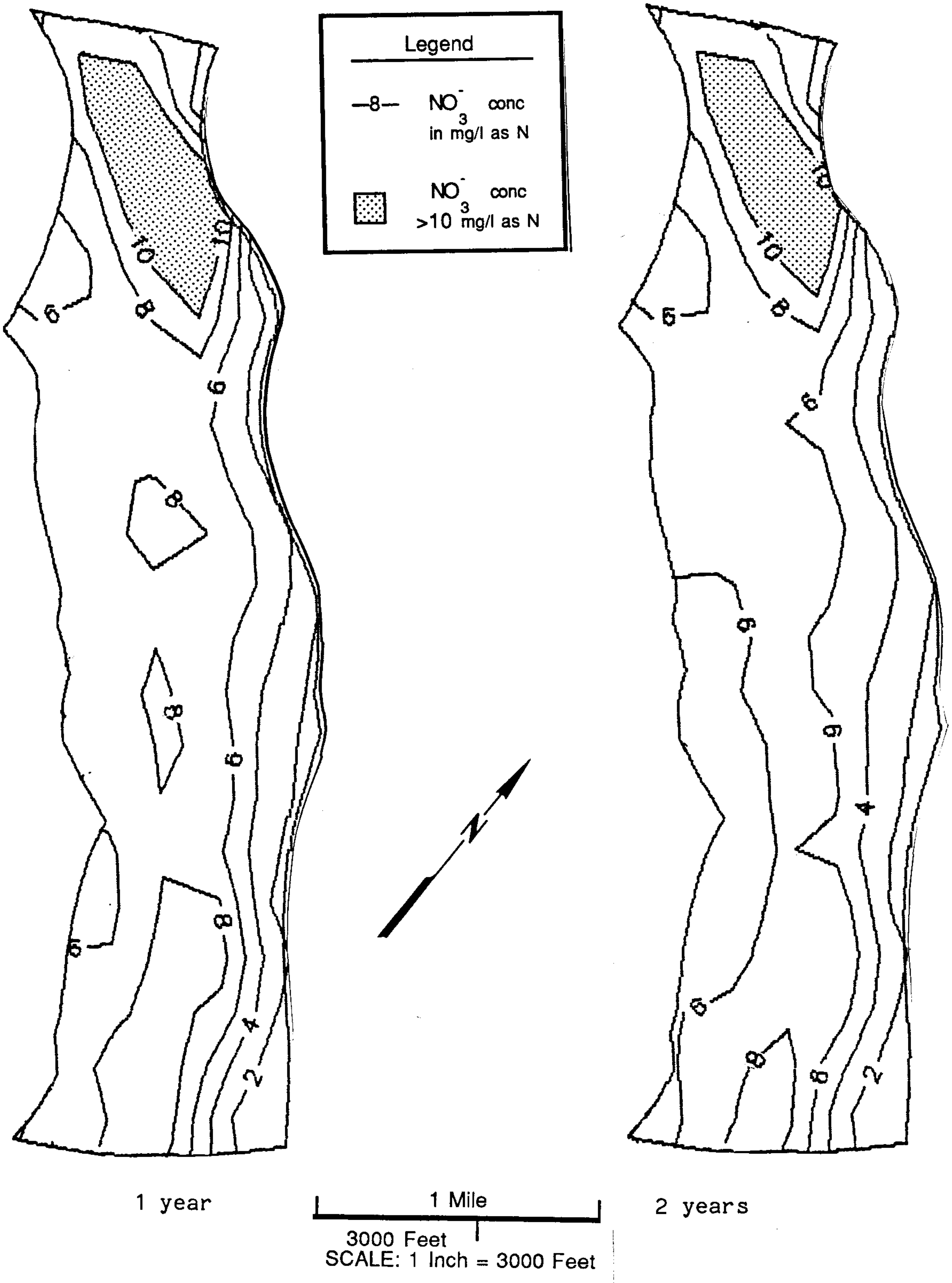


Figure 20. Restoration of Current Conditions with 1 mg/l as N Recharging from Fountain Creek

amount of adsorbed ammonium stored in the aquifer, current nitrate concentrations could drop quickly to much lower levels. As demonstrated with the companion nitrification model, only a shallow depth of less than two feet is subjected to active nitrification. The amount of ammonium adsorbed in this layer will be nitrified quickly and should not be a future source of ammonium for nitrification. With recharge water containing only 1 mg/l as N, nitrate levels at steady state in the Pinello well field dropped to less than 4 mg/l as N. Stratmoor Hills and Security wells dropped to below 6 mg/l as N. The effects of such ammonium free water could be very beneficial.

It may be extremely costly and impractical for the treatment plant to ensure recharge concentrations of only 1 mg/l as N. A more practical solution would be to reduce the ammonium in the effluent so about 6 mg/l as N is present in the recharge area (Figure 21). The steady state nitrate distribution after a two year simulation also predicts that the concentrations drop to safe levels, below 8 mg/l as N in all the well fields. This simulation seems to show very positive results because reducing the ammonium concentration to 6 mg/l as N in the area of recharge could be achieved by either partial ammonium removal at the treatment plant or by dilution.

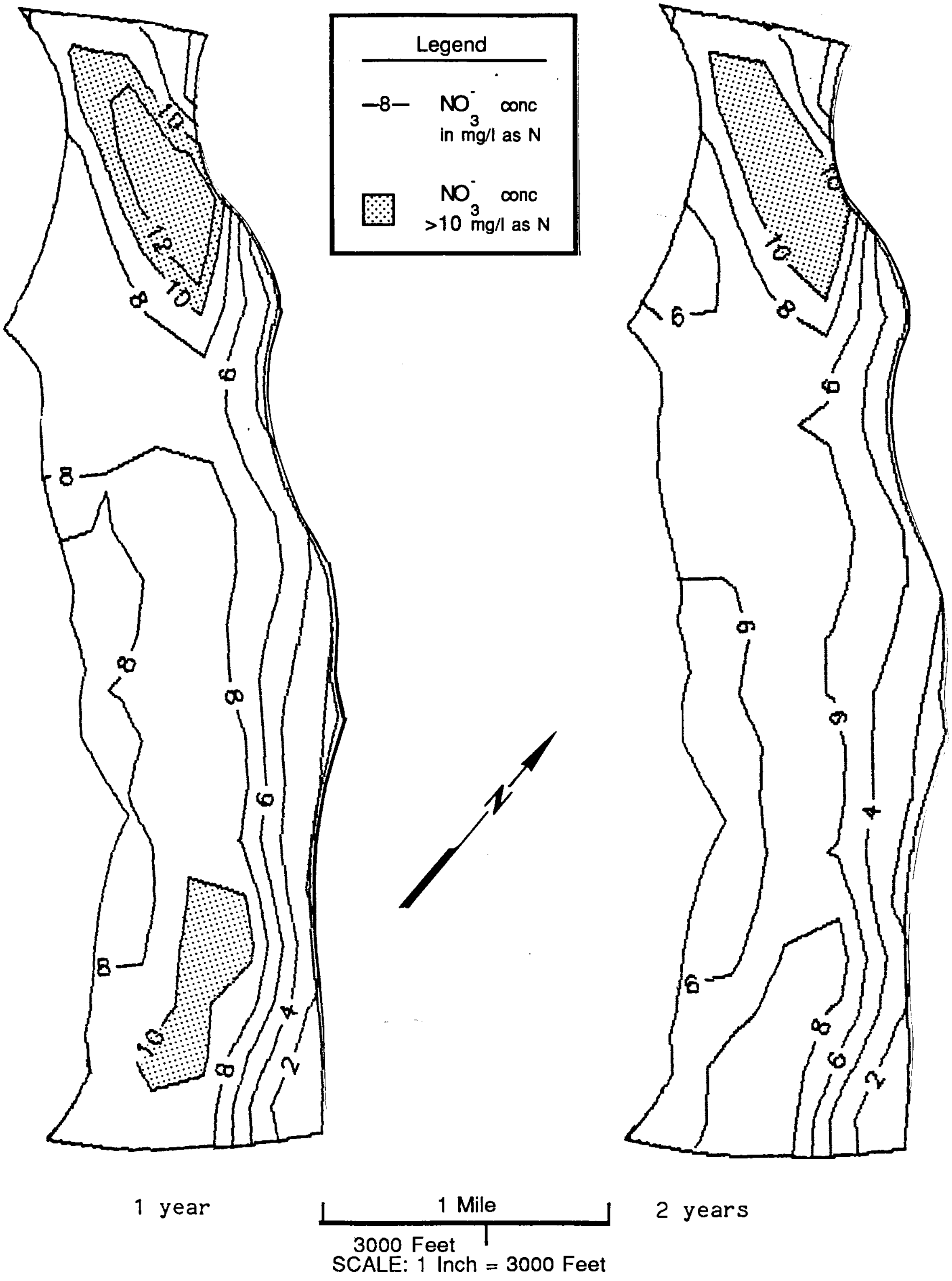
A long term situation leading to extremely polluted conditions could arise if no action was taken to reduce nitrogen concentrations. Assuming that the previously discussed "worst case" scenario were to happen, would a nitrogen reduction scheme still have any beneficial effects? Figure 22 shows the results of reducing the nitrate recharge from 22 mg/l as N to 6 mg/l as N. Again, after two years, when a steady state nitrate distribution has been reached, the recharging water



1 year

2 years

Figure 21. Restoration of Current Conditions with 6 mg/l as N Recharging from Fountain Creek



1 year

2 years

Figure 22. Restoration of Highly Polluted Conditions with 6 mg/l as N Recharging from Fountain Creek

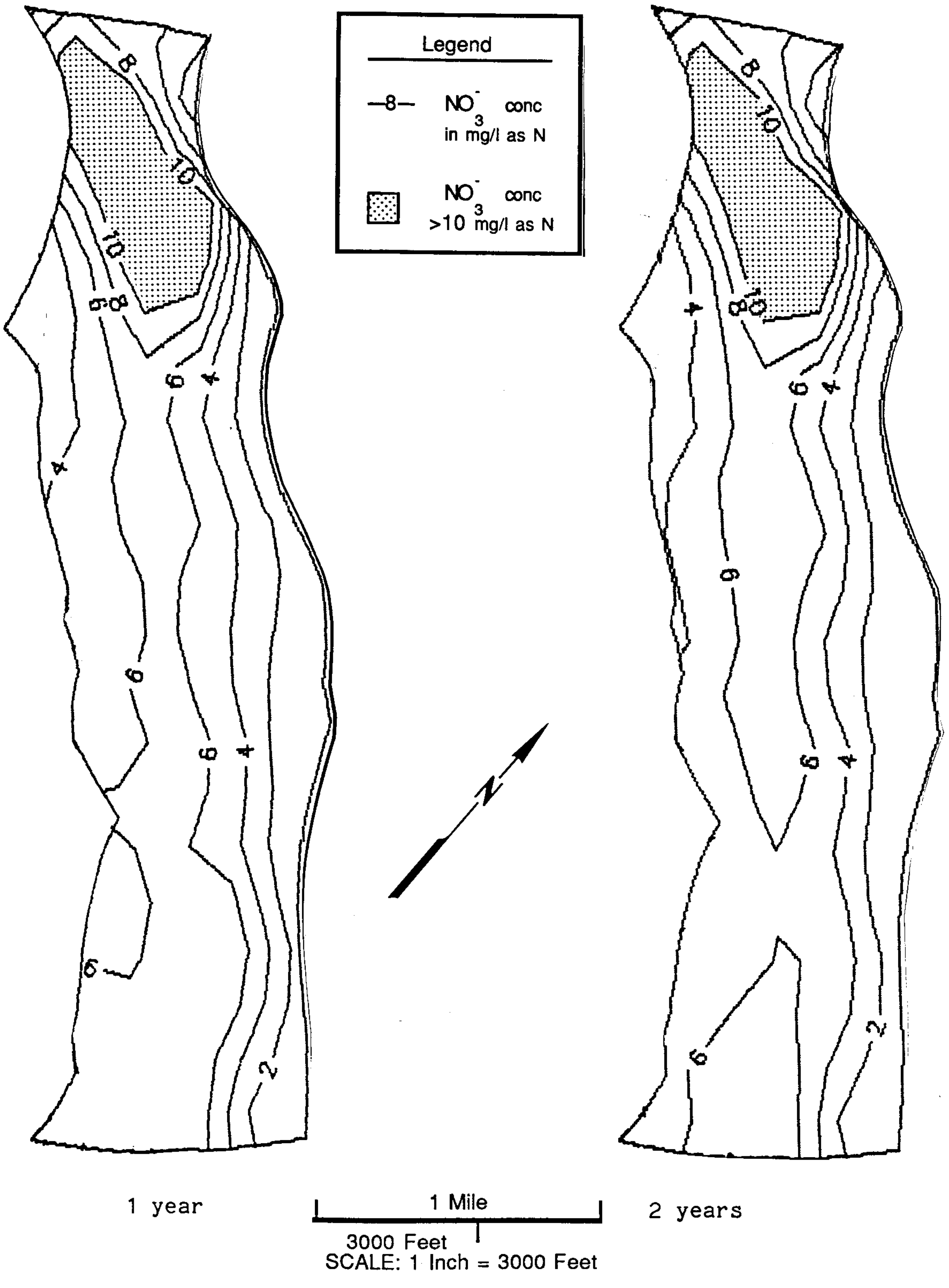
replaces and dilutes the highly polluted water. The Pinello, Stratmoor Hills, and Security well fields that were pumping nitrate concentrations significantly over the drinking water standard, could be restored to pumping water with nitrate concentrations in the range of 6 to 8 mg/l as N. Therefore, if no action was taken and conditions were allowed to degrade, restoration of safe drinking water still seems possible.

5.3 Effects of moving the point of discharge

Moving the point of sewage effluent discharge down-gradient of the recharge area may have a positive effect by lowering nitrate concentrations, but may also significantly reduce the volume of water available to users. The sewage effluent accounts for over half of the water in Fountain Creek the majority of the time. With this water supply removed, the main well field area in the up-gradient part of the aqufier could experience an average drawdown of 14 feet. At steady state the nitrate concentrations are generally in the 6 mg/l as N range (Figure 23) but the decrease of water left in storage should also be considered. Colorado water law governs the quantity aspect of water use very closely. With a change in discharge point, the Widefield aquifer water users could have their water rights impaired, making this both a quantity and quality issue.

5.4 Direct recharge to groundwater

One possible way to prevent a quantity problem would be direct recharge to the groundwater far up-gradient of the Widefield aquifer. The same amount of effluent would be allowed to seep into the up-gradient alluvium and ideally would flow along the Fountain valley



1 year

2 years

Figure 23. Nitrate Distribution when the Treatment Plant's Discharge Point is Moved Down-gradient

alluvium to recharge the Widefield aquifer. The recharge from Fountain Creek would be decreased, but the recharge from the up-gradient alluvium would be increased. If no nitrification occurred in this recharge system, then it might work exceptionally well. When no nitrifiers are present, ammonium adsorbs readily and does not move far at all. Figure 24 depicts an idealized 50 foot x 50 foot recharge basin. Without nitrification, ammonium movement is very hindered due to adsorption on the aquifer material. After 1 year (Figure 25) concentrations of 2 mg/l as N have only moved about 300 feet. If the recharge ponds were placed near the Colorado Springs wastewater treatment plant, about 2 miles north-west of the Widefield aquifer, it would take years before significant ammonium levels reached the aquifer.

One problem with this option is that a recharge system involving ammonium will quickly develop a population of nitrifying bacteria. After the nitrifiers become acclimated to the conditions, the once adsorbed ammonium would be converted to mobile nitrate. Nitrate would move rapidly (Figure 26) and higher concentrations would eventually migrate to the Widefield aquifer. The problem of nitrate contamination would not be solved, the source would only be moved. Recharge ponds also require a large area to accomodate large flows that would come from a treatment plant of this size. Over 100 acres could be required depending on the rate of infiltration and other factors. This consideration also makes it impractical to use direct groundwater recharge for this situation.

Direct recharge to groundwater does have some positive effects on treated wastewater. Acting like a sand filter employed in water treatment facilities, many constituents could be removed. Suspended

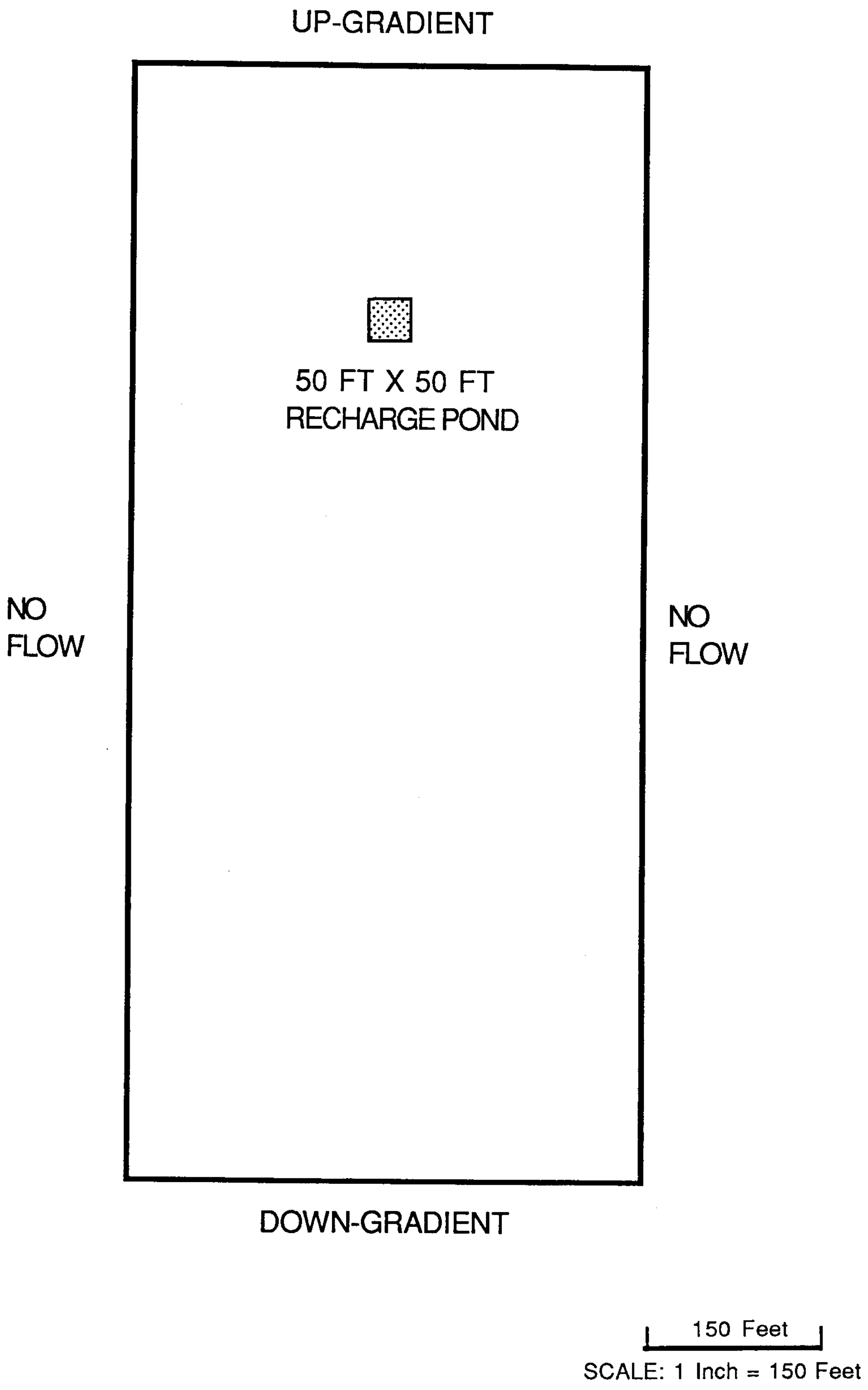


Figure 24. Idealized Recharge Basin

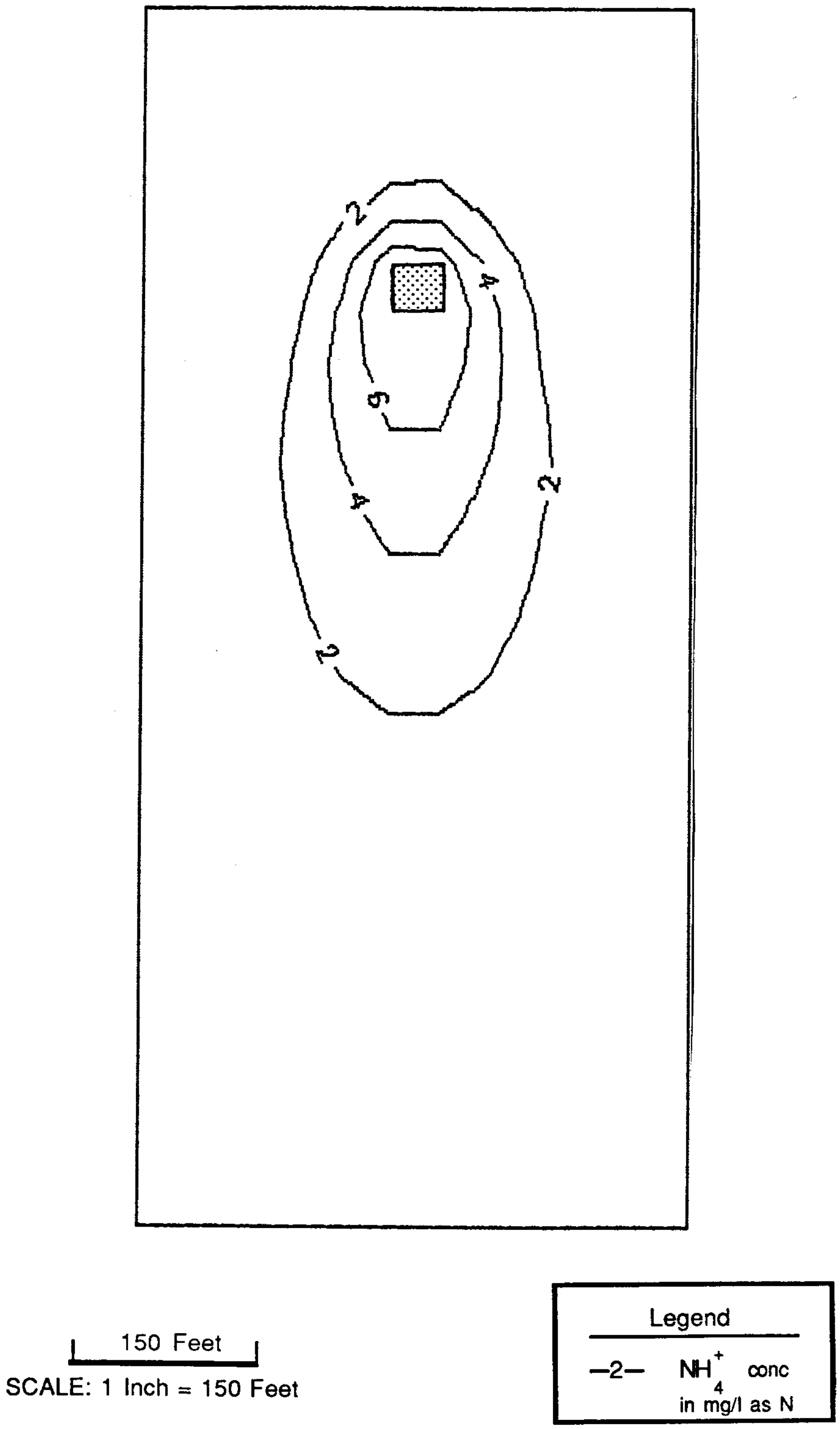


Figure 25. Ammonium Distribution from a 50 ft x 50 ft Recharge Basin after 1 year

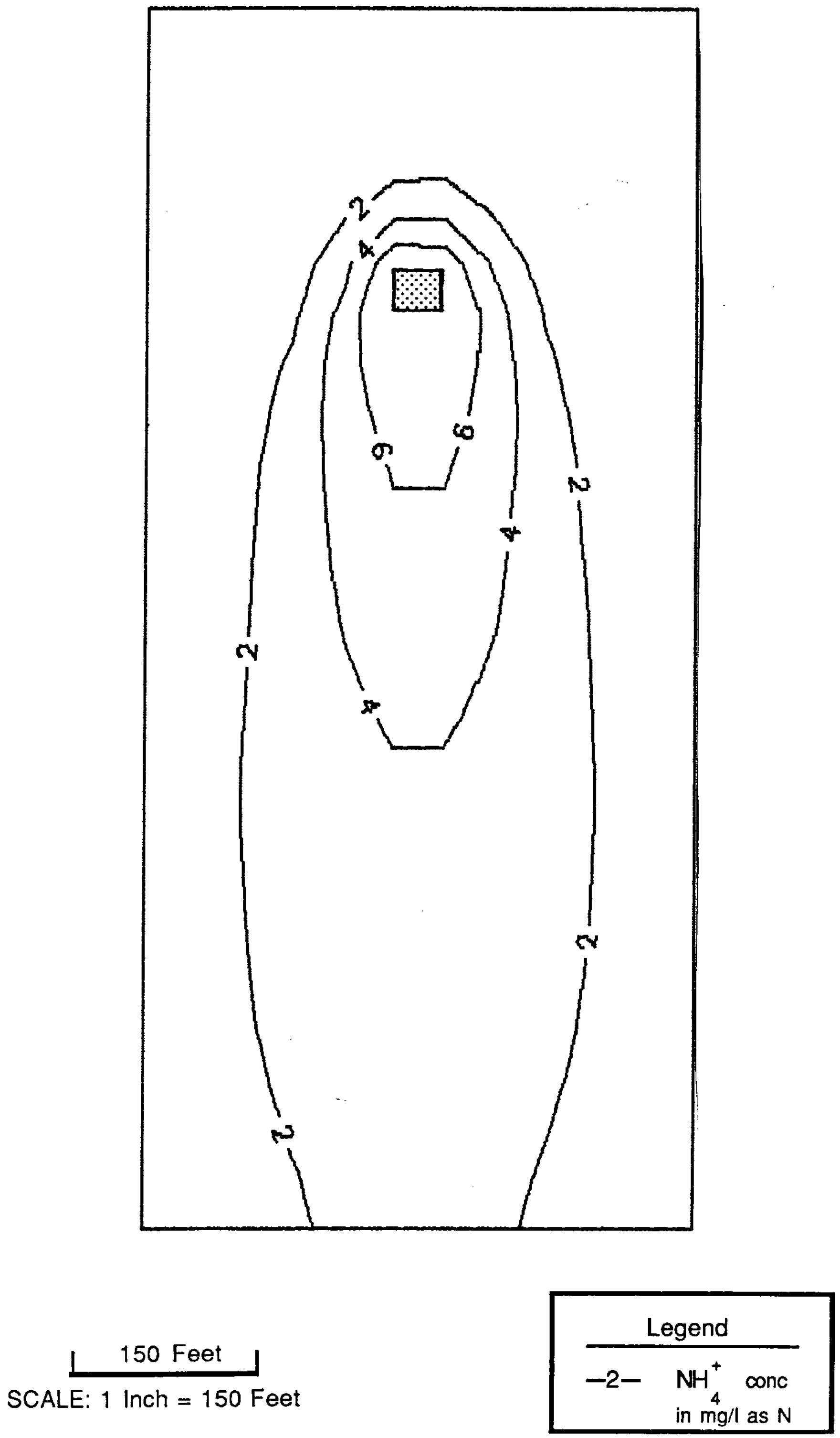


Figure 26. Nitrate Distribution from a 50 ft x 50 ft Recharge Basin after 1 year

solids, organic material, and bacteria could all be filtered out. However, for potable water to be removed from a recharge system involving wastewater, advanced treatment is indicated. The main problem to be corrected with advanced treatment would be the high ammonium concentrations. Without ammonium removal, nitrate contamination can become serious as seen in the Widefield aquifer.

5.5 Altered pumping schemes by the water users

The Colorado Springs sewage treatment plant is not the only variable in this system. The water users themselves have an impact on the aquifer. To see if the water users could reduce the nitrate concentrations themselves, both decreased and increased pumping schemes were simulated. For the increased pumping, all wells were set to pump 1.5 times their average pumping rate, and for the decreased pumping, the wells were set to half of their average rate. A situation was modeled with no decrease in ammonium entering the aquifer from Fountain Creek. Neither a decreased nor an increased pumping scheme seemed to have any effect on the nitrate distribution (Figures 27 and 28). The water storage on the other hand was notably affected. During increased pumping the average water table was lowered by 5 feet while decreased pumping allowed it to rise by about 5 feet. The amount of recharge from Fountain Creek was also altered by changing the pumping schemes. Pumping one and one-half times the average rates caused the recharge from Fountain Creek to increase by about 15%, while pumping at half the average rates decreased recharge by about 15%. With no ammonium reduction plan by the Colorado Springs, the water users alone would probably have little influence on the water quality in the aquifer.

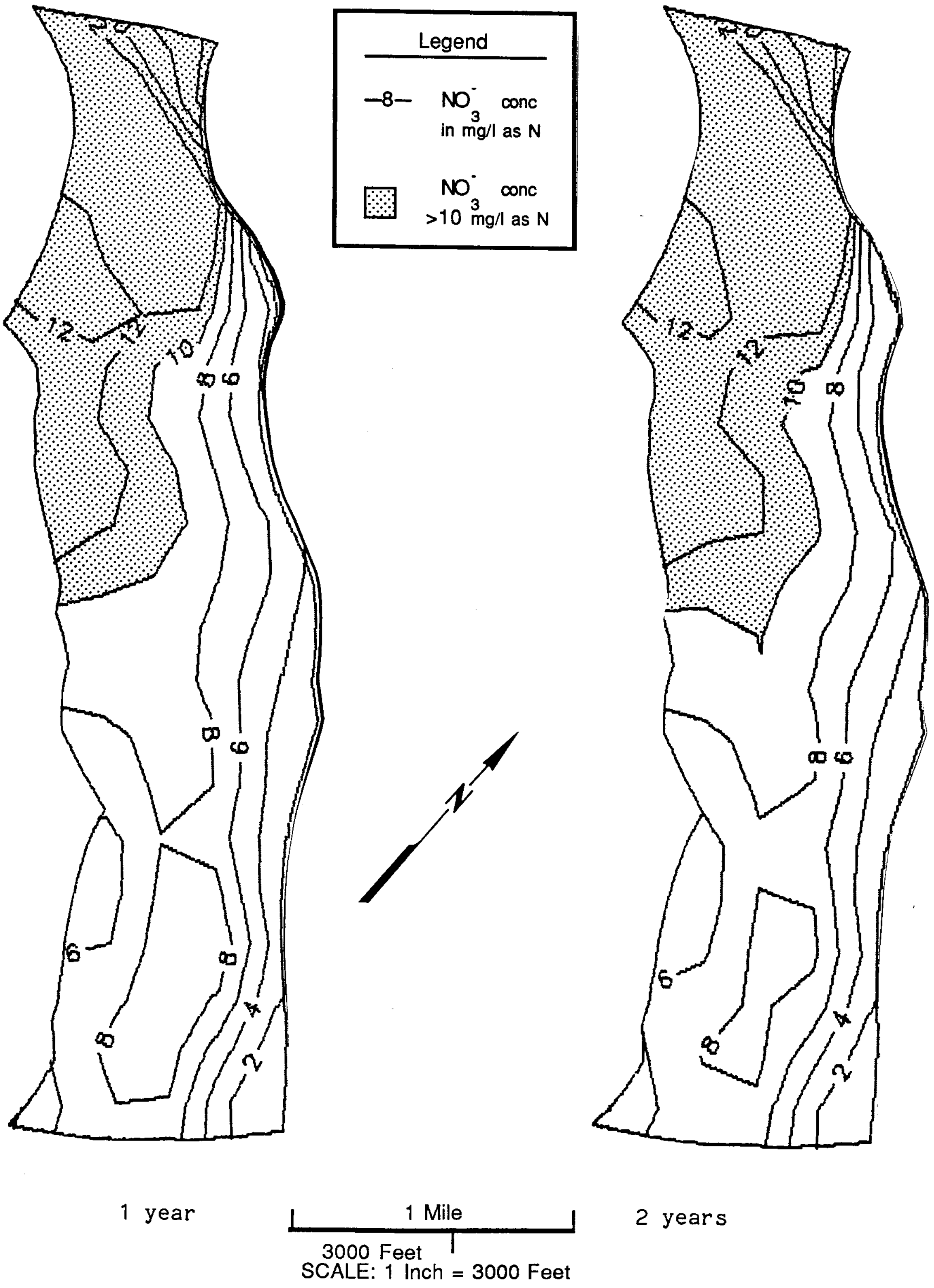
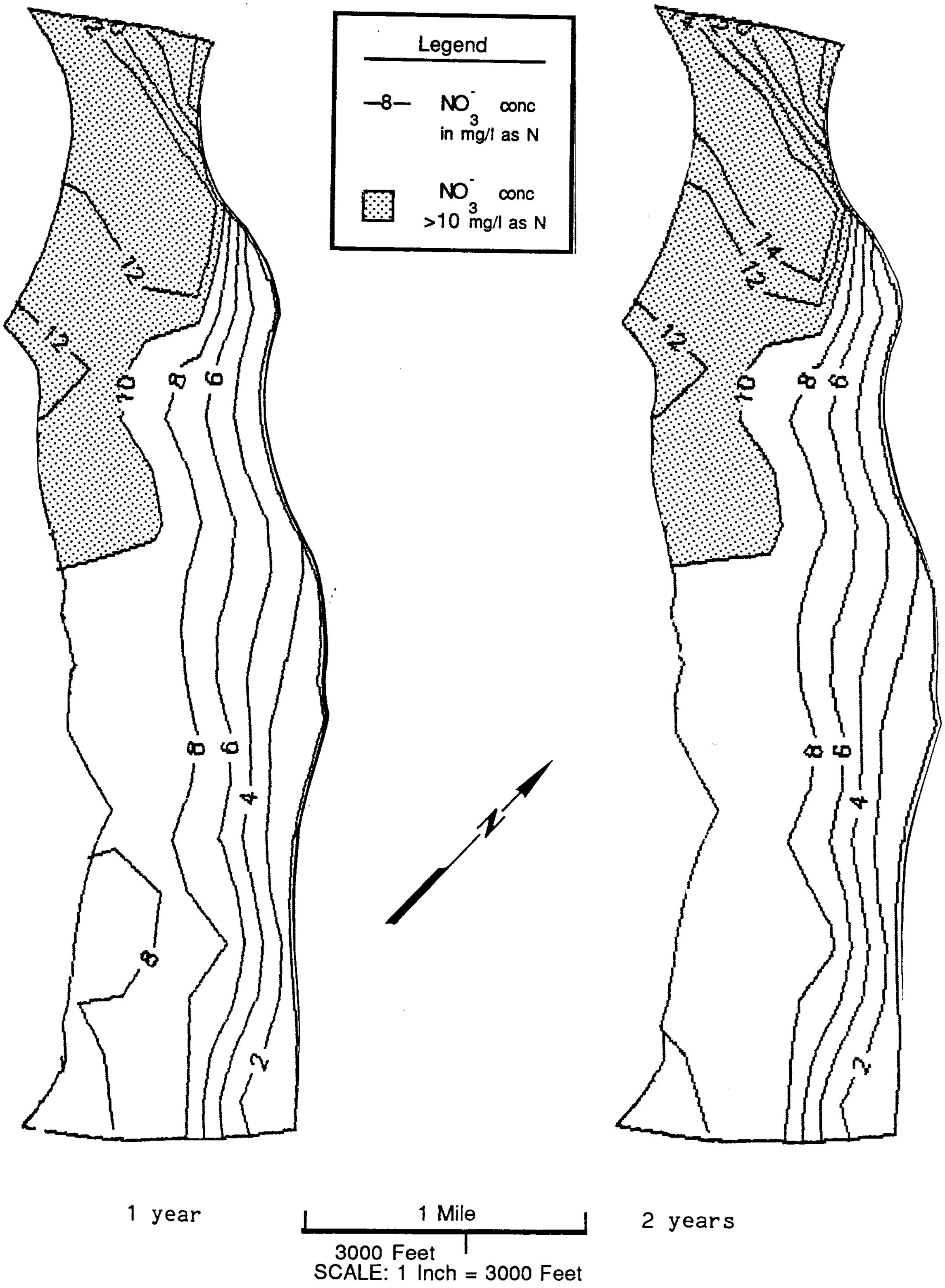


Figure 27. Nitrate Distribution After Decreased Pumping



1 year

2 years

Figure 28. Nitrate Distribution After Increased Pumping

where:

Kd = Freundlich isotherm coefficient
ρ = Bulk density of the adsorbent
Φ = Porosity

Using a bulk density of 1.6 gm/cm^3 and a porostiy of 0.25, the Dk for chloroform would be about 10. With a recharge concentration of 10 ug/l from Fountain Creek, the chloroform moves very slowly (Figures 29 and 30). After 8 years only the Stratmoor Hills wells and a few of the Pinello wells would be pumping chloroform concentrations greater than 8 ug/l. More than half of the aquifer would detect chloroform concentrations less than 2 ug/l. It must be kept in mind that the retardation is caused by storage of the chemical in the aquifer due to adsorption. In the long run this may lead to a very serious aquifer contamination problem.

The results would be similar for other adsorbing chemicals. If adsorbing organics were known to be present in Fountain Creek, they would most likely be seen immeadiately adjacent to the recharge area first. Some chemicals are strongly adsorbed and might not be detecable in groundwater samples for quite some time. An aquifer's adsorptive capacity could be a short term solution by slowing the movement of certain chemicals. Once concentrations of a paricular chemical are detected at dangerous levels, those high levels might persist indefinitely due to the large adsorbed supply. Extreme caution should be used when an aquifer so close to water supply wells is part of a contaminant removal system.

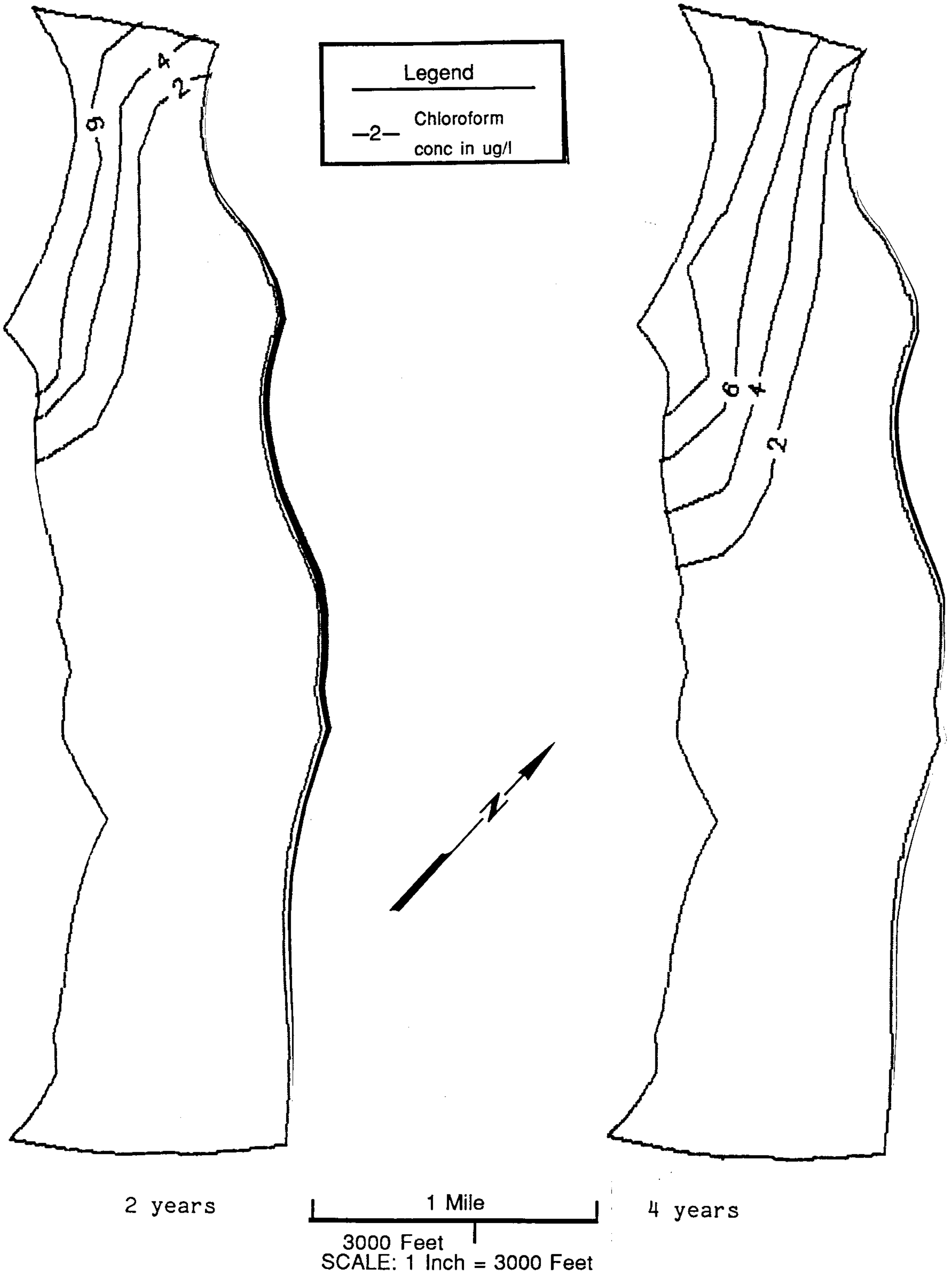
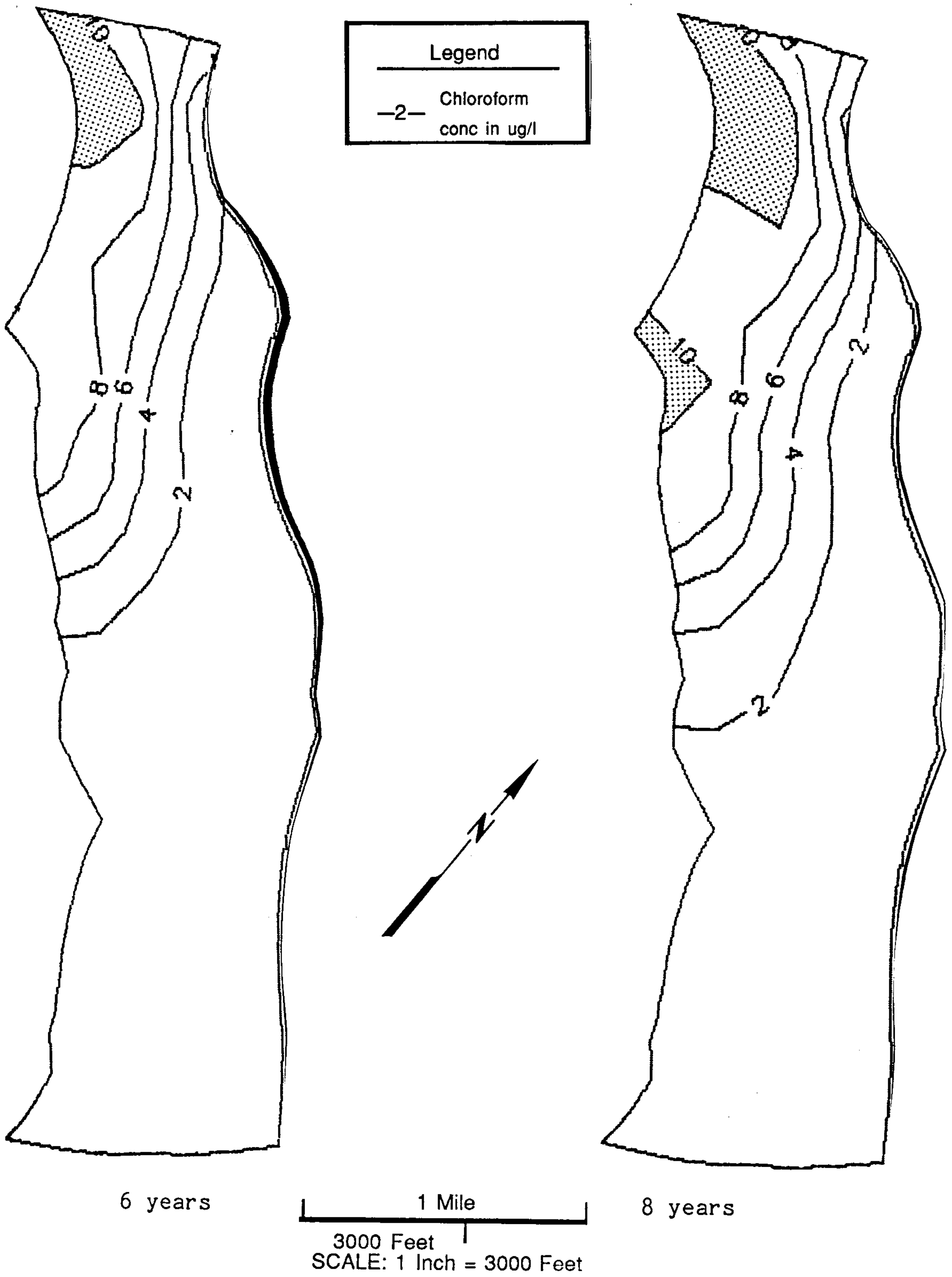


Figure 29. Chloroform Distribution in the Widefield Aquifer under Adsorbing Conditions



6 years

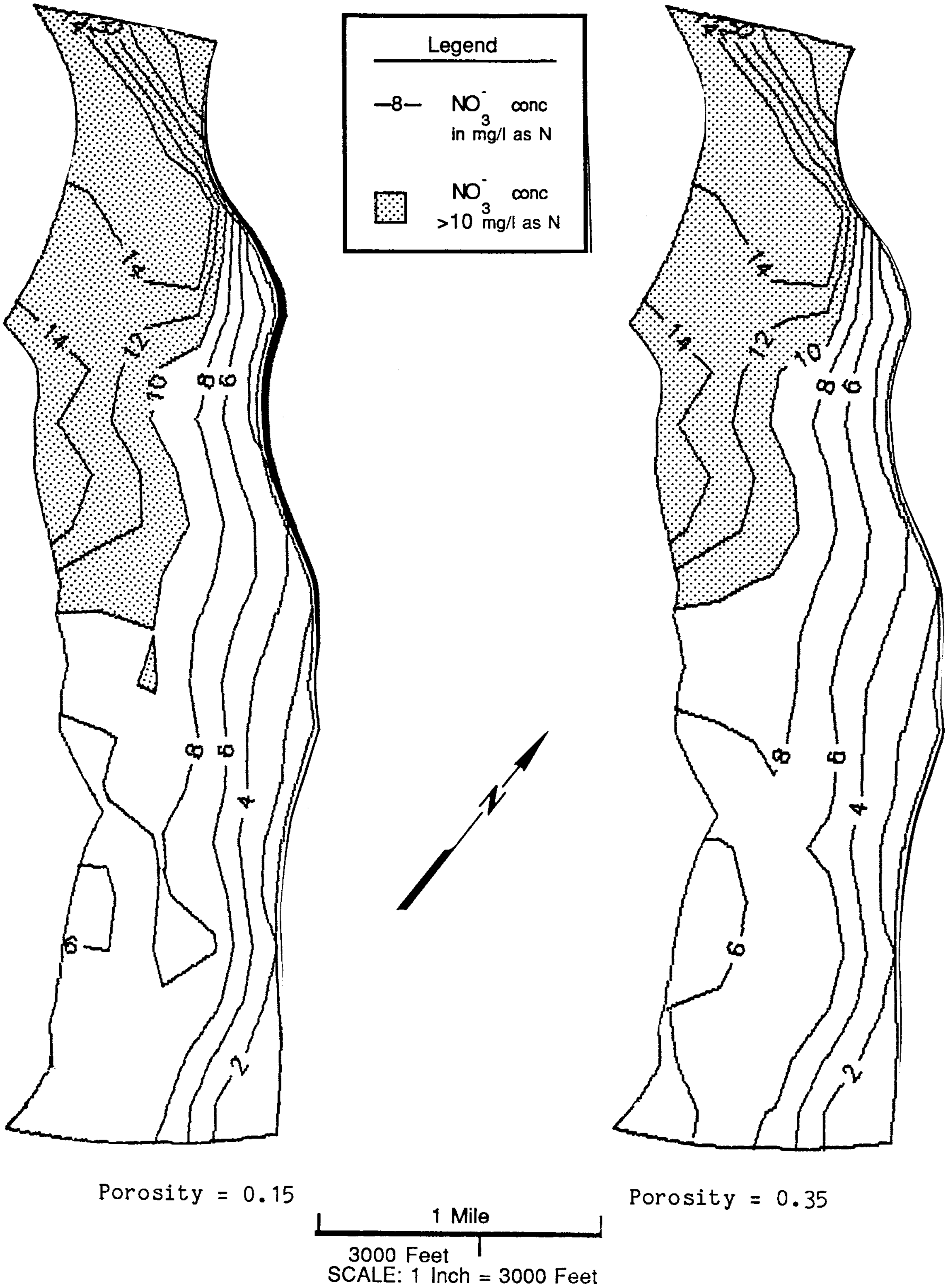
8 years

Figure 30. Chloroform distribution in the Widefield Aquifer under Adsorbing Conditions

5.7 Sensitivity analysis

The model has been most sensitive to changes of the nitrate concentration at the Fountain Creek boundary. Variations of nitrate concentrations in the Fountain Creek alluvial recharge between 6 and 8 mg/l as N showed no notable changes. Recharge nitrate concentrations were also varied for the distributed recharge areas between 4 and 8 mg/l as N. Only slight effects were seen in the very southern portion of the model area. Local highs historically seen in this southern region may be influenced by such distributed recharge or other local sources. Only changes made in the Fountain Creek recharge area had significant effects on the concentration distribution.

Two other properties were tested for sensitivity: porosity and the ratio of transverse to longitudinal dispersivity. Simulations to this point were run with a porosity of 0.25. Holding all other variables the same as the 14 mg/l as N nitrate recharge scenario (Figure 17), the porosity was first lowered to 0.15 and then increased to 0.35. Results from the lowered porosity (Figure 31) show only a slight increase in down-gradient nitrate migration. Increased porosity (Figure 31) showed even less of an effect. Decreasing the ratio of transverse to longitudinal dispersivity from 0.25 to 0.10 had the effect of decreasing the transverse dispersion. As with the decreased porosity a small increase in down-gradient nitrate migration was seen (Figure 32). Neither porosity nor the ratio of transverse to longitudinal dispersivity had any pronounced effect on the results of these simulations.



Porosity = 0.15

Porosity = 0.35

Figure 31. Effects of Varied Porosity on Nitrate Ditribution when 14 mg/l as N Recharged from Fountain Creek

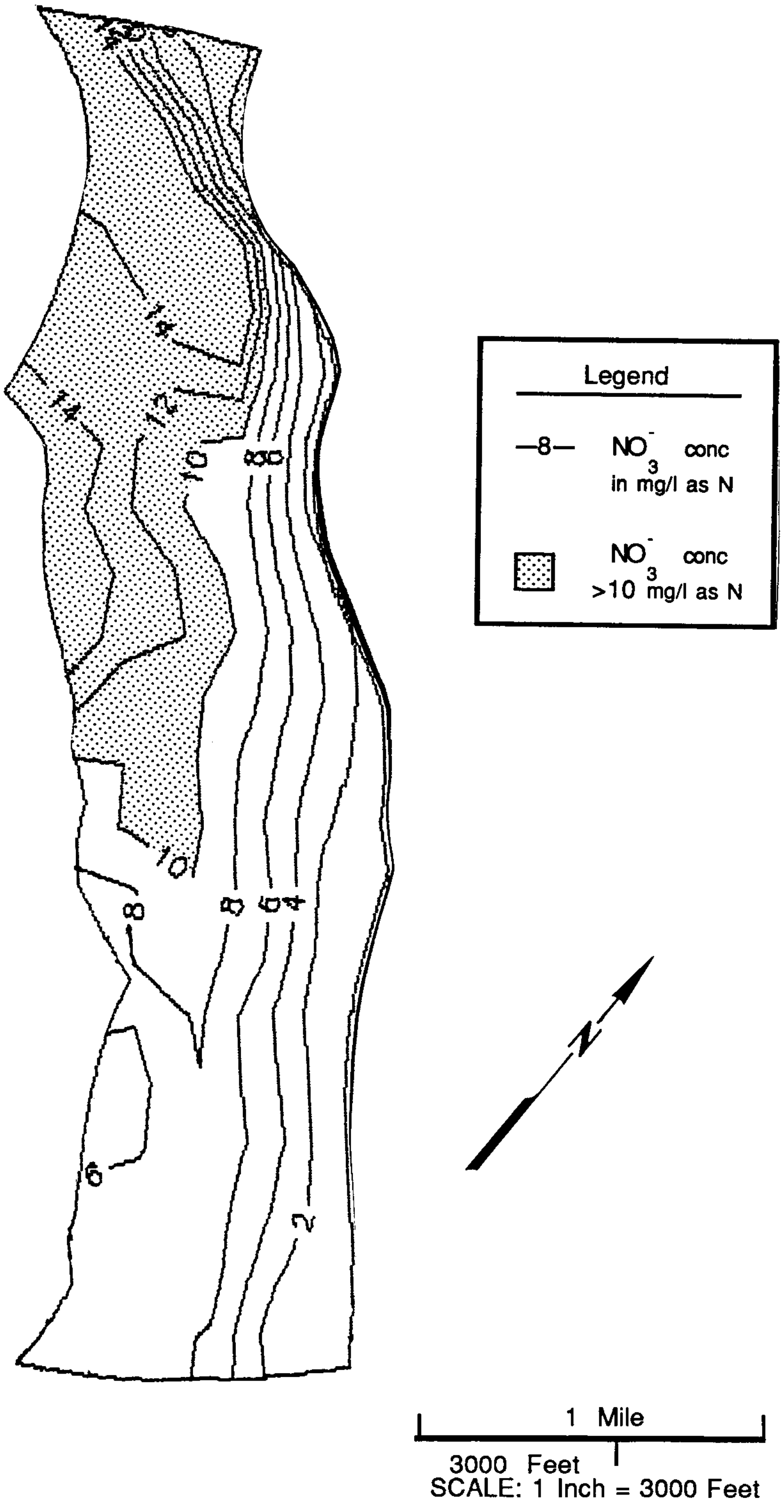


Figure 32. Effects of Decreasing the Ratio of Transverse to Longitudinal Dispersivity

CHAPTER 6

CONCLUSIONS AND SUMMARY

Although it is difficult to draw hard and fast conclusions concerning the fate of nitrate in the Widefield aquifer, several findings are definitely noteworthy. If the current average nitrate concentration (10 mg/l as N) continues to recharge the aquifer from Fountain Creek, then it appears that the nitrate concentration distribution in the aquifer has reached a steady state and will not increase significantly in the future. Wells near the area of Fountain Creek recharge will probably continue to have higher concentrations of nitrate. However, the majority of downgradient wells should not exhibit nitrate concentration increases above the current drinking water standard (Figure 15). Some local unaccounted or unknown sources, such as seepage from sewage lagoons may greatly increase nitrate concentrations in certain local areas.

Continuous increases of sewage effluent discharged to Fountain Creek may have a serious impact on the water quality in the Widefield aquifer. The Colorado Springs sewage treatment plant currently discharges 30 MGD. An increase to 39 MGD would cause a slight increase of ammonium in the area of recharge to 12 mg/l as N and may only effect the Stratmoor Hills wells with nitrate concentrations slightly over the drinking water standard. If the sewage treatment plant discharges its maximum design capacity, about 60 MGD, then more serious water quality degradation would be seen in the Widefield aquifer. Recharging water with 14 mg/l as N may contaminate the entire Pinello well Field, the up-gradient half of the Security wells and the Stratmoor Hills well field with nitrate concentrations in excess of the drinking water standard. As the recharging concentration continues to increase the nitrate concentrations in the aquifer also increase. With each increase, the up-gradient wells near the area of recharge apparently suffer the worst. There is enough tributary dilution available moving down-gradient that the southern portion of the aquifer does not seem to experience such sharp increases of nitrate concentrations. In the future, unchecked increases from Colorado Springs sewage treatment plant may continue to degrade the quality of water in the Widefield aquifer with respect to nitrate concentrations, especially in the upgradient portion near the area of recharge.

The important findings of this study can be summarized as follows:

1) The current nitrate concentration distribution in the Widefield aquifer can be attributed to the recharge nitrate concentration of 10 mg/l as N from Fountain Creek. The observed average concentration of ammonia and nitrate in Fountain Creek is currently (1981-1982) 10 mg/l as N. Therefore, the assumption that all the recharging ammonium is conservatively converted to nitrate via. biochemical nitrification may be justified.

2) Increasing the recharge nitrate concentrations from Fountain Creek in turn increases the nitrate concentration distribution in the aquifer. As the recharging nitrate concentrations are increased beyond

10 mg/l as N, more and more of the wells in the Widefield aquifer may produce water with nitrate concentrations that would exceed the drinking water standard of 10 mg/l as N.

3) Restoration of the aquifer is possible by decreasing the nitrate concentration due to the Fountian Creek recharge. This may be accomplished by reducing the concentration of ammonia produced by the Colorado Springs wastewater treatment plant, or by supplying additional dilution water. Restoration to safe drinking water levels could occur within two years if the recharging nitrate concentration was reduced to 6 mg/l as N. No significant time advantage would be gained by reducing the recharging nitrate concentrations to 1 mg/l as N. Even under highly polluted conditions where the nitrate concentrations range from 8 to 22 mg/l as N, restoration could still be possible within two years.

4) Moving the treatment plant's point of discharge below the area of recharge to the Widefield aquifer may help reduce the nitrate concentrations, but might also seriously reduce the amount of water available to users. At the present time the volume of water depended upon for municipal water supply would probably prevent any action such as this. Both quantity and quality issues should be addressed at the same time concerning the future use of the Widefield aquifer.

5) Directly recharging the sewage treatment plant's effluent to groundwater far up-gradient of the Widefield aqufier would probably not help solve the nitrate problem at all. Initially the ammonium may adsorb to the aquifer material, but as soon as a nitrifying bacterial

population develops, nitrate would be produced. Recharging the effluent near the treatment plant would simply change the location of the nitrate source. Without any form of permanent nitrogen removal, the highly mobile nitrate would still be free to recharge the Widefield aquifer.

6) Increasing or decreasing pumping rates in the well fields apparently has little to no effect on the nitrate concentration distribution in the aquifer. A change in pumping scheme would probably not help reduce nitrate concentrations in the Widefield aquifer unless the incoming nitrate concentration was lowered at the same time.

7) Other conservative non-reactive contaminants in the Widefield aquifer, such as chloride and detergents, would tend to migrate in the same manner as the nitrate simulations. adsorbing chemicals would be significantly retarded, and would tend to be stored on the aquifer material making them a more lasting problem. To date, no other contaminants besides nitrate have been found to be near dangerous levels in the Widefield aquifer. The aquifer will continue to be monitored as part of a USGS project and as data becomes available other contaminant modeling studies may be indicated.

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APPENDIX A

Computer listing of the Fortran program NITRAD

```
      PROGRAM NITRAD
C
C
C     THIS PROGRAM WILL SOLVE BOTH NITRIFICATION AND ADSORPTION
C     OF AMMONIUM MOVING THROUGH A SOIL COLUMN.  THE PROGRAM SHOULD
C     BE RUN TO A STEADY STATE NITRATE OUTPUT FOR A GIVEN SET OF
C     BOUNDARY CONDITIONS.  IT IS ASSUMED THAT OXYGEN WILL BE THE
C     LIMITING FACTOR IN THE OVERALL NITRATE PRODUCTION.  PROGRAMED
C     BY KIMBALL S. LOOMIS, COLORADO STATE UNIVERSITY, DEPT. OF CIVIL
C     ENGINEERING.   JULY 21, 1987
C
C
C
C   VARIABLE NAME LIST
C       ITMAX - NUMBER OF ITERATIONS
C       QFC - FLOW IN FOUNTAIN CREEK UPSTREAM OF COLO SPRINGS, CFS
C       QSTP - FLOW FROM COLO SPRINGS SEWAGE TREATMENT PLANT, MGD
C       NHCIN - NH4+ CONC IN THE RECHARGE AREA, MG/L
C       NHCR - NH4+ CONC REMAINING AFTER OXIDATION AND OR ADSORPTION
C       MAXLYR - NUMBER OF LAYERS IN SIMULATION
C       NHCOX - CONC OF NH4+ OXIDIZABLE
C       OXCONC(L) - CONC OF OXYGEN IN EACH LAYER
C       NITC - CONC OF NITRATE PRODUCED
C       DELOX - EXCESS OXYGEN LEFT WHEN NH4+ LIMITS REACTION
C       NHCA(L) - ADSORBED NH4+ IN EACH LAYER AS A CONC
C       LNITC(L) - NITRATE CONC IN EACH LAYER
C       CNITC(IT) - CUMMULATIVE NITRATE CONC PER ITERATION
C       SMNITC - TOTAL NITRATE CONC
C       NHAPG - NH4+ ADSORBED PER GRAM SOIL
C       KD - COEFFICIENT FOR THE FREUNDLICH ISOTHERM ML/GM
C       ALPHA - EXPONENT FOR THE FREUNDLICH ISOTHERM
C       MXNHMA - MAX NH4+ ADSORBABLE IN THE LAYER
C       SOILM(L) - MASS OF SOIL IN LAYER
C       MXNHCA - MAX NH4+ ADSORBABLE EXPRESSED AS A CONC
C       WTRVOL - VOLUME OF WATER IN LAYER
C       DNHCA - CHANGE IN NH4+ ADSORBED AS A CONC
C       CNHCA(IT) - CUMMULATIVE NH4+ ADSORBED OR DESORBED PER ITERATION
C       SMNHCA - TOTAL NH4+ ADSORBED OR DESORBED
C       LVOLV - LAYER BULK VOLUME
C       AREA - CROSS SECTIONAL AREA OF COLUMN, SQUARE METERS
C       DX(L) - DEPTH INCREMENT, CM
C       POR - POROSITY
C       BD - BULK DESITY OF AQUIFER MATERIAL GM/CM
```

```
C
C
      REAL NHCIN,NHCR,NHCOX,NITC,NHCA,LNITC,NHAPG,KD,MXNHMA,
     +MXNHCA,LVOLB,NHSTP
C
      CHARACTER*80 DUMMY,TITLE1
      CHARACTER*12 FNAME1,FNAME2
C
      DIMENSION OXCONC(20),NHCA(20),LNITC(20),CNITC(100),SOILM(20),
     +WTRVOL(20),CNHCA(100),DX(20),LVOLB(20),MXNHCA(20)
C
C  READ INPUT DATA
C
      WRITE(*,4)
 4    FORMAT(1X,'ENTER THE NAME OF THE INPUT DATA FILE')
      READ(*,12) FNAME1
      OPEN(5,FILE=FNAME1,STATUS='OLD')
      WRITE(*,6)
 6    FORMAT(1X,'ENTER THE NAME OF THE OUTPUT FILE')
      READ(*,12)FNAME2
      OPEN(6,FILE=FNAME2,STATUS='NEW')
C
      READ(5,10) TITLE1
      READ(5,20) MAXLYR,ITMAX
      READ(5,10) DUMMY
      DO 50 L=1,MAXLYR
          READ(5,30) OXCONC(L),NHCA(L),DX(L)
 50   CONTINUE
      READ(5,60) AREA,POR
      READ(5,60) BD,NHSTP
      READ(5,60) QSTP,QFC
      READ(5,60) KD,ALPHA
C
C  READ FORMAT STATEMENTS
C
 10   FORMAT(A)
 12   FORMAT(A12)
 20   FORMAT(2I5)
 30   FORMAT(3F10.2)
 60   FORMAT(2F8.3)
C
C  INITIAL CALCULATIONS
C
      DO 100 L=1,MAXLYR
          LVOLB(L) = AREA * DX(L)
          WTRVOL(L) = LVOLB(L) * POR * 1000.
          SOILM(L) = LVOLB(L) * BD * 1E06
 100  CONTINUE
C
C  CONVERT MGD TO CFS, CALC NH4 CONC IN RECHARGE AREA
      QSTP = QSTP * 1.55
      NHCIN = NHSTP * QSTP / (QSTP + QFC)
C
C  INITIALIZE SMNHCA & CNITC ARRAY AND NHCA ARRAY
```

```
C
      DELOX = 0.0
      DNHCA = 0.0
      SMNHCA = 0.0
      DO 105 L=1,MAXLYR
          SMNHCA = SMNHCA + NHCA(L)
          MXNHCA(L) = 0.0
 105  CONTINUE
C
C
      DO 110 IT=1,ITMAX
          CNHCA(IT) = 0.0
          CNITC(IT) = 0.0
 110  CONTINUE
C
C  ITERATION LOOP BOUNDARY CONDITIONS MAY BE CHANGED HERE
C  FOR VARIOUS SIMULATIONS
C
      WRITE(6,10) TITLE1
      WRITE(6,670) NHSTP
      WRITE(6,680) QSTP
      WRITE(6,690) QFC
      WRITE(6,700) NHCIN
      WRITE(6,720)
C
C
C  MAIN LOOP TO NUMBER OF INTERATIONS
C
      DO 500 IT=1,ITMAX
          NHCR = NHCIN
          DO 120 L=1,MAXLYR
              LNITC(L) = 0.0
 120      CONTINUE
C
C  INNER LOOP FOR NUMBER OF LAYERS
C   OXIDATION CALCULATIONS
C
          DO 300 L=1,MAXLYR
              NHCOX = OXCONC(L) / 4.33
C
C ****CHECK IF OXYGEN OR NH4 LIMITS REACTION
C
              IF(NHCOX.LE.NHCR) THEN
                NITC = NHCOX
                NHCR = NHCR - NITC
              ELSE IF(NHCOX.GT.NHCR) THEN
                DELOX = NHCOX - NHCR
                IF(DELOX.LE.NHCA(L)) THEN
                  NITC = NHCR + DELOX
                  NHCA(L) = NHCA(L) - DELOX
                  DNHCA = - DELOX
                  NHCR = 0.0
                ELSE IF(DELOX.GT.NHCA(L)) THEN
                  NITC = NHCR + NHCA(L)
```

```
                NHCA(L) = 0.0
                DNHCA = - NHCA(L)
                NHCR = 0.0
              ENDIF
            ENDIF
C
C  ADD NITRATE PRODUCED FOR EACH LAYER AND ITERATION
C
          LNITC(L) = LNITC(L) + NITC
          CNITC(IT) = CNITC(IT) + NITC
C
C
C   CHECK IF NH4 IN SOLN GOES NEG THEN SKIP MAX ADSOPTION CALC
C
          IF(NHCR.LT.0.0) NHCR = 0.0
          IF(NHCR.LE.0.0) GOTO 280
C
C  ADSORPTION CALCULATIONS
C
          NHAPG = KD * NHCR ** ALPHA
          MXNHMA = NHAPG * SOILM(L) / 1000.
          MXNHCA(L) = MXNHMA / WTRVOL(L)
C
C
          IF(NHCR + NHCA(L).LE.MXNHCA(L)) THEN
            NHCA(L) = NHCA(L) + NHCR
            DNHCA = NHCR
            NHCR = 0.0
          ELSE IF(NHCR + NHCA(L).GT.MXNHCA(L)) THEN
            DNHCA = MXNHCA(L) - NHCA(L)
            NHCA(L) = MXNHCA(L)
            IF(DNHCA.GE.0.0) NHCR = NHCR - DNHCA
          ENDIF
C
 280      CNHCA(IT) = CNHCA(IT) + DNHCA
          SMNHCA = SMNHCA + DNHCA
          IF(NHCR.LE.0.0) NHCR = 0.0
 300  CONTINUE
C
C  OUTPUT FOR EACH ITERATION
C
 400  WRITE(6,600) IT
      WRITE(6,610)
      DO 450 L=1,MAXLYR
          WRITE(6,620) L,OXCONC(L),LNITC(L),NHCA(L),MXNHCA(L)
 450  CONTINUE
      WRITE(6,630) CNITC(IT)
      WRITE(6,640) CNHCA(IT)
      WRITE(6,650) SMNHCA
      WRITE(6,660) NHCR
      WRITE(6,720)
 500  CONTINUE
C
C
```

```
C  WRITE FORMAT STATEMENTS
C
 600  FORMAT(5X,'ITERATION NUMBER    ',I5)
 610  FORMAT(1X,'LAYER     OX CONC    NITRATE CONC     NH4 ADS',
    + '    MAX NH4 ADS')
 620  FORMAT(1X,I5,3X,F7.2,4X,F12.2,4X,F7.2,F15.2)
 630  FORMAT(3X,'NITRATE PRODUCED FROM THIS ITERATION (MG/L)',2X,F7.2)
 640  FORMAT(3X,'NH4 ADSORBED FOR THIS ITERATION (MG/L)',2X,F12.2)
 650  FORMAT(3X,'CUMMULATIVE NH4 ADSORBED (MG/L)',2X,F19.2)
 660  FORMAT(3X,'REMAINING NH4 NOT ADSORBED OR OX (MG/L)',2X,F11.2)
 670  FORMAT(3X,'NH4 CONC FROM CSSTP (MG/L)',2X,F12.2)
 680  FORMAT(3X,'AVERAGE FLOW FROM CSSTP (CFS)',2X,F9.2)
 690  FORMAT(3X,'AVE FLOW IN FC ABOVE CSSTP (CFS)',2X,F6.2)
 700  FORMAT(3X,'NH4 CONC ENTERING RECHARGE AREA',2X,F7.2)
 720  FORMAT(1X,'-----------------------------------------------------')
C
      STOP
      END
```

The following instructions are provided for the user to construct a data set for a nitrification problem similar to the one presented in this study. A sample data set is given after these instructions.

DATA DECK INSTRUCTIONS:

LINE #	VARIABLE	COMMENTS
1	TITLE	may contain up to 80 characters
2	MAXLYR,ITMAX	(2I5) enter maximum # of layers and maximum # of iterations
3	DUMMY	heading for layer input variables may by up to 80 characters
4	OXCONC(L) NHCA(L) DX(L)	(3F10.2) for each layer enter the conc. of O_2(mg/l), the amount of NH_4^+ previously adsorbed expressed as a concentration, and the thickness of each layer in meters.
5	" " " " " "	
6	" " " " " "	
.	" " " " " "	
.	" " " " " "	
.	" " " " " "	
MAXLYR	" " " " " "	
MAXLYR+1	AREA,POR	(2F8.3) enter the x-sectional area in m^2, and porosity which is unitless.
MAXLYR+2	BD,NHSTP	(2F8.3) enter the bulk density in gm/cm^3, and the ammonium concentration in the sewage effluent in mg/l as N.
MAXLYR+3	QSTP,QFC	(2F8.3) enter the flow from the treatment plant in MGD, and the base flow in Fountain Creek in cfs.
MAXLYR+4	KD,ALPHA	(2F8.3) enter the coefficient KD in ml/gm, and the exponent, ALPHA for the Freundlich isotherm.

Example data set for an situation undergoing both nitrification and adsorption. There is no previously adsorbed ammonium.

```
TEST PROBLEM    TEST RUN 4 9/10/87
   5  100                 L,ITMAX
 OXCONC(L)    NHCA(L)     DX(L)     (3F10.2)
      10.5        0.0      0.03
       9.0        0.0      0.03
       8.0        0.0      0.03
       7.0        0.0      0.03
       6.0        0.0      0.03
     1.0     0.25         AREA, POROS (2F8.3)
    1.65     20.0         BD, NH4 CONC FROM STP (2F8.3)
    26.0     35.0         QSTP,QFC (2F8.3)
     2.0     1.00         KD, ALPHA (2F8.3)
```

Output from the above data set is shown here for every tenth iteration. It can be seen the under these initial and boundary conditions that the system comes to a steady state after 70 interations.

```
TEST PROBLEM    TEST RUN 4 9/10/87
   NH4 CONC FROM CSSTP (MG/L)          20.00
   AVERAGE FLOW FROM CSSTP (CFS)       40.30
   AVE FLOW IN FC ABOVE CSSTP (CFS)    35.00
   NH4 CONC ENTERING RECHARGE AREA     10.70
 ------------------------------------------------------
     ITERATION NUMBER          1
 LAYER     OX CONC     NITRATE CONC     NH4 ADS     MAX NH4 ADS
     1       10.50             2.42        8.28          109.28
     2        9.00              .00         .00             .00
     3        8.00              .00         .00             .00
     4        7.00              .00         .00             .00
     5        6.00              .00         .00             .00
   NITRATE PRODUCED FROM THIS ITERATION (MG/L)        2.42
   NH4 ADSORBED FOR THIS ITERATION (MG/L)             8.28
   CUMMULATIVE NH4 ADSORBED (MG/L)                    8.28
   REMAINING NH4 NOT ADSORBED OR OX (MG/L)             .00
 ------------------------------------------------------
     ITERATION NUMBER         10
 LAYER     OX CONC     NITRATE CONC     NH4 ADS     MAX NH4 ADS
     1       10.50             2.42       82.79          109.28
     2        9.00              .00         .00             .00
     3        8.00              .00         .00             .00
     4        7.00              .00         .00             .00
     5        6.00              .00         .00             .00
   NITRATE PRODUCED FROM THIS ITERATION (MG/L)        2.42
   NH4 ADSORBED FOR THIS ITERATION (MG/L)             8.28
   CUMMULATIVE NH4 ADSORBED (MG/L)                   82.79
   REMAINING NH4 NOT ADSORBED OR OX (MG/L)             .00
 ------------------------------------------------------
```

```
    ITERATION NUMBER       20
LAYER     OX CONC    NITRATE CONC     NH4 ADS      MAX NH4 ADS
    1      10.50             2.42     109.28          109.28
    2       9.00             2.08      41.75           81.85
    3       8.00              .00        .00             .00
    4       7.00              .00        .00             .00
    5       6.00              .00        .00             .00
  NITRATE PRODUCED FROM THIS ITERATION (MG/L)        4.50
  NH4 ADSORBED FOR THIS ITERATION (MG/L)             6.20
  CUMMULATIVE NH4 ADSORBED (MG/L)                  151.03
  REMAINING NH4 NOT ADSORBED OR OX (MG/L)             .00
-----------------------------------------------------------
    ITERATION NUMBER       30
LAYER     OX CONC    NITRATE CONC     NH4 ADS      MAX NH4 ADS
    1      10.50             2.42     109.28          109.28
    2       9.00             2.08      81.85           81.85
    3       8.00             1.85      14.52           57.46
    4       7.00              .00        .00             .00
    5       6.00              .00        .00             .00
  NITRATE PRODUCED FROM THIS ITERATION (MG/L)        6.35
  NH4 ADSORBED FOR THIS ITERATION (MG/L)             4.35
  CUMMULATIVE NH4 ADSORBED (MG/L)                  205.64
  REMAINING NH4 NOT ADSORBED OR OX (MG/L)             .00
-----------------------------------------------------------
    ITERATION NUMBER       40
LAYER     OX CONC    NITRATE CONC     NH4 ADS      MAX NH4 ADS
    1      10.50             2.42     109.28          109.28
    2       9.00             2.08      81.85           81.85
    3       8.00             1.85      57.46           57.46
    4       7.00              .59        .00             .00
    5       6.00              .00        .00             .00
  NITRATE PRODUCED FROM THIS ITERATION (MG/L)        6.94
  NH4 ADSORBED FOR THIS ITERATION (MG/L)             3.77
  CUMMULATIVE NH4 ADSORBED (MG/L)                  248.58
  REMAINING NH4 NOT ADSORBED OR OX (MG/L)             .00
-----------------------------------------------------------
    ITERATION NUMBER       50
LAYER     OX CONC    NITRATE CONC     NH4 ADS      MAX NH4 ADS
    1      10.50             2.42     109.28          109.28
    2       9.00             2.08      81.85           81.85
    3       8.00             1.85      57.46           57.46
    4       7.00             1.62      27.36           36.12
    5       6.00              .00        .00             .00
  NITRATE PRODUCED FROM THIS ITERATION (MG/L)        7.97
  NH4 ADSORBED FOR THIS ITERATION (MG/L)             2.74
  CUMMULATIVE NH4 ADSORBED (MG/L)                  275.95
  REMAINING NH4 NOT ADSORBED OR OX (MG/L)             .00
-----------------------------------------------------------
    ITERATION NUMBER       60
LAYER     OX CONC    NITRATE CONC     NH4 ADS      MAX NH4 ADS
    1      10.50             2.42     109.28          109.28
    2       9.00             2.08      81.85           81.85
    3       8.00             1.85      57.46           57.46
    4       7.00             1.62      36.12           36.12
```

```
   5     6.00            1.39      8.91         17.83
 NITRATE PRODUCED FROM THIS ITERATION (MG/L)     9.35
 NH4 ADSORBED FOR THIS ITERATION (MG/L)          1.35
 CUMMULATIVE NH4 ADSORBED (MG/L)               293.61
 REMAINING NH4 NOT ADSORBED OR OX (MG/L)          .00
-----------------------------------------------------
   ITERATION NUMBER      70
LAYER    OX CONC    NITRATE CONC    NH4 ADS    MAX NH4 ADS
   1      10.50           2.42     109.28        109.28
   2       9.00           2.08      81.85         81.85
   3       8.00           1.85      57.46         57.46
   4       7.00           1.62      36.12         36.12
   5       6.00           1.39      17.83         17.83
 NITRATE PRODUCED FROM THIS ITERATION (MG/L)     9.35
 NH4 ADSORBED FOR THIS ITERATION (MG/L)           .00
 CUMMULATIVE NH4 ADSORBED (MG/L)               302.53
 REMAINING NH4 NOT ADSORBED OR OX (MG/L)         1.35
-----------------------------------------------------
   ITERATION NUMBER      80
LAYER    OX CONC    NITRATE CONC    NH4 ADS    MAX NH4 ADS
   1      10.50           2.42     109.28        109.28
   2       9.00           2.08      81.85         81.85
   3       8.00           1.85      57.46         57.46
   4       7.00           1.62      36.12         36.12
   5       6.00           1.39      17.83         17.83
 NITRATE PRODUCED FROM THIS ITERATION (MG/L)     9.35
 NH4 ADSORBED FOR THIS ITERATION (MG/L)           .00
 CUMMULATIVE NH4 ADSORBED (MG/L)               302.53
 REMAINING NH4 NOT ADSORBED OR OX (MG/L)         1.35
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