SOLUTE TRANSPORT MODELING OF AGRICULTURAL CHEMICALS IN AN ALLUVIAL TERRACE DEPOSIT NEAR PERKINS, OKLAHOMA

BY

MICHELLE JOY VAN ALSTINE

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1991

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1995

SOLUTE TRANSPORT MODELING OF AGRICULTURAL

CHEMICALS IN AN ALLUVIAL TERRACE

DEPOSIT NEAR PERKINS,

OKLAHOMA

Thesis Approved:

Douglas C. Kent
Thesis Adviser

S. L. Burks

A. W. Young

Thomas C. Collins
Dean of Graduate College

ACKNOWLEDGEMENTS

I wish to extend heartfelt thanks to my graduate committee members Dr. Doug C. Kent, Mr. Jim Naney and Dr. Bud Burks for their time and consideration. I wish to express my sincere appreciation to my advisor Dr. Doug C. Kent for his encouragement, direction in my research, and advice throughout my graduate program. Mr. Jim Naney's guidance and wisdom was integral to my thesis research and development. A special thanks is extended to Dr. Frank Schiebe and Dr. Sam Smith of the USDA-NAWQL for their support through the ARS 1040 trainee program. My thesis research would not have been possible without their support.

My parents, Bill and Jackie Van Alstine, and my sister, Heather Van Alstine, encouraged and supported me all the way through my college career and always reminded me of my capability to be whatever I so desired. My future husband, John Field, provided moral as well as technical support and always believed in me, even when I wasn't sure that I did.

I wish to sincerely thank Bill Barnes, Dale Pardue, Gary Heathman, Elaine Mead, Billie Rodgers and Vicki Beames of the USDA-NAWQL in Durant, OK for their technical support as well as their friendship throughout my research.

TABLE OF CONTENTS

Chapter		Page
I.	INTRODUCTION	1
	Objectives	2
	Methods of Investigation	6
II.	LITERATURE REVIEW	8
	Previous Investigations	8
	Computer Modeling	10
	Conceptual Model	10
	Mathematical Model	11
	Methods of Solution	11
	Modeling Studies	12
	Geophysical Studies	14
III.	HYDROGEOLOGIC INVESTIGATION	16
	Site Background	16
	Physiography	16
	Climatology	16
	Surface Waters and Drainage	17
	Soil Characteristics	17
	Teller Soil	17
	Konawa Soil	19
	Geologic Framework	19
	Bedrock	22
	Unconsolidated Sediments	24
	Land Use and Chemical Application	24
	Land Use	25
	Fertilizer and Pesticide Application	26
	Precipitation and Water Quality	27
	Pesticides	27
	Fertilizers	35
	Review of Hydrogeologic Investigation	39
IV.	PHASE I - DEVELOPMENT OF CONCEPTUAL MODEL	43
	Definition of Aquifer Boundaries	44
	Monitoring Wells/Piezometers	44
	Geophysical Surveys	48
	Geologic Cross-Sections	48
	Bedrock and Potentiometric Surfaces/ Groundwater Flowpaths	52

Chapter Page

Definition of Aquifer Characteristics...... 58
Aquifer Tests.......................... 58
Hydraulic Variables/
Aquifer Coefficients................. 59
Simplifying Assumptions.................... 61
The Porous Medium as a Continuum...... 61
Horizontal Two-Dimensional Modeling... 61

V. PHASE II - DESIGN OF MATHEMATICAL MODEL......... 62

Numerical Model and Code................... 63
Coefficients and Parameters................ 64
Temporal and Spatial Arrangement........... 66
Additional Assumptions..................... 69

VI. PHASE III - CALIBRATION AND VERIFICATION
OF MODEL............................ 72

Head Only Runs............................. 72
Calibration........................... 74
Verification.......................... 77
Sensitivity Analysis.................. 78
Solute Transport Runs...................... 80
Calibration and Verification.......... 80
Sensitivity Analysis.................. 85

VII. PHASE IV - PREDICTION OF SOLUTE TRANSPORT....... 89
Development and Movement
of Nitrate Plume...................... 90
Source A Movement..................... 95
Source B Movement..................... 102
Simulation Results......................... 102

VIII. SUMMARY AND CONCLUSIONS......................... 104

Summary of Study........................... 104
Phase I - Development of
Conceptual Model.................... 107
Phase II - Design of
Mathematical Model.................. 108
Phase III - Calibration and
Verification of Model............... 109
Phase IV - Prediction of
Solute Transport.................... 110
Conclusions................................ 111
Recommendations............................ 112
Unsaturated Hydraulic Conductivity.... 112
Unsaturated Zone Modeling............. 114
Linked Model System................... 115

REFERENCES... 116

Chapter Page

APPENDIXES..122

APPENDIX A - LAND USE AND APPLICATION MAPS..... 123

APPENDIX B - GEOPHYSICAL SURVEYS................ 138

APPENDIX C - AQUIFER TESTS...................... 158

APPENDIX D - CONTOURING DATA.................... 192

APPENDIX E - AQUIFER TEST PLOTS................. 201

APPENDIX F - COMPUTER MODELING PRINTOUTS....... 215

LIST OF TABLES

Table		Page
I.	Pesticides Used on the Perkins Station	28
II.	Pesticide Application and Recovery	33
III.	Perkins Station Monitoring Well Statistics	47
IV.	Coefficients and Parameters for Solute Transport Computer Run	65
V.	Computer Run Titles, Time Periods and Sensitivity	73
VI.	Cumulative Precipitation and Recharge Calculations	75
VII.	Observed Versus Calculated Potentiometric Head Measurements	76
VIII.	Observed Versus Calculated Nitrate Concentrations in Solute Transport Runs	86
IX.	Sensitivity Analysis for Solute Transport Runs - Monitoring Well Number 21	87

LIST OF FIGURES

Figure		Page
1.	Site Location Map	3
2.	Regional Site Map	4
3.	Perkins Station Map	5
4.	Generalized Soils Map for Perkins Station	18
5.	Regional Geologic Map	20
6.	Geologic Unit Description	21
7.	Generalized Regional Cross-Section	23
8.	Composite Hydrographs for Monitoring Wells #1, 2, and 10	30
9.	Application Areas on Perkins Station	32
10.	Comparison of Water Levels, Nitrate Levels and Precipitation - Short Term	37
11.	Comparison of Water Levels, Nitrate Levels and Precipitation - Long Term	38
12.	Typical Monitoring Well Schematic - Clustered Wells in Northern Terrace Deposits	45
13.	Perkins Station Topographic Map with Cross-Section Locations	49
14.	North-South Cross-Section of Perkins Station	50
15.	East-West Cross-Section of Perkins Station	51
16.	Regional Water Table Map	53
17.	Local Water Table Map	54
18.	Detailed Water Table Map	55
19.	Regional Bedrock Map	57

20. Southern Terrace of Perkins Station - Computer Modeling Area.......................... 67

21. Southern Terrace of Perkins Station - Gridded for Modeling............................ 68

22. Water Table Elevation Map with Computer Grid Overlay........................... 70

23. Node ID Computer Grid.............................. 71

24. Fertilizer Application Areas - Spring 1992........ 82

25. Source Areas for Solute Transport Prediction Simulation.. 91

26. Source A - NO_3-N Plume Simulation - 1992 to 1993....................... 93

27. Source B - NO_3-N Plume Simulation - 1992 to 1993....................... 94

28. Source A - NO_3-N Plume Simulation - 1993 to 1994....................... 96

29. Source B - NO_3-N Plume Simulation - 1993 to 1994....................... 97

30. Source A - NO_3-N Plume Simulation - 1994 to 1995....................... 98

31. Source B - NO_3-N Plume Simulation - 1994 to 1995....................... 99

32. Source A - NO_3-N Plume Simulation - 1995 to 1996....................... 100

33. Source B - NO_3-N Plume Simulation - 1995 to 1996....................... 101

CHAPTER I

INTRODUCTION

Agriculture is often cited as one of the largest sources of groundwater contamination today and is being categorized along with heavy industry by the public in matters of pollution. The media cites cases of groundwater contamination on a regular basis, usually implicating agricultural activities as the primary cause. Public concern regarding agricultural chemicals began in the 1960's with pesticides use and has continued to the recent issue of nitrate levels in groundwater.

Agriculture is more dynamic and effective in the United States than anywhere else in the world (Scifres, 1989). Agriculture, more than any other industry, depends upon an abundant supply of clean water. Agricultural research and technology development continuously strive to produce optimum crop yields while minimizing risks to the environment and groundwater supplies. Individual agricultural research farms are working to develop and implement the best practical management practices in order to obtain these goals.

The Oklahoma State University Agronomy Research Station (Perkins Station) is located one mile north of

Perkins, OK at the intersection of state highways 177 and 33. The Perkins Station includes all of Section 36, T18N, R2E, Payne County, OK (see Figure 1). The station is operated under the supervision of the OSU Agronomy Department in Stillwater, OK. A regional site map extending from the north side of the Perkins Station to the Cimarron River is depicted in Figure 2. A localized map of the station, which encompasses all of Section 36, is depicted in Figure 3.

Objectives

The objective of this project was to characterize the movement of agricultural chemicals in alluvial terrace deposits underlying the Perkins Station. Specifically, the goal was to simulate the movement of nitrates present in the groundwater of the southern terrace deposits through the use of the Nuclear Research Center (Tracy, 1982) version of the KONIKOW (Konikow, et. al., 1978) groundwater model, a two dimensional transport model developed by the United States Geological Survey and modified by the Agronomy Research Service (Kent, et. al., 1986a). A preprocessor was developed for the NRC model by Kent, et. al. and modified by the Agronomy Research Service (Kent, et. al., 1986a). The accuracy of the simulation was ensured through calibration and verification of the output data with historical water level and water quality data. Predictions of the amount of nitrates leaving the station

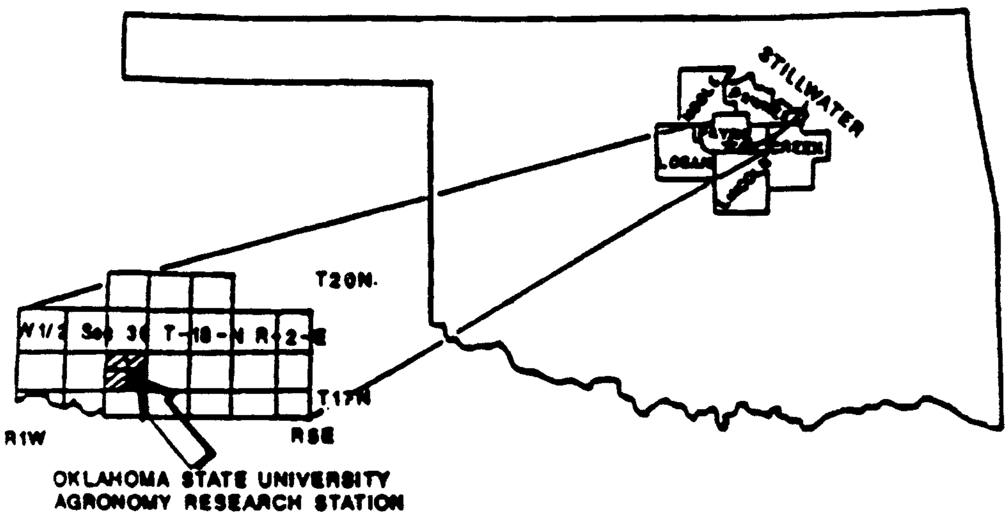


Figure 1. Site Location Map (From Dwivedi, 1989)

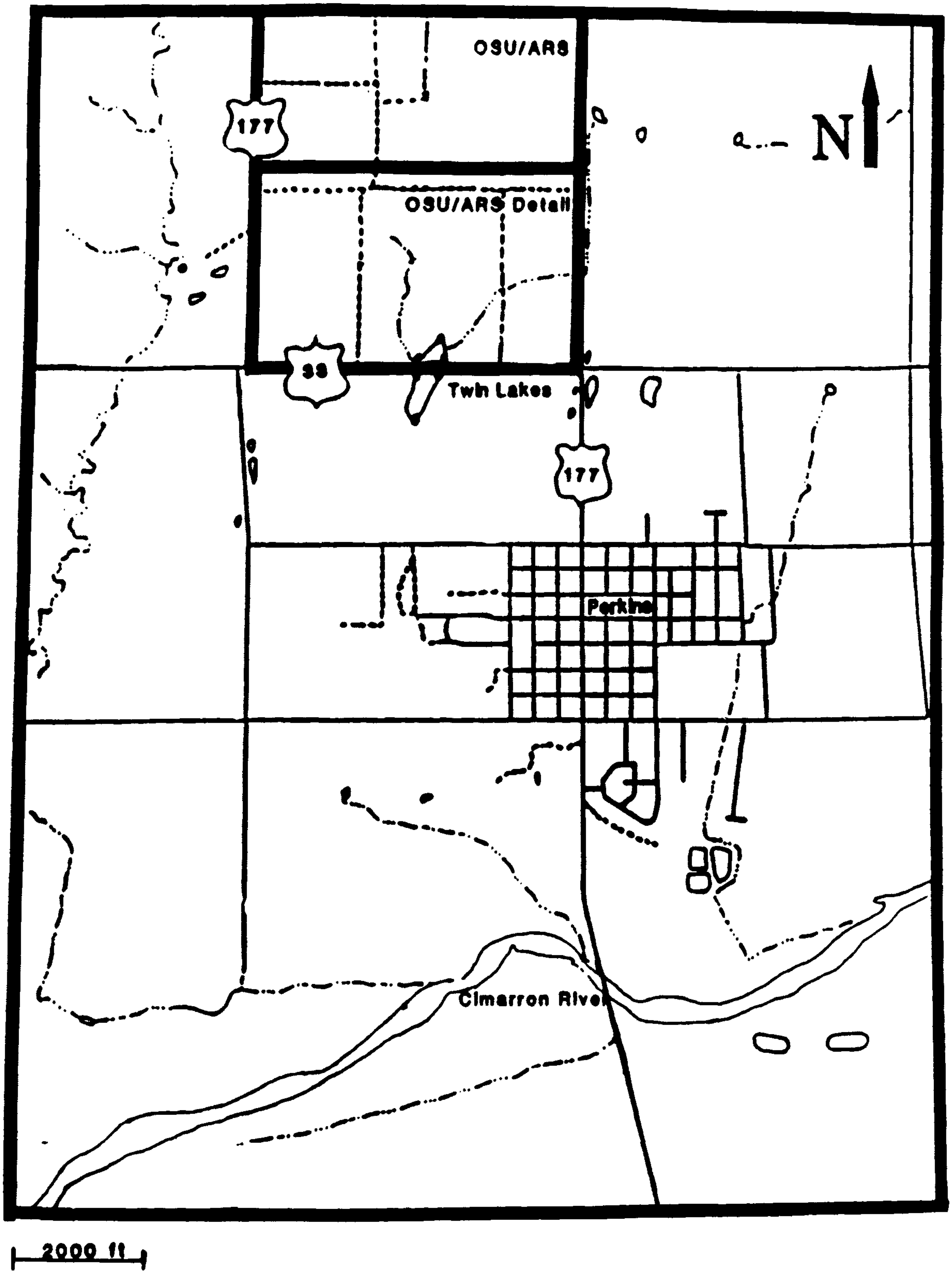


Figure 2. Regional Site Map

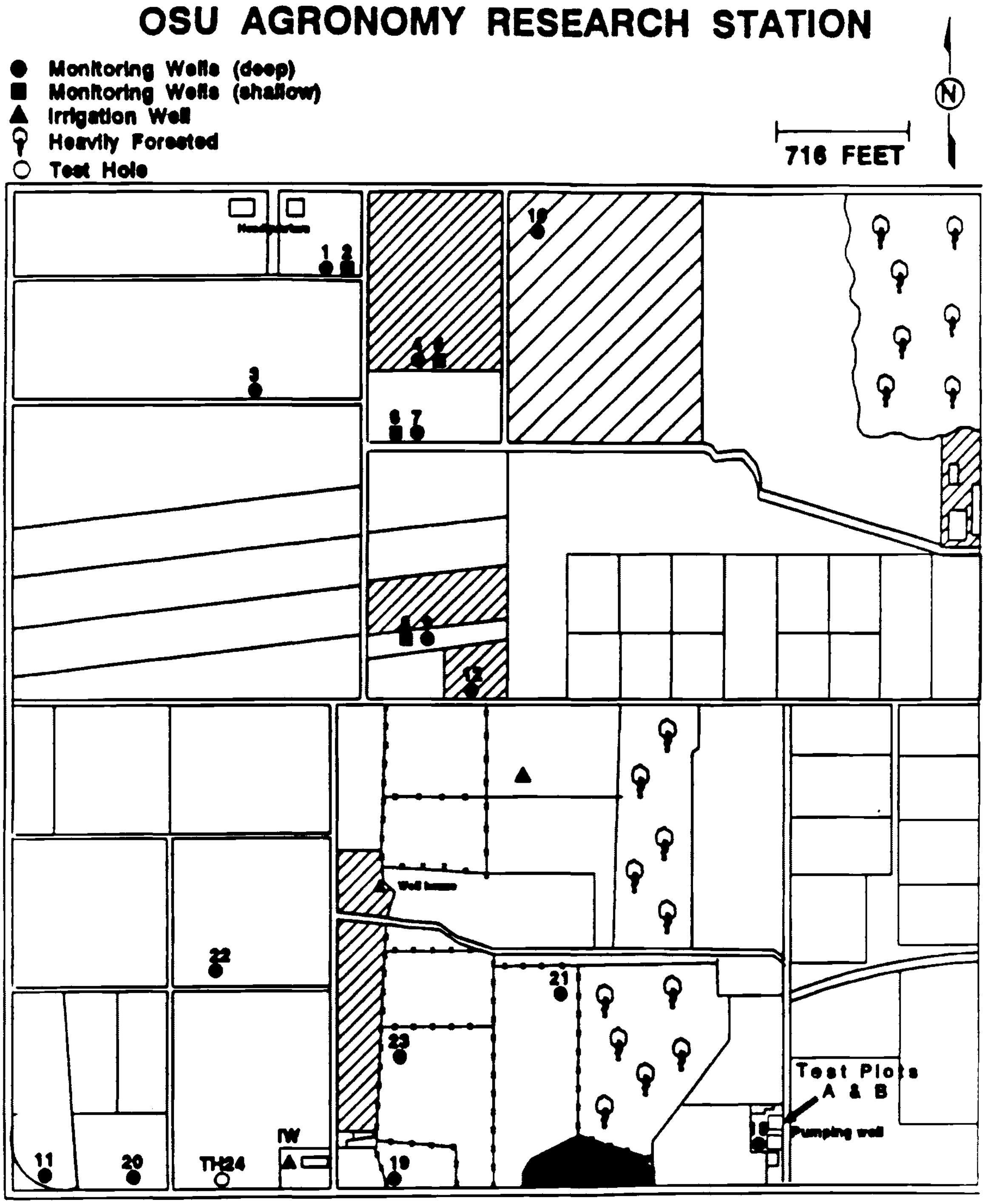


Figure 3. Perkins Station Map

in the groundwater provide essential information for exposure assessment for downgradient residences and communities.

Methods of Investigation

A comprehensive hydrogeologic investigation of the Perkins Station has been ongoing since 1986 through the cooperation of the United States Department of Agriculture National Agricultural Water Quality Laboratory, the OSU School of Geology, the OSU Experimental Station and the OSU Agronomy Department. A summary of the data collected and the significant findings is currently being published by the USDA-NAWQL through the OSU Agronomy Department as an Experimental Station bulletin entitled "Hydrogeology and Solute Transport of Agricultural Chemicals in Alluvial Deposits Near Perkins, Oklahoma" by D.C. Kent, J.W. Naney, R. Westerman, M.J. Van Alstine and R.L. Dwivedi.

The methods of investigation for this thesis research project were conducted in four specific phases:

Phase I - Development of conceptual model:

1) Definition of aquifer boundaries using
   a. Monitoring wells
   b. Geophysics
2) Definition of aquifer characteristics using
   a. Pumping tests
   b. Slug tests
   c. Tracer tests

Phase II - Design of mathematical model using data from Phase I.

Phase III - Sensitivity analysis, calibration and verification of KONIKOW using historical water level and water quality data.

Phase IV - Prediction of solute transport of nitrates in the southern terrace deposits.

CHAPTER II

LITERATURE REVIEW

Previous Investigations

A Ph. D. dissertation project was completed for the study area by Rajeev Lochan Dwivedi in 1989 at Oklahoma State University. His project involved characterizing agricultural impacts on groundwater quality and acquiring input parameters for the simulation of the fate and transport of chemicals in the unsaturated and saturated zones of the Perkins aquifer. This project developed the beginning of a long term data base for the Perkins Station including the monitoring of water level fluctuations and water quality. This work was presented as an invited paper at the American Association for the Advancement of Science in San Francisco (Kent et. al., 1989).

A thesis project combining the used of a groundwater tracer test and a groundwater numerical model to characterize solute transport of agricultural chemicals in the saturated zone of the Perkins aquifer was completed by Atef Kamal Farid Saad in 1992 at OSU. Hydraulic conductivities calculated from pumping test analyses were confirmed through tracer test evaluation. Model application was used to show similarities between actual and simulated chemical movement.

A number of published papers have resulted from the Perkins Station research through the cooperative efforts of members of the OSU Geology Department and the USDA-NAWQL in Durant, OK. A general description of the Cimarron River alluvium beneath the OSU Agronomy Research Station near Perkins, Oklahoma has been published previously (Naney et. al. 1987 and Kent et. al. 1987, 1989). These documents include general descriptions of lithological features encountered during core drilling near potential monitoring well sites on the research station. Descriptions of typical land use and farming practices for plots and small watersheds with associated nitrate levels in the groundwater have been described in several publications (Naney et. al. 1988a, 1988b, 1990, 1991) present the general distribution of agricultural practices on the OSU Agronomy Research Station and the position and relative depth of wells used initially for these studies. Specialized studies involving computer modeling and tracer studies which were conducted at the station were reported by Kent et. al. (1989, 1990) Naney et. al. (1988b), Saad (1992) and Dwivedi (1989). An extensive compilation of data collected at the site along with the preliminary interpretation of the data used to characterize the hydrogeology and solute transport of agricultural chemicals in the alluvial deposits has been included in a document to be published in 1996 (Kent, et. al., 1996).

Computer Modeling

A groundwater model is a simplified version of a real-world system which approximately simulates future spatial distributions of contaminant concentrations, water levels, etc. in the system. A groundwater model is therefore a useful tool for the prediction of the transport of agricultural chemicals introduced into an aquifer. Simplification of complex real-world systems is necessary to make the model practical as well as both time and cost efficient. Modeling includes the development of a conceptual model, the design of a mathematical model followed by calibration and verification before actually being used for solving problems in real-world systems.

Conceptual Model

The first step in modeling is the development of a conceptual model consisting of a set of assumptions to describe the nature of the system while simplifying its features to a useable form (Bear, et. al., 1992). Assumptions relate to items such as the geometry of the aquifer boundaries, the nature of the porous medium and the way heterogeneities will be smoothed out. Of course, the availability of field data required for parameter estimation and model calibration dictates the degree of approximation involved. The development of a conceptual model is not a conclusive step completed at the initial stage of modeling, but rather a dynamic, ongoing activity. Assumptions are re-examined, re-evaluated and altered by necessity throughout the modeling process.

Mathematical Model

The next step in the modeling process is to implement the conceptual model assumptions in the form of a mathematical model in order to yield predictions of real-world systems (Bear, et. al., 1992). Mathematical models contain the same information as conceptual models but in the form of equations for analytical or numerical solution. Mathematical models express balances of the quantity under consideration (i.e. mass of water or mass of solute) in the form of a partial differential equation. A mathematical model and code must be chosen and the coefficients and parameters to be used must be designated. Additional simplifying assumptions should be analyzed and added to the model at this point if necessary.

Methods of Solution

Following mathematical model development, the model must be solved for a given set of conditions (Bear et. al, 1992). Methods of solution are either analytical or numerical. Analytical models offer simple, inexpensive ways to evaluate an aquifer's characteristics. They can be envisioned as a homogeneous box with simple algebra used to make calculations at individual points within the box.

Numerical models are more useful to simulate complex real-world systems with inhomogeneities and irregular boundaries. Spatial distribution of parameters can be detailed because numerical models are divided into matrices composed of two dimensional nodes. Complex algebra calculations are made within each node, thus each node will render a unique answer.

Modeling Studies

Mathematical modeling of solute transport in the subsurface has been utilized by many researchers. Mathematical models are used to assist the United States Environmental Protection Agency's groundwater protection programs in various ways: determining the physical extent and quality of groundwater; assessing the potential impact of domestic, agricultural and industrial activities; evaluating the effectiveness of remedial actions and providing exposure estimates for risk assessments (Molz, et. al., 1987).

Zukowski and Tumeo, 1991, developed GWFREEZE to model solute-transport in groundwater under freezing or near freezing conditions. They theorized that under these conditions, solute transport is effected by groundwater viscosity changes and solute immobilization. Research rendered concentration profiles significantly different than those from solute transport models which did not account for these conditions.

Wong, et. al., 1987, presented a predictive application of a geohydrology model to an actual site. A finite-element computer model was calibrated with field data, then integrated over time using actual rainfall, infiltration and pumping rates. Predicted potentiometric head for the area compared well with field data, therefore ensuring substantial confidence in the predictive capability of the model.

Molz, et. al., 1987, used aquifer tracer tests to deduce that scale-dependence of dispersivity values used in contaminant transport models to estimate the spreading of plumes by hydrodynamic dispersion was inconsequential in current modeling techniques. They developed innovative modeling approaches to simulate solute transport by emphasizing advective transport over dispersive transport.

A review of key works on computer solute transport modeling was compiled by Naymik, 1987. The article discusses the main concepts involved in solute transport modeling and presents a review of seven case studies where computer simulation was employed. The review indicates that solute transport processes with the exception of advection are poorly understood. The review concludes that computer models are useful for managing and storing data, investigation of natural processes and simulating mass balance of solutes under certain natural conditions with a high degree of accuracy.

The objective of this project was to simulate solute transport using a mathematical model. Following the development of a conceptual model based on field data collected at the Perkins Station, a numerical model with particle tracking abilities was chosen for computer simulations of solute transport. The USGS KONIKOW model is a method of characteristics model which uses particle density differentiation for solute transport simulation. After selection and the design of the numerical model to be used, the estimated aquifer coefficients and parameters were used to run a sensitivity analysis of the model. Calibration and verification of the model was possible with the use of historical water quality and water level data. Predictions of solute travel within the aquifer were then simulated.

Geophysical Studies

Geophysical surveys have been utilized by many researchers for groundwater studies. Research conducted by Wachs, et. al., 1979, used a combination of classical geological methods along with geophysical techniques to locate groundwater in an arid, mountainous area of the Santa Catherina region of southern Sinai. Groundwater was found to flow mainly through the joints of crystalline bedrock and to concentrate in alluvial valley fill of the region.

Shallow seismic-reflection techniques were used by Miller, et. al., 1989, to locate the interface between alluvium and bedrock near a chemical evaporation pond in the Texas panhandle. The resulting bedrock contour map showed improved resolution and detected a bedrock valley not interpretable from drilling data alone. This geophysical study allowed the optimum placement of water-quality monitoring wells near the evaporation pond.

Duguid, 1968, used a shallow refraction technique to detect two interfaces in an alluvial deposit. The upper interface proved to be the water table and the lower interface the bedrock surface. More recently, seismic refraction techniques were utilized by Ayers, 1990, to map the bedrock configuration and determine the thickness of the alluvial overburden of the floodplain of the Platte River in east-central Nebraska.

D.C. Resistivity methods were used by Park, et. al., 1990, to confirm the existence of the Bryn Mawr fault and determine its ability to act as a groundwater barrier in the Bunker Hill basin beneath the San Bernadino Valley, California. Resistivity measurements located the fault and determined its attitude. The gouge was found to decrease in resistivity with depth due to increasing clay content. According to interpretation, the ability of the fault to act as a barrier to groundwater flow increases with declining water levels in the region.

CHAPTER III

HYDROGEOLOGIC INVESTIGATION

Site Background

Physiography

Payne County is situated in a transitional zone between the Central Redbed Plains and the Northern Limestone Cuesta Plains. The study area has Redbed Plains characteristics of rolling plains with broad hills and valleys formed by nonresistant red shales and lenticular sandstones. The relief is subdued and the general slope of the land is to the southeast.

Climatology

Payne County is hot in summer and cool in winter with generally mild temperatures. The average temperature at the Perkins Station is 35 degrees Fahrenheit in winter and 74 degrees Fahrenheit in summer. The total average annual precipitation at the station is approximately 30 inches with 70 percent usually falling between April and September. The growing season for most crops falls within this time frame. The average seasonal snowfall is infrequent and tornadoes and severe thunderstorms occur occasionally.

Surface Waters and Drainage

The Perkins Station is situated within the Cimarron River drainage basin. The Cimarron flows east, northeast through Payne County approximately a mile and a half south of the station and has the characteristics of both a braided and meandering stream. The station is drained by a dendritic pattern of small ephemeral creeks trending south easterly to the Cimarron River. Other surface waters include small isolated farm ponds, intermittent creeks and undesignated wetland areas which occur at points at which the water table discharges into topographically low areas.

Soil Characteristics

The geologic framework of the area exerts a strong influence on soil development. The soils can be cultivated only where the surface is flat and not subject to rapid erosion. A generalized soil distribution map for the Perkins Stations is included in Figure 4. The Teller and Konawa soil groups occur over almost 80 percent of the station.

Teller Soil Teller soils occur on ridgetops and side slopes. These soils are deep, nearly level to gently sloping and well drained. Typically, the surface layer is reddish brown loam. The subsoil consists of reddish brown loam, yellowish clay loam and red fine sandy loam. These soils are well suited for raising small grains, sorghum,

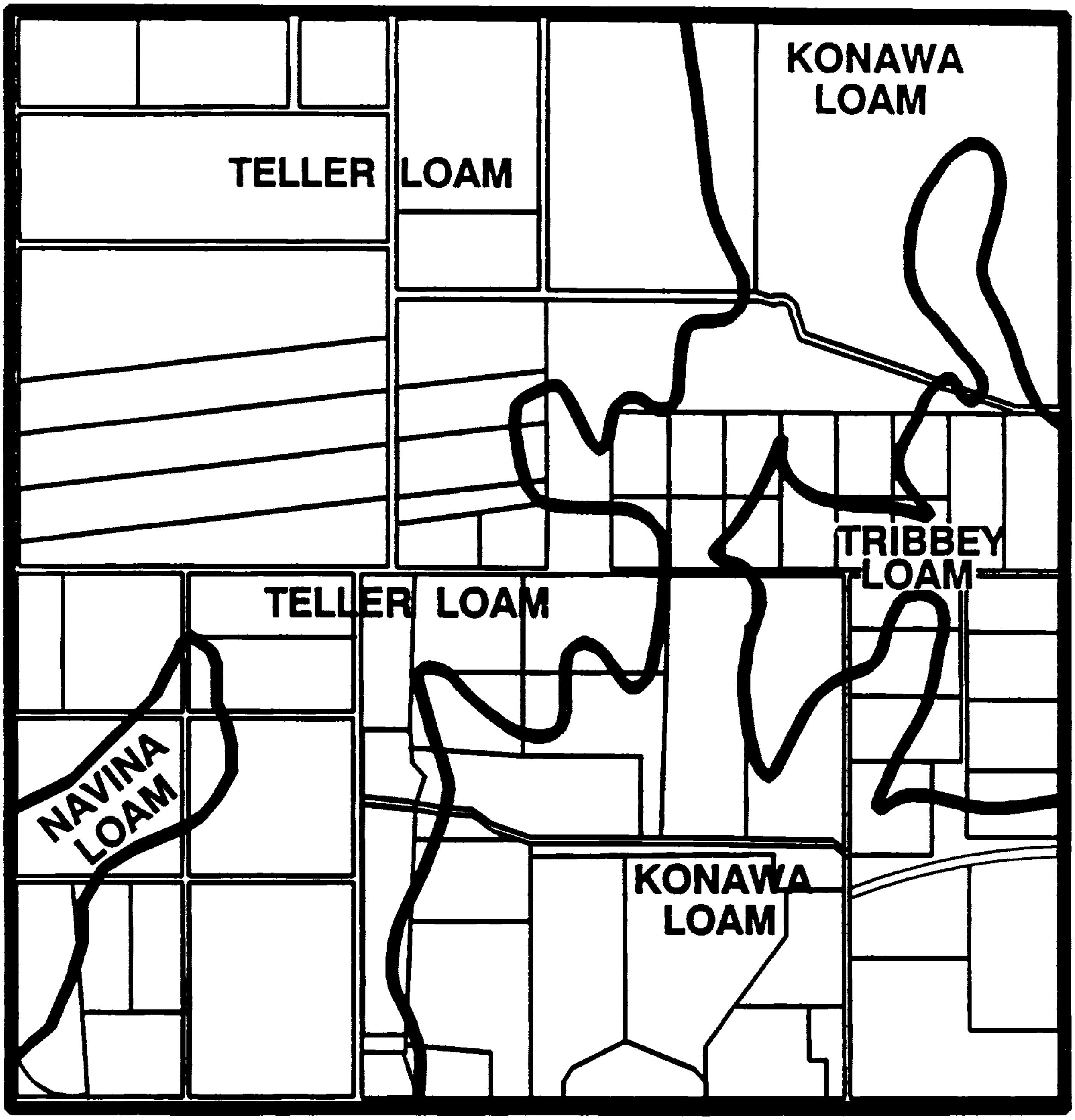


Figure 4. Generalized Soils Map for Perkins Station (Modified After Henley, Gelnar and Mayhugh, 1987)

cotton, legumes and grasses (Henley et. al., 1987).

Konawa Soil Konowa soils also occur on ridgetops and side slopes. These soils are deep, very gently sloping to sloping and well drained. Typically, the surface layer consists of brown and light reddish-brown, fine, sandy loam. The subsoil contains red, sandy, clay loam and red, fine sandy loam (Henley et. al., 1987).

Geologic Framework

Regionally, Payne County is situated on the stable Northern Oklahoma Platform on which unconformities are common. The Paleozoic depositional environments range from shallow marine to alluvial deposits.

The regional surface geology is shown in Figure 5 to be predominantly Quaternary sediments made up of terrace and alluvial deposits. A detailed lithologic description is included in Figure 6. In the north, lower Permian deposits of the Wellington Formation are exposed and upper Pennsylvanian deposits of the Doyle Shale outcrop south of the Cimarron River. Because the surface rock dips gently westward in Payne County, progressively younger beds are exposed in a westward direction. Drilling conducted on the Perkins Station was used to determine that the bedrock is dominated by the Wellington Formation. The unconsolidated Quaternary alluvial and terrace sediments which overlie the Wellington Formation and Oscar Group represent an

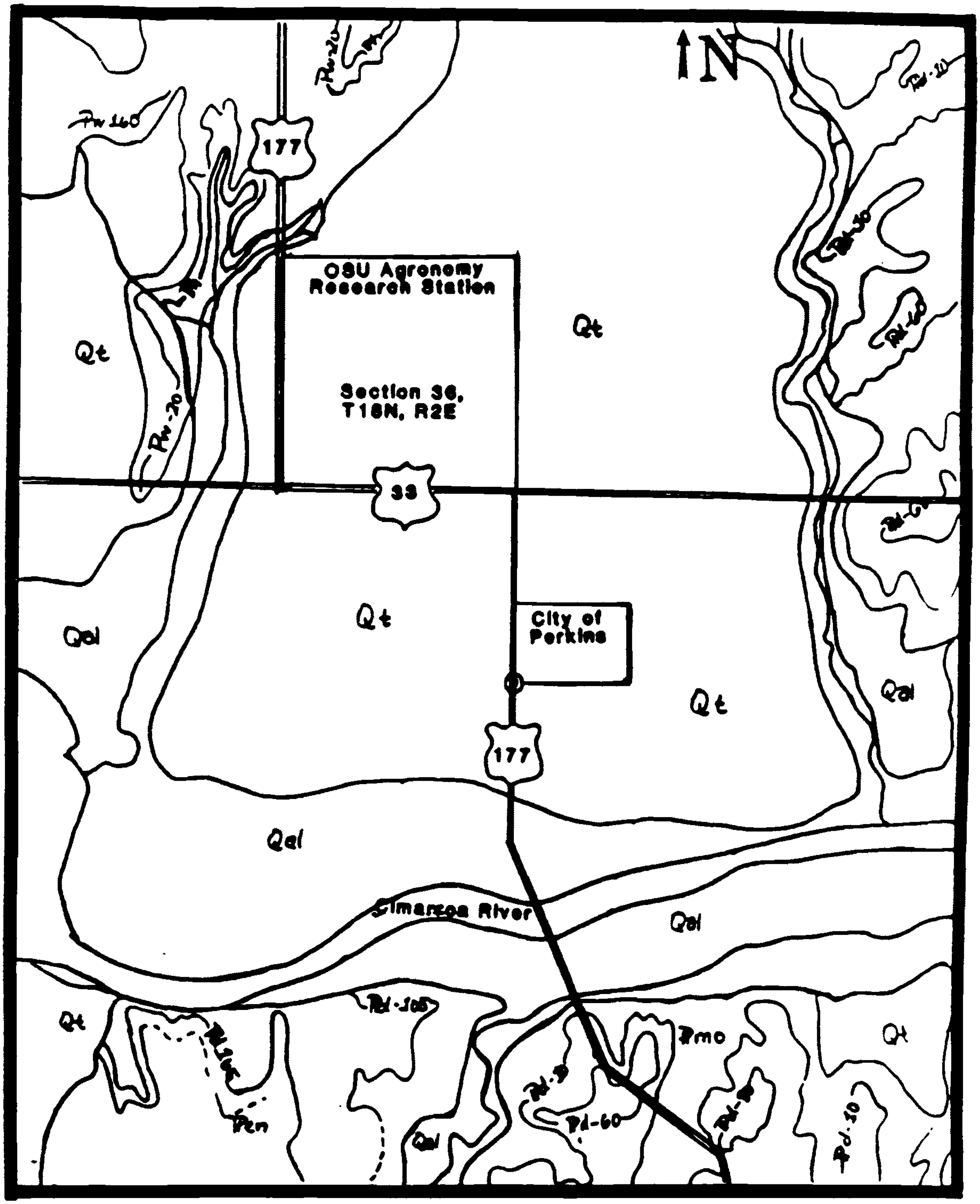


Figure 5. Regional Geologic Map (Modified After Shelton, Ross, Garden and Franks, 1985)

Qal

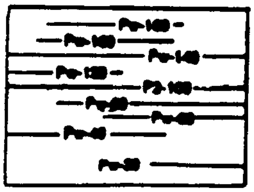
Alluvium

Sand, silt, and clay of present streams

Qt

TERRACE DEPOSITS

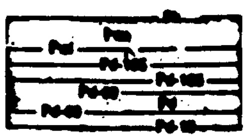
Sand, silt, and clay with associated eolian deposits



WELLINGTON FORMATION Pw.

Red lenticular sandstones and mudrock with thin nodular carbonate beds. Approximately 780 ft of formation crops out in western Payne County. Two key beds divide formation into three units (Pw_1, Pw_2, and Pw_3). Carbonate units are most prominent in upper unit, sandstone is most prominent in middle unit, and mudrock is most prominent in lower unit. The following unnamed beds are mapped (intervals given are approximate):

Pw-160—Sandstone, 160 feet above base
Pw-140—Sandstone, 140 feet above base
Pw-120—Sandstone, 120 feet above base
Pw-100—Sandstone, 100 feet above base
Pw-80—Sandstone, 80 feet above base
Pw-60—Sandstone, 60 feet above base
Pw-40—Sandstone, 40 feet above base
Pw-20—Sandstone, 20 feet above base



OSCAR GROUP[1]

Red claystone with lenticular sandstones and nodular dolomites above Pu, which is a persistent carbonate unit. Average thickness of Oscar Group is approximately 600 feet. The group contains the following units:

Ph Herington Limestone
Pen Enterprise Shale
Pwi Winfield Shale
Pd Doyle Shale
Pd-165—Sandstone, 165 feet above base
Pd-105—Sandstone, 105 feet above base
Pd-90—Sandstone, 90 feet above base
Pd-60—Sandstone, 60 feet above base
Pd-10—Sandstone, 10 feet above base

Figure 6. Geologic Unit Description (Modified After Shelton, Ross, Garden and Franks, 1985)

unconfined water table aquifer.

The unconsolidated sediments represent different stages of deposition in the north half and the south half of the station. This can be noted on the generalized north-south regional geologic cross-section in Figure 7. The terrace alluvial deposits in the north half were deposited by fluvial action and consequentially eroded to some extent before the southern fluvial material was deposited. The cyclic nature of these deposits were caused by fluctuating sea levels which occurred during the alternating glacial and interglacial epochs. Stabilized sand dunes are present on the lower terrace and account for the hummocky appearance of the surface topography. Alluvial floodplain deposits dominate the channel and floodplain of the Cimarron River.

Bedrock The bedrock of the site is a transitional zone between the Permian Wellington Formation and the Pennsylvanian Oscar Group. The Wellington Formation is the lowest unit of the Cimarron Series and is composed of red lenticular sandstones and mudstone with thin nodular carbonate beds. Two key beds divide the formation into three basic units with carbonate units prominent in the upper unit, sandstone in the middle unit and mudrock prominent in the lowest unit.

The Oscar Group is composed of red claystone with lenticular sandstones and nodular dolomites. The following units outcrop around the site: Doyle Shale, Enterprise

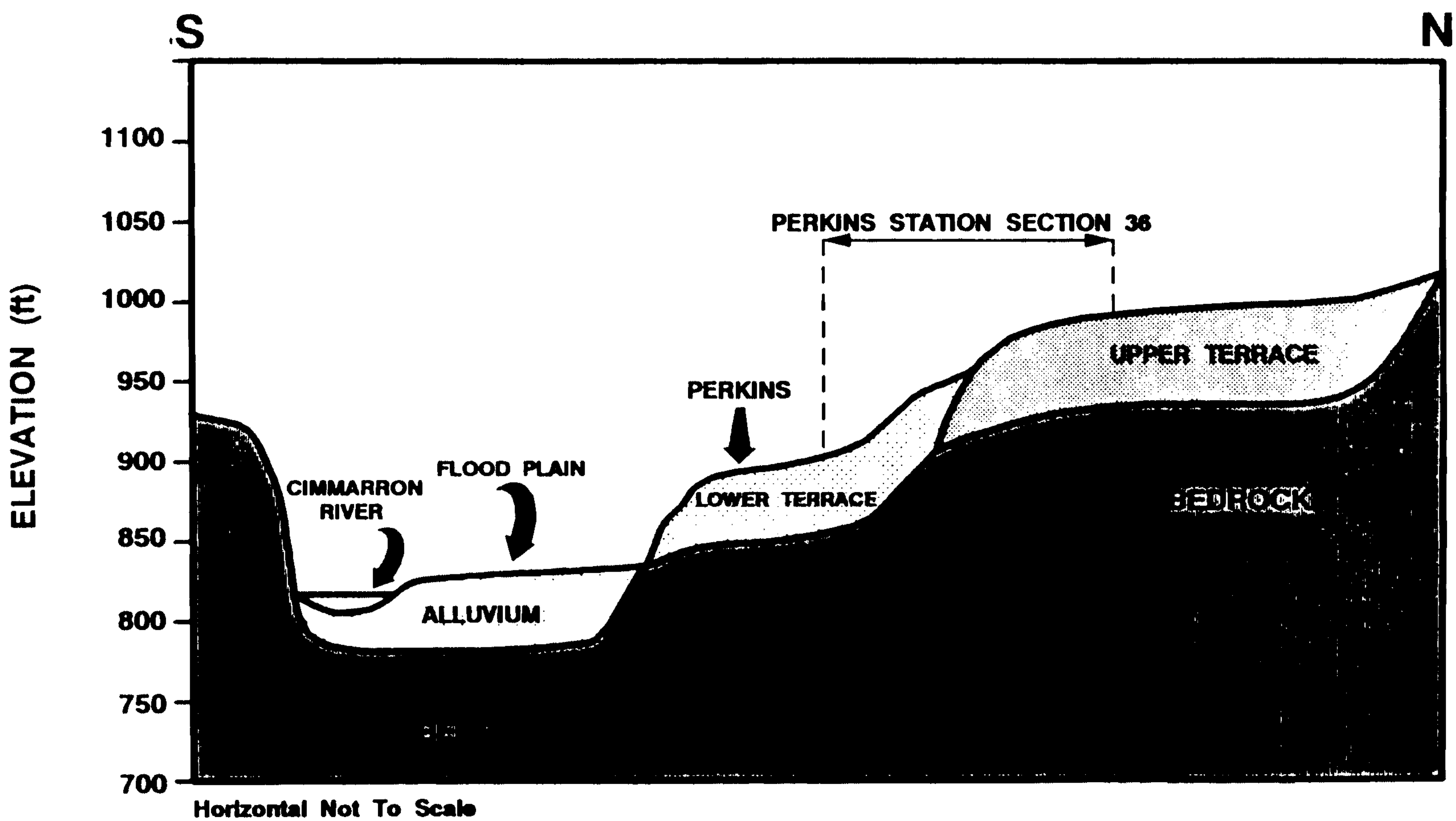


Figure 7. Generalized Regional Cross-Section

Shale, and Herington Limestone. Red-brown fine grained sandstones with thin interbedded limestones were encountered during drilling at the site.

Unconsolidated Sediments The Quaternary deposits of the study area occur as mappable units in the alluvium of the floodplain and terrace deposits of the Cimarron River and along major creeks. These deposits consist of sand, silt and clay overlain by eolian sand and silt. These alluvial deposits make up the principle unconfined water table aquifer in the study area and are referred to collectively as the Perkins Terrace Aquifer. The aquifer averages in saturated thickness from 30 feet in the upper terrace to 50 feet in the lower terrace.

The dominant sediments consist of orange and red fine grained sand and tan silty sands separated by isolated and discontinuous lenses of yellow, tan and gray silty clay. Clean sands occur at the base of the alluvial terrace deposits and are overlain by siltier sands and discontinuous clay lenses. Complete detailed drillers and borehole logs have been recorded in Appendix A of the Publication by Kent, et. al. (1993).

Land Use and Chemical Application

Natural vegetation in the area consists mostly of low lying shrubs, brush and prairie grass with small deciduous trees and evergreens. Twenty percent of the land in Payne

County is used for crops and nearly seventy percent is used for pasture and rangeland for cattle. Primary agricultural crops include cotton, peanuts, wheat, alfalfa, and various grasses.

The entire station serves as a training ground for students of various disciplines. Approximately 295 acres of the west side of the Perkins Station are used for agronomic research and 205 acres of the northeast part are used for horticulture research. Large sections are also used by the forestry and pathology departments.

Land Use

The use of the land on the Perkins Station is highly complex. Crop type and placement varies from season to season according to individual research and cropping needs. No commodity control for major changes in land use exists on the Perkins Agronomy Research Station. Land use from the spring of 1986 to the present has been recorded in map form and is included in Appendix E of Kent, et. al., 1993. Only subtle changes in crop type took place from one season to another and one year to the next.

Although the method of tillage used on each plot varies, most of these plots undergo only minimum tillage during each crop rotation. Residual vegetation can range from 0 to 100 percent depending on the type of implements used in tilling and the number of times that the plot is worked over. No standard is used in minimum tillage on the

Perkins Station. Generally, 30 to 40 percent residuum is left in a plot after one tilling scenario.

Fertilizer and Pesticide Application

Without question, pesticide and fertilizer development during the twentieth century has improved the quality of life, especially in the area of public health. Devastating diseases such as malaria and typhus along with agricultural pests such as insects, weeds and plant diseases have all been controlled so that lives have been saved, crop production has increased and food prices have been controlled.

Pesticide and fertilizer losses from application areas by surface runoff and infiltration due to precipitation and irrigation causes a monetary loss for farmers as well as a threat to the environment through contamination of surface water and groundwater. The technology exists today to estimate the potential contamination of groundwater by loss of specific agricultural chemicals through these two main pathways (surface runoff and leaching) therefore enabling farmers to improve their management strategies. Management strategies include land management combined with agricultural chemical management in order to decrease the risk of potential groundwater pollution and maximize the benefits of fertilizers and pesticides to crops.

Fertilizer is applied during the growing seasons (Spring and Fall) on the Perkins Station in three basic forms. The first is a solid Urea $[CO(NH_2)_2]$ which is an organic nitrogen material composed of 45-46 percent Nitrogen. The second is a solid mixture of Diammonium Phosphate and the third is a mixture of specific percentages of Nitrogen (N), Phosphate (P_2O_5) and Potash (K_2O). For example, the latter may appear as an application of 18-46-0 indicating a mixture of 18 percent Nitrogen, 46 percent Phosphate and 0 percent Potash. Records of seasonal application since the spring of 1986 have been recorded in map form and are included in Appendix A.

The main pesticides applied at the Perkins Station are herbicides intended to rid the station of unwanted weeds and grasses. Those which have been applied on the station are tabulated in Table I including their popular brand names, actual chemical names and specific chemical properties as designated by the chemical database of the OSU Agronomy Department in 1990. Records of seasonal application since the spring of 1986 have been recorded in map form and can be found in conjunction with fertilizer applications in Appendix A.

Precipitation and Water Quality

The main source of recharge to the aquifer in the immediate area is the infiltration of precipitation. The area receives a total annual rainfall ranging between 20 and 40 inches. Approximately 5-10 percent of precipitation actually infiltrates with the remaining precipitation being lost to evaporation, transpiration, and runoff. The total

TABLE I

PESTICIDES USED ON THE PERKINS STATION

Brand	Chemical	t 1/2 (days)	Persistence	PC (mg/g OC)	Sorption
Attrex	Atrazine	60	Moderate	100	Low
Banvel	Dicamba	14	Non	2	Low
Blazer	Acifluorfen	30	Non	139	Low
Dual	Metolochlor	20	Non	200	Low
Furaden	Carbofuran	50	Moderate	22	Low
Lasso	Alachlor	15	Non	170	Low
Milogard	Propazine	135	Highly	154	Low
Princep90	Simazine	75	Moderate	138	Low
Ramrod	Propachlor	6	Non	80	Low
Sancap	Dipropetryn	30	Non	1180	Moderate
Treflan	Trifluralin	60	Moderate	7000	High
2-4D	2-4D	10	Non	1000	Moderate
Vernam	Vernolate	12	Non	330	Low

Non Persistent = t 1/2 of 30 days or less
Moderately Persistent = t 1/2 >30 days but <100 days
Persistent = t 1/2 >100 days

recharge for the aquifer is between 3 and 6 inches a year.

A combination of precipitation and potentiometric surface elevation data for the Perkins Station has been used to show the correlation of precipitation with water table response and to analyze the effects of water table fluctuation on groundwater nitrate concentration. A composite plot containing hydrographs for select monitoring wells is included in Figure 8. The hydrographs correlate closely with the frequency and magnitude of the precipitation and indicate a lag time of 30 to 60 days between the maximum water level increase and the time of precipitation. Composite hydrographs for the remaining monitoring wells depicting similar results are included in Appendix B of Kent, et. al., 1993.

Pesticides

Integrated Pest Management is an overall pest management strategy being used on agricultural research farms including pest monitoring and biological controls as well as pesticide selection. Pesticide selection is based upon various factors including cost, effectiveness, toxicity to non-target organisms as well as solubility in water and persistence.

While pesticides have been applied to crops seasonally on the Perkins Station, none have been found in appreciable amounts in the groundwater. The areas of crops located directly upgradient from monitoring wells targeted for

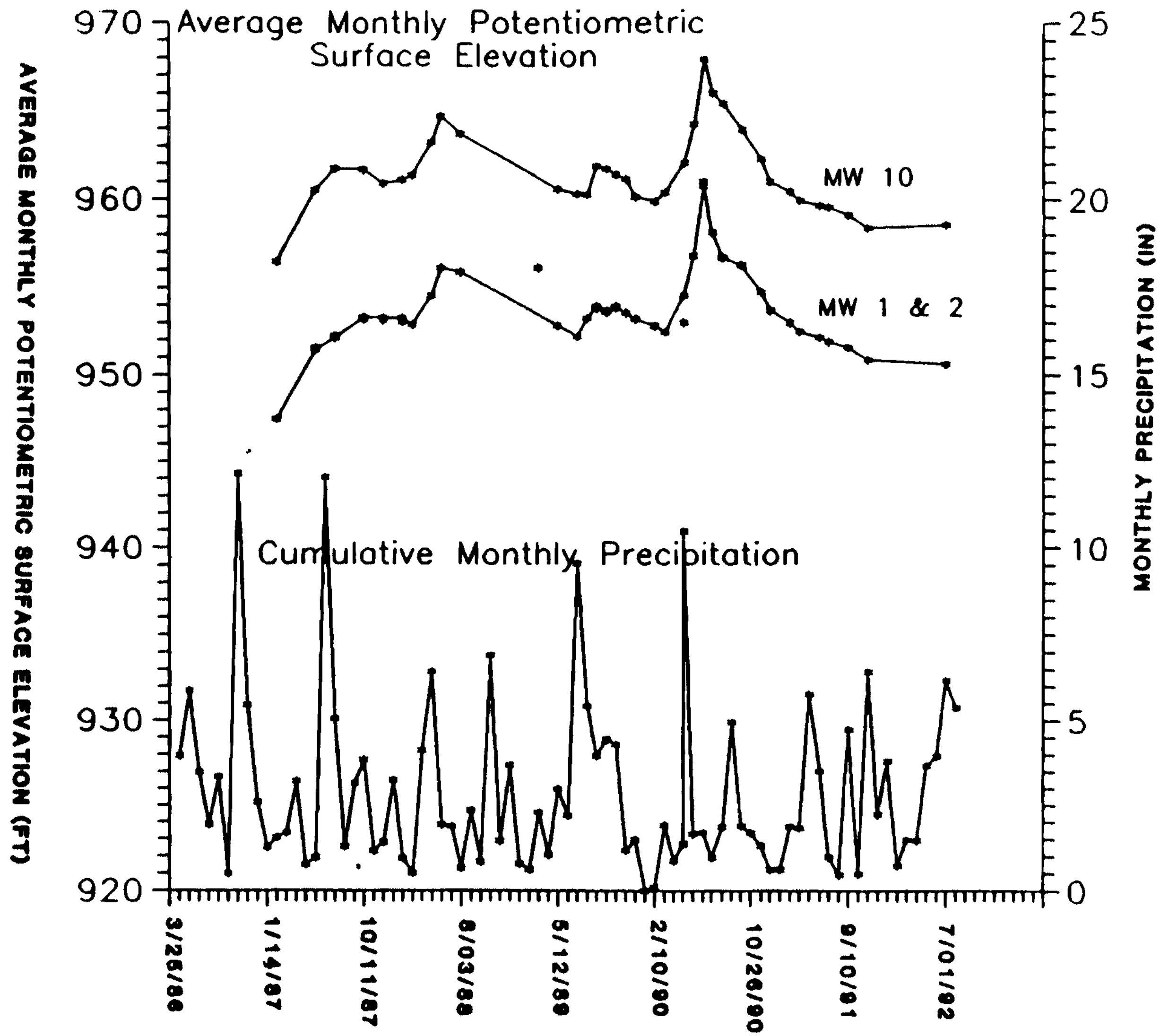


Figure 8. Composite Hydrographs for Monitoring Wells #1,2 and 10

sampling of pesticides have been divided into sections A - H in Figure 9. Upgradient application of pesticides and the subsequent concentrations found in groundwater samples taken from corresponding downgradient wells are tabulated in Table II. Even though appreciable amounts of Attrex (Atrazine) and Treflan (Trifluralin) were applied from 1986 to 1989, groundwater samples taken in the spring and fall of 1989 showed minimal to no detection of these chemicals (see Table II). Although the use of Lindane was discontinued on the station after 1986, it was detected in the groundwater and pond sediment samples in 1989.

Atrazine has a relatively short half-life of 60 days and small partition coefficient of 100 mg/g OC while Trifluralin has a relatively short half-life of 60 days and a large partition coefficient of 7000 mg/g OC (see Table I). These two chemicals are considered to be only moderately persistent because their half lives are greater than 30 days but less than 100 days. For a complete discussion of how these chemical properties indicate persistence and solubility in soils, see Rao et. al., 1983.

Atrazine is not likely to be adsorbed onto organic carbon within soil profiles to a great extent. Trifluralin with a partition coefficient of 7000 mg/g OC is very likely to undergo a great amount of adsorption onto organic matter. As stated previously, the apparent lag time between precipitation and corresponding response in the saturated zone is 30-60 days. This would indicate that

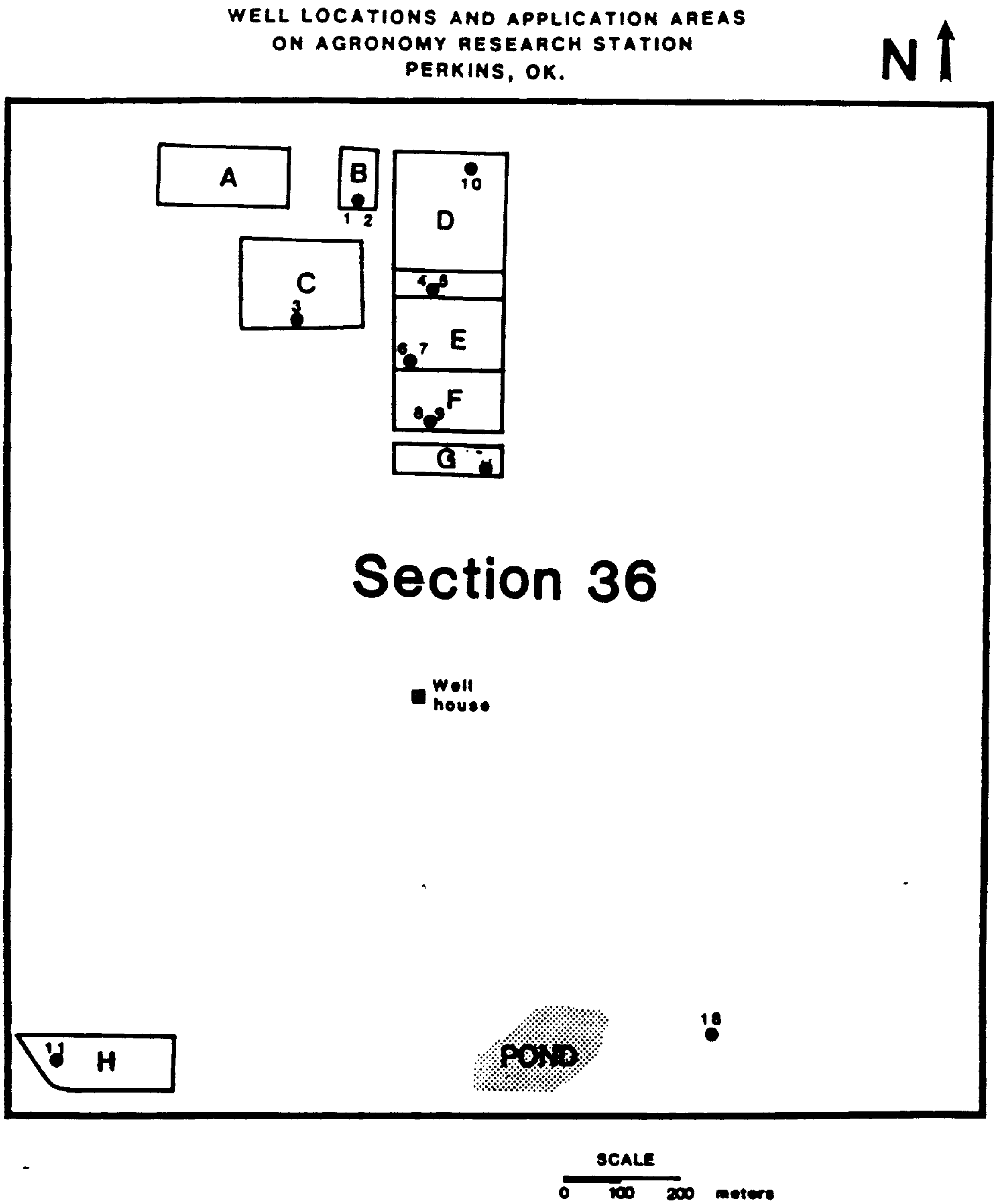


Figure 9. Application Areas on Perkins Station

TABLE II

PESTICIDE APPLICATION AND RECOVERY

Upgradient Pesticide Application

Area C	Area E,F and G
Cotton/Beans/Sorghum	Min-Wheat/Con-Wheat
1986	1986
ATRAZINE	NONE
June - 1 pt/Acre	
1987	1987
TRIFLURALIN	NONE
April - 1 pt/Acre	
1988	1988
No Data	No Data
1989	1989
ATRAZINE	
May - 1.25 qt/Acre	
TRIFLURALIN	TRIFLURALIN
April - 1 pt/Acre	June - .75 qt/Acre
June - .75 qt/Acre	

Downgradient Groundwater Concentration (mg/l)

May 1989

Well #3	Well #5	Well #8
ATRAZINE .011	ATRAZINE ND	ATRAZINE ND
LINDANE .006	LINDANE .002	LINDANE ND
	Well #6	Well #9
	ATRAZINE ND	ATRAZINE ND
	LINDANE ND	LINDANE .003

Sept 1989

Well #3	Well #5	Well #8
TRIFLURALIN ND	TRIFLURALIN ND	TRIFLURALIN ND
ATRAZINE ND	ATRAZINE ND	ATRAZINE ND
LINDANE ND	LINDANE ND	LINDANE ND
	Well #6	Well #9
	TRIFLURALIN ND	TRIFLURALIN ND
	ATRAZINE ND	ATRAZINE Trace
	LINDANE ND	LINDANE ND

Pond Sediment (mg/kg)

May 1989	Sept 1989	
	TRIFLURALIN .011	
ATRAZINE Trace	ATRAZINE ND	
LINDANE .003	LINDANE ND	

Note: ND = Not Detectable at <.001 mg/l

these two pesticides with 60-day half-lives wold decay below detectable limits by the time they reach the water table and moved downgradient within the saturated zone at a velocity of 1 ft/day (according to tracer studies).

Atrazine is more likely than Trifluralin to contaminate groundwater due to its small partition coefficient. Conversely, Trifluralin is more likely to contaminate surface runoff due to its large partition coefficient. These chemical characteristics account for the minimal detection of Atrazine and the lack of detection of Trifluralin in the downgradient groundwater samples (see Table II). In general, these chemicals will adsorb onto the organic matter in soils to some degree and decay to a great extent before leaching or surface runoff can occur. Lindane, which is not presently used at the site, is much more persistent than Trifluralin and Atrazine with a half-life of 400 days. It would therefore be expected to be detected in the groundwater within this span of time. The travel time within the saturated zone would result in a distance of 400 ft. Lindane was noted in both groundwater samples and pond sediments (see Table II).

Solubility and persistence of pesticides are of great importance when the application site is underlain by permeable soils and a shallow aquifer. The Perkins Station is located directly above a water table aquifer in which the depth to water ranges between 10 and 30 feet below the surface. The aquifer is composed of permeable terrace deposits and overlain by sandy loams in the southern half of the station. Chemicals with short half-lives and intermediate to large partition coefficients are preferable in this situation. Atrazine and Trifluralin are ideal pesticides to be used on the Perkins Station and have been found to be effective herbicides while not being detected in appreciable amount in the groundwater.

The majority of the pesticides used on the Perkins station are distributed in low concentrations adn are characterized as being non to moderately persistent with low to moderate sorption capability and therefore with low potential impact to the groundwater or surface water. Propazine is characterized by high persistence (with a half life greater than 100 days) and low sorption and therefore represents a high potential impact to the groundwater and should be monitored for during its use on the site.

Fertilizers

Unlike other elements found in groundwater, nitrates are not sourced in aquifer materials. Nitrates emanate from the biosphere and hydrosphere from plants, sewage and fertilizers. Nitrogen fertilizers which are applied to the surface of the Perkins Station have been found to increase the nitrate-nitrogen (NO_3-N) concentrations in the groundwater through natural infiltration of contaminated surface water. In general, it has been found that NO_3-N levels in groundwater correspond closely to the water table fluctuations indicating that as infiltrating water recharges the aquifer, it carries dissolved NO_3-N with it. The short term and long term water table and NO_3-N level response to precipitation has been compared in plots such as Figures 10 and 11. Nitrate levels in the groundwater detected in monitoring wells on the station range between 1 and 150 mg/l. Nitrate levels change significantly over time with respect to water table fluctuations. (See Figures 10 and 11). Similar trends have been noted in other monitoring wells on the station.

It has been found that nitrate-nitrogen ingested through contaminated drinking water can cause serious health problems, especially to young infants and cattle. Methemoglobinemia, commonly known as "blue baby", occurs when nitrates are converted to nitrites in the intestines resulting in an overabundance of methemoglobin molecules causing possible toxic effects (Driscoll, 1986). More recent studies have shown that elevated levels of nitrate-nitrogen alone in drinking water do not significantly contribute to this phenomenon. Nitrate in conjunction with chloride, indicating a possible sewage leachate problem in the groundwater, has been found to be the catalyst for methemoglobinemia.

Natural nitrate-nitrogen concentrations in groundwater range from 0.1 to 10 mg/l according to Davis and DeWiest (1966) but have been found to be as high as 2000 mg/l in some areas. The U.S. Environmental Protection Agency has

Monitoring Well #12

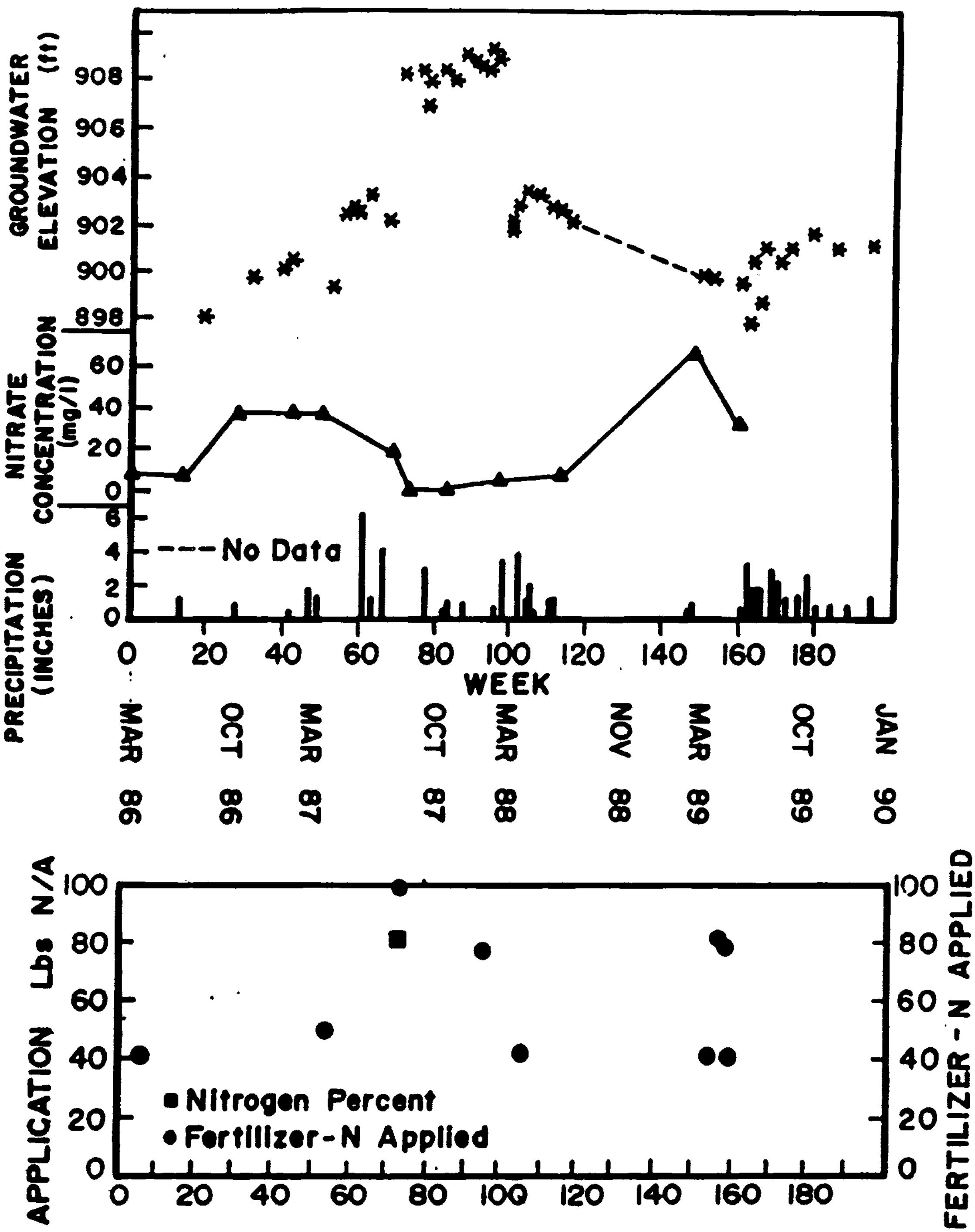


Figure 10. Comparison of Water Levels, Nitrate Levels and Precipitation - Short Term

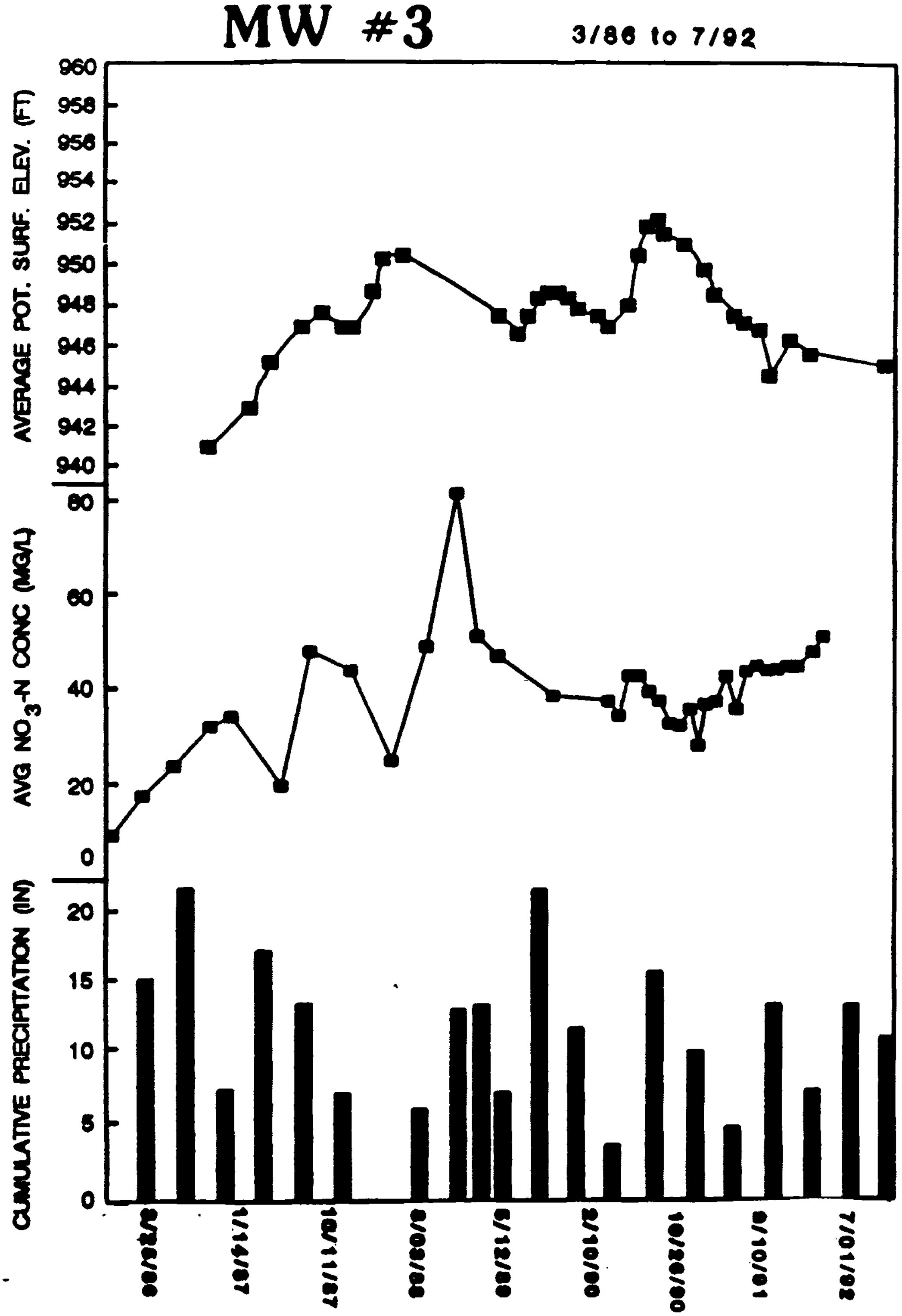


Figure 11. Comparison of Water Levels, Nitrate Levels and Precipitation - Long Term

set the safe nitrate limit for domestic water at 45 mg/l (10 mg/l of elemental nitrogen). It has been found that nitrate levels of 20 to 90 mg/l in drinking water to be harmful to infants (Driscoll, 1986).

Research conducted by the OSU Department of Agronomy has shown that land applications of nitrogen fertilizer within an "environmentally safe window" of 60 to 90 lbs/acre will not cause significant nitrate accumulation in soil profiles (Boman and Westerman, 1992). Records have shown in the past that the fertilizer applications on the Perkins Station have exceeded this "window" of 60 - 90 lbs/acre.

Review of Hydrogeologic Investigations

The Perkins Station project has been a long term site assessment to characterize the potential of agricultural contamination in groundwater. An extensive database of water quality analysis and water level measurements has been created and recorded on a computer database at the USDA- NAWQL in Durant, Oklahoma. Important physical and chemical parameters of both the unsaturated and saturated zones have been determined. Hydrologic and water quality responses within the aquifer have been characterized.

Geophysical surveys have been used to further define the water table and the bedrock configurations of the study area. Detailed discussions of the seismic, resistivity and ground penetrating radar methods used in this study are included in Appendix B. Aquifer tests have been used in order to determine the hydraulic characteristics of the Perkins Terrace Aquifer. Detailed descriptions of the pumping test, slug test and tracer test methods used in this study are included as Appendix C.

The site geology has been characterized through borehole logs, drilling logs and geophysical techniques. The aquifer underlying the station is an unconfined water table aquifer made up of highly permeable Quaternary aged terrace alluvial deposits.

Important physical and chemical properties of the unsaturated zone have been determined. Soil moisture profiles have been used to analyze the change in saturation with depth and thus the soils ability to conduct solutes to the water table. Tracer tests have been utilized to indicate that the silty and clayey nature of the unconsolidated material as well as macropore flow affects solute transport in the unsaturated zone. Nitrification is a possible contributor to the concentration of nitrate at depth after fertilizer application.

Geophysical techniques, water level measurements and drilling logs have been successfully used to define aquifer boundaries. The Direct Current Resistivity surface surveys and gamma ray borehole surveys proved to be the most successful techniques. Potentiometric surface contour maps have been constructed on various scales to define groundwater flowpaths as potential pathways for contaminant migration.

Important physical and chemical properties of the saturated zone have been characterized by aquifer tests and tracer tests. The upper terrace deposits have been found to have very low transmissivities due to the fine nature of the materials. Therefore, the upper terrace deposits are not likely to conduct contaminants at a rapid rate. The lower terrace deposits have been determined to have very high transmissivities and therefore have the ability to rapidly conduct contaminants leached into the aquifer. Tracer tests have been used to indicate that dispersion along with convection as the physical processes responsible for solute transport within the aquifer. Values for saturated hydraulic conductivity calculated by aquifer tests analysis were found to fall within the range of hydraulic conductivity values determined through Seepage and Darcian velocity methods of tracer test analysis.

Composite hydrographs have been used to show long term correlation of water table elevations with the frequency and magnitude of precipitation events. A lag time of 30-60 days exists between the maximum water level increase and the time of precipitation.

Water quality has also been found to fluctuate with recharge. In general, all parameters except those for nitrates decrease with an increase in recharge. Nitrates have been found to increase with recharge indicating that fertilizer is leaching to the groundwater and/or nitrification is occurring at depth. As yet, a correlation of the combined effect of land use, tillage and agricultural chemical application on water quality has not been found.

Even though pesticides have been applied to crops on a yearly basis, none have been detected in appreciable amounts in the groundwater. Thus, the Integrated Pest Management used by this research farm has been successful in selecting effective pesticides which pose little contamination threat to the aquifer. The undesignated wetland area on the southern edge of the Perkins Station may be acting as a site of concentration of pesticides. Lindane was detected in pond sediments three years after use on the station was discontinued.

In the process of characterizing the unsaturated and saturated zones, parameters required for the simulation of the fate and transport of agricultural chemicals have been determined. Computer modeling has proved a useful tool for simulating chemical movement in both the unsaturated and saturated zones. Tracer tests in the aquifer have been closely replicated through computer modeling. Modeling in the unsaturated zone has indicated that no pesticides are reaching the groundwater in detectable amounts.

CHAPTER IV

PHASE I - DEVELOPMENT OF CONCEPTUAL MODEL

The previous chapters describe the problem to be investigated by computer simulation. Specifically, while pesticides have not been found in the groundwater in detectable amounts, nitrate (NO_3-N) levels greater than 10 mg/l have been detected and have been found to increase with water table increases in response to precipitation events. Nitrate contamination of groundwater traveling off the Perkins Station is of concern in this study. Solute transport of nitrates will be simulated to determine the possible impact to human health and environment off the site.

The objective of this chapter is to construct the conceptual model of the problem including the problem domain and the transport phenomena taking place in it. The aquifer boundaries are defined using monitoring wells, piezometers and geophysical surveys and the aquifer characteristics are defined using pumping tests, slug tests and tracer test results.

Definition of Aquifer Boundaries

Monitoring Wells / Piezometers

A network of monitoring wells and shallow piezometers has been installed on the Perkins Station for collecting water quality samples and for monitoring the elevation of the water table within the unconfined aquifer. Monitoring well locations on the station are shown in Figure 3. Twenty two wells of 2 inch diameter and four wells of 4 inch diameter have been installed using the hollow stem auger drilling method. This method is more time efficient than rotary drilling and does not require drilling fluid thereby eliminating contamination of subsurface materials by drilling additives. Split spoon samples and grab samples were taken in order to characterize the unconsolidated sediments. All of the monitoring wells were completed within the unconsolidated sediments with only a few actually reaching the bedrock.

Four sets of clustered monitoring wells were designed to sample the water quality in both the shallow and deep intervals of the aquifer. A diagram depicting the typical monitoring well cluster design installed in the northern upper terrace deposits is included in Figure 12. Driller's logs and geophysical logs of the groundwater monitoring wells are included in Appendix A of Kent, et. al., 1993. All wells were surveyed in order to establish the top of casing elevation (TOC). The monitoring well statistics

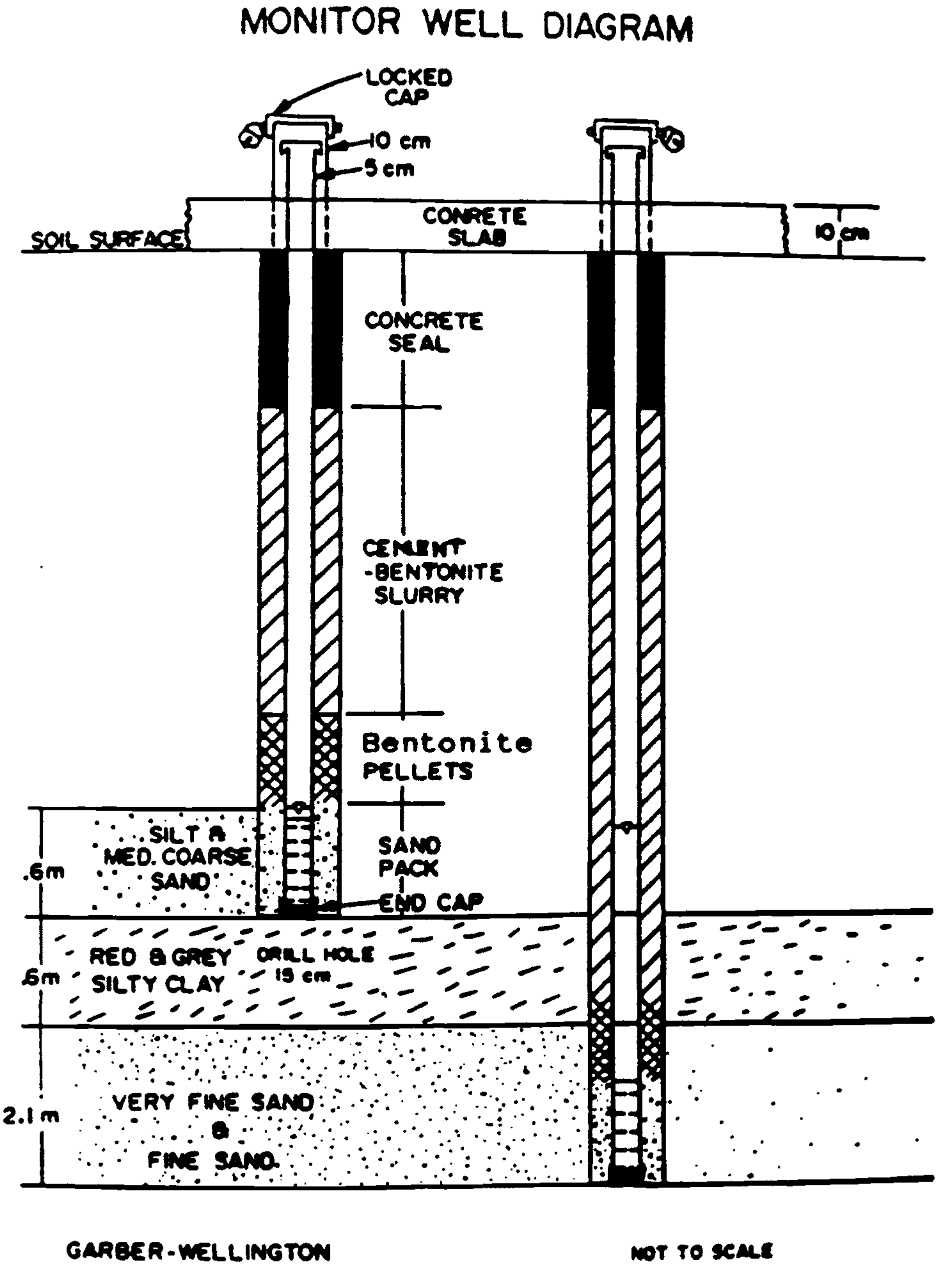


Figure 12. Typical Monitoring Well Schematic - Clustered Wells in Northern Terrace Deposits (Modified After Dwivedi, 1989)

(i.e. top of casing elevation and depth to bedrock) are depicted in Table III.

Eighteen shallow piezometers were also installed by using a hydraulic Bull soil sampler and hand auger in order to define the cross sectional perspective of the water table through the ponded and wetland area in the south half of the site. These piezometers were hand slotted and screened with nylon hose. The screened interval of the annulus was sand packed above the screen. The annulus was sealed to the ground surface with bentonite. Once proper elevations were established for each piezometer, the nature of the pond as a discharge/recharge area was determined.

Groundwater level measurements from the monitoring wells have been recorded along with precipitation data for the Perkins Station from March 1986 to the present. Both of these records are kept on the computer database at the USDA NAWQL in Durant, OK. Complete records are included in Appendix B of Kent, et. al., 1993. The water levels have been recorded on a weekly to biweekly basis as depth to water in feet. The water levels have been converted to potentiometric surface elevations for the period between March 1986 and the present using the top of casing elevations. Complete water level measurements, potentiometric surface elevation calculations and precipitation records are tabulated in Appendix B of Kent, et. al., 1993.

TABLE III

PERKINS STATION MONITORING WELL STATISTICS

WELL ID	TOP OF STEEL CASING ELEVATION	ELEVATION OF PAD (FT)	TOP OF PVC CASING ELEVATION	STICK UP (FT)	LAND SURFACE ELEV (FT)	DEPTH TO BEDROCK FROM SURFACE	BEDROCK ELEVATION	TOTAL DEPTH
1 (D)	971.48	970.00	970.92	1.42	972.58	30	942.58	30
2 (S)	971.47	970.00	971.08	1.38	972.62	N/A	N/A	25
3 (D)	962.93	961.44	962.11	1.50	962.50	25	937.5	25.5
4 (D)	964.86	963.30	963.84	1.46	965.54	46.5	919.04	47
5 (S)	964.83	963.30	964.60	1.30	965.51	N/A	N/A	28
6 (S)	960.31	959.24	959.95	1.20	960.80	N/A	N/A	25
7 (D)	960.34	959.24	959.85	1.20	960.80	39	921.80	39.5
8 (S)	944.66	943.24	943.94	1.40	943.60	N/A	N/A	25
9 (D)	944.53	943.24	943.44	1.27	943.73	35	908.73	35.5
10 (D)	979.15	977.78	978.57	1.40	977.60	39	938.60	39.5
11 (D)	911.11	909.82	910.34	1.29	910.71	51	850.71	51.5
12 (D)	928.05	926.64	927.33	1.55	928.45	51	877.45	51.5
Kp(MW18)	914.14	913.80	913.95	0.00	913.85	57	856.85	58.2
19 (D)	N/A	N/A	919.74	0.61	919.13	40	879.13	34.2
20 (S)	N/A	N/A	910.57	2.71	907.86	50	857.86	25
21 (D)	N/A	N/A	917.22	2.42	914.80	45-50	869.80	40
22 (S)	N/A	N/A	915.53	1.82	913.71	45-50	868.71	35.25
23 (D)	N/A	N/A	915.28	1.13	914.15	36	878.15	36.5
TW 24 (D)	N/A	N/A	N/A	N/A	913.27	49	864.27	N/A
W. House	N/A	N/A	920.57	3.22	917.35	N/A	N/A	N/A

(D) : Deep
(S) : Shallow
N/A : Not Available

Geophysical Surveys

Geophysical logs and driller's logs were both utilized to create the water table and bedrock maps. In general, the driller's logs correlated well with the geophysical surveys for proper elevations of water table and bedrock. For example, the D.C. Resistivity plot in figures 13 and 14 confirms the depth to water and depth to bedrock found through drilling.

The 100 megahertz analog system GPR survey conducted at the pumping test site (MW #18) on the Perkins Station did not result in any clearly defined subsurface interfaces due to the high clay content of the soils. However, higher resolution GPR techniques may be of use for this site in the future.

Geologic Cross Sections

A topographic map for the Perkins Station with the profile locations for the generalized geologic cross-sections, north-south (A-A') and east-west (B-B'), is included in Figure 13. These cross-sections were constructed by profiling topographic and bedrock elevations and filling in the lithologies according to drilling logs (see Figures 14 and 15). Generally, the terrace deposits of the north half of the station consist of finer materials

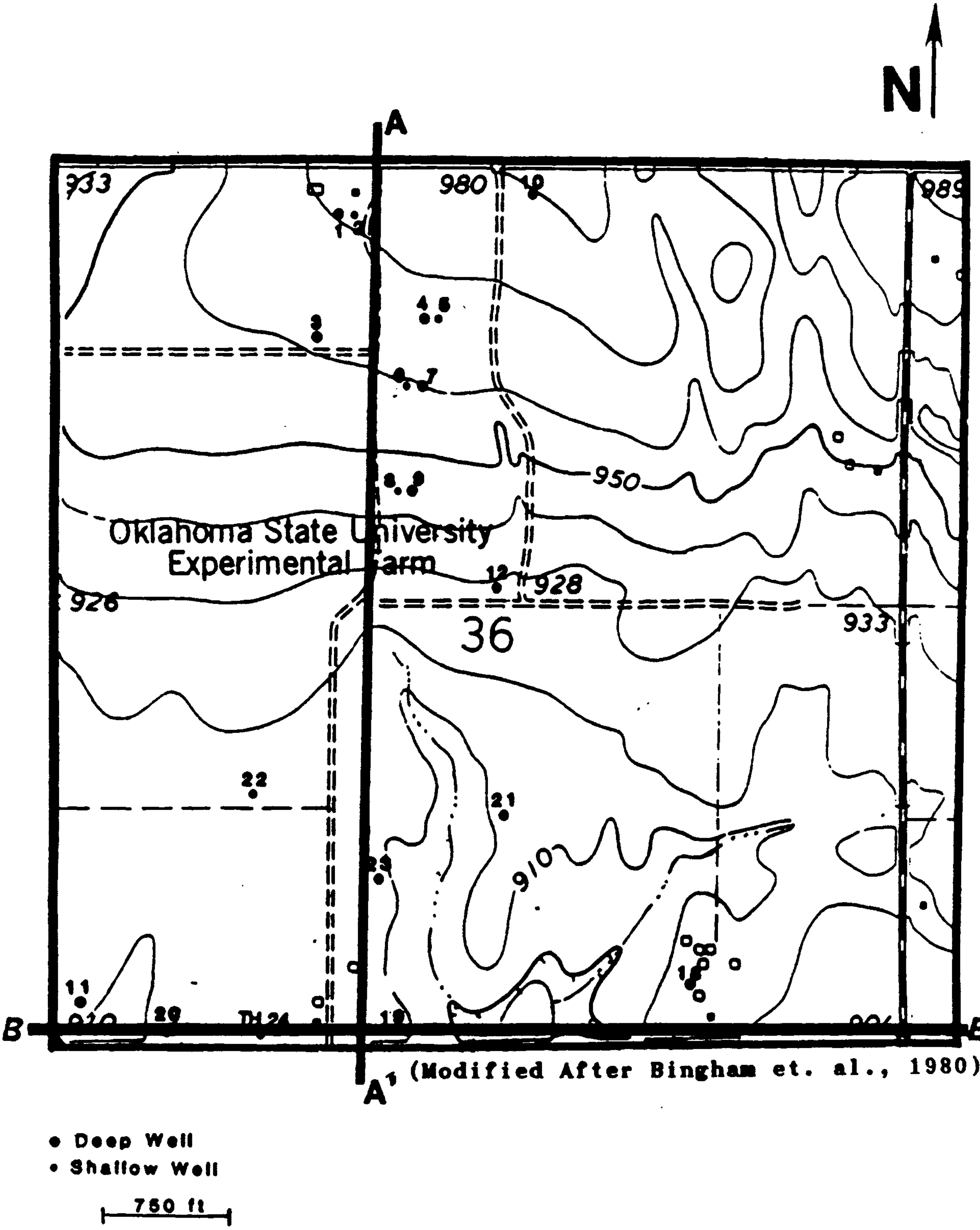


Figure 13. Perkins Station Topographic Map with Cross-Section Locations (Modified After Bingham and Bergman, 1980)

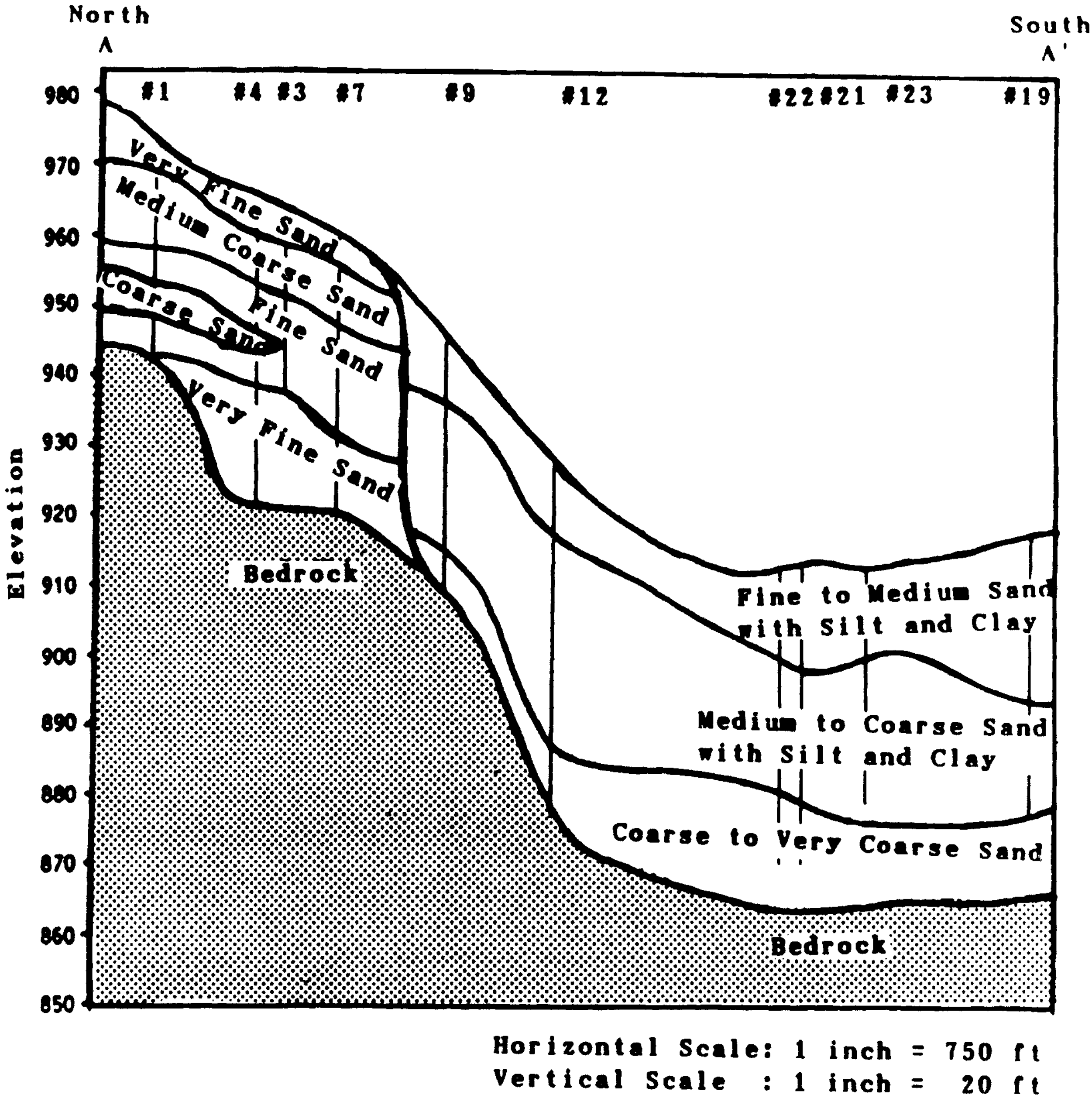
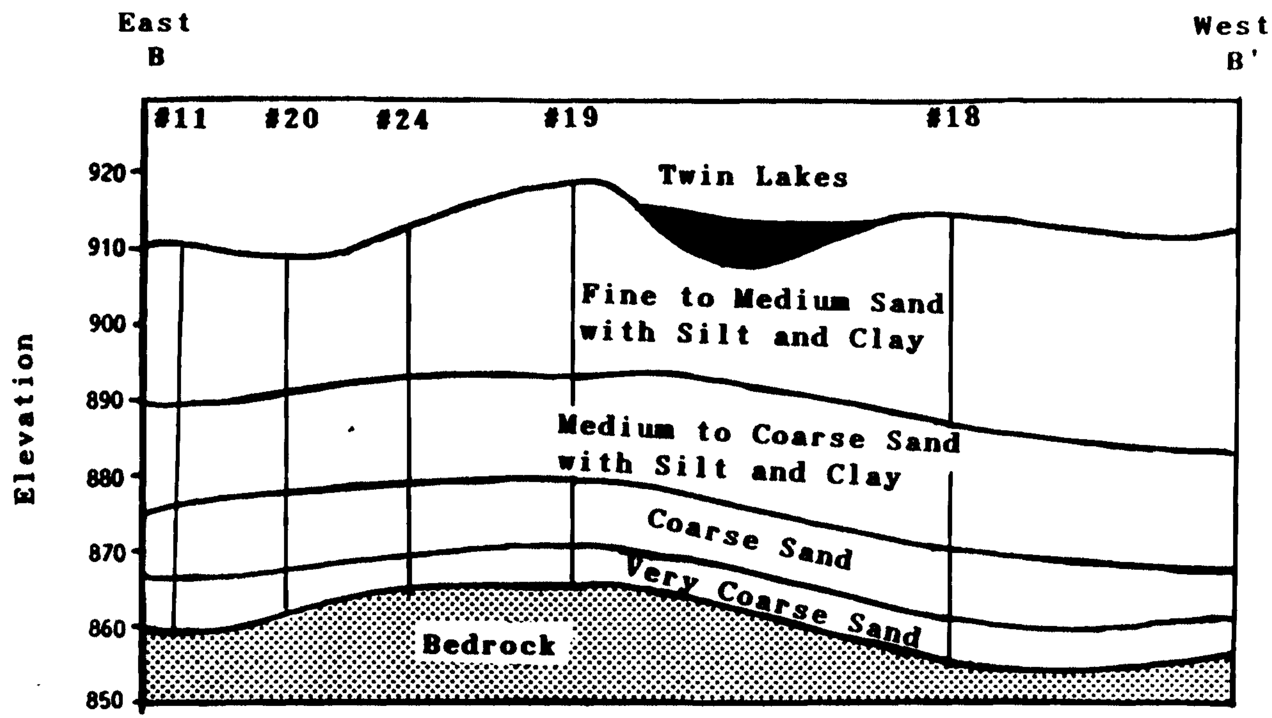


Figure 14. North-South Cross-Section of Perkins Station



Horizontal Scale: 1 inch = 750 ft
Vertical Scale : 1 inch = 20 ft

Figure 15. East-West Cross-Section of Perkins Station

than those located in the south half. The importance of these cross sections is the definition of layers of high hydraulic conductivity as well as layers that impede or slow saturated flow.

Bedrock and Potentiometric Surfaces/ Groundwater Flowpaths

Potentiometric surface contour maps with predicted groundwater flowpaths have been constructed on various scales (see Figures 16, 17, and 18) using the most conclusive water table data available (see Appendix D). Golden Graphics SURFER computer contouring software was used as an aide in contouring the data using the Kriging technique. The general location and trend of potential pathways for solute migration are important to determine so that predictions of possible environmental and human exposure can be addressed.

The regional geology consists of a series of terraces which have been built up by the Cimarron River upon bedrock and consequently eroded (refer to Figure 7). It is apparent that the groundwater flowpaths in this area are actually controlled by tributary bedrock channels that have been eroded out of the bedrock by river activity and subsequently buried by terrace deposits. These buried tributary bedrock channels may contain materials of higher permeability such as coarse sands and gravels which explain their preferential conductance of groundwater and solute.

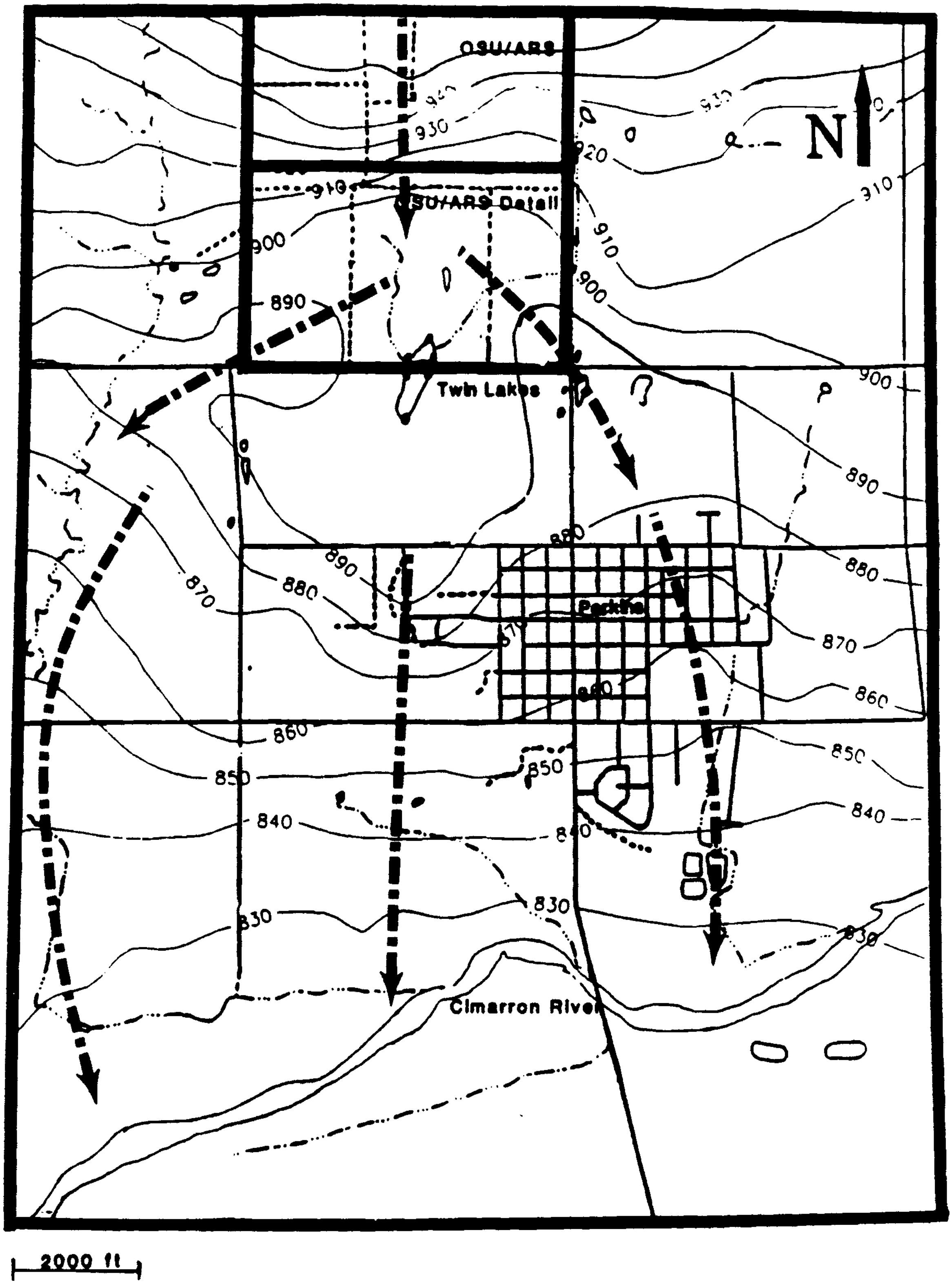


Figure 16. Regional Water Table Map

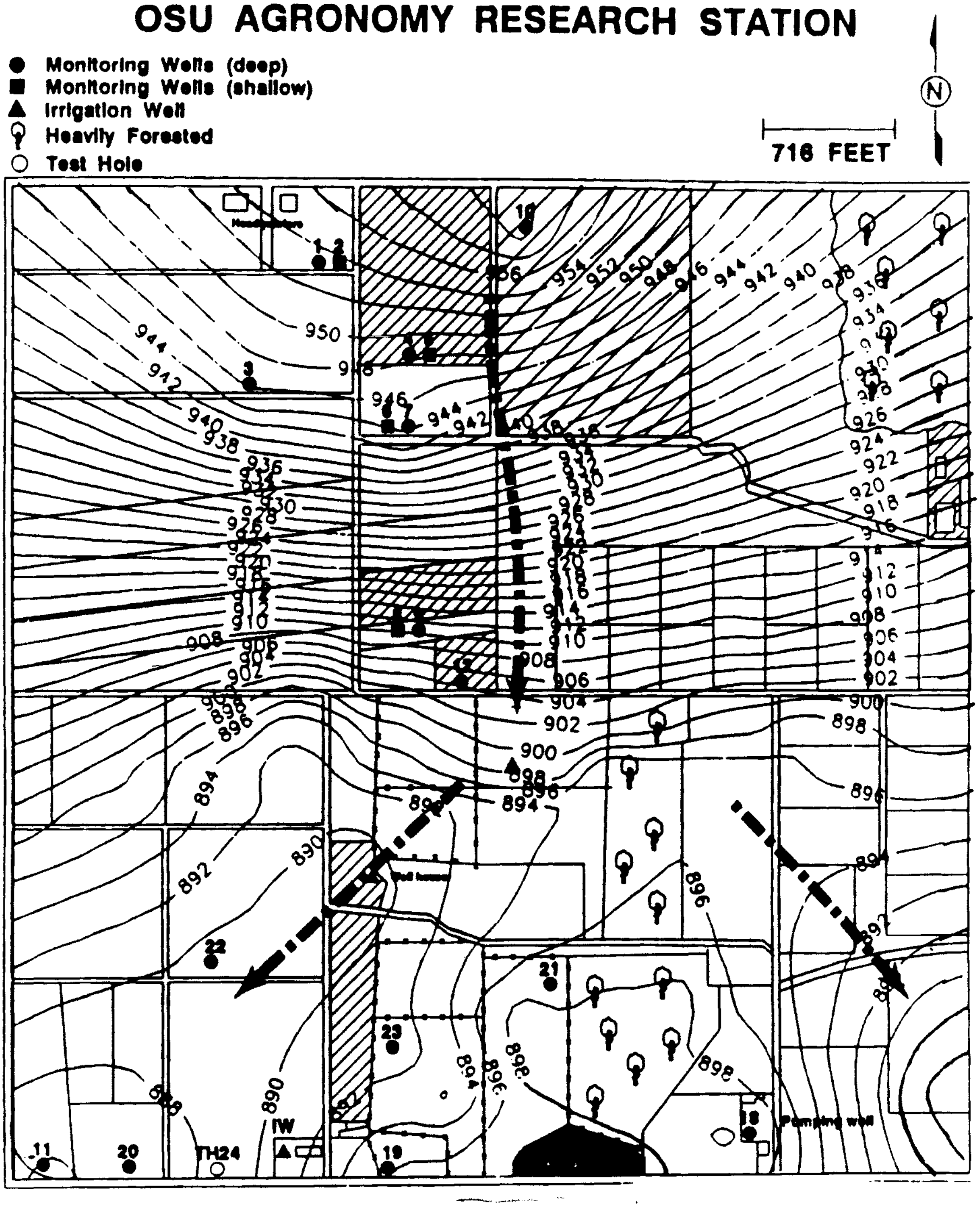


Figure 17. Local Water Table Map

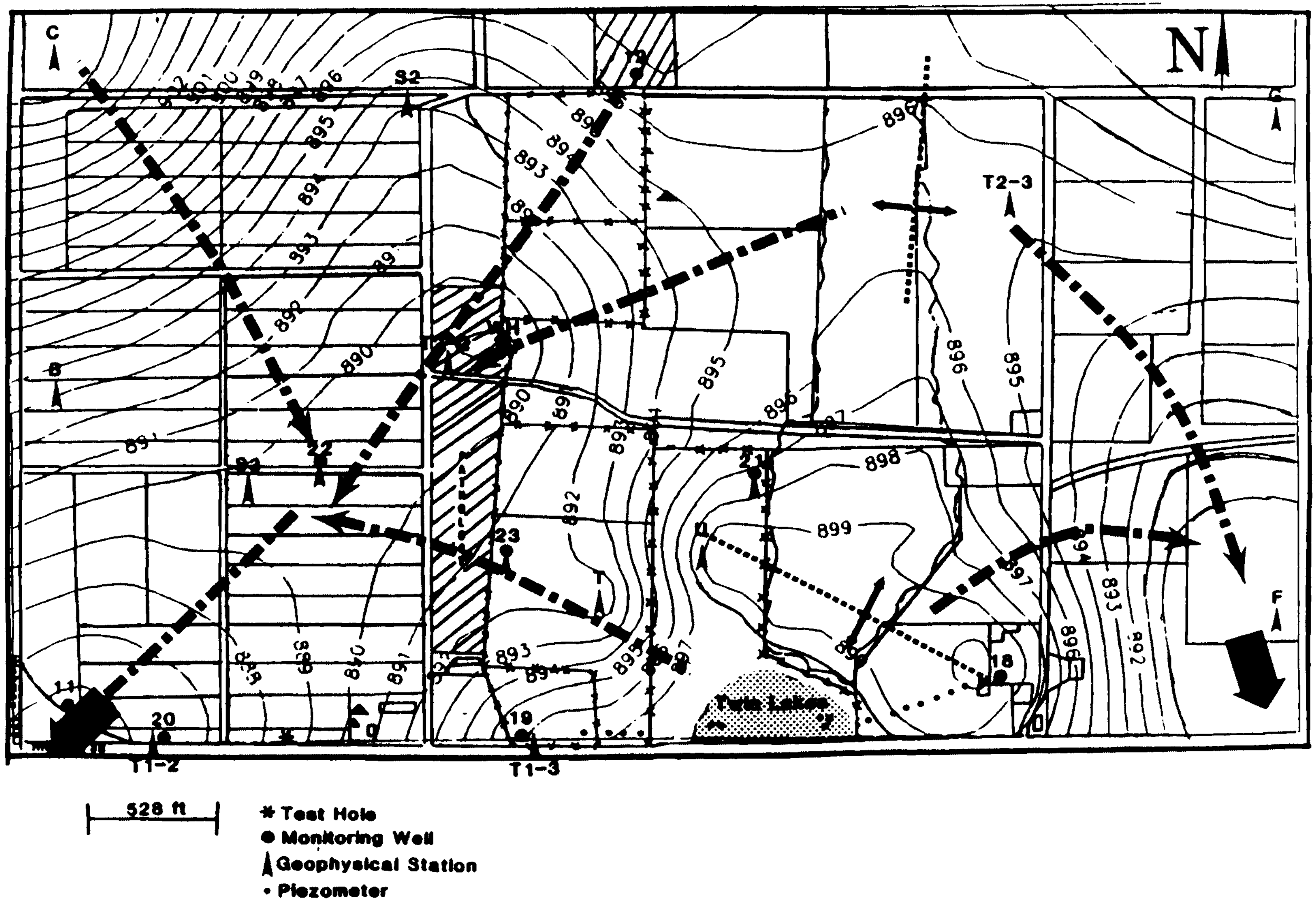


Figure 18. Detailed Water Table Map

The regional bedrock surface as well as recharge (Figure 19) controls the configuration of the regional water table. The regional direction of groundwater flow is southeast towards the Cimarron River. A major buried tributary bedrock channel is evident in the southwestern quarter of the Perkins Station. Bedrock channels contribute to local depressions of the potentiometric surface as well as groundwater divides. The existing groundwater divides and pathways of flow are well defined on the local and detailed water table maps (Figures 17 and 18). The dominant direction of groundwater flow from the Perkins Station is to the southwest.

A groundwater recharge/discharge area exists as a shallow ponded area called Twin Lakes at the south edge of the station. Groundwater flow lines converge from the north and east to recharge the pond. Flow lines diverge from the pond causing the groundwater to flow away from the pond to the southwest. This is a sensitive undesignated wetland area which could possible be a receptor of possible concentration of contaminants. For example, small amounts of the pesticide chemical Lindane (0.003 ppm) were detected in pond sediments as long as three years after upgradient application had been discontinued.

A major bedrock channel trending northeast to southwest is located in the west half of the southern terrace. Groundwater flow is therefore flows from the station to the southwest. A more minor bedrock channel

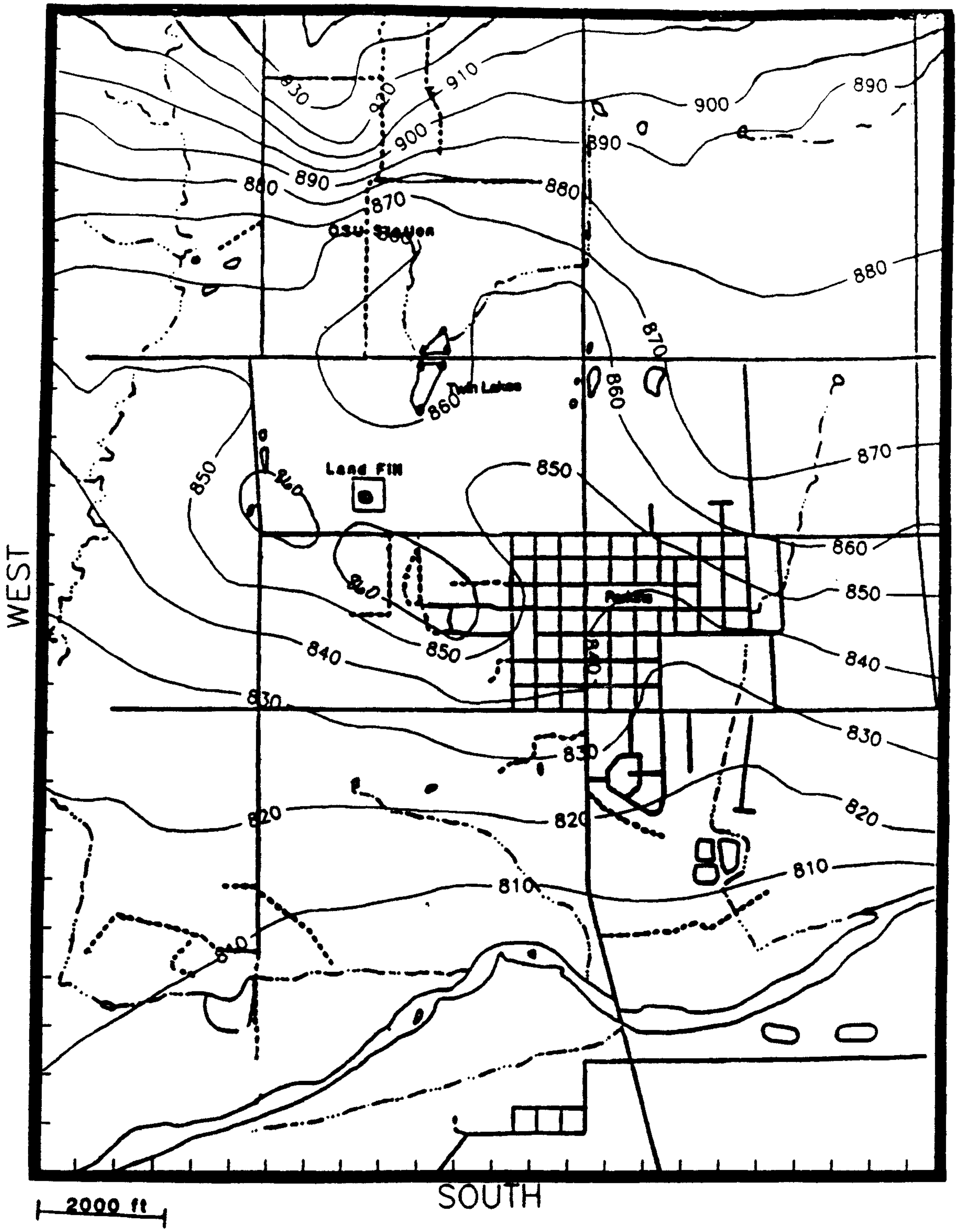


Figure 19. Regional Bedrock Map

trending northwest to southeast appears to exist in the east half of the southern terrace. Groundwater flow is focused off the station to the southeast in this area to a wetland type area which exists year round. A groundwater divide in the north portion of the southern terrace causes the groundwater to bifurcate to the east and west. Another groundwater divide directly north of the ponded area forces groundwater to flow north and south. The water table contours wrap around the ponded area so that flow lines depict the discharge of groundwater into the pond from the northeast and out of the pond to the southwest.

Definition of Aquifer Characteristics

Aquifer Tests

Discharge rates for individual pumping tests have varied from 30 to 60 gpm. A 1992 pumping test with a discharge rate of 47 gpm rendered highly erratic measurements in the observation wells. The high discharge rate stressed the aquifer to the point that the data was difficult to interpret. A 1989 pumping test using a pumping rate of 32 gpm rendered more reasonable drawdown patterns for the observation wells and has subsequently been used to calculate hydraulic property values for the southern alluvial sediments. The data collected from this pumping test is included in Appendix E. Typical data plots for Jacob and Prickett analysis with calculations for hydraulic properties for the 1989 pumping test at the Perkins Station are included in Appendix C. Additional data plots for both of these methods are presented in Appendix E.

The slug tests conducted on the clustered monitoring wells in the northern half of the station are of interest to this project since they are completed in materials of lower conductivity than those aquifer materials in the southern half. Graphical plots of slug test data for the clustered monitoring wells #4 (deep) and #5 (shallow) are shown in Appendix C. The pertinent data and graphs used in these analyses are presented in Appendix E.

Tracer tests conducted at the Perkins Station have rendered specific information on velocity distribution and dispersivity properties for the lower terrace deposits of the Perkins Station. Dispersion along with convection are the main physical processes responsible for solute transport. No differential flowpaths are associated with the saturated zone of the alluvial deposits and therefore, mixing of solutes is assumed throughout the saturated column. Chemical tracers have been found to travel approximately 1 ft/day. Seepage velocity appears to be associated with the principle mass of a slug release breakthrough curve.

Hydraulic Variables /
Aquifer Coefficients

The portion of the Perkins Terrace aquifer located beneath the Perkins Station has been characterized as to the rate at which groundwater is conducted and the aquifer's storage capacity. Aquifer coefficients calculated by analyzing pumping test data from the fall of 1989 and the spring of 1992 are tabulated in Appendix C. The slug tests conducted in the upper terrace deposits resulted in transmissivities of 0.28 to 18.9 gpd/ft while pumping tests conducted in the lower terrace deposits rendered transmissivity values ranging from 14,669 to 20,373 gpd/ft. The pertinent data and graphs used in these analyses are included in Appendix E.

The large difference between the transmissivity values for the upper and lower terrace deposits can be accounted for by the much higher silt and clay content of the thinner upper terrace deposits. The lower thicker terrace deposits have relatively high transmissivity and should be of great concern in the transport of solutes. The storativity of the lower terrace deposits was calculated to range between 0.06 and 0.10 through pumping test analysis (Prickett Method). These values are considered low for an unconfined aquifer which normally ranges from between 0.10 and 0.30. A storativity of 0.20 usually represents coarser materials such as those which make up the lower terrace deposits. The calculated storativities may be unusually low due to delayed drainage caused by discontinuous impeding layers of clay and silt present at the pumping test site (see cross-section in Appendix C.

Simplifying Assumptions

The following discussion introduces two fundamental assumptions in conceptual models which are always made when modeling groundwater flow and contaminant transport.

The Porous Medium as a Continuum

An aquifer is a complex system comprised of solids and voids filled with fluids. Detailed data and measurements of water flow and contaminant transport on a microscopic level through this system of solids and voids are essentially unobtainable. The porous medium is therefore defined as a continuum at a macroscopic level. The complex geometry of the void-solid interface is replaced by various solid matrix coefficients such as porosity, permeability and dispersivity.

Horizontal Two-Dimensional Modeling

Actual groundwater flow and contaminant transport are three dimensional in nature in an aquifer. Regionally, the ration of aquifer thickness to horizontal length is so small, that flow in the aquifer is practically horizontal. Therefore, most aquifer models are written for two dimensions only. Transforming a three dimensional problem into a two dimensional one brings about the need for aquifer transport and storage coefficients such as aquifer transmissivity and storativity.

CHAPTER V

PHASE II - DESIGN OF MATHEMATICAL MODEL

At this point in modeling, the conceptual model must be translated into a complete, well-posed mathematical model. Firstly, a numerical model and code must be employed. The model variables should be analyzed and further simplifying assumptions added to the original conceptual model. A complete listing of coefficients and parameters to be used in the model should be compiled with available and estimated values indicated. During model development, it is important to conduct a sensitivity analysis in order to determine the significance of the coefficients and parameters of the model.

Some important concepts were developed from the Perkins Station hydrogeologic investigation (Chapter III) and the design of the conceptual model (Chapter IV). Pesticides have not been found in the groundwater in appreciable amounts. Nitrates have been found to fluctuate with the water table in response to precipitation events. Therefore, nitrates will be used for solute transport simulation in this project. The northern terrace deposits were found to have very small transmissivity properties due to the fine grained nature of the aquifer materials. In contrast, the southern terrace deposits have appreciably high transmissivity properties and an increased saturated thickness. Therefore, only the southern half of the station will be modeled in this project.

Numerical Model and Code

A modified Nuclear Regulatory Commission (NRC) version of the U.S.G.S. solute transport model KONIKOW (Kent, et. al., 1986) was chosen for this project. This program includes an interactive preprocessor program used in creating and editing input data sets as well as a mathematical model program for actual problem solution. This version of the preproscessor was originally written in PL1 language but has been converted to a more user friendly Fortran version used in this project. All of the modeling scenarios in this project were run on a 386 IBM compatible personal computer.

The Fortran version of the KONIKOW mathematical model has been altered to make the program output files more usable. Three versions of the KONIKOW model were created: "KONIDRI" will create output files for use with the Geographical Information System program INDRISI, "KONGRAF" will create output files for use with the Golden graphing packages GRAPHER and SURFER, and "KONBOTH" will create both types of output files. The second version was the most useful for this project and has been further altered to output only the potentiometric head and concentration matrices at the end of each pumping period in the model.

Coefficients and Parameters

The KONIKOW model preprocessor is compartmentalized into menus of hydraulic and chemical data coefficients and parameters. Computer echos of the hydraulic and chemical menus of the preprocessor are included in Appendix F. A list of coefficients and parameters along with their values for an actual solute transport computer run completed in this research project are tabulated in Table IV. Hydraulic variables are divided into categories of overall flags, spatial and temporal limits, printing commands, constant coefficients and matrices of aquifer characteristics and stresses. Chemical variables are divided into categories of chemical flags (decay and sorption), particles limits, printing commands, chemical constants (dispersivity) and chemical concentration matrices for concentration designation. Complete variable listings for the most significant computer runs are included in Appendix F.

The coefficients and parameters used for modeling in this project have been determined by field analysis techniques (see Chapter III and Appendix C) or estimated from previous computer modeling scenarios. All of the runs were completed for an unconfined aquifer in a planar configuration. Storativity, specific yield, hydraulic conductivity and constant natural gradient were derived from field tests. Recharge was calculated as a percentage of the actual precipitation measured at the station.

TABLE IV

COEFFCIENTS AND PARAMETERS FOR SOLUTE TRANSPORT COMPUTER RUN

Run: Solute Transport - January 1992 thru January 1993
Filename: CONC8
First pumping period = 6 months of fertilizer infiltration
(active concentration matrices)
Second pumping period = 6 months of infiltration
(inactive concentration matrices)

HYDRAULIC: TITLE AND FLAGS

1) TITLE = Solute Transport - Jan 1992 to Jan 1993

2) IHEAD = 0 (Head Calculation + Solute Transport)

3) ISOLV = 0 (ADIP)

4) ITP = 1 (Hydraulic Conductivity)

5) IXSECT = 0 (Plannar)

6) FCON = 1 (Unconfined)

7) NCYC = 0

8) CHKDTA = 0

HYDRAULIC: LIMITS

1) NPMP = 2 (6 months each - Spring and Fall Seasons)

2) NX = 17

3) NY = 17

4) XDEL = 264 ft

5) YDEL = 264 ft

6) NTIM = 6 (one month each)

7) ITMAX = 50

8) NITP = 4

HYDRAULIC: PRINT

1) NPNT = 1

2) NPNTVL = 0

3) NPNTD = 0

4) NPNCHV = 0

5) NSTRT = 0

Aquifer characteristics such as water table and bedrock configurations were derived from monitoring well and geophysical data while land surface configuration was determined through elevation surveys. Because these aquifer characteristics are in matrix format, simplification of the real world system was necessary for successful modeling.

Temporal and Spatial Arrangement

Initial runs of KONIKOW for calibration were simplified by necessity yet calibrated to be accurate according to historical records. KONIKOW is temporally arranged into pumping periods divided into time steps. Initial runs were designed on an annual basis: one pumping period consisting of twelve time steps of one month each. Due to the fact that recharge could not be specified for individual pumping periods or time steps, calibration was only completed on an annual basis.

KONIKOW is spatially arranged into specific x and y nodes which can be used to designate aquifer characteristics and stresses such as potentiometric surface and recharge information. A southern portion of the station (Figure 20) was divided into a 17 by 17 grid of nodes, each with a 264 square foot area (see Figure 21). This grid encompasses the major area of concern, the southern terrace deposits of the Perkins Station.

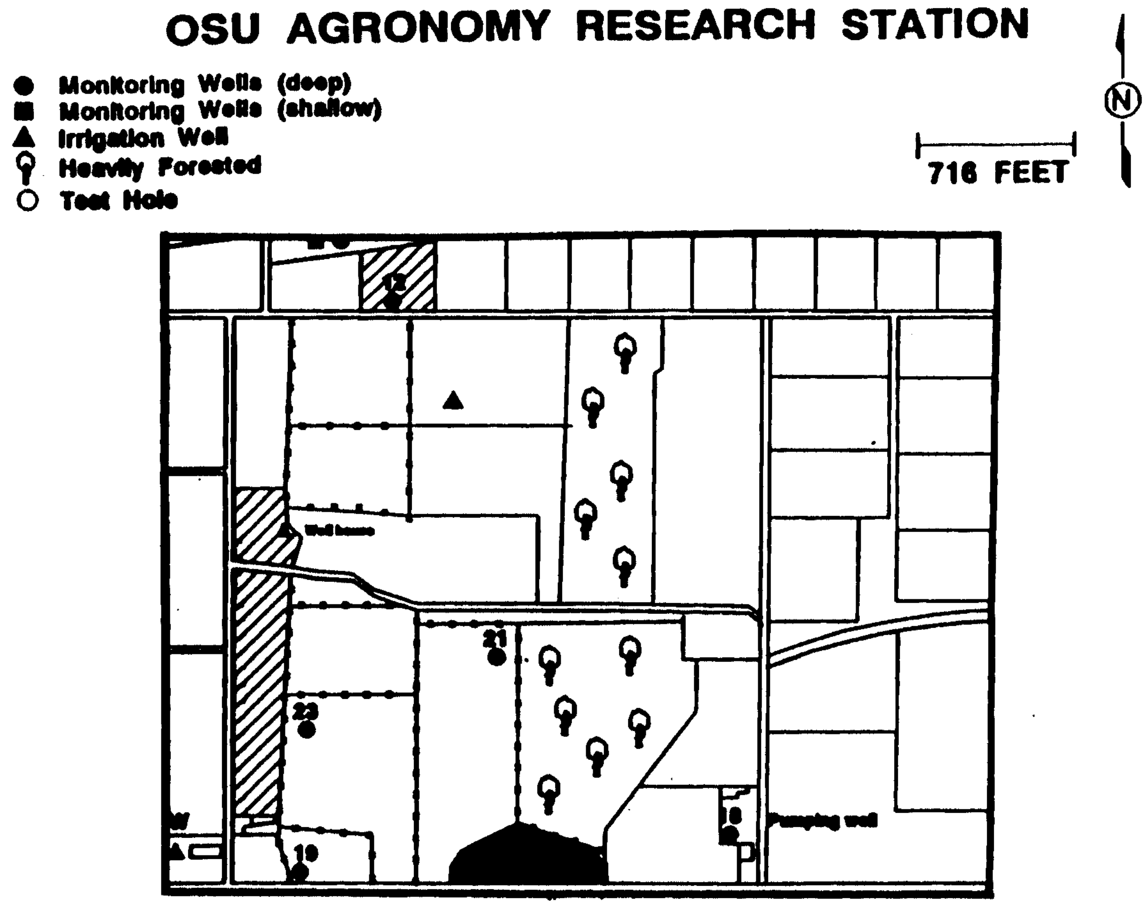


Figure 20. Southern Terrace of Perkins Station - Computer Modeling Area

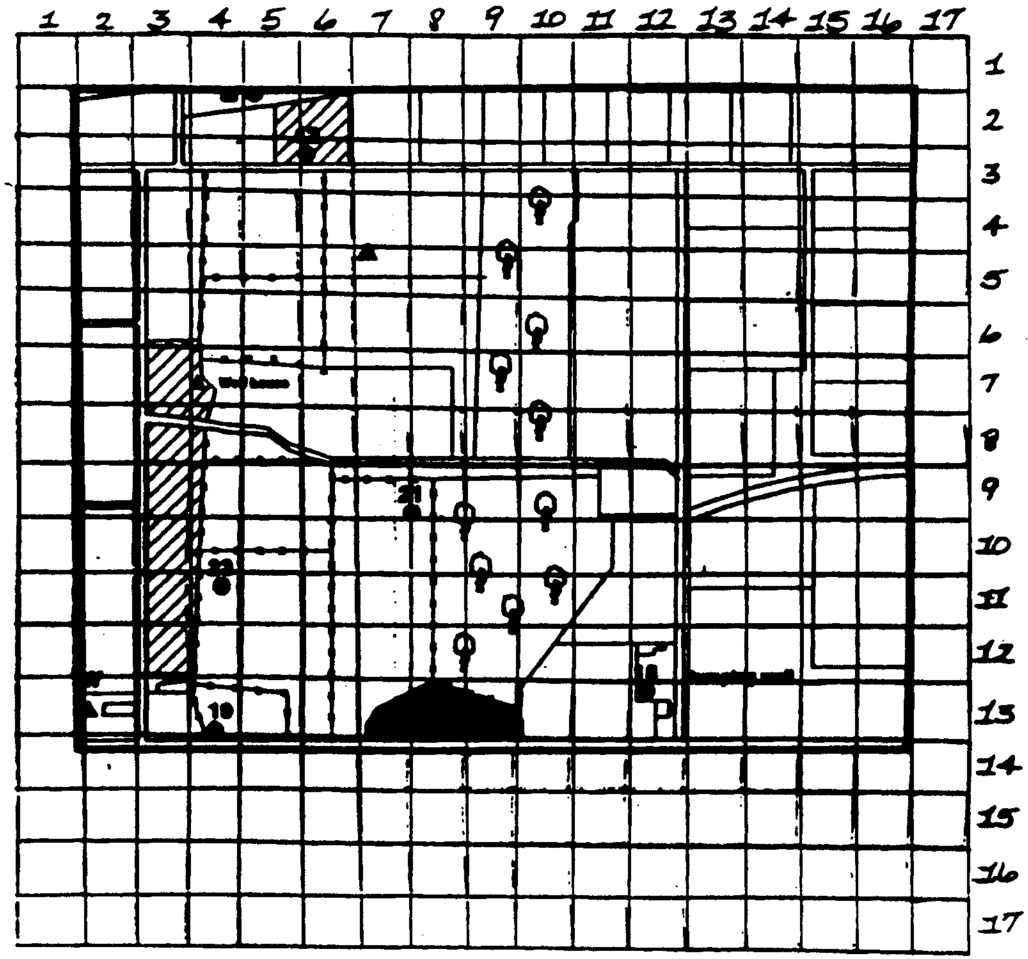


Figure 21. Southern Terrace of Perkins Station - Gridded for Modeling

Additional Assumptions

Additional assumptions had to be made upon designing the actual mathematical model. The aquifer is assumed to be both homogeneous and isotropic for the simplicity of calculations. The saturated thickness is held at a constant thickness of 40 feet and the thickness of the vadose zone at a constant thickness of 20 feet. This will alleviate abrupt changes in saturated thickness complicating the computer calculations. Effective porosity, specific yield and storativity are held at a constant value of 40 percent to facilitate the simulation and lower the sensitivity of the model. Aquifer characteristic matrices of land surface, water table elevation and bedrock elevation were created by overlaying the computer model grid onto elevation maps. Elevation values were selected for each mode in the grid and entered into the computer (see Figure 22 for an example). As indicated, simplification of the configuration of the elevation maps was necessary for conversion to a matrix format. A node ID grid was used in order to facilitate a constant head boundary at the north and south borders of the computer grid (Figure 23).

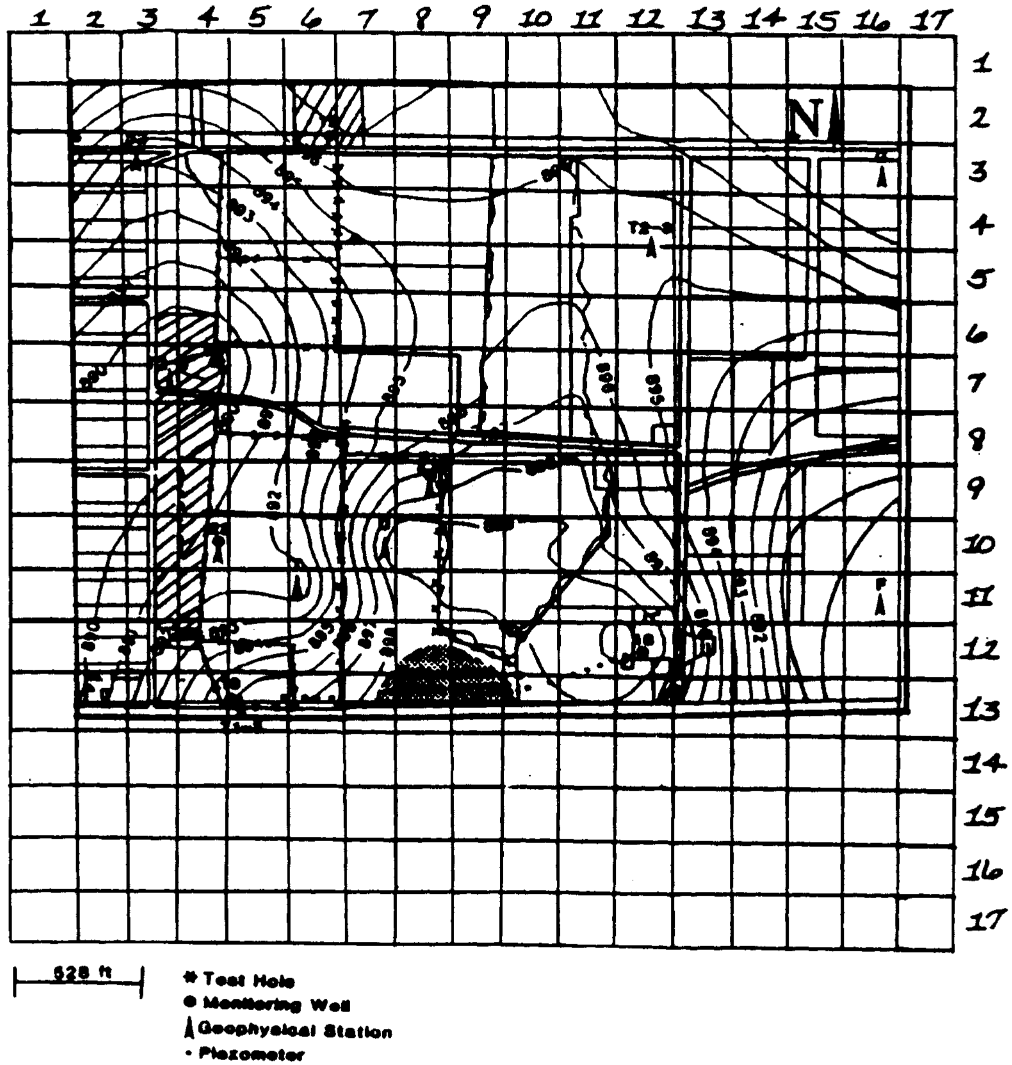


Figure 22. Water Table Elevation Map with Computer Grid Overlay

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	2
0																0	3
0																0	4
0																0	5
0																0	6
0																0	7
0																0	8
0																0	9
0																0	10
0																0	11
0																0	12
0																0	13
0																0	14
0																0	15
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	16
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17

Figure 23. Node ID Computer Grid

CHAPTER VI

PHASE III - CALIBRATION AND VERIFICATION OF MODEL

The KONIKOW model was calibrated in a point to point manner for potentiometric head at specific observation wells over the period of one year (January 1989 to January 1990). The model was then run for head only for three years (January 1990 through January 1993) in order to verify the output data with historical monitoring well data. Once the potentiometric head was calibrated and verified, the solute transport of nitrates was introduced. The model was calibrated for nitrate concentration in specific observation wells over the period of one year (January 1992 to January 1993) and the nitrate concentrations verified with historical monitoring well water quality data. Appendix F contains all of the pertinent computer modeling material.

Head Only Runs

Appendix F contains lists of the input coefficients and parameters, input data, and potentiometric head output file for the final verification run (VERF3) for the head only scenarios (January 1992 - January 1993). Table V lists

TABLE V

COMPUTER RUN TITLES, TIME PERIODS AND SENSITIVITY

	Title	Time Period	Sensitivity
Head Only			Recharge:
Calibration	INIT1	Jan 1989 - Jan 1990	6.15 inch
	INIT2	Jan 1989 - Jan 1990	6.15 inch
Verification	VERF1	Jan 1990 - Jan 1991	3.52 inch
	VERF2	Jan 1991 - Jan 1992	3.80 inch
	VERF3	Jan 1992 - Jan 1993	6.10 inch
Solute Transport			Injection Rate:
@*	CONC1	Jan 1992 - Jan 1993	0.667 ft/day
@*	CONC2	Jan 1992 - Jan 1993	1.333 ft/day
@*	CONC3	Jan 1992 - Jan 1993	2.667 ft/day
			Decay Rate:
@	CONC4	Jan 1992 - Jan 1993	0.50 year
@	CONC5	Jan 1992 - Jan 1993	0.25 year
Two pumping period scenarios 6 months injection with concentration and 6 months injection with no concentration			
			Background Conc:
	CONC6	Jan 1992 - Jan 1993	35 ppm
	CONC7	Jan 1992 - Jan 1993	30 ppm
	CONC8	Jan 1992 - Jan 1993	25 ppm
	CONC9	Jan 1992 - Jan 1993	t 1/2 = 0.125 yr

Final Selection for Sensitive Variables

Recharge = 6.10 inch
Injection Rate = 2.667 ft/day
Decay Rate = 0.25 year half-life
Background Concentration = 25 ppm

* No Decay, Sorption or Background Concentration
@ No Background Concentration

the name of the computer runs with their corresponding time interval.

Calibration

A specific year (January 1989 to January 1990) of historical potentiometric surface data was chosen for initial calibration. Recharge was estimated from Perkins Station precipitation records (see Table VI). The model was run for one year (one pumping period of 12 time steps) and the potentiometric head output was analyzed for accuracy according to historical potentiometric head records.

Calibration was completed on a point to point basis using observation wells. Three monitoring wells installed in the southern terrace deposits were chosen as observation wells at specific points for checking calibration (MW #12, MW # 18 and the Well House). The observed and calculated potentiometric head measurements at the end of the pumping period (January 1990) for all three observation wells were tabulated in Table VII. Calculated values were almost identical to the actual observed values with a percent error of 0.06 to 0.50 by the computer calculations (see Table VII). During a typical computer run, a percent error between 2.0% and 3.0% is considered excellent and provides reliable results.

TABLE VI

CUMULATIVE PRECIPITATION AND RECHARGE CALCULATIONS

	Cumulative Precipitation (inches)	Calibrated Recharge (in/yr)
1989	41.00	6.15
1990	23.44	3.52
1991	25.36	3.80
1992	40.44	6.10

TABLE VII

OBSERVED VERSUS CALCULATED POTENTIOMETRIC HEAD MEASUREMENTS (IN FEET)

	Observation Wells #1 / Monitoring Wells #12	#2 / #18	#3 / WH	#4 / #19	#5 / #21
January 1990					
Observed	899.13	900.39	897.39	--	--
Calculated	899.63	895.75	896.41	--	--
Error	.06%	.50%	.11%	--	--
January 1991					
Observed	900.28	899.90	897.22	--	--
Calculated	899.75	896.10	896.78	894.23	896.48
Error	.06%	.42%	.05%	--	--
January 1992					
Observed	896.53	897.20	892.15	894.05	894.24
Calculated	899.74	896.07	896.75	894.20	896.45
Error	.36%	.13%	.52%	.02%	.25%

Verification

Verification of the model was carried out following calibration by running the model for three consecutive years (January 1990 to January 1993) and checking the potentiometric surface data from the observation wells. In the 1990 to 1991 run, three observation wells were present in the southern terrace deposits of the station. Table VII contains potentiometric head measurements at the observation wells at the end of the pumping period (January 1991). Again, the observed and calculated values were almost identical with a percent error of 0.05 to 0.42 for the computer calculations. Five observation wells were present in the 1991 to 1992 modeling run. Two extra monitoring wells were installed in the southern terrace deposits of the station during the year. Table VII contains potentiometric head measurements at the observation wells at the end of the pumping period (January 1992). Again, the observed and calculated values were almost identical with a percent error of 2% to 52% for the computer calculations. Table VII also contains results of the 1992-1993 computer run with a percent error ranging from 10% and 33%. Results of the head only calibration and verification run were determined to be highly reliable with less than a one half percent error in all computer runs.

Sensitivity Analysis

During calibration, certain coefficients and parameters affected the sensitivity of the calculations more than others. Therefore, these variables are very significant to calibrate so that modeling scenarios will be accurately completed. Sensitivity for the head only runs was affected to the greatest degree by the hydraulic coefficient and parameters of recharge, hydraulic conductivity, effective porosity, and storativity. Of these variables, recharge was determined to be the most highly sensitive variable.

Recharge was calculated as a percentage of the cumulative precipitation of the year being modeled. Recharge usually accounts for 10 to 15 percent of the cumulative precipitation with the remaining 85 to 90 percent being lost to evaporation, transpiration, and surface runoff. Through calibration, a 15 percent recharge rate was found to be an appropriate estimate. Calculating cumulative recharge for the years modeled, it was determined that the relatively dry years of 1990 and 1991 (23 to 26 inches of precipitation) were bracketed by the relatively wet years of 1989 and 1992 (49 to 41 inches of precipitation). The variation of cumulative precipitation could greatly effect the solute transport of nitrates in the Perkins Terrace Aquifer. Wetter years will tend to move the nitrates into the groundwater faster.

Hydraulic conductivity values had previously been determined by aquifer tests conducted in the southern terrace deposits. As previously determined, the most reasonable values for hydraulic conductivity ranged between 350 and 450 $g/d/ft_2$ (see Appendix C). A best fit for the data was achieved using 350 $g/d/ft^2$.

Effective porosity and storativity are closely related coefficients. The unconfined southern terrace alluvial deposits range from clay to silt to sand with some gravel. Reasonable effective porosity values for these materials range from 10 to 40 percent.

Specific yield is defined as the ratio of the volume of water that a given aquifer will yield by gravity to the volume of the aquifer itself (Driscoll, 1986). Specific yield of the aquifer depends upon the amount of retention the materials exert upon groundwater storage during drainage. Smaller average grain size materials such as clay and fine sand will retain groundwater, causing it not to be released during drainage. Larger grain size materials such as coarse sand and gravel will more readily release groundwater from storage.

Storativity is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Driscoll, 1986). Specific yield of an unconfined aquifer is equal to the storativity of the aquifer. In past computer simulations, these latter three coefficients have been found to be the most sensitive of all the variables. The simplistic approach of assuming high values for these coefficients have been found to be the most successful. For calibration of this model, effective porosity, storativity and specific yield were assumed to be 40 percent, not an unreasonable estimate for an effectively producing alluvial aquifer such as the Perkins Terrace aquifer.

Solute Transport Runs

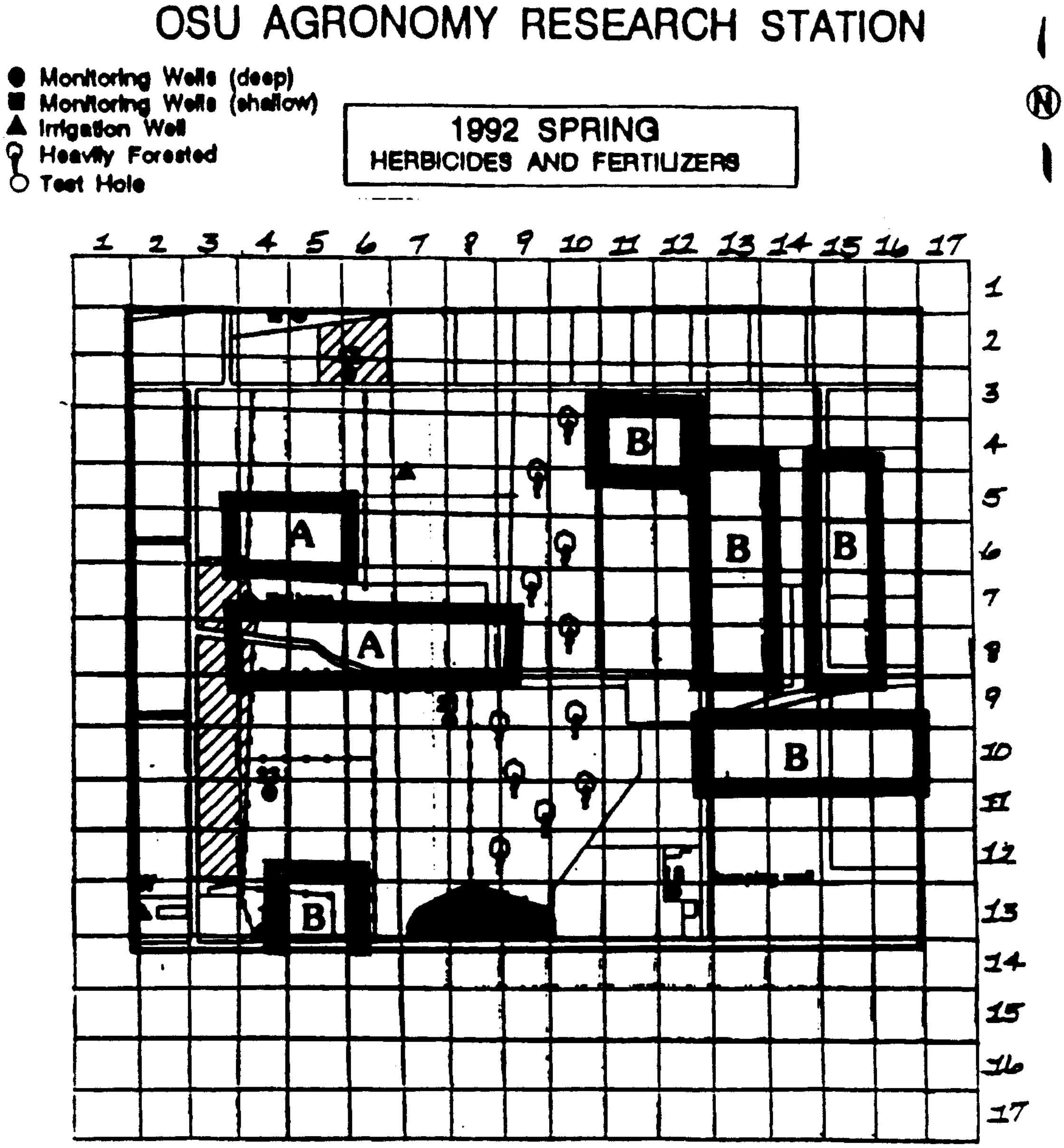
Calibration and Verification

In order to facilitate solute transport, chemical data was added to the already existing hydraulic data of the head only runs for calibration and verification. January 1992 to January 1993 is the most complete time period for fertilizer application to crops as well as water quality data for a number of widely spaced observation wells. This time period was calibrated for potentiometric head with excellent accuracy as described above. Due to the constraints of the water quality data available for the southern terrace area, the year of January 1992 to January 1993 was the only year used to calibrate and verify the KONIKOW model for solute transport.

Nitrogen fertilizer was introduced to the simulated aquifer as point source contamination in the form of injection wells. This is reasonable since fertilizers are applied in bulk upon agricultural plots and are leached into the groundwater by infiltrating precipitation. Each injection well is represented as one cell (264 feet by 264 feet) in the hydraulic matrices. Figure 24 depicts the application areas and their injection concentrations. The concentration of the nitrate-nitrogen being injected in included in the chemical matrices of the model in the cells corresponding to the injection wells. Even mixing throughout the saturated column is assumed since earlier studies did not indicate preferential flow paths.

The injection rate was determined by considering the lag time between nitrate-nitrogen application and water quality detection according to historical records. Both short term and long term trends (see Figures 10 and 11) have shown a lag time of 30 to 60 days for nitrates reaching the water table: 30 days during a wet season and 60 days during a dry season. The year between January 1992 and January 1993 was considered a wet year with over 40 inches of cumulative precipitation. The average depth of the unsaturated zone (depth to the water table) in the southern terrace deposits is 20 feet. Assuming that nitrate-nitrogen would leach through 20 feet in 30 days during this wet year, an injection rate of 0.667 ft/day (7.8 E-6 ft/sec) would be reasonable.

Through calibration runs of the KONIKOW model, an injection rate twice the original rate (1.33 ft/day or 7.8 E-3 ft/sec) was determined to be a more reasonable rate. This increased rate of injection can be attributed to both the presence of macropores and crop irrigation which serve



A 61 lbs/acre 1,252 ppm

B 75 lbs/acre 1,539 ppm

Figure 24. Fertilizer Application Areas - Spring 1992

to speed the travel of contaminants to the water table.

The concentration of the nitrate-nitrogen for injection was determined through actual records of fertilizer application (in the form of nitrates) on the Perkins Station (see Appendix A). The application areas and specific amount of nitrate applied for the spring of 1992 were designated on the KONIKOW grid (see Figure 24) in the corresponding cells. Each application was either in the amount of 61 lbs/acre or 75 lbs/acre which were easily converted to 1252 ppm and 1539 ppm, respectively, for use as injected concentration in the KONIKOW model.

Once the injection rate was calibrated, the rate of decay for nitrate-nitrogen was determined. Nitrate-nitrogen is an inorganic ion and does not actually decay in the same manner as organic compounds do. Nitrate-nitrogen does not undergo sorption onto soil particles or organic material. When nitrate-nitrogen is introduced into the subsurface, it is either taken up for use by plants or its components undergo chemical changes as they travel through the soil column. Both nitrification and denitrification processes cause nitrates to convert to ammonia and back again. Other chemical reactions also take place. Considering this, decay was added to the KONIKOW scenarios in order to simulate the change in concentration of nitrate-nitrogen once it is introduced into the groundwater. Modeling runs for a decay rate of 1/2 year 1/4 year and 1/8 year were completed with the latter rate being the most reasonable estimate.

Fertilization occurs on the Perkins Station on a seasonal basis during the growing season (January through July). During the rest of the year, the nitrate-nitrogen derived from fertilizers is either taken up by plant, runs off in surface water or infiltrates through the root zone. For this reason, the solute transport simulation runs were developed into two pumping periods of six month each. The first pumping period represent the growing season, (April to September) when nitrogen fertilizers are applied with the injection wells of the model actually adding nitrate concentration to the simulated aquifer. The second pumping period (October - March) represents the infiltration period when no nitrogen fertilizers are applied, therefore concentrations are not added by the injection wells to the simulated aquifer during this one half year cycle.

The background concentration for the southern terrace deposits was estimated from the water quality data for monitoring well #12. Monitoring well #12 is located north of the nitrate application areas used for solute transport simulation and directly south of the norther terrace deposits of the Perkins Station. Monitoring well #12 is a good measure of the nitrate concentration entering the southern terrace deposits from the northern terrace deposits. Consulting water quality records for monitoring well #12 indicated that the median nitrate concentration ranged between 25 and 35 ppm, therefore a background concentration was entered into the model as initial aquifer concentration. Through the process of calibration, 25 ppm background concentration for the southern terrace deposits was found to be the most reasonable amount.

Five monitoring well (#12, #18, #19, #21 and #23) existed in the southern terrace during this time period (January 1992 - January 1993). As depicted in Figure 24, monitoring well #12 is located sufficiently upgradient of the fertilizer sources to be disregarded as an observation well. Calculations of nitrate concentrations in January 1993 for the four observation wells in the southern terrace deposits are tabulated in Table VIII. Through adjusting the most sensitive values for solute transport of the model acceptable nitrate concentrations were arrived at with a two season pumping period configuration, an injection rate of 1.333 ft/day, a half-life of 0.125 year and a background concentration of 25 ppm. A considerably smaller injection rate would be acceptable it were pro-rated over the area represented. The observed concentration according to historical water quality data and the computer calculated concentrations were compared. A range between 12 and 32% error was observed.

Sensitivity Analysis

The most sensitive coefficients and parameters in the solute transport calibration and verification were the injection rate, decay rate and background concentration of nitrate. Table IX depicts a sensitivity analysis for

TABLE VIII

OBSERVED VERSUS CALCULATED NITRATE CONCENTRATIONS IN SOLUTE TRANSPORT RUNS

Calculated Concentrations (ppm)				
	Computer Model Designated Obervation Wells			
	#2	#3	#4	#5
	Field Designated Monitoring Wells			
	#18	#19	#21	#23
Injection Rate:				
0.667 ft/day	0.000012	0.000079	0.2504	0.0069
2.667 ft/day	0.0256	0.0871	221.14	9.8828
1.333 ft/day	15.164	5.850	14.313	6.8287
Half Life:				
0.50 year	7.086	2.5912	7.288	3.2337
0.25 year	3.564	1.218	4.241	1.5917
	Two pumping period scenarios			
Background Concentration:				
35 ppm	7.349	1.307	4.894	2.1023
30 ppm	10.124	0.898	1.983	1.0901
25 ppm	12.06	0.2371	0.6889	0.3198
Half Life:				
0.125 year	6.948	0.0645	0.3272	0.158
Calculated January 1993	**6.948**	**0.0645**	**0.3272**	**0.158**
Observed January 1993	**9.95**	**0.09**	**0.34**	**0.14**
Error	**30.17%**	**28.3%**	**3.76%**	**12.85%**

TABLE IX

SENSITIVITY ANALYSIS FOR SOLUTE TRANSPORT RUNS - MONITORING WELL NUMBER 21

	<u>Calculated Nitrate Concentrations (ppm)</u>
Injection Rate:	
0.667 ft/day	0.0069
2.667 ft/day	9.8828
1.333 ft/day	6.8287
Half Life:	
0.50 year	3.2337
0.25 year	1.5917
<u>Two pumping period scenarios</u>	
Background Concentration:	
35 ppm	2.1023
30 ppm	1.0901
25 ppm	0.3198
Half Life:	
0.125 year	0.158
<u>Calculated</u> January 1993	**0.158**
<u>Observed</u> January 1993	**0.14**
<u>Error</u>	**12.85%**

monitoring well #21.

The initial injection rate of 0.667 ft/day calculated through records of nitrate lag time to the water table was determined to caused far too little movement of nitrates into the subsurface. This injection rate would probable be acceptable if it was pro-rated over the area of interest. For the purposes of this study, recharge was combined into fewer wells.

Plume development of the KONIKOW output files represented nitrate levels below detection limits in all observation wells. Historical water quality records indicated higher levels. By doubling the injection rate to 1.333 ft/day, predicted nitrate levels correlated well with the magnitude of the nitrates detected in the observation wells.

The determination of the appropriate decay rate for nitrate-nitrogen was a trial and error process. Half lives of 1 year, 1/2 year, and 1/4 year were used to bring the calculated nitrate levels into reasonable range. Each step down essentially halved the calculated nitrate concentration. A half life of 0.125 year was determined to be the most reasonable. This short time span can be attributed to uptake by plants and rapid chemical transformation. Calculated nitrate concentration and observed nitrate concentrations in monitoring well #12 were within a 12% error (see Table IX).

CHAPTER VII

PHASE IV - PREDICTION OF SOLUTE TRANSPORT

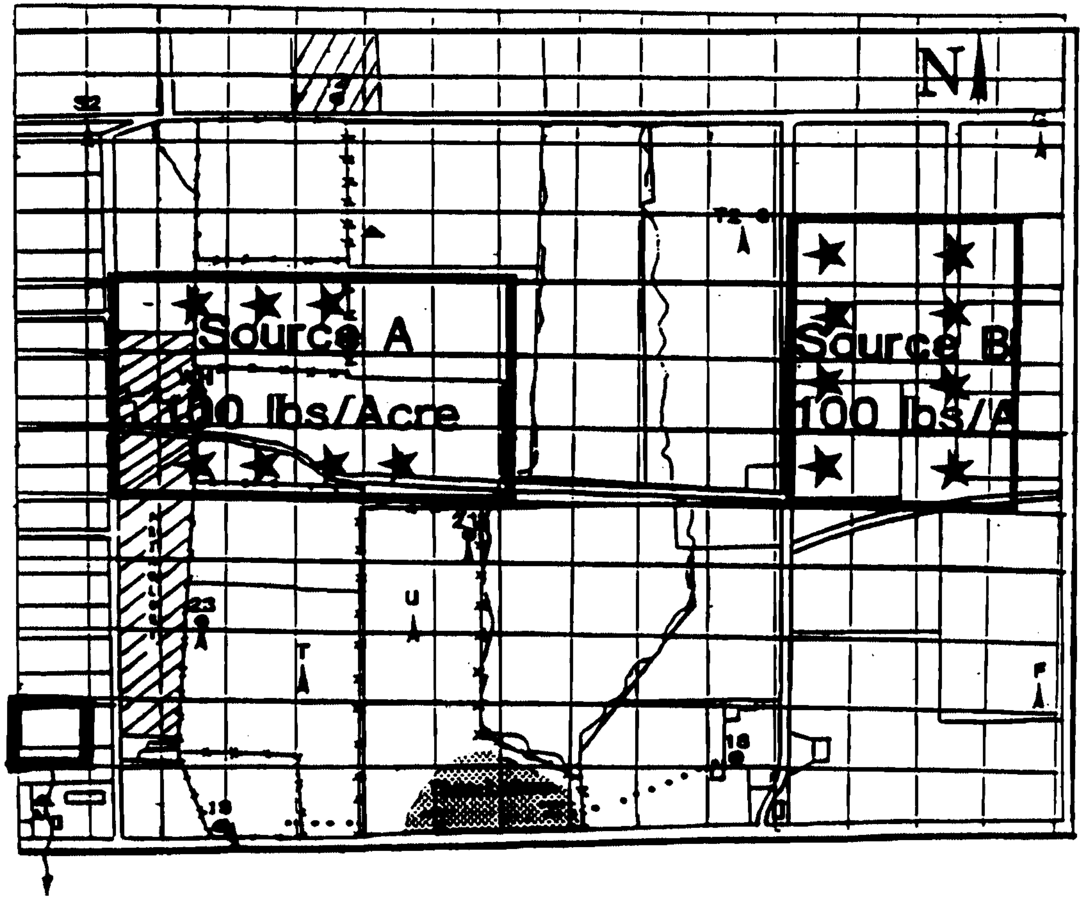
Once a hydrogeolgic system has been conceptualized, translated into a mathematical model, the model is calibrated and verified under real-world conditions in order to facilitate the prediction of future water table configurations and chemical transport patterns. This project involved tracking the movement of fertilizers which were applied on the station during the spring of 1992 over the course of five years in the terrace deposits of the southern half of the Agronomy station. The KONIKOW model was used to simulate the plume of nitrate-nitrogen in the water table in response to the 1992 fertilizer application as described in Chapter VI. This effort involved the use of a Golden graphics software package "SURFER" to map the chemical output from the model. The goal was to be able to determine if one seasonal application of nitrate-nitrogen fertilizers would be present in appreciable amounts in the groundwater leaving the boundaries of the station. Large amounts of nitrate-nitrogen in the groundwater could impact both the ponded area (Twin Lakes) as well as the downgradient residential areas and communities.

Development and Movement of Nitrate Plume

Two of the most active areas of fertilizer application on the southern terrace of the station were targeted as NO^3-N injection areas. Figure 25 depicts these two general areas (Source A and Source B) with specific nodes designated as injection wells. Each injection well represents an entire computer grid node measuring 264 by 264 feet which is slightly larger than a square acre (210 feet squared).

Both Source A and Source B were simulated to inject one seasonal application of 100 lbs/Acre of nitrate fertilizer, a commonly applied amount on the Perkins Station. The sources were simulated separately to alleviate any interference of two nitrate-nitrogen plumes. The calibrated and verified coefficients and parameters discussed in Chapter VI (injection rate, decay rate, etc.) were used for the predictive simulations. It was assumed that each year of the simulations would be wet years with over 40 inches of annual cumulative precipitation and therefore over 6 inches of recharge to the aquifer.

The chemical concentration matrices in the KONIKOW output files were imported to the Golden Graphics package SURFER. Contour maps of the nitrate plumes were constructed by referencing the KONIKOW computer grid nodes to the actual map coordinates of the southern terrace of



Each Node Measures 264 ft by 264 ft

★ Injection Well

Figure 25. Source Areas for Solute Transport Prediction Simulation

the station. These chemical plots were then overlaid upon the southern terrace location maps to determine the nitrate-nitrogen movement on the station.

Initially, the creation of the nitrate-nitrogen plumes in the groundwater was accomplished by running the solute transport model for one year representing 1992 to 1993. This simulation consisted of two pumping periods, 6 months of injection of the 100 lbs/Acre NO^3-N concentration (representing the infiltration of fertilizer to the groundwater) and 6 months of injection without concentration.

Figures 26 and 27 depict the nitrate-nitrogen plumes created during this first year of simulation. Both plumes have formed uniformly around the injection well areas. The plumes spread in a circular pattern outward from the source area by dispersion and convection. Convection is the main driving force caused by the gradient of the water table. Dispersivity is a secondary force caused by the actual nature of the aquifer's material. The concentrations gradient is from the center outward with the highest values (280 - 440 ppm) at the injection sources and the lowest values (40 ppm) at the outer edge of the plumes.

Three computer simulation scenarios of three consecutive years (1993 - 1994, 1994 - 1995, 1995 - 1996) were run for both sources with injection but no concentration. These simulations were run to represent the spread of the initial nitrate-nitrogen plumes under the

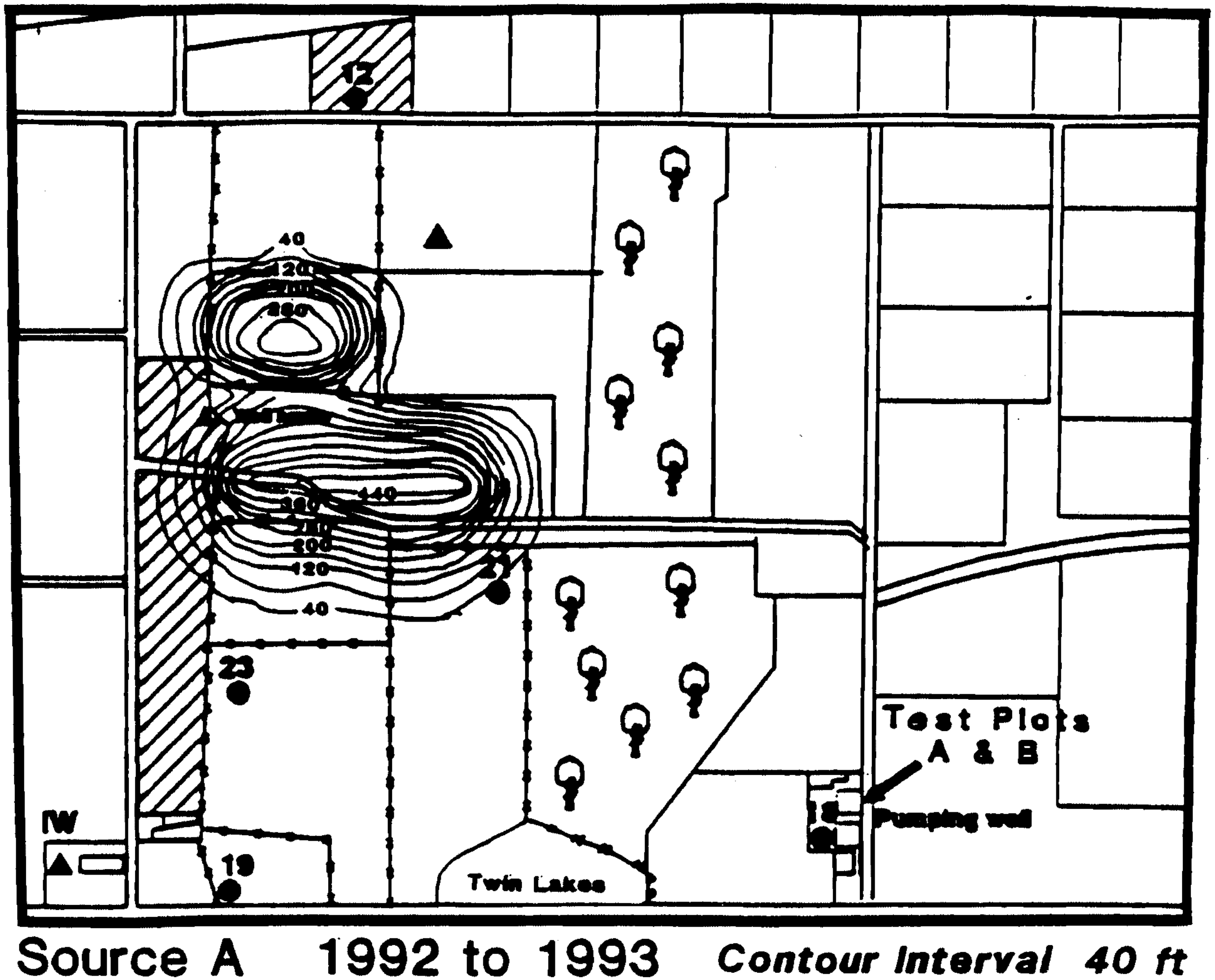
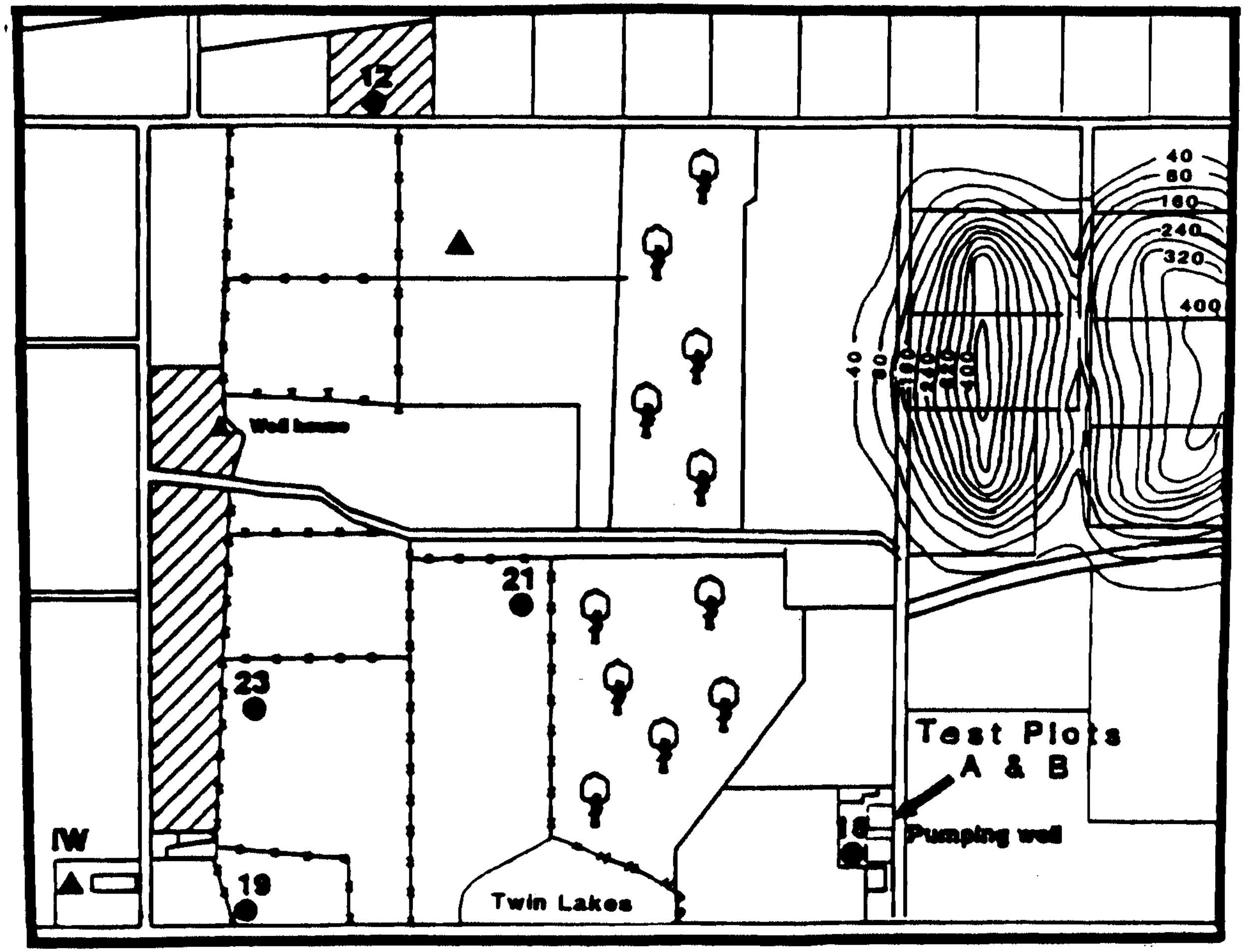


Figure 26. Source A, Nitrate-Nitrogen Plume Simulation, 1992 to 1993



Source B 1992 to 1993 *Contour Interval 40 ft*

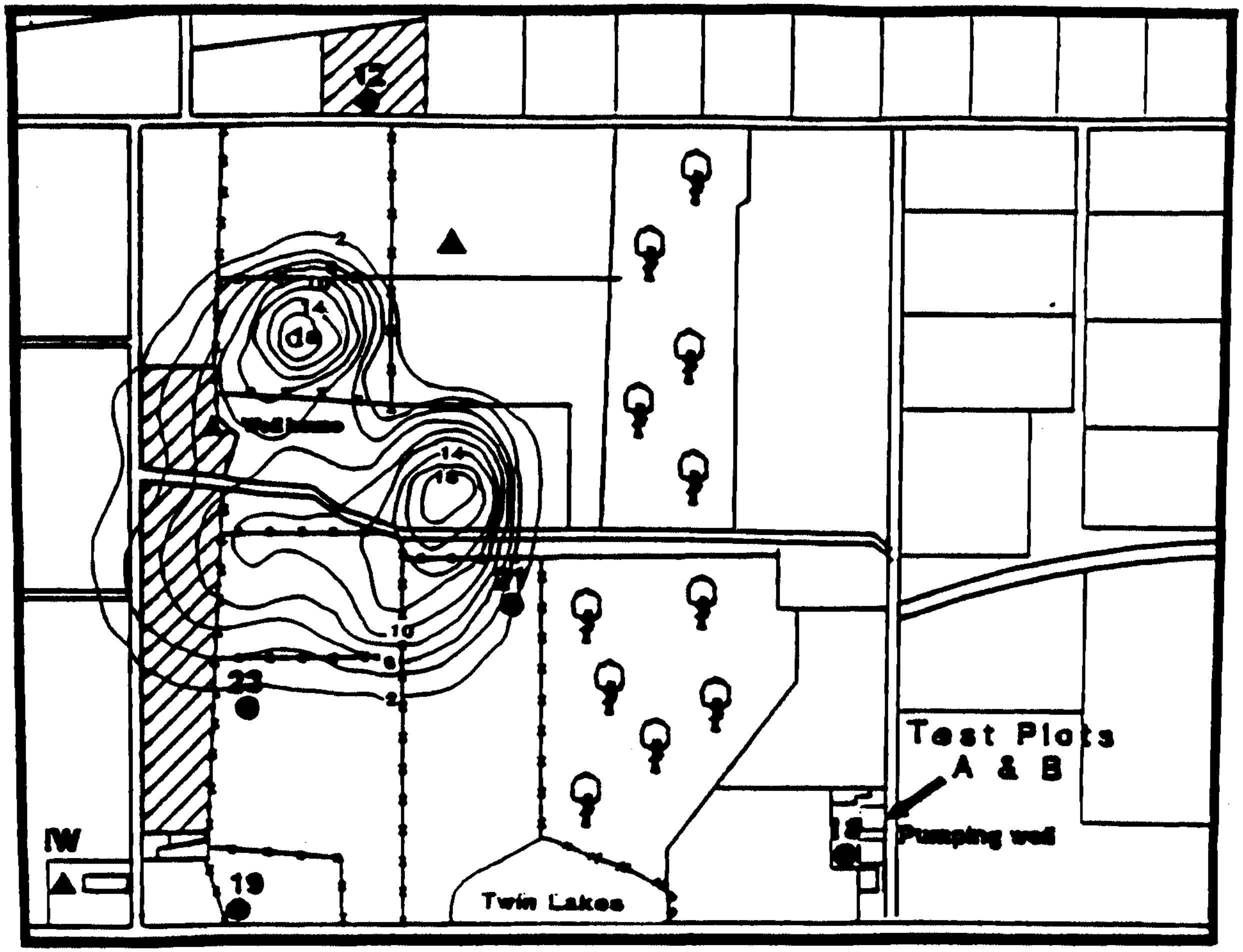
Figure 27. Source B, Nitrate-Nitrogen Plume Simulation, 1992 to 1993

following three conditions: (1)injection without concentration, (2)influence of natural recharge, and (3)irrigation.

Source A Movement

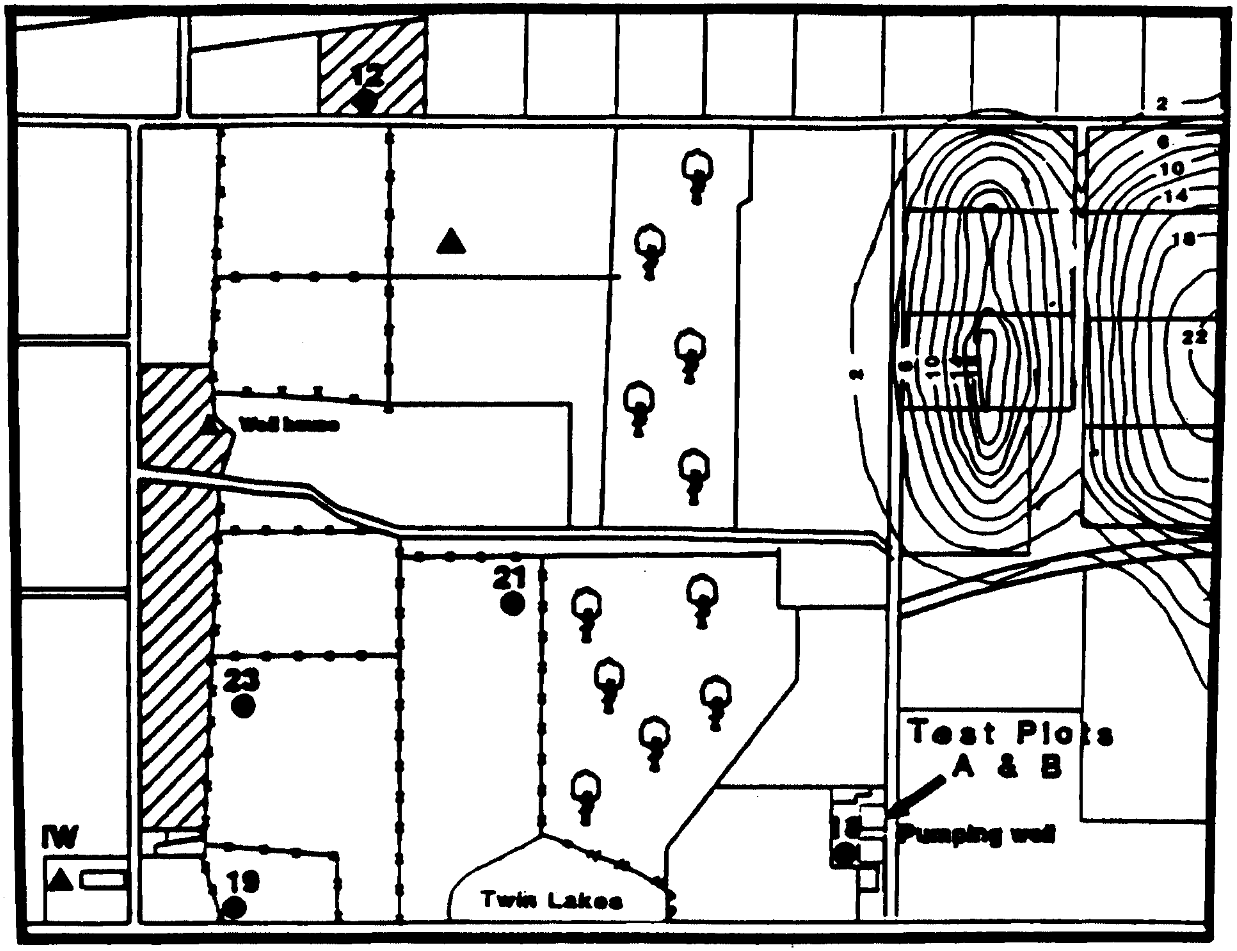
Figures 26, 28, 30, and 32 depict the NO^3-N plume movement for Source A. The dominant direction of plume movement is to the southwest along the bedrock channel indicated by earlier maps of the aquifer boundaries of the station. The plume moves only a minimal amount to the north and east since these directions were upgradient from the application area.

By the second year of simulation (1993 - 1994), the entire nitrate-nitrogen plume has degraded and diluted to a range of concentration between 2 to 18 ppm (Figure 28). These concentrations straddle the NO^3-N level recommended by USEPA safe drinking water standards (10 ppm as N). All of the concentration levels were below 1 ppm after the third year of simulation (Figure 30). In the fourth year, all the nitrate-nitrogen levels were below 0.1 ppm (Figure 32). After the fifth year of simulation, the nitrate-nitrogen plume levels completely degraded and diluted to below 0 ppm. After five years, nitrate-nitrogen did not exist in concentrations large enough to contour.



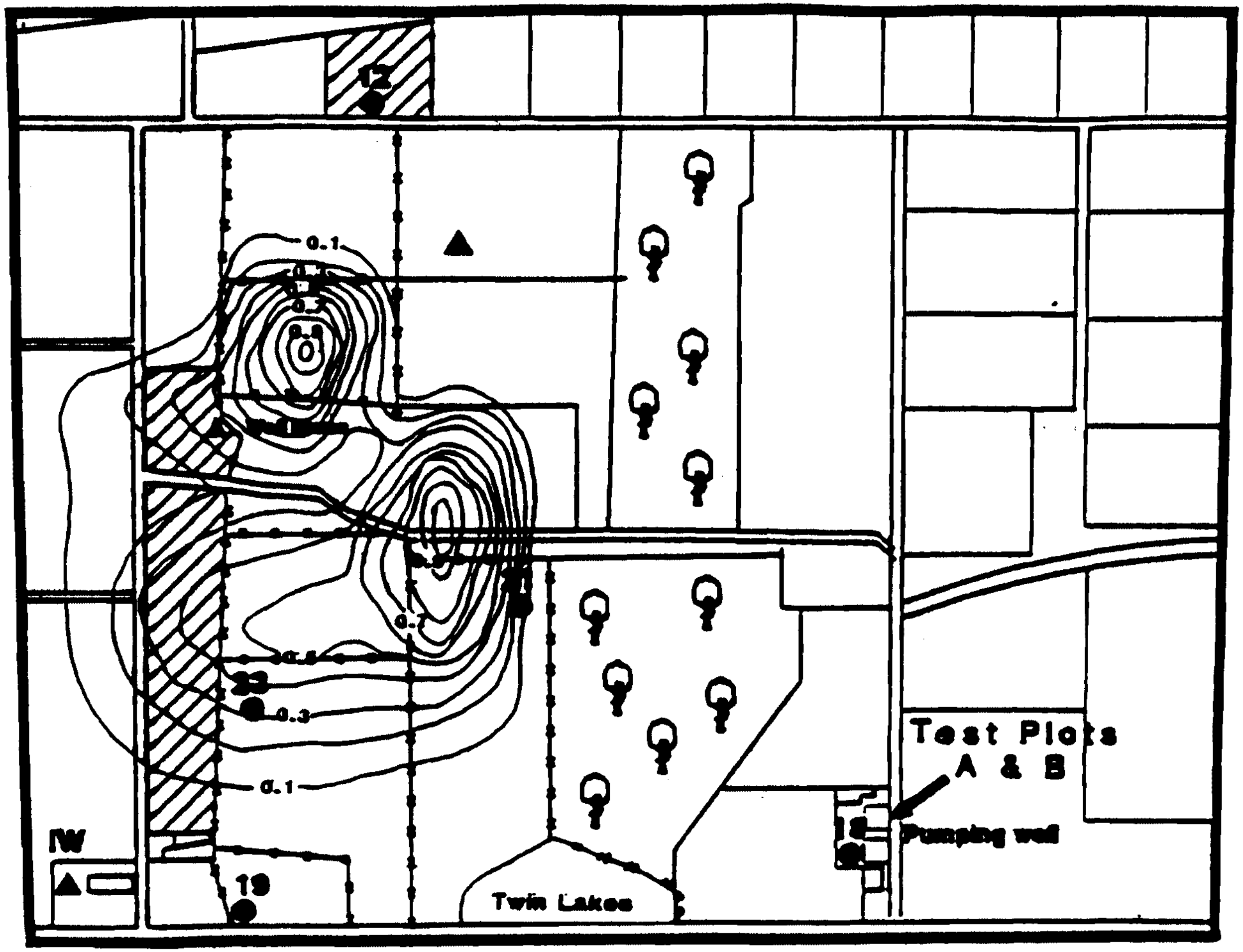
Source A 1993 to 1994 *Contour Interval 2 ft*

Figure 28. Source A, Nitrate-Nitrogen Plume Simulation, 1993 to 1994



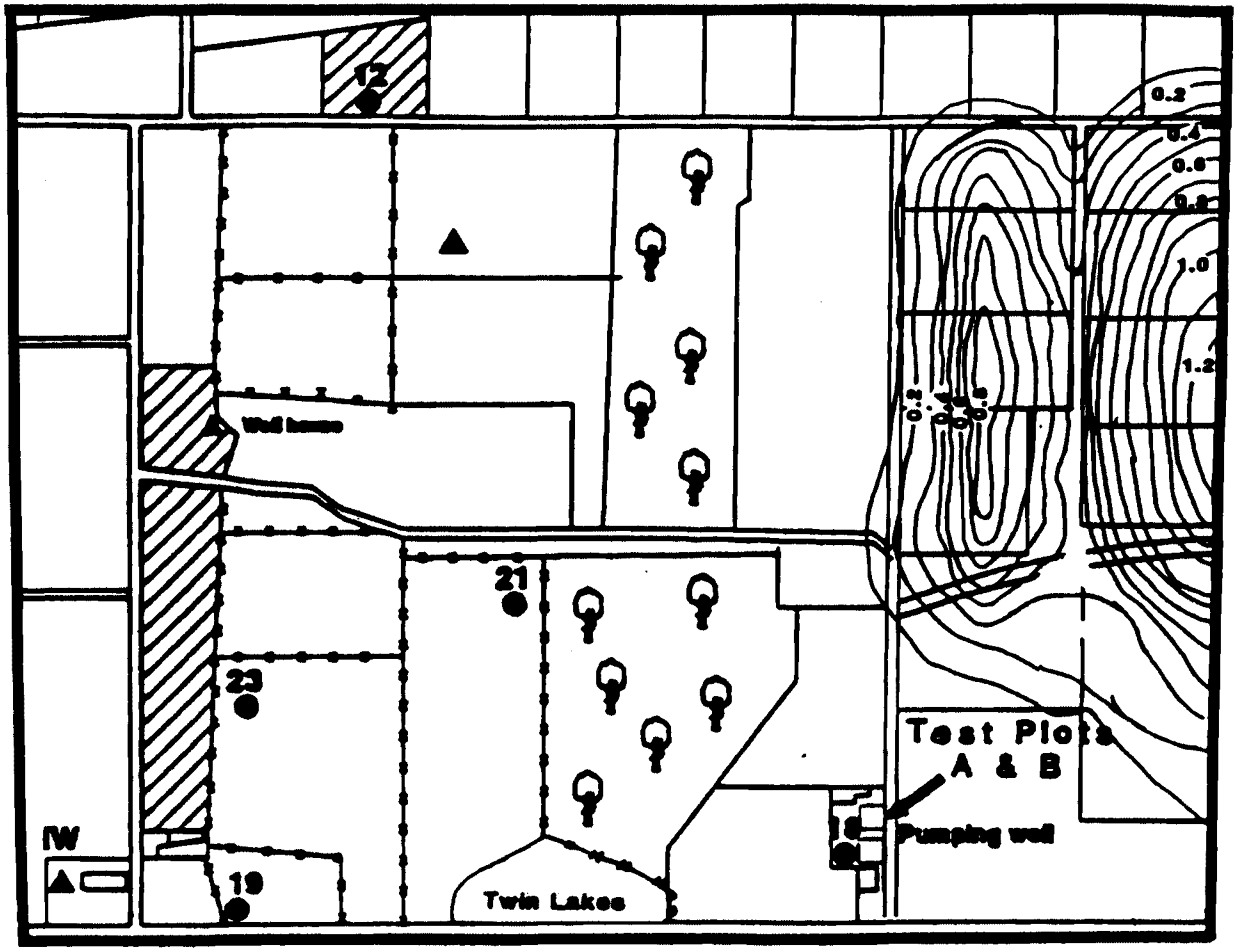
Source B 1993 to 1994 ***Contour Interval 2 ft***

Figure 29. Source B, Nitrate-Nitrogen Plume Simulation, 1993 to 1994



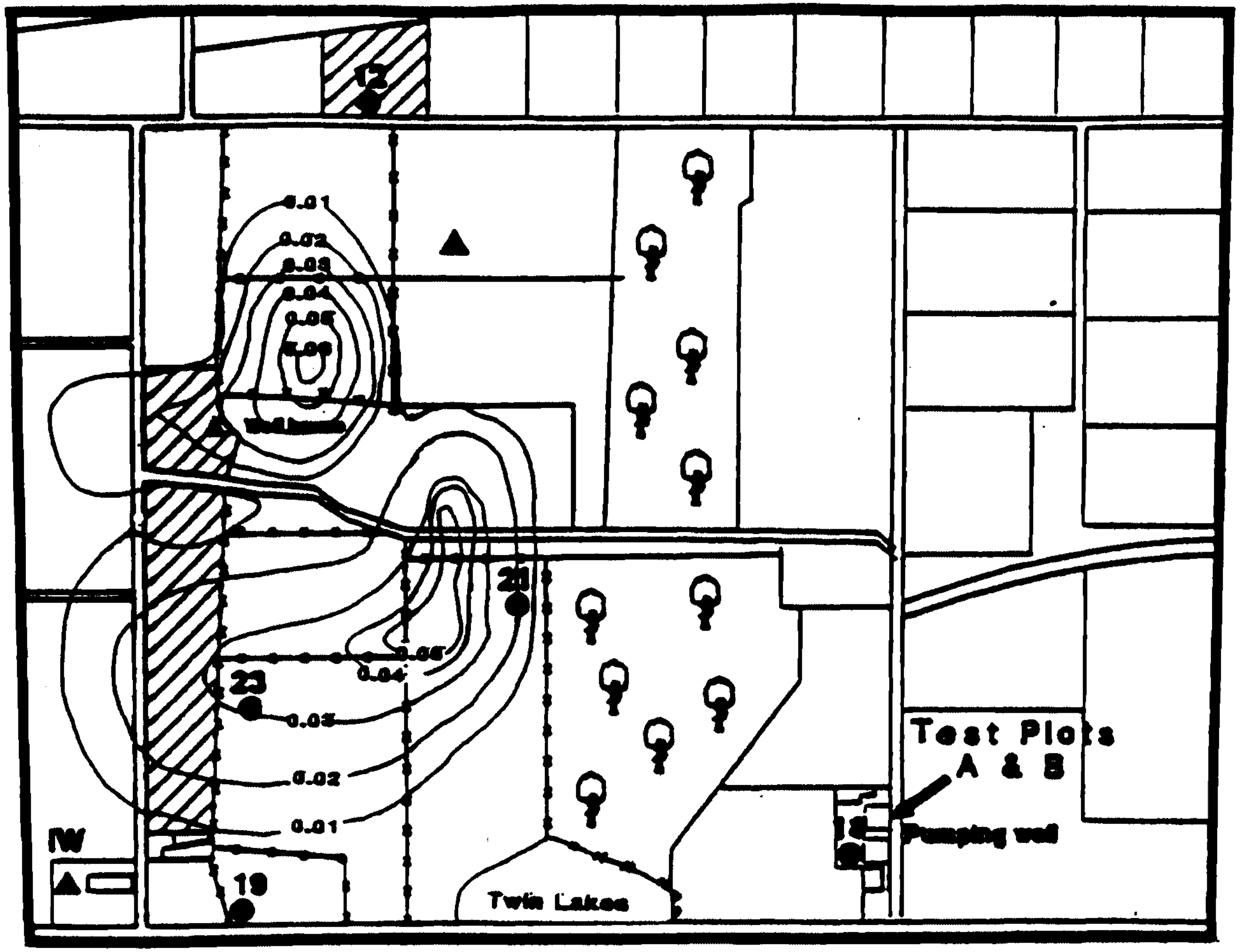
Source A 1994 to 1995 *Contour Interval 0.1 ft*

Figure 30. Source A, Nitrate-Nitrogen Plume Simulation, 1994 to 1995



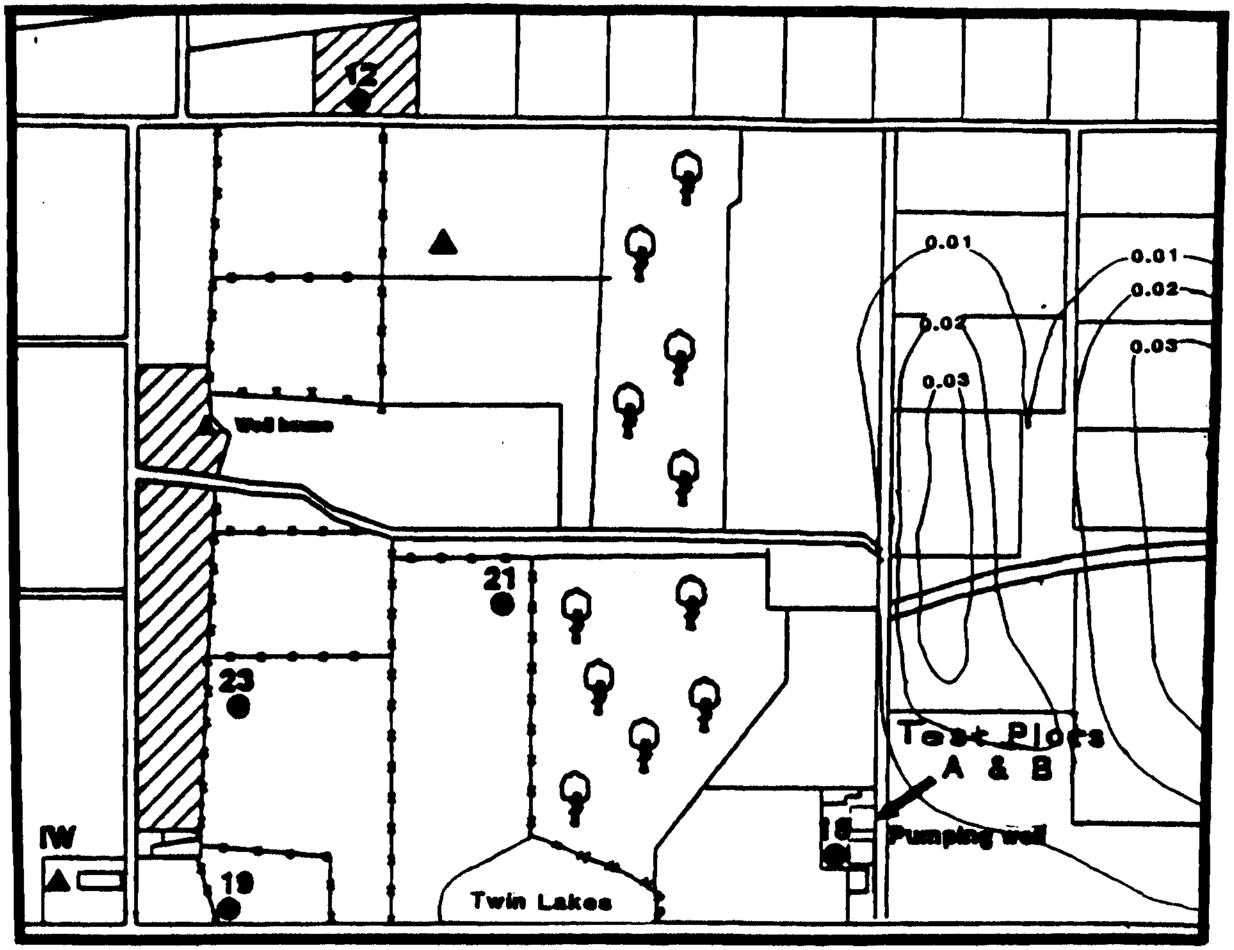
Source B 1994 to 1995 *Contour Interval 0.1 ft*

Figure 31. Source B, Nitrate-Nitrogen Plume Simulation, 1994 to 1995



Source A 1995 to 1996 *Contour Interval 0.01 ft*

Figure 32. Source A, Nitrate-Nitrogen Plume Simulation, 1995 to 1996



Source B 1995 to 1996 ***Contour Interval 0.01 ft***

Figure 33. Source B, Nitrate-Nitrogen Plume Simulation, 1995 to 1996

Source B Movement

Figures 27, 29, 31 and 33 depict the NO^3-N plume movement for Source B. The dominant direction of plume movement is to the southeast along the bedrock channel indicated by earlier maps of the aquifer boundaries of the station. The plume moves only a minimal amount to the north and west since these directions were upgradient from the sources.

By the second year of simulation(1995 - 1996), the entire nitrate-nitrogen plume has degraded and diluted to a range of concentrations from 2 to 18 ppm (Figure 29). In the third year of simulation, all of the concentration levels were below 1.0 ppm (Figure 31). In the fourth year, all the nitrate-nitrogen plume levels completely degraded and diluted to below 0.00 ppm (Figure 33). After five years, nitrate-nitrogen did not exist in concentrations large enough to contour.

Simulation Results

Computer simulation depicted that one seasonal application of 100 lbs/Acre of fertilizer under the influence of normal recharge and irrigation patterns would degrade to levels well below the EPA safe drinking water level within three years and to non-detectable levels within five years. Basically, the nitrate concentration decreased by one magnitude of order each year of the solute transport runs. Simulation also showed that the nitrate-nitrogen plumes in the groundwater move off the site to the southwest and southeast, therefore not directly impacting the potential wetland area known as Twin Lakes. While the groundwater does trend regionally toward the community located directly south of the Perkins Station, these computer simulation results depict that nitrate-nitrogen from one seasonal application of fertilizer which leaches into the groundwater will not leave the boundaries of the station in appreciable amounts.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

Summary of Study

The objective of this research project was to characterize the movement of agricultural chemicals in the alluvial deposits of the Perkins Terrace Aquifer underlying the Perkins Station through the use of a two-dimensional solute transport model. Through an extensive hydrogeologic investigation, it has been determined that the pesticides applied to the crops on the station are not being leached to the groundwater in significant amounts. Pesticides with short half lives (non to moderately persistent) and intermediate to large partition coefficients are the most ideal chemicals for use on a site with permeable soils and a shallow aquifer such as the Perkins alluvial terrace aquifer.

The majority of the pesticides used on the Perkins station are distributed in low concentrations and are characterized as being non to moderately persistent with low to moderate sorption capability and therefore with low potential impact to the groundwater or surface water. Propazine is characterized by high persistence (with a half life greater than 100 days) and low sorption and therefore represents a high potential impact to the groundwater and should be monitored for during its use on the site. Lindane which is characterized by a high half-life has been detected in both the groundwater and pond sediments, but use of this chemical has been discontinued.

The pesticides atrazine and trifluralin are only moderately persistent and the majority of the chemical will most likely either be carried off in surface runoff or decay before reaching the groundwater. Only minor amounts of atrazine (0.011 ppm) have been detected in the groundwater and trifluralin has not been detected in the groundwater. The integrated pest management strategies being employed on the station appear to be working to the benefit of both the farmer and the environment.

Rises in nitrate levels have been found to closely correspond with the occurrence of precipitation events and fluctuations in the water table. Both short term and long term trends indicate that NO3-N from fertilizer applications is being leached through the unsaturated zone to the groundwater. The levels of nitrates found in drinking water has become of great concern to the public. The EPA has established a safe nitrate (NO3-N) limit for domestic water at 10 ppm. Nitrate levels in the groundwater sampled from monitoring wells on the station range between 1 and 150 ppm.

The hydrogeologic investigation determined that the northern terrace deposits have a very low capability of transporting solutes due to the fine grained nature of the aquifer materials. On the other hand, the southern alluvial deposits conduct appreciable amount of groundwater. Unfortunately, the southern terrace deposits help support irrigation and therefore accelerates recharge rates. Therefore the southern alluvial deposits could serve to transport contaminants to drinking water sources. Therefore, this project focused on the simulation of the movement of nitrates present in the groundwater of the southern terrace alluvial deposits with the solute transport model KONIKOW.

The solute transport modeling of nitrate-nitrogen was accomplished in four specific phases. In Phase I, a conceptual model of the problem was designed to define the aquifer domain and the transport phenomena taking place in it. In Phase II, a numerical model and code were employed for actual simulation of the real-world system. A mathematical model was designed using data collected in the hydrogeologic investigation and Phase I. In Phase III, calibration and verification of the model was completed on a point to point basis for head only and solute transport scenarios using historical water level and water quality data. A sensitivity analysis was used to assess the effect of sensitive coefficients and parameters on the model results. In Phase IV, the solute transport of NO3-N was completed for the southern terrace deposits of the Perkins

Station in order to determine the concentration of nitrates in the groundwater entering the ponded area and leaving the station boundaries.

Phase I - Development of Conceptual Model

The aquifer boundaries were defined using monitoring wells, piezometers and geophysical surveys. Bedrock and water table maps were constructed to depict the groundwater flow and potential pathways for migration. The water table of the northern half of the station has a moderately steep but steady gradient directly south. Groundwater flow is more complex in the southern half of the station. Essentially, groundwater flow has two dominant directions of flow at the station, to the southwest and the southeast due to buried bedrock channels. Groundwater discharges into the pond from the northeast and flows from the pond to the southwest. These main directions of groundwater flow depict the possible routes of contaminant migration.

Aquifer characteristics were defined using aquifer tests. Pumping tests and slug tests have been used to determine that the northern terrace deposits conduct groundwater with a maximum hydraulic conductivity of 10 gpd/ft while the coarser deposits in the southern half of the site are characterized by a hydraulic conductivity of 350 - 450 gpd/ft. Dispersion along with convection are the main physical processes responsible for solute transport according to tracer tests. No hard evidence of differential flowpaths in the shallow alluvial sediments exists. Chemical tracers travel at a rate of 10 feet per day during active tracer tests. Taking into account the natural gradient of the southern deposits at 0.01 ft/day, actual tracer rate of movement is decreased to 1 foot per day.

Phase II - Design of Mathematical Model

A modified Nuclear Regulatory Commission version of the USGS solute transport model KONIKOW with an interactive preprocessor as well as a mathematical program written in Fortran language was used for this project. The simulation package created output files of potentiometric head and chemical concentration distribution from each pumping period for direct importation to Golden Graphics contouring package SURFER. The coefficients and parameters used for the modeling were determined by field analysis techniques such as geophysics and aquifer tests or estimated from previous computer modeling exercises.

The KONIKOW model was temporally arranged into pumping periods of one year, 12 times steps of one month each for calibration and verification. The model was spatially arranged into a 17 by 17 grid of nodes, each with a 264 square foot area, encompassing the southern terrace deposits.

The following assumptions were used during the design and use of the model.

- The porous medium is viewed as a continuum at a macroscopic level. Complex geometry of void-solid interface is replaced by solid matrix coefficients such as porosity, permeability, and dispersivity.
- Since the ratio of aquifer thickness to horizontal length is small, flow in the aquifer is practically horizontal. Transforming a three dimensional problem to a two dimensional brings about the need for aquifer transmissivity and storativity.
- The aquifer is homogeneous and isotropic.
- Saturated thickness is constant.

Phase III - Calibration and Verification of Model

The KONIKOW model was calibrated and verified in a point to point manner an annual basis for potentiometric head configuration as well as for chemical concentration (NO3-N). Historical monitoring well and water quality data were used to compare observed values to computer calculated potentiometric head and nitrate concentrations.

The model was calibrated for head only by adjusting the variables for recharge and hydraulic conductivity. Once calibrated for the year 1989 to 1990, the potentiometric surface of the model was verified for 3 consecutive years

(1990 through 1993). All observed and calculated measurements matched within one half of one percent error.

The model was calibrated and verified for the year with the most complete record of fertilizer application and water quality data for a number of widely spaced observation wells located in the southern terrace deposits, January 1992 to January 1993. Observed and calculated nitrate concentrations compared within a 31 percent error.

As a result of the sensitivity analysis, injection rate, decay rate and background concentration were found to be the most sensitive variables and parameters.

Phase IV - Prediction of Solute Transport

The KONIKOW model was used to simulate the leaching of nitrate plumes from two separate sources (A and B) after one application to the subsurface and to track their movement in the groundwater. Two of the most often used areas for fertilizer application (Source A and Source B) were used to target injection. The calibrated and verified coefficients and parameters from Phase III were used and each year was assumed to be wet years with 40 inches of precipitation and 6 inches of recharge.

One six month season of injecting concentrations of 100 lbs/acre of fertilizer followed by one season of injection without concentration formed the nitrate plume (the year of 1992 - 1993). The model was then run for three consecutive years of injection without concentration to represent the spread of the nitrate plumes.

The Golden Graphics package SURFER was used to map the contours of the nitrate plume on a yearly basis. The potential impact on the community drinking water supply as well as the ponded area were then assessed.

Conclusions

Two definite and separate terrace alluvial deposits exist at the site. The northern deposits are characterized by a low hydraulic conductivity and the southern deposits are characterized by a high hydraulic conductivity.

The integrated pest management applied on the station appears to be working to benefit the farmers as well as the environment. Pesticides are not being detected in the groundwater in appreciable amounts. Significant amounts of nitrates have been detected in the groundwater at the site and nitrate levels fluctuate due to fertilizer application.

Due to the ability of the southern terrace deposits to conduct large amounts of solute and the fact that pesticides do not appear to be leaching into the groundwater in appreciable amounts, the computer modeling portion of this project focused on the simulation of nitrates in the southern terrace deposits of the site. Computer simulation assisted in determining that one yearly application of 100 lbs/Acre of fertilizer under the influence of normal recharge and irrigation patterns would degrade to levels well below the EPA safe drinking water level within one year and to 0 ppm within 5 years. Basically, the nitrate concentration decreased by one magnitude of order each year of the solute transport runs. Simulation showed that the nitrate plumes move off the site to the southwest and southeast, therefore not directly impacting the potential wetland area known as Twin Lakes.

While the groundwater does trend regionally toward the community located directly south of the Perkins Station, simulation results have assisted in determining that nitrates from one yearly application of fertilizer which leaches into the groundwater will not leave the station in appreciable amounts. It is important to note that this simulation was limited to only one yearly application of fertilizer. Further investigation and simulation are necessary in order to determine the effect of multiple years of fertilization on the nitrate levels in the groundwater.

Recommendations

Unsaturated Hydraulic Conductivity

Application of mathematical theories and models of soil physics to the description of prediction of actual processes in the field requires knowledge of hydraulic characteristics of soils. Functional relations of hydraulic conductivity and matrix suction to soil moisture therefore need to be determined for soils of concern. The internal drainage method is a recommended in situ field method of determining soil characteristics because alteration of soil hydraulics due to disturbance of structure is eliminated. This method should be used on the Perkins Station in the future in order to better define important variables use in computer modeling of the unsaturated zone.

Hillel et. al., 1972, gives a detailed description of a simplified procedure for determining the intrinsic hydraulic properties of a layered soil profile in situ. This method requires frequent and simultaneous measurements of soil wetness and matrix suction within a soil profile under conditions of drainage alone. With these measurements, instantaneous values of the potential gradients and fluxes within the soil. Therefore, unsaturated hydraulic conductivity can be determined.

Portable double ring infiltration rings could be used to establish temporary internal drainage basins at the Perkins Station. Because the set up is portable and temporary, the test could be conducted at several different sites within the soil type being examined in order to verify results. The internal drainage basins should be equipped with tensiometers and a soil moisture tube. A hand-held strain gauge pressure transducer (tensimeter) could be used to measure soil moisture suction while soil wetness could be determined with a neutron moisture probe. Field test conducted with both nuclear and non-nuclear source probes have shown that these two tools provide similar results (Heathman, G., persona communication). The advantage of the Resonant Frequency Capacitance Probe (non-nuclear source) is obvious. The Perkins Station is a good site for further evaluation of the RFC Probe alongside the nuclear source probe.

Studies conducted by the USDA have developed a method for determining the unsaturated hydraulic conductivity from tensiometeric data alone (Ahuja, et. al., 1988). This should be considered a complimentary method to be incorporated into future field work.

Unsaturated Zone Modeling

Most of the modeling conducted in the unsaturated zone of the Perkins Station has been accomplished by the use of computer models such as CMIS and CMLS developed in the OSU Agronomy department by Nofziger et. al.,1985, 1988. As previously described in the unsaturated computer modeling section, the CMIS and CMLS models have an already established database of soil parameters and precipitation records for the central Oklahoma region. Unfortunately, the main mechanism for movement of solutes through soil profiles is considered to be piston flow only, therefore ignoring macropore flow. A more reasonable type of model for determining the movement and degradation of pesticide residues in the unsaturated zone is the USDA Root Zone Water Quality Model (RZWQM). Studies with RZWQM should be conducted in the future at the Perkins Station in order to track pesticide movement within and below the root zone and to compare the predicted impact on groundwater to actual field results.

Linked Model System

EPA regulations require that the potential risk from the use of toxic chemicals to human health be evaluated. Specifically, human exposure to pesticides through leaching to groundwater and ingestion of contaminated water must be predicted.

The unsaturated and saturated zones can not be addressed separately in the prediction of the fate of agricultural chemicals in the subsurface. Simulating potential exposure to pesticides includes prediction of the fate of the chemical after application on the surface, as it is transported by water through the vadose zone, into the saturated zone and to a drinking water well.

A complete simulation package consisting of a set of linked models with the capability to handle a variety of hydrogeological, soils, climate and pesticide scenarios is needed. Linking the USDA's RZWQM with the USGS's KONIKOW model is recommended for future research. A linked modeling system for evaluating the impacts of agricultural chemical use has been developed by Dean and Carsel, 1990.

REFERENCES

Ahuja, L.R., Ross, J.D., Bruce, R.R., and D.K. Cassel. 1988. Determining Unsaturated Hydraulic Conductivity from Tensiometric Data Alone. Soil Science Society of America Journal, v. 52, no. 1.

Anderson, M. 1981. Using Models to Simulate the Movement of Contaminants through Groundwater Flow Systems. CRC Critical Reviews in Environmental Control, Vol. 9, Issue 2.

Ayers, J.F. 1990. Application and Comparison of Shallow Seismic Methods in the Study of an Alluvial Aquifer. Groundwater, v. 27. pp. 550-63, July/August.

Bear, J., Milovan, S.B., and R.R. Ross. 1992. Fundementals of Groundwater Modeling. EPA Groundwater Issue, EPA/540/S-92/005. Robert S. Kerr Environmental Research Lab, Ada, OK.

Benson, R. et. al. with TECHNOS, Inc. 1988. Geophysical Techniques for Sensing Buried Wastes and Waste Migration. NGWA, Dublin, OH.

Bingam, R.H. and D.L. Bergman. 1980. Reconnaissance of the Water Resources of the Enid Quadrangle, North-Central Oklahoma. Oklahoma Geological Society, Hydrologic Atlas #7.

Bowman, R.K. and R.L. Westerman. 1992. Effect of Nitrogen Rate and Timing of Application on Yield of Winter Wheat and Residual Nitrate Distribution in Soil. Efficient Use of Fertilizers, Agronomy Department, Oklahoma State University, Stillwater, OK.

Carsel, R.F., Mulkey, L.A., Lorber, M.N. and L.B. Baskin. 1985. The Pesticide Root Zone Model (PRZM): A Procedure for Evaluating Pesticide Leaching Threats to groundwater. Ecol. Modelling, V. 30, p. 49-69.

Cohrssen, J.J. and V.T. Covello. 1989. Risk Analysis: A Guide to Principles and Methods for Analyzing Health and Environmental Risks. U.S. Council on Environmental Quality Executive Office of the President.

Davidson, J.M. et. al . 1969. Field Measurements and Use of Soil Water Properties. Water Resources Research, v. 5., no. 6.

Davis, S.N. et. al. 1985. Groundwater Tracers. National Water Well Association. Worthington, Ohio.

Dean, J.D., and R.F. Carsel. 1990. A Linked Modeling System for Evaluating Impacts of Agricultural Chemical Use. U.S. Environmental Protection Agency, College Station Road, Athens, GA.

Dobrin, M.B. and C.H. Savit. 1988. Introduction to Geophysical Prospecting (4th Ed.). McGraw-Hill Book Co., New York, NY.

Driscoll, F.G. 1989. Groundwater and Wells. Johnson Filtration Systems, Inc., St. Paul, Minn.

Duguid, J.O. 1968. Refraction Determination of Water Table Depth and Alluvium Thickness. Geophysics, v. 33, no. 3, pg. 481--488.

Dwivedi, R. 1989. Fate and Transport of Agricultural Chemicals in a Sandy Aquifer Near Perkins, Oklahoma. Unpublished Ph.D Dissertation, Oklahoma State University, Stillwater, OK.

Fetter, C.W. 1988j. Applied Hydrogeology (2nd Ed.). Merril Publishing Co., Columbus, OH.

Fetter, C.W. 1993. Contaminant Hydrogeology. Macmillan Publishing Company, New York.

Hillel, D. 1980. Fundementals of Soil Physics. Academic Press, Inc., Orlando, Florida.

Hillel, D. 1982. Introduction to Soil Physics. Academic Press, Inc., San Diego, California.

Hillel, D., Krentos, V.D., and Y. Stylianou. 1972. Procedure and test of an internal drainage method for measuring soil hydraulic characteristics in situ. Soil Science 114.

Keisling, T.G. 1974. Precision with which selected physical properties of similar soils can be estimated. Unpublished Ph.D. Dissertation, Oklahoma State University, Stillwater, OK.

Kent, D.C., Dwivedi, R. and Naney, J. 1987. Hydrogeology and groundwater quality of Perkins Terrace Aquifer, in abstracts. 1987 Oklahoma Water Res. Conf. Abstr., p.7.

Kent, D.C., Lemaster, L., and J. Wagner. 1986a. Modified N.R.C. Version of the U.S.G.S. Solute Transport Model, Volume 2: Preprocessor. U.S. Environmental Protection Agency, CR-811142-01-0.

Kent, D.C., Lemaster, L., and J. Wagner. 1986b. Modified N.R.C. Version of the U.S.G.S. Solute Transport Model, Volume 1: Modifications. U.S. Environmental Protection Agency, CR-811142-01-0.

Kent, D.C., Naney, J.W., and B.B. Barnes. 1973. "An approach to Hydrogeologic Investigations of River Alluvium by the Use of Computerized Data". Groundwater, v. 11, no. 4 National Water Well Association, Dublin, OH.

Kent, D.C., Naney, J.W., and R.C. Dwivedi. 1990. Characterization of Input Parameters for Fate and Transport Modeling of Agricultural Chemicals, in abstracts. Geological Society of America, South-Central Section.

Kent, D.C., Naney, J., Smith, S., and R. Dwivedi. 1989. Fate and Transport of Agricultural Chemicals in a Sandy Aquifer, in abstracts. American Association for the advancement of Science (AAAS).

Kent, D.C., Naney, J.W., Westerman, R., Van Alstine, M.J. and R.L. Dwivedi. 1996. Collection, Compilation and Preliminary Interpretation of Data Used to Characterize the Hydrogeology and Solute Transport of Agricultural Chemicals in Alluvial Deposits Near Perkins, Oklahoma. Agronomy Research Station Bulletin, OSU Agronomy Department, Stillwater,OK.

Keys, W.S. 1988. Borehole Geophysics Applied to Ground-Water Investigations. U.S. Geological Survey Open-File Report 87-539. United States Geological Survey, Denver, CO.

Konikow, L.F. and S.D. Bredehoeft. 1978. Computer Model for Two-Dimensional Solute Transport and Dispersion in Groundwater. Technique of Water Resources Investigation of the U.S. Geological Survey, Book 7, Ch. 2.

Meidav, T. 1970. Arrays and Nomograms for Electrical Resistivity Exploration. Institute of Geophysics and Planetary Physics, University of CA, Riverside. Geophysical Prospecting, v. 18, 1970.

Miller, R.D., Steeples, D.W. and M. Brannan. 1989. Mapping a bedrock surface under dry alluvium with shallow seismic reflections. Geophysics, v. 54, pp. 1528-34, December.

Miller, R.D. 1991. Field Comparison of Shallow Seismic Sources near Chino, CA. Geophysics, v. 57, no. 5 (May 1992); pp. 693-709.

Moltz, F.J., Guven, O., and J.G. Melville. 1987. Performance and analysis of aquifer tracer tests with implications for contaminant transport modeling - a project summary. Groundwater, v. 25, pp. 337-41, May/June.

Naney, J.W., Barnes, B.B., and D.C. Kent. 1976. "A User's Manual for Computerization of Hydrogeologic Data for a River Alluvium". Agricultural Research Service, Technical Publication Services, ARS-S-138.

Naney, J.W., Kent, D.C., Smith, S.J. and W.A. Berg. 1990. Characterizing ground-water quality impacted by tillage and cropping practices. Water Well Journal, Vol. 1:97- 111. NWWA, Dublin, OH.

Naney, J.W., Smith, S.J., Berg, W.A., Kent, D.C. and Webb, B.B. 1988a. Agricultural chemicals in shallow aquifers of the southern plains. In Proc, Int'l. Symp. on Modeling Agricultural, Forest and Rangeland Hydrology, ASAE, pp. 206-218.

Naney, J.W., Smith, S.J., Kent, D.C., Berg, W.A. and Webb, B.B. 1988b. Ground-water quality beneath agricultural land in Oklahoma. In Twenty-second Oklahoma Agricultural Chemical Conf., pp. 27-31.

Naney, J.W., Smith, S.J., Kent, D.C. and W.A. Berg. 1991. Impacts of agricultural practices on nitrate concentrations of groundwater in the Southern Plains. In Proc. Toward a Sustainable Agriculture for the Great Plains, Jan. 19-20, 1989, Ft. Collins, CO.

Naney, J.W., Smith, S.J., Kent, D.C., Berg, W.A. and Webb, B.B. 1987. Variability of ground-water quality under sloping agricultural watersheds in Oklahoma. In Proc. Symp. on Monitoring, Modeling, and Mediating Water Quality, Amer. Water Res. Assoc. pp. 189-198.

Naymik, T.G. 1987. Mathematical modeling of solute transport in the subsurface. Critical Reviews in Environmental Control, v. 17, no. 3, pp. 229-51.

Nofziger, D.L. and A.G. Hornsby. 1985. Chemical Movement in Layered Soils: IBM PC user's guide. Computer Series, Software in Soil Science. Circular 654, University of Florida.

Nofziger, D.L. and A.G. Hornsby. 1987. Chemical Movement in Layered Soils: IBM PC user's manual. Computer Software Series, CSS-30. Circular 780, University of Florida Institute of Food and Agricultural Sciences.

Palmer, C.D. and R.L. Johnson. 1989. Physical Processes Controlling the Transport of Contaminants in the Aqueous Phase. Ch. 2 of the Transport and Fate of Contaminants in the Subsurface. U.S.E.P.A., Technology Transfer, Seminar Publication, EPA/625/4-89/019.

Park, S.K., Lambert, D.W. and T. Lee. 1990. Investigation by D.C. Resistivity methods of a ground-water barrier beneath the San Bernardino valley, southern California, groundwater, v. 28, pp. 344-49, May/June.

Rao, P.S.C., Hornsby, A.G. and O.N. Nesheim. 1988. Regulation of Pesticide Use. Soil Science Fact Sheet SL-53, Florida Cooperative Extension Service, University of Florida.

Rao, P.S.C., Mansell, R.S., Baldwin and M.F. Laurent. 1983. Pesticide and Their Behavior in Soil and Water. Soil Science Fact Sheet SL-40, Florida Cooperative Extension Service, University of Florida.

Robinson, E.S. and C. Coruh. 1988. Basic Exploration Geophysics. John Wiley and Sons, New York, NY.

Saad, Atef. 1992. The Combined Use of Tracer Tests and Groundwater Models to characterize Solute Transport of Agricultural Chemicals in an Alluvial Aquifer. Unpublished M.S. Thesis, Oklahoma State University, Stillwater, OK.

Sawyer, S.N. and T.L. McCarty. 1967. Chemistry for Sanitary Engineers (2nd Edition), 518 pp. McGraw-Hill Book Company, New York.

U.S. Dept. Interior. 1971. FWPCA methods for chemical analysis of water wastes. FCN 16020-7171. Nat. Environ. Res. Center Anal. Control Lab., Cincinnatti, OH.

U.S. Environmental Protection Agency. 1973. Water Quality Criteria 1973. U.S. Government Printing Office, Washington D.C. Environmental Protection Agency. 1976. Water Quality Criteria 1976. U.S. Government Printing Office, Washington D.C.

Walton, W.C. 1970. Groundwater Resource Evaluation. McGraw-Hill Book Co., New York, NY.

Wachs, Daniel, Arad, Arnon, Ol Shina, Avi. 1979. Locating Groundwater in the Santa Caterina Area Using Geophysical Methods. Groundwater, v. 17, no. 3, pg. 258-263.

Wong, K.F.V., Yeh, G.T. and E.C. Davis. 1987. Predictive Application of an ORNL Geohydrology Model. Groundwater, v. 25. no. 3, pg. 342.

Zukowski, M.D., and M.A. Tumeo. 1991. Modeling solute transport in groundwater at or near freezing. Ground Water. v. 29, pp. 21-25, January/February.

APPENDIXES

APPENDIX A

LAND USE AND APPLICATION MAPS

Pesticide and Fertiliser Key for
Land Use and Application Maps

Symbol	Pesticide Brand Name
A	Attrex
B	Banvel
C	Blazer
D	Dual
E	Furaden
F	Lasso
G	Milogard
H	Princep 90
I	Ramrod
J	Sancap
K	Treflan
L	2-4,D
M	Vernam
N	Nitrate
P	Phosphate
Q	Lime
# - # - #	% Nitrogen, % Phosphate, % Potassium

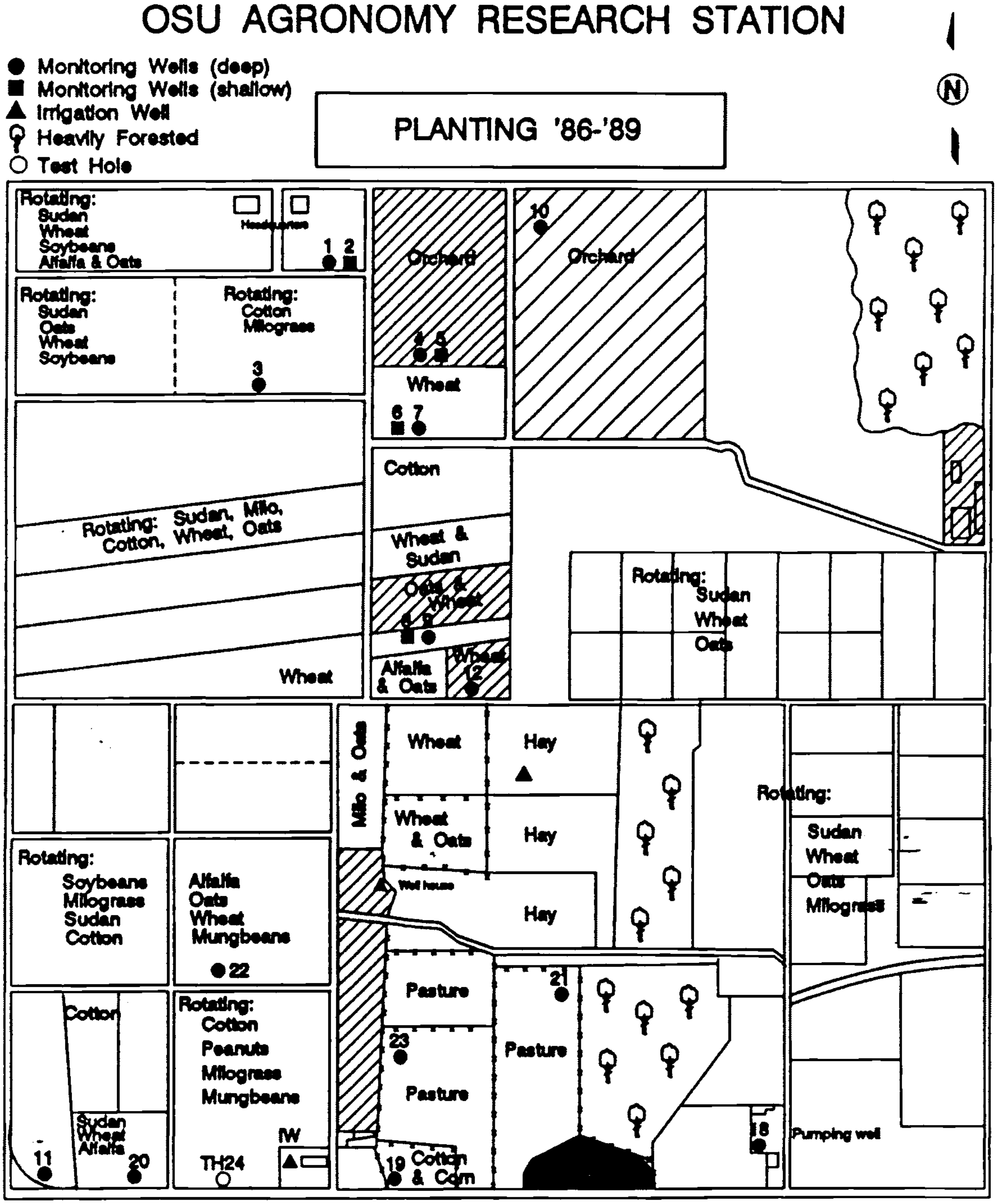
Abbreviations :

Ac = Acre
lb = pound
pt = pint
qt = quart

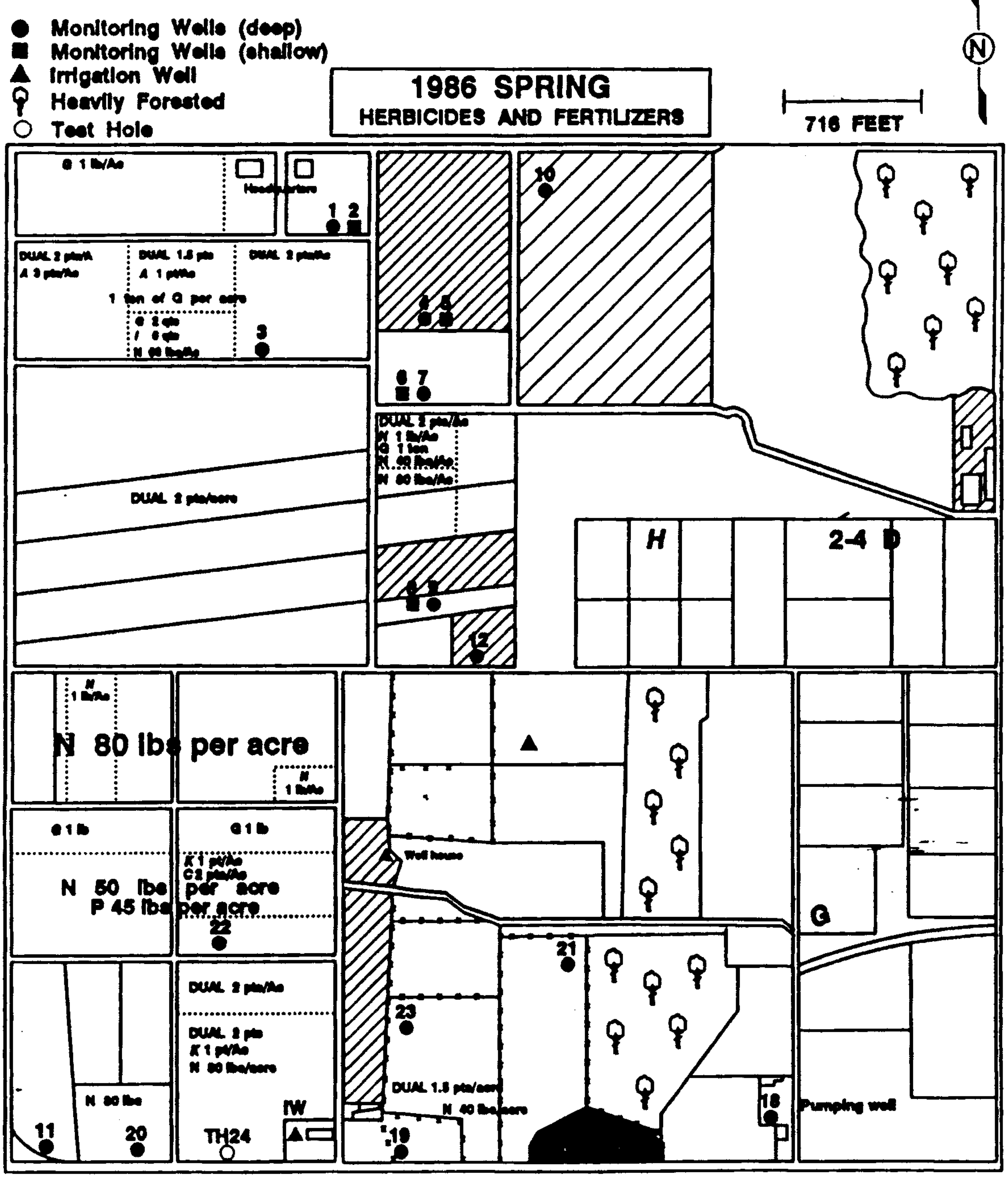
Symbols :

● Monitoring Wells (deep)
■ Monitoring Wells (shallow)
▲ Irrigation Well
Heavily Forested
○ Test Hole

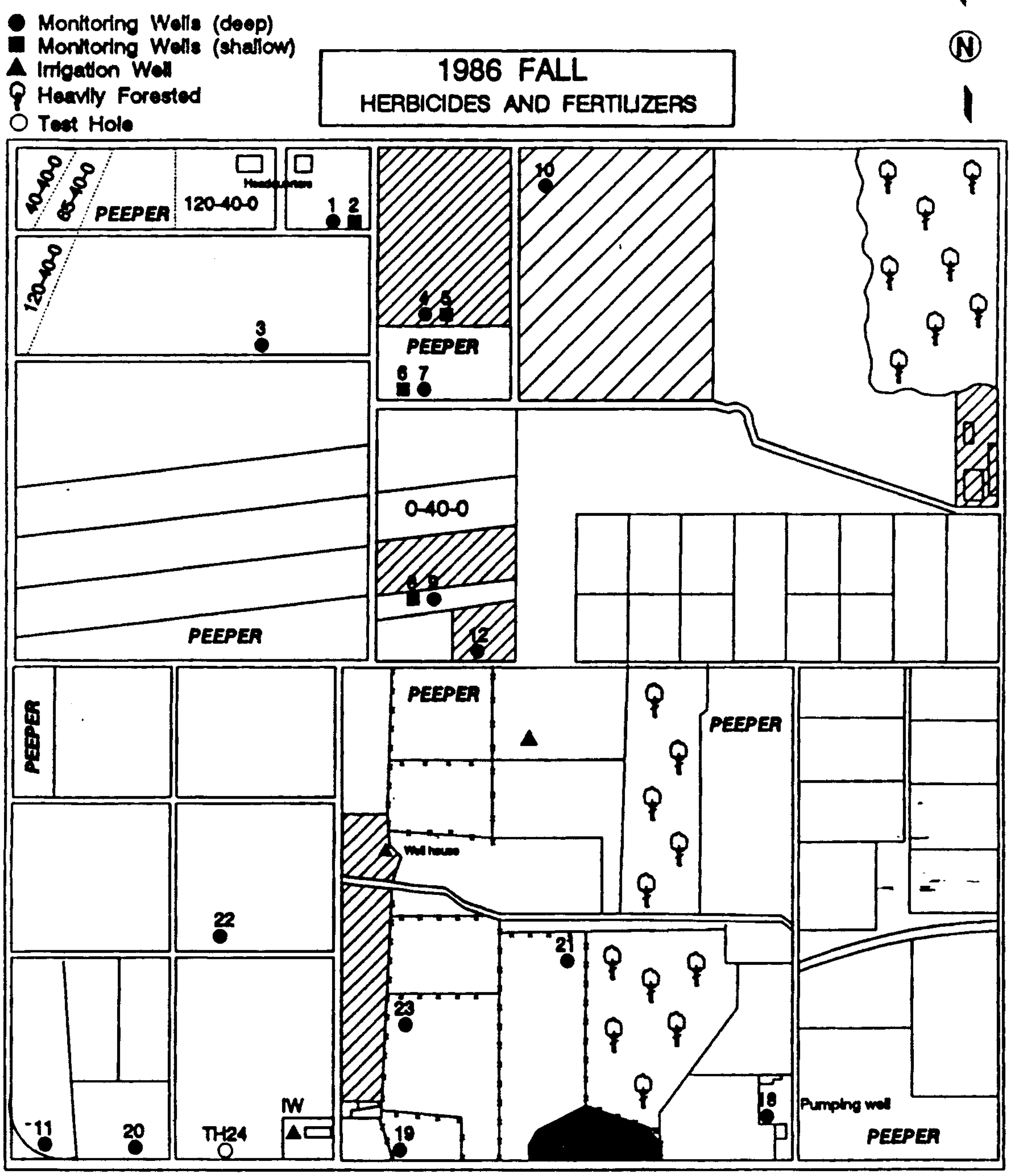
OSU AGRONOMY RESEARCH STATION



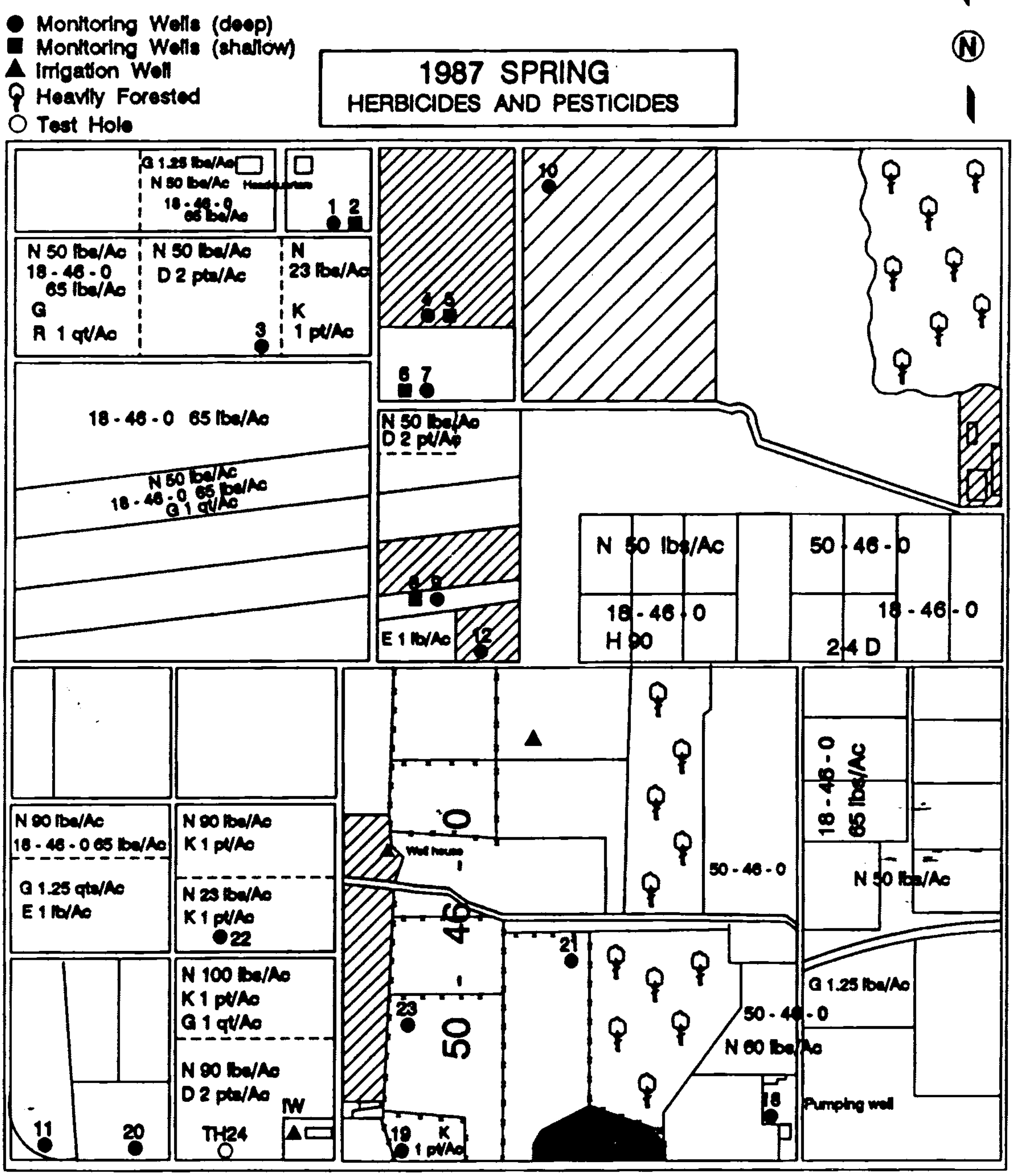
OSU AGRONOMY RESEARCH STATION



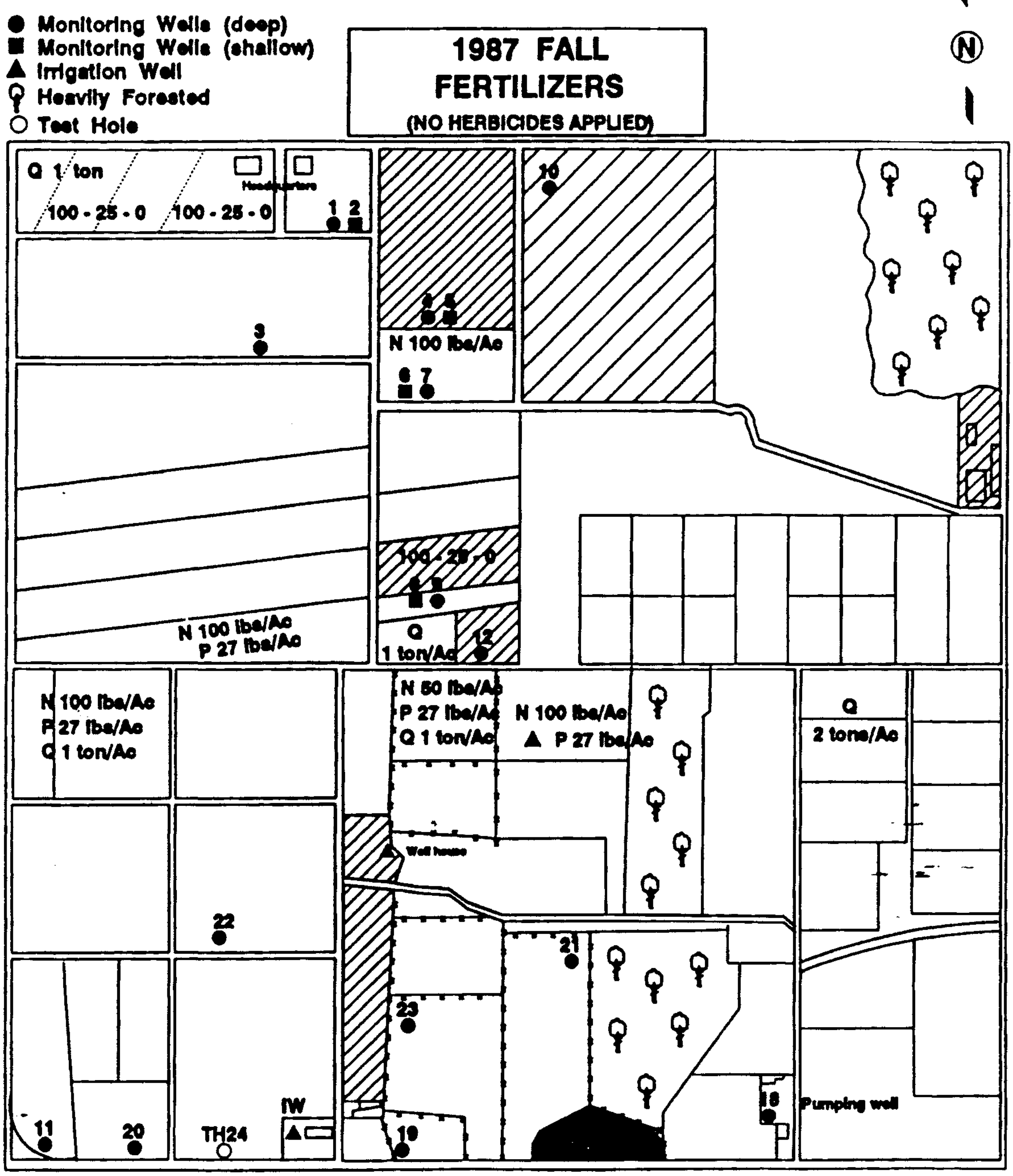
OSU AGRONOMY RESEARCH STATION



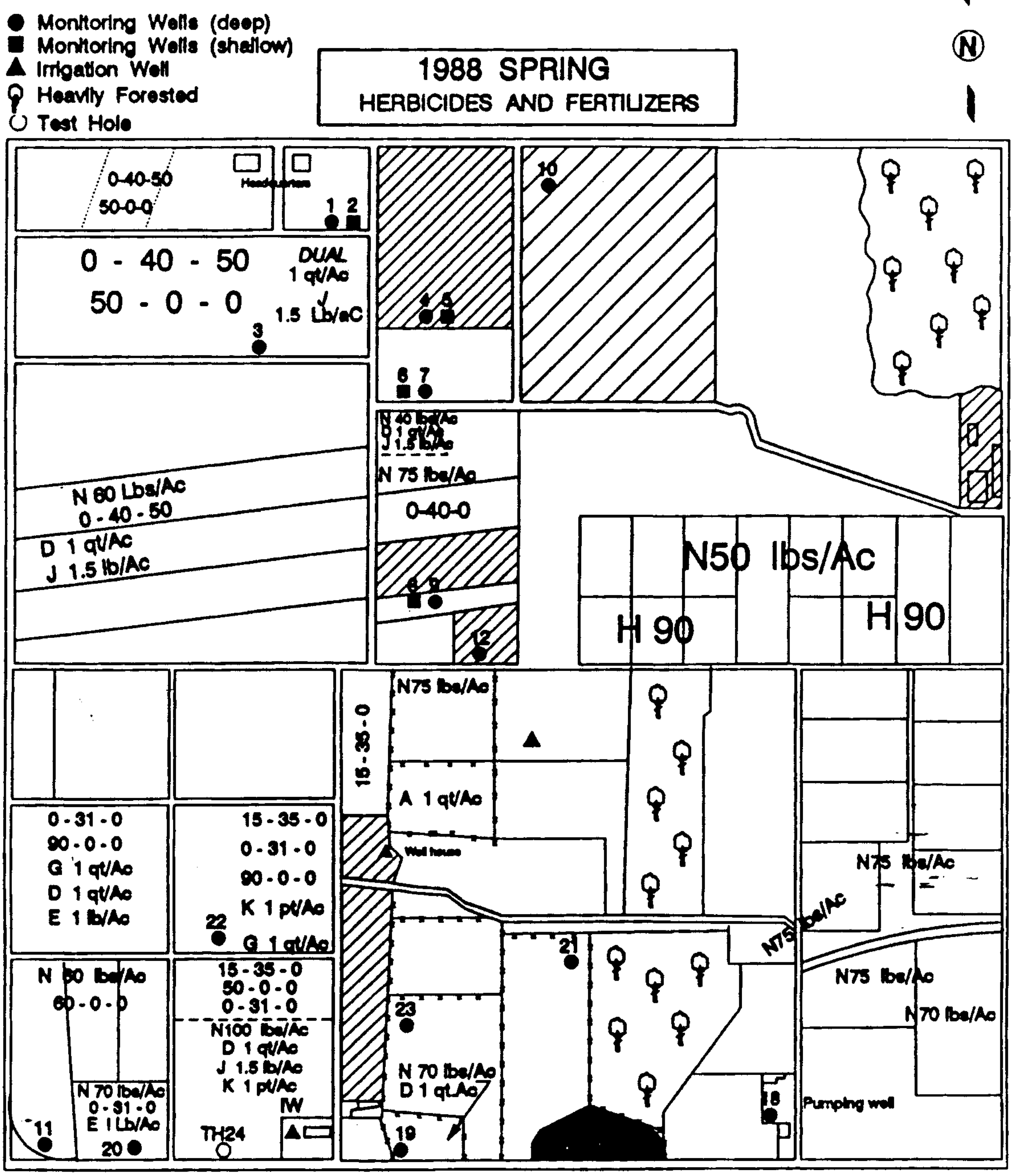
OSU AGRONOMY RESEARCH STATION



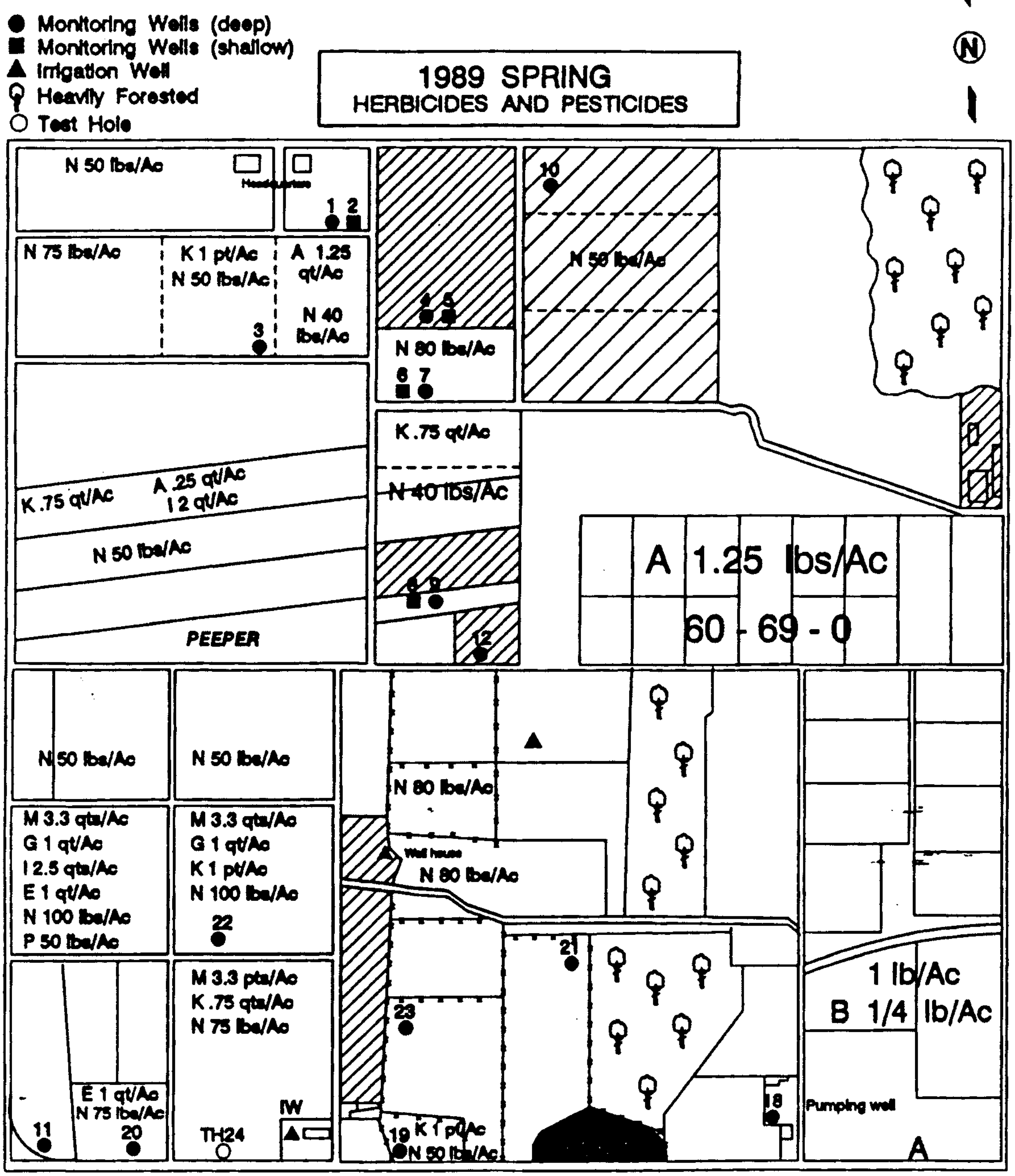
OSU AGRONOMY RESEARCH STATION



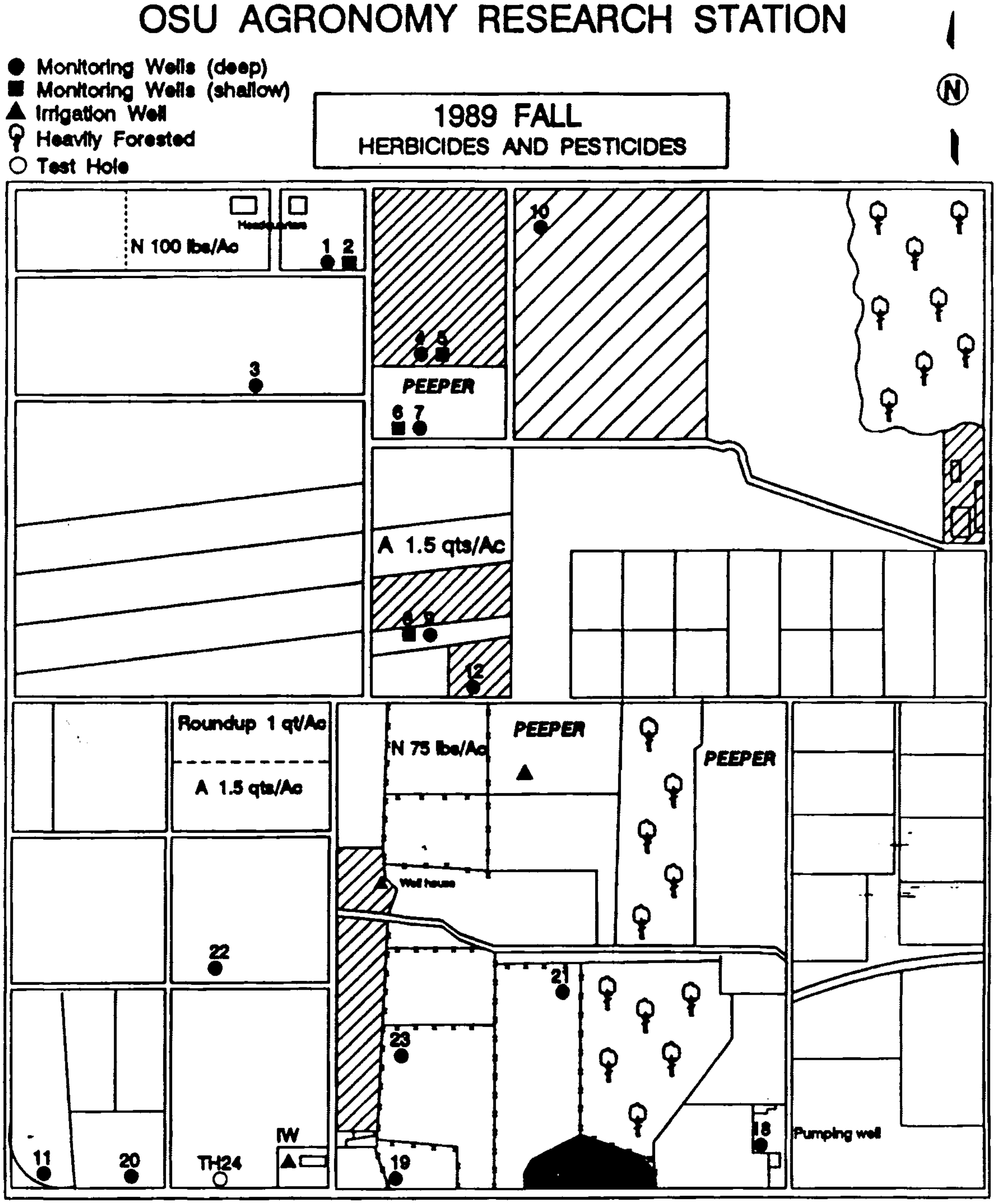
OSU AGRONOMY RESEARCH STATION



OSU AGRONOMY RESEARCH STATION



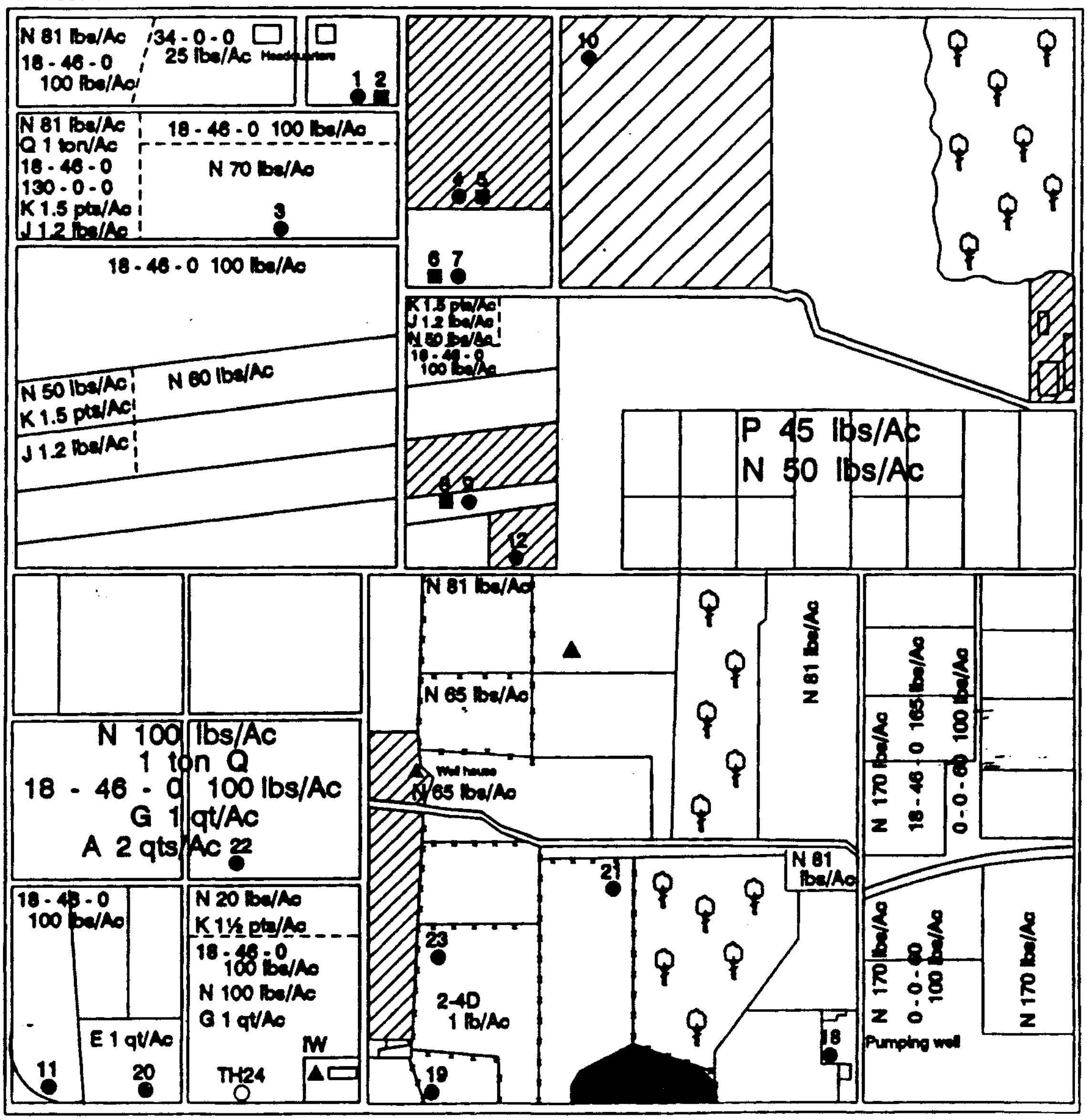
OSU AGRONOMY RESEARCH STATION

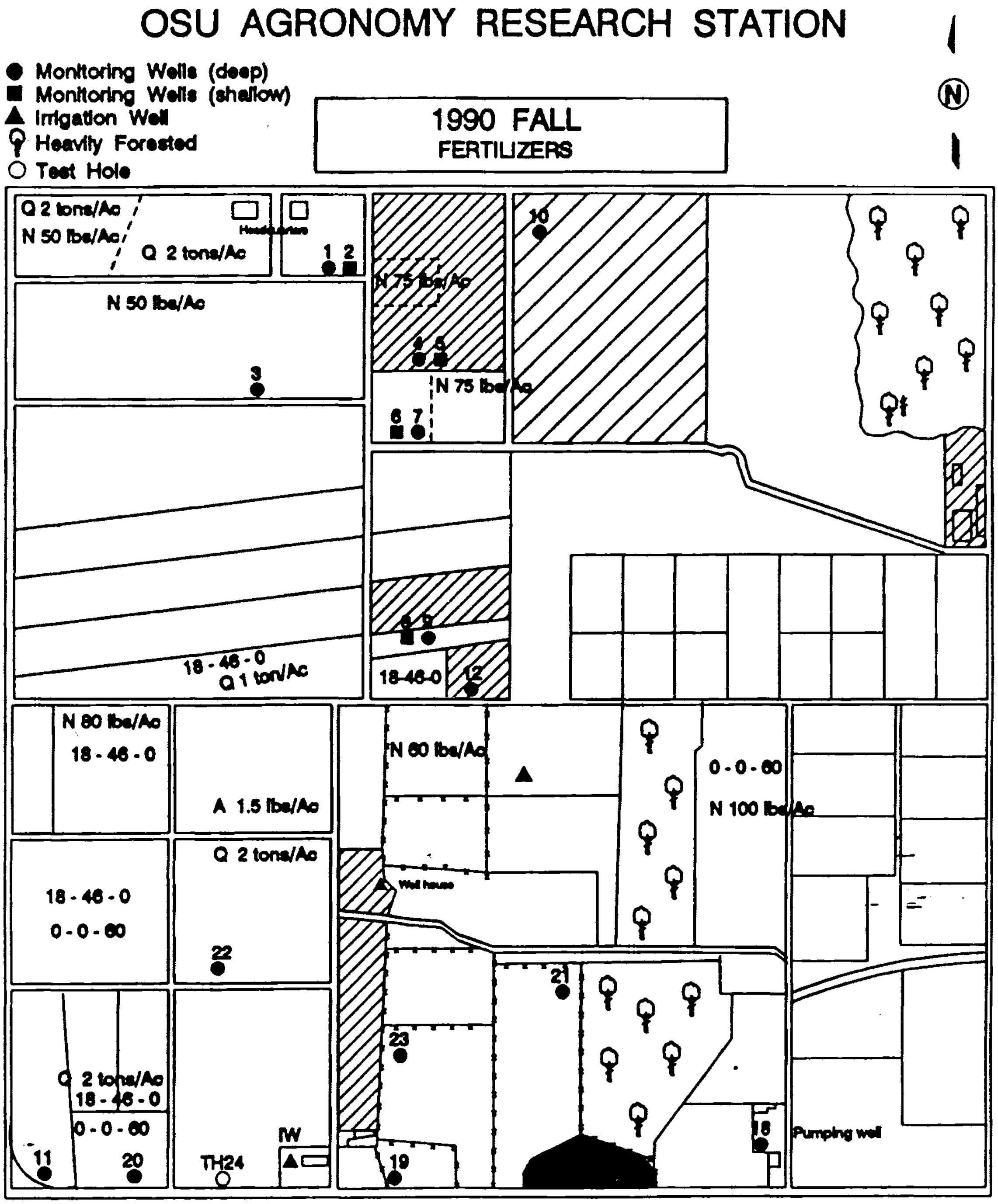


OSU AGRONOMY RESEARCH STATION

● Monitoring Wells (deep)
■ Monitoring Wells (shallow)
▲ Irrigation Well
Heavily Forested
○ Test Hole

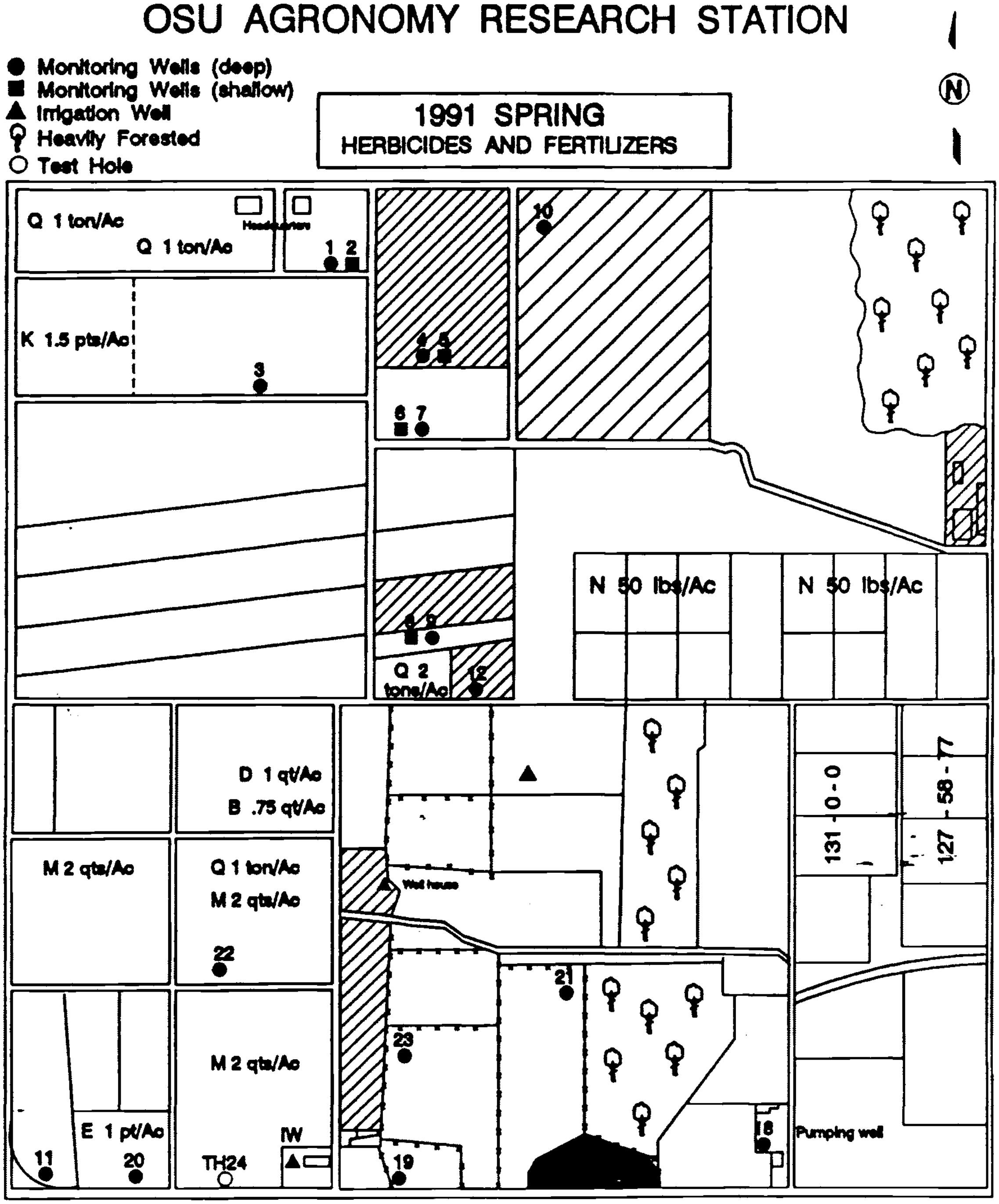
1990 SPRING
HERBICIDES AND FERTILIZERS



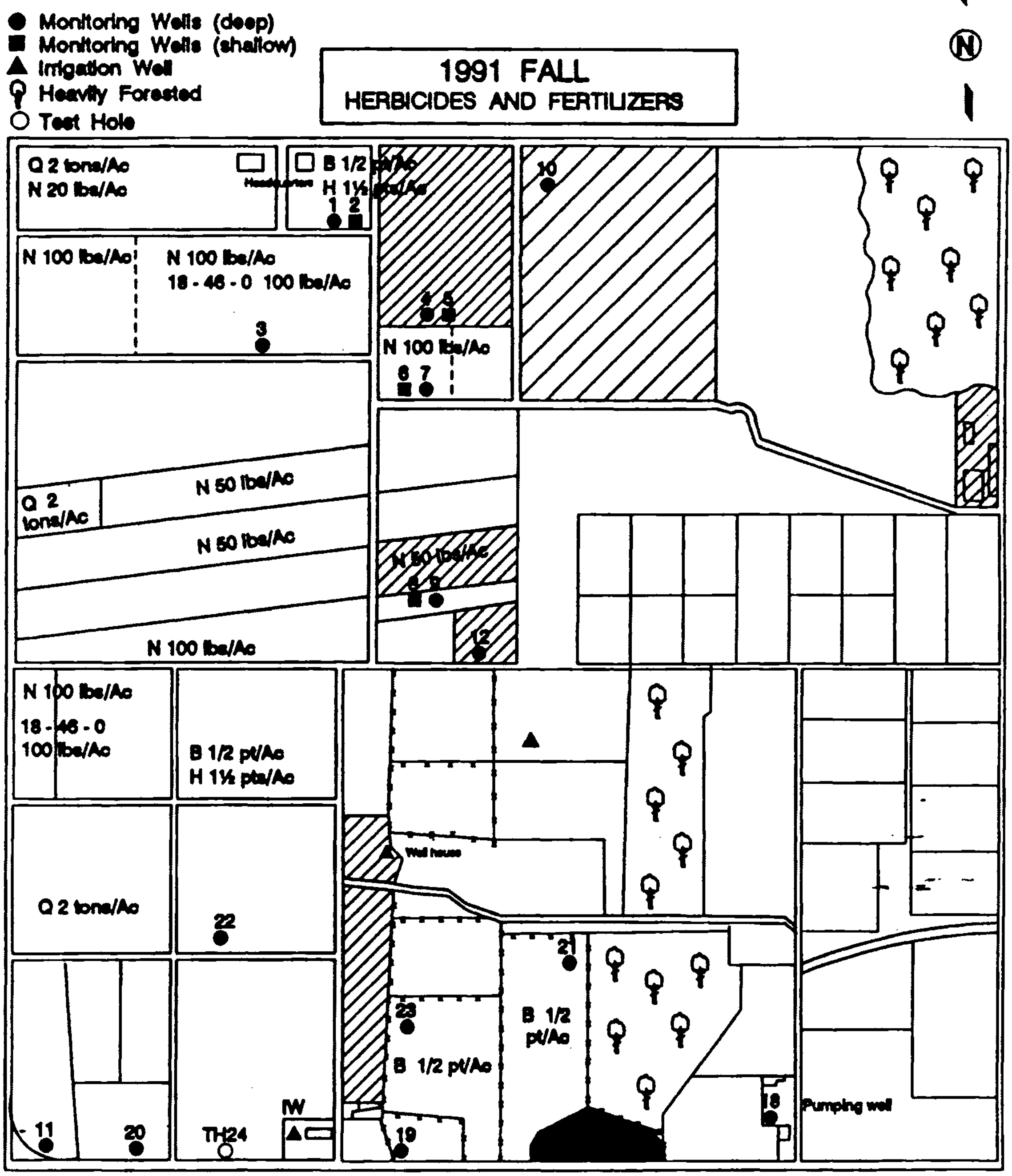


OSU AGRONOMY RESEARCH STATION
Monitoring Wells (deep)
Monitoring Wells (shallow)
Irrigation Well
Heavily Forested
Test Hole
N
1990 FALL
FERTILIZERS
Q 2 tons/Ac
N 50 lbs/Ac
Q 2 tons/Ac
N 50 lbs/Ac
N 75 lbs/Ac
N 75 lbs/Ac
18 - 46 - 0
Q 1 ton/Ac
18-46-0
N 60 lbs/Ac
18 - 46 - 0
A 1.5 lbs/Ac
N 60 lbs/Ac
0 - 0 - 60
N 100 lbs/Ac
18 - 46 - 0
0 - 0 - 60
Q 2 tons/Ac
Q 2 tons/Ac
18 - 46 - 0
0 - 0 - 60
TH24
IW
Pumping well

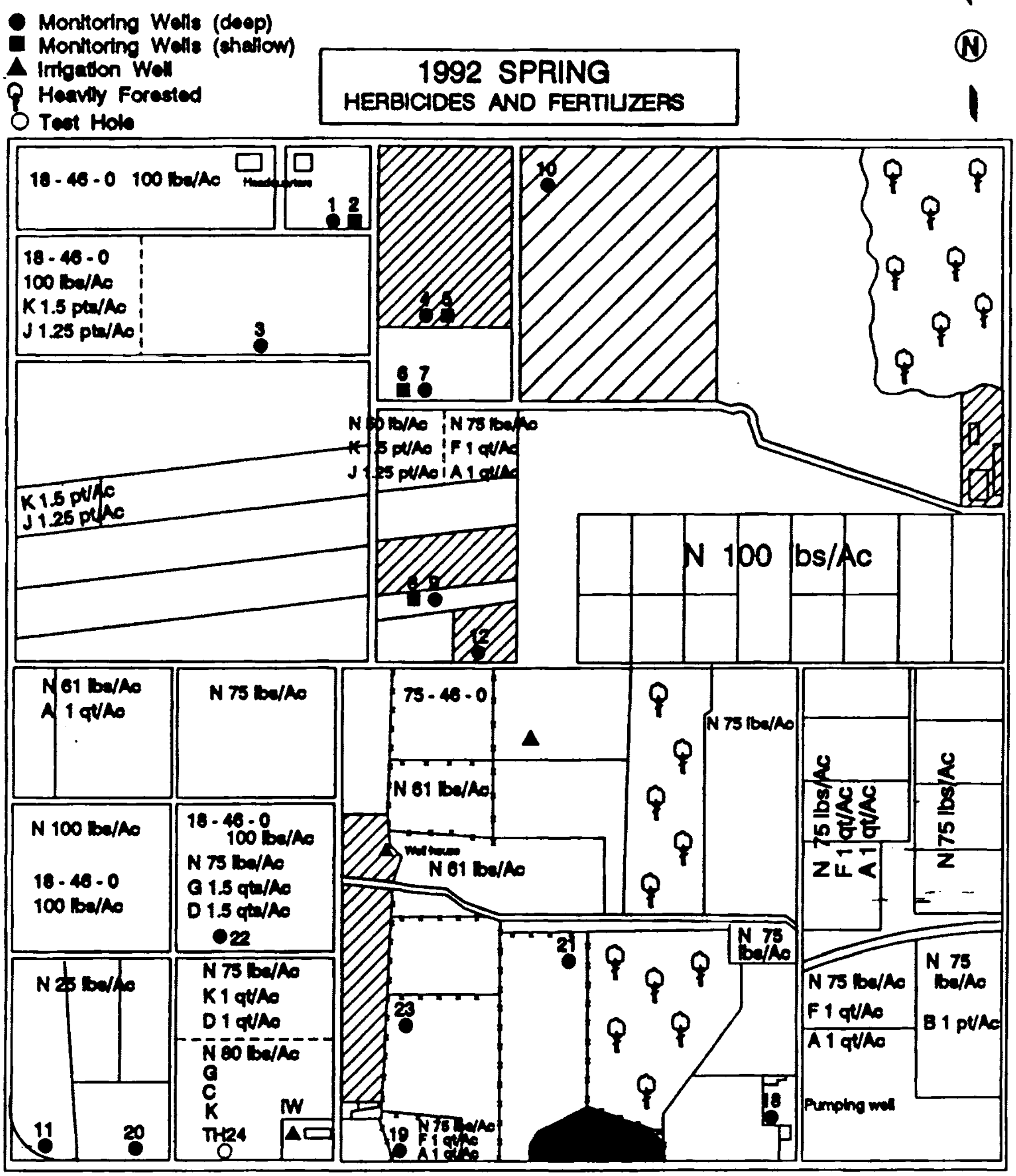
OSU AGRONOMY RESEARCH STATION



OSU AGRONOMY RESEARCH STATION



OSU AGRONOMY RESEARCH STATION



APPENDIX B

GEOPHYSICAL SURVEYS

APPENDIX B

GEOPHYSICAL SURVEYS

Geophysical surveys have been used to further define the water table and bedrock configurations of the study area. Figure B1 depicts the specific points on the southern half of the Perkins station where geophysical surveys were conducted. The Perkins geophysical survey combined three specific types of non-destructive methods: seismic, resistivity and ground penetrating radar. Correlation with borehole and drilling logs from previously drilled monitoring wells was necessary to control the interpretation of the data collected in the surveys.

Seismic Methods

Seismic methods use artificially generated seismic waves to determine the thickness and depth of geologic layers (Driscoll, 1989). For taking measurements, a source, a geophone and a recorder are needed. Geophones located at the surface determine the arrival time of the waves from the source at a number of different spacings (Benson, 1988) (see Figure B2 for example). Pulses of seismic waves are recorded as irregular traces on a seismograph at a receiver with each pulse consisting of discrete vibrations, one for each path taken by a seismic wave through the earth.

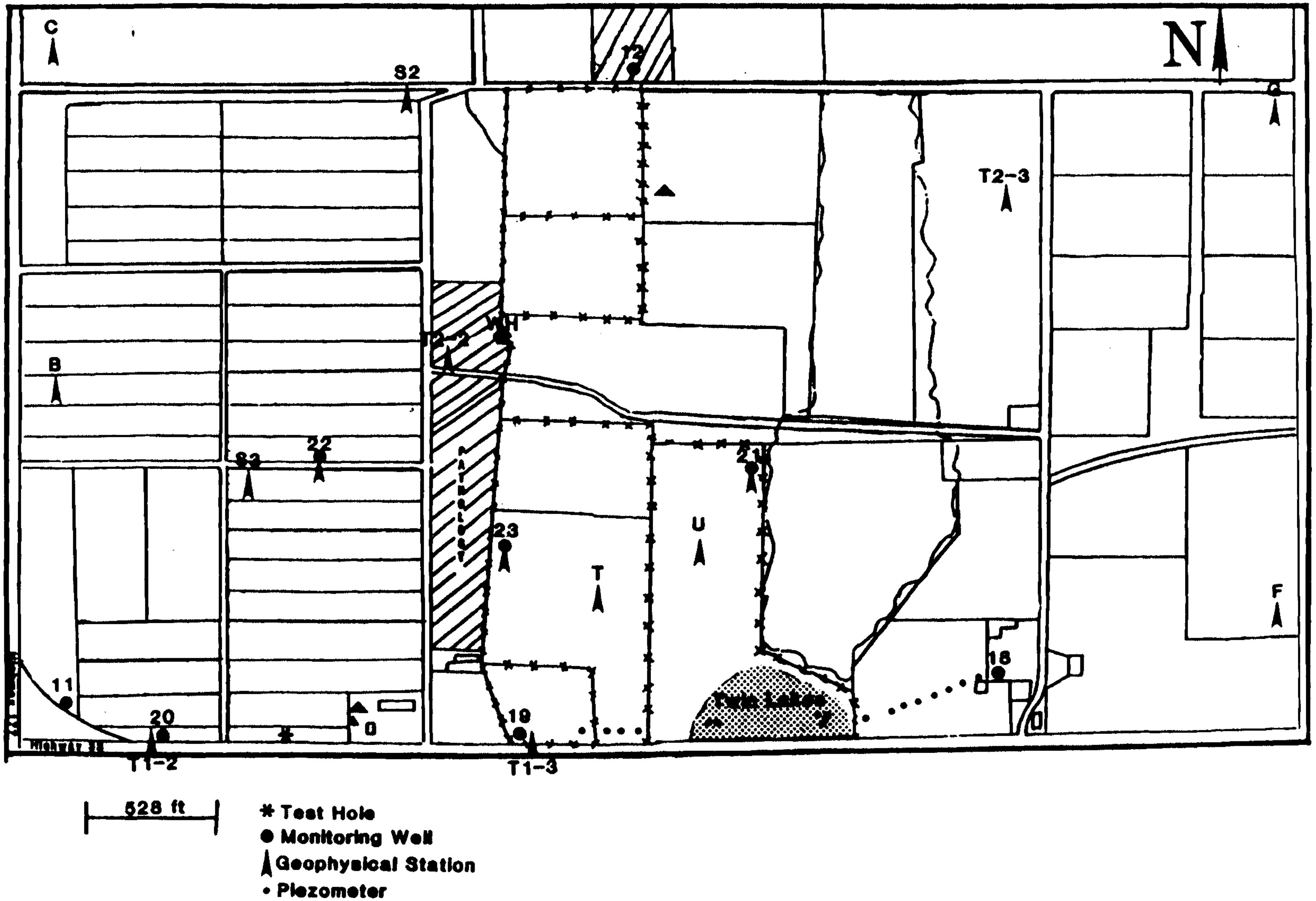


Figure B1. Southern Terrace of Perkins Station

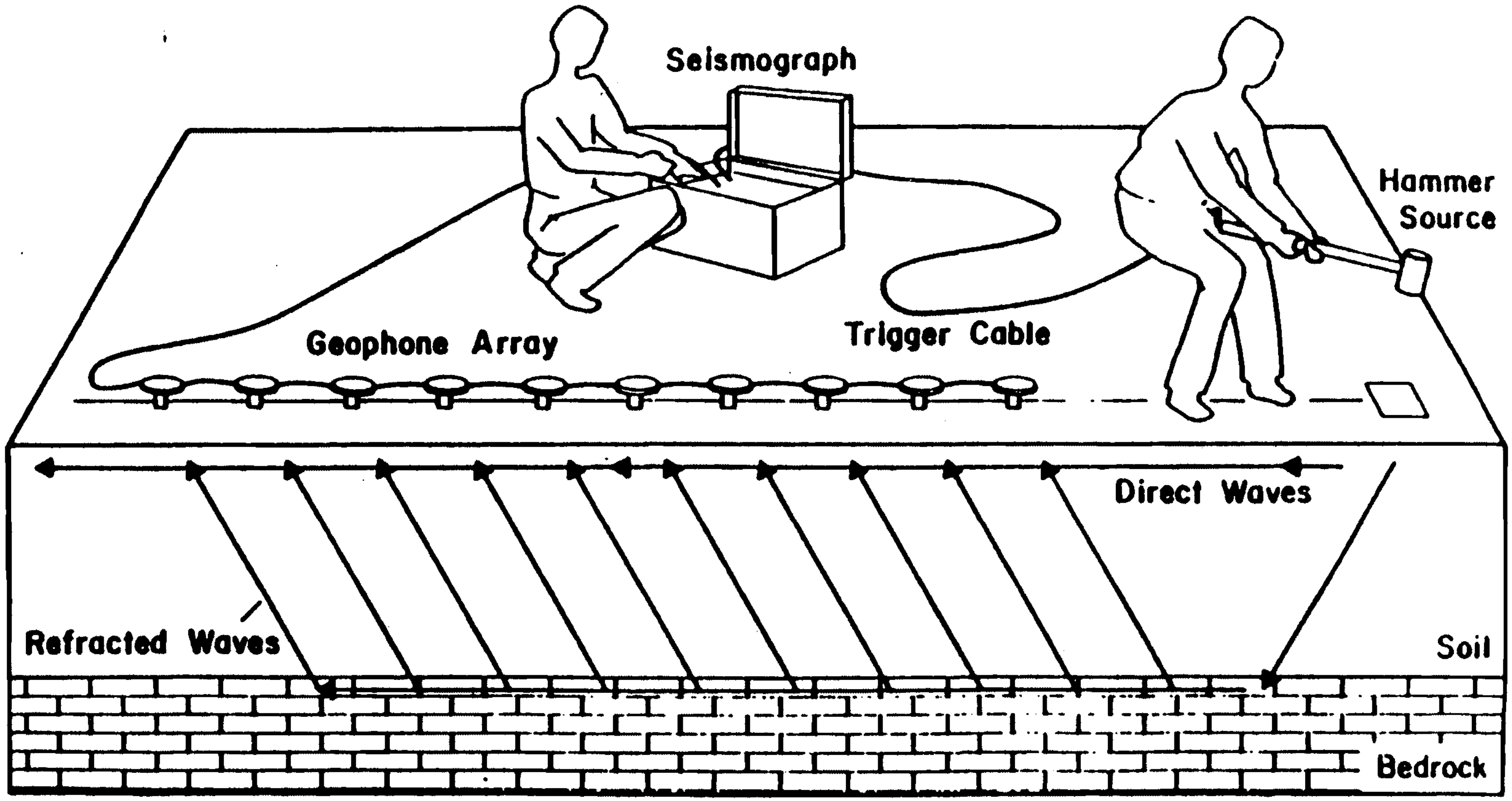


Figure B2. Field Schematic of Seismograph (From Benson, 1988)

Refracted waves (compressional P waves) are the preferred interpretive tool of seismic methods since they usually reach the geophones as a first arrival peak which is the easiest discernable peak on the seismograph.

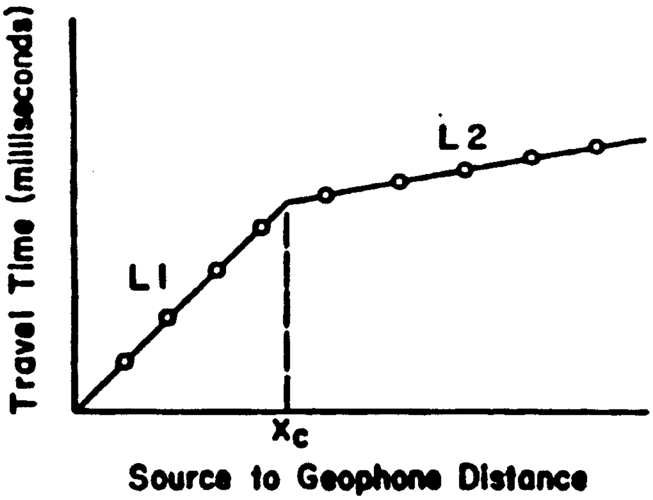
Geologic formations have characteristic seismic velocities for compressional P waves (see Table B1). The wave velocity in each layer of material is directly related to physical properties such as density and elasticity which are directly affected by the material's porosity, mineral composition, and water content. Energy is easily dissipated in low density, poorly consolidated sediments while energy is readily transferred through high density, consolidated sediments.

A one channel Bison seismic instrument was used in the Perkins surveys for recording refracted seismic waves. Times of first arrivals of refracted waves were recorded from the instrument seismograph and then plotted at the corresponding geophone distances on a graph (see Figure B3 for example). Lines were drawn through straight alignments of points to create a time-travel curve. The slopes of these straight lines are determined and the velocities calculated from the reciprocals of these slopes. On a time-travel graph, the straight lines intersect at points known as crossing distances or cross over distances (Robinson, 1988). The velocities of the layers, the crossing distances and the intercept times of the straight lines in time-travel graphs can be used to determine the actual depth to

TABLE B1

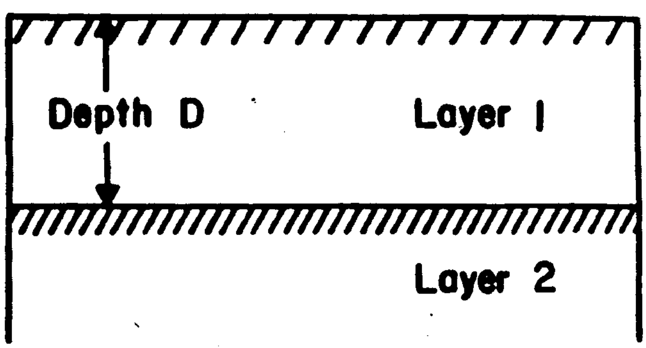
RANGE OF VELOCITIES FOR COMPRESSIONAL WAVES IN GEOLOGIC MATERIALS (Modified After Bensen, 1988)

Common Geologic Materials	Velocity (meters/sec)
Weathered Surface Material	305 - 610
Gravel/Unsaturated Sand	465 - 915
Saturated Sand	610 - 1830
Sandstone	1830 - 3970
Shale	2750 - 4270
Chalk	1830 - 3970
Limestone	2140 - 6100
Salt	4270 - 5190
Granite	4380 - 5800
Metamorphic Rocks	3050 - 7020



L1 = Layer 1
L2 = Layer 2
V1 = Velocity of Layer 1 = 1/Slope of L1
V2 = Velocity of Layer 2 = 1/Slope of L2
Xc = Cross Over Distance

Figure B3. Time/Distance Plot for a Simple Two-Layer Structure (Modified After Bensen, 1988)



For Two Horizontal Layers:

$$\text{Depth to Interface} = \frac{Xc}{2}\sqrt{\frac{V2 - V1}{V2 + V1}}$$

Figure B4. Interpretation of Seismic Data (Modified After Bensen, 1988) water and the depth to bedrock (see Figure B4 for example).

A typical data plot with interpretation for a seismic survey completed on the Perkins Station in the Fall of 1991 is depicted in Figure B5. Three layers of material are interpreted, each with a different seismic velocity. Calculations of depth to interfaces between these layers using the cross-over method of analysis for this plot are included in Figure B6. The first two interfaces are interpreted to represent abrupt vertical changes in grain size or clay lenses. The saturated zone is characterized by slightly elevated velocities which do not adequately refract seismic waves. The third interface is interpreted to be the depth to bedrock surface at the point of the survey.

Resistivity Methods

The electrical resistivity method of "sounding" was used in the Perkins Station geophysical surveys. Resistivity is the resistance of a geologic medium to current flow when a potential (voltage) difference is applied (Driscoll, 1989) (see Figure B7). The technique uses a pair of surface electrodes (current electrodes designated with a C) to introduce a direct electrical current into the subsurface creating a potential field. This potential field is then measured at two other surface electrodes (potential electrodes designated with a P) placed between the current electrodes.

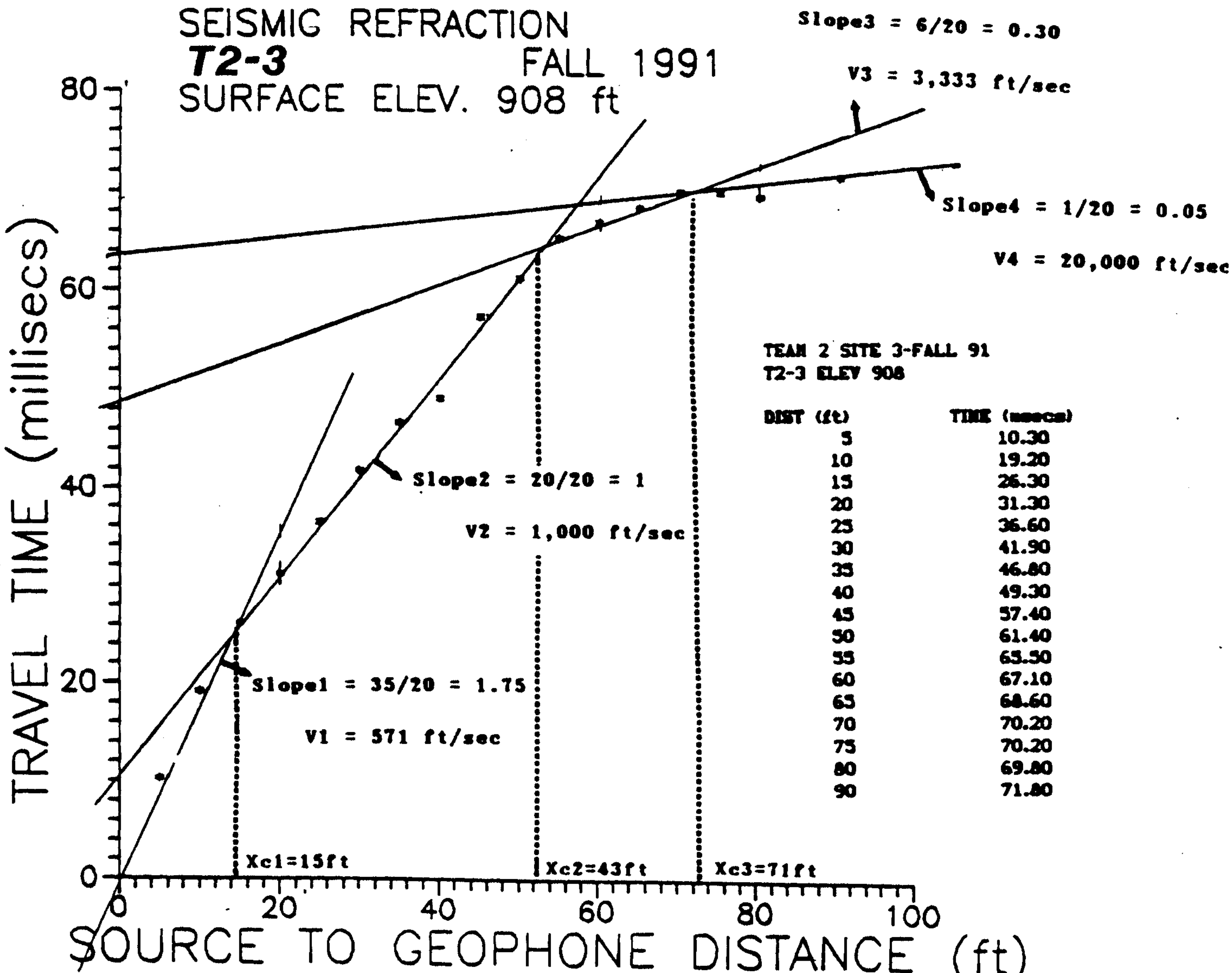


Figure B5. Seismic Refraction Method Example

Figure B6. Seismic Refraction Example Calculations

T2-3 FALL 1991

Surface Elevation 908 ft

V1 = 571
V2 = 1,000
V3 = 3,333
V4 = 20,000

Cross Over Method:

Xc1 = 15 ft

$$D1 = (1/2) * (15) * \sqrt{\frac{1{,}000 - 571}{1{,}000 + 571}} = 3.92$$

First Layer (D1) = 3.92 ft

Xc2 = 43 ft

$$D2 = (1/2) * (43) * \sqrt{\frac{3{,}333 - 1{,}000}{3{,}333 + 1{,}000}} = 15.70$$

Second Layer (D2) = 15.70 + 3.92 ft

Xc3 = 71 ft

$$D3 = (1/2) * (71) * \sqrt{\frac{20{,}000 - 3{,}333}{20{,}000 + 3{,}333}} = 30.00$$

Depth to Bedrock (D3) = 30.00 ft + 15.70 ft + 3.92 ft

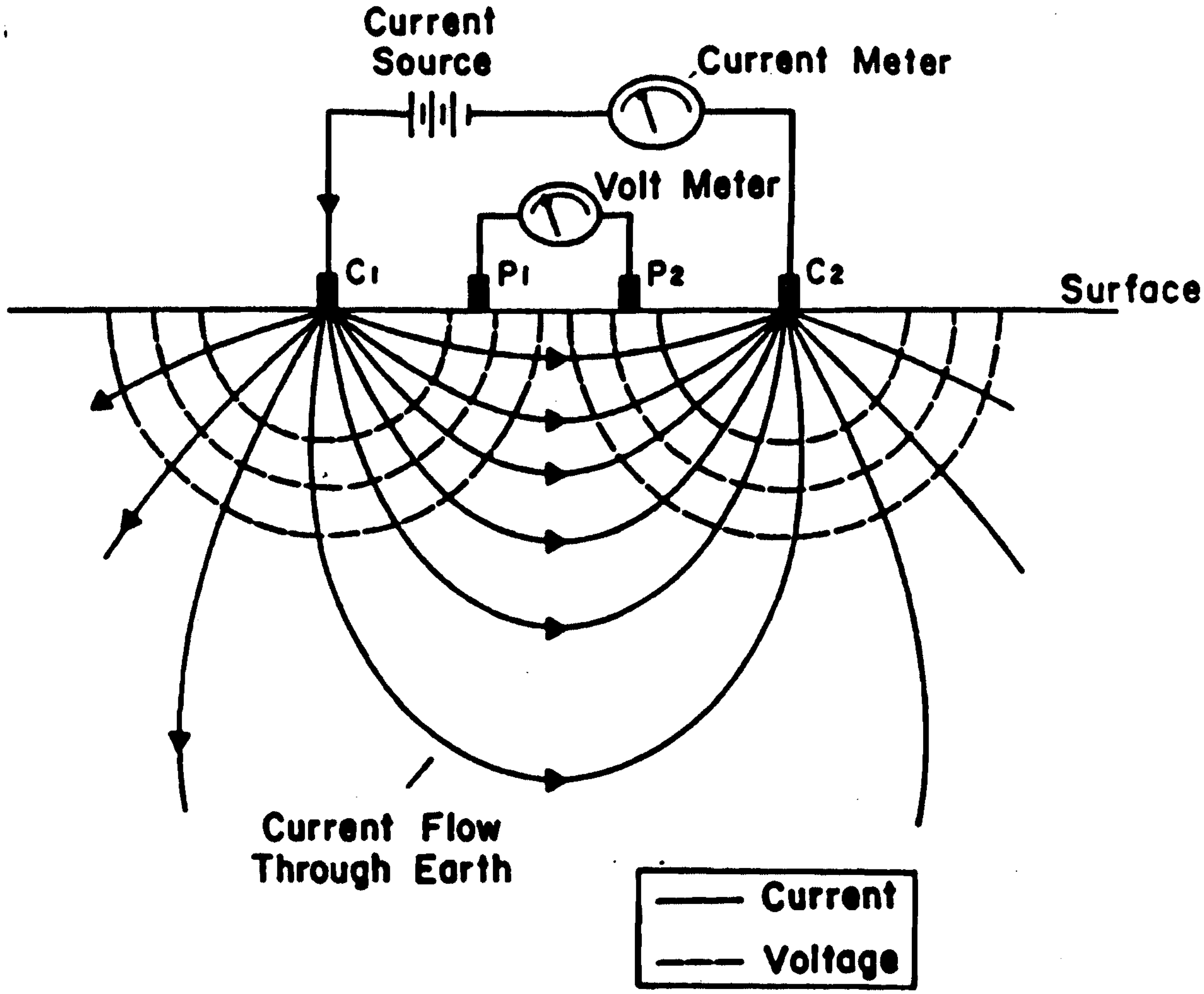


Figure B7. Diagram Showing Basic Concept of Resistivity Measurement (From Bensen, 1988)

Geologic materials provide resistance to the electrical current produced according to their porosity, permeability, and the volume and conductivity of moisture within the pores. This resistance will be detected and measured as a voltage drop between the current and potential electrodes. Geologic materials do not have characteristic resistivities, but in general, resistivity decreases as porosity, hydraulic conductivity, water content and salinity increase. Figure B8 presents a schematic depiction of the general range of the resistivities of geologic materials commonly encountered.

Different types of electrode spacing arrays are used in resistivity surveys according to the project objectives and the existing site conditions. The two most common electrode arrangements are the Wenner and Schlumberger arrays. The Wenner array offers a simple electrical geometry and is the most often used in North America (Driscoll, 1989). With equal spacing maintained between electrodes (a spacing), potential electrodes (P) are centered on a line between the current electrodes (C) (see Figure B9). The Schlumberger arrangement is more useful for very deep geologic investigations. Spacing between the outer current electrodes and the inner potential electrodes (L) is increased for each reading while the distance between the inner electrodes remains constant (see Figure B10).

Current is applied to the subsurface by the two outer

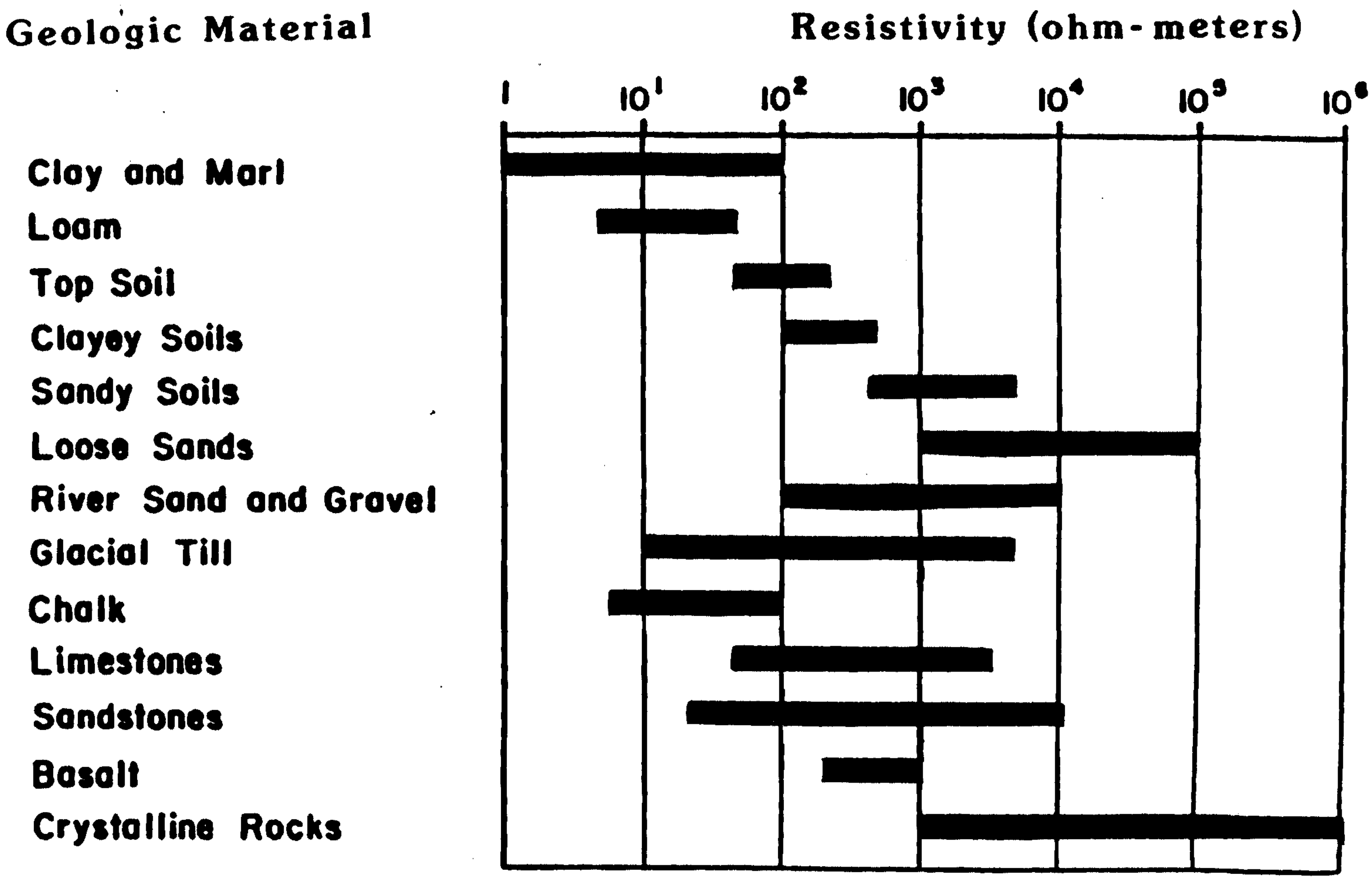


Figure B8. Range of Resistivities in Commonly-Occurring Soils and Rocks (Modified After Bensen, 1988)

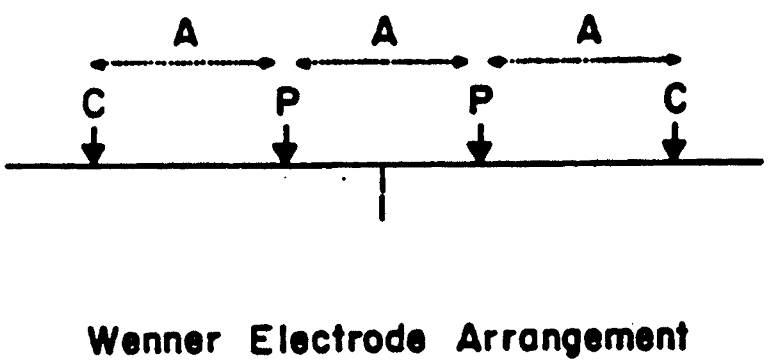


Figure B9. Wenner Electrode Arrangement (Modified After Bensen, 1988)

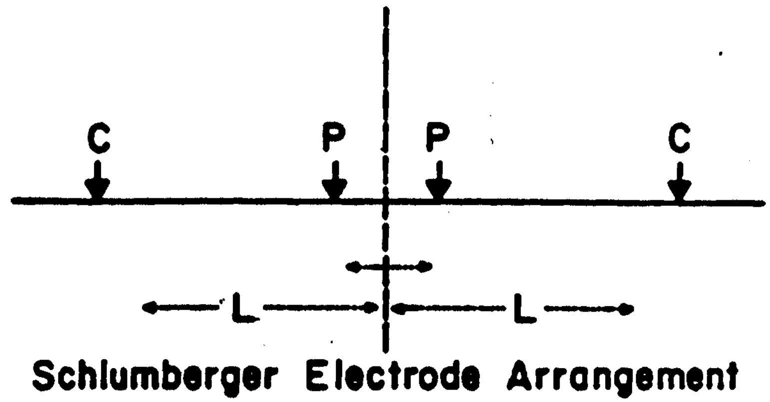


Figure B10. Schlumberger Electrode Arrangement (Modified After Bensen, 1988) current flow within the subsurface produces an electric field with lines of equal potential perpendicular to the lines of current (Benson, 1988) (See Figure B7). The applied current will be affected by the resistivity of subsurfacematerials causing subsequent potential drops which will be measured by a voltmeter at the two inner electrodes.

The apparent resistivities of subsurface materials for the Wenner configuration are calculated using the formula:

Apparent resistivity = 2π * a spacing * V/I * multiplier

Apparent resistivity in ohm*ft is calculated by multiplying two by the A spacing in feet by the instrument reading (V/I) in ohms by the dimensionless instrument multiplier. The term apparent resistivity simply refers to the fact that each reading is an average of the resistivity of the materials from the surface to the depth of the measurement (A spacing). Measurements taken at increased A spacings will render apparent resistivity values for successively deeper materials. Wenner configuration data is plotted as A spacing versus apparent resistivity for interpretation (see Figure B11 for example). The A spacings used in the Perkins survey were 2 to 5 feet apart, therefore it is reasonable to assume a 2 to 5 foot error in all of the elevation picks made.

A typical Wenner array data plot with interpretation for a D.C. resistivity survey completed on the Perkins

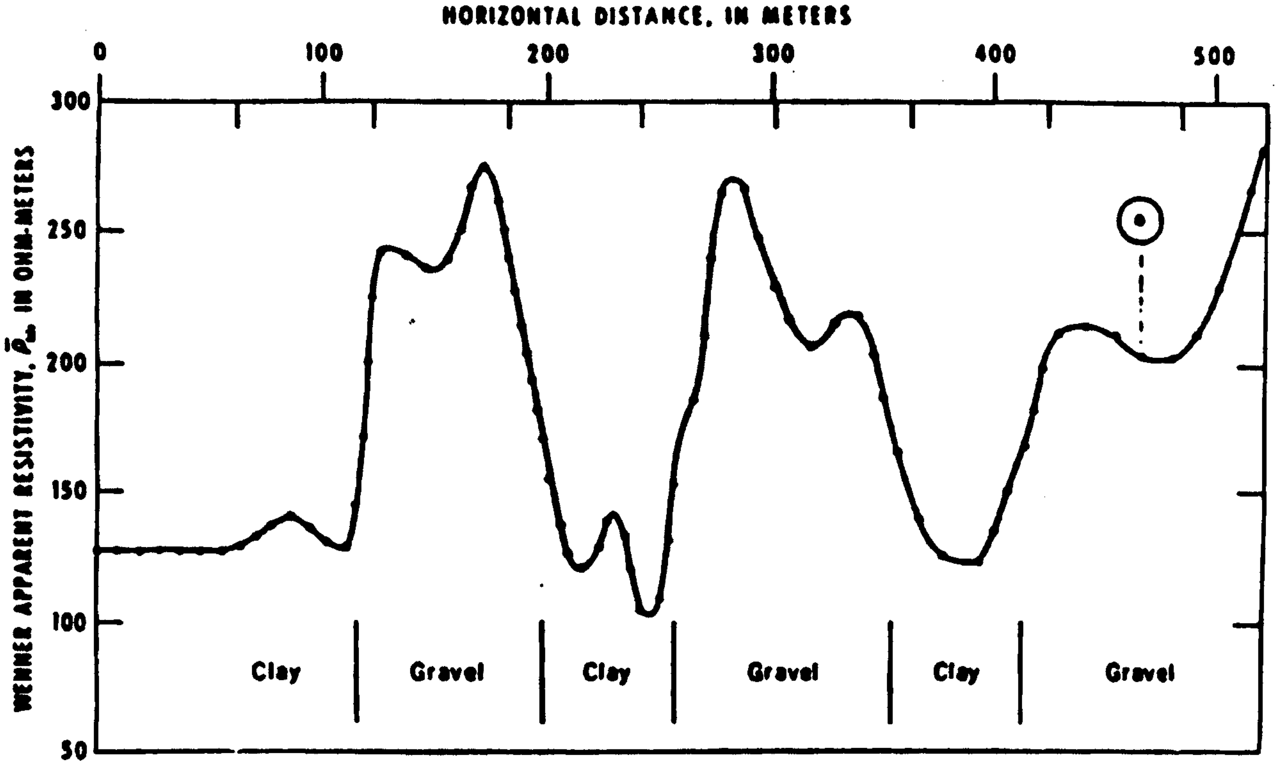


Figure B11. Resistivity Profile Across Glacial Clays and Gravels (From Bensen, 1988)

Station is depicted in Figure B12. The water table elevation is interpreted as the point where the apparent resistivity is lowered by the more conductive saturated zone. The bedrock elevation is interpreted as the point where the apparent resistivity decreases to a constant value where more conductive claystone (shales) are encountered. These elevations were easily validated since this survey was run immediately adjacent to the existing monitoring well #23. Comparable results were found through analyzing the Schlumberger array geophysical profile taken at the same location (see Figure B13).

Ground Penetrating Radar

A 100 megahertz frequency analog system Ground Penetrating Radar (GPR) tool was utilized near the pumping well site (MW #18) on the Perkins Station. GPR is a non-destructive geophysical technique which uses high frequency radio waves to probe the internal structure of the ground. The signal is sent by a transmitting antenna and picked up by a receiver antenna. The radar wave reflections which are detected result from the subsurface interfaces between lithologies with different electrical properties.

Signals are input at chosen increments along survey lines and their output is recorded in digital format. Resolution is controlled by the frequency of the radar and the size of the increments. The data is printed out as continuous lines and can be processed like seismic lines in

Station is depicted in Figure B12. The water table elevation is interpreted as the point where the apparent resistivity is lowered by the more conductive saturated zone. The bedrock elevation is interpreted as the point where the apparent resistivity decreases to a constant value where more conductive claystone (shales) are encountered. These elevations were easily validated since this survey was run immediately adjacent to the existing monitoring well #23. Comparable results were found through analyzing the Schlumberger array geophysical profile taken at the same location (see Figure B13).

Ground Penetrating Radar

A 100 megahertz frequency analog system Ground Penetrating Radar (GPR) tool was utilized near the pumping well site (MW #18) on the Perkins Station. GPR is a non-destructive geophysical technique which uses high frequency radio waves to probe the internal structure of the ground. The signal is sent by a transmitting antenna and picked up by a receiver antenna. The radar wave reflections which are detected result from the subsurface interfaces between lithologies with different electrical properties.

Signals are input at chosen increments along survey lines and their output is recorded in digital format. Resolution is controlled by the frequency of the radar and the size of the increments. The data is printed out as continuous lines and can be processed like seismic lines in

D.C. RESISTIVITY SURVEY MW 23

Wenner Array

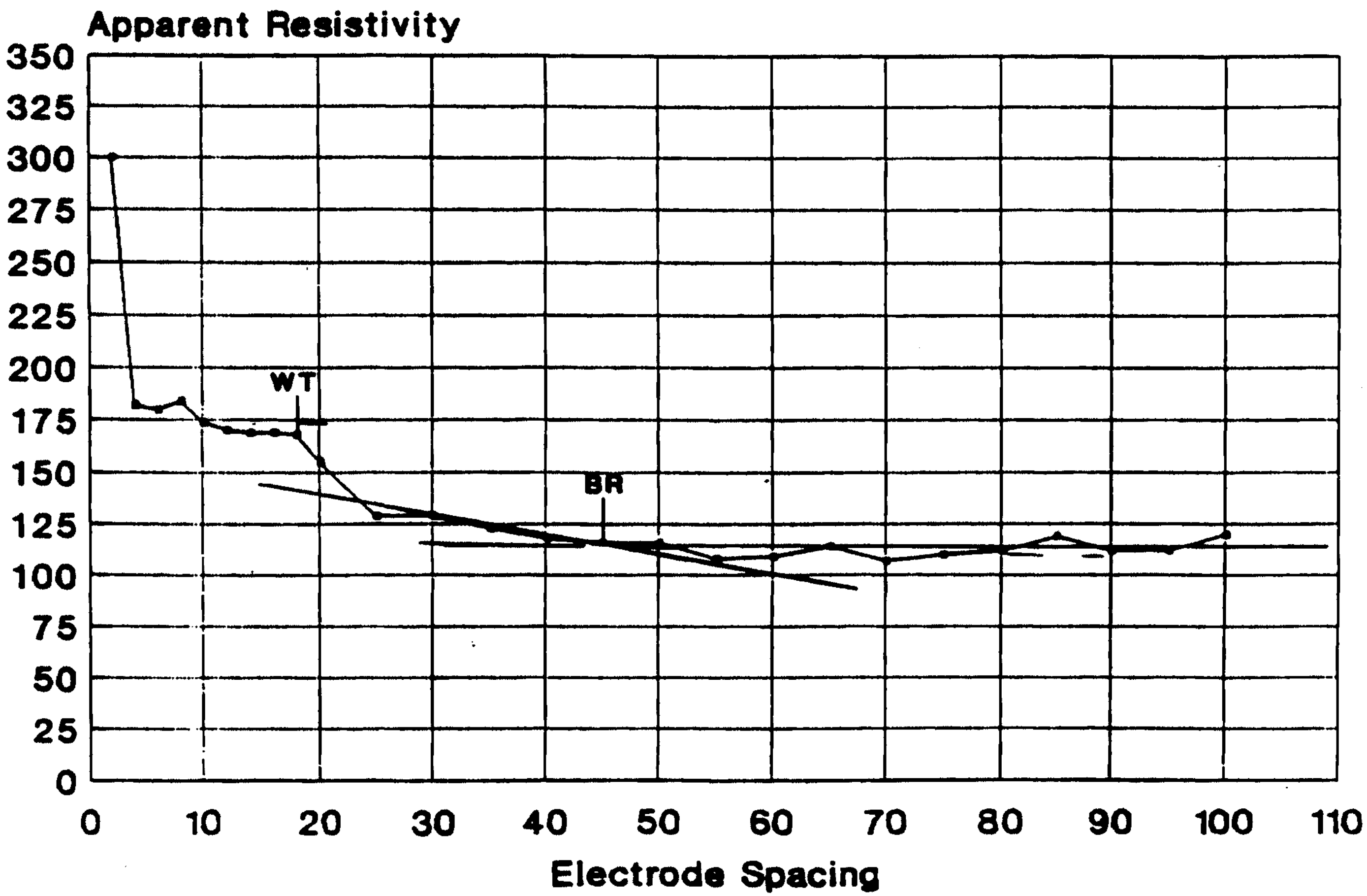


Figure B12. Resistivity Method Example - Wenner Array

D.C. RESISTIVITY MW-23
Schlumberger Array

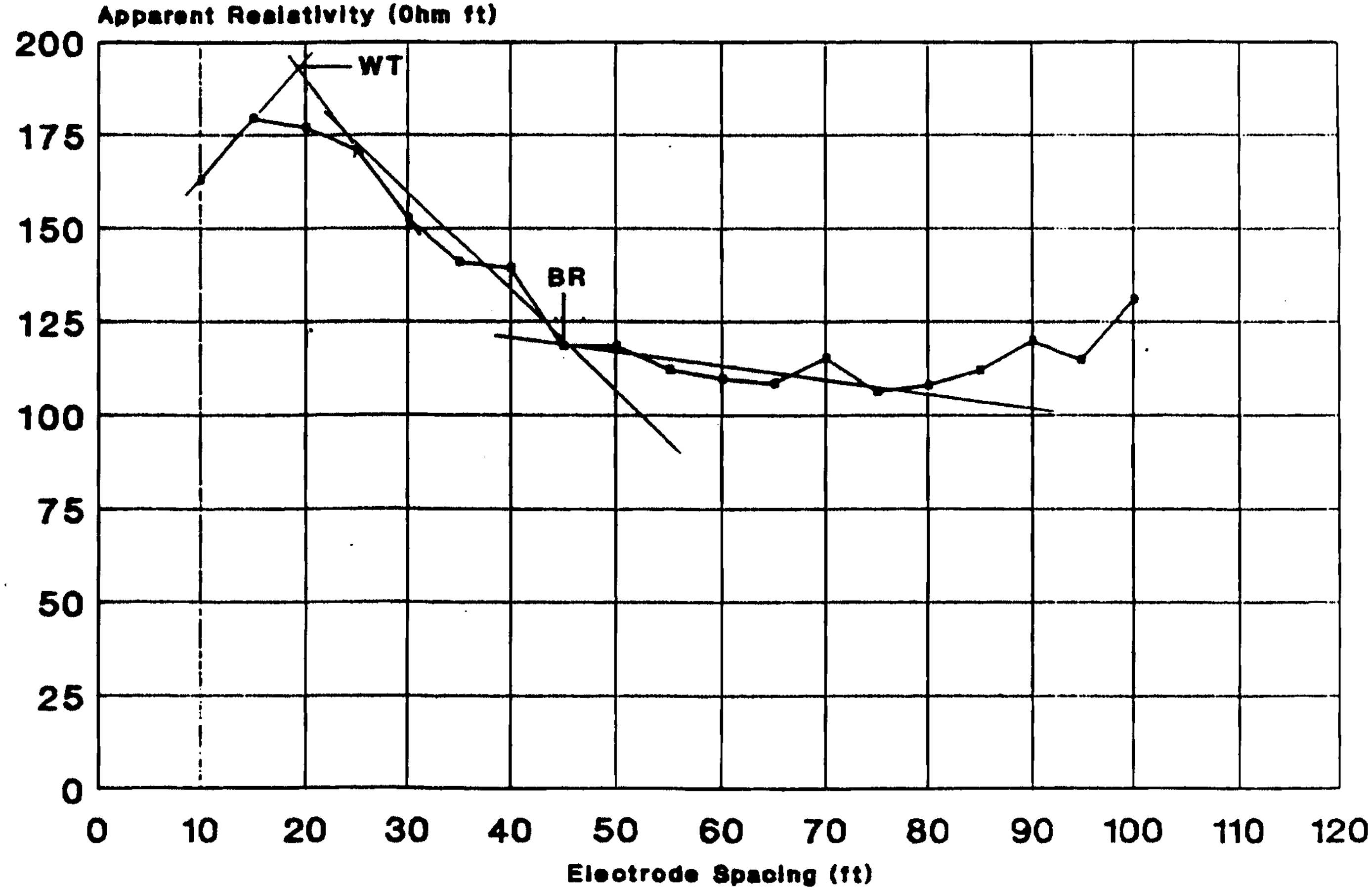


Figure B13. Resistivity Method Example - Schlumberger Array

order to enhance the recorded data. The depth of penetration of the radar signals is site specific. Penetration is significantly better in dry, sandy conditions than in wet, clay rich materials.

APPENDIX C

AQUIFER TESTS

APPENDIX C

AQUIFER TESTS

Pumping Test Methods

Several different kinds of aquifer tests have been used in order to determine the hydraulic characteristics of the aquifer. Pumping tests for the Perkins Terrace water table aquifer have been conducted in the tracer cluster area around pumping well Ep (#18). See Figure C1 for the planar view and Figure C2 for the cross sectional view of the tracer cluster area. Drawdowns were measured over time in each of the observation wells while discharge was measured at the flow line terminus which is located sufficiently downgradient to eliminate the effects of artificial recharge. The field data was then plotted and analyzed using the Jacob (Driscoll, 1989) and Prickett (Walton, 1970) methods to determine hydraulic values such as transmissivity and storativity.

In the several aquifer tests which have been performed at the pump site over the last three years, the discharge rates for individual tests have varied from 30 to 60 gallons per minute (gpm). It has been determined that a discharge rate exceeding 30 gpm stresses the aquifer, making hydraulic variables difficult to calculate. For

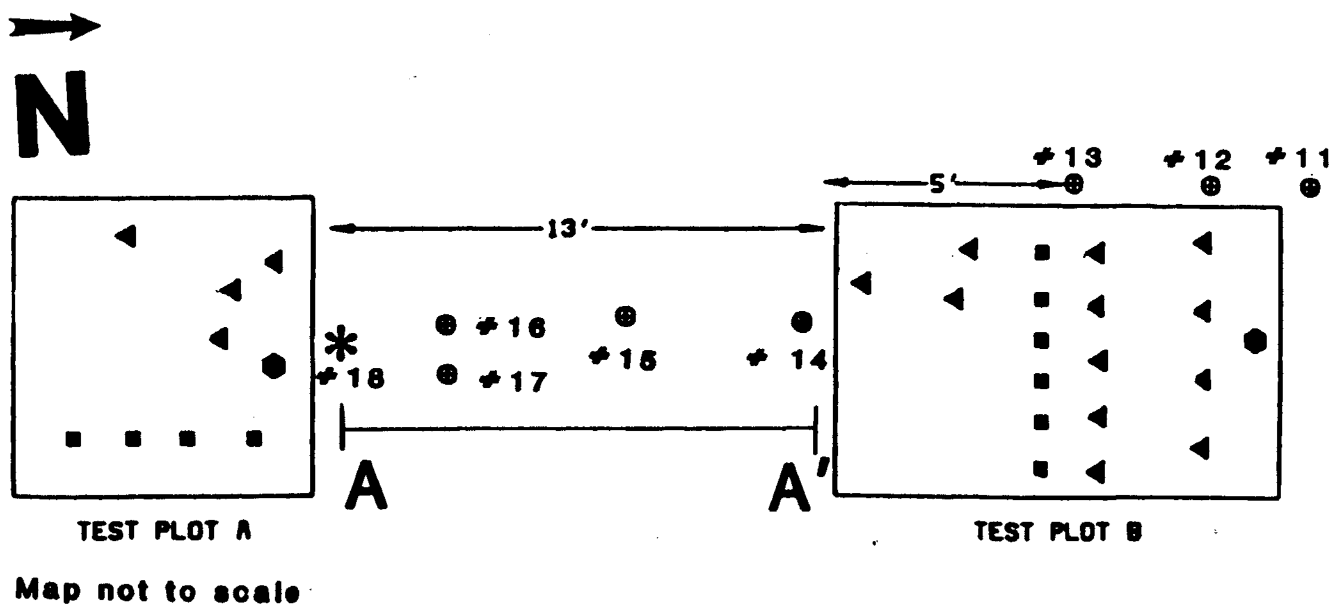


Figure C1. Plan Map of Tracer/Pumping Test Area (Modified After Dwivedi, 1989)

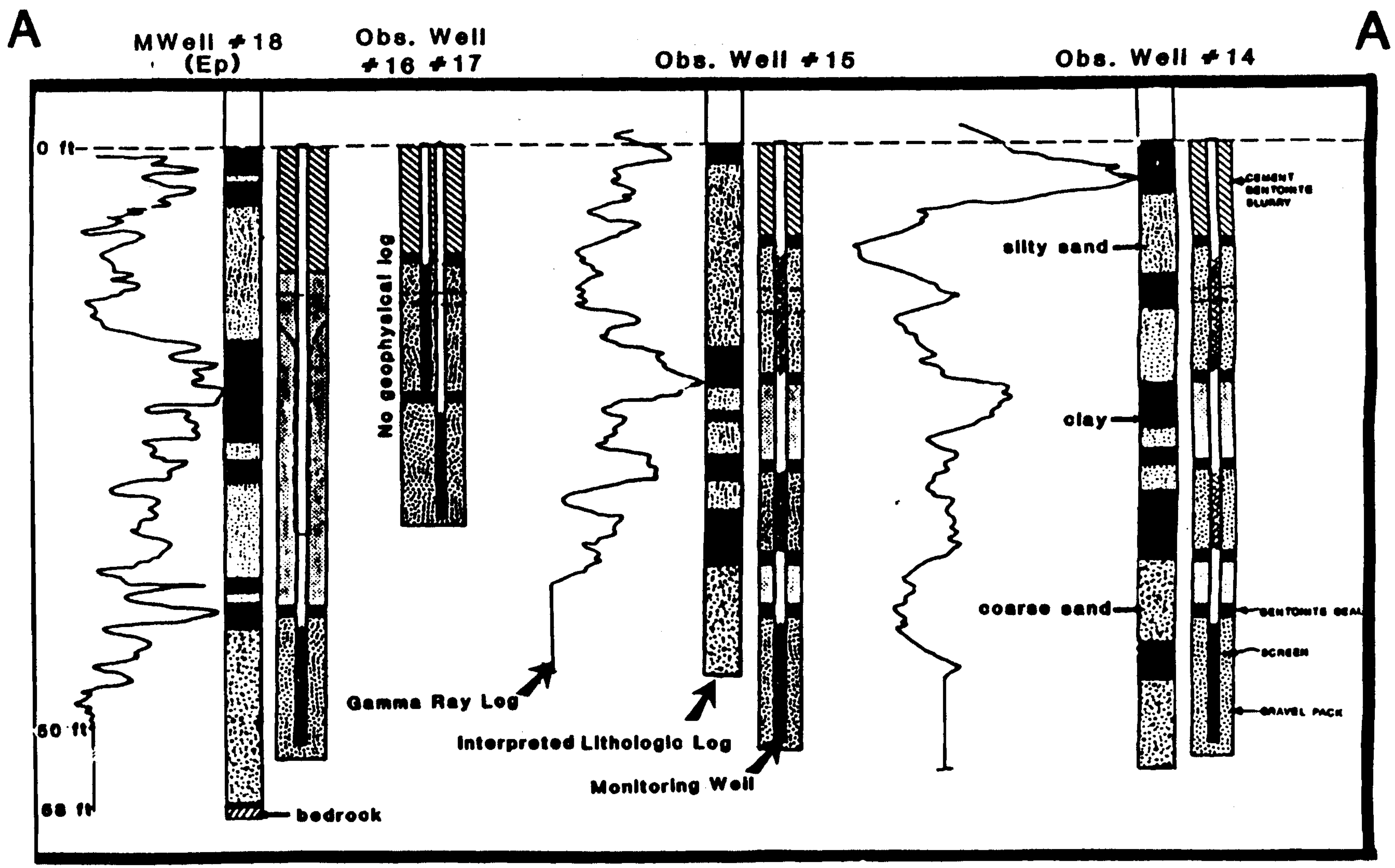


Figure C2. Cross-Section of Tracer/Pumping Test Area example, in a 1992 aquifer pumping test with a discharge rate of 47 gpm, the drawdown in each observation well was highly erratic making data difficult to interpret. A 1989 pumping test with a discharge of 32 gpm rendered more reasonable drawdown patterns for each observation well and has subsequently been used for calculating hydraulic values for the southern alluvial sediments (see Table C1).

Before plotting unconfined aquifer test data, the field data should be corrected for effects of decrease in aquifer thickness and partial penetration losses. In this particular aquifer test, the differences in drawdown measurements would be negligible with a minimum change of 1.15E-5 ft and a maximum change of .08 ft.

Jacob Method of Analysis The simplest and most time efficient approach for analyzing observation well data is using the Jacob-Cooper (Driscoll, 1989) modified nonequilibrium equation for confined aquifers. Cooper and Jacob (1946) found that when the time length of the pumping test is sufficiently large and the radius from the pumping well to the observation well is sufficiently small, the Theis nonequilibrium equation can be simplified to the following form without significant
error (Driscoll, 1989):

$$ds = 264Q/T * \log 0.3Tt_o / r^2S$$

Where:

Q = Discharge in gpm
T = Transmissivity in gpd/ft

TABLE C1.

AQUIFER TEST DATA - FALL 1989

Q=32gpm	DRAWDOWN (FT)				DRAWDOWN (FT)	
Time(min	MW E2 r = 40 ft	MW E3 r = 80 ft		Time(min	MW E2	MW E3
0	0.00	0.00				
4	0.29			50	0.90	
7	0.46			176	1.26	
12	0.61	0.18		178		0.86
14	0.76			308	0.91	
16		0.25		309		0.84
17	0.72			369	0.93	
20	0.75			372		0.84
22		0.30		433	1.21	
25	0.75			436		0.85
30	0.82			6044	1.33	
32		0.36		6046		0.86
35	0.84			8640	1.40	0.97
38		0.40		18720	1.61	1.16
40	0.86			28800	1.87	1.31
45		0.43		34860	2.05	1.54

S = Storage Coefficient (dimensionless)
ds = the slope of the time-drawdown graph in feet representing the change in drawdown between any two times on the log scale whose ratio is 10 (spanning exactly one log cycle)
t_o = intercept of straight line at zero drawdown in days
r = distance from pumping well to observation well in feet where the drawdown measurements were taken

In aquifer tests where the pumping rate is held constant, Q, T, and S are all constants. The only variables in the above equation are s and t. By plotting the pumping test data as time versus drawdown on semilogarithmic scaled graphs, transmissivity and the coefficient of storage are calculated using the following related equations:

$T = 264Q/ds$ $S = 0.3Tt/r^2$

The first few minutes of each data plot is not useful for this technique because it represents casing storage depletion, but most of the early data falls on an approximate straight line. The slope of the straight line spanning exactly one log cycle of time represents ds in feet. The intercept of the straight line at zero drawdown represents t_o in days.

The Jacob plot from the 1989 pumping test for observation well E3 and the interpretation is included in Figure C3. In the early part of the plot, the drawdown in each observation well lowers at a constant rate as the cone of depression forms and enlarges (straight line section). A "steady state" condition seems to be reached in the middle section of the Jacob plot when the cone of depression is thought to stabilize and drawdown in the observation wells

JACOB ANALYSIS PLOT

OBSERVATION WELL E3

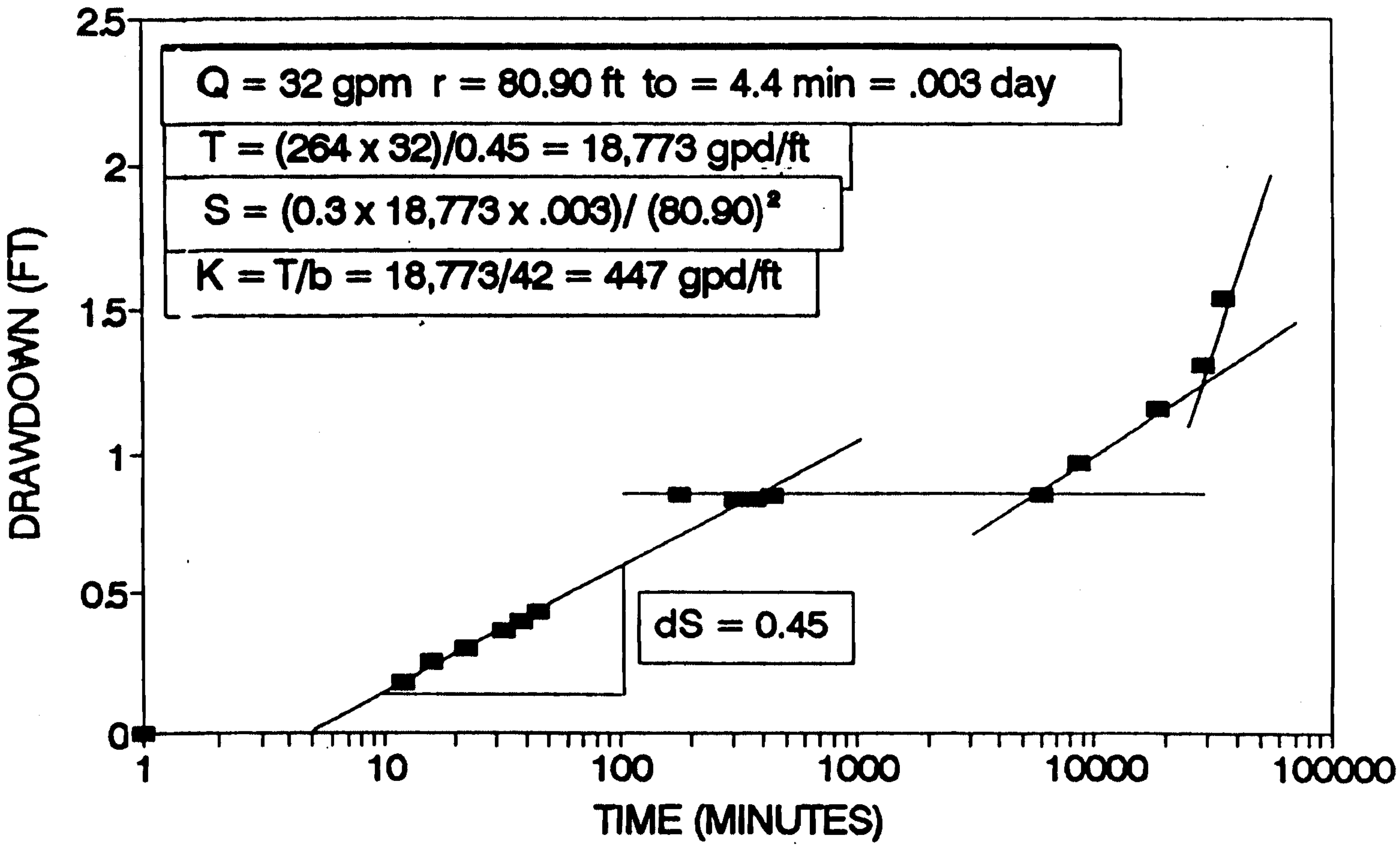


Figure C3. Jacob Method Example - Observation Well E3

ceases to change significantly. The drawdown pattern showsthe possible influence of a negative lateral boundary late in the pumping test. The latter section of the plot shows a sudden increase in drawdown which could be caused by the cone of depression intercepting a unit of lower permeability, thinner saturated thickness, etc.

A summary of calculated aquifer coefficients for the 1989 pumping test (T, K, and S) is presented in Table C2. Because the Jacob-Cooper method is intended to apply to confined aquifers, the Coefficient of Storage calculated by analyzing this unconfined aquifer data is invalid but, the values of Transmissivity and Hydraulic Conductivity are good estimates.

Prickett Method of Analysis A type-curve graphical method has been developed by Boulton (1963) and described by Prickett (1965) for accommodating the dewatering of unconfined aquifers during pumping tests (Walton, 1970). This method uses a set of nonsteady-state water table type curves included in Figure C4. Essentially, the type curves which lie to the left of the r/D printed values are designated as "type A curves" and are essentially the same as the set of leaky artesian curves. They are used to analyze early time-drawdown data of an aquifer test. The type curves which are shown to the right of the values of r/D are termed "type Y curves" and are used to analyze late time-drawdown data. This method requires labor intensive curve matching but is a more accurate approach for

TABLE C2.

SUMMARY OF AQUIFER COEFFICIENTS - 1989

Transmissivity (T), in gpd/ft
Hydraulic Conductivity (K), in gpd/ft2
Coefficient of Storage (S), dimensionless
----, not applicable
***, most accurate values

PUMPING TEST RESULTS SOUTHERN TERRACE DEPOSITS

Observation Well #		Jacob Method	Prickett Method Early	Prickett Method Late
E0	T=	17,600	14,669	----
	K=	419	349	----
	S=	----	----	----
E1	T=	18,773	20,373	20,373
	K=	447	485	485
	S=	----	----	----
E2	T=	18,773	15,280***	14,669***
	K=	447	364 ***	349 ***
	S=	----	----	.062 ***
E3	T=	18,773	14,669***	14,669***
	K=	447	349 ***	349 ***
	S=	----	----	.092 ***

SLUG TEST RESULTS NORTHERN TERRACE DEPOSITS

Date	MW #4 (D)	MW #5 (S)	MW #7 (D)	MW# 8 (S)
3/26/88	----	----	----	T= 2.16
	----	----	----	S= 0.0001
3/92	----	----	T= 2.03	----
	----	----	S= 0.0001	----
6/20/92	T= 18.9	T= 0.28	----	----
	S= 0.0001	S= 0.0001	----	----
6/27/92	T= 10.3	T= 0.30	----	----
	S= 0.0001	S= 0.0001	----	----

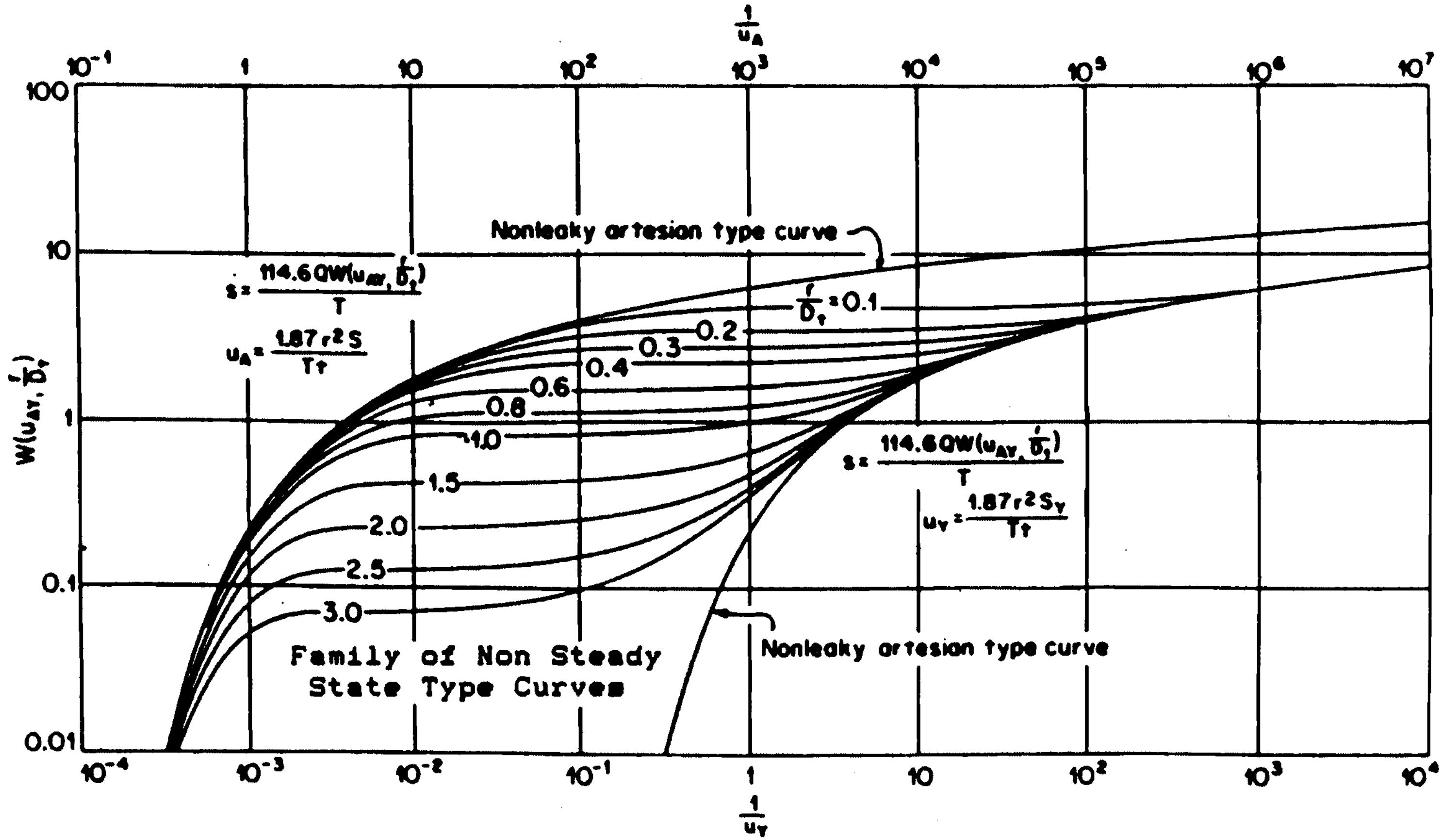


Figure C4. Prickett Method Type Curves (Modified After Walton, 1970)

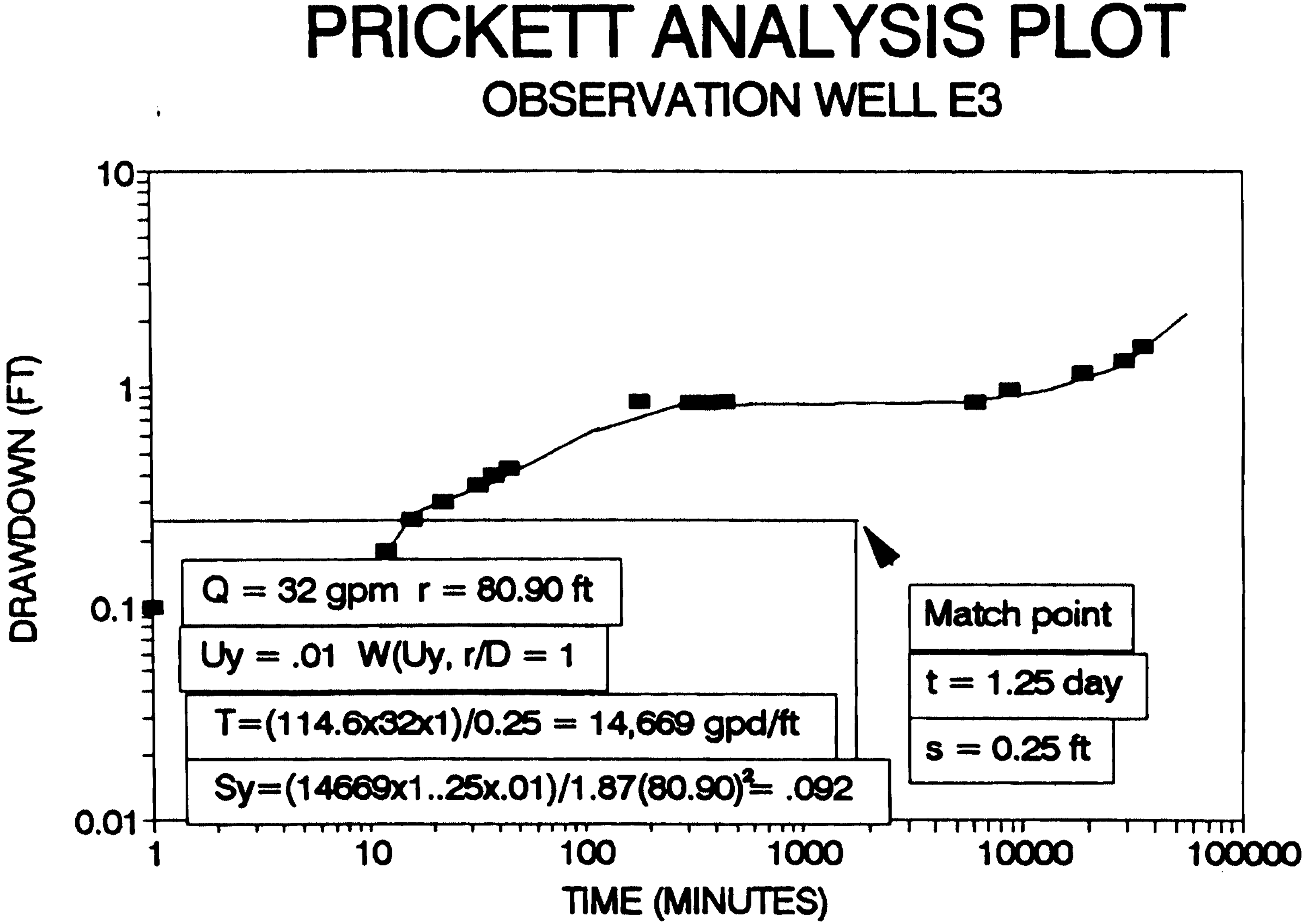


Figure C5. Prickett Method - Observation Well E3

The time-drawdown curves are then superimposed on the Prickett type curves. First, the early portion of the time-drawdown data curves are matched to the type A curves while keeping the drawdown (s) and time (t) axes of the time-drawdown curves parallel to the $W(u_{ay}, r/D)$ and $1/u_a$ axes of the type curve. In the matched position, a point at one of the intersections of the major axes of the type curves is selected and marked on the time-drawdown curve. Both the type curve coordinates [$W(u_{ay}, r/D)$ and $1/u_a$] and the time-drawdown coordinates (s and t) for the match point are noted. At this point, transmissivity can be calculated using:

$$T = 114.6\ Q/s * W(u_{ay}, r/D)$$

The coefficient of storage could also be calculated at this point, but the value would be useless since it represents the storage of a confined aquifer.

The time-drawdown curve was then moved horizontally (not vertically) to be superposed on a type Y curve with the same r/D value as used in the early match. In this second matched position, a point at the intersection of the major axes of the type curves is selected and marked on the time-drawdown curve. Both the type curve coordinates [$W(u_{ay}, r/D)$ and $1/u_y$] and the time-drawdown coordinates (s and t) for the second match point are noted. At this point, transmissivity and specific yield can be calculated using:

$$T = [114.6\ Q/s] * [W(u_{ay}, r/D)]$$

$$S_y = T\ t\ u_y/1.87\ r^2$$

A summary of calculated aquifer coefficients is included in Table C3. Values rendered through the Prickett method for observation well E1 data are considered anomalies based upon past behavior during aquifer tests. The second and most important match point was not possible for observation well E0 data. As expected, the transmissivity values calculated by the Prickett method for observation wells E2 and E3 were approximately equivalent at both match points. The storage values calculated with the data from these observation wells are reasonable, but very low. The results from these two wells are considered to be the most representative of the existing aquifer conditions.

The time-drawdown plots of the pumping test data for the Jacob-Cooper method rendered curves showing possible negative boundaries late in the test (see Figure C3). The Prickett time-drawdown curves and process of curve matching showed that the trend of the later data actually represents delayed drainage. This is possibly the effect of a retarding layer of clay known to exist approximately 15 feet below the surface. This retarding layer is also partially responsible for the coefficients of storage being lower than expected.

Slug Test Methods

Slug tests have been performed on most of the monitoring wells installed on the Perkins Station farm

TABLE C3.

TRACER TEST RESULTS - FALL 1989

	First Arrival	Maximum Peak
	MW #18 = 30 hrs	MW #18 = 90 hrs
Darcian Velocity Method : K = V / I	$K = 769\ gpd/ft^2$	$K = 257\ gpd/ft^2$
Seepage Velocity Method: K = (V * n) / I	$K = 231\ gpd/ft^2$	$K = 77\ gpd/ft^2$

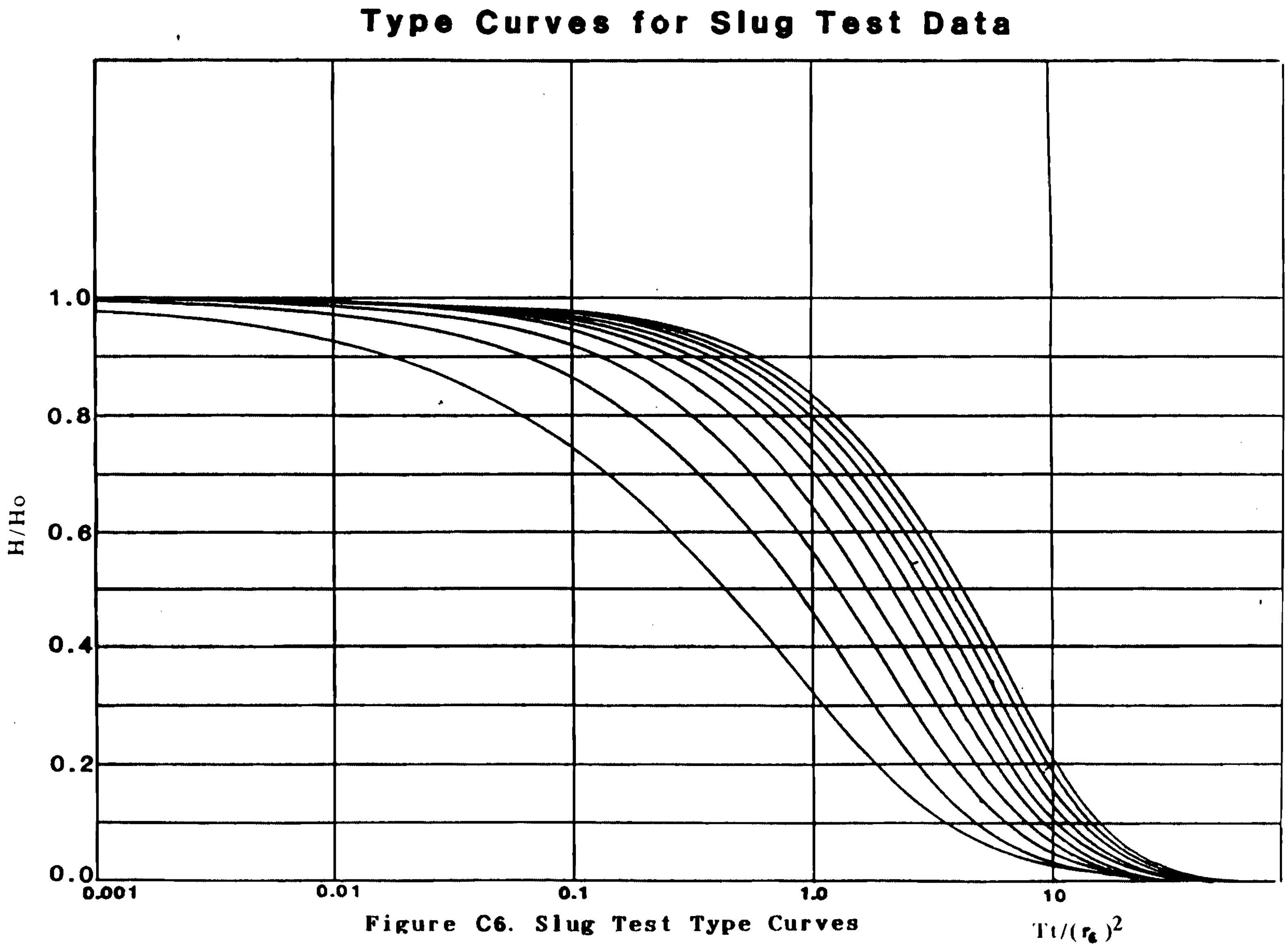


Figure C6. Slug Test Type Curves

Type Curves for Slug Test Data

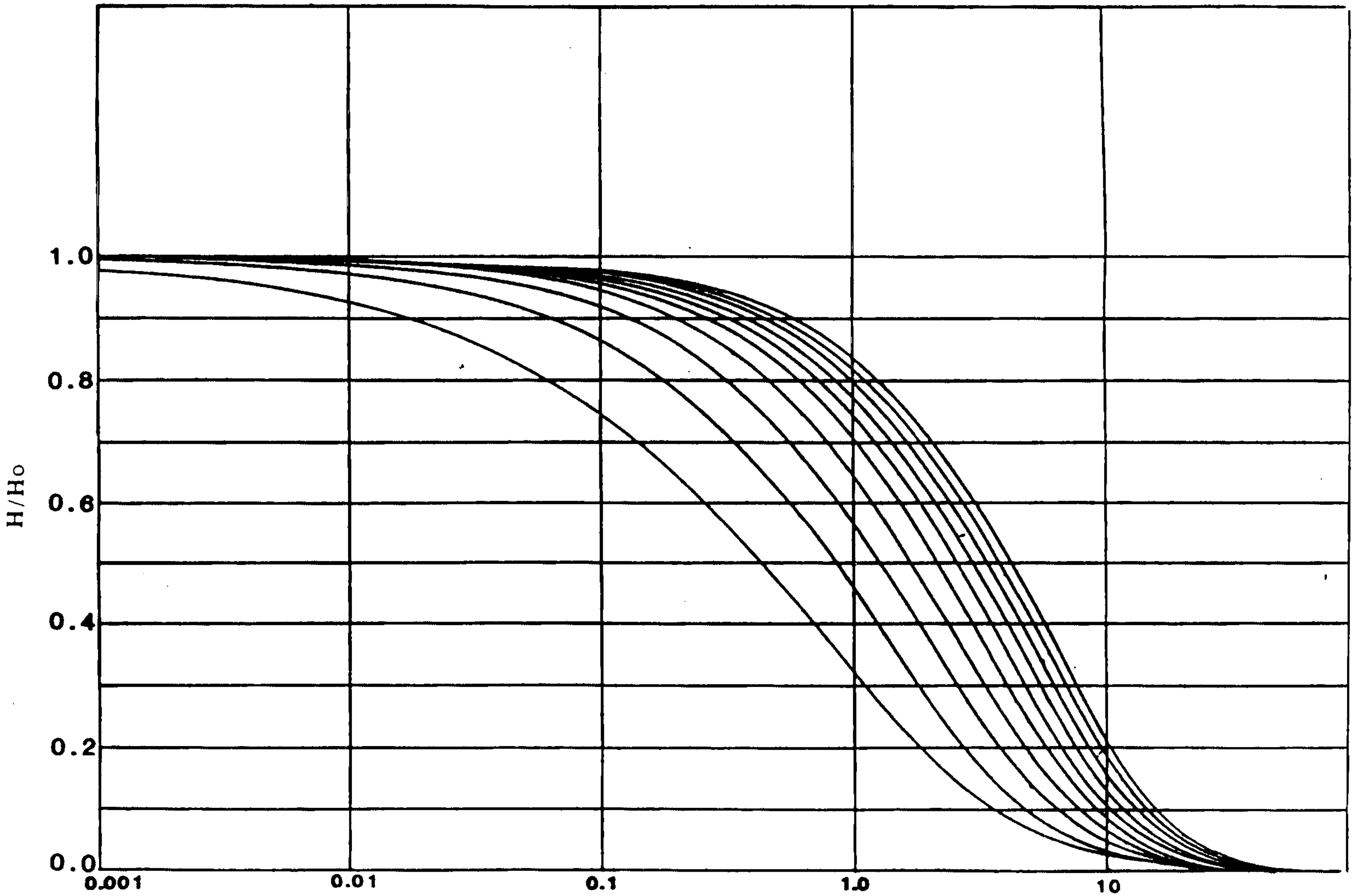


Figure C6. Slug Test Type Curves

using the Cooper, Bredehoeft, and Papadopulos method (Fetter, 1988). This method is a simple, quick and inexpensive way of estimating hydraulic conductivity in the field using only a single test well and is especially useful in aquifers with permeabilities too low for pumping tests. For the purposes of this study, the clustered monitoring wells in the northern half of the section were tested by this method since they are completed in materials of lower conductivity than those aquifer materials in the southern half.

The alternative of this method used at the Perkins Station involves the removal of a slug of water of known volume from a well. Aquifer characteristics control the rate at which the water level in the well rises after removal. Immediately after withdrawal, the water level in the well has a depth (Ho) below the static water level. As the water level rises, the difference (H) in depth to water measurements at time t and at the original head are made. A plot of the ratio of the measured head to the head after removal (H/Ho) is made as a function of time (in seconds) on semilogarithmic paper with H/Ho on the arithmetic scale. Using a set of type curves developed by Papadopulos, Bredehoeft and Cooper (see Figure C6), the data are matched to the type curve which has the same curvature and a match point time (in seconds) is determined and transmissivity can be calculated.

$T = 1.0\ r^2\ /t$

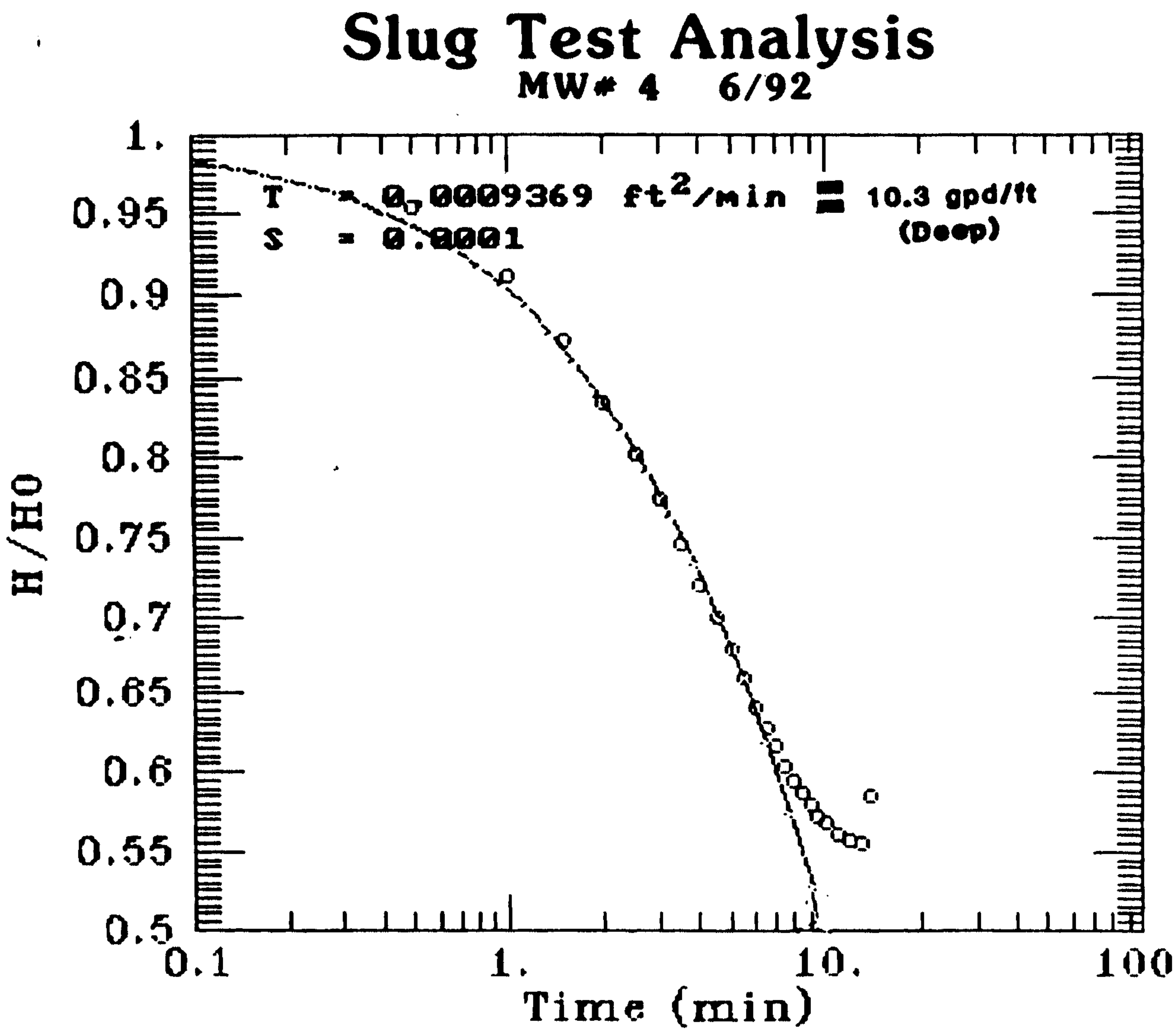


Figure C7. Slug Test Method Example - Monitoring Well #4

Where:

T = transmissivity in gpd/ftr = effective radius in ft

t = match point time since removal of slug in seconds

Figures C7 and C8 depict slug test analyses of data obtained from monitoring wells #4 and #5 on the Perkins Station. Monitoring well #4 is a deep well which rendered a transmissivity of 10.3 gpd/ft while the shallow monitoring well #5 only rendered 0.28 gpd/ft. These differences reflect the different thicknesses of saturated intervals which the clustered monitoring wells penetrate. A summary of transmissivity and storativity values calculated by slug tests are tabulated in Table C3. The low range of these values indicate the fine grained nature of the northern terrace deposits. Therefore, these deposits are not of great concern in the transport of contaminants.

Tracer Test Methods

Originally, tracer tests utilizing dyes and salts were conducted to find hydraulic connections in karst areas. Tracer application in hydrogeology has advanced to characterizing aquifer parameters such as hydraulic conductivity, porosity and dispersivity. Such factors are important to understand in predicting and simulating the fate and transport of solutes in groundwater.

The cross-sectional design of the multi-level groundwater monitoring well network is depicted in

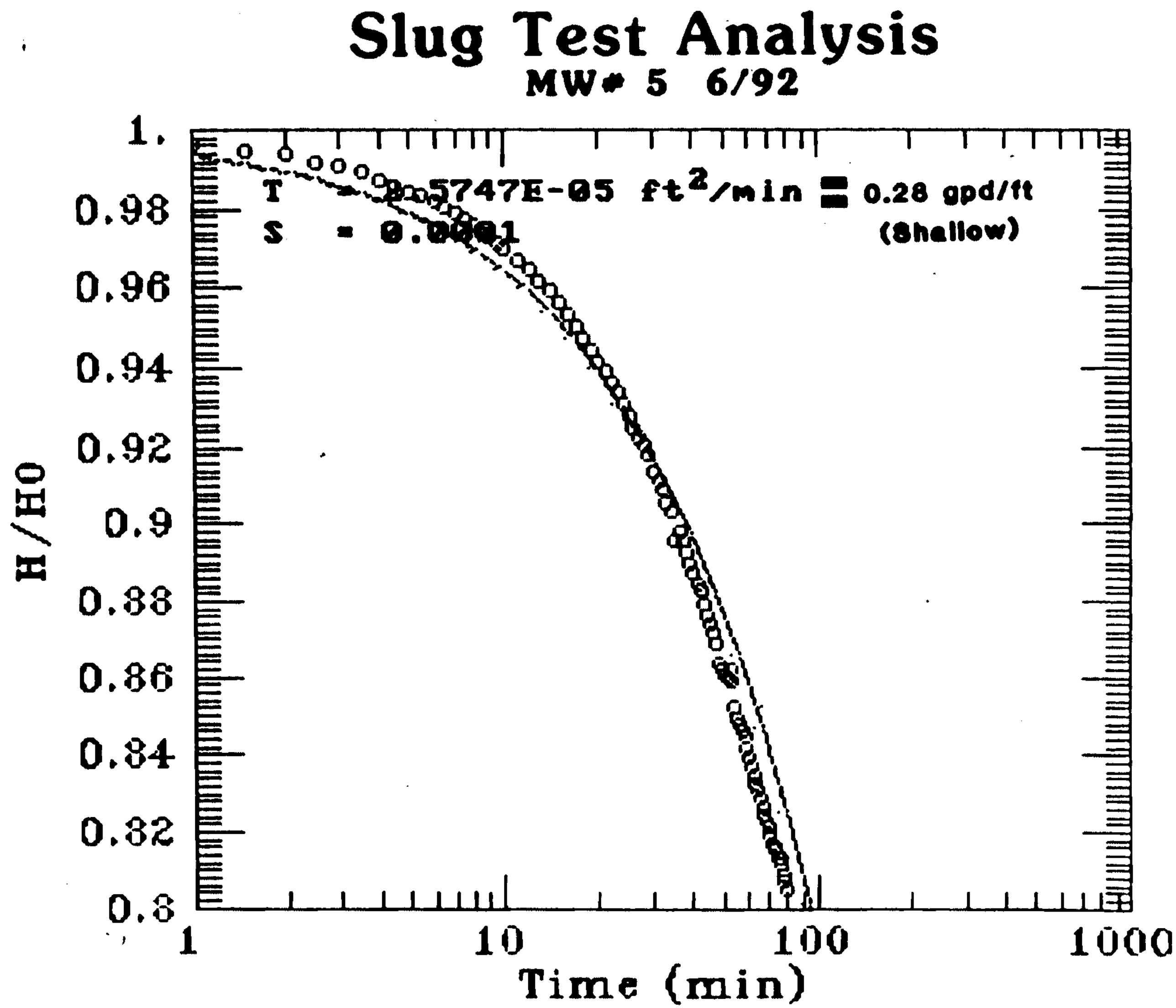


Figure C8. Slug Test Method Example - Monitoring Well #5

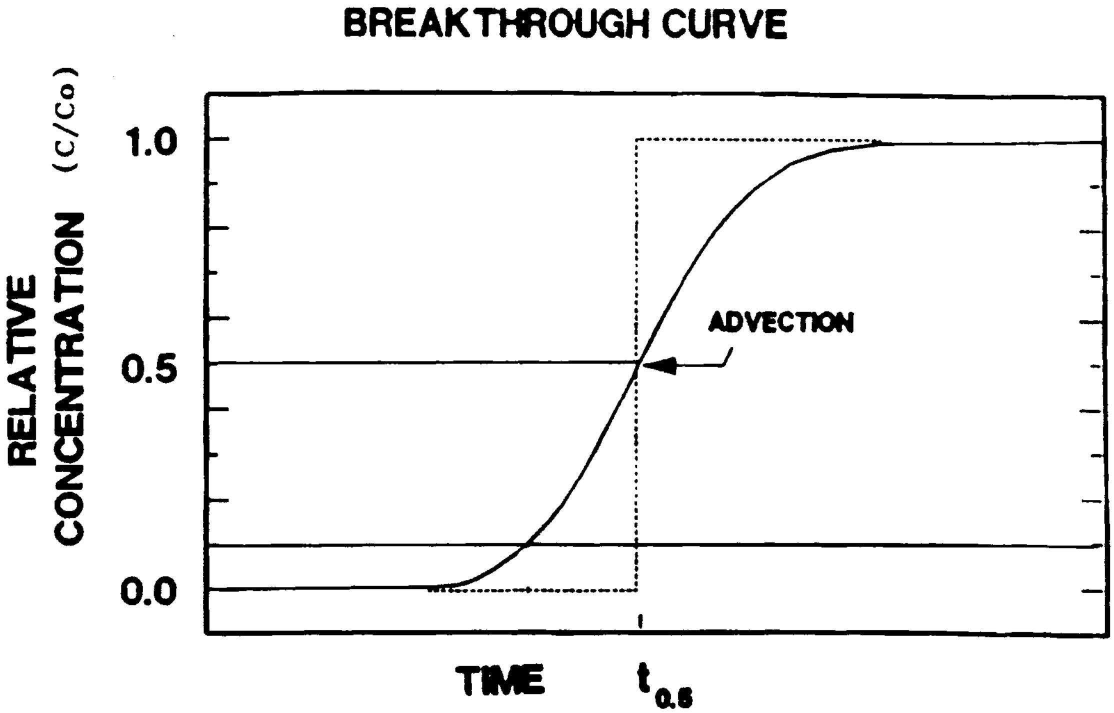


Figure C9. Textbook Example of Breakthrough Curve (Modified After Palmer and Johnson, 1989)

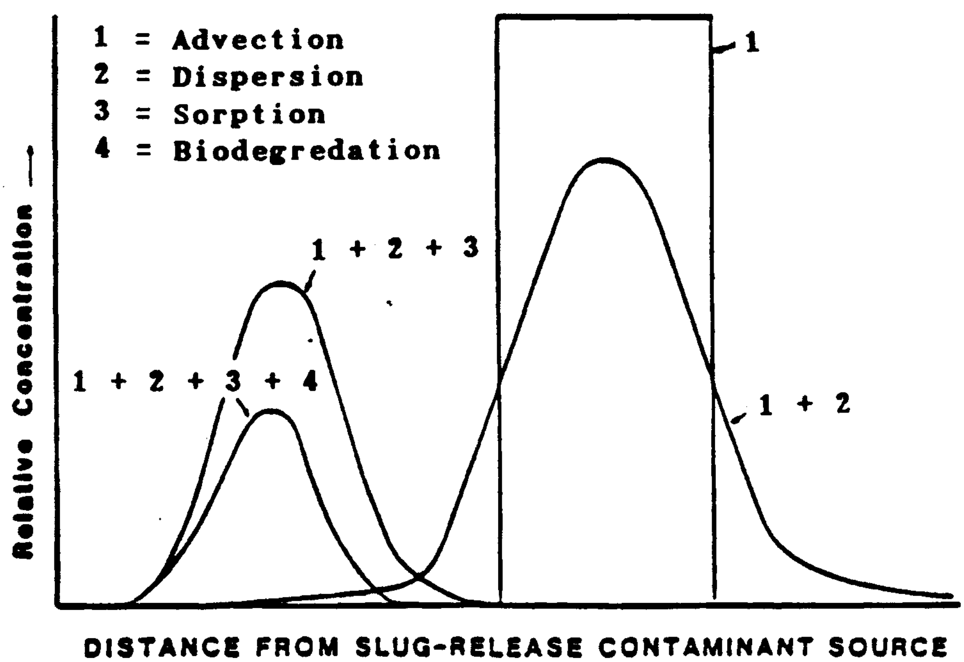


Figure C10. Influence of Natural Processes on Levels of Contaminants (Modified After Palmer and Johnson, 1989)

Figure C2. Several different scenarios of tracer studies have been conducted at the site since 1986 using chemical ions and fluorescent dyes. In all cases, a slug release contaminant source was utilized instead of a continuous release source to realistically replicate field conditions. Agricultural chemicals are applied in bulk at specific times not gradually over time. From these tests, information about both aquifer hydraulics and aquifer geochemical characteristics was collected. Tracer tests conducted at the Perkins Station have rendered specific information on velocity distribution and dispersivity properties for the lower terrace deposits of the Perkins Station.

Dispersivity Properties Concentration breakthrough curves are obtained from tracer tests by graphing time versus normalized concentrations of tracer chemicals. A textbook example of a breakthrough curve is shown in Figure C9. In the graph, the concentration increases gently in a S shaped curve rather than an abrupt step function. In a typical velocity dominated concentration distribution (due to convection alone), a sharp concentration front with concentrations throughout the plume equal to the input concentration is expected. The influence of natural processes on levels of contaminants detected downgradient from a slug release source are shown in Figure C10. The arrival of the center of mass is the result of advection while the spread of the curve is the result of dispersion.

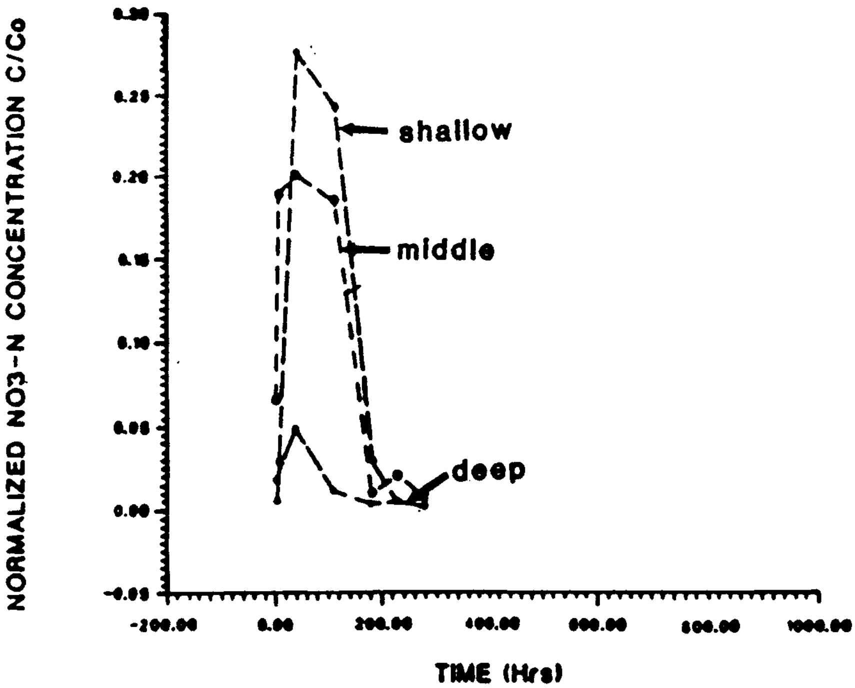


Figure C11. Nitrate Breakthrough Curve for 1988 Tracer (Modified After Dwivedi, 1989)

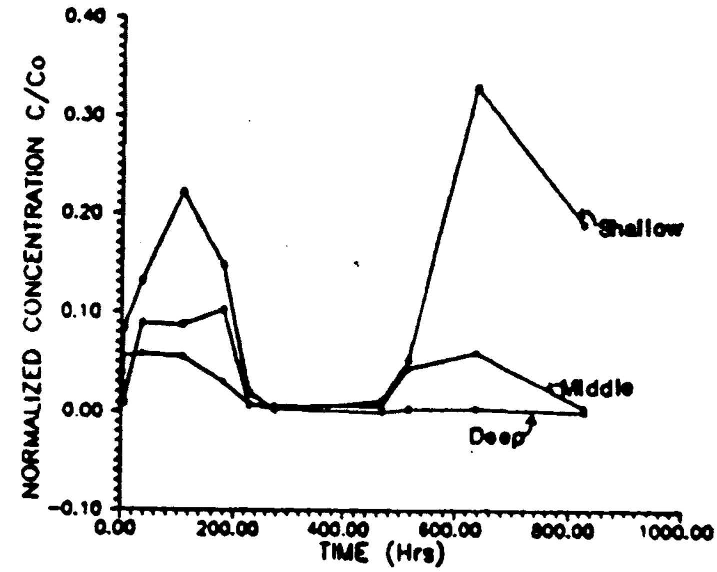


Figure C12. Chloride Breakthrough Curve for 1988 Tracer (Modified After Dwivedi, 1989)

Nitrate and chloride breakthrough curves were constructed for observation well #15 for the 1988 tracer test (see Figures C11 and C12). The distinct bell shaped curves indicate that dispersion along with convection are the physical processes responsible for solute transport. Although samples taken at discreet depths (shallow, middle, deep) within single and clustered observation wells differed in concentration, the arrival times of the chemicals peaks did not vary with depth. The same effects were noticed in the breakthrough curves constructed for the more recent 1992 tracer test (see Figure C13). The lack of differences in arrival times at different depths indicate that there are apparently no differential flowpaths associated with the saturated zone of the alluvial deposits. Therefore, even mixing of solutes throughout the saturated column is assumed.

Velocity Distribution The hydraulic conductivity of aquifer materials can be found by calculating velocity distribution based on the arrival times of chemicals in observation wells during tracer tests. There are two basic methods of velocity calculation: Darcian velocity (average linear discharge) and Seepage velocity (specific discharge).

Darcian velocity is an apparent velocity calculated from Darcy's Law which represents the flow rate at which water would flow in an aquifer if the aquifer were an open conduit (Fetter, 1988). Simply stated, when water flows

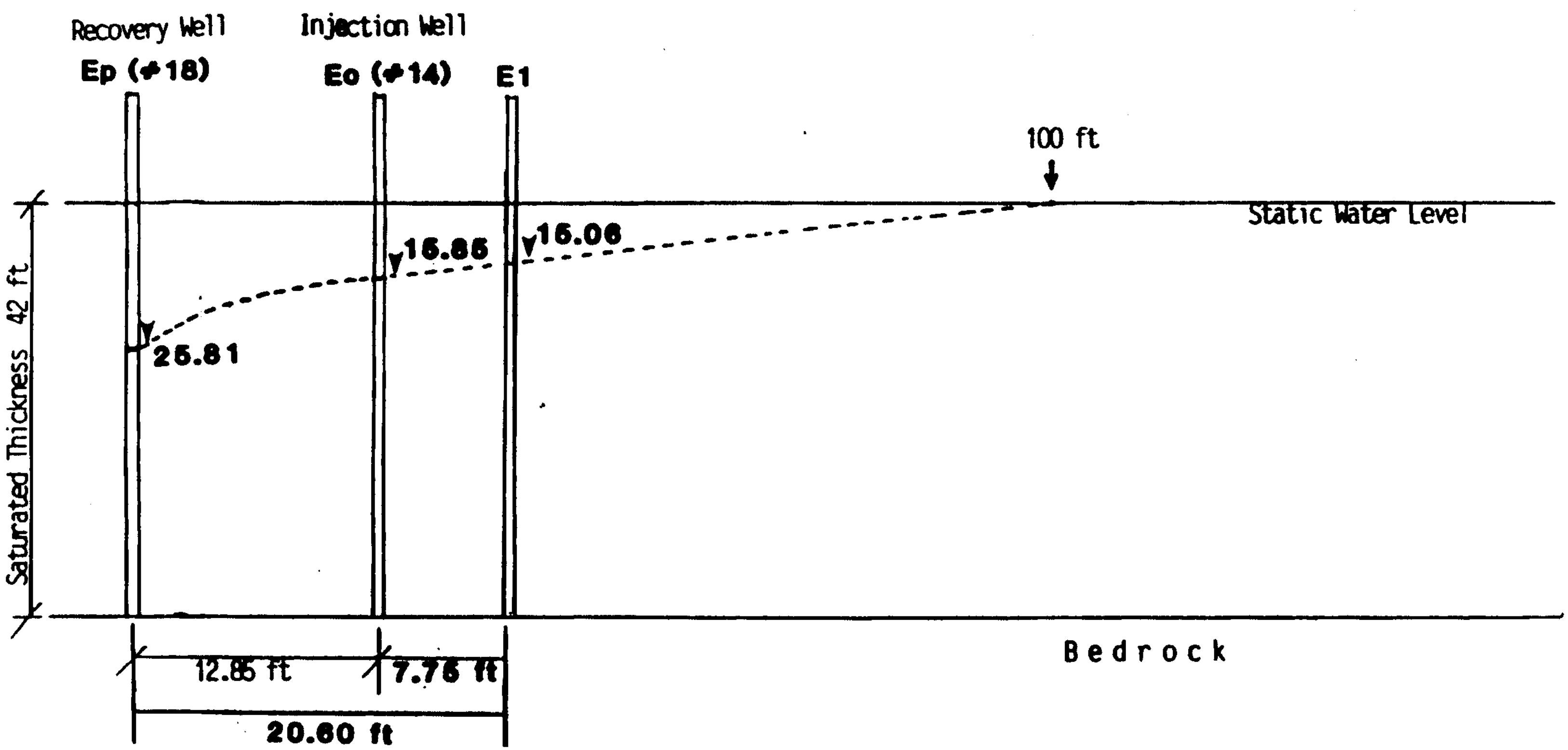


Figure C14. Schematic for Tracer Test

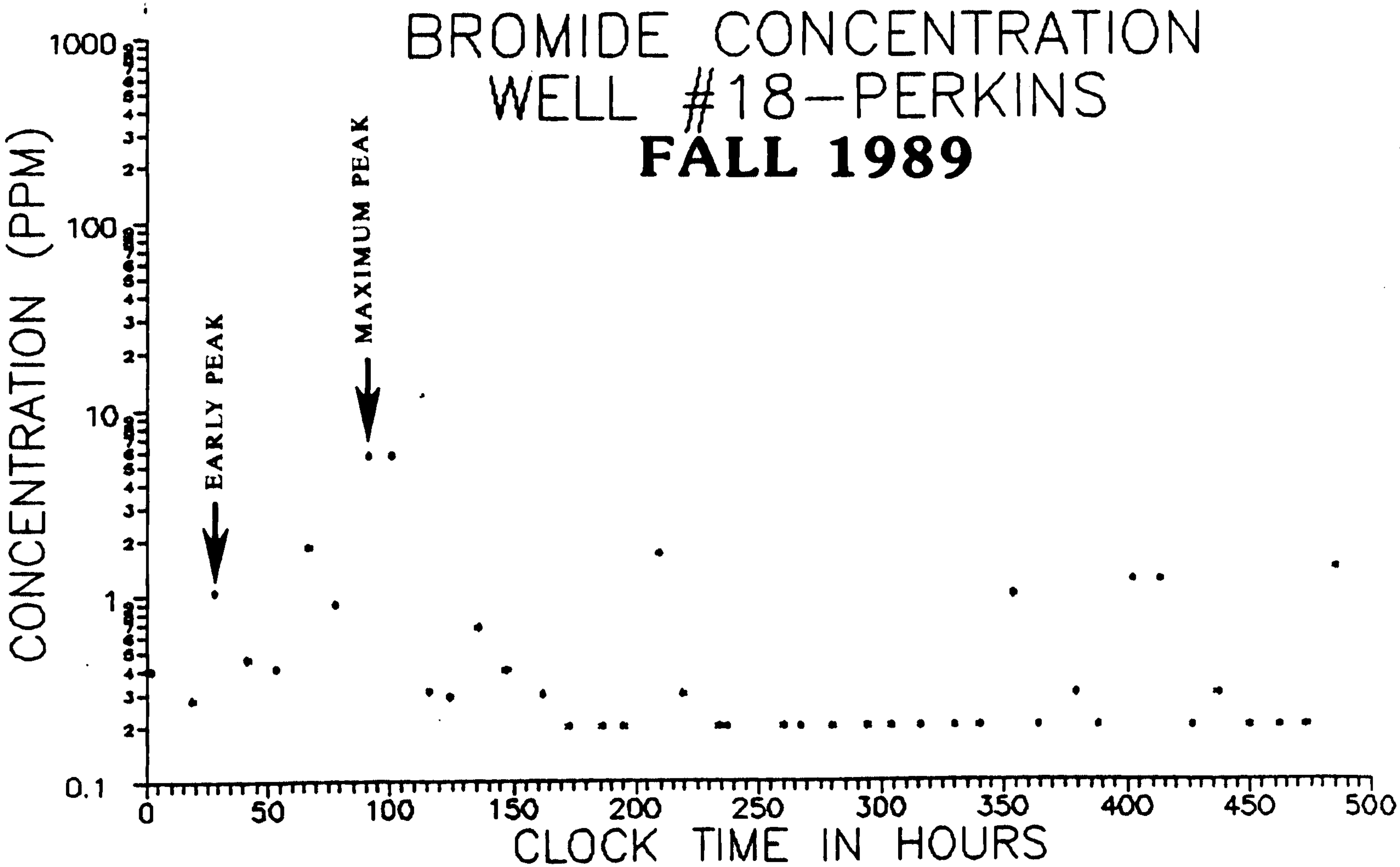


Figure C15. Bromide Concentration in Monitoring Well #18 in Fall 1989 Tracer Test

through an open pipe, the discharge is equal to the product of the velocity and the cross-sectional area of the pipe.

$$Q = V * A \quad \text{or} \quad V = \frac{Q}{A}$$

Darcy's Law (Fetter, 1988) states that: $Q = K\,A\,\frac{dh}{dl}$

Substituting renders **Darcian velocity**: $V = \frac{Q}{A} = K\,\frac{dh}{dl}$

Therefore, hydraulic conductivity (K) is the found by dividing the velocity (V) of a chemical in a tracer test by the gradient (I = dh/dl) obtained during the tracer test.

Seepage velocity is the rate of movement of fluid particles through the aquifer material (Fetter, 1988) when restricted to the voids. Effective porosity of the aquifer material must be accounted for since water can only move through the pore spaces. Therefore, Darcian velocity must be divided by effective porosity (n) to render seepage velocity.

Seepage velocity : $V = \frac{K}{n}\,\frac{dh}{dl}$

Therefore, hydraulic conductivity (K) is the product of the velocity (V) of a chemical in a tracer test and the effective porosity (n) of the aquifer material divided by the gradient (I = dh/dh) obtained during a tracer test.

Calculations of chemical tracer velocities for the tracer test conducted in the spring of 1989 utilized the arrival times at specific observation wells located in the groundwater flowpath between the source well and the pumping well. The source well (#14) is located 12.85 feet from the pumping well (#18) (see Figure C14).

The first arrival time of the bromide pulse at the pumping well was 30 hours (see early peak in Figure C15) . The Seepage and Darcian velocity equations were used to calculate hydraulic conductivity values ranging from 231 to 769 gpd/ft2 for bromide (see Figure C16). The maximum peak arrival time of the bromide pulse at the pumping well was determined to be 90 hours (see Figure C15). The Seepage andDarcian velocity equations were used to calculate hydraulic conductivity values ranging from 77 to 257 gpd/ft2 forbromide (see Figure C17).

A gradient of 0.10 was established with pumping (see Figure C14). Resultant velocity was 10 ft/day (see Figure C16). The natural gradient in the southern half of the station is 0.01; therefore, the tracer velocity would be reduced to approximately 0.1 ft/day.

Results of the velocity method calculations are tabulated in Table C4. Seepage velocity appears to be associated with the front edge of a slug release breakthrough curve affected by dispersion (see Figure C10). The hydraulic conductivity calculated for the first arrival of the Bromide tracer in MW # 18 by the Seepage velocity method correlates closely to the hydraulic conductivity values calculated from aquifer tests. Darcian velocity appears to be associated with the principle mass of a slug

Figure C16. Travel Time for First Arrival of Concentration of Bromide in Well #18

T = 30 hours
dl = 12.85 ft

$V = \frac{dl}{T} = \frac{12.85\ ft}{30\ hr} = 0.428\ ft/hr = 10.28\ ft/day$

dh = 15.85 - 15.06 = 0.79 ft
dl = 7.75 ft

$I = \frac{dh}{dl} = 0.10$ n = 0.30

Darcian

$K = \frac{V}{I} = 102.8\ ft/day \times 7.48\ g/ft3$ K = 769 gpd/ft2

Seepage

$K = \frac{V}{I} * n = 30.84\ ft/day \times 7.48\ g/ft3$ K = 231 gpd/ft2

Measured K from aquifer tests ranges:

447 gpd/ft2	to	357 gpd/ft2
by the		by the
Jacob Method		Prickett Method

Figure C17. Travel Time for Maximum Peak of Concentration of Bromide in Well #18

T = 90 hours
dl = 12.85 ft

$$V = \frac{dl}{T} = \frac{12.85\ ft}{90\ hr} = 0.143\ ft/hr = 3.43\ ft/day$$

dh = 15.85 - 15.06 = 0.79 ft
dl = 7.75 ft

$$I = \frac{dh}{dl} = 0.10 \qquad n = 0.30$$

Darcian

$$K = \frac{V}{I} = 34.3\ ft/day \times 7.48\ g/ft3 \qquad K = 257\ gpd/ft2$$

Seepage

$$K = \frac{V}{I} * n = 10.29\ ft/day \times 7.48\ g/ft3 \qquad K = 77\ gpd/ft2$$

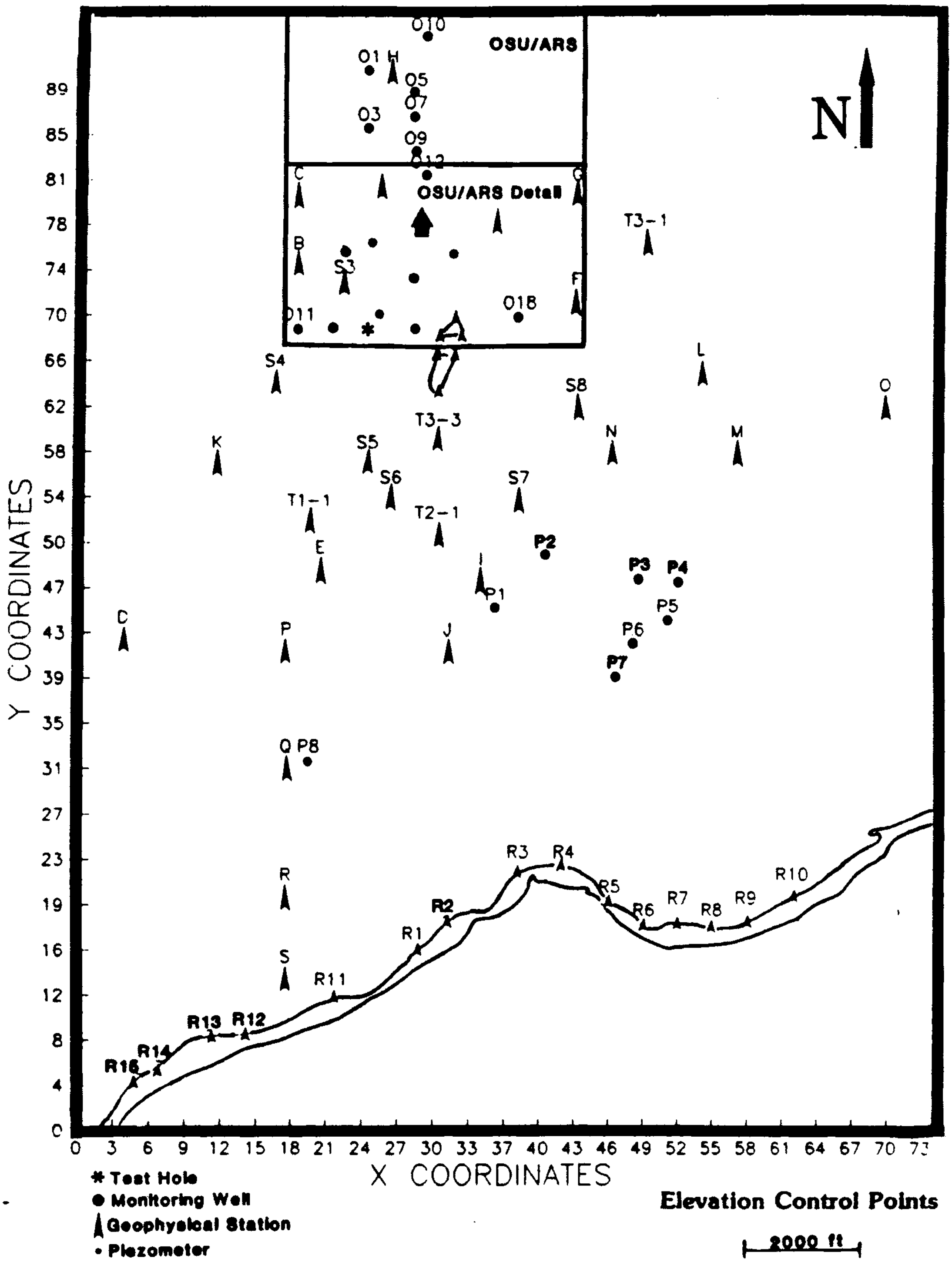
Measured K from aquifer tests ranges:

447 gpd/ft2 by the Jacob Method to 357 gpd/ft2 by the Prickett Method

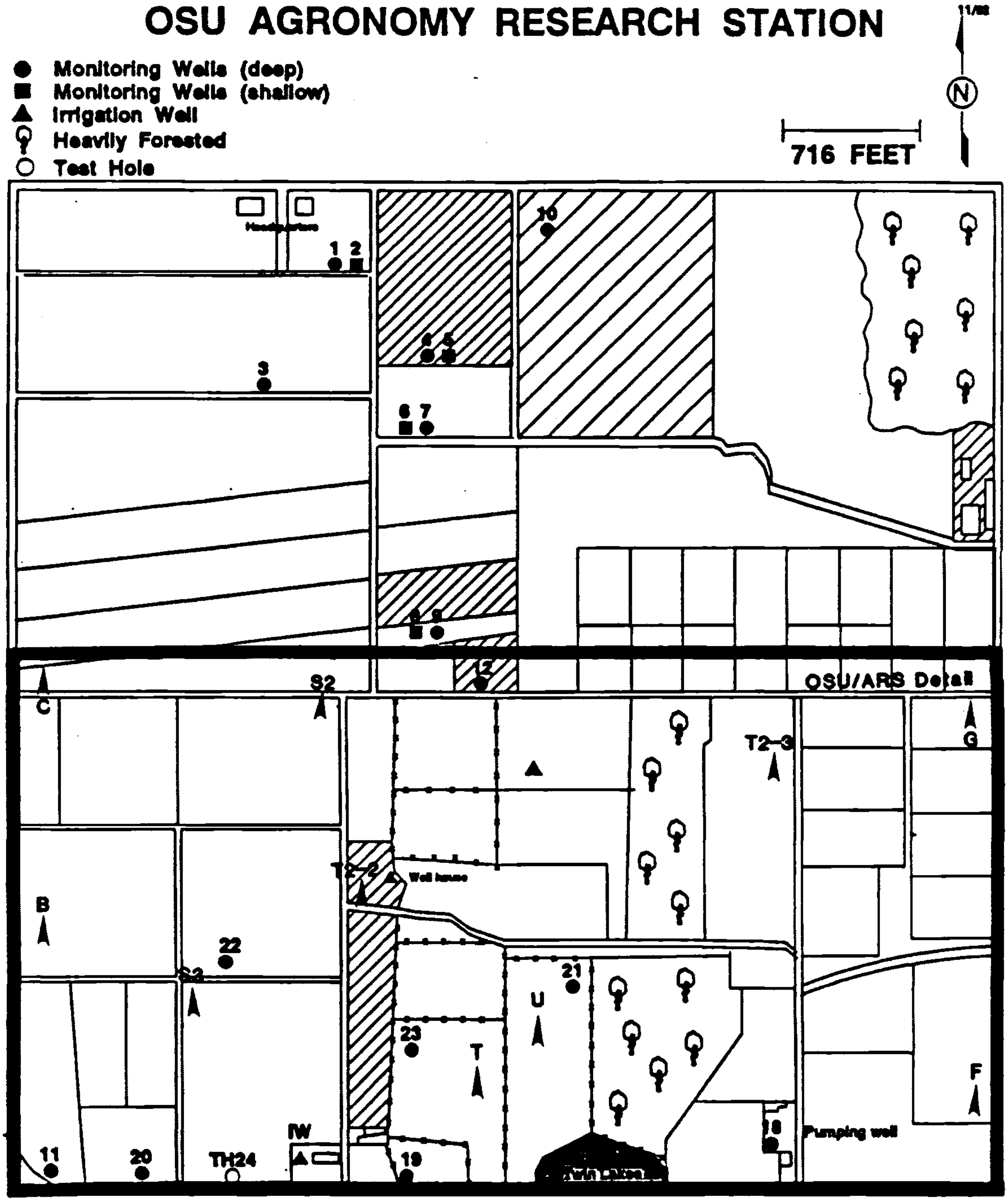
release breakthrough curve (see Figure C10) when the maximum concentration of a tracer chemical is observed in the well. The hydraulic conductivity calculated for the maximum peak arrival of the Bromide tracer in MW #18 by the Darcian velocity method correlates closely to the hydraulic conductivity values calculated from aquifer tests.

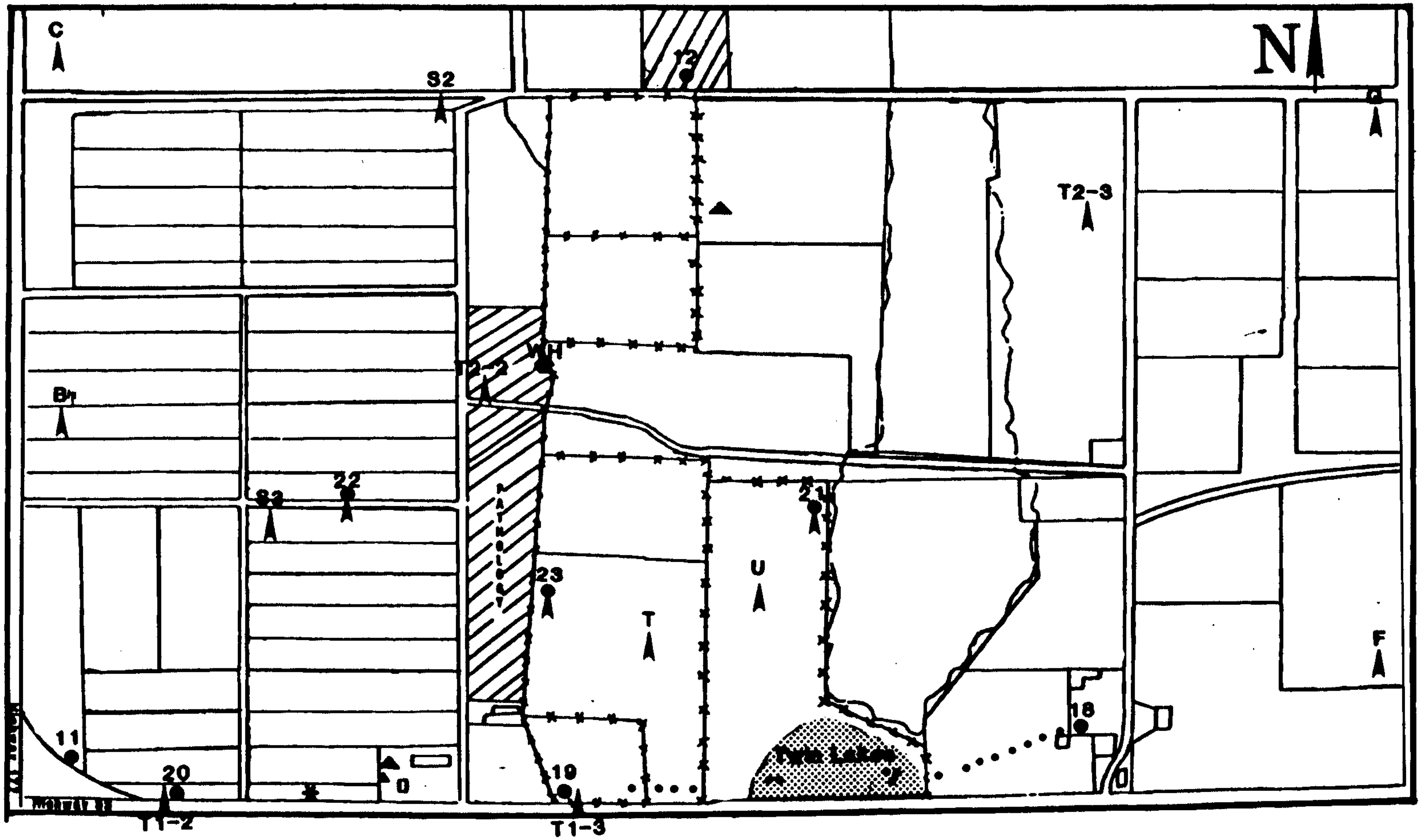
APPENDIX D

CONTOURING DATA


OSU/ARS
OSU/ARS Detail
N
Y COORDINATES
X COORDINATES
* Test Hole
● Monitoring Well
Geophysical Station
• Piezometer
Elevation Control Points
2000 ft

OSU AGRONOMY RESEARCH STATION





* Test Hole
● Monitoring Well
Geophysical Station
• Piezometer

OSU/ARS Detail

ELEVATIONS FOR PERKINS REGION

D = D.C. Resistivity
Sm = Seismic
L = Driller/Gamma Ray Log
(D) = Deep Well (35-50ft)
W = Collected DTW data converted to PSELEV
N/A = Not available or Not applicable

Su = Surveyed with Transit
T = Topo Map
C = Previous class data
(S) = Shallow Well (20-35ft)

A. CONSTANT CONTROL

CONTROL POINT LABEL	TOP OF CASING ELEVATION(FT)	DEPTH TO BEDROCK FROM SURFACE (FT)	TOTAL DEPTH FROM SURFACE (FT)
OSU/ARS Monitoring Wells			
01 (D)	970.92Su	30 L	30 L
02 (S)	971.08Su	N/A	25 L
03 (D)	962.11Su	25 L	25.5 L
04 (D)	963.84Su	46.5 L	47 L
05 (S)	964.60Su	N/A	25 L
06 (S)	959.95Su	N/A	25 L
07 (D)	959.85Su	35 L	39.5 L
08 (S)	943.94Su	N/A	25 L
09 (D)	943.44Su	35 L	35.5 L
010 (D)	978.57Su	39 L	39.5 L
011 (D)	910.34Su	51 L	51.5 L
012 (D)	927.33Su	51 L	51.5 L
018 (D)	913.95Su	57 L	58.2 L
019 (D)	919.74Su	N/A	34.2 L
020 (S)	910.57Su	N/A	25 L
021 (D)	917.22Su	N/A	40 L
022 (S)	915.53Su	N/A	35.25 L
023 (D)	915.28Su	36 L	36.5 L
TH24	913.27Su	49 L	Not Completed
Piezometers (Cross Section Through Pond)	Locations indicated only on OSU Station Detail map		
P2	912.83Su	N/A	15 L
P3	911.16Su	N/A	14 L
P4	905.04Su	N/A	8 L
P5	902.76Su	N/A	7 L
P6	902.49Su	N/A	6.5 L
P7	900.68Su	N/A	7 L
P8	901.30Su	N/A	8 L
P11	901.42Su	N/A	11.5 L
P11b	898.45Su	N/A	4 L
P11c	898.71Su	N/A	8 L
P11d	898.72Su	N/A	6 L
P12	898.73Su	N/A	8.5 L
P12b	899.96Su	N/A	2.5 L

CONTROL POINT LABEL	TOP OF CASING ELEVATION(FT)	DEPTH TO BEDROCK FROM SURFACE (FT)	TOTAL DEPTH FROM SURFACE (FT)
P12c	899.95Su	N/A	4 L
P13	899.80Su	N/A	12.5 L
P14	900.54Su	N/A	7.5 L
P15	906.67Su	N/A	20 L
Well House			
WH	917.35Su	N/A	N/A
Irrigation Well			
IW	912.88Su	N/A	N/A

B. GEOPHYSICAL CONTROL

CONTROL POINT LABEL	SURFACE ELEVATION(FT)	BEDROCK ELEVATION(FT)	WATER TABLE ELEVATION(FT)
OSU/ARS Monitoring Wells			
01	970.92Su	938.92*D	950.92*D
02	971.08Su	N/A	N/A
03	962.11Su	937.11*L	N/A
04	963.84Su	919.84*D	940.84*D
05	964.60Su	N/A	N/A
06	959.95Su	N/A	947.85*D
07	959.85Su	923.85*D	N/A
08	943.94Su	N/A	927.44*D
09	943.44Su	907.44*D	N/A
010	978.57Su	939.57*D	958.57*D
011	910.34Su	858.34*D	879.34*D
012	927.33Su	876.33L	N/A
018	913.95Su	857.00L	N/A
019	919.74Su	N/A	N/A
020	910.57Su	859.00L	N/A
021	917.22Su	N/A	N/A
022	915.53Su	N/A	N/A
023	915.28Su	878.78L	N/A
TH24	913.27Su	864.27L	N/A

CONTROL POINT LABEL	SURFACE ELEVATION(FT)	BEDROCK ELEVATION(FT)	WATER TABLE ELEVATION(FT)
Geophysical Team Sites			
Fall '91			
(Team 1 Site 1 = T1-1)			
T1-1	898.00T	870.00Sm	888.00*D,Sm
T1-2	908.00T	858.00D,Sm	879.00D
T1-3	920.00T	884.00D,Sm	892.00D
T2-1	912.00T	882.00*D	894.00*D
T2-2	912.00T	867.00*D	894.00*D
T2-3	908.00T	878.00*D	902.00*D
T3-1	929.00T	879.00*D	889.00*D
T3-3	899.00T	851.00*D	879.00*D
Geophysical Stations 1-8			
Fall '90			
S1	933.00Su	881.00D	903.00*D
S2	914.60Su	876.60*D	892.60*D
S3	914.60Su	875.60*D	894.60*D
S4	891.80Su	851.80*D	873.80*D
S5	906.80Su	851.80*D	890.80*D
S6	907.09Su	857.09*D	889.09*D
S7	909.00Su	854.00*D	889.00*D
S8	908.35Su	863.35*D	892.35*D
Geophysical Station A to S			
Fall '88 - Spr '91			
B	915.00C	860.00C	893.00C (FALL '88)
C	920.00C	875.00C	908.00C "
D	870.00C	826.00C	850.00C "
E	895.00C	847.00C	865.00C "
F	910.00C	860.00C	882.00C "
G	925.00C	877.00C	900.00C "
H	960.00C	912.00C	940.00C "
I	910.00C	866.00C	883.00C "
J	885.00C	837.00C	863.00C "
K	895.00C	846.00C	873.00C "
L	910.00C	874.00C	885.00C "
M	900.00C	873.00C	881.00C "
N	910.00C	850.00C	883.00C "
O	915.00C	872.00C	896.00C "
P	885.00C	833.00*D	873.00*D "
Q	846.00C	814.00*D	826.00*D "
R	840.00C	810.00Sm	828.00*D "
S	838.00C	806.00*D	822.00*D "
T	901.13Su	866.13D	891.13D (SPR '91)
U	912.13Su	867.13D	900.13D "

C. MISCELLANEOUS CONTROL

City of Perkins Wells			
P1	897.00C	853.00L	873.30C (FALL '88)
P2	905.00C	N/A	871.00C "
P3	895.00C	N/A	868.50C "
P4	895.00C	N/A	861.00C "
P5	886.00C	824.80L	858.20C "
P6	884.00C	839.70L	860.20C "
P7	875.00C	N/A	854.00C "
P8	850.00C	820.00L	839.00C "
Elevations to Represent the Cimmarron River			
R1 to R15	N/A	805.00T	825.00T
Elevations to Represent Twin Lakes			
L1 to L6	N/A	N/A	898.65 (8/92) Staff Gage

CONTROL POINT LABEL	TOP OF CASING ELEVATION(FT)	DEPTH TO WATER 7/14/92	8/07/92
OSU/ARS Monitoring Wells			
01 (D)	970.92Su	18.50 W	18.51 W
02 (S)	971.08Su	18.65 W	18.65 W
03 (D)	962.11Su	16.30 W	15.95 W
04 (D)	963.84Su	16.45 W	16.12 W
05 (S)	964.60Su	17.18 W	16.83 W
06 (S)	959.95Su	15.72 W	15.40 W
07 (D)	959.85Su	15.61 W	15.30 W
08 (S)	943.94Su	14.85 W	14.64 W
09 (D)	943.44Su	14.26 W	14.05 W
010 (D)	978.57Su	18.22 W	18.30 W
011 (D)	910.34Su	24.76 W	24.70 W
012 (D)	927.33Su	30.18 W	29.61 W
018 (D)	913.95Su	13.29 W	13.22 W
019 (D)	919.74Su	23.07 W	22.89 W
020 (S)	910.57Su	24.13 W	24.07 W
021 (D)	917.22Su	20.17 W	20.24 W
022 (S)	915.53Su	26.01 W	25.93 W
023 (D)	915.28Su	23.82 W	23.74 W
Piezometers (Cross Section Through Pond)			
P2	912.83Su	12.22 W	
P3	911.16Su	10.85 W	
P4	905.04Su	5.20 W	
P5	902.76Su	2.86 W	
P6	902.49Su	2.65 W	
P7	900.68Su	1.00 W	
P8	901.30Su	2.00 W	
P11	901.42Su	2.74 W	
P11b	898.45Su	IN POND	
P11c	898.71Su	IN POND	
P11d	898.72Su	IN POND	
P12	898.73Su	UNDER WATER	
P12b	899.96Su	IN POND	
P12c	899.95Su	IN POND	
P13	899.80Su	UNDER WATER	
P14	900.54Su	UNDER WATER	
P15	906.67Su	15.32 W	
Well House			
WH	917.35Su	28.60 W	
Irrigation Well			
IW	912.88Su	26.81	

APPENDIX E

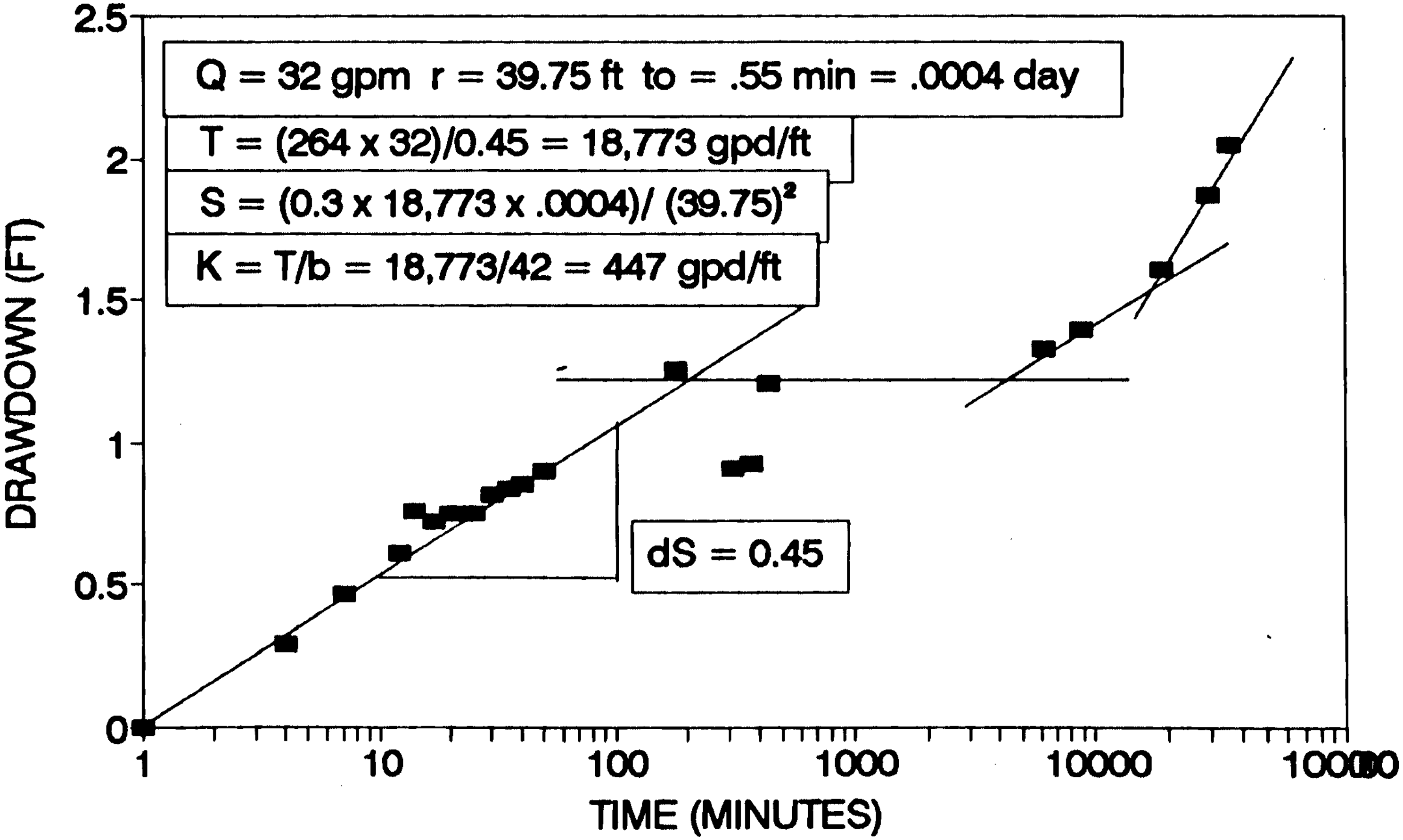
AQUIFER TEST PLOTS

AQUIFER TEST DATA - FALL 1989

Q=32gpm	DRAWDOWN (FT)				DRAWDOWN (FT)	
Time(min	MW E2 r = 40 ft	MW E3 r = 80 ft		Time(min	MW E2	MW E3
0	0.00	0.00				
4	0.29			50	0.90	
7	0.46			176	1.26	
12	0.61	0.18		178		0.86
14	0.76			308	0.91	
16		0.25		309		0.84
17	0.72			369	0.93	
20	0.75			372		0.84
22		0.30		433	1.21	
25	0.75			436		0.85
30	0.82			6044	1.33	
32		0.36		6046		0.86
35	0.84			8640	1.40	0.97
38		0.40		18720	1.61	1.16
40	0.86			28800	1.87	1.31
45		0.43		34860	2.05	1.54

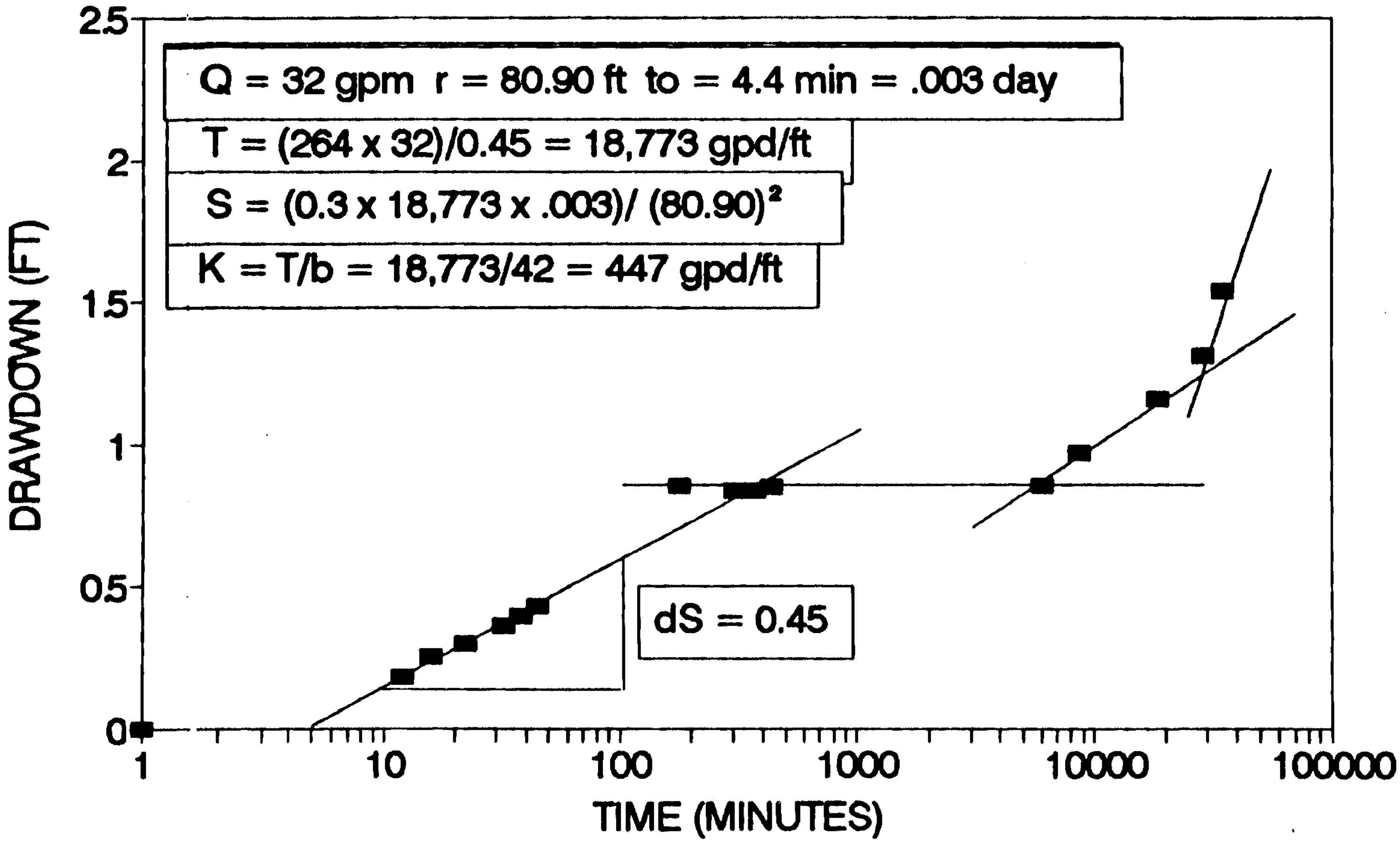
JACOB ANALYSIS PLOT

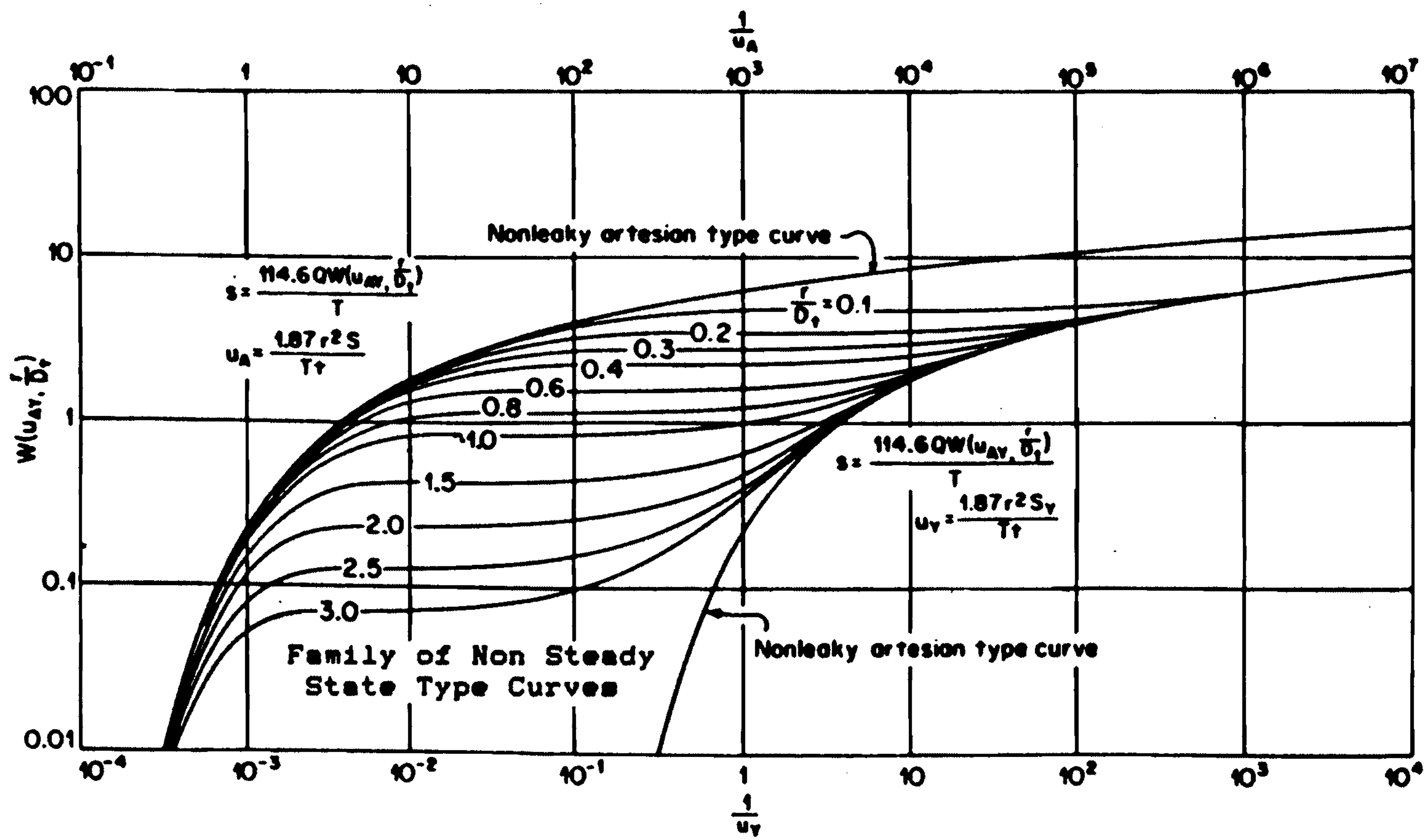
OBSERVATION WELL E2



JACOB ANALYSIS PLOT

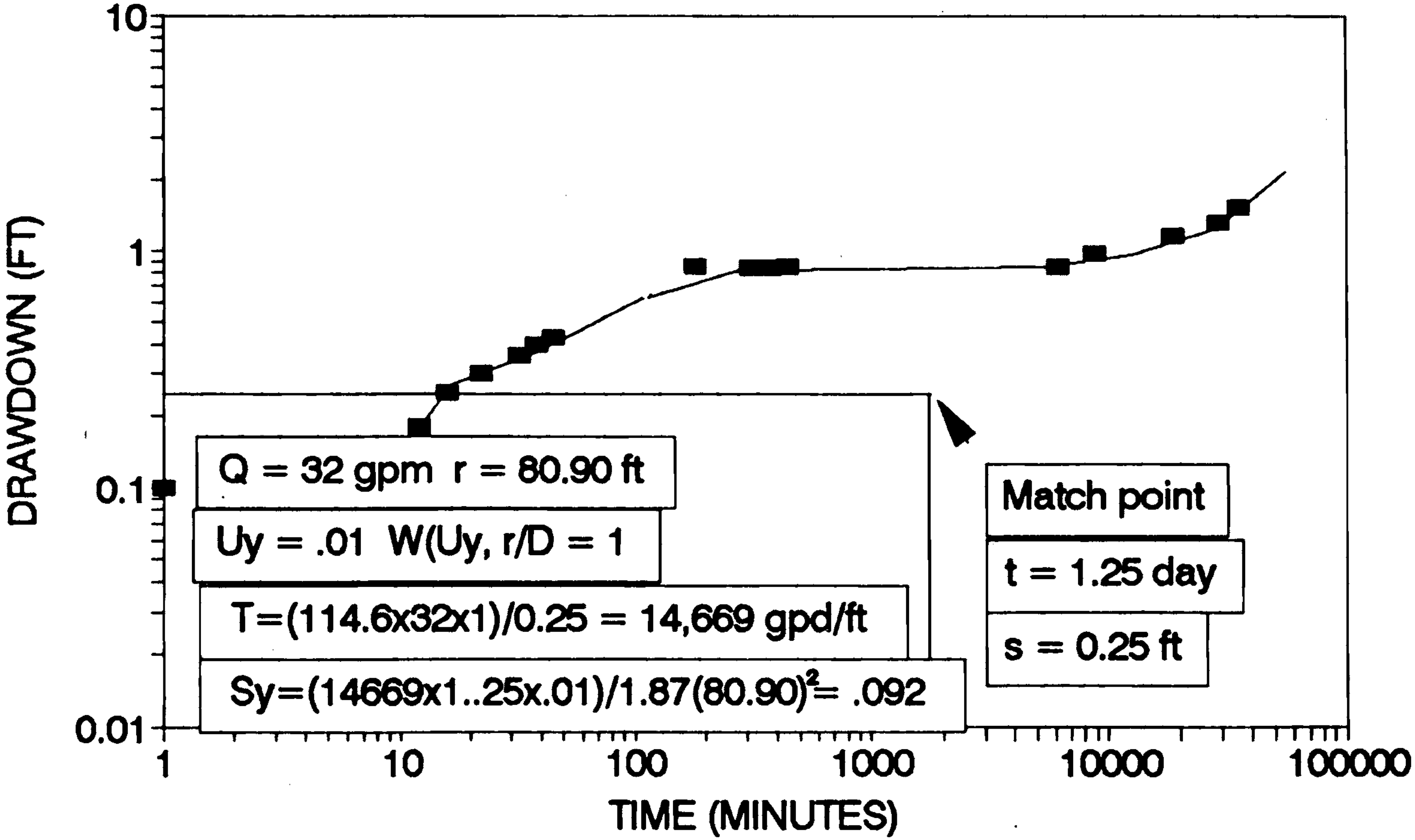
OBSERVATION WELL E3



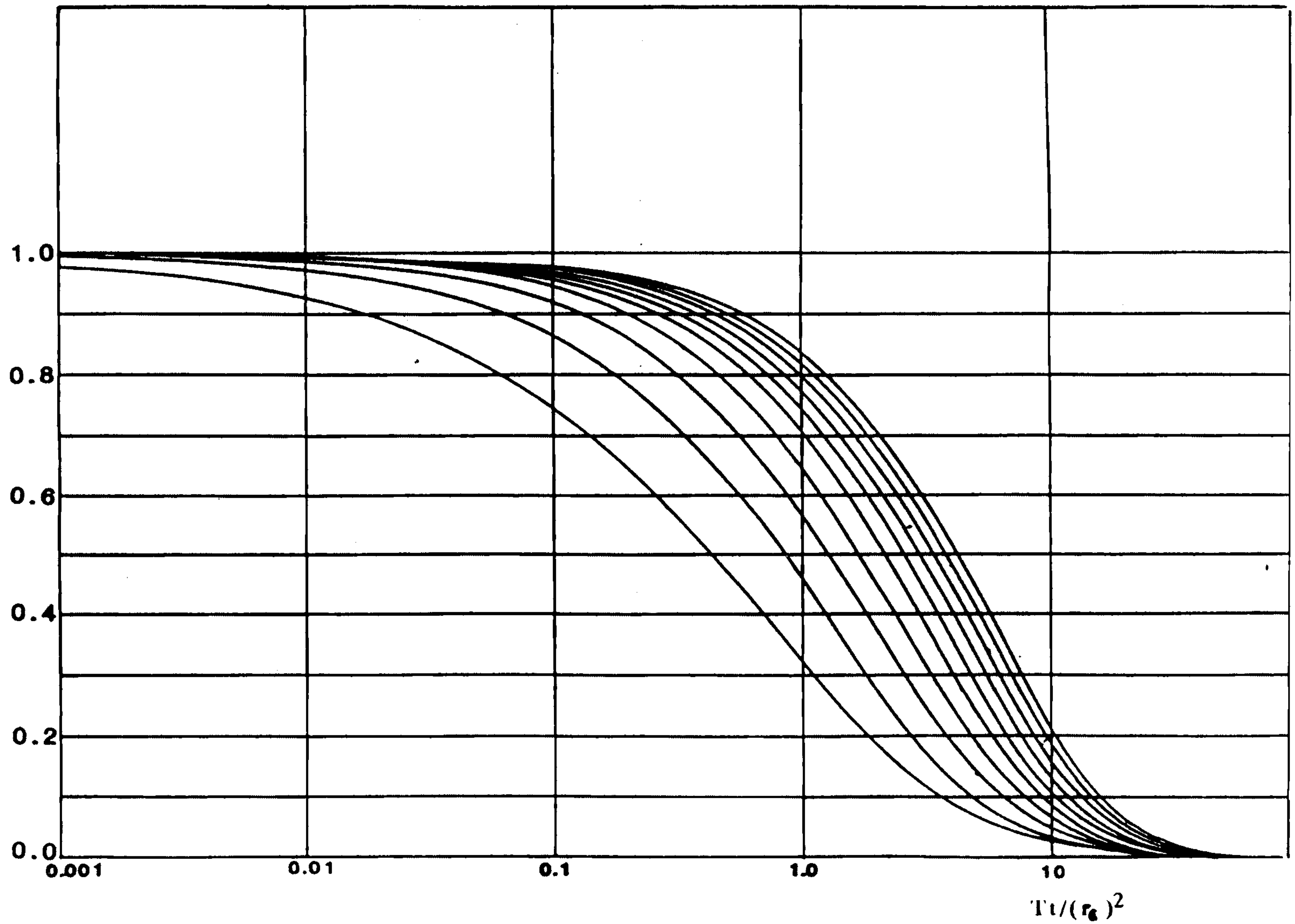


Water-table, fully penetrating, constant-discharge, time-drawdown type curves.
Modified after Prickett, 1965)

PRICKETT ANALYSIS PLOT
OBSERVATION WELL E3



Type Curves for Slug Test Data



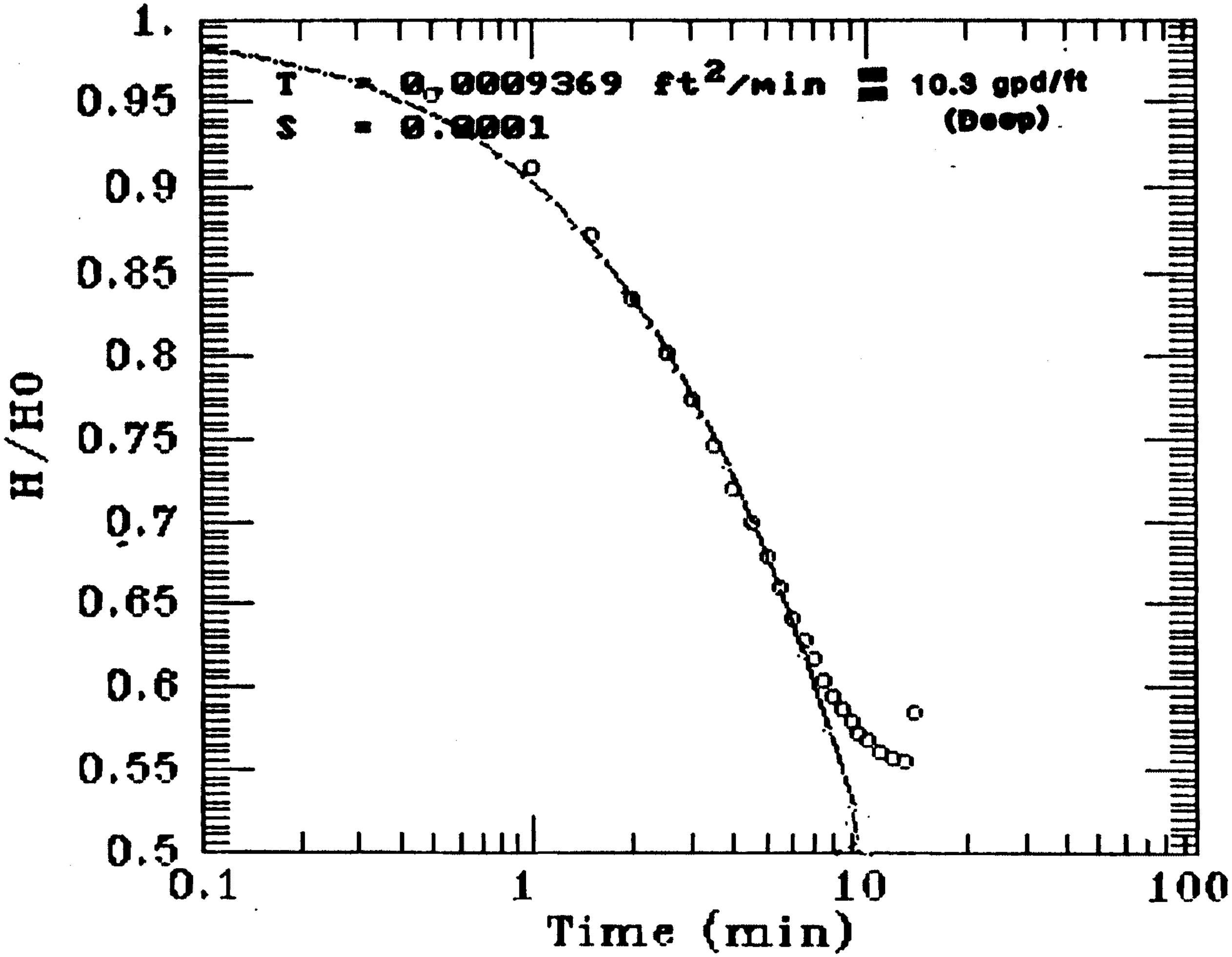
Site Characterization Field Trip
Perkins Agricultural Research Station
June 27, 1992
Slug Test - Monitoring Well 4 - Group A
Static Water Level - 17.85 ft.

Seconds	Run 1 Depth	Run 2 Depth
0	32.30	26.90
30	30.82	25.78
60	29.44	25.30
90	28.19	24.61
120	26.95	24.05
150	25.95	23.48
180	25.00	22.97
210	24.10	22.50
240	23.28	22.03
270	22.58	21.63
300	21.92	21.25
330	21.30	20.90
360	20.75	20.57
390	20.30	20.27
420	19.92	19.98
450	19.52	19.76
480	19.21	19.57
510	18.95	19.38
540	18.70	19.22
570	18.51	19.07
600	18.36	18.93
660	18.12	18.69
720	18.00	18.50
780	17.94	18.33
840	17.91	18.22
900		18.12
960		18.06
1020		18.01

Conditions: Sunny, cool, breezy

Slug Test Analysis

MW# 4 6/92



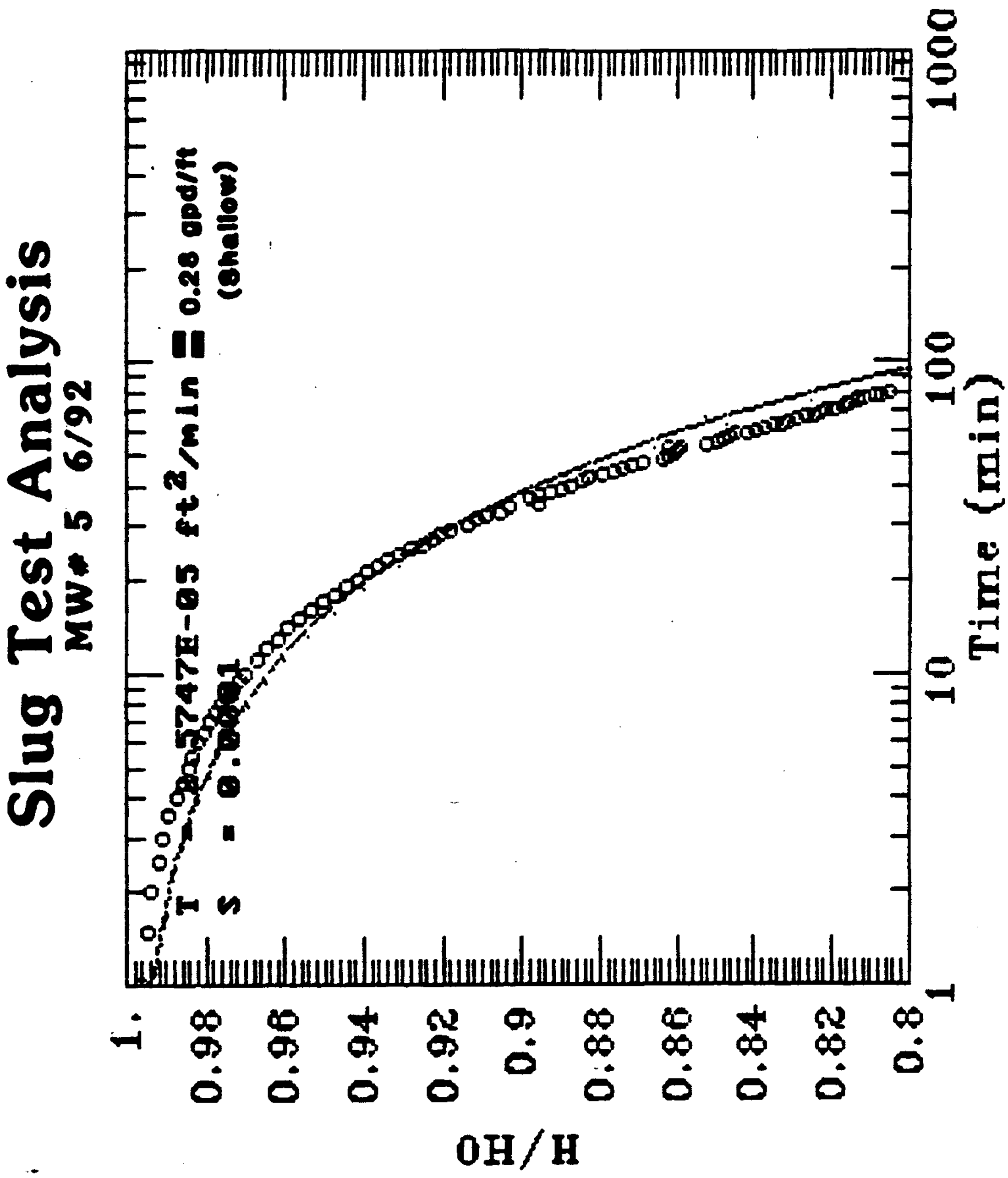
SLUG TEST

Perkins Agricultural Research Center
June 20, 1992

Monitoring Well No. 5

Seconds	Depth	Seconds	Depth
0	24.70	2100	22.12
30	24.55	2160	22.18
60	24.60	2220	22.13
90	24.57	2280	22.05
120	24.54	2340	21.98
150	24.50	2400	21.92
180	24.47	2460	21.85
210	24.43	2520	21.81
240	24.38	2580	21.71
270	24.35	2640	21.64
300	24.31	2700	21.59
330	24.29	(Minutes) 46	21.52
360	24.25	47	21.46
390	24.21	48	21.40
420	24.17	49	21.32
450	24.14	50	21.29
480	24.10	51	21.24
510	24.05	52	21.21
540	24.03	53	21.29
570	23.99	54	21.13
600	23.95	55	21.05
660	23.88	56	20.98
720	23.82	57	20.94
780	23.75	58	20.90
840	23.70	59	20.87
900	23.62	60	20.78
960	23.54	61	20.725
1020	23.48	62	20.675
1080	23.40	63	20.62
1140	23.33	64	20.57
1200	23.26	65	20.52
1260	23.19	66	20.465
1320	23.12	67	20.42
1380	23.06	68	20.37
1440	22.99	69	20.32
1500	22.92	70	20.275
1560	22.85	71	20.23
1620	22.79	72	20.18
1680	22.73	73	20.15
1740	22.67	74	20.14
1800	22.57	75	20.08
1860	22.52	76	20.08
1920	22.45	77	20.05
1980	22.37	78	19.97
2040	22.30	79	19.94
		80	19.88

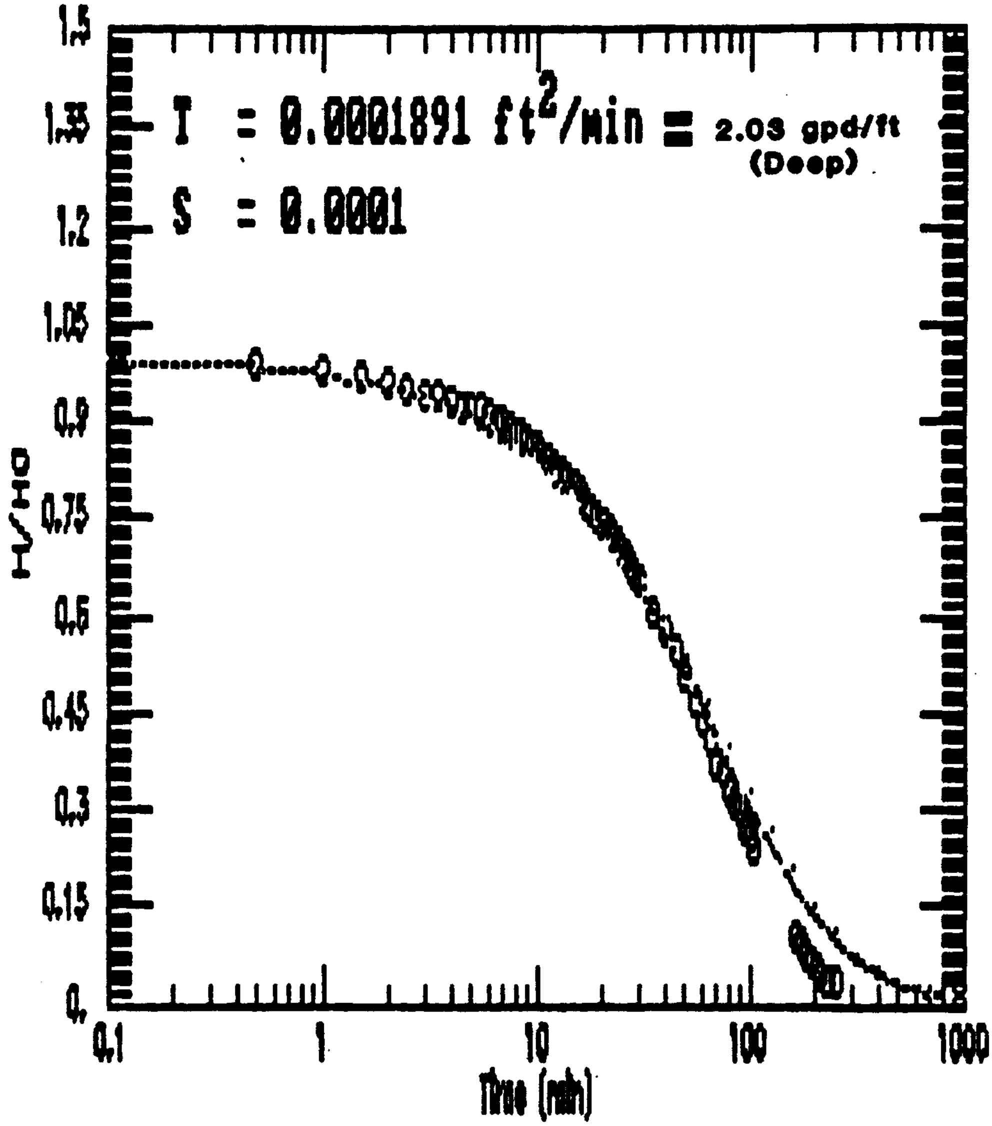
Static water level = 18.12 ft.

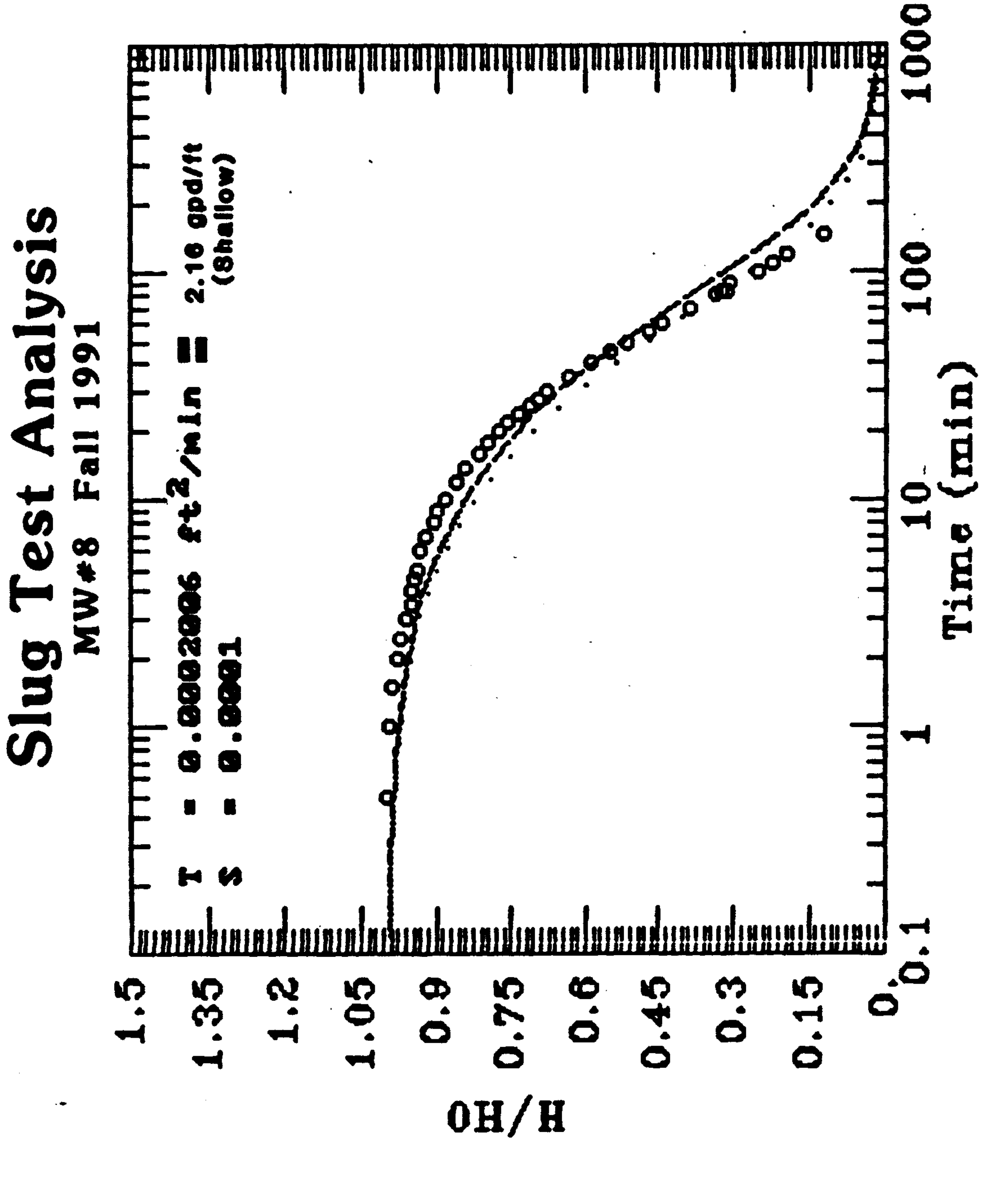


Slug Test Analysis
MW# 5 6/92
T = 5.5747E-05 ft^2/min = 0.28 gpd/ft
(Shallow)
S = 0.0001
H/HO
1.
0.98
0.96
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
1
10
100
1000
Time (min)

Slug Test Analysis

MW# 7 Fall 1991





Slug Test Analysis
MW#8 Fall 1991
T = 0.0002006 ft2/min = 2.16 gpd/ft
(Shallow)
S = 0.0001
H/H0
1.5
1.35
1.2
1.05
0.9
0.75
0.6
0.45
0.3
0.15
0
0.1
1
10
100
1000
Time (min)

APPENDIX F

COMPUTER MODELING PRINTOUTS

COEFFCIENTS AND PARAMETERS FOR SOLUTE TRANSPORT COMPUTER RUN

Run: Solute Transport - January 1992 thru January 1993
Filename: CONC8
First pumping period = 6 months of fertilizer infiltration
(active concentration matrices)
Second pumping period = 6 months of infiltration
(inactive concentration matrices)

HYDRAULIC: TITLE AND FLAGS

1) TITLE = Solute Transport - Jan 1992 to Jan 1993

2) IHEAD = 0 (Head Calculation + Solute Transport)

3) ISOLV = 0 (ADIP)

4) ITP = 1 (Hydraulic Conductivity)

5) IXSECT = 0 (Plannar)

6) FCON = 1 (Unconfined)

7) NCYC = 0

8) CHKDTA = 0

HYDRAULIC: LIMITS

1) NPMP = 2 (6 months each - Spring and Fall Seasons)

2) NX = 17

3) NY = 17

4) XDEL = 264 ft

5) YDEL = 264 ft

6) NTIM = 6 (one month each)

7) ITMAX = 50

8) NITP = 4

HYDRAULIC: PRINT

1) NPNT = 1

2) NPNTVL = 0

3) NPNTD = 0

4) NPNCHV = 0

5) NSTRT = 0

HYDRAULIC: CONSTANTS

1) PINT = 0.50

2) TOL = 0.01

3) POROS = 0.40

4) S = 0.40

5) TIMX = 1

6) TINIT = 2.6E6 (one month in seconds)

7) ANFCTR = 1

8) SS = NOT REQUIRED

9) QET = 0

10) ETDPTH = 0

11) SATLM = 0

12) RVDPTH = 0

13) RAREA = 0

HYDRAULIC: OTHER

1) NSY = 0 (Specific Yield)

2) SYPRM = NOT REQUIRED

3) NCODES = 1

4) NUMOBS = 5

WELL LOCATIONS MENU:

#	X	Y	Monitoring Well
1	6	3	#12
2	12	12	#18
3	4	7	Well House
4	5	13	#19
5	8	9	#21

HYDRAULIC MATRICES: AQUIFER CHARACTERISTICS

1) WT = 1 (Variable Matrix), 1 (Multiplication Factor)

2) RIVER = NOT REQUIRED

3) LAND = 1 — 1 (Constant 20 ft to wt)

4) TOP = NOT REQUIRED

5) BTM = 1 — 1 (Constant m = 40 ft)

6) VPRM = 0 — 350 GPD/FT
5.42e-4 FT/SEC

7) SY = 0 — 0.40

HYDRAULIC MATRICES: AQUIFER STRESSES

1) PRIOR = NONE (No prior pumping)

2) REC = 1 (Variable Matrix), 1 (Multiplication Factor)
Injection/Pumping Rates

3) GRAD = 0.01

4) NODEID = 1 (Variable Matrix), 1 (Multiplier)
Node Identification Matrix

5) RECH = 6.10 inches = 15% of 40.44 inches

CHEMICAL: FLAGS

1) NDECAY = 1 (Decay Simulation)

2) NSORB = 0 (No Sorption Simulation)

CHEMICAL: LIMITS

1) NPMAX = 6400 (Maximum no. of particles to be used for transport)

2) NPTPND = 4 (Number of particles per node)

CHEMICAL: PRINT

1) NPNTMV = 0 (Print particle movement interval only at end of time step)

2) NPDELC = 0 (Do not print computed changes in concentration)

CHEMICAL: CONSTANTS

1) CELDIS = 0.5 (Maximum cell distance per particle move)

2) BETA = 100 (Longitudinal Dispersivity)

3) DLTRAT = 0.20 (Ratio of Transverse to Longitudinal Dispersivity)

CHEMICAL MATRICES: CONCENTRATIONS

1) CNRCH = 1 (Variable Matrix), 1 (Multiplier)
Injection Well Concentrations

2) CONC = 0 (Constant Value), 25 ppm
Initial Aquifer Concentration = Background Concentrations

HYDRAULIC: TITLE AND FLAGS PAGE 1 OF 3

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
1	TITLE	DESCRIPTION OF PROBLEM	(CURRENT VALUE ON NEXT LINE)		
		INITIAL CONDITIONS-JAN 1989 TO JAN 1990			
2	IHEAD	CONTROLS SOLUTE TRANSPORT SIMULATION 0-HYDRAULIC HEAD AND SOLUTE TRANSPORT 1-HYDRAULIC HEAD ONLY	0	1	1
3	ISOLV	ITERATIVE TECHNIQUE FOR SOLVING FLUID-FLOW EQUATION 0-ALTERNATING DIRECTION IMPLICIT PROC. (ADIP) 1-STRONGLY IMPLICIT PROC. (SIP)	0	1	0
4	ITP	CHOOSE INPUT OF TRANSMISSIVITY OR HYDRAULIC CONDUCTIVITY MATRIX 0-TRANSMISSIVITY 1-HYDRAULIC CONDUCTIVITY	0	1	1

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

HYDRAULIC: TITLE AND FLAGS PAGE 2 OF 3

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
5	IXSECT	CHOOSE TWO-DIMENSIONAL PERSPECTIVE OF SIMULATION 0-PLANAR SIMULATION 1-CROSS SECTIONAL SIMULATION	0	1	0
6	FCON	DESCRIBES CONDITIONS AT TOP OF AQUIFER 0-CONFINED (NECESSARY FOR CROSS SECTION) 1-UNCONFINED (WATER TABLE) 2-PARTIALLY CONFINED	0	2	1
7	NCYC	NUMBER OF PUMPING PERIODS IN A HYDRAULIC (SEASONAL) CYCLE	0	4	0

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

```
                         HYDRAULIC:   TITLE AND FLAGS              PAGE  3 OF  3
-------------------------------------------------------------------------------
#   VARIABLE                  DEFINITION                 MIN      MAX    CURRENT
-------------------------------------------------------------------------------

8   CHKDTA    CONTROLS CHECKING OF INITIAL DATA           0        1          0
               0-DO NOT END AFTER CHECK OF INITIAL DATA
               1-END MODEL SIMULATION AFTER CHECK OF INITIAL DATA
               (USE FOR DEBUGGING)
-------------------------------------------------------------------------------
ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->
```

```
                              HYDRAULIC:  LIMITS                PAGE  1 OF  2
-------------------------------------------------------------------------------
#   VARIABLE                  DEFINITION                 MIN      MAX    CURRENT
-------------------------------------------------------------------------------
1   NPMP      NUMBER OF PUMPING PERIODS                   1       40          1
              IF MORE THAN LIMIT IS DESIRED, USE RESTART OPTION

2   NX        NUMBER OF COLUMNS                           3       24         17
              (SPECIFY AS NEGATIVE IF A SMALLER, SECONDARY GRID
               FOR TRANSPORT IS TO BE USED)

3   NY        NUMBER OF ROWS                              3       24         17

4   XDEL      WIDTH OF FINITE-DIFFERENCE CELL IN X        0        -        264
              DIRECTION, IN FEET

5   YDEL      WIDTH OF FINITE-DIFFERENCE CELL IN Y        0        -        264
              DIRECTION, IN FEET
-------------------------------------------------------------------------------
ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->
```

```
                              HYDRAULIC:  LIMITS                PAGE  2 OF  2
-------------------------------------------------------------------------------
#   VARIABLE                  DEFINITION                 MIN      MAX    CURRENT
-------------------------------------------------------------------------------
6   NTIM      MAXIMUM NUMBER OF TIME STEPS IN             1      100         12
              PUMPING PERIOD   1

7   ITMAX     MAXIMUM NUMBER OF ITERATIONS FOR EACH       1      200         50
              TIME STEP IN PUMPING PERIOD   1

8   NITP      NUMBER OF ITERATION PARAMETERS FOR          1       16          4
              ADIP IN PUMPING PERIOD   1
-------------------------------------------------------------------------------
ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->
```

HYDRAULIC: PRINT PAGE 1 OF 2

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
1	NPNT	TIME STEP INTERVAL FOR PRINTING OUTPUT DATA IN PUMPING PERIOD 1	0	-	1
2	NPNTVL	CONTROLS PRINTING OF COMPUTED VELOCITIES IN PUMPING PERIOD 1 0-DO NOT PRINT 1-PRINT FOR FIRST TIME STEP 2-PRINT FOR ALL TIME STEPS	0	2	0
3	NPNTD	CONTROLS PRINTING OF COMPUTED DISPERSION EQUATION COEFFICIENTS IN PUMPING PERIOD 1 0-DO NOT PRINT 1-PRINT FOR FIRST TIME STEP 2-PRINT FOR ALL TIME STEPS	0	2	0

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

HYDRAULIC: PRINT PAGE 2 OF 2

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
4	NPNCHV	CONTROLS PRINTING VELOCITY DATA TO A SEPARATE FILE IN PUMPING PERIOD 1 0-DO NOT PRINT 1-PRINT FOR FIRST TIME STEP 2-PRINT FOR ALL TIME STEPS	0	2	0
5	NSTRT	CONTROLS USE OF RESTART FILE 0-RESTART FILE NOT USED 1-RESTART FILE USED	0	1	0

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

HYDRAULIC: CONSTANTS PAGE 1 OF 3

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
1	PINT	LENGTH OF PUMPING PERIOD 1 IN YEARS	0	-	1.0
2	TOL	CONVERGENCE CRITERIA IN ADIP AND SIP USUALLY <= 0.01	0	-	0.01
3	POROS	EFFECTIVE POROSITY	0	-	0.4
4	S	STORAGE COEFFICIENT (SET S=0 FOR STEADY FLOW PROBLEMS)	0	-	0.4
5	TIMX	TIME INCREMENT MULTIPLIER FOR TRANSIENT FLOW IN PUMPING PERIOD 1	0	-	1
6	TINIT	SIZE OF INITIAL TIME STEP, IN SECONDS, FOR PUMPING PERIOD 1	0	-	2.6E6

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

HYDRAULIC: CONSTANTS PAGE 2 OF 3

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
7	ANFCTR	RATIO OF T(YY) TO T(XX) (ANFCTR=1 FOR HOMOGENEOUS AQUIFER)	-	-	1.
8	SS	SPECIFIC STORAGE OF CONFINING (RIVER) BED	*** NOT REQUIRED ***		
9	QET	TRANSIENT EVAPOTRANSPIRATION RATE IN FT/SEC	0	-	0.0
10	ETDPTH	MAXIMUM DEPTH AT WHICH TRANSIENT EVAPOTRANSPIRATION OCCURS, IN FEET	0	-	0.0
11	SATLM	MINIMUM SATURATED THICKNESS FOR PUMPING TO OCCUR, IN FEET	0	-	0.0

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

HYDRAULIC: CONSTANTS PAGE 3 OF 3

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
12	RVDPTH	MAXIMUM DEPTH BELOW RIVER BOTTOM AT	0	-	0.0

HYDRAULIC: CONSTANTS PAGE 3 OF 3

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
12	RVDPTH	MAXIMUM DEPTH BELOW RIVER BOTTOM AT WHICH RIVER LEAKAGE AFFECTS AQUIFER, IN FEET	0	-	0.0
13	RAREA	AVERAGE AREA OF NODE OCCUPIED BY RIVER OR OTHER CONFINING SURFACE, IN SQUARE FEET	0	-	0.0

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

HYDRAULIC MATRICES: AQUIFER CHARACTERISTICS PAGE 1 OF 2

#	MATRIX NAME	DEFINITION	INPUT FORM: 0-CONSTANT VALUE 1-VARIABLE MATRIX	MULTIPLICATION FACTOR
1	WT	WATER TABLE ELEVATION	1	1
2	RIVER	RIVER HEAD ELEVATION	*** NOT REQUIRED ***	
3	LAND	LAND SURFACE ELEVATION	1	1
4	TOP	TOP OF CONFINED PORTION	*** NOT REQUIRED ***	
5	BTM	BOTTOM ELEVATION	1	1

ENTER MATRIX # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

HYDRAULIC MATRICES: AQUIFER CHARACTERISTICS PAGE 2 OF 2

#	MATRIX NAME	DEFINITION	INPUT FORM: 0-CONSTANT VALUE 1-VARIABLE MATRIX	MULTIPLICATION FACTOR
6	VPRM	HYDRAULIC CONDUCTIVITY	0	5.42E-4
7	SY	SPECIFIC YIELD	0	0.40

ENTER MATRIX # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

HYDRAULIC MATRICES: AQUIFER STRESSES PAGE 1 OF 1

#	MATRIX NAME	DEFINITION	INPUT FORM: 0-CONSTANT VALUE 1-VARIABLE MATRIX	MULTIPLICATION FACTOR
1	PRIOR	PRIOR RIGHTS PUMPING RATES	0	0.0
2	REC	PUMPING AND INJECTION RATES	0	0.0
3	GRAD	CONSTANT GRADIENT	0	0.01
4	NODEID	NODE IDENTIFICATION	1	1
5	RECH	DIFFUSE RECHARGE/DISCHARGE	0	1.7E-8

ENTER MATRIX # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

HYDRAULIC: OTHER PAGE 1 OF 1

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
1	NSY	NUMBER OF SPECIFIC YIELD-PERMEABILITY PAIRS FOR SY CURVE (IF NSY=0, A SPECIFIC YIELD MATRIX IS USED INSTEAD OF THE CURVE)	3	8	0
2	SYPRM	SPECIFIC YIELD-PERMEABILITY PAIRS MENU	*** NOT USED (NSY=0) ***		
3	NCODES	NUMBER OF ICODES USED IN NODEID MATRIX	0	10	1
4		ICODES DESCRIPTION MENU			
5	NUMOBS	NUMBER OF OBSERVATION WELLS	0	5	3
6		OBSERVATION WELL LOCATIONS MENU			

ENTER # TO EDIT, 0 (ZERO) TO END MENU,

OBSERVATION WELLS MENU PAGE 1 OF 1

#	X LOCATION (COLUMN)	Y LOCATION (ROW)
1	6	3
2	12	12
3	4	7

ENTER PAIR # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

KONIKOW Preprocessor Variables

Date: 4/28/93
Run: Verification - January 1992 thru January 1993
Filename: VERF3

HYDRAULIC: TITLE AND FLAGS

1) TITLE = Verification Run-Jan 1992 to Jan 1993

2) IHEAD = 1 (Head Only)

3) ISOLV = 0 (ADIP)

4) ITP = 1 (Hydraulic Conductivity)

5) IXSECT = 0 (Plannar)

6) FCON = 1 (Unconfined)

7) NCYC = 0

8) CHKDTA = 0

HYDRAULIC: LIMITS

1) NPMP = 1 (one year)

2) NX = 17

3) NY = 17

4) XDEL = 264 ft

5) YDEL = 264 ft

6) NTIM = 12 (one month each)

7) ITMAX = 50

8) NITP = 4

HYDRAULIC: PRINT

1) NPNT = 1

2) NPNTVL = 0

3) NPNTD = 0

4) NPNCHV = 0

5) NSTRT = 0

HYDRAULIC: CONSTANTS

1) PINT = 1

2) TOL = 0.01

3) POROS = 0.40

4) S = 0.40

5) TIMX = 1

6) TINIT = 2.6E6

7) ANFCTR = 1

8) SS = NOT REQUIRED

9) QET = 0

10) ETDPTH = 0

11) SATLM = 0

12) RVDPTH = 0

13) RAREA = 0

HYDRAULIC: OTHER

1) NSY = 0 (Specific Yield)

2) SYPRM = NOT REQUIRED

3) NCODES = 1

4) NUMOBS = 5

WELL LOCATIONS MENU:

#	X	Y	Monitoring Well
1	6	3	#12
2	12	12	#18
3	4	7	Well House
4	5	13	#19
5	8	9	#21

HYDRAULIC MATRICES: AQUIFER CHARACTERISTICS

1) WT = 1 (Variable Matrix), 1 (Multiplication Factor)

2) RIVER = NOT REQUIRED

3) LAND = 1 1 (Constant 20 ft to wt)

4) TOP = NOT REQUIRED

5) BTM = 1 1 (Constant m = 40 ft)

6) VPRM = 0 350 GPD/FT
5.42e-4 FT/SEC

7) SY = 0 0.40

HYDRAULIC MATRICES: AQUIFER STRESSES

1) PRIOR = NONE

2) REC = NONE

3) GRAD = 0.01

4) NODEID = 1 (Variable Matrix), 1 (Multiplier)

5) RECH = 6.10 inches = 15% of 40.44 inches

Sensitivity

n = 0.40
S = 0.40
Sy= 0.40
Recharge = 6.10 inches/year
K = 350 gpd/ft

```
TYPE VERF3.DAT
Verification - Jan 1992 to Jan 1993
  12   1  17  176400   1 - 4-   5  50   0   4   1   0   0   0   0   0
  1.0 0.01  0.4 100.  0.4     12.6E6  264  264 0.30  0.5   1.
   0    0        0.0        0.0        0.0        0.0        0.0
  0   1   1   0   1   0   0   0  0.0  0.0  0.0  0.0  0.0  0.0
 %%NOBS -             5 (OBSERVATION WELLS)
 6 3
1212
 4 7
 513
 8 9
 %% -- WT (WATER TABLE) --
1         1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0    0
   0 900 900 900 900 900 902 902 902 902 902 902 904 904 904 904    0
   0 896 896 896 896 896 900 900 900 900 900 900 902 902 902 902    0
   0 894 894 894 894 896 896 896 896 896 896 896 900 900 900 900    0
   0 892 892 892 892 894 896 896 896 896 896 896 896 896 896 896    0
   0 891 891 891 891 892 894 896 896 896 896 895 895 895 895 895    0
   0 890 890 890 891 892 894 896 896 896 896 895 895 894 894 894    0
   0 890 890 890 891 892 894 896 896 896 896 895 895 894 890 890    0
   0 890 890 891 892 894 896 900 900 900 900 896 895 894 890 888    0
   0 890 891 892 894 894 896 898 898 898 900 896 895 894 890 888    0
   0 890 891 892 894 894 896 898 898 898 900 896 895 894 890 888    0
   0 890 891 892 894 894 896 898 898 898 900 896 895 894 890 888    0
   0 890 891 892 894 894 896 896 896 898 900 896 895 894 890 888    0
   0 890 891 892 894 894 896 896 896 898 900 896 895 894 894 890    0
   0 890 891 892 894 894 896 896 896 898 900 896 895 894 894 890    0
   0 890 891 892 894 894 896 896 896 898 900 896 895 894 894 890    0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0    0
 %% -- CONF -             1 (LAND)
1         1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0    0
   0 920 920 920 920 920 922 922 922 922 922 922 924 924 924 924    0
   0 916 916 916 916 916 920 920 920 920 920 920 922 922 922 922    0
   0 914 914 914 914 916 916 916 916 916 916 916 920 920 920 920    0
   0 912 912 912 912 914 916 916 916 916 916 916 916 916 916 916    0
   0 911 911 911 911 912 914 916 916 916 916 915 915 915 915 915    0
   0 910 910 910 911 912 914 916 916 916 916 915 915 914 914 914    0
   0 910 910 910 911 912 914 916 916 916 916 915 915 914 910 910    0
   0 910 910 911 912 914 916 920 920 920 920 916 915 914 910 908    0
   0 910 911 912 914 914 916 918 918 918 920 916 915 914 910 908    0
   0 910 911 912 914 914 916 918 918 918 920 916 915 914 910 908    0
   0 910 911 912 914 914 916 918 918 918 920 916 915 914 910 908    0
   0 910 911 912 914 914 916 916 916 918 920 916 915 914 910 908    0
   0 910 911 912 914 914 916 916 916 918 920 916 915 914 910 908    0
   0 910 911 912 914 914 916 916 916 918 920 916 915 914 910 908    0
   0 910 911 912 914 914 916 916 916 918 920 916 915 914 910 908    0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0    0
 %% -- CONF -             1 (BTM)
1         1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0    0
   0 860 860 860 860 860 862 862 862 862 862 862 864 864 864 864    0
   0 856 856 856 856 856 860 860 860 860 860 860 862 862 862 862    0
   0 854 854 854 854 856 856 856 856 856 856 856 850 850 850 850    0
   0 852 852 852 852 854 856 856 856 856 856 856 856 856 856 856    0
   0 851 851 851 851 852 854 856 856 856 856 855 855 855 855 855    0
   0 850 850 850 851 852 864 856 856 856 856 855 855 854 854 854    0
   0 850 850 850 851 852 854 856 856 856 856 855 855 854 850 850    0
   0 850 850 851 852 854 856 850 850 850 850 856 855 854 850 848    0
   0 850 851 852 854 854 856 858 858 858 860 856 855 854 850 848    0
   0 850 851 852 854 854 856 858 858 858 860 856 855 854 850 848    0
   0 850 851 852 854 854 856 858 858 858 860 856 855 854 850 848    0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888    0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888    0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888    0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888    0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0    0
 %% -- CONF -             1 (VPRM)
0   5.42E-4
 %%SYN -           0 CONF -           1 (SPECIFIC YIELD)
0      0.40
 %%SYN -           0 CONF -           1 (CONSTANT GRADIENT)
0      0.01
 %%SYN -           0 CONF -           1 (DIFFUSE RECHARGE/DISCHARGE)
0   1.7E-8
 %%SYN -           0 CONF -           1 NODEID (NODE IDENITY)
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
%% -- CONF -             1 (BTM)
1         1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   0 860 860 860 860 860 862 862 862 862 862 862 864 864 864 864   0
   0 856 856 856 856 856 860 860 860 860 860 860 862 862 862 862   0
   0 854 854 854 854 856 856 856 856 856 856 856 850 850 850 850   0
   0 852 852 852 852 854 856 856 856 856 856 856 856 856 856 856   0
   0 851 851 851 851 852 854 856 856 856 856 855 855 855 855 855   0
   0 850 850 850 851 852 854 856 856 856 856 855 855 854 854 854   0
   0 850 850 850 851 852 854 856 856 856 856 855 855 854 850 850   0
   0 850 850 851 852 854 856 850 850 850 850 856 855 854 850 848   0
   0 850 851 852 854 854 856 858 858 858 860 856 855 854 850 848   0
   0 850 851 852 854 854 856 858 858 858 860 856 855 854 850 848   0
   0 850 851 852 854 854 856 858 858 858 860 856 855 854 850 848   0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888   0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888   0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888   0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888   0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
%% -- CONF -             1 (VPRM)
0   5.42E-4
%%SYN -           0 CONF -          1 (SPECIFIC YIELD)
0      0.40
%%SYN -           0 CONF -          1 (CONSTANT GRADIENT)
0      0.01
%%SYN -           0 CONF -          1 (DIFFUSE RECHARGE/DISCHARGE)
0   1.7E-8
%%SYN -           0 CONF -          1 NODEID (NODE IDENITY)
1         1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   0   1   1   1   1   1   1   1   1   1   1   1   1   1   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
   0   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
%%CODES -           1 (ICODE, FCTR1,ETC.)
1          1        0.0        0.0 0
%%CODES -           1 (INITIAL CONCENTRATION)
0         0.0
%% -- (PRIOR PUMPING RATES) --
0         0.0
%% -- (PUMPING/INJECTION RATES) --
0         0.0
%% -- (CONCENTRATION FOR INJECTION WELLS) --
0         0.0
```

CHEMICAL: FLAGS PAGE 1 OF 1

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
1	NDECAY	CONTROLS SIMULATION OF DECAY 0-NO DECAY SIMULATION 1-DECAY SIMULATION	0	1	0
2	NSORB	CONTROLS SORPTION SIMULATION 0-NO SORPTION SIMULATION 1-SIMULATION USES A LINEAR SOLVER 2-SIMULATION USES THE LANGMUIR SOLVER 3-SIMULATION USES THE FREUNDLICH SOLVER	0	3	0

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

CHEMICAL: LIMITS PAGE 1 OF 1

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
1	NPMAX	MAXIMUM NUMBER OF PARTICLES TO BE USED FOR CHEMICAL TRANSPORT	0	6400	6400
2	NPTPND	INITIAL NUMBER OF PARTICALS PER NODE CHOICES: 1, 4, 5, 8, 9, OR 16	1	16	4

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

CHEMICAL: PRINT PAGE 1 OF 1

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
1	NPNTMV	PARTICLE MOVEMENT INTERVAL FOR PRINTING CHEMICAL OUTPUT IN PUMPING PERIOD 1 SPECIFY 0 (ZERO) TO PRINT ONLY AT END OF TIME STEPS	0	-	0
2	NPDELC	CONTROLS PRINTING OF COMPUTED CHANGES IN CONCENTRATION FOR PUMPING PERIOD 1 0-DO NOT PRINT 1-PRINT	0	1	0

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

CHEMICAL: CONSTANTS PAGE 1 OF 1

#	VARIABLE	DEFINITION	MIN	MAX	CURRENT
1	CELDIS	MAXIMUM CELL DISTANCE PER PARTICLE MOVE	0	1	0.5
2	BETA	CHARACTERISTIC LENGTH (LONGITUDINAL DISPERSIVITY), IN FEET	0	-	100.
3	DLTRAT	RATIO OF TRANSVERSE TO LONGITUDINAL DISPERSIVITY	0	-	0.20

ENTER # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

CHEMICAL MATRICES: CONCENTRATIONS PAGE 1 OF 1

#	MATRIX NAME	DEFINITION	INPUT FORM: 0-CONSTANT VALUE 1-VARIABLE MATRIX	MULTIPLICATION FACTOR
1	CNRCH	INJECTION WELL CONCENTRATIONS	1	1
2	CONC	INITIAL AQUIFER CONCENTRATION	0	0.0

ENTER MATRIX # TO EDIT, 0 (ZERO) TO END MENU,
+ FOR NEXT PAGE OF MENU, - FOR PREVIOUS PAGE OF MENU:-->

TABLE X

COEFFCIENTS AND PARAMETERS FOR SOLUTE TRANSPORT COMPUTER RUN

Date: 5/28/93
Run: Solute Transport - January 1992 thru January 1993
Filename: CONC8
First pumping period = 6 months of fertilizer infiltration (active concentration matrices)
Second pumping period = 6 months of infiltration (inactive concentration matrices)

HYDRAULIC: TITLE AND FLAGS

1) TITLE = Solute Transport - Jan 1992 to Jan 1993

2) IHEAD = 0 (Head Calculation + Solute Transport)

3) ISOLV = 0 (ADIP)

4) ITP = 1 (Hydraulic Conductivity)

5) IXSECT = 0 (Plannar)

6) FCON = 1 (Unconfined)

7) NCYC = 0

8) CHKDTA = 0

HYDRAULIC: LIMITS.

1) NPMP = 2 (6 months each - Spring and Fall Seasons)

2) NX = 17

3) NY = 17

4) XDEL = 264 ft

5) YDEL = 264 ft

6) NTIM = 6 (one month each)

7) ITMAX = 50

8) NITP = 4

HYDRAULIC: PRINT

1) NPNT = 1

2) NPNTVL = 0

3) NPNTD = 0

4) NPNCHV = 0

5) NSTRT = 0

HYDRAULIC: CONSTANTS

1) PINT = 0.50

2) TOL = 0.01

3) POROS = 0.40

4) S = 0.40

5) TIMX = 1

6) TINIT = 2.6E6 (one month in seconds)

7) ANFCTR = 1

8) SS = NOT REQUIRED

9) QET = 0

10) ETDPTH = 0

11) SATLM = 0

12) RVDPTH = 0

13) RAREA = 0

HYDRAULIC: OTHER

1) NSY = 0 (Specific Yield)

2) SYPRM = NOT REQUIRED

3) NCODES = 1

4) NUMOBS = 5

WELL LOCATIONS MENU:

#	X	Y	Monitoring Well
1	6	3	#12
2	12	12	#18
3	4	7	Well House
4	5	13	#19
5	8	9	#21

HYDRAULIC MATRICES: AQUIFER CHARACTERISTICS

1) WT = 1 (Variable Matrix), 1 (Multiplication Factor)

2) RIVER = NOT REQUIRED

3) LAND = 1   1 (Constant 20 ft to wt)

4) TOP = NOT REQUIRED

5) BTM = 1   1 (Constant m = 40 ft)

6) VPRM = 0   350 GPD/FT
5.42e-4 FT/SEC

7) SY = 0   0.40

HYDRAULIC MATRICES: AQUIFER STRESSES

1) PRIOR = NONE (No prior pumping)

2) REC = 1 (Variable Matrix), 1 (Multiplication Factor)
Injection/Pumping Rates

3) GRAD = 0.01

4) NODEID = 1 (Variable Matrix), 1 (Multiplier)
Node Identification Matrix

5) RECH = 6.10 inches = 15% of 40.44 inches

CHEMICAL: FLAGS

1) NDECAY = 1 (Decay Simulation)

2) NSORB = 0 (No Sorption Simulation)

CHEMICAL: LIMITS

1) NPMAX = 6400 (Maximum no. of particles to be used for transport)

2) NPTPND = 4 (Number of particles per node)

CHEMICAL: PRINT

1) NPNTMV = 0 (Print particle movement interval only at end of time step)

2) NPDELC = 0 (Do not print computed changes in concentration)

CHEMICAL: CONSTANTS

1) CELDIS = 0.5 (Maximum cell distance per particle move)

2) BETA = 100 (Longitudinal Dispersivity)

3) DLTRAT = 0.20 (Ratio of Transverse to Longitudinal Dispersivity)

CHEMICAL MATRICES: CONCENTRATIONS

1) CNRCH = 1 (Variable Matrix), 1 (Multiplier)
Injection Well Concentrations

2) CONC = 0 (Constant Value), 25 ppm
Initial Aquifer Concentration = Background Concentrations

```
SOLUTE TRANSPORT-JAN 92 TO JAN 93
 %% -- CONTROL PARAMETERS --
   6    2  17  176400    1     4      5   50     0     4    1     0     0     0     0     0
 0.50 0.01  0.4 100.  0.4       12.6E6   264   264  0.20   0.5   1.
    1     0        0.25         0.0         0.0         0.0         0.0
   0    0    1    0    1    0    0    0  0.0  0.0  0.0  0.0  0.0  0.0
 %%NOBS -              5 (OBSERVATION WELLS)
 6 3
1212
 411
 513
 8 9
 %% -- WT (WATER TABLE) --
1         1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   0 900 900 900 900 900 902 902 902 902 902 902 904 904 904 904   0
   0 896 896 896 896 896 900 900 900 900 900 900 902 902 902 902   0
   0 894 894 894 894 896 896 896 896 896 896 896 900 900 900 900   0
   0 892 892 892 892 894 896 896 896 896 896 896 896 896 896 896   0
   0 891 891 891 891 892 894 896 896 896 896 895 895 895 895 895   0
   0 890 890 890 891 892 894 896 896 896 896 895 895 894 894 894   0
   0 890 890 890 891 892 894 896 896 896 896 895 895 894 890 890   0
   0 890 890 891 892 894 896 900 900 900 900 896 895 894 890 888   0
   0 890 891 892 894 894 896 898 898 898 900 896 895 894 890 888   0
   0 890 891 892 894 894 896 898 898 898 900 896 895 894 890 888   0
   0 890 891 892 894 894 896 898 898 898 900 896 895 894 890 888   0
   0 890 891 892 894 894 896 896 896 898 900 896 895 894 890 888   0
   0 890 891 892 894 894 896 896 896 898 900 896 895 894 894 890   0
   0 890 891 892 894 894 896 896 896 898 900 896 895 894 894 890   0
   0 890 891 892 894 894 896 896 896 898 900 896 895 894 894 890   0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
 %% -- CONF -            1 (LAND)
1         1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   0 920 920 920 920 920 922 922 922 922 922 922 924 924 924 924   0
   0 916 916 916 916 916 920 920 920 920 920 920 922 922 922 922   0
   0 914 914 914 914 916 916 916 916 916 916 916 920 920 920 920   0
   0 912 912 912 912 914 916 916 916 916 916 916 916 916 916 916   0
   0 911 911 911 911 912 914 916 916 916 916 915 915 915 915 915   0
   0 910 910 910 911 912 914 916 916 916 916 915 915 914 914 914   0
   0 910 910 910 911 912 914 916 916 916 916 915 915 914 910 910   0
   0 910 910 911 912 914 916 920 920 920 920 916 915 914 910 908   0
   0 910 911 912 914 914 916 918 918 918 920 916 915 914 910 908   0
   0 910 911 912 914 914 916 918 918 918 920 916 915 914 910 908   0
   0 910 911 912 914 914 916 918 918 918 920 916 915 914 910 908   0
   0 910 911 912 914 914 916 916 916 918 920 916 915 914 910 908   0
   0 910 911 912 914 914 916 916 916 918 920 916 915 914 910 908   0
   0 910 911 912 914 914 916 916 916 918 920 916 915 914 910 908   0
   0 910 911 912 914 914 916 916 916 918 920 916 915 914 910 908   0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
 %% -- CONF -            1 (BTM)
1         1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   0 860 860 860 860 860 862 862 862 862 862 862 864 864 864 864   0
   0 856 856 856 856 856 860 860 860 860 860 860 862 862 862 862   0
   0 854 854 854 854 856 856 856 856 856 856 856 850 850 850 850   0
   0 852 852 852 852 854 856 856 856 856 856 856 856 856 856 856   0
   0 851 851 851 851 852 854 856 856 856 856 855 855 855 855 855   0
   0 850 850 850 851 852 854 856 856 856 856 855 855 854 854 854   0
   0 850 850 850 851 852 854 856 856 856 856 855 855 854 850 850   0
   0 850 850 851 852 854 856 850 850 850 850 856 855 854 850 848   0
   0 850 851 852 854 854 856 858 858 858 860 856 855 854 850 848   0
   0 850 851 852 854 854 856 858 858 858 860 856 855 854 850 848   0
   0 850 851 852 854 854 856 858 858 858 860 856 855 854 850 848   0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888   0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888   0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888   0
   0 850 851 852 854 854 856 856 856 858 860 856 855 854 850 888   0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
 %% -- CONF -            1 (VPRM)
0   5.42E-4
 %%SYN -            0 CONF -            1 (SPECIFIC YIELD)
0       0.40
 %%SYN -            0 CONF -            1 (CONSTANT GRADIENT)
0       0.01
 %%SYN -            0 CONF -            1 (DIFFUSE RECHARGE/DISCHARGE)
0   1.7E-8
 %%SYN -            0 CONF -            1 NODEID (NODE IDENITY)
1         1
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
   0   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   0
   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
```

NUMBER OF TIME STEPS = 6

0	0	0	0	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	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	5	28	19	-2	0	0	0
0	0	0	0	0	0	0	0	1	8	218	741	752	21	1	22	2
0	0	0	0	1	1	0	0	1	7	126	158	132	713	27	733	23
0	0	0	5	60	62	1	0	0	2	7	21	251	751	159	744	173
0	0	0	3	5	12	0	0	0	0	3	18	305	748	34	738	125
0	0	0	5	60	63	64	65	1	0	0	19	147	731	34	678	123
0	0	0	3	20	19	30	22	0	1	15	166	708	131	30	300	25
0	0	0	1	2	2	1	2	0	1	10	95	245	·600	613	503	674
0	0	0	0	0	0	0	0	0	0	3	13	38	183	179	166	162
0	0	0	0	1	0	0	0	0	0	0	2	7	24	24	20	16
0	0	0	6	65	1	0	0	0	0	0	0	1	4	3	3	0
0	0	0	5	19	0	0	0	0	0	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

CHEMICAL MASS BALANCE

```
        MASS IN BOUNDARIES      =  1.75732E+06
        MASS OUT BOUNDARIES     = -4.97351E+05
        MASS PUMPED IN          =  5.68855E+10
        MASS PUMPED OUT         = -4.05455E+08
        INFLOW MINUS OUTFLOW    =  5.64813E+10
        INITIAL MASS STORED     =  0.00000E+00
        PRESENT MASS STORED     =  2.07637E+10
        CHANGE MASS STORED      =  2.07637E+10
        DECAY OF SOLUTE MASS    = -3.57002E+10
      COMPARE RESIDUAL WITH NET FLUX AND MASS ACCUMULATION:
        MASS BALANCE RESIDUAL   =  1.74920E+07
        ERROR  (AS PERCENT)     =  3.07485E-02
```

1SOLUTE TRANSPORT-JAN 92 TO JAN 93

0 TIME VERSUS HEAD AND CONCENTRATION AT SELECTED OBSERVATION POINTS

PUMPING PERIOD NO. 2

0 TRANSIENT SOLUTION

OOBS.WELL NO.	X	Y	N	HEAD (FT)	CONC.(MG/L)	TIME (YEARS)
1	6	3				
			0	896.00	25.000	0.00000
			1	899.92	0.92350E-04	0.57672
			2	900.04	0.96256E-04	0.65911
			3	900.16	0.87555E-04	0.74150
			4	900.25	0.77541E-04	0.82389
			5	900.34	0.58375E-04	0.90628
			6	900.41	0.44439E-04	0.98867

OOBS.WELL NO.	X	Y	N	HEAD (FT)	CONC.(MG/L)	TIME (YEARS)
2	12	12				
			0	896.00	25.000	0.00000
			1	897.34	0.90523	0.57672
			2	897.69	3.0980	0.65911
			3	898.02	5.0363	0.74150
			4	898.34	5.9580	0.82389
			5	898.64	6.1007	0.90628
			6	898.91	6.9480	0.98867

OOBS.WELL NO.	X	Y	N	HEAD (FT)	CONC.(MG/L)	TIME (YEARS)
3	4	11				
			0	892.00	25.000	0.00000
			1	895.11	0.74908E-02	0.57672
			[illegible]	[illegible]	[illegible]	[illegible]

```
0       0.40
 %%SYN  -             0 CONF  -            1 (CONSTANT GRADIENT)
0       0.01
 %%SYN  -             0 CONF  -            1 (DIFFUSE RECHARGE/DISCHARGE)
0    1.7E-8
 %%SYN  -             0 CONF  -            1 NODEID (NODE IDENITY)
1         1
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    1    1    1    1    1    1    1    1    1    1    1    1    1    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
    0    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
 %%CODES  -              1 (ICODE, FCTR1,ETC.)
 1         1        0.0       0.0 0
 %%CODES  -              1 (INITIAL CONCENTRATION)
0         25
 %% -- (PRIOR PUMPING RATES) --
0        0.0
 %% -- (PUMPING/INJECTION RATES) --
1    -3.9E-2
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    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    1    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    1    0    1    0    0
    0    0    0    1    1    0    0    0    0    0    0    0    1    0    1    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    1    0    1    0    0
    0    0    0    1    1    1    1    0    0    0    0    0    1    0    1    0    0
    0    0    0    0    0    0    0    0    0    0    0    1    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    1    1    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    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
 %% -- (CONCENTRATION FOR INJECTION WELLS) --
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    4    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    030003000    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    03000    03000    0    0
    0    0    0  250  250    0    0    0    0    0    0    03000    03000    0    0
    0    0    0    0    0    0    0    0    0    0    0    03000    03000    0    0
    0    0    0  250  250  250  250  250    0    0    0    03000    03000    0    0
    0    0    0    0    0    0    0    0    0    0 03000    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    03000300030003000    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0  250    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
 %% -- MULTIPLE PUMPING PERIOD DATA --
1
 %% -- ADDITIONAL PUMPING PERIOD -          2
    6    1    4   50    0    0    0    0    0 0.50     12.6E6
```

0 TIME VERSUS HEAD AND CONCENTRATION AT SELECTED OBSERVATION POINTS

PUMPING PERIOD NO. 2

0 TRANSIENT SOLUTION

OOBS.WELL NO.	X	Y	N	HEAD (FT)	CONC.(MG/L)	TIME (YEARS)
1	6	3				
			0	896.00	25.000	0.00000
			1	899.92	0.92350E-04	0.57672
			2	900.04	0.96256E-04	0.65911
			3	900.16	0.87555E-04	0.74150
			4	900.25	0.77541E-04	0.82389
			5	900.34	0.58375E-04	0.90628
			6	900.41	0.44439E-04	0.98867
OOBS.WELL NO.	X	Y	N	HEAD (FT)	CONC.(MG/L)	TIME (YEARS)
2	12	12				
			0	896.00	25.000	0.00000
			1	897.34	0.90523	0.57672
			2	897.69	3.0980	0.65911
			3	898.02	5.0363	0.74150
			4	898.34	5.9580	0.82389
			5	898.64	6.1007	0.90628
			6	898.91	6.9480	0.98867
OOBS.WELL NO.	X	Y	N	HEAD (FT)	CONC.(MG/L)	TIME (YEARS)
3	4	11				
			0	892.00	25.000	0.00000
			1	895.11	0.74908E-02	0.57672
			2	895.48	0.17452E-01	0.65911
			3	895.82	0.32636E-01	0.74150
			4	896.14	0.14557	0.82389
			5	896.42	0.22128	0.90628
			6	896.69	0.23714	0.98867
OOBS.WELL NO.	X	Y	N	HEAD (FT)	CONC.(MG/L)	TIME (YEARS)
4	5	13				
			0	894.00	25.000	0.00000
			1	894.64	0.54888	0.57672
			2	894.85	0.59294	0.65911
			3	895.06	0.65257	0.74150
			4	895.26	0.56924	0.82389
			5	895.45	0.57071	0.90628
			6	895.63	0.68896	0.98867
OOBS.WELL NO.	X	Y	N	HEAD (FT)	CONC.(MG/L)	TIME (YEARS)
5	8	9				
			0	900.00	25.000	0.00000
			1	897.63	0.82572E-01	0.57672
			2	898.02	0.15036E-01	0.65911
			3	898.39	0.56803E-01	0.74150
			4	898.74	0.31403	0.82389
			5	899.06	0.35259	0.90628
			6	899.36	0.31982	0.98867

NORMAL RUN TERMINATED.

VITA

Michelle J. Van Alstine

Candidate for the Degree of

Master of Science

Thesis: SOLUTE TRANSPORT MODELING OF AGRICULTURAL CHEMICALS IN AN ALLUVIAL TERRACE DEPOSIT NEAR PERKINS, OKLAHOMA

Major Field: Geology

Biographical:

Personal Data: Born in Duncan, Oklahoma, May 9, 1968, the daughter of Bill and Jackie Van Alstine

Education: Graduated from Duncan High School, Duncan, Oklahoma in May 1986; received Bachelor of Science Degree in Geology from Oklahoma State University in May, 1991; completed requirements for the Master of Science Degree at Oklahoma State University in December, 1995.

Professional Experience: Physical Science Assistant for the United States Department of Agriculture- National Water Quality Lab in Durant, Oklahoma through the ARS 1040 trainee program.