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Application of a Transport Model to a Contamination Site In Southeast Nebraska, Including Parameter Estimation Effects

by

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Howard-
Thanks for my start
in hydrogeology
Love Marty

Application of a Transport Model to a Contamination Site In Southeast Nebraska, Including Parameter Estimation Effects

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A fertilizer production plant located in Section 14 of T4N, R5E, Gage County, Nebraska, experienced a leak in its product basin in April, 1985. The leaked product, 32% urea-ammonium-nitrate (UAN), is denser than water and sank to the bottom of the aquifer. Ponding and adsorption of UAN occurred at the base of the aquifer, thus providing a continuing source of contaminants to the groundwater.

Two common methods were used to determine hydraulic conductivity from field data. The range of values calculated was used in the Two Dimensional Solute Transport and Dispersion in Groundwater (MOC) computer model (Konikow and Bredehoeft, 1978). Dispersivity was varied to test the model's sensitivity to this parameter. The model results were also compared to field data and used as a tool to better estimate field hydraulic conductivity values. All other aquifer parameters were held constant in the simulations.

As hydraulic conductivity was increased in the model, the plume migrated more rapidly. When the hydraulic conductivity was low, the modeled recovery wells removed a

greater amount of contaminant and stabilized the plume migration. Modeled plume patterns were relatively insensitive to changes in dispersivity.

Contaminant was introduced into the modeled aquifer in the initial concentration array. Numerical oscillation in modeled concentration output occurred when contaminant was introduced with injection wells.

Density flow and adsorption and desorption of contaminant at the base of the aquifer occurred. The MOC model can not simulate density flow or desorption of contaminants and therefore can not accurately predict observed field data.

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CHAPTER 1
INTRODUCTION

Computer groundwater models are increasingly used by consulting firms and state and federal regulatory agencies to characterize, evaluate, and predict the movement of contaminants in groundwater. Often the results of modeling efforts are accepted as an absolute description of events, past, present and future. In reality, computer modeling is merely another tool to be used by the hydrogeologist to interpret groundwater movement. A computer model's value lies in its flexibility to try different scenarios and combinations of possible existing or hypothetical conditions.

Because of anisotropy and heterogeneity, geologic conditions at most sites to be modeled are difficult to interpret. Problems arise when one tries to assign appropriate aquifer parameters to an area being modeled. Several field methods aid in aquifer characterization, but often give conflicting results. Field data are also usually sparse and unevenly distributed. If, when setting up the input file for a computer model, poor or ill-founded choices are made from seemingly adequate field information the results of modeling may be questionable or even invalid.

Purpose

The purpose of this study is to use published and field data as inputs in the United States Geological Survey (USGS)

Two Dimensional Solute Transport and Dispersion Groundwater computer model (known as MOC) of Konikow and Bredehoeft (1978). Two different methods were used to calculate the hydraulic conductivity values. The range of values calculated was used in MOC. Dispersivity was varied to test the sensitivity of the model to this parameter. The resultant plume patterns in the form of iso-concentration contour maps for specific instants in time from the computer output were compared to each other and field data. The model results were also compared to field data and used as a tool to better estimate field hydraulic conductivity.

Location, Geology, and Hydrogeology of the Study Area

The study area is located in section 14 of T4N R5E northwest of Beatrice in Gage County, Nebraska (Figure 1.1). The southwest quarter of section 14 is the specific area targeted for this study. Here, a contamination event consisting of the loss of raw fertilizer product from a mixing basin occurred in April, 1985 at a fertilizer production plant owned by Cominco American, Inc.. The event occurred over a one to two week time period.

Part of the Beatrice West Quadrangle topographic map is reproduced in Figure 1.2. This map also shows the location of a cross section of unconsolidated sediments along the south edge of section 14.

In general, the upper silts and clays in the study area

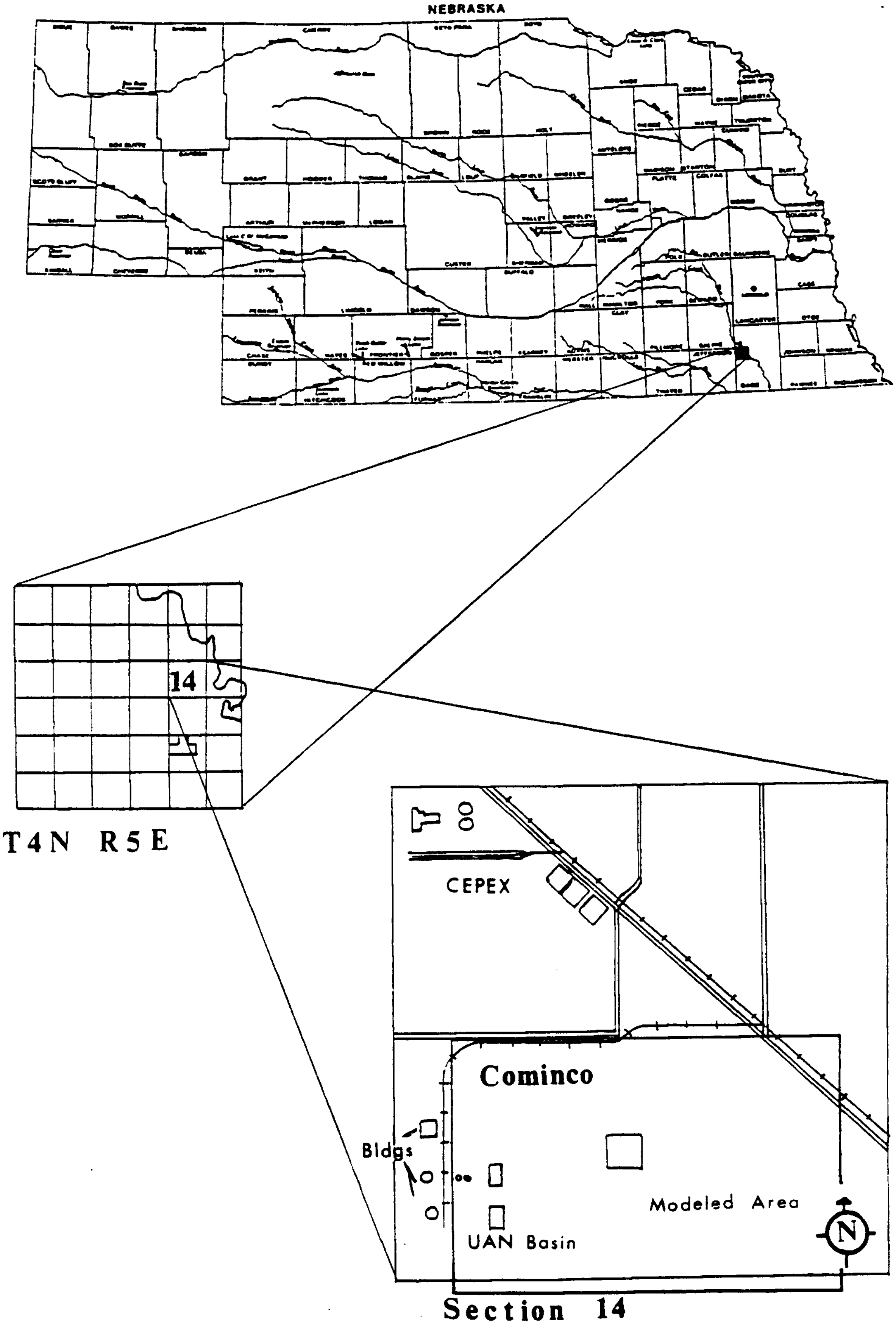


Figure 1.1 Location of Study Area

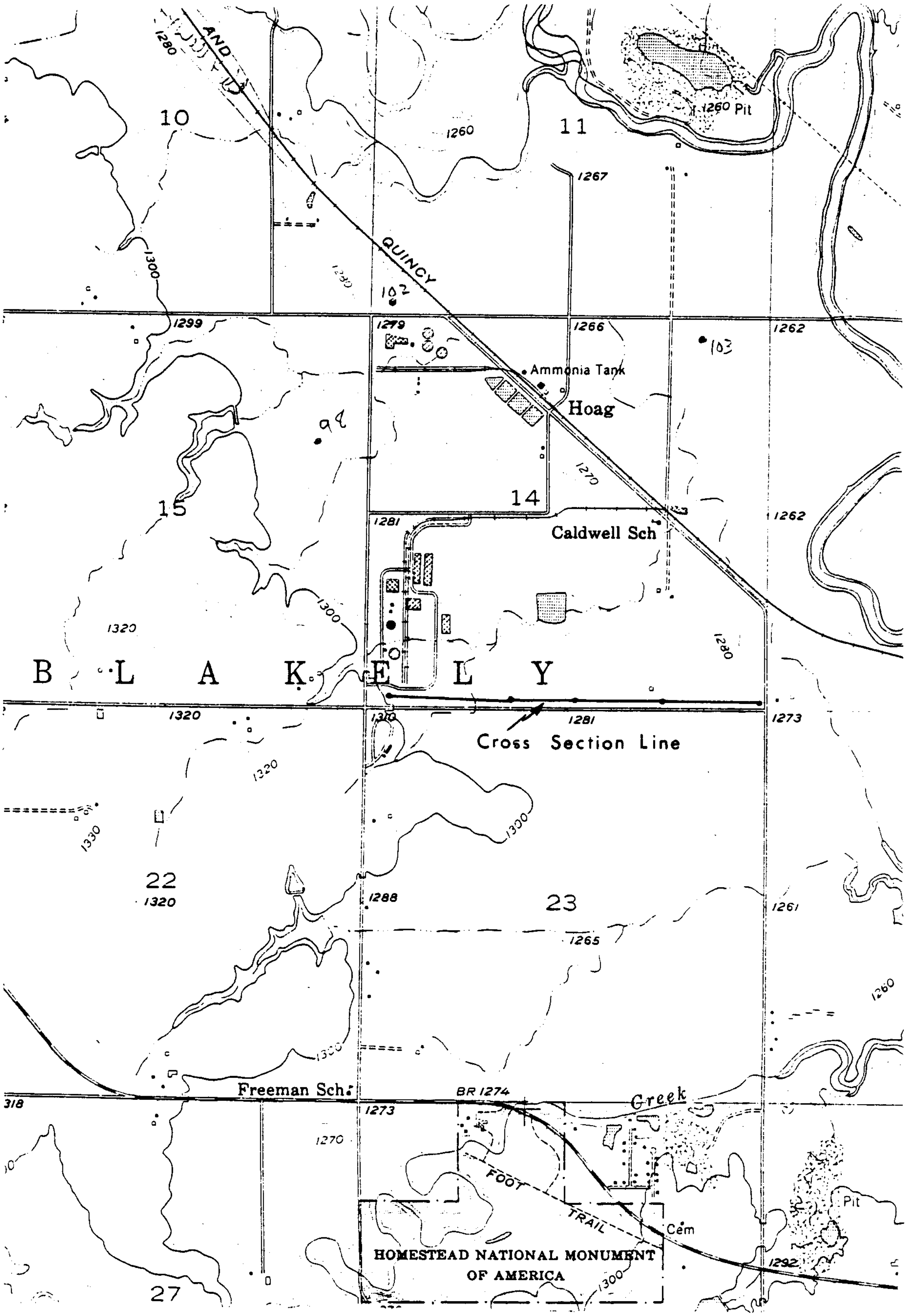


Figure 1.2 Part of the Beatrice West Quadrangle and Location of Cross Section

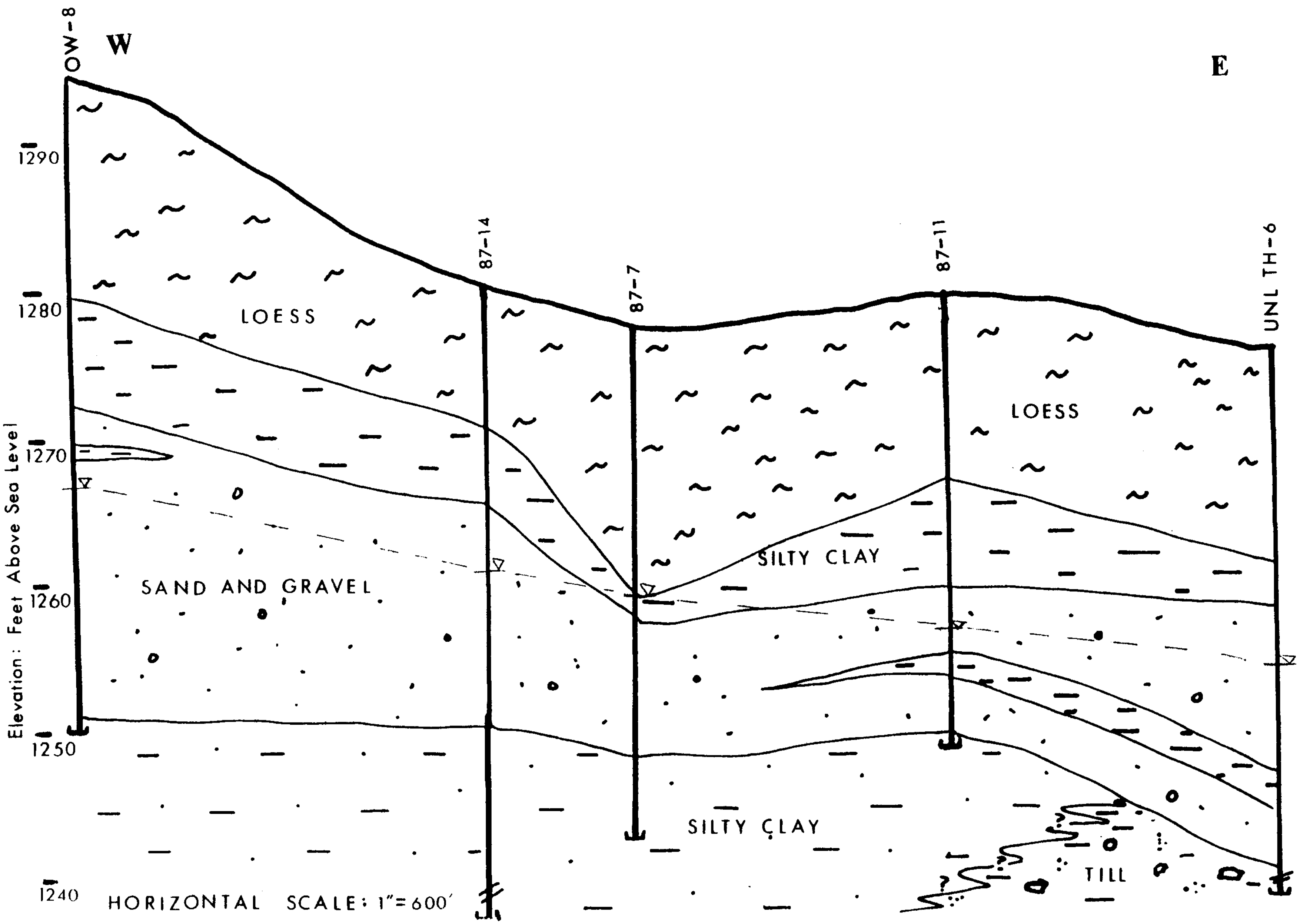


Figure 1.3 Cross Section Along Southern Edge of Section 14

are not saturated. The sand and gravel unit is saturated. The lower silt or silty clay has a low permeability.

A thick deposit of interbedded sands and gravels lies in a buried paleovalley directly north of the study area (Ellis, 1981). These sand and gravel deposits range from 0 to 200 feet in thickness and are the main source of groundwater for much of that area, including the City of Beatrice. The paleovalley was cut into Cretaceous age Dakota Group shales and sandstones and Permian shales and limestones (Ellis, 1981). The Dakota is absent along the axis of the paleovalley (Tabidian, 1987).

Few wells in this area are completed in the Permian limestones because of low yields. Some wells are reported to be completed in the Dakota sandstone and have relatively high yield (Ellis, 1981). Most domestic wells are completed in shallow alluvial sand and gravel units or the buried paleovalley sediments.

Chapter 2
PREVIOUS INVESTIGATIONS

Aquifer Parameters

Major sources of information came from the Nebraska Department of Environmental Control (NDEC) files for Cominco American Inc. (1985-1989), and CEPEX, formally Phillips Petroleum, (1980-1988). Well logs, groundwater elevations, and lab results of nitrate analyses were included in these files.

Wood (1985), Kitchen (1987), Tabidian (1987), and Dreeszen and Reed (1956) were reviewed for geologic and hydrogeologic conditions in the area surrounding the study site. A study of stream-aquifer relationships in the Big Blue River by Ellis (1981) and county test hole log documentation (Conservation and Survey Division, 1953) were also consulted.

History of Contamination and Clean Up Efforts

Cominco American Inc., a fertilizer production plant located in the southwest quarter of section 14 of T4N, R5E, northwest of Beatrice, Nebraska, has two basins used for the mixing and storage of raw nitrogen fertilizer product. The plastic liner in one of these basins developed a tear during April, 1985. Approximately one to two weeks passed before the tear was discovered and mended. Subsequently, an estimated 30,000 gallons (50 tons of nitrogen) of 32% Urea-Ammonium-Nitrate (UAN) leaked into the subsurface.

The actual amount of UAN solution which leaked is not known. HWS Technologies (HWST, 1985), the geologic consultant hired by Cominco to do all the field investigations and reports, estimated approximately 10,000 gallons (~17 tons of nitrogen) or less had been lost through the tear in the plastic liner. An independent consultant, Science Applications International Corp. (SAIC, 1986), estimated approximately 25,000 gallons (42.5 tons of nitrogen) had been lost. A later HWST report (1987) used 30,000 gallons (50 tons of nitrogen) as the volume which had leaked.

A second leak from the same basin is thought to have occurred from approximately December, 1985 until May, 1986. Few field data are available concerning this leak. Clean up operations were underway when the second leak was discovered and these actions were felt to be appropriate and adequate to handle it. No additional investigation of this leak was undertaken.

Upon discovery of the liner tear, Cominco began basin repair and an evaluation of contamination potential. A recovery well immediately adjacent to the basin was installed in the summer of 1985 by HWST. The water pumped from this well (Recovery Well-1) contained nitrogen levels high enough to be reused in the fertilizer production plant (see Table 2.2). Ten observation wells were also installed

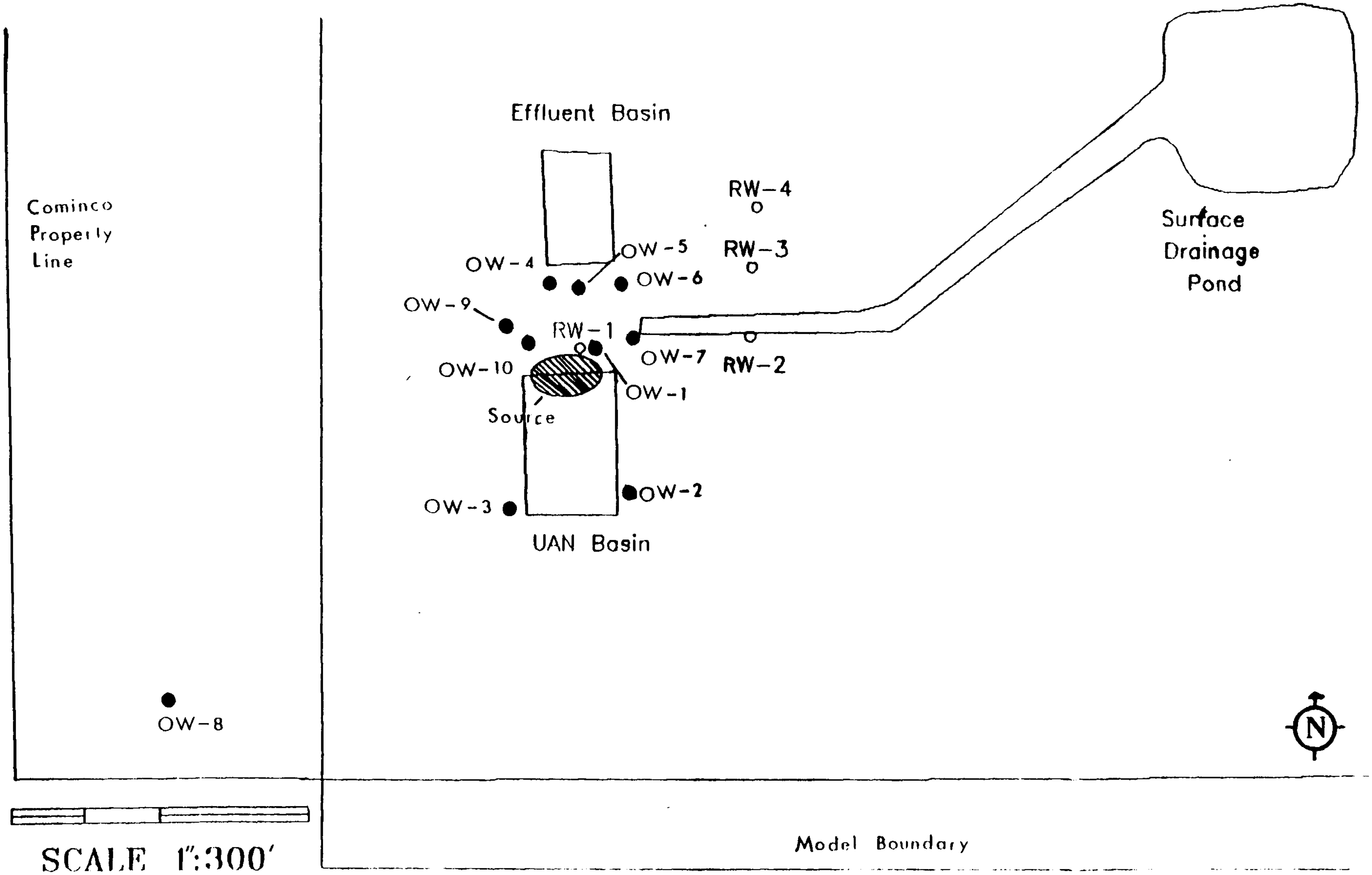


Figure 2.1 Location of Recovery Wells, Observation Wells, and Source of Contamination

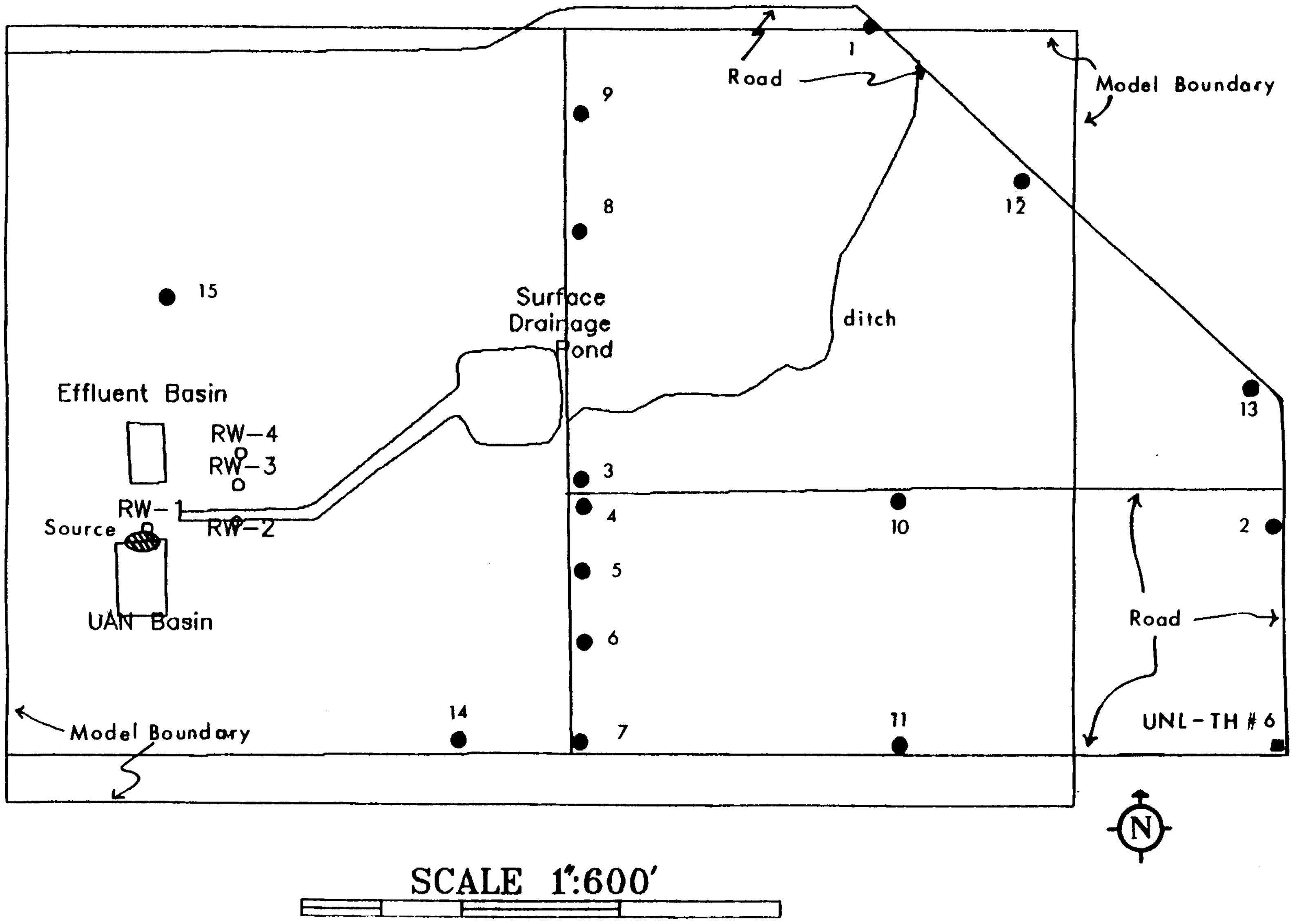


Figure 2.2 Location of Test Holes Drilled in October, 1987

at that time (Figure 2.1). Three more recovery wells were installed in December 1985 (Figure 2.1). The drillers' logs of the 4 recovery wells and the 10 observation wells are included in Appendix A. Surface elevation (surveyed in) and water table elevation data of the recovery and observation wells are also included in Appendix A.

Thirteen test holes using a solid stem auger and 2 test holes using a hollow stem auger were drilled in October, 1987 (~2.5 years after the leak) to further delineate aquifer contamination (see Figure 2.2 for locations, Appendix A for drillers' logs). At that time, aquifer samples from different depths were retrieved using a split spoon device, stored on ice, and later analyzed for total nitrogen content (Table 2.1). Shelby tube samples were taken of the underlying silty clay unit for permeability testing. This testing yielded a value of 1×10^{-6} cm/sec ($\sim 2.2 \times 10^{-2}$ gpd/ft^2) (HWST, 1987).

The following table summarizes the nitrogen data from the split spoon sampling done in October, 1987. The samples were retrieved from the 1 1/2 foot split spoon device at five foot intervals.

Table 2.1
Nitrogen Data from Oct. 1987 Drilling Program[1]

Test Hole #	Depth of Sample feet	Total Nitrogen mg/kg	Sediment Type c or f[2]
1	35-36.5	0.1	f
2	20-21	0.1	c
3	20-21.5	0.1	c
4	17	1.3	c
	20-21.5	0.1	c
5	20-21.5	0.1	c
6	20-21.5	0.1	c
7	20-21.5	2.8	c
	25-26.5	0.1	c
8	20-21.5	0.1	c
	25-26.5	0.14	c
9	13-15	0.1	c
	25-26.5	2.4	c
10	20-21.5	4.4	c
	25-26.5	11.4	c
11	20-21.5	0.5	c
	25-26.5	14.0	c
12	25-26.5	2.7	c
14	20-21.5	10.6	c
	25-26.5	10.0	c
	31-31.5	9.9	c
	34	52.4	c
15	14	31.1	c
	20-21.5	195.0	c
	25-26.5	6.9	c
	29	127.1	c

[1] Source: HWST (1988)
[2] c = coarse grained sediment, sand and/or gravel
f = fine grained sediment, clay and/or silty clay

A seven hour pump test was carried out on July 3, 1985 at Recovery Well 1 (RW-1). The well pumped at an average rate of 20 gallons per minute (gpm). Using the data from this test and the graphical distance-drawdown method of analysis (the Cooper-Jacob method, U.S. Dept. of the Interior, 1981) a hydraulic conductivity of 1500 gallons per day per square foot (gpd/ft^2) was calculated. The data from this test are included in Appendix B.

Water samples from the recovery wells were analyzed for nitrate-nitrogen by HWST's and Cominco's laboratories. These data are presented in Table 2.2 and in Appendix C. This information was useful in determining contaminant plume position and rate of movement.

Table 2.2
Nitrate-Nitrogen Data (mg/l), 1985-1986

		Well						
Date	Days After Leak[*]	RW-1	RW-2	RW-3	RW-4	OW-1	OW-7	OW-8[1]
1985								
5-21[2]	51	--	--	--	--	45,000	325	62
6-14	75	11,460	--	--	--	21,000	412	--
6-19	80	12,000	--	--	--	--	--	--
7-3[3]	94	3,500	--	--	--	5,500	1,000	18
7-3[4]	94	2,600	--	--	--	1,300	800	--
7-10	101	--	--	--	--	--	24,700	--
8-5	127	40,000	--	--	--	--	--	--
9-11	163	16,000	--	--	--	--	--	--
9-17	169	39,000	--	--	--	--	18,500	--
9-23	175	22,400	--	--	--	--	1,300	--
10-17	200	--	--	--	--	11,200	2,025	--
11-18	232	26,000	--	--	--	--	--	--
12-11[2]	255	--	520	230	200	--	--	--
1986								
1-8	283	5,900	--	--	--	--	--	--
1-15	290	--	580	180	148	--	--	--
2-28	333	2,600	965	206	173	--	--	--
3-20	354	--	2,000	650	130	9,600	5,600	21
7-17	473	--	1,200	900	190	4,100	4,300	16

Notes:
[*] Approximate, assuming April 1 as beginning of leak
[1] Background Well
[2] After Drilling
[3] Before Pump Test
[4] After Pump Test
Source: HWST (1986)

Some detection of high nitrate-nitrogen levels in the groundwater was done with specific conductance metering by HWST (1986, 1987). The addition of UAN to water was correlated in a relative manner to an increase in the conductivity (specific conductance) of the water by HWST (1986). These data are available in Status of Monitoring and Remediation Report by HWST (1986). It was determined that no other anions were present in the groundwater which would increase the conductivity. Therefore, conductivity measurements were used to detect nitrate contamination. The initial nitrate-nitrogen detection using this method occurred in Observation Well 7 (OW-7) June 19, 1985, approximately 80 days after the leak. This well is about 150 feet down gradient from the leak, therefore

$$\frac{150 \text{ ft.}}{80 \text{ days}} = 1.875 \text{ ft./day.}$$

However, HWST (1985) used estimated aquifer parameter values and calculated groundwater velocity to be approximately 0.3 ft./day using the formula (Freeze and Cherry, 1979, p.71)

$$v = \frac{K\,i}{n}$$

where v = specific discharge
K = hydraulic conductivity
i = piezometric gradient
and n = porosity

$$0.3 \text{ ft./day} = \frac{60 \text{ ft./day } (.001 \text{ ft./ft.})}{0.20}$$

This earlier groundwater velocity value calculated by HWST is far below the measured value. This calculation was done previous to any extensive field investigations and points out the discrepancies which can occur between field measurements and office calculations.

Preliminary Computer Modeling of Site

A computer model of groundwater flow and contaminant transport was prepared in December, 1986 (HWST, 1987). The PLASM (Prickett and Lonnquist, 1984) model was used to determine steady state conditions at the contamination site and the adjacent quarter section. Using the resultant steady state head values, the RANDOM WALK (Prickett et al, 1981) transport model was applied. The two known contaminant leaks and several pumping periods were simulated. One of the conclusions of this study was that the leading edge of the contaminant plume may have moved off Cominco property by January, 1987. Continued computer modeling was recommended "to evaluate the progress of aquifer restoration" (HWST, 1987).

Essential aquifer parameters such as transmissivity and permeability can not be varied spatially across the modeled area using RANDOM WALK. When modeling was continued for the Cominco site, the MOC model was chosen. Aquifer thickness and transmissivity can more accurately represent varying aquifer conditions than the RANDOM WALK model.

Properties of Contaminant

The density of 32% UAN is 11.1 pounds per gallon, compared to 8.34 pounds per gallon for water. Because of this high density, 32% UAN will behave as a Dense Non-Aqueous Phase Liquid (DNAPL). It has high solubility in water, approximately 118 g/100cc in water 0°C (Perry and Chilton, 1973). Table 2.3 summarizes some of the physical and chemical properties of 32% UAN.

Table 2.3
Properties of 32% UAN *

specific gravity	1.327 at 60°F
density	11.1 lbs./gal.
chemical properties	
nitrate	45.2 %
urea	34.7 %
water	20.1 %
nitrogen analysis	
ammonia	7.9 %
nitrate	7.9 %
urea	16.2 %
free ammonia	0.04 %
Total	32 % (320,000 mg/l)
chemical formulas	
urea	CH_4N_2O
ammonium nitrate	NH_4NO_3

*source: HWST, 1986

Chapter 3
MODEL DEVELOPMENT

Model Description

The USGS computer model of Two-Dimensional Solute Transport and Dispersion in Groundwater (Konikow and Bredehoeft, 1978) was used to model the study area. Input data such as hydraulic conductivity and dispersivity are relatively easy to vary in the MOC model. The version used allows for a maximum of 40 rows by 40 columns for the groundwater flow simulation and a maximum grid size of 20 rows by 20 columns for the solute transport component. An example of the input file is included in Appendix D.

The transport model links the groundwater flow equation with the solute-transport equation. An alternating direction implicit procedure is used to solve a finite-difference approximation to the groundwater flow equation and the method of characteristics (MOC) is used to solve the solute-transport equation. Hence, the name MOC for the model. The method of characteristics is a particle-tracking scheme used to represent convective transport.

The model will allow for withdrawal and/or injection wells, limited only by the total number of cells used in the simulation (one injection or withdrawal well possible for each cell). Spatial variability of aquifer thickness, transmissivity, boundary conditions, diffuse recharge and discharge, and initial heads and concentrations are also options available in the MOC model. It is limited in other aspects, however. Limiting assumptions are as follows (Konikow and Bredehoeft, 1978, p.4):

> "1. Darcy's law is valid and hydraulic head gradients are the only significant driving mechanism for fluid flow.
>
> 2. The porosity and hydraulic conductivity of the aquifer are constant with time, and porosity is uniform in space.
>
> 3. Gradients of fluid density, viscosity, and temperature do not affect the velocity distribution.
>
> 4. No chemical reactions occur that affect the concentration of the solute, the fluid properties, or the aquifer properties.
>
> 5. Ionic and molecular diffusion are negligible contributors to the total dispersive flux.
>
> 6. Vertical variations in head and concentration are negligible.
>
> 7. The aquifer is homogeneous and isotropic with respect to the coefficients of longitudinal and transverse dispersivity."

Only three of the above statements appear valid for the modeled area and situation. No vertical head variations are believed to occur at the site, at the scale which is being examined (the first part of number 6). Darcy's law is believed to be valid (the first part of number 1) and porosity and hydraulic conductivity of the aquifer are constant with time (number 2).

Other assumptions do not appear to be valid for the field site and are possible sources of inaccuracies and deficiencies in the final model output. The 32% UAN which leaked into the groundwater had a very high density (11.1 lbs./gal.). This density almost certainly caused the contaminant to immediately sink to the bottom of the aquifer, without significant mixing with the groundwater it passed through (contrary to the second part of assumption 6). Unknown relief in the configuration of the bottom of the aquifer may have led to ponding of dense UAN and/or flow of UAN in unpredictable directions due to gravitational forces. The density factor may have been a significant driving mechanism for fluid flow (the second part of number 1). The high density of the UAN may have affected the velocity distribution, also (number 3).

Nitrate (NO_3-)is the stable form of nitrogen in the groundwater. Little ammonia was found in the groundwater. The nitrogen present in UAN solution changed to nitrate through an oxidation process, nitrification. This chemical reaction is contrary to assumption 4, which states no reactions occur.

Drillers' logs indicate fining upwards sequences within the sand. This evidence negates assumption number 2, which states porosity is spatially uniform.

Model Set Up

Figure 3.1 shows the modeled area and the grid layout used for the model. The groundwater flow component used the larger 40 by 29 grid outlined in this figure, while the transport part of the MOC model used the 20 by 20 grid outlined with a thicker line within the larger grid.

The MOC model specifies the outer rows and columns of the grid as no-flow boundaries. Constant head boundaries were specified just inside the no-flow boundaries on the outer edges. This was done because the boundaries are beyond the influences of pumping stresses. The model was run in the transient mode because of the variable pumping schedule used.

Aquifer Parameters

The aquifer parameters which varied spatially were transmissivity, aquifer thickness, and initial water elevation. Figures 3.2 and 3.3 are computer generated contour maps which were made from the input arrays for aquifer thickness and initial water elevation respectively. Transmissivity (T) is a function of saturated aquifer thickness (b) and hydraulic conductivity (K),

$$T = K\,b.$$

Figure 3.4 is a contour map which represents the transmissivity when hydraulic conductivity is uniformly 1500 gpd/ft^2. This value for hydraulic conductivity is the original estimate made by HWST (1986) from pump test data.

The aquifer thickness map was derived from drillers' logs of the recovery and observation wells and test borings

Grid Layout, Thicker Line is Transport Grid

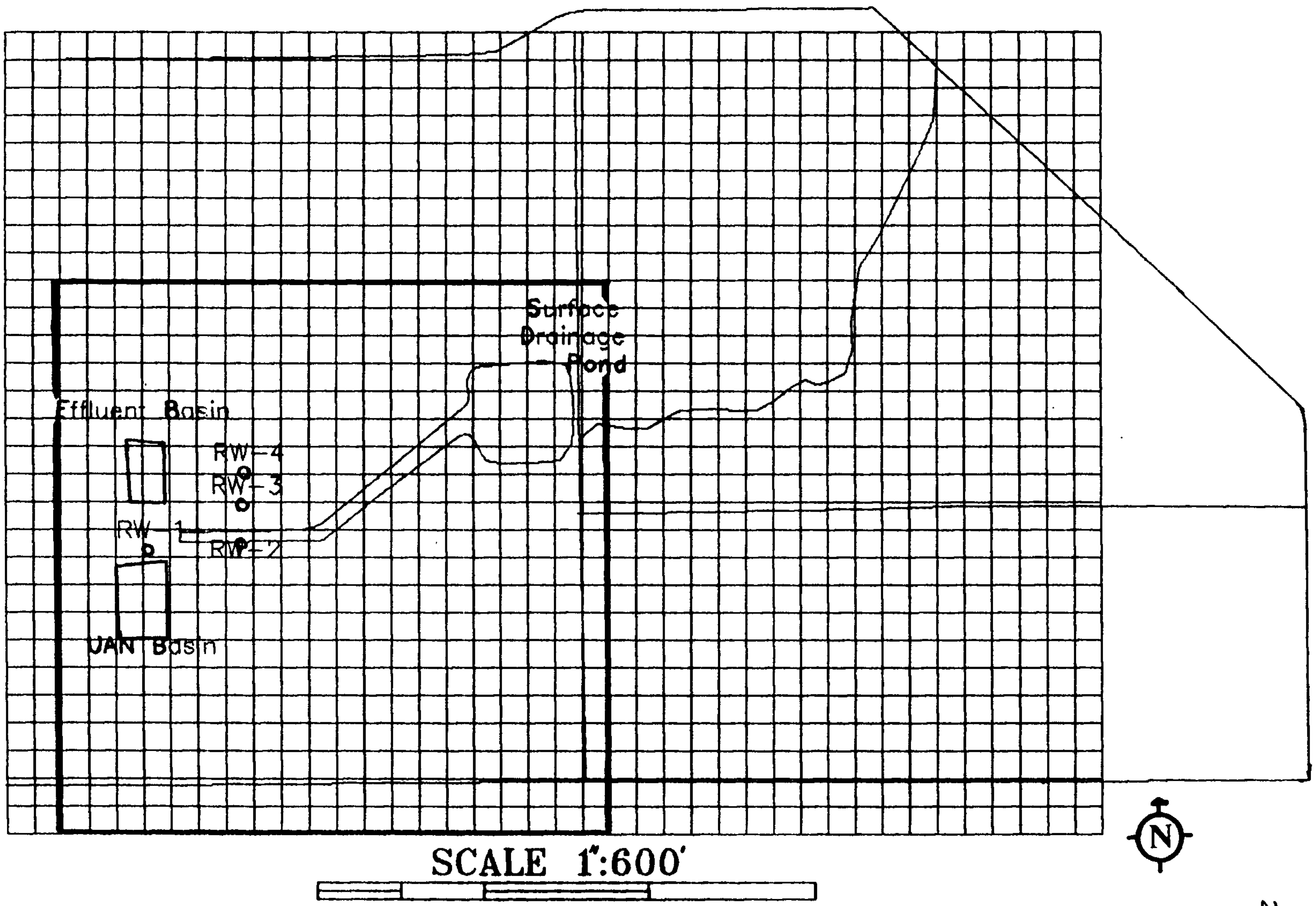
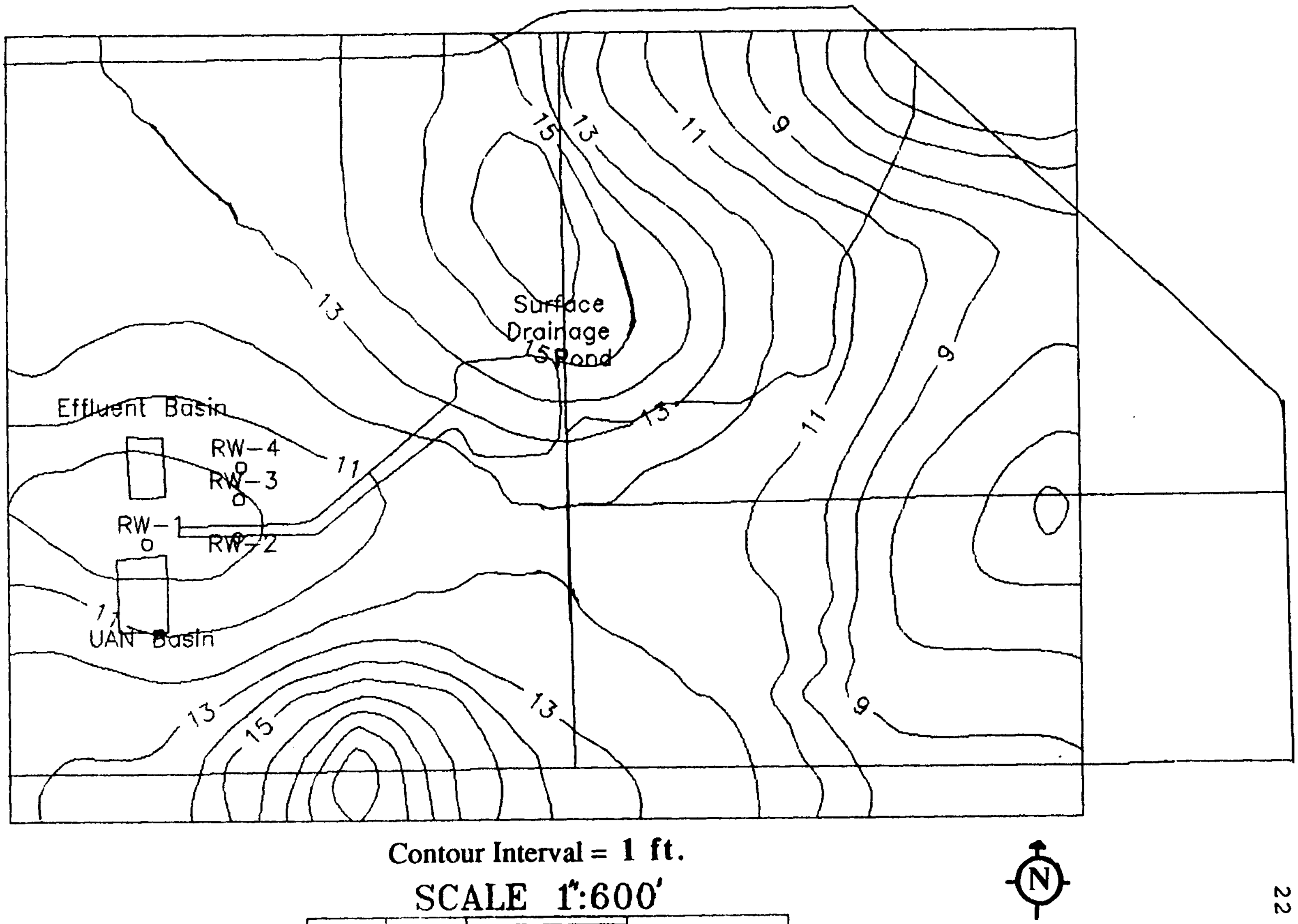


Figure 3.1 Grid Layout

Aquifer Thickness

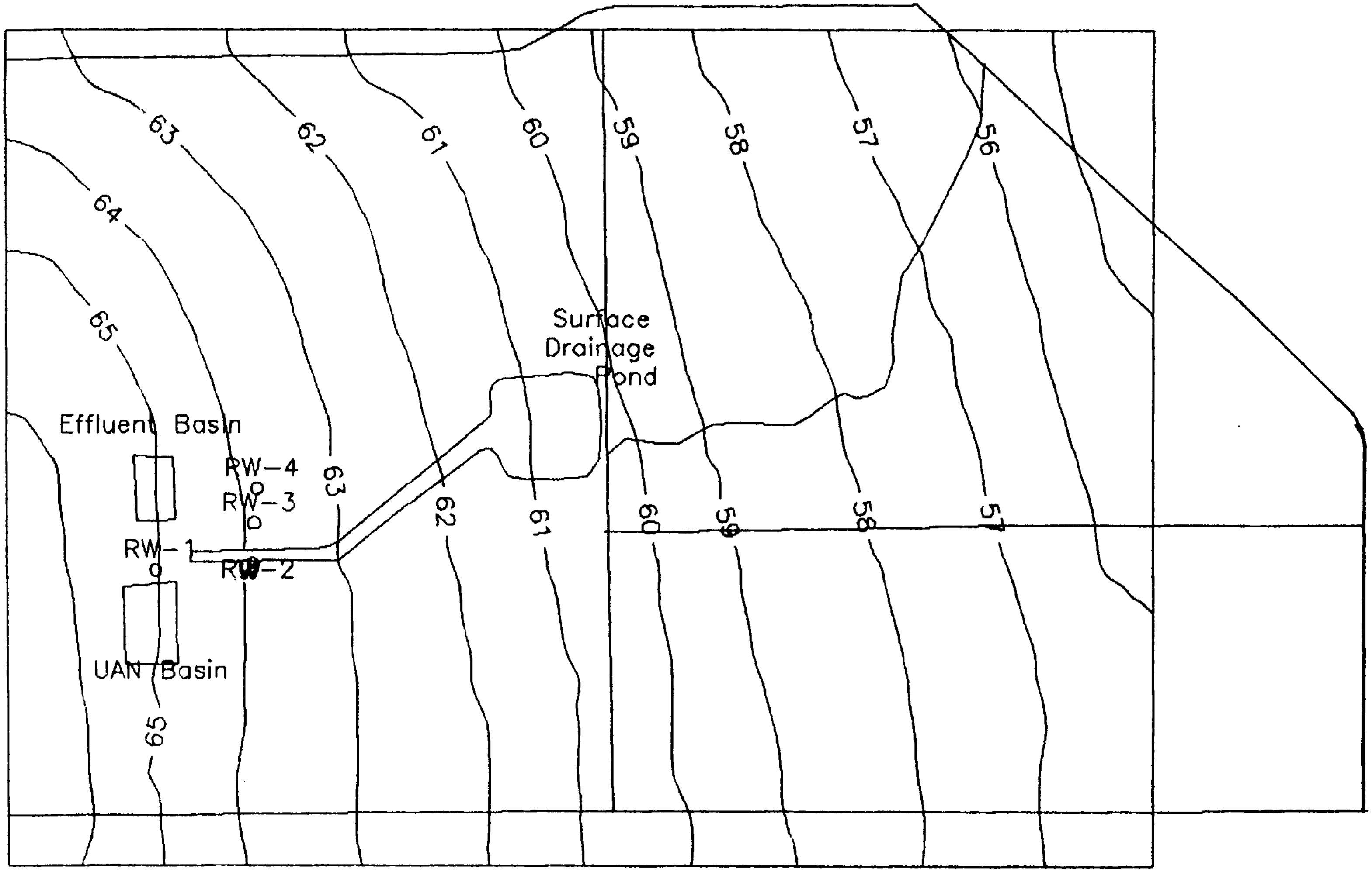


Contour Interval = 1 ft.

SCALE 1":600'

Figure 3.2 Aquifer Thickness

Initial Water Table Elevation



Contour Interval = 1 ft., 59=1259 feet above sea level

SCALE 1":600'

Figure 3.3 Water Elevation

Transmissivity (gpd/ft.)

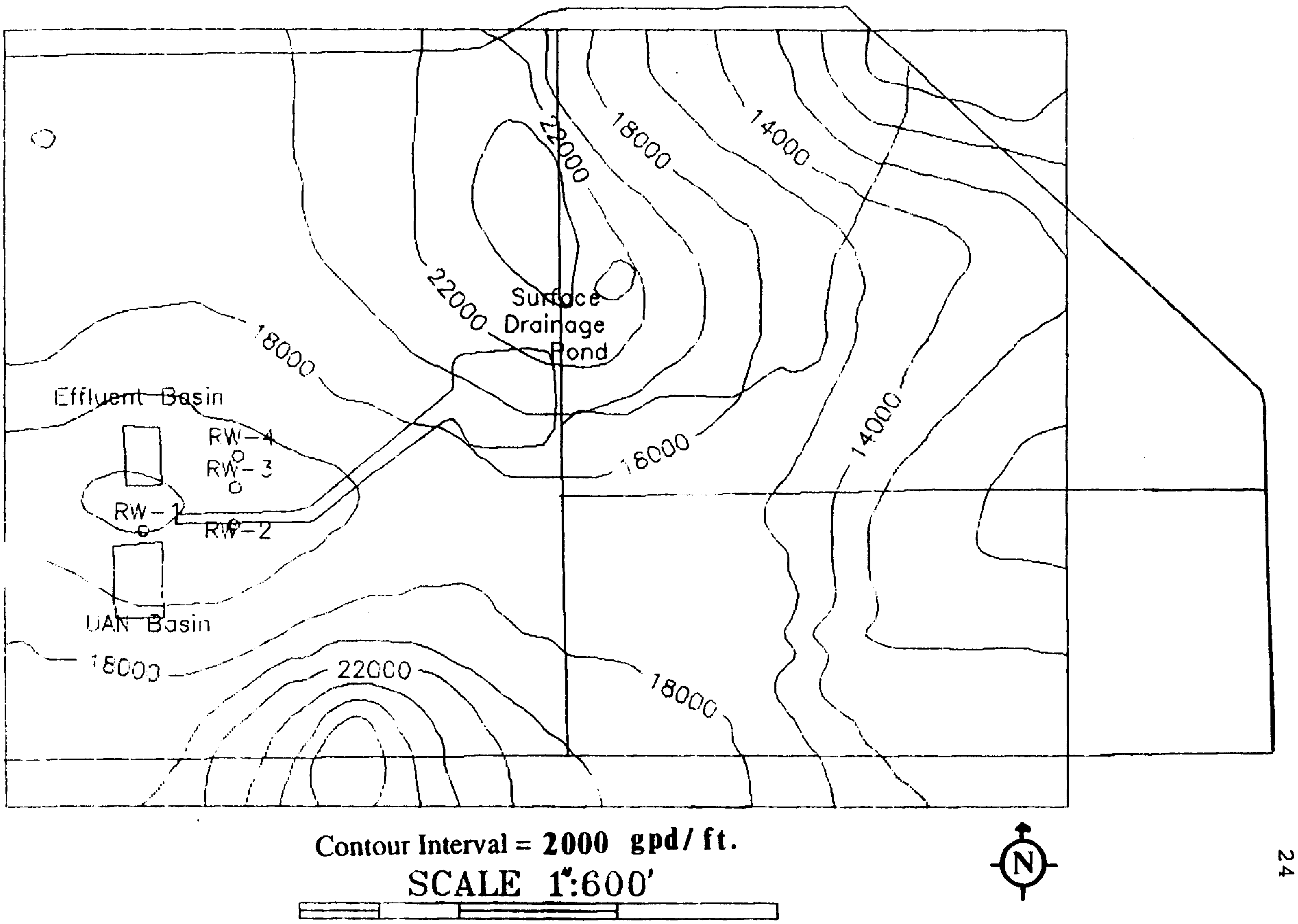


Figure 3.4 Transmissivity

included in Cominco's monitoring and status reports (HWST, 1985-1988). Aquifer thickness values for the center of each grid were interpolated from a hand drawn contour map (in the pocket) made using this information.

The initial water elevation map was derived from the same sources as the aquifer thickness map (in pocket). Piezometric contour maps from Wood (1985) and Tabidian (1987) were compared to the available data. These maps were for a larger area, covering several square miles, but agreed in the general direction and gradient of groundwater flow and were compared to the initial water elevation map made for this model.

A Fortran program (Appendix E, Baxter, 1989) was written to multiply the aquifer thickness array by the (constant) hydraulic conductivity, to arrive at an array for the input file for transmissivity.

The non-variable aquifer parameters and model set up information are summarized in Table 3.1. They were chosen from information in the monitoring and status reports of Cominco American Inc. (HWST, 1985-1989). Freeze and Cherry (1979, p.37) give a range of values of porosities for sand and gravel. The porosity of 25% (0.25) used in the model is at the low end of their range. However, poorly sorted sediment has a lower porosity than well sorted sediment. The sand and gravel unit at the study site is poorly sorted.

The storage coefficient of 0.14 was obtained from the pump test data. This value falls in the range of values

Freeze and Cherry (1978, p.61) give for an unconfined aquifer. A significantly different value of storage coefficient may have been realized had the pump test continued longer. Todd (1980) suggests a minimum of 30 hours of pumping time for a aquifer composed primarily of fine sand. The impact of delayed yield from gravity drainage of water in the unsaturated zone can be significant, especially in an unconfined aquifer.

A recharge value of 2 inches per year was used in the initial modeling effort (HWST, 1987) and in this model. Emery (1966) estimated a groundwater recharge of 1.5 inches per year for Saline County, which is about 10 miles northwest of the study area.

Table 3.1 summarizes the aquifer parameters which were not varied spatially within the model.

Table 3.1
Non-Variable Model Parameters

Porosity	0.25
Storage Coefficient	0.14
Longitudinal Dispersivity	10* ft.
Transverse Dispersivity	4* ft.
Diffuse Recharge	2 inches/year**
cell size	100 ft. x 100 ft.
number of rows	29
number of columns	40
number of particles	2925
particles per node	9

* used for most model runs, exceptions noted in text and on figures
** can be a variable array

Longitudinal and transverse dispersivity values of 10 and 4 feet respectively which are used in the model are estimates based on trial-and-error adjustments. Konikow (1977) used this method in the Rocky Mountain Arsenal study. Dispersivity (both longitudinal and transverse) was set at 100 feet in Konikow's MOC simulation. Various references, including Anderson (1979), Freeze and Cherry (1979), and Jensen (1987) have stated that the value of dispersivity is a function of the transport distance. According to Anderson (1979), field tests of dispersivity impart larger values than laboratory tests using the same sediment and contaminant. Longitudinal dispersivity values ranging from 0.034 to 15.2 meters (0.11 to 49.8 feet) for alluvial aquifers are listed in Anderson (1979).

Hydraulic Conductivity Estimation

A range of values for hydraulic conductivity was used because of the difference seen in values calculated from pump test data and the particle size method of hydraulic conductivity estimation. Table 3.2, a particle size analysis chart (Rowan, 1986), was used in conjunction with drillers' logs to determine hydraulic conductivity. Only sediment in the sand and gravel unit (below the top 10 to 12 feet of clay and silt) was considered. A hydraulic conductivity value for each sediment interval was multiplied by the thickness of that interval. All values were added together and divided by the total thickness examined. The results are presented in Table 3.3.

Table 3.2
Estimated Hydraulic Conductivity from Particle Size Descriptions
(Rowan, 1986, modified from Reed and Piskin)

	Degree of Sorting			Silt Content		
Grain Size	Poor	Moderate	Well	Slight	Mod.	Very
CLAY AND SILT						
Clay	0					
Clay, silty	10					
Silt, clayey	20					
Silt	50					
Silt, sandy	80					
SAND AND GRAVEL						
Very fine sand	100	150	200	170	140	100
VF to F sand	200	200		180	150	100
VF to M sand	270			240	200	155
VF to C sand	360			300	230	180
VF to VC sand	440			380	300	220
VF sand to F gravel	570			500	390	285
VF sand to M gravel	740			600	490	370
VF sand to C gravel	960			800	640	480
Fine sand	200	300	400	250	200	150
F to M sand	400	500		360	295	225
F to C sand	430			400	320	240
F to VC sand	525			450	355	260
F sand to F gravel	660			550	440	330
F sand to M gravel	850			700	560	425
F sand to C gravel	1085			800	650	540
Medium sand	500	600	700	475	385	300
M to C sand	550	700		540	430	315
M to VC sand	630			550	455	365
M sand to F gravel	775			625	510	390
M sand to M gravel	980			850	610	490
M sand to C gravel	1230			1000	810	615
Coarse sand	600	800	1000	700	550	400
C to VC sand	700	1000		700	560	425
C sand to F gravel	870			800	655	510
C sand to M gravel	1100			850	700	550
C sand to C gravel	1380			1000	745	690
Very coarse sand	800	1100	1400	850	700	550
VC sand to F gravel	1000	1600		900	775	650
VC sand to M gravel	1270			1100	920	740
VC sand to C gravel	1550			1200	985	775
GRAVEL						
Fine gravel	1200	1600	2000	1200	1050	800
F to M gravel	1500	2500		1500	1250	1000
F to C gravel	1830			1750	1415	1080
Medium gravel	1800	2400	3000	1800	1500	1200
M to C gravel	2200	3500		2200	1815	1425
Coarse gravel	2500	3500	4500	2500	2125	1750

(NOTE: Units are gallons per day per square foot)

Table 3.3
Average Hydraulic Conductivity Using Particle Size Descriptions[3]

Well[1]	Aquifer Thickness	Average Hydraulic Conductivity (gpd/ft^2)
RW-1	9.5	316
RW-2	10	460
OW-1	10	425
OW-2	11	500
OW-3	12	521
OW-4	10	348
OW-5	8	425
OW-6	8	275
OW-7	10	390
OW-8	17	296
OW-9	9	400
OW-10	9.5	318
UNL TH6[2]	21	405

[1] RW-3 and RW-4 logs unavailable
[2] Univ. of Nebr. Test Hole #6
[3] from Drillers' Logs

The average of the 13 values in Table 3.3 is 391 gpd/ft^2, considerably lower than the 1500 gpd/ft^2 value derived from pump test data. There are several possible reasons for this difference. 1) The pump test was conducted for only 7 hours. This may not have been enough time to give a true representation of aquifer conditions. 2) The observation wells may have been too close to the pumping well to give accurate readings. Equations used in analyzing pump test data are based on groundwater flow being horizontal with no vertical components. 3) The drillers' logs may be biased toward finer sediments (silt to very fine sand) and therefore hydraulic conductivity estimation would be too low. 4) The particle size chart agrees with ranges and Todd (1980) and is widely used, but may not be entirely accurate.

Concentration

An initial concentration array was used to introduce the contaminant into the modeled area. In early trials, several simulated wells were used to inject the pollutant. Numerical oscillation and numerical dispersion were seen in the concentration output during runs of the model when the contaminant was introduced in this manner. This problem is inherent to this and other models in the first six or so time periods (Konikow, personal communication, 1989). Anderson (1979, p.130) states that "numerical dispersion arises because of the truncation of the Taylor series commonly used to generate finite difference approximations." Anderson suggests using small grid spacings when the dispersion coefficient is small. Initial model simulations used a spacing of 400 feet by 300 feet, which proved to be too large.

Actual concentrations of the leaked contaminant were too large for the format of the input array. 1000 milligrams per liter (mg/l) was used to represent the initial concentration of the contaminant.

It was found that the modeled pattern of the contaminant movement remained the same, despite the initial input concentration of the contaminant. The initial modeled concentration was entered into the grid in the cells located at column 4, row 20 and column 5, row 20. This model location corresponds to the northern edge of the basin which leaked (see Figure 2.1). The output concentration arrays may be viewed as a scaled version of the original contaminant rather than an actual concentration.

The second leak was not modeled because it would have required the use of injection wells. As mentioned previously, this particular method of introducing pollutant caused numerical oscillation and instability in the output of early trials. The instability was found in the first six or so time periods. The results of these first time periods could be ignored, as is often recommended (Konikow, personal communication, 1989). However, the first time periods were crucial in calibrating the model to field data in this model simulation and could not be thrown out.

Calibration

Initial water table elevations were calibrated by comparing them to field data available in Cominco monitoring and status reports (HWST, 1985-1989). Regional water table configuration maps (Conservation and Survey Div., 1980) were consulted as were the water table maps in Wood (1985) and Tabidian (1987). Early model runs utilized an initial time period of five years to check water levels and drawdowns. No pumping or contamination activity occurred during this five year period. The water levels were consistent over time, drawdowns minimal, and mass balance calculations stayed below ±10%.

Different combinations of constant head boundary conditions were tried during early runs of the model. These had little significant effect on the flow regime of the model. A constant head boundary on the outer edges was used. This was valid because the boundaries are beyond the influences of hydraulic stresses.

Pumping Schedule

The actual pumping schedule employed by Cominco was sporadic, especially at the beginning of the remediation endeavor. The following table (Table 3.4) summarizes the pumping schedule used in the model simulations. The grid location of each well is given as a footnote (see Figure 3.1 for location). The pumping rate is given in gallons per minute (gpm) and in cubic feet per second (cfs). The MOC model required the pumping rates be in cubic feet per second. The notation 1.4E-02 represents 1.4×10^{-2}.

Table 3.4
Pumping Schedule used for Computer Model

Model Pumping Period	Length of Time (yrs/days)	Time Accumulated (yrs/days)	Model Grid Location* of Wells	Pumping Rate cfs	Pumping Rate gpm
1	.08/29	.08/29	np		
2	.25/91	.33/120	np		
3	.08/29	.41/149	5-19	1.4E-02	6.28
4	.34/124	.75/273	np		
5	.08/29	.83/302	5-19	1.4E-02	6.28
			8-19	1.4E-02	6.28
			8-18	1.4E-02	6.28
			8-16	1.4E-02	6.28
6	.25/91	1.08/393	np		
7	.08/29	1.16/422	5-19	1.4E-02	6.28
			8-19	1.4E-02	6.28
			8-18	1.4E-02	6.28
			8-16	1.4E-02	6.28
8	.33/120	1.49/542	np		
9	.17/62	1.66/604	5-19	8.8E-03	3.95
			8-19	8.8E-03	3.95
			8-18	8.8E-03	3.95
			8-16	8.8E-03	3.95
10	.17/62	1.83/666	np		
11	.25/91	2.08/757	5-19	1.4E-02	6.28
			8-19	1.4E-02	6.28
			8-18	1.4E-02	6.28
			8-16	1.4E-02	6.28
12	.08/29	2.16/786	5-19	3.7E-03	1.66
			8-19	3.7E-03	1.66
			8-18	3.7E-03	1.66
			8-16	3.7E-03	1.66
13	.17/62	2.33/848	5-19	3.0E-03	1.35
			8-19	3.0E-03	1.35
			8-18	3.0E-03	1.35
			8-16	3.0E-03	1.35
14	.08/29	2.41/877	5-19	3.8E-03	17.1
			8-19	3.8E-02	17.1
			8-18	3.8E-02	17.1
			8-16	3.8E-02	17.1
15	.08/29	2.49/906	5-19	5.1E-02	22.9
			8-19	5.1E-02	22.9
16	.17/62	2.66/968	5-19	2.6E-02	11.7
			8-19	2.6E-02	11.7
			8-18	2.6E-02	11.7
			8-16	2.6E-02	11.7
17	.17/62	2.83/1030	5-19	5.0E-02	22.4
			8-19	5.0E-02	22.4
			8-18	5.0E-02	22.4
			8-16	5.0E-02	22.4

* np = no pumping
5-19 = RW-1, 8-19 = RW-4, 8-18 = RW-3, 8-16 = RW-2

Chapter 4
MODEL SIMULATIONS AND RESULTS

The MOC model was run varying hydraulic conductivity and dispersivity. Table 4.1 summarizes the combinations of hydraulic conductivity and dispersion used in the model simulations. All other aquifer parameters were held constant and were discussed in Chapter 3.

Table 4.1

Combinations of Hydraulic Conductivity and Dispersivity Used in MOC Simulations

Hydraulic Conductivity gpd/ft^2	Longitudinal Dispersivity feet	Transverse Dispersivity feet
2000	10	4
1500*	10	4
1000	10	4
750	10	4
500	10	4
375	10	4
1500	30	12
500	30	12
500	25	10

* Value calculated from pump test data

Model Sensitivities

The following table (Table 4.2) lists the specific iso-concentration maps to be discussed. Individual maps do not have the same contour intervals due to the wide range of the concentrations from time period to time period. Contour intervals are listed in the table as well as on the specific figure.

Table 4.3

List of Figures to be Discussed

Figure Number	K gpd/ft^2	Time days	Longitudinal Dispersivity feet	Contour Interval ppm
4.1	1500	29	10	25,300,600
4.2		149		25,200,400
4.3		394		10,50,100,200,300
4.4		423		10,50,100,200
4.5		544		5,10,50,100,150,200
4.6		668		5,10,50,100,150
4.7		880		5,25,50,75,100
4.8	1000	29	10	25,300,600
4.9		149		25,200,400
4.10		394		10,50,100,150,200
4.11		423		10,50,100,200
4.12		544		10,50,100,200
4.13		668		10,50,100,150
4.14		880		5,50,100
4.15	500	29	10	25,300,600
4.16		149		25,200,400
4.17		394		10,50,100
4.18		423		5,10,25
4.19		544		5,10
4.20		668		5,10
4.21		880		5,10
4.22	2000	149	10	10,25,100,200,300,400
4.23	750	149	10	25,200,400,500
4.24	375	149	10	25,100,250,500,600
4.25	500	149	25	25,100,200
4.26	500	149	30	25,100,200,300
4.27	1500	149	30	25,100,200

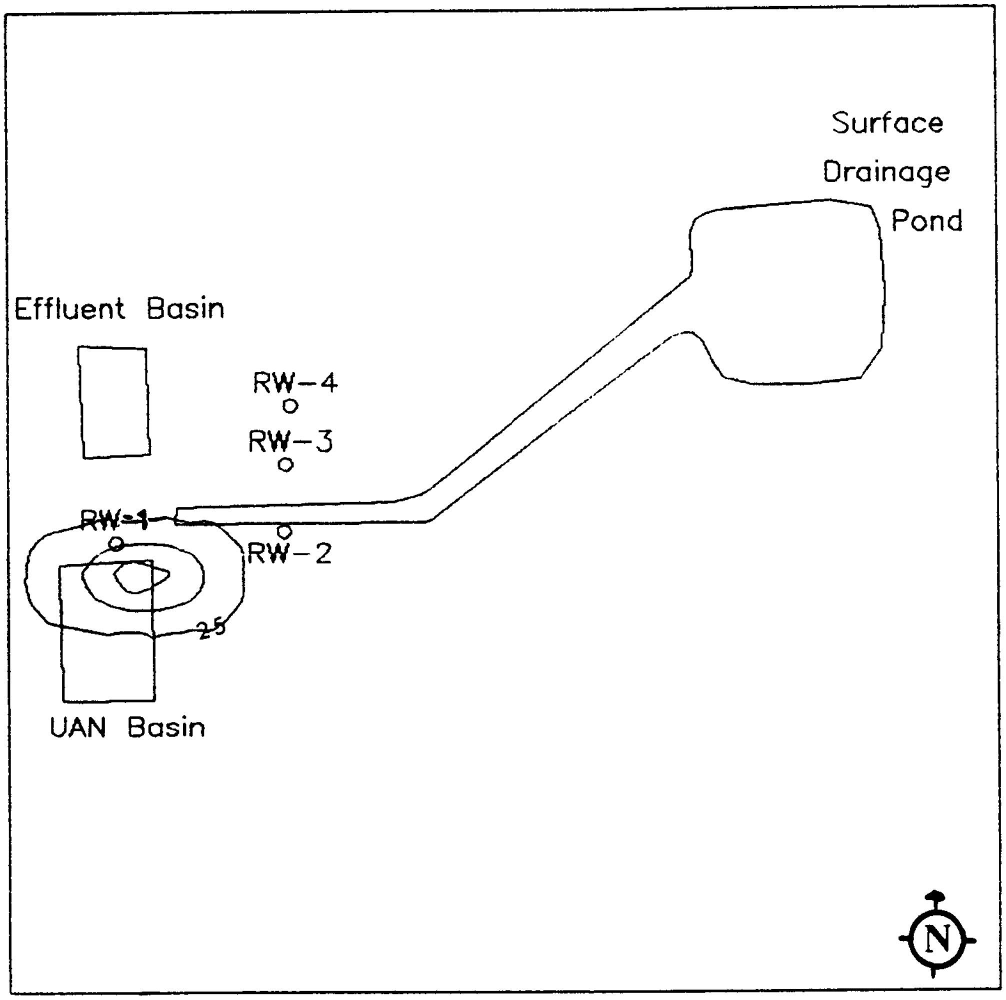
Model Sensitivity to Differing Hydraulic Conductivity

The contamination which entered the groundwater system was assumed to have moved by advective (convective) and dispersive processes for modeling purposes. Because groundwater velocity is directly related to hydraulic conductivity (K), the modeled plume of contaminant moves away from the source faster when K = 2000 than when K = 375 gpd/ft^2, as would be expected.

The same plume pattern can be obtained by either increasing the hydraulic conductivity or increasing the amount of time which has passed at a lower hydraulic conductivity.

Figures 4.2, 4.9, 4.16, 4.22, 4.23, and 4.24 show the effects of varying K (with longitudinal dispersivity set at 10 feet) at 149 days from the approximate spill date. When the hydraulic conductivity is 375 gpd/ft^2 (Figure 4.24), the level of contaminant at RW-1 is approximately 25% of the original concentration input. When K is 2000 gpd/ft^2 (Figure 4.22), however, there is less than 1% of the original concentration present at RW-1. Very little pumping had occurred at 149 days after the spill, so plume movement was not affected by pumping due to remediation efforts at this time. The value of hydraulic conductivity which most closely matches field data at 149 days is 500 gpd/ft^2 as seen in Figure 4.16 and Table 2.2.

The model shows concentration levels to be less than 1% of the original concentration near the recovery wells when the hydraulic conductivity (K) is 1500 gpd/ft^2, at 423 days (Figure 4.4). At the same point of time in the model when K is 1000 gpd/ft^2 (Figure 4.11), approximately 1% of the original concentration is at the recovery wells, and about

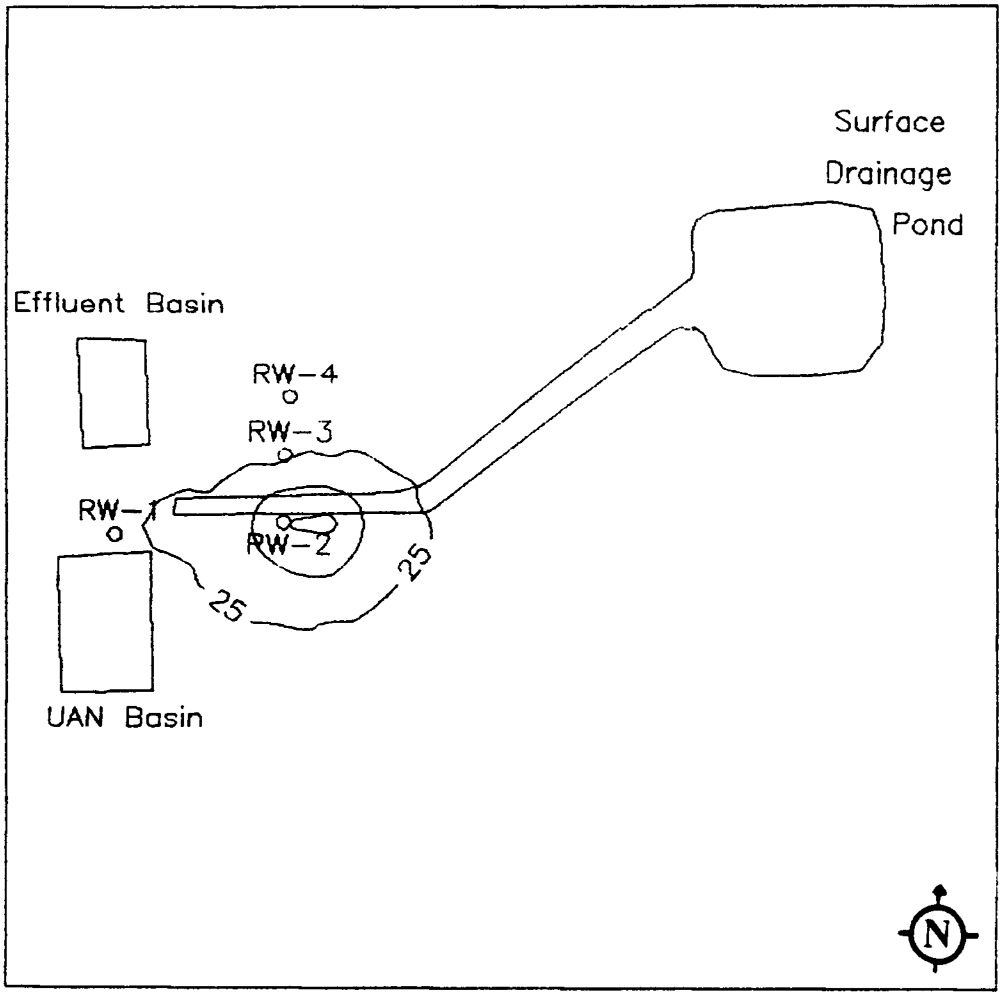


K= 1500 gpd/sq.ft., Dl= 10, time= 29 days

Contour Interval = 25, 300, 600 mg/l

Scale: 1" = 400'

Figure 4.1 Iso-Concentration Contour Map of Modeled Plume

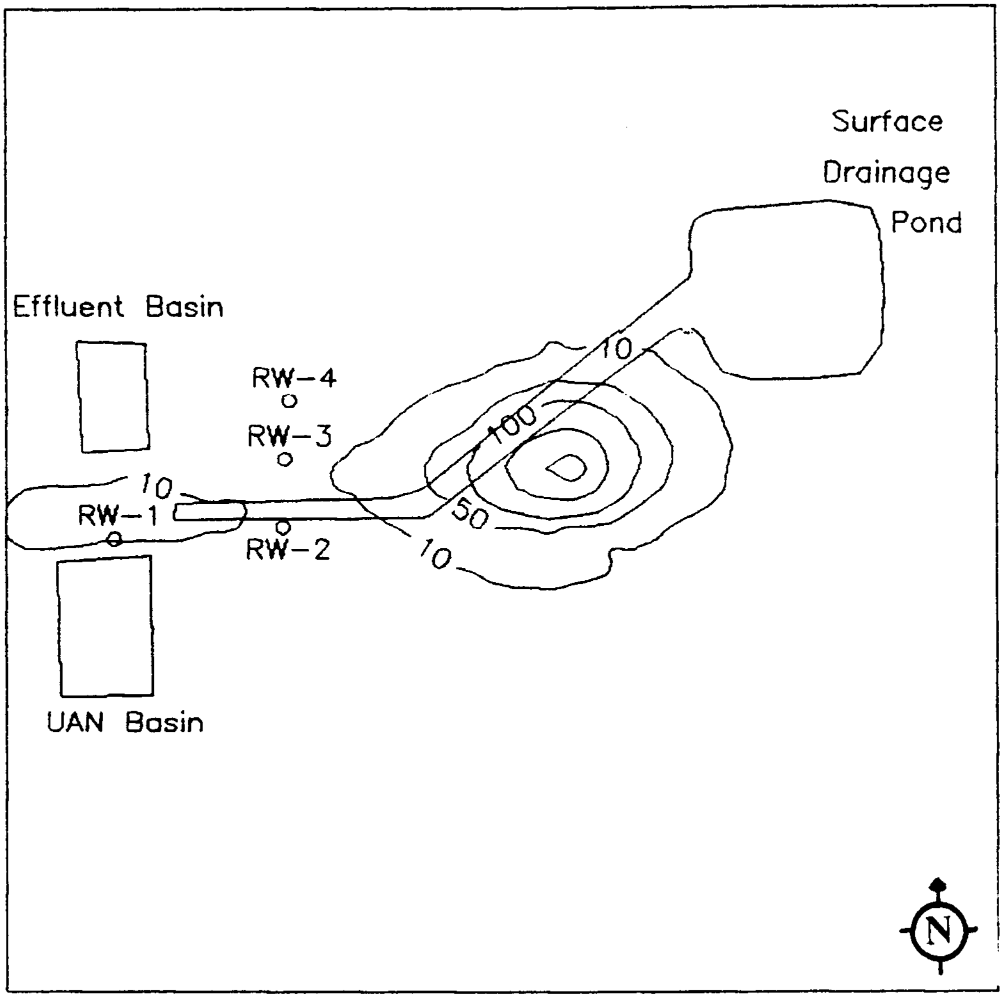


K= 1500 gpd/sq.ft., Dl= 10, time= 149 days

Contour Interval = 25, 200, 400 mg/l

Scale: 1" = 400'

Figure 4.2 Iso-Concentration Contour Map of Modeled Plume

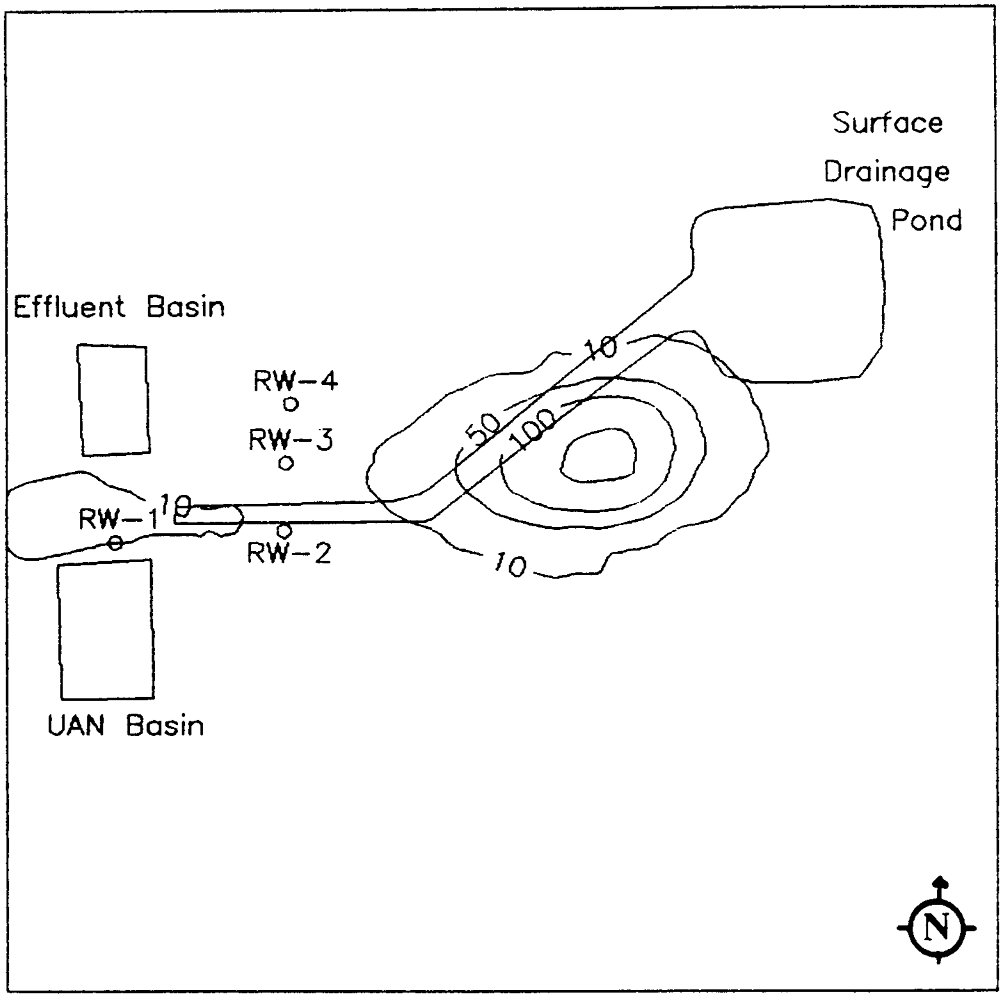


K= 1500 gpd/sq.ft., Dl= 10, time= 394 days

Contour Interval = 10, 50, 100, 200, 300 mg/l

Scale: 1" = 400'

Figure 4.3 Iso-Concentration Contour Map of Modeled Plume

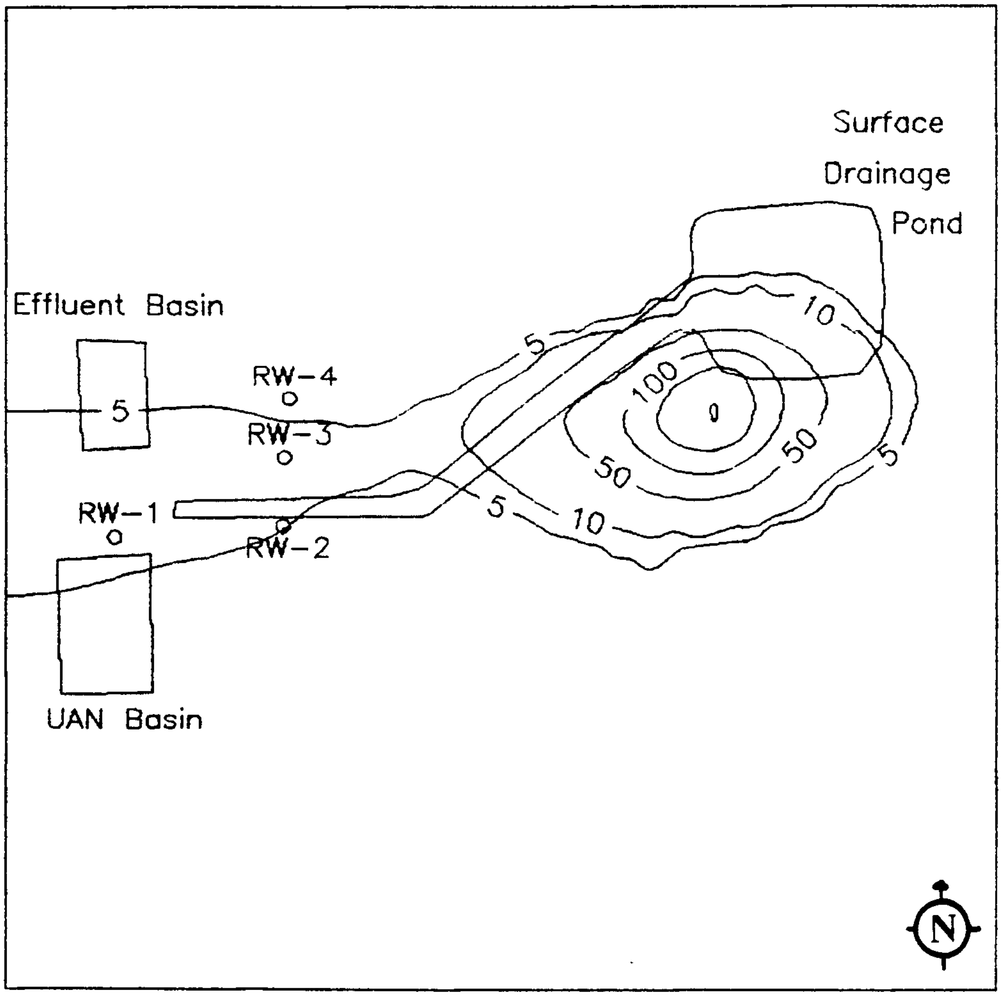


K= 1500 gpd/sq.ft., Dl= 10, time= 423 days

Contour Interval = 10, 50, 100, 200 mg/l

Scale: 1" = 400'

Figure 4.4 Iso-Concentration Contour Map of Modeled Plume

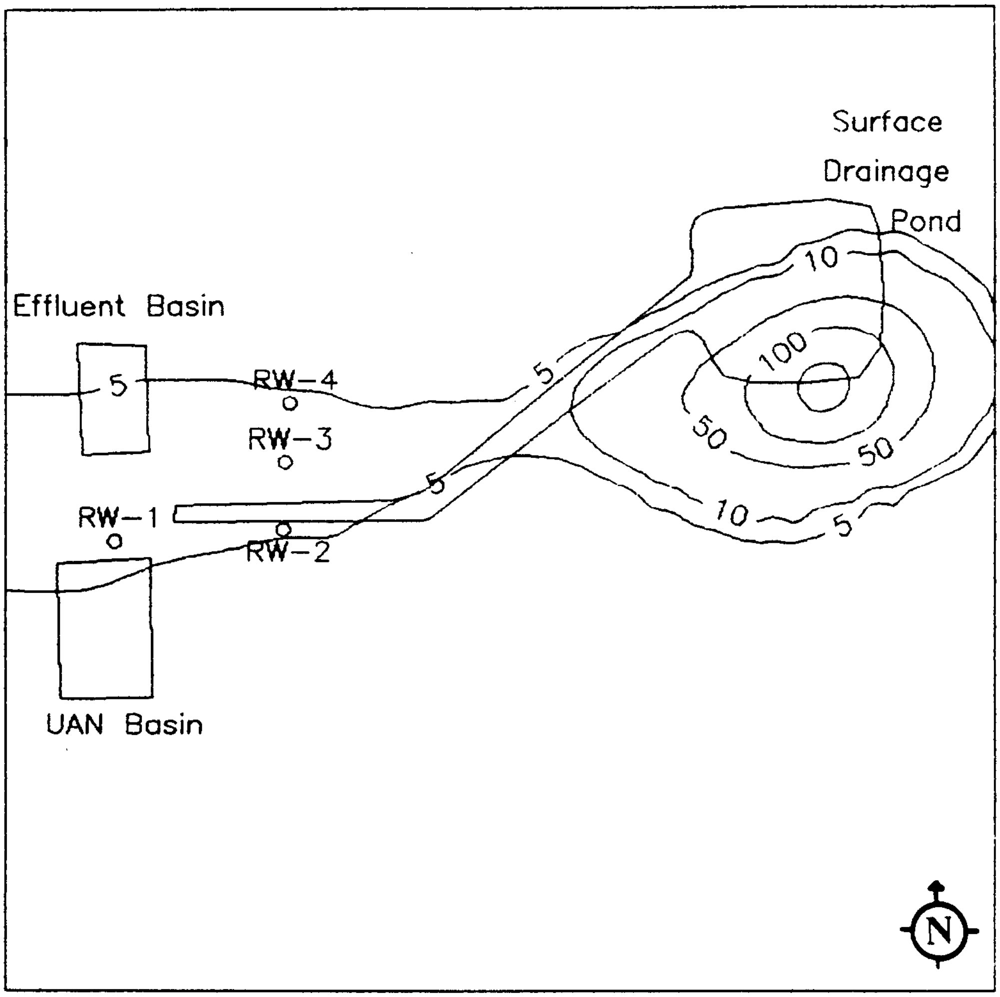


K= 1500 gpd/sq.ft., Dl= 10, time= 544 days

Contour Interval = 5, 10, 50, 100, 150, 200 mg/l

Scale: 1" = 400'

Figure 4.5 Iso-Concentration Contour Map of Modeled Plume

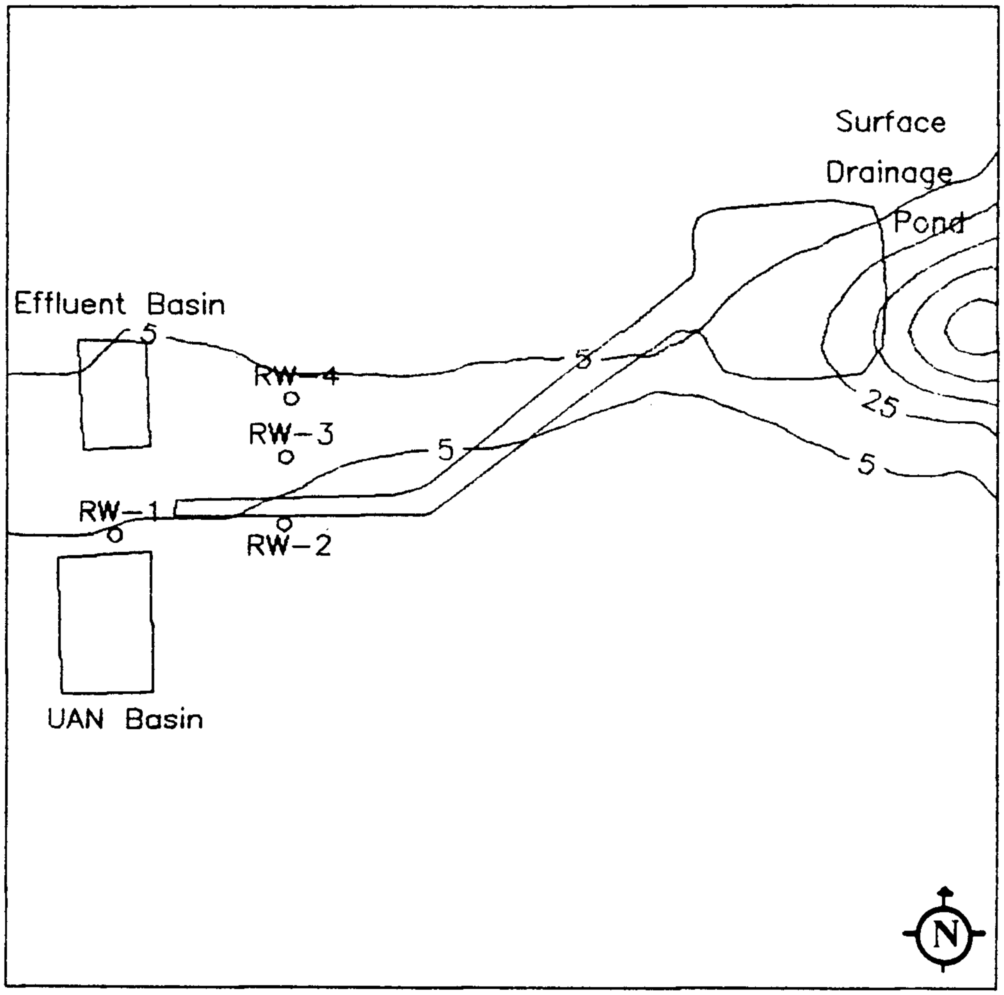


K= 1500 gpd/sq.ft., Dl= 10, time= 688 days

Contour Interval = 5, 10, 50, 100, 150 mg/l

Scale: 1" = 400'

Figure 4.6 Iso-Concentration Contour Map of Modeled Plume

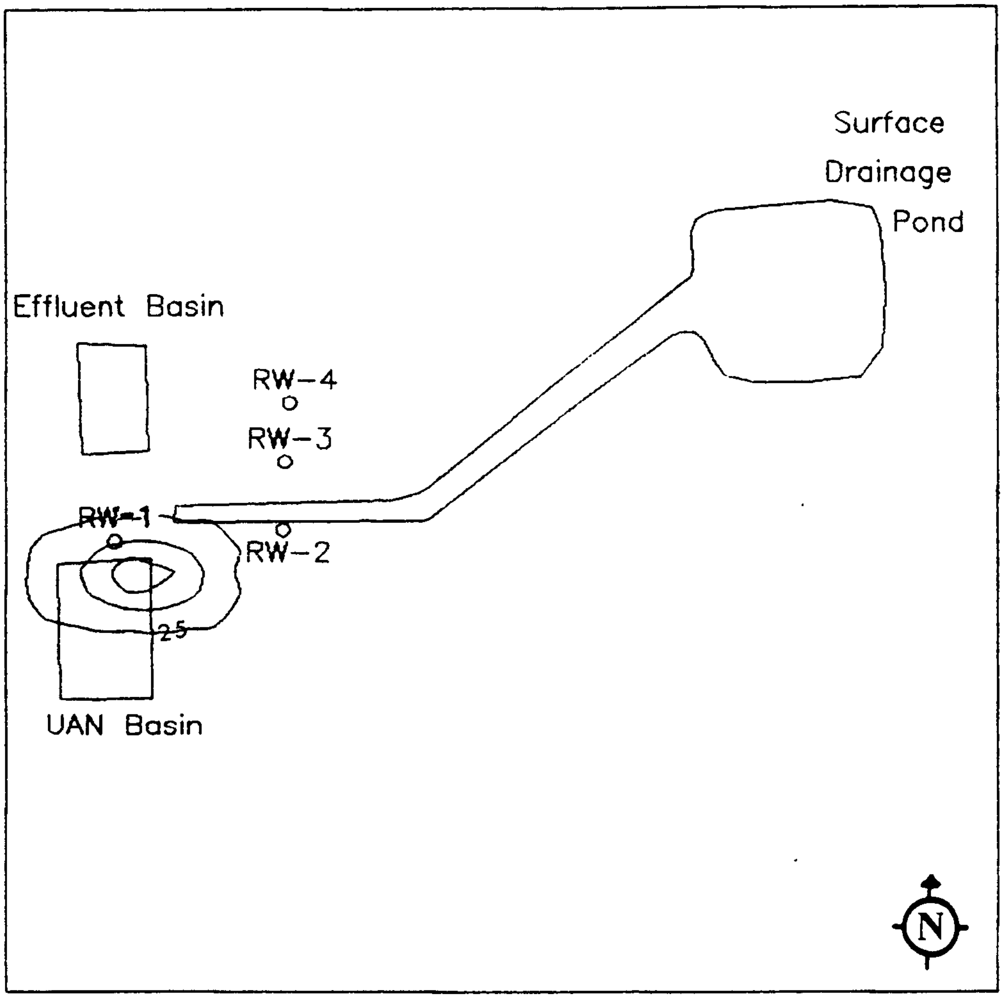


K= 1500 gpd/sq.ft., Dl= 10, time= 880 days

Contour Interval= 5, 25, 50, 75, 100 mg/l

Scale: 1" = 400'

Figure 4.7 Iso-Concentration Contour Map of Modeled Plume

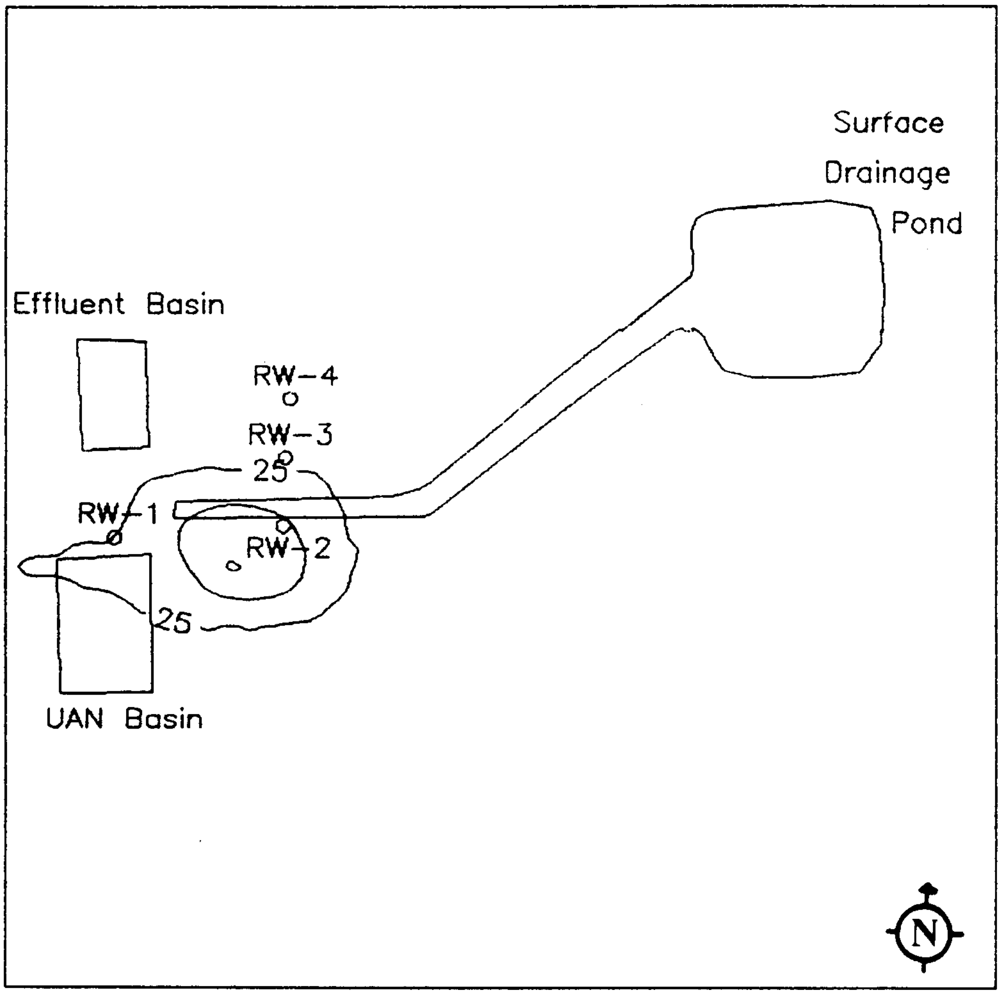


K= 1000 gpd/sq.ft., Dl= 10, time= 29 days

Contour Interval = 25, 300, 600 mg/l

Scale: 1" = 400'

Figure 4.8 Iso-Concentration Contour Map of Modeled Plume

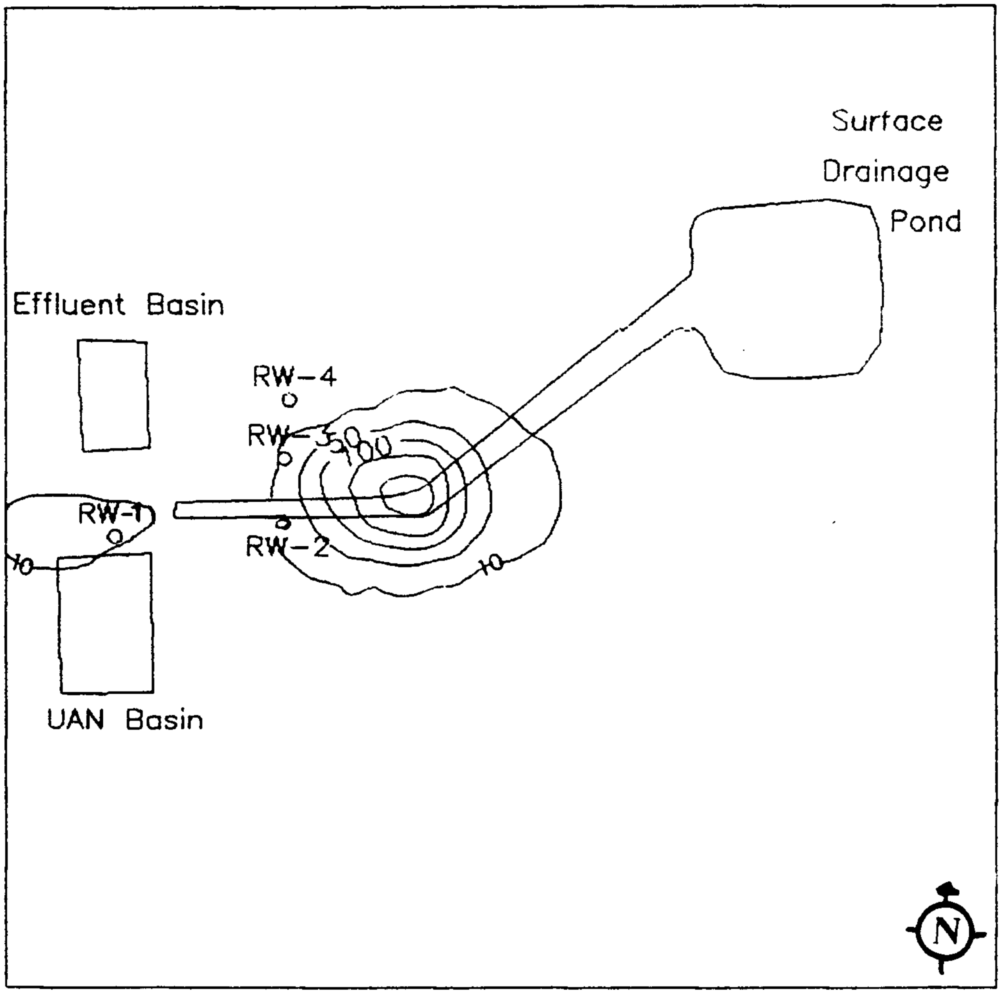


K= 1000 gpd/sq.ft., Dl= 10, time= 149 days

Contour Interval = 25, 200, 400 mg/l

Scale: 1" = 400'

Figure 4.9 Iso-Concentration Contour Map of Modeled Plume

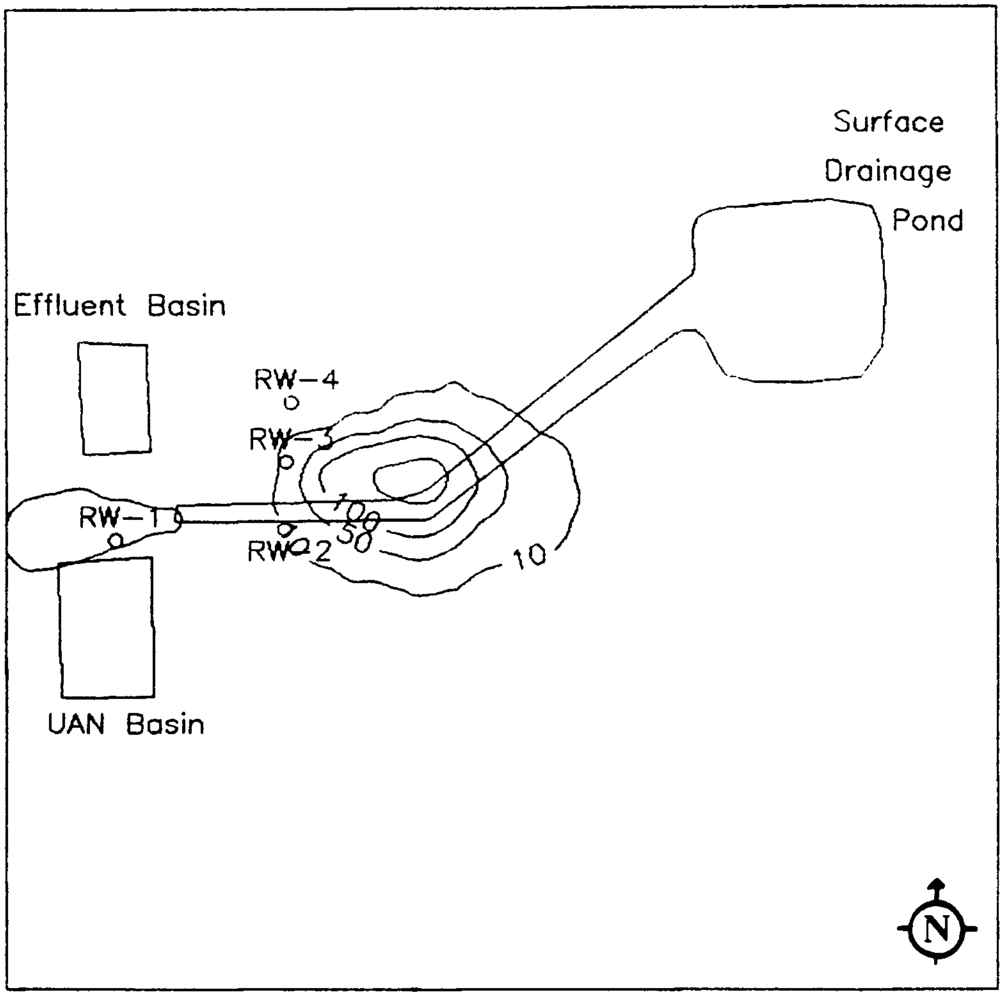


K= 1000 gpd/sq.ft., Dl= 10, time= 394 days

Contour Interval = 10, 50, 100, 150, 200 mg/l

Scale: 1" = 400'

Figure 4.10 Iso-Concentration Contour Map of Modeled Plume

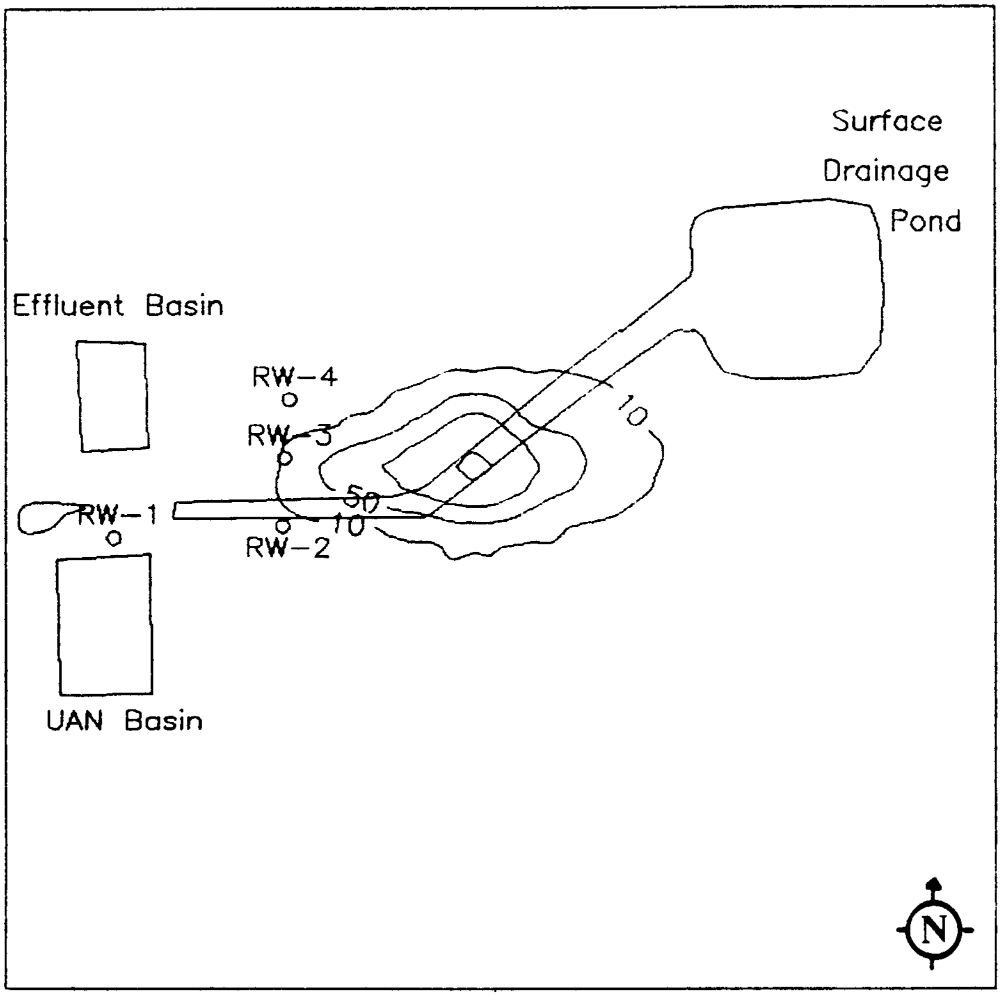


K= 1000 gpd/sq.ft., Dl= 10, time= 423 days

Contour Interval = 10, 50, 100, 200 mg/l

Scale: 1" = 400'

Figure 4.11 Iso-Concentration Contour Map of Modeled Plume

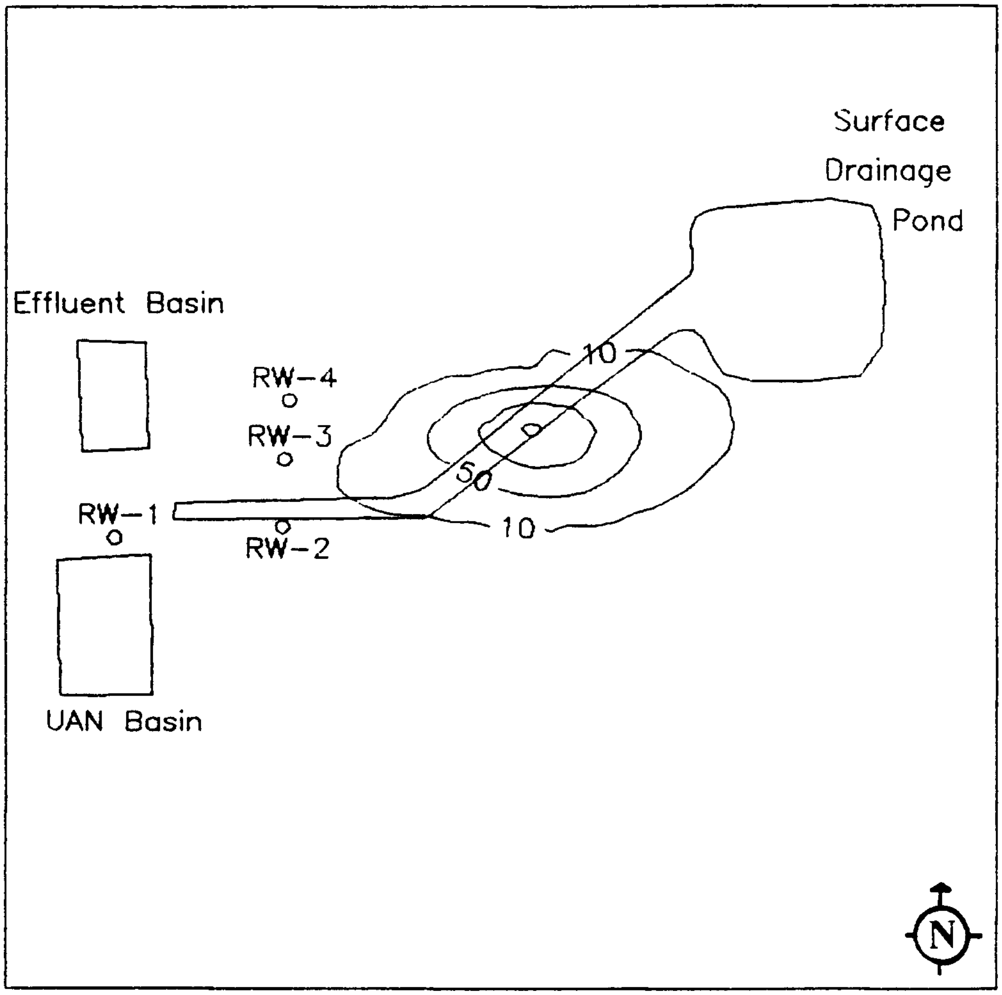


K= 1000 gpd/sq.ft., Dl= 10, time= 544 days

Contour Interval = 10, 50, 100, 200 mg/l

Scale: 1" = 400'

Figure 4.12 Iso-Concentration Contour Map of Modeled Plume

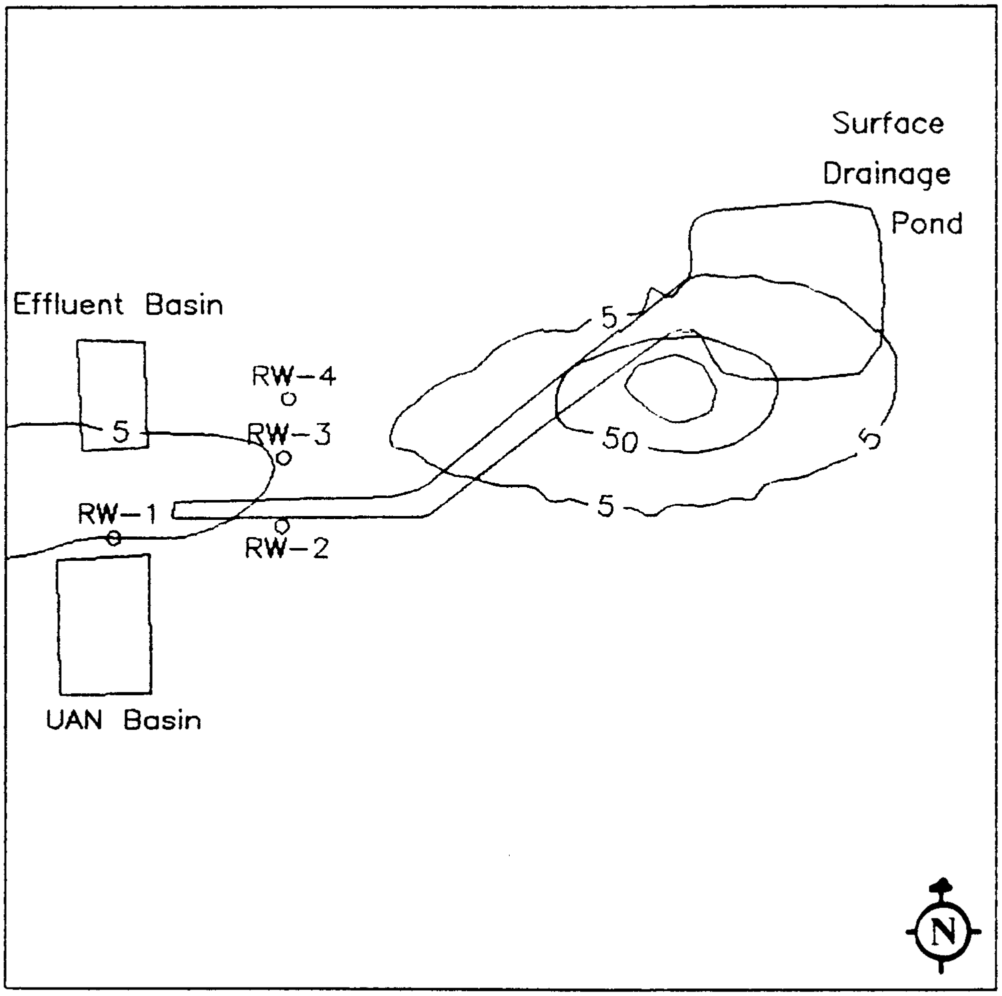


K= 1000 gpd/sq.ft., Dl= 10, time= 668 days

Contour Interval = 10, 50, 100, 150 mg/l

Scale: 1" = 400'

Figure 4.13 Iso-Concentration Contour Map of Modeled Plume

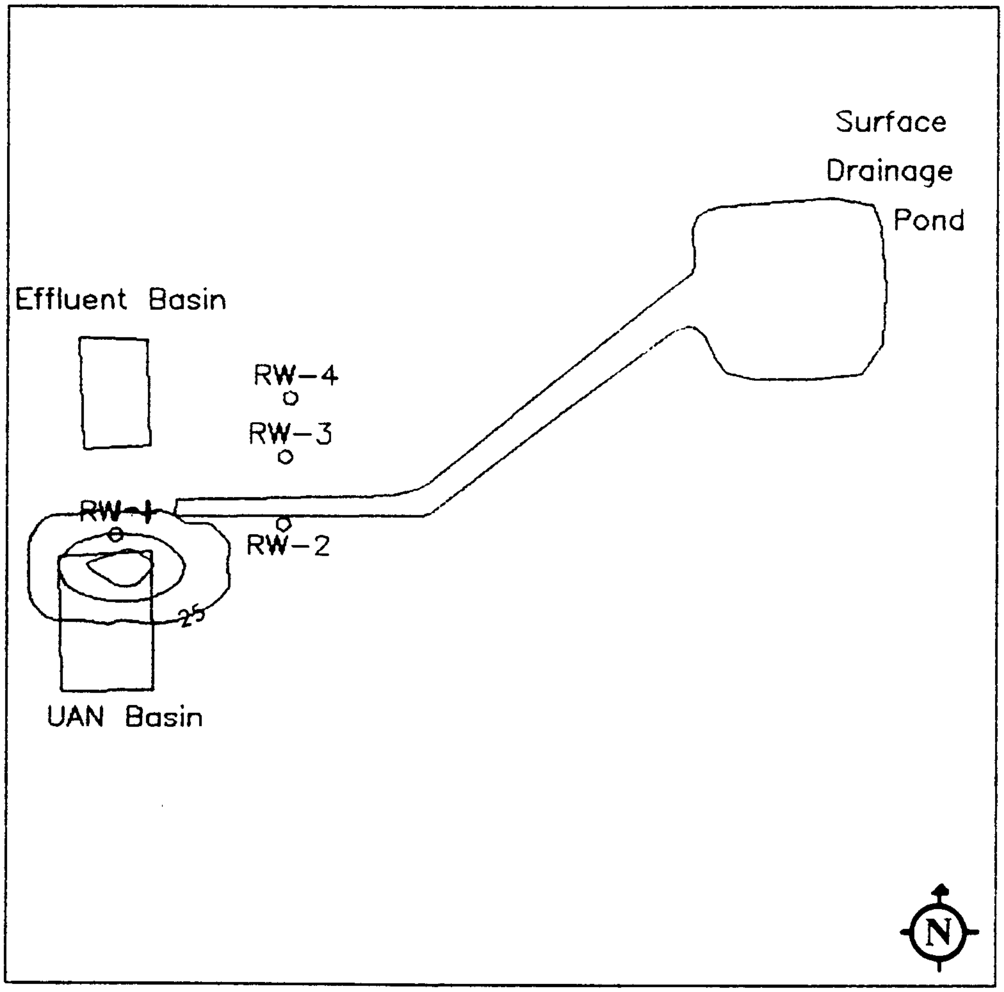


K= 1000 gpd/sq.ft., Dl= 10, time= 880 days

Contour Interval = 5, 50, 100 mg/l

Scale: 1" = 400'

Figure 4.14 Iso-Concentration Contour Map of Modeled Plume

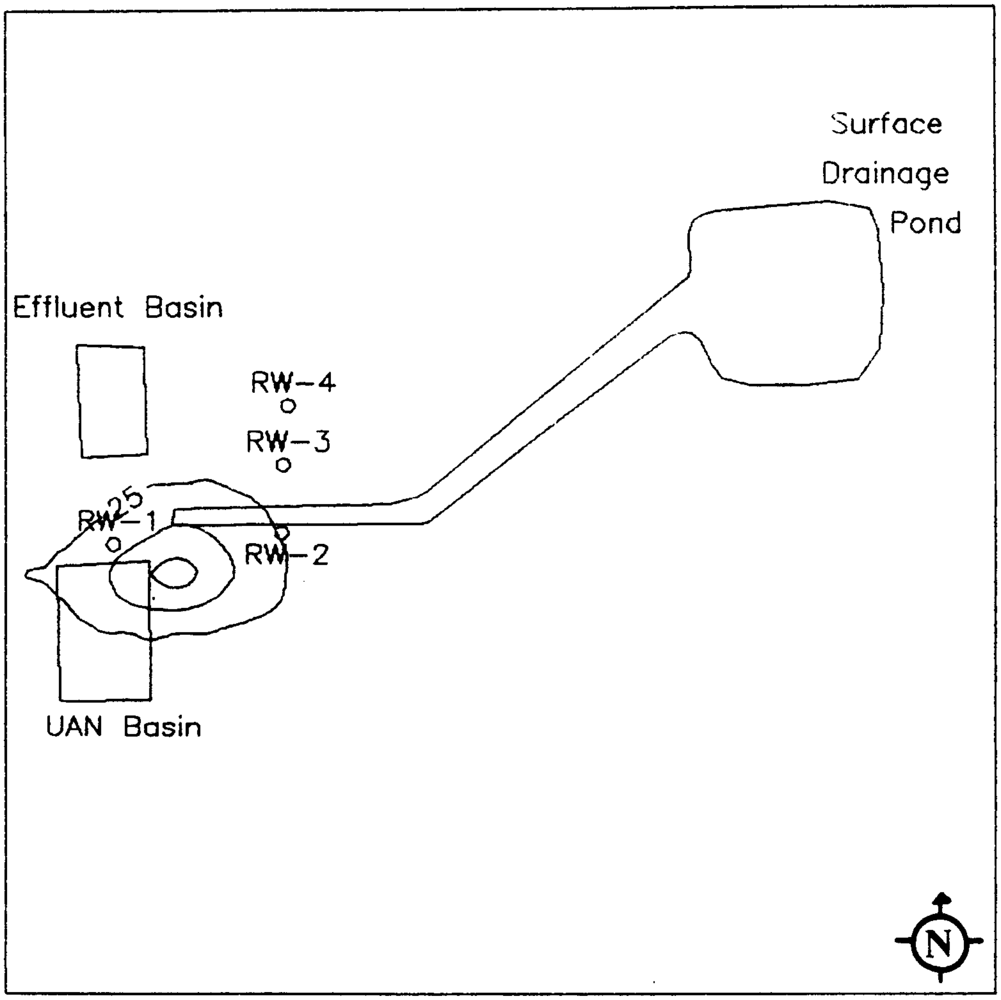


K= 500 gpd/sq.ft., Dl= 10, time= 29 days

Contour Interval = 25, 300, 600 mg/l

Scale: 1" = 400'

Figure 4.15 Iso-Concentration Contour Map of Modeled Plume

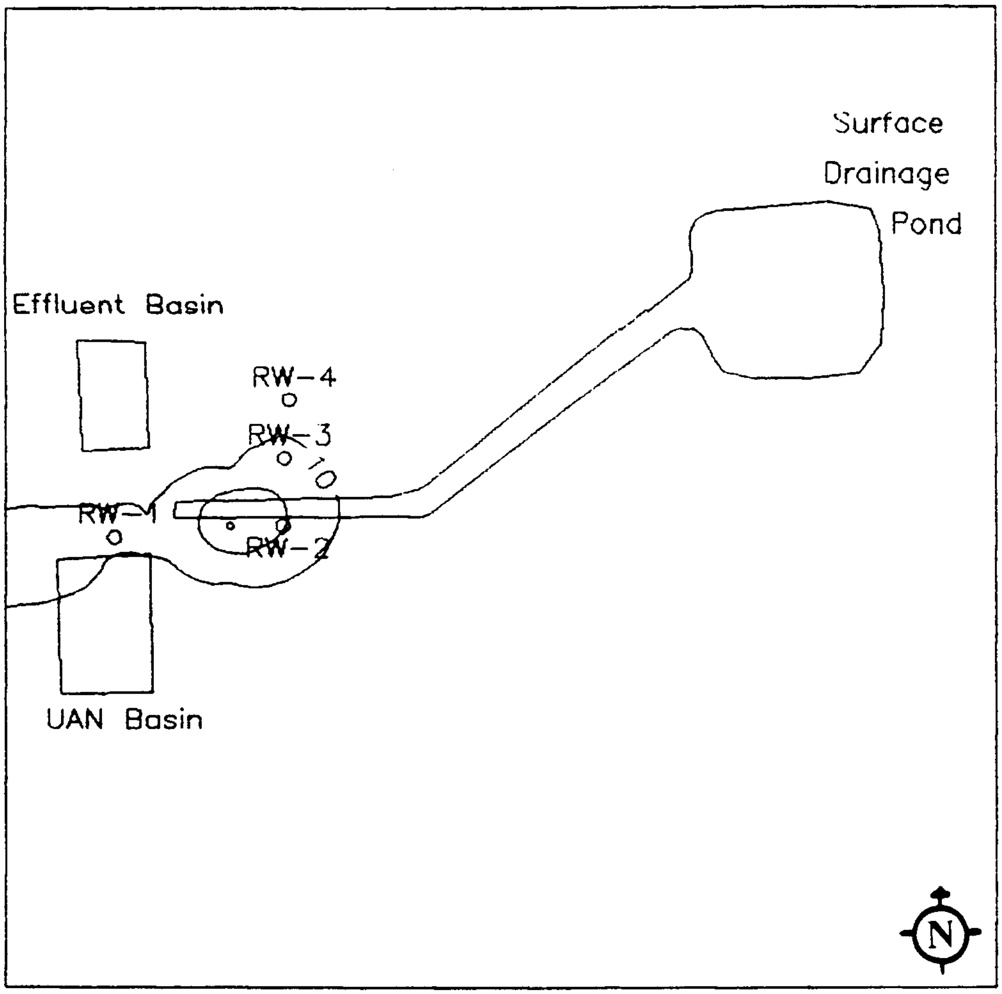


K= 500 gpd/sq.ft., Dl= 10, time= 149 days

Contour Interval = 25, 200, 400 mg/l

Scale: 1" = 400'

Figure 4.16 Iso-Concentration Contour Map of Modeled Plume

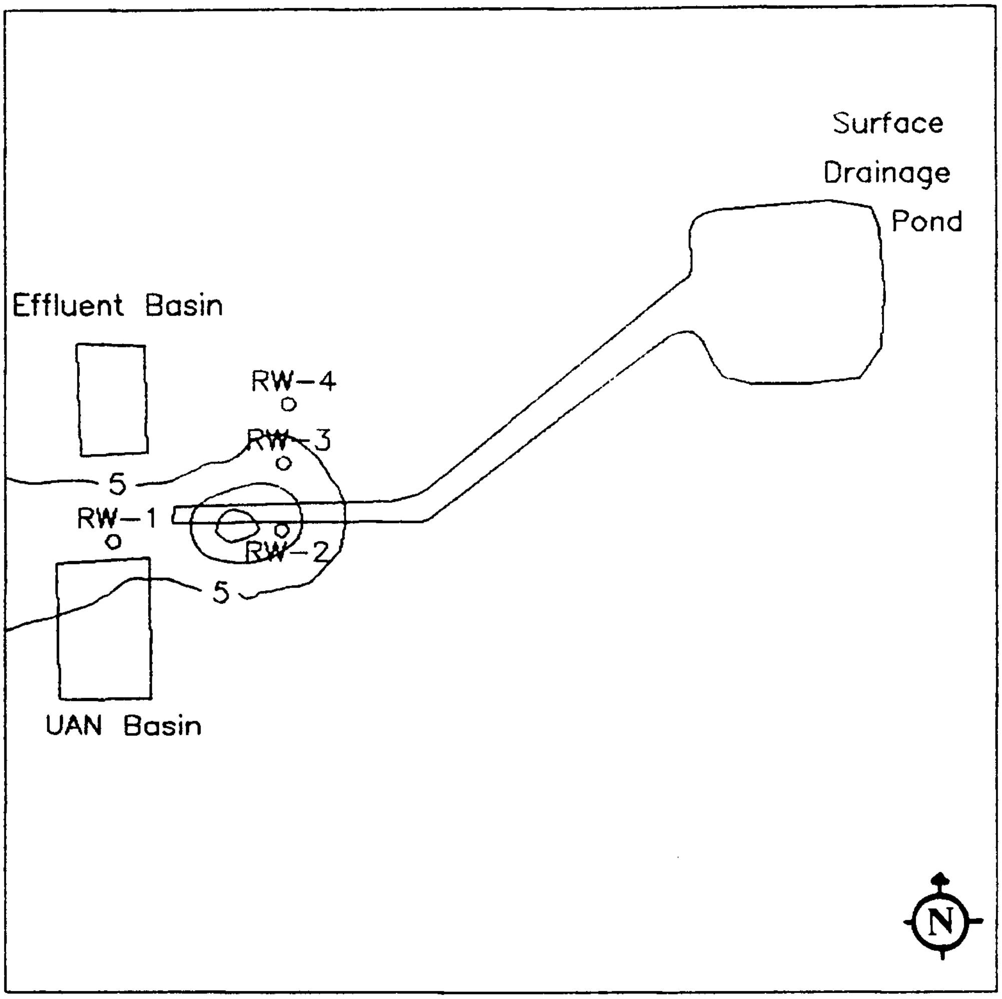


K= 500 gpd/sq.ft., Dl= 10, time= 394 days

Contour Interval = 10, 50, 100 mg/l

Scale: 1" = 400'

Figure 4.17 Iso-Concentration Contour Map of Modeled Plume

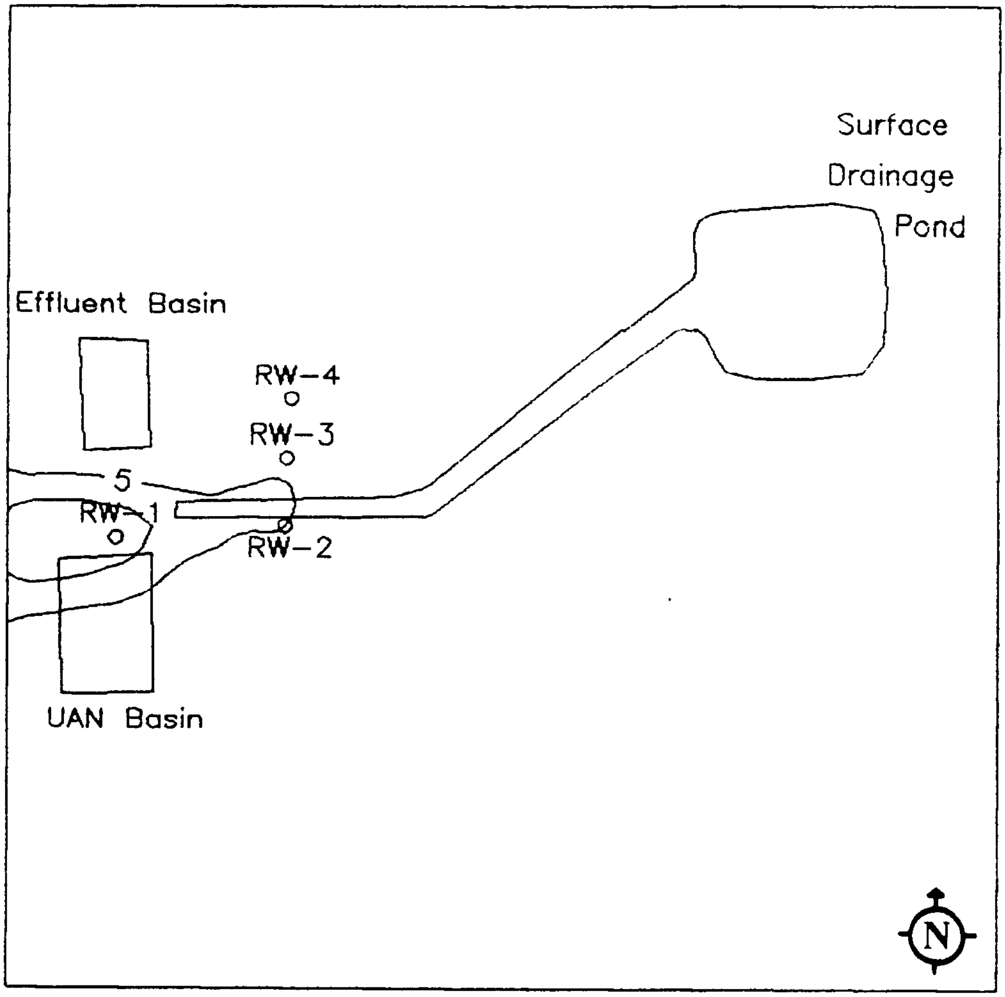


K= 500 gpd/sq.ft., Dl= 10, time= 423 days

Contour Interval = 5, 10, 25 mg/l

Scale: 1" = 400'

Figure 4.18 Iso-Concentration Contour Map of Modeled Plume

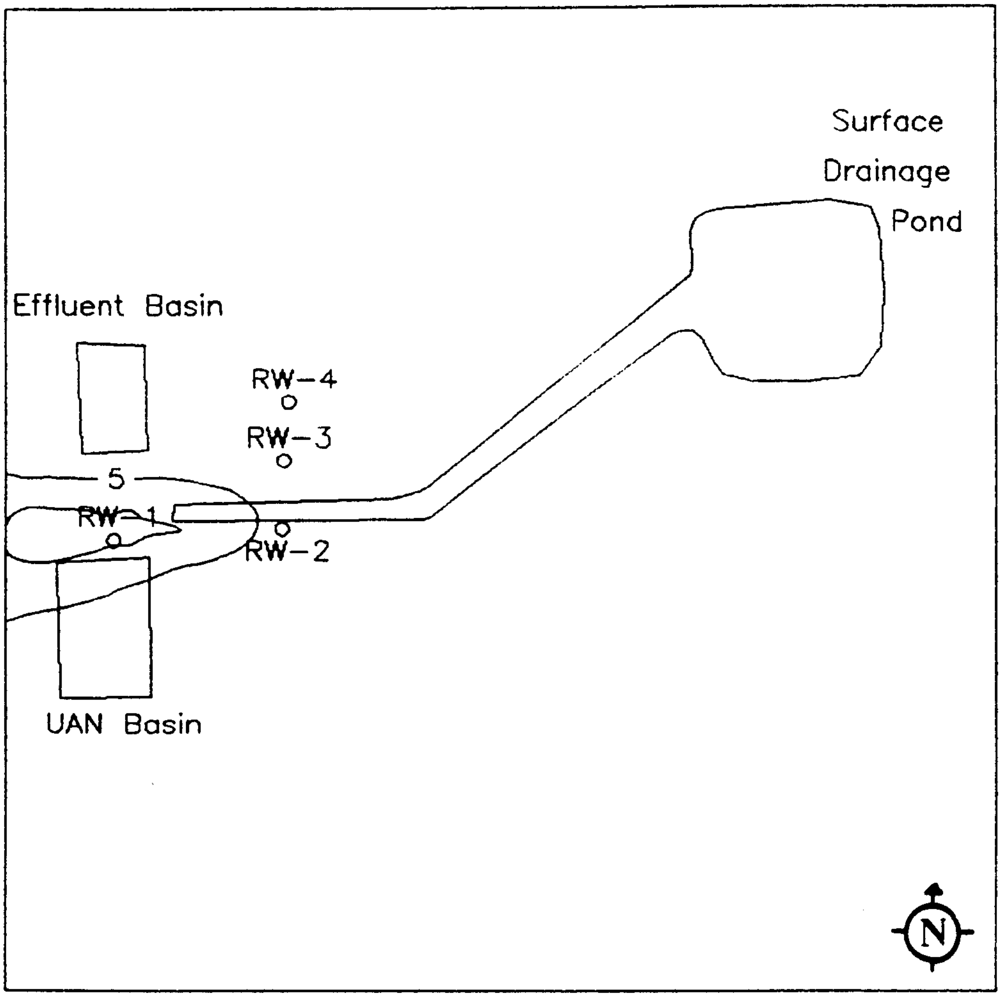


K= 500 gpd/sq.ft., Dl= 10, time= 544 days

Contour Interval = 5, 10 mg/l

Scale: 1" = 400'

Figure 4.19 Iso-Concentration Contour Map of Modeled Plume

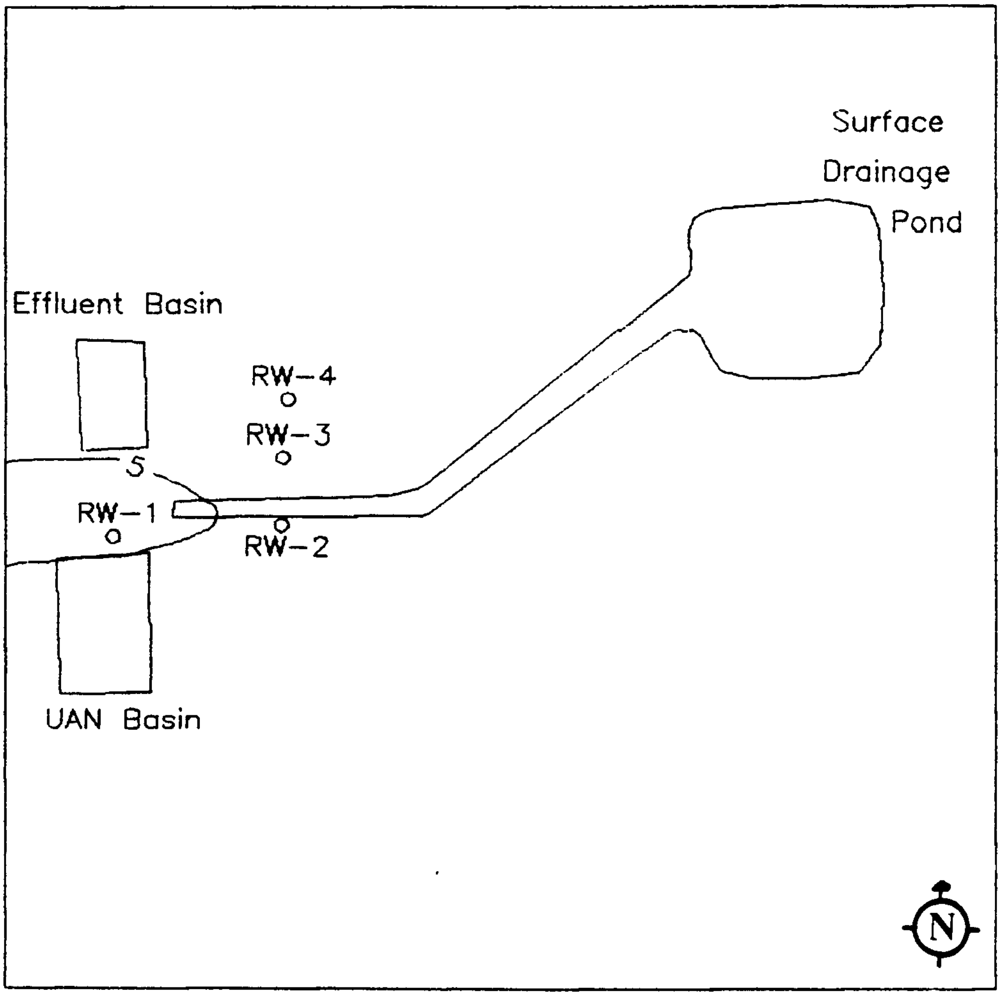


K= 500 gpd/sq.ft., Dl= 10, time= 668 days

Contour Interval = 5, 10 mg/l

Scale: 1" = 400'

Figure 4.20 Iso-Concentration Contour Map of Modeled Plume

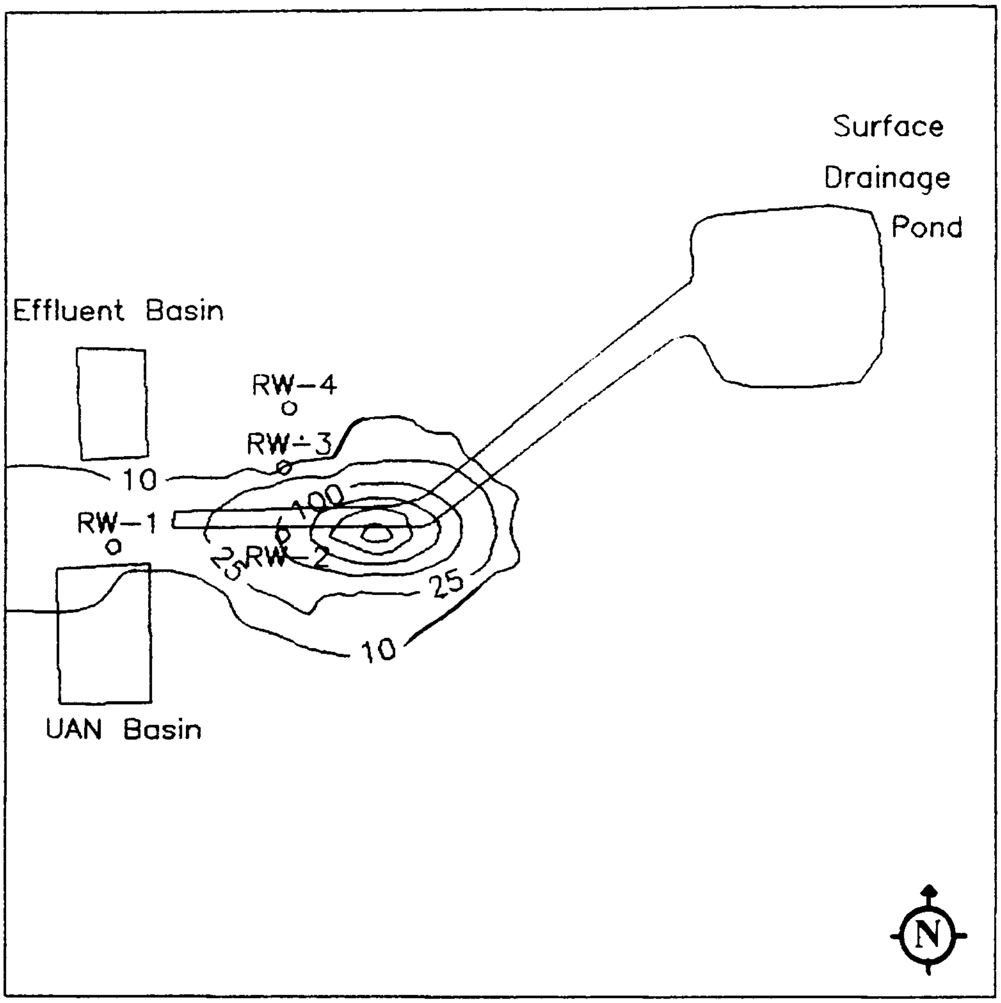


K= 500 gpd/sq.ft., Dl= 10, time= 880 days

Contour Interval = 5, 10 mg/l

Scale: 1" = 400'

Figure 4.21 Iso-Concentration Contour Map of Modeled Plume

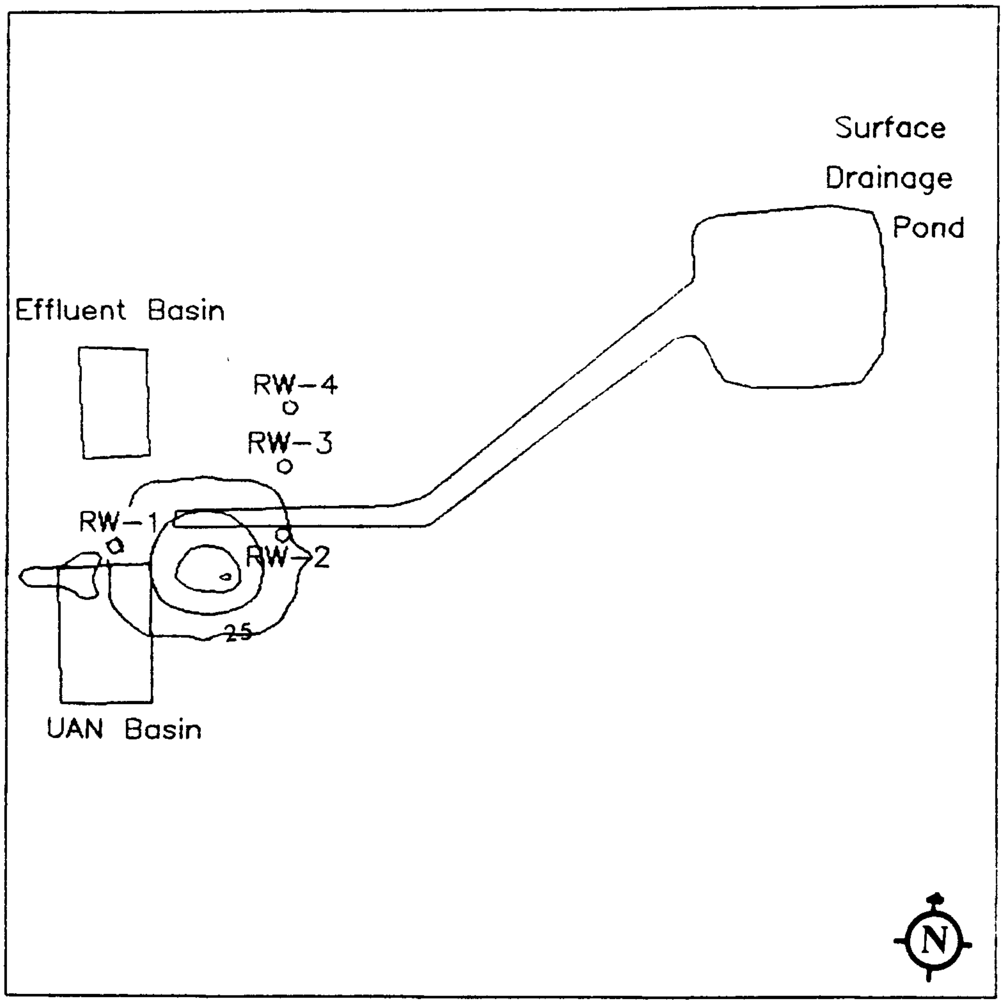


K= 2000 gpd/sq.ft., Dl= 10, time= 149 days

Contour Interval = 10, 25, 100, 200, 300, 400 mg/l

Scale: 1" = 400'

Figure 4.22 Iso-Concentration Contour Map of Modeled Plume

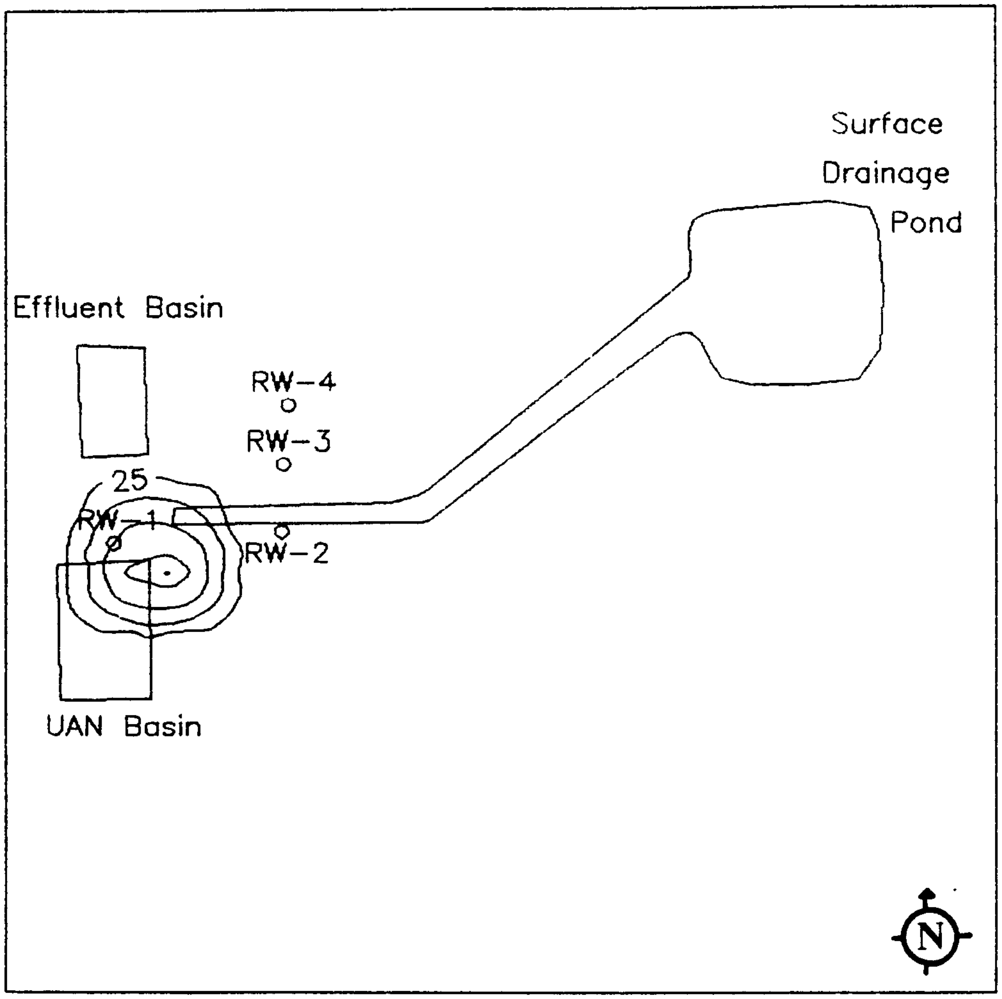


K= 750 gpd/sq.ft., Dl= 10, time= 149 days

Contour Interval = 25, 200, 400, 500 mg/l

Scale: 1" = 400'

Figure 4.23 Iso-Concentration Contour Map of Modeled Plume

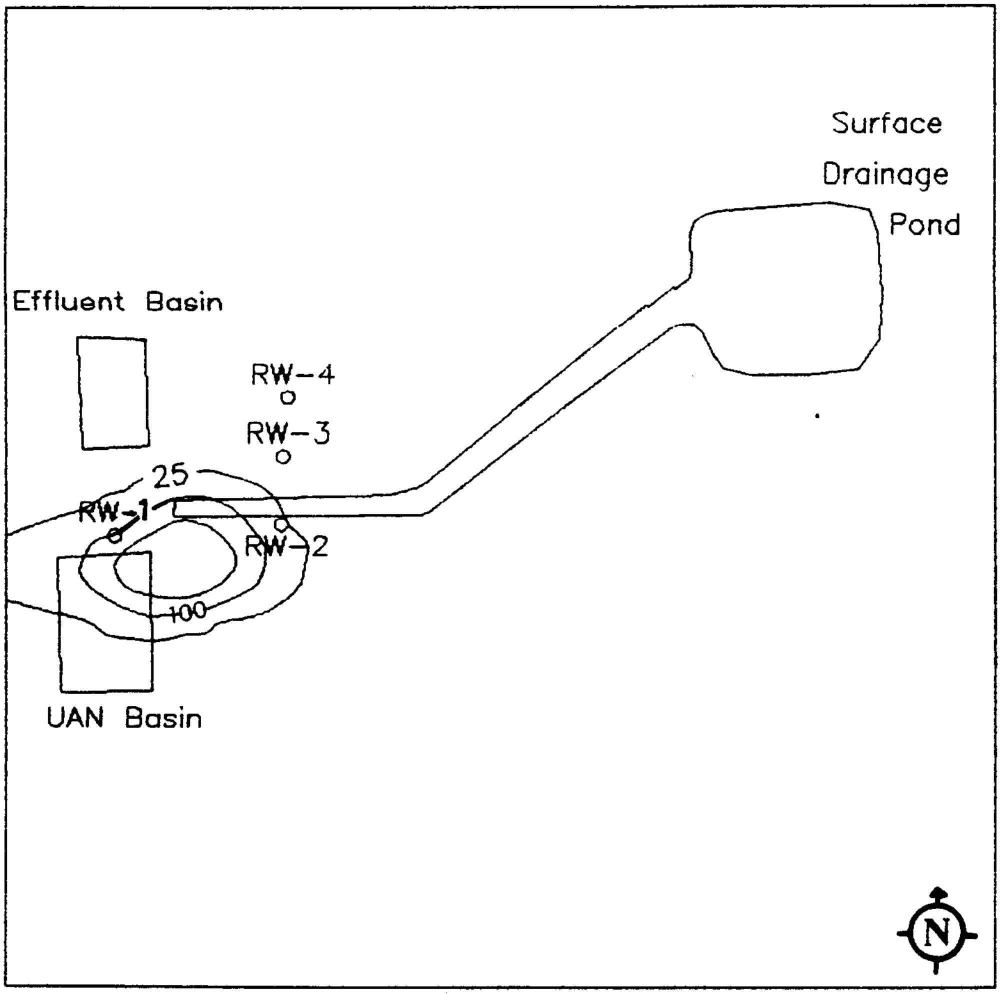


K= 375 gpd/sq.ft., Dl= 10, time= 149 days

Contour Interval = 25, 100, 250, 500, 600 mg/l

Scale: 1" = 400'

Figure 4.24 Iso-Concentration Contour Map of Modeled Plume

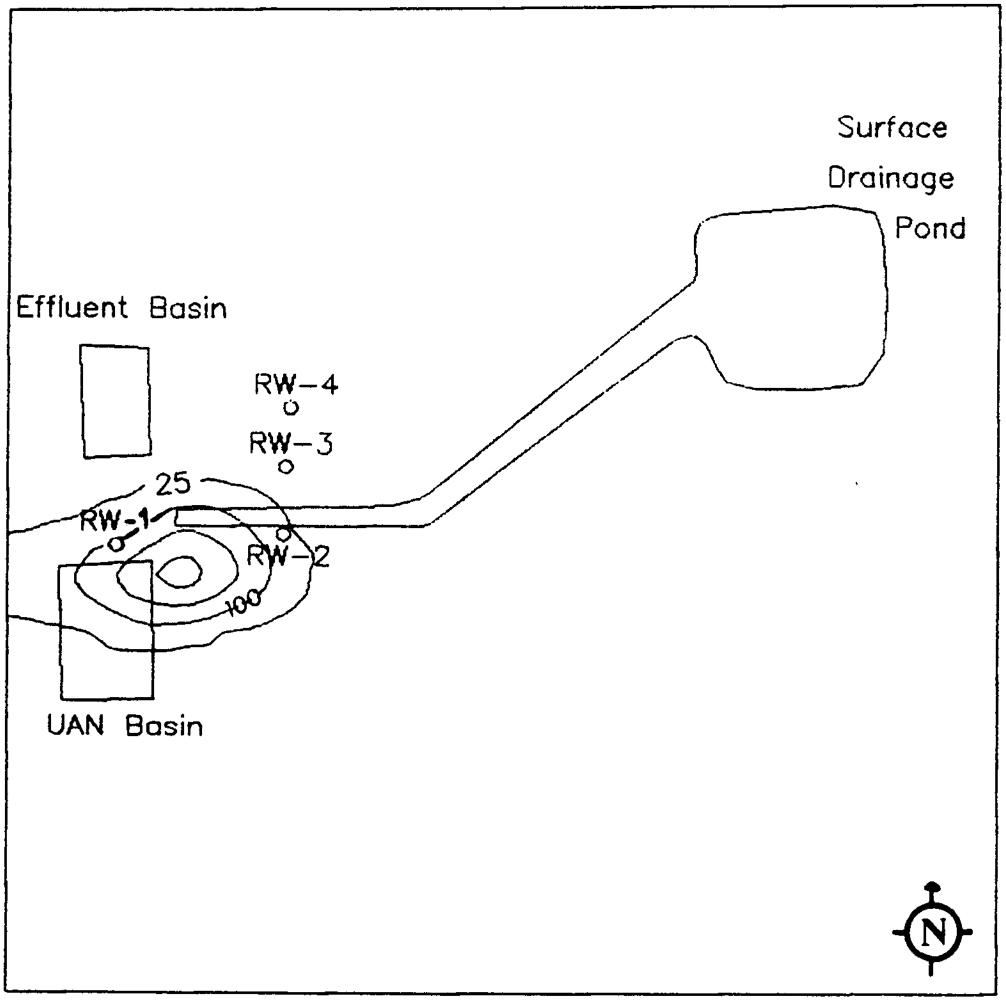


K= 500 gpd/sq.ft., Dl= 25, time= 149 days

Contour Interval = 25, 100, 200 mg/l

Scale: 1" = 400'

Figure 4.25 Iso-Concentration Contour Map of Modeled Plume

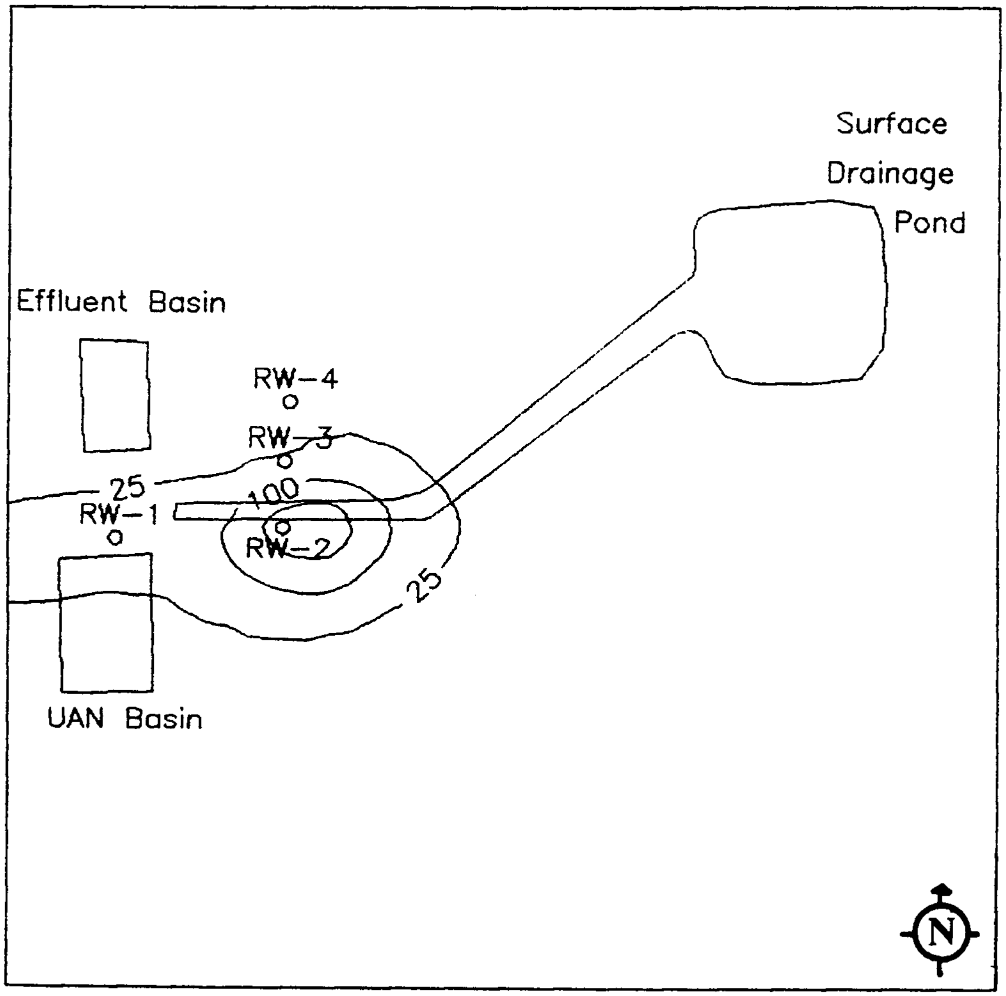


K= 500 gpd/sq.ft., Dl= 30, time= 149 days

Contour Interval = 25, 100, 200, 300 mg/l

Scale: 1" = 400'

Figure 4.26 Iso-Concentration Contour Map of Modeled Plume



K= 1500 gpd/sq.ft., Dl= 30, time= 149 days

Contour Interval = 25, 100, 200 mg/l

Scale: 1" = 400'

Figure 4.27 Iso-Concentration Contour Map of Modeled Plume

1/2% when K is 500 gpd/ft^2 (Figure 4.18). In the cases of the two higher hydraulic conductivities, the plume has left the basin area. In the case of the lower hydraulic conductivity (500 gpd/ft^2), the modeled pumping wells have captured much of the contaminant and have kept the plume from moving away from the source area.

The drilling program along the half-section line of section 14 in October of 1987 (HWST, 1987) approximately corresponds with the 880 day maps (Figures 4.7, 4.14, and 4.21). According to the model, the plume should be past this area when hydraulic conductivity is 1500 gpd/ft^2 or just approaching this area when K is 1000 gpd/ft^2. The nitrogen analysis of the sediment samples taken during the 1987 drilling program is presented in Table 2.1. Practically no nitrogen was detected in holes drilled along the half-section line (see Figure 2.2), near the surface drainage pond. This tends to support a lower hydraulic conductivity value.

Because groundwater flow direction and gradient are not as crucial to the results of the model close to the source, analysis of contaminant recovery by the pumping wells is a better way to evaluate the results of the model. The recovery wells were pumped at a maximum of approximately 22 gpm. The recovery wells did not pump continuously. This sporadic and low rate of pumping had little affect on the groundwater flow system. Minimal reversal of groundwater flow gradient was seen due to the recovery wells, according to the model.

The recovery wells were not pumping on a regular schedule early in the remediation endeavor. A little more than a year after the leak was detected the wells were pumping on a more consistent schedule. This time corresponds roughly with the 423 and 544 day maps (Figures 4.4, 4.11, and 4.18 for 423 days and Figures 4.5, 4.12, and 4.19 for 544 days). These maps can be compared to data from the July, 1986 water sample analyses (Table 2.2). These water analyses data indicate about 3.5 times as much nitrate in OW-1 and OW-7 as in RW-2. This information, along with the results of previous analyses, would seem to imply that the concentrated part of the plume had traveled beyond the area immediately surrounding the source basin, but had not yet reached the line of recovery wells (RW-2, RW-3, RW-4), 250 feet east of the source basin.

Model Sensitivity to Dispersivity

Model dispersivity was changed from 10 feet (longitudinal) to 25 and 30 feet in Figures 4.25, 4.26, and 4.27 (all at 149 days). When compared to Figures 4.16 and 4.2 (longitudinal dispersivity set at 10 feet) this change had the expected effect of broadening the plume from an oval to a more circular figure. Variations in dispersivity did not have a great effect on the modeled plume pattern in this model.

Chapter 5
DISCUSSION

Density

A major limitation in the simulation was the contaminant density factor. The model can not account for density flow. The 32% UAN solution which leaked from the basin probably sank quickly to the bottom of the aquifer with little initial mixing. HWST (1986) reported higher concentrations of nitrate in water samples from the lower part of the aquifer than from the upper part. MOC assumes immediate mixing of the solute and groundwater throughout the entire saturated thickness of aquifer within an element.

A hypothetical example of what may have occurred at Cominco is shown in Figure 5.1. This diagram (adapted from Schwille, 1981) shows a Dense Non-Aqueous Phase Liquid (DNAPL) sinking to the bottom of the aquifer. Low permeability layers of sediment can cause the DNAPL to be deflected or diverted. A depression in the bottom of the aquifer can allow the DNAPL to pond. A slope on the bottom of the aquifer can cause the DNAPL to flow in a different direction from the groundwater flow direction due to gravitational and density forces. Ponded contaminant can act as a more or less continuous source for high nitrates as fresher groundwater flows past and gradual mixing occurs. An approximate configuration of the base of the sand and gravel aquifer in the immediate vicinity of the recovery and

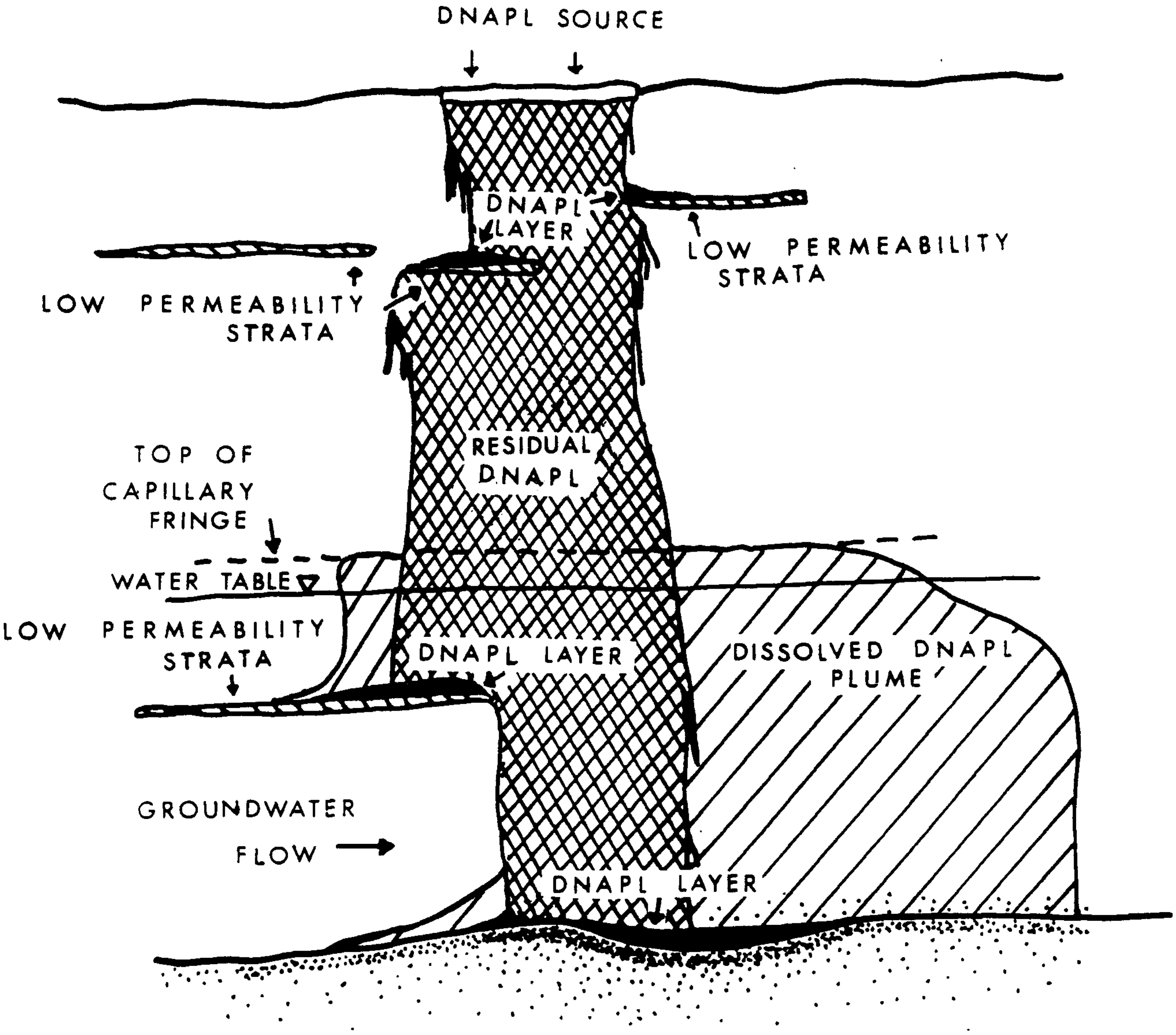


Figure 5.1 Idealized Behavior of DNAPL in Subsurface (adapted from Schwille, 1981)

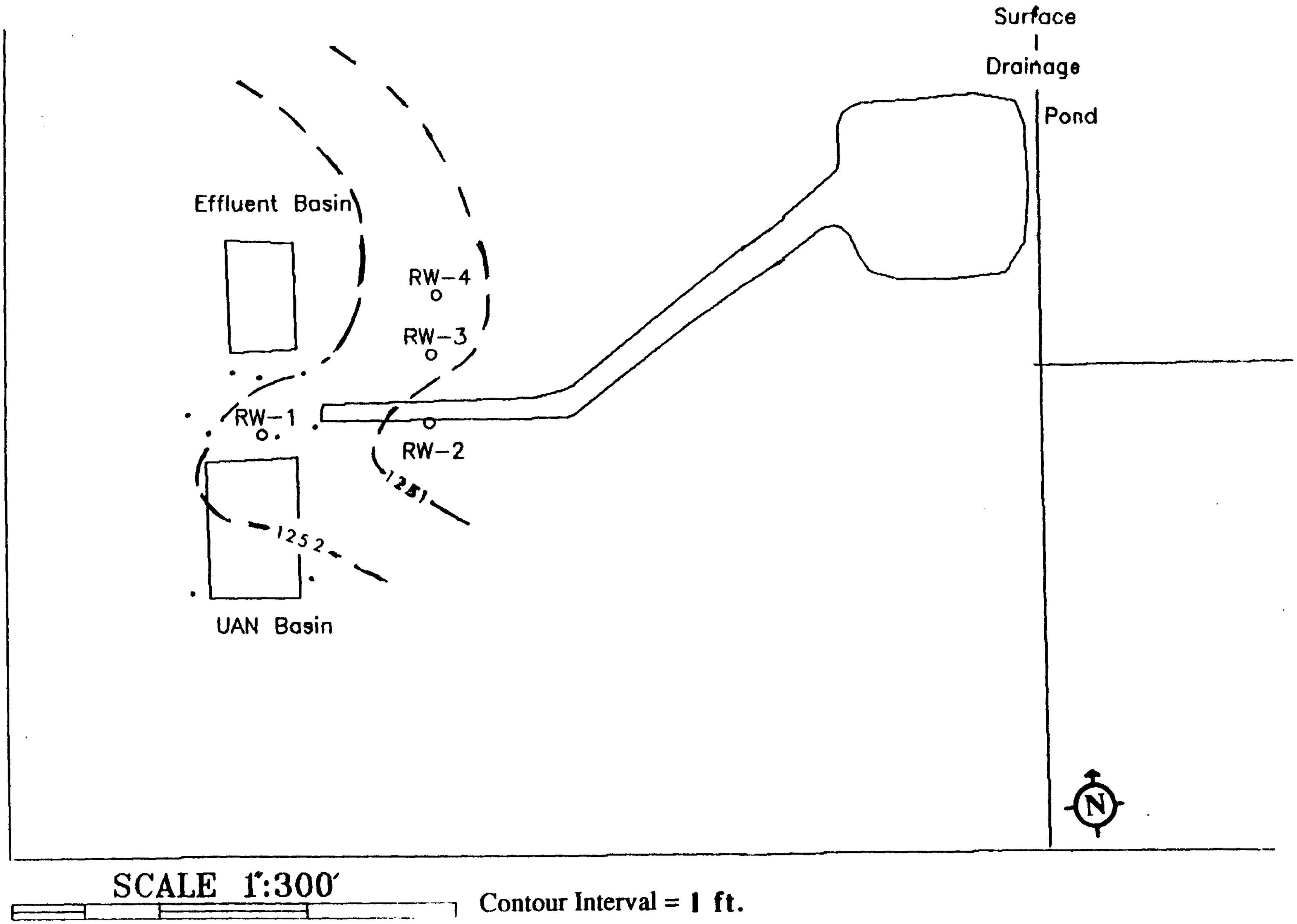


Figure 5.2 Approximate Configuration of the Base of the Recovery and Observation Wells

observation wells is shown in Figure 5.2. This diagram shows a slight depression near RW-2.

Slow Release of Contaminant from Clay

The MOC model used does not allow for release of contaminant by desorption. The model can be made to simulate adsorption of contaminant in a radioactive decay option. A considerable amount of high density contaminant may have been adsorbed by the lower clay unit at the base of the aquifer. HWST (1987) calculated that in a 20-acre area as much as 2.6×10^6 gallons of high nitrate water per year, or approximately 10.8 tons of nitrogen, could have seeped into the underlying silty clay under the influence of density flow. As fresh groundwater flowed over the silty clay, it may have mixed with small amounts of nitrates released by desorption. This release of contaminant may have been sufficient to act as a constant source of contamination.

If ponding of high density contaminant or adsorption and desorption of nitrogen by the clay occurred, there could be a steady release of nitrates, even several years after the contamination event. This would account, in part, for the relatively high levels of nitrate pumped from the recovery wells as late as October, 1988. Cominco (Cominco Monthly Status Reports, 1989) reported nitrate levels of 230 ppm from their recovery wells in October, 1988.

Dispersivity

The MOC model is insensitive to changes in dispersivity. An increase in dispersivity of two to three times had the effect of rounding the modeled plume pattern.

Hydraulic Conductivity

The MOC model is sensitive to changes in hydraulic conductivity. When the model was run with the hydraulic conductivity calculated from the pump test data (1500 gpd/ft^2), the plume of high nitrate water moved relatively rapidly away from the source area. After 2.5 years, the simulated plume was beyond the surface drainage pond, near the half section line (see Figure 4.7). Data from a drilling program from approximately the same time period (the October, 1987 drilling program, HWST, 1987) did not indicate the presence of any contamination. This would imply a lower hydraulic conductivity (and therefore a lower groundwater velocity). If actual groundwater velocity were greater than that modeled, a residue or "trail" of higher nitrate water would be expected to be found during the October, 1987 drilling program. Very low concentrations of total nitrogen were found.

Hydraulic conductivity could be as low as 500 gpd/ft^2, or conceivably lower, according to the particle size analysis method of estimating hydraulic conductivity. The model showed that the recovery wells should capture much of the contamination after ~2.5 years, using 500 gpd/ft^2 as the hydraulic conductivity. The status reports compiled by Cominco (Cominco Monthly Status Reports, 1987-1989) detailing nitrate concentrations and amounts of pumped water show that approximately 113 tons of nitrogen have been recovered as of December, 1988. This number is much higher than the original estimate of 50 tons of nitrogen (30,000 gallons) lost (HWST, 1987).

Model Output Compared to Field Data

Numerous problems exist when comparing model output with field data. These problems are listed as follows:

1) The actual groundwater flow direction may be slightly different than that modeled. This would result in the actual plume in a location not drilled.

2) The actual groundwater gradient may be greater or less than the modeled gradient and the plume could have been either past the area drilled in 1987 or not yet at that position.

3) The high density of the 32% UAN may have caused most of the contaminant to sink to the bottom of the aquifer. Low concentrations would be observed away from the source area as the UAN gradually mixed with groundwater and was carried away.

Chapter 6
CONCLUSIONS

1) As hydraulic conductivity was increased in the model, the plume migrated more rapidly. The pattern of the modeled plume is a function of hydraulic conductivity and time.

2) The modeled recovery wells removed a greater amount of contaminant and kept the plume from moving away from the source area when the hydraulic conductivity was low.

3) Field data indicated no contaminants had reached the center of section 14 by October, 1987, ~2.5 years after the product basin leak. Cominco's recovery wells have removed more than twice the amount of nitrogen estimated lost initially.

4) The model results were relatively insensitive to changes in dispersivity.

5) 32% UAN entered the groundwater as a DNAPL.

6) Adsorption and ponding of UAN may have occurred at the base of the aquifer beneath the product basin which leaked. Fresh groundwater mixed with UAN as it flowed over the base of the aquifer and thus provided a continuous source of contaminant.

7) The MOC model can not simulate density flow or desorption and therefore can not accurately predict observed field data.

8) Actual concentrations of the leaked contaminant were too large for the format of the input array of the model. Scaled concentrations were found to have the same plume patterns.

9) Oscillation in modeled concentration output required that the contaminant be entered as an initial concentration array instead of modeled injection wells.

10) Two widely accepted methods of determining hydraulic conductivity are pump test data calculations and particle size analysis estimation. These two methods were used on field data and gave differing values for hydraulic conductivity.

In conclusion, Konikow (1981) summarizes the role models should play in groundwater quality problems as follows:

> For applications to field problems, these solute-transport models impose data requirements that, in general, exceed our practical capabilities to accurately describe the field properties and stresses of the hydraulic and chemical system. Thus, interpretations based on model analyses must recognize the significance of uncertainties in input data. Models of ground-water systems should be regarded as just one tool among many that can be used in the analysis of a ground-water quality problem.

Numerical simulation can help the analyst integrate available data, evaluate conceptual models, test hypotheses pertaining to flow and quality changes, and predict system responses to alternative stresses. The models do not replace field data, but they do offer a feedback mechanism that can help to guide the design of a more effective and more efficient data-collection program.

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APPENDIX A

GENERALIZED WELL LOGS

DEPTH	DESCRIPTION
	OW-1
0	Silty clay
19	Sand, fine to coarse
29	Silty Clay
30	BOH
	OW-2
0	Silty Clay
15	Sand, fine to medium
26	Silty clay
27	BOH
	OW-3
0	Silty clay
20	Sand, fine to coarse
32	Silty clay
33	BOH
	OW-4
0	Silty clay
18	Sand, fine to medium
27	Silty clay
28	BOH
	OW-5
0	Silty clay
19	Sand, fine
27	Silty clay
27.5	BOH
	OW-6
0	Silty clay
15	Clayey sand
19	Sand, fine
27	Silty clay
28	BOH

DEPTH	DESCRIPTION
	OW-7
0	Silty clay
18	Sand, fine to coarse
28	Silty clay
29	BOH
	OW-8
0	Silty clay
23	Sand, fine
25	Silty clay
26	Sand, fine to coarse, some gravel
35	Sand, fine
43	Silty clay
44	BOH
	OW-9
0	Silty clay
19	Sand, fine to medium
28	BOH
	OW-10
0	Silty clay
19	Sand, fine to medium
28.5	Silty clay
29	BOH
	RW-1
0	Silty clay
19	Sand, fine
26	Sand, fine to coarse
28.5	Silty clay
29	BOH
	RW-2
0	Silty clay
18	Sand, fine to medium
28	Silty clay
28.5	BOH

University of Nebraska Test Hole #6 (UNL TH6)

DEPTH	DESCRIPTION
0	Topsoil
2	Clay, brown
14	Sand, coarse
15	Clay, brown
17	Sand, medium coarse and gravel
28	Clay, brown
31	Sand and gravel
35	Limestone, gravel
40	BOH

Logs of October, 1987 Drilling Program

87-1

0	Clay, Topsoil
3	Clay
15.5	Silty sand, 30% fine
20	Silty clay
26	Sandy silt
32	Fine gravel
36	Clay
41.5	BOH

87-2

0	Clay, Topsoil
5.5	Clay
13.5	Sand, fine
16	Silty clay
20	Gravel
22	Clay
28.5	Clayey sand
30.5	Silty clay with 10 cm. chert rocks, till
38	Sandy clay
40.5	Sand
44.5	Clay
50	BOH

87-3

0	Topsoil
1	Clay
12.5	Silty sand
13	Sand, medium to coarse
24.5	Silt
35	BOH

DEPTH	DESCRIPTION
	87-4
0	Topsoil
2	Clay
15.5	Silty sand, fine
19.5	Sand, coarse, some fine gravel
25	Silty clay
67.5	BOH
	87-5
0	Topsoil
1	Clay
12.5	Sand
25	Silt
26.5	BOH
	87-6
0	Topsoil
2.5	Clay
14	Silty sand
19	Sand, fine
23.5	Silty clay
26.5	BOH
	87-7
0	Topsoil
3	Clay
12.5	Sandy clay
13.5	Sand, fine
26.5	Silt
35	BOH
	87-8
0	Topsoil
2	Clay
12.5	Sand, medium
29	Clay
31.5	BOH

DEPTH	DESCRIPTION
	87-9
0	Topsoil
2	Clay
13	Sand, fine to medium
29	Silty sand
30	Silty clay
31.5	BOH
	87-10
0	Topsoil
2	Clay
16	Sandy silt
19	Sand, coarse
27	Sandy silt
31.5	BOH
	87-11
0	Topsoil
3	Clay
19	Sand
23.5	Sandy silt
25	Sand, fine to very coarse
29	Silt
31.5	BOH
	87-12
0	Topsoil
2	Clay
16	Sand
25	Gravel, medium, with sand and clay; till
35	BOH
	87-13
0	Topsoil
3	Clay
11	Silty sand, fine
14	Silt
15	Sand, fine to very coarse, with gravel
20	Silt
25	BOH

DEPTH	DESCRIPTION
	87-14
0	Topsoil
3	Clay
15	Sand, medium to fine
25	Sand with gravel
30	Silty sand
35	Sandy silt
45	BOH
	87-15
0	Topsoil
2	Clay
13	Sand, fine to medium
29	Silt
35	BOH

Surface and Water Elevations

Well No.	Surface Elevation	Static Water Elevation
	(feet above mean sea level)	
RW-1	1280.25	1261.25
RW-2	1278.06	1260.06
RW-3	1278.55	1260.55
RW-4	1278.65	1260.65
OW-2	1278.79	1259.79
OW-3	1284.51	1260.51
OW-4	1279.58	1259.58
OW-5	1279.12	1260.12
OW-6	1278.91	1259.91
OW-7	1279.44	1260.44
OW-8	~1290	~1256
OW-9	1281.88	1260.88
OW-10	1280.50	not available
87-1	1263.34	not available
87-2	1259.92	"
87-3	1274.45	"
87-4	1275.31	"
87-5	1275.76	"
87-6	1276.55	"
87-7	1277.18	"
87-8	1277.59	"
87-9	1277.85	"
87-10	1275.33	"
87-11	1278.93	"
87-12	1261.41	"
87-13	1259.44	"
87-14	1280.13	"
87-15	1279.55	"

APPENDIX B

DATA FROM JULY, 1985 PUMP TEST

Well RW-1 Static Water Level = 19.7 ft. below measuring point
Distance from Pumping Well (RW-1) = 0.2 ft. (radius of well)

Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)	
0	19.7	0	
0.5	21.2	1.5	
1	21.35	1.65	
1.5	21.4	1.7	
2	21.4	1.7	
2.5	21.4	1.7	
3	21.45	1.75	
3.5	21.6	1.9	
4	21.6	1.9	
4.5	21.6	1.9	
5	21.6	1.9	
6	21.6	1.9	
10	21.6	1.9	
12	21.65	1.95	
15	21.6	1.9	
20	20.1	0.4	(pump shut off ~10 sec.)
25	21.6	1.9	
30	21.6	1.9	
35	21.65	1.95	
40	21.65	1.95	
45	21.65	1.95	
50	21.65	1.95	
60	21.7	2.0	
78	21.7	2.0	
90	21.7	2.0	
120	21.7	2.0	
180	21.7	2.0	
240	21.7	2.0	
270	21.7	2.0	
300	21.7	2.0	
360	21.75	2.05	
420	21.75	2.05	
420	20.15	0.65	

Well OW-1 Static Water Level =19.5 ft. below measuring point
Distance from Pumping Well (RW-1) = 11.9 ft.

Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)
0	19.5	0
1	19.8	0.3
2	19.8	0.3
3	19.85	0.35
4	19.85	0.35
5	19.9	0.4
6	19.95	0.45
7	19.95	0.45
8	19.95	0.45
10	19.95	0.45
12	19.95	0.45
15	19.95	0.45
20	19.75	0.25
25	19.95	0.45
30	20.0	0.5
35	20.0	0.5
40	20.0	0.5
45	20.0	0.5
50	20.0	0.5
60	20.0	0.5
75	20.0	0.5
90	20.05	0.55
120	20.1	0.6
180	20.1	0.6
240	20.1	0.6
300	20.15	0.65
360	20.15	0.65

Well OW-2 **Static Water Level =** 18.6 ft. below measuring point
Distance from Pumping Well (RW-1) = not noted in report

Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)
0	18.6	0
427	18.6	0

Well OW-3 **Static Water Level =** 23.5 ft. below measuring point
Distance from Pumping Well (RW-1) = not noted in report

Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)
0	23.5	0
440	23.5	0

Well OW-4 **Static Water Level =** 18.9 ft. below measuring point
Distance from Pumping Well (RW-1) = not noted in report

Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)
0	18.9	0
63	18.9	0
126	18.9	0
190	18.9	0
277	18.9	0
420	18.9	0

Well OW-5 **Static Water Level =** 18.5 ft. below measuring point
Distance from Pumping Well (RW-1) = not noted in report

Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)
0	18.5	0
65	18.5	0
128	18.5	0
192	18.6	0.1
278	18.6	0.1
423	18.6	0.1

Well OW-6 **Static Water Level =** 18.4 ft. below measuring point
Distance from Pumping Well (RW-1) = not noted in report

Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)
0	18.4	0
67	18.4	0
130	18.4	0
195	18.4	0
281	18.4	0
425	18.4	0

Well OW-7 **Static Water Level =** 19.4 ft. below measuring point
Distance from Pumping Well (RW-1) = not noted in report

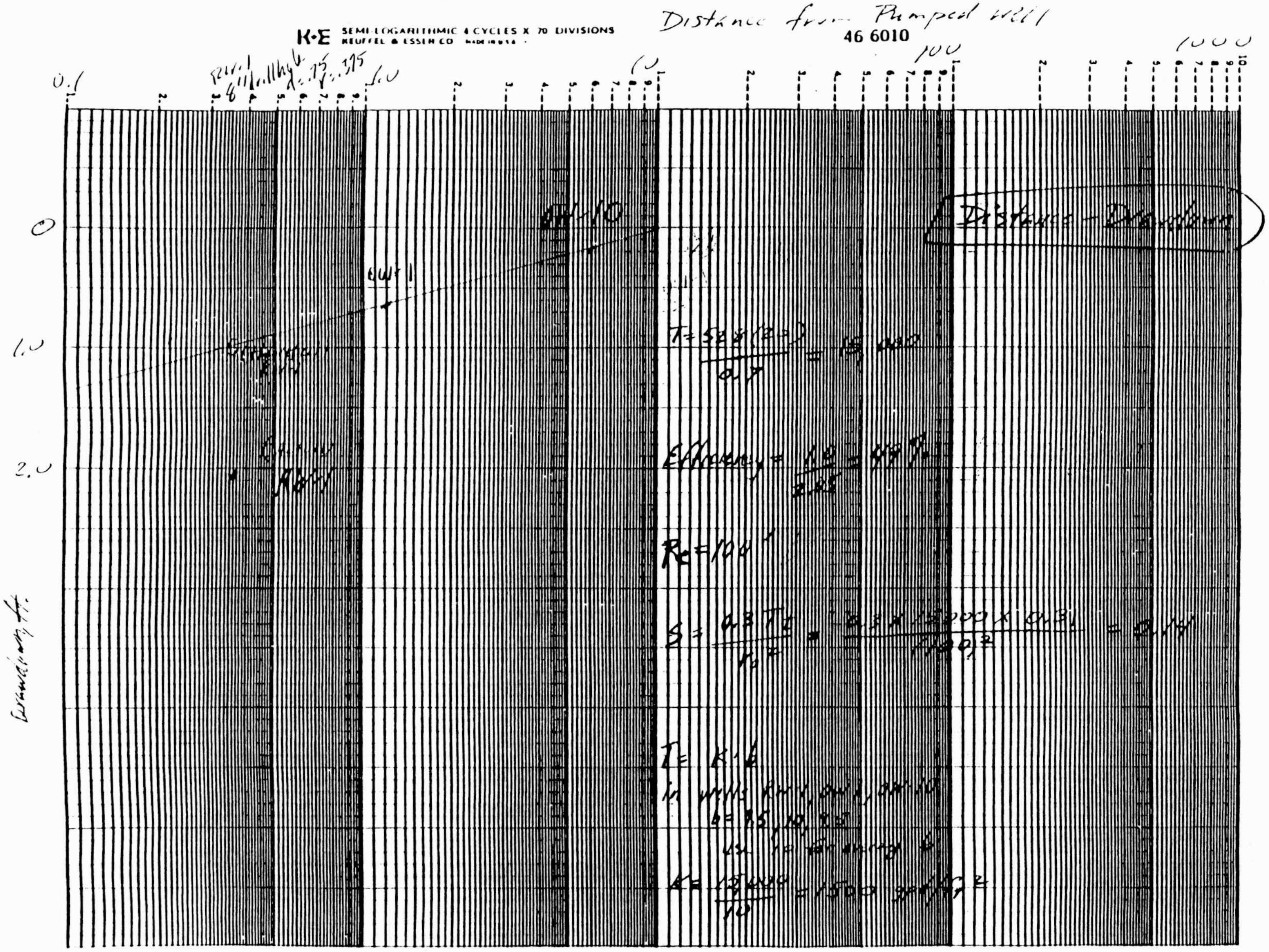
Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)
0	19.4	0
70	19.45	0.05
133	19.5	0.1
198	19.5	0.1
284	19.5	0.1
430	19.5	0.1

Well OW-9 Static Water Level = 21.1 ft. below measuring point
Distance from Pumping Well (RW-1) = not noted in report

Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)
0	21.1	0
75	21.1	0
187	21.1	0
275	21.1	0
418	21.2	0.1

Well OW-10 Static Water Level = 21.3 ft. below measuring point
Distance from Pumping Well (RW-1) = 60 feet

Elapsed Time (minutes)	Water Level (feet)	Drawdown (feet)
0	21.3	0
8	21.35	0.05
16	21.45	0.15
26	21.35	0.05
46	21.4	0.1
76	21.4	0.1
110	21.45	0.15
150	21.45	0.15
270	21.5	0.2
435	21.5	0.2



$T = \frac{528(20)}{0.7} = 15{,}000$

Efficiency $= \frac{1.0}{2.25} = 44\%$

$R_o = 1100'$

$S = \frac{0.3\,T\,t}{r_o^2} = \frac{0.3 \times 15000 \times 0.31}{(1100)^2} = 0.14$

$T = K\,b$

in wells RW-1, OW-1, OW-10

$b = 15, 10, 9.5$

use 10 for average b

$K = \frac{15000}{10} = 1500$ gpd/ft^2

APPENDIX C
Nitrate-Nitrogen Data (mg/l) from 1985 and 1986[1]

WELL

Date	OW-2	OW-3	OW-4	OW-5	OW-6	OW-9	OW-10
1985							
5-21[2]	75	120	850	480	590	255	--
6-14	22.5	22	262	220	210	94	16300
7-3[3]	30	300	250	205	175	125	400
7-3[4]	104	55	190	330	180	100	260
7-10	4800	--	--	--	--	--	--
9-17	2500	--	400	13900	450	--	--
9-23	900	--	--	3400	300	--	--
10-17	65	33	109	113	1850	45	113
11-11	--	--	--	1100	--	--	900
11-18	--	--	--	3500	--	--	7500
12-5	--	--	--	700	--	--	6900
1986							
3-20[5]	10	23	240	380	1800	76	500
7-17	10	14	140	500	440	120	400

Notes:

[1] These data are a continuation of the data presented in Table 2.2

[2] After Drilling

[3] Before Pump Test

[4] After Pump Test

[5] No data available for these wells except on these dates in 1986

Source: HWST (1986)

APPENDIX D

Sample Input File for Model

```
Dec.13  COMINCO  -5 YR    ss     17 PUMPING PERIODS w.t.ver3a
 - Konikow's sugg
   6  17 -40  292500   1   7   0 100   0   9   1   0   0   0
  0   0   0
    3.9.22.28
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0.   0.   0.   0.   0.   0.   0.   0.   0.   0.
1   1.0
```

```
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.1000.1000.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
  0.    0.    0.    0.    0.    0.    0.    0.
1
  12   6   7 100   0   0   0   0   0   0  .25 1.209E+05
1
   6   3   7 100   1   0   0   0   0   0  .08 1.209E+05
 519 .14E-01 .00
1
  14   7   7 100   0   0   0   0   0   0  .34 1.209E+05
1
   6   3   7 100   4   0   0   0   0   0  .08 1.209E+05
 819 .14E-01 .00
 818 .14E-01 .00
 816 .14E-01 .00
 519 .14E-01 .00
1
  12   6   7 100   0   0   0   0   0   0  .25 1.209E+05
```

```
1
   6   3   7 100    4    0    0    0    0    0  .08 1.209E+05
 819 .14E-01 .00
 818 .14E-01 .00
 816 .14E-01 .00
 519 .14E-01 .00
1
  14   7   7 100    0    0    0    0    0    0  .33 1.209E+05
1
   8   4   7 100    4    0    0    0    0    0  .17 1.209E+05
 819 .88E-02 .00
 818 .88E-02 .00
 816 .88E-02 .00
 519 .88E-02 .00
1
   8   4   7 100    0    0    0    0    0    0  .17 1.209E+05
1
  12   6   7 100    4    0    0    0    0    0  .25 1.209E+05
 819 .14E-01 .00
 818 .14E-01 .00
 816 .14E-01 .00
 519 .14E-01 .00
1
   6   3   7 100    4    0    0    0    0    0  .08 1.209E+05
 819 .37E-01 .00
 818 .37E-01 .00
 816 .37E-01 .00
 519 .37E-01 .00
1
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 818 .30E-02 .00
 816 .30E-02 .00
 519 .30E-02 .00
1
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 818 .38E-01 .00
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 519 .38E-01 .00
1
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 519 .51E-01 .00
 818 .51E-01 .00
1
   8   4   7 100    4    0    0    0    0    0  .17 1.209E+05
 819 .26E-01 .00
 818 .26E-01 .00
 816 .26E-01 .00
 519 .26E-01 .00
1
   8   4   7 100    4    0    0    0    0    0  .17 1.209E+05
 819 .50E-01 .00
 818 .50E-01 .00
 816 .50E-01 .00
 519 .50E-01 .00
```
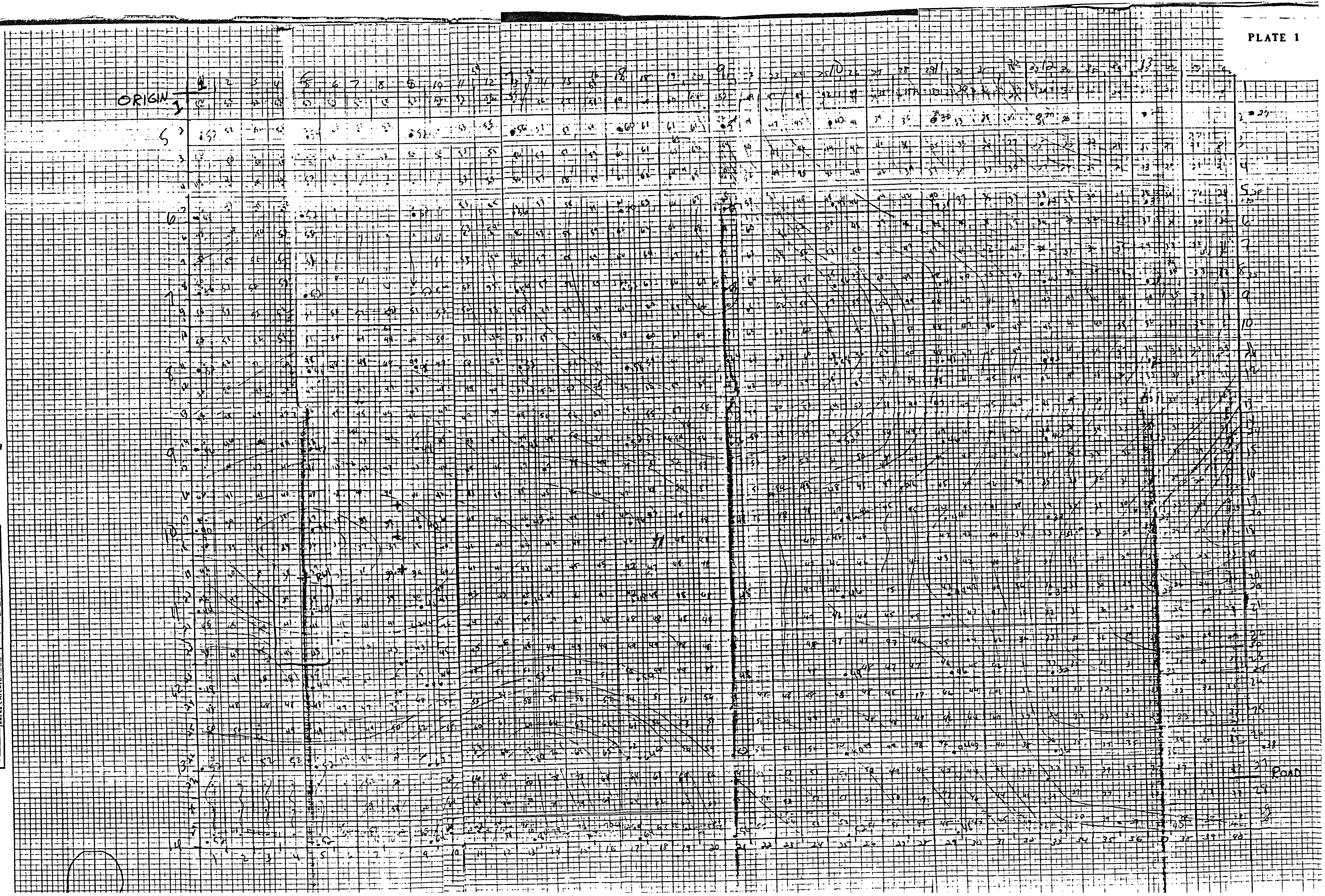

APPENDIX E

```
C     JOHN T. BAXTER
C     JANUARY, 1989
C     LINCOLN, NEBRASKA

C     ARRAY.FOR
C     PROGRAM TO MULTIPLY AN ARRAY BY A USER ENTERED CONSTANT

C     THE ARRARY MUST BE 50 BY 50 OR SMALLER UNLESS THE DIMENSION
C     AND FORMAT STATEMENT ARE CHANGED.

      DIMENSION XOLD(50,50),XNEW(50,50)

C     PROMPT USER FOR THE SIZE OF THE ARRAY TO BE CONVERTED

      WRITE(*,*)'ENTER # ROWS AND # COLUMNS, SEPERATED BY A COMMA'
      READ(*,*)IROW,ICOL
      WRITE(*,*)IROW,ICOL

C     PROMPT USER FOR INPUT FILE NAME AND READ ARRAY FROM INPUT FILE

      DO 10 I=1,IROW
      READ(4,5)(XOLD(I,K),K=1,ICOL)
    5 FORMAT(50F3.0)
   10 CONTINUE

C     PROMPT USER FOR MULTIPLICATION FACTOR

      WRITE (*,75)
   75 FORMAT (1X,'Enter the Constant (CONST) to multiply the array by')
      READ (*,*)CONST
      WRITE(*,*)CONST

C     MULTIPLY INPUT ARRAY BY THE USER SUPPLIED CONSTANT TO GENERATE
C     NEW ARRAY

      DO 100 I=1,IROW
      DO 100 J=1,ICOL
      XNEW(I,J)=XOLD(I,J)*CONST
  100 CONTINUE

C     PROMPT USER FOR OUTPUT FILE NAME AND WRITE NEW ARRAY TO FILE

      DO 200 II=1,IROW
       WRITE (2,150) (XNEW(II,JJ),JJ=1,ICOL)
  150  FORMAT (1X,50F4.0)
  200 CONTINUE
      STOP
      END
```

PLATE 1



•250

FINAL SURVEY
SURVEYED
PLOTTED
TEMPLATE
AREAS CHK.
NOTE BOOK
NO.
DATE

Reduced From Original

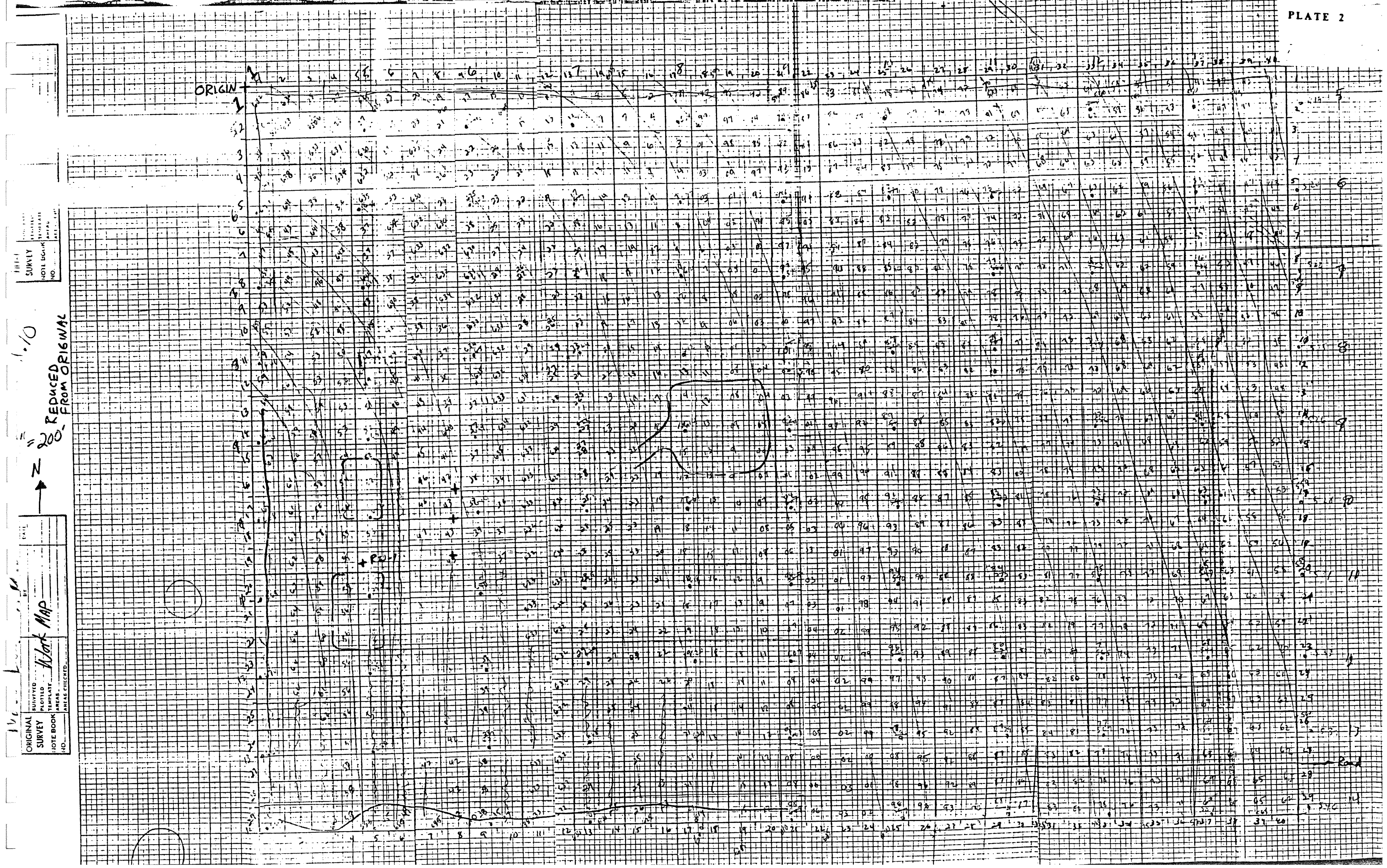
1" = 200'

→ N

Ag Thickness X 0.23

ORIGINAL SURVEY
SURVEYED
BY
WORK MAP
PLOTTED
TEMPLATE
AREAS CHECKED
NOTE BOOK NO.
DATE

PLATE 2


ORIGIN
N
1" = 200'
REDUCED FROM ORIGINAL
Work Map
RD-1
Road
SURVEY
NOTE BOOK
NO.
ORIGINAL SURVEY
NOTE BOOK
NO.
SURVEYED
PLOTTED
TEMPLATE
AREAS
AREAS CHECKED