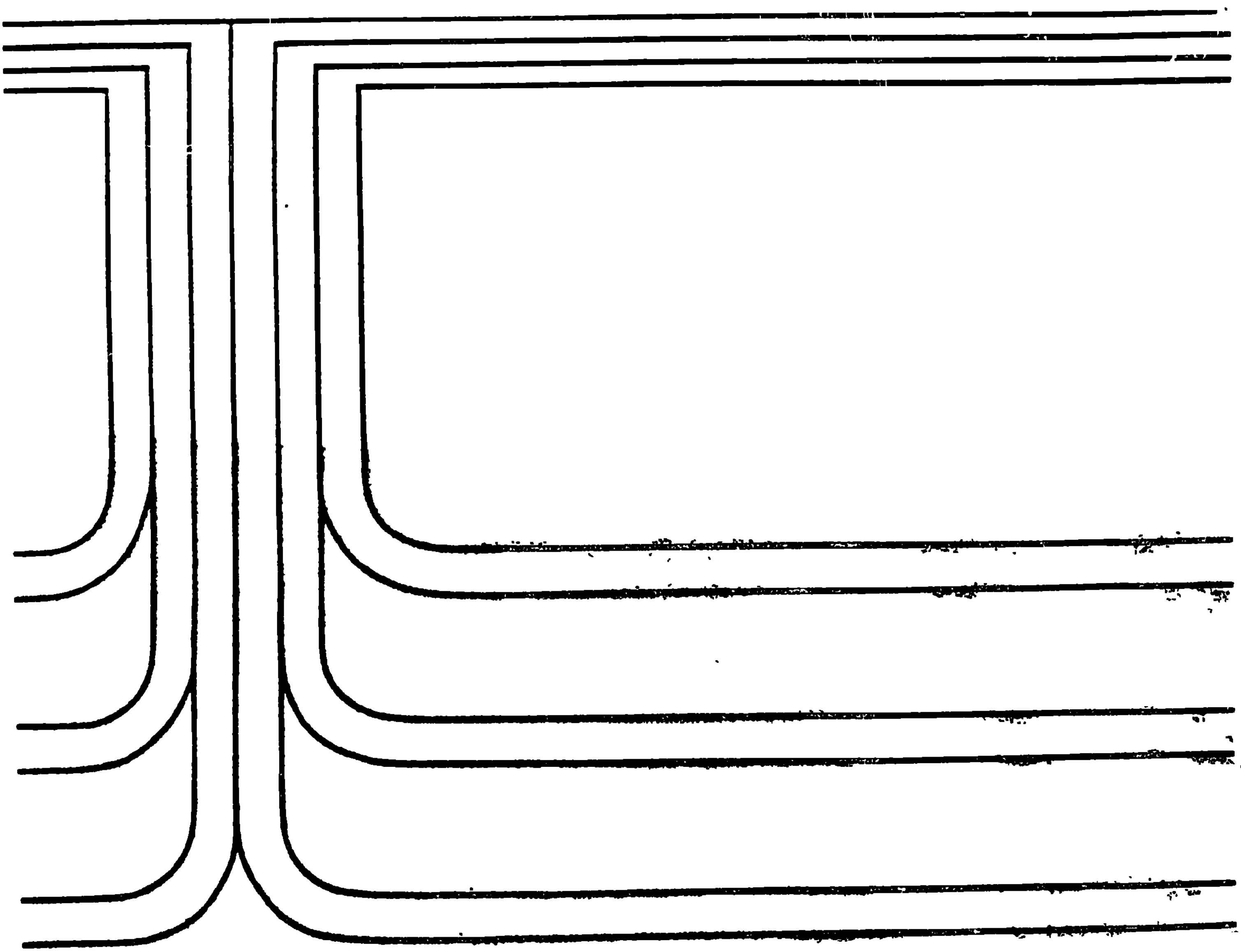
WELLHEAD PROTECTION AREA DELINEATION

A "HANDS-ON" TRAINING COURSE

August 23 - 25, 1988 • FAIRFAX, VIRGINIA

Office of Ground-Water Protection
U.S. Environmental Protection Agency
Washington, D.C.



Acknowledgment

This manual was prepared by the Environmental Protection Agency, Office of Ground-Water Protection (OGWP) (Washington, D.C.). Technical assistance was provided by Geraghty and Miller, Inc. (Annapolis, MD.); logistical and management assistance was provided by ICF, Inc. (Fairfax, VA.) (Contract #68-C8-003).

Disclaimer

This manual is intended for use in the series of training courses for Wellhead Protection Area (WHPA) Delineation held during the fall of 1988. The methods and models presented in this text and for the courses do not represent EPA standards nor does their use constitute endorsement. These methods and models are compiled from activities conducted by the states and are presented for general training purposes only.

WELLHEAD PROTECTION AREA DELINEATION

A "HANDS-ON" TRAINING COURSE

		AGENDA TOPIC
Day 1		
AM	8:30 - 9:00	Registration
	9:00 - 10:00	Introduction - Course Objectives and Format - Review of Wellhead Protection Program
	10:00 - 10:15	**BREAK**
	10:15 - 12:00	Fundamentals - Ground-Water Flow - Contaminant Transport - Well Hydraulics - Fundamental Concepts Exercise
PM	**12:00 - 1:00**	**LUNCH**
	1:00 - 3:00	Elements of Wellhead Protection - Wellhead Terminology - Wellhead Delineation Criteria (Overview) - Wellhead Delineation Methods (Overview) - Adequacy of Delineation
	3:00 - 3:15	**BREAK**
	3:15 - 5:00	Fixed Radii and Simplified Variable Shapes Methods - Arbitrary Fixed Radius Method - Calculated Fixed Radius Method - Calculated Fixed Radius Exercise - Simplified Variable Shapes
	5:00	**END OF TRAINING FOR DAY 1**
Day 2		
AM	8:00 - 10:00	Analytical Methods - Analytical Drawdown Method - Analytical Time-of-Travel Method
	10:00 - 10:15	**BREAK**

WELLHEAD PROTECTION AREA DELINEATION (CONTINUED)

A "HANDS-ON" TRAINING COURSE

		AGENDA TOPIC
Day 2 (continued)		
	10:15 - 12:00	Analytical Methods (Continued) - Analytical Zone of Contribution Method - Analytical Methods Exercise
PM	**12:00 - 1:00**	**LUNCH**
	1:00 - 2:45	Hydrogeologic Mapping - Overview of Methods - Mapping Exercise
	2:45 - 3:00	**BREAK**
	3:00 - 5:00	Group Exercise (3-5 per group) - Problem Introduction - Exercise Part 1 and Discussion - Exercise Part 2 and Discussion - Exercise Part 3 and Discussion
	5:00	**END OF TRAINING FOR DAY 2**
Day 3		
AM	8:00 - 10:00	Numerical Modeling Methods - Review of Numerical Modeling - Checkpoints for Reviewing a Modeling Study
	10:00 - 10:15	**BREAK**
	10:15 - 11:30	- Demonstration Case Study - Second Case Study
	11:30 - 12:00	Course Evaluation
PM	**12:00 - 1:00**	**LUNCH**
	1:00 - 2:30	Comparative Analyses - Case Study 1 - Case Study 2 - Case Study 3
	2:30 - 2:45	Concluding Remarks
	2:45	**END OF TRAINING COURSE**

TABLE OF CONTENTS*

*Each Text Section is Preceded by Presentation Slides

TABLE OF CONTENTS
(Continued)

LIST OF ACRONYMS, PARAMETERS, AND COEFFICIENTS

A = Cross-sectional area (L_2)
b = Aquifer thickness (L)
C = Concentration (M/L_3)
C_o = Concentration at source (M/L^3)
cf = Cubic feet (L^3)
cfs = Cubic feet per second (L^3/T)
COD = Cone of depression (L^2/T)
D = Dispersion coefficient
DEQE = Department of Environmental Quality Engineering, Massachusetts
dh/dr = Hydraulic gradient (dimensionless)
DWNR = Department of Water and Natural Resources
EPA = Environmental Protection Agency
EPA HQ = Environmental Protection Agency Head Quarters'
FY = Federal fiscal year
g = Acceleration due to gravity (L/T^2)
gpd = Gallons per day (L^3/T)
GWPATH = Particle-tracking computer code
h = Hydraulic head (L)
i = Hydraulic gradient (dimensionless)
K = Hydraulic conductivity (L/T)
k = Intrinsic permeability (L_2)
L = Leakance (T^{-1})
m = Fluid dynamic viscosity (M/LT)
mgd = Million gallons per day (L^3/T)
MOC = Method of characteristics
MODFLOW = 3-dimensional finite-difference ground-water flow code
n = Porosity (dimensionless)
OGWP = Office of Ground-Water Protection
p = Fluid density (M/L^3)
P = Pressure head (L)
Q = Discharge (L^3/T)
q = Specific discharge (L/T)
r = Radius (L)
RESSQ = Analytical solute transport code
s = Drawdown (L)
S = Storativity/storage coefficient (dimensionless)
SDWA = Safe Drinking Water Act
SSA = Sole source aquifer
t = Time (T)
T = Transmissivity (L^2/T)
TAD = Technical Assistance Document
THWELLS = Analytical well-hydraulics code
TOT = Time-of-travel
TWC = Texas Water Commission

LIST OF ACRONYMS, PARAMETERS, AND COEFFICIENTS
(Continued)

U.S.G.S. = U.S. Geological Survey
v = Average ground-water flow velocity (L/T)
WCRWSA = West Coast Regional Water Supply Authority, Florida
WHP = Wellhead Protection Program
WHPA = Wellhead Protection Area
W(u) = Theis well function
z = Elevation head (L)
ZOC = Zone of contribution
ZOI = Zone of influence
ZOT = Zone of transport

1. Introduction

PRESENTATION SLIDES

WELLHEAD PROTECTION AREA DELINEATION

TRAINING COURSE INTRODUCTION

WELLHEAD PROTECTION AREA DELINEATION TRAINING COURSE OBJECTIVES

- DEVELOP A PRACTICAL UNDERSTANDING OF THE METHODS USED TO TRANSLATE DELINEATION CRITERIA TO ON-THE-MAP WELLHEAD PROTECTION AREAS

  THIS WILL BE ACCOMPLISHED THROUGH:

  - INSTRUCTION
  - CLASSROOM EXAMPLES
  - ACTUAL CASE STUDIES
  - HANDS-ON EXERCISES

- INTRODUCE AND EVALUATE VARIOUS ANALYTICAL AND NUMERCIAL TOOLS AVAILABLE TO IMPLEMENT WHPA DELINEATION METHODS

  INCLUDING:

  - UNIFORM FLOW EQUATIONS
  - WELL HYDRAULICS EQUATIONS
  - ANALYTICAL FLOW AND TRANSPORT CODES
  - NUMERICAL FLOW CODES
  - PARTICLE TRACKING TECHNIQUES

WELLHEAD PROTECTION AREA DELINEATION TRAINING COURSE FORMAT

- REVIEW OF WELLHEAD PROTECTION PROGRAM REQUIREMENTS CONCERNING WHPA DELINEATION CRITERIA AND METHODS

- REVIEW OF HYDROGEOLOGY FUNDAMENTALS

- DISCUSSION OF FACTORS INFLUENCING SELECTION OF WHPA DELINEATION CRITERIA AND METHODS

- INTRODUCTION TO METHODS INCLUDING:
  - EXPLANATION OF TECHNIQUES
  - EXAMPLES AND CASE STUDIES
  - COMPUTER DEMONSTRATIONS
  - HANDS-ON EXERCISES

- COMPARATIVE ANALYSES

- ALL MATERIAL WILL BE OVERED IN LECTURES; TEXT IN TRAINING MANUAL IS ONLY FOR LATER REFERENCE

- QUESTIONS WELCOME AT ANY TIME DURING LECTURES; INSTRUCTORS AVAILABLE AT END OF DAY FOR Q & A SESSIONS

PRESENTATION SLIDES

OVERVIEW OF WELLHEAD PROTECTION PROGRAM

Slide 1.04

DISCUSSION TOPICS

- PURPOSE AND OBJECTIVES OF PROGRAM
- KEY PROGRAM COMPONENTS
- PROGRAM PHASES
- E.P.A. TECHNICAL ASSISTANCE EFFORTS

PURPOSE

- Focuses on the resource requiring protection
- Protects wellhead area around public water wells and wellfields from contaminants

OBJECTIVES

- Meet the goals of the Statute
- Recognize diversity of hydrogeologic settings and sources of contamination
- Maximize State creativity and flexibility
- Be sensitive to Federal involvement in land use and water allocation
- Help coordinate State efforts to protect ground water

SDWA SUBSECTION 1428(A)

- Each State WHP shall, at a minimum:
  - Specify duties
  - Determine wellhead protection areas
  - Identify potential sources of contamination
  - Specify management approaches
  - Include contingency plans
  - Address new (future) wells

STATE PROGRAM GOAL

SDWA Section 1428(a) establishes the fundamental goal for State WHP Programs "...to protect wellhead areas within their jurisdiction from contaminants which may have any adverse effects on the health of persons."

REQUIRED SUBMITTALS

- Description of how the State Program will achieve this goal
- Overall approach
- Methods for evaluating and measuring progress

STATUTE/KEY TERM

For each State WHP Program, the State:

> "...shall, at a minimum...specify the **duties** for State agencies, local governmental entities, and public water supply systems with respect to the development and implementation of programs required by this section."

STATE PROGRAM SUBMITTAL

- Identification of relevant agencies and the lead management agency
- Assignment of duties
- Mechanisms for coordination, integration

FUNDAMENTAL DEFINITION

Subsection 1428(e):

". . . the term **'wellhead protection area'** means the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are likely to move toward and reach such water well or wellfield."

BACKGROUND

- EPA required to release these guidelines by SDWA (1428(e))
- States not required to use guidelines
- Developed by EPA with consultation from Hydrogeology Technical Committee
- Reflects analysis of existing programs in States, localities and Western Europe

STATUTE/KEY TERMS

For each State WHP Program, the State:

"...shall, at a minimum...identify within each wellhead protection area all potential **anthropogenic sources of contaminants** which may have any adverse effect on the health of persons."

EXHIBIT 1.5-2
OPERATIONS WITH POTENTIAL THREAT TO GROUND WATER

1. Gas stations/service stations, truck terminals
2. Fuel/oil distributors/ storers
3. Oil pipelines
4. Auto repair/body shops/ rust proofers
5. Auto chemical supplies storers/retailers, pesticide/ herbicide storers/retailers
6. Small engine repair shops
7. Dry cleaners, furniture strippers/painters/finishers, photo processors, appliance repairers, printers
8. Auto washes
9. Laundromats, beauty salons, medical/dental/ vet offices
10. Research laboratories
11. Food processors, meat packers, slaughter houses
12. Concrete/asphalt/tar/ coal companies
13. Salt piles/sand-salt piles
14. Snow dumps, railroad yards, stormwater impoundment sites, graveyards
15. Airport maintenance/ fueling operations areas
16. Industrial manufacturers: chemicals, pesticides/herbicides, paper, leather products, textiles, rubber, plastic/fiberglass, silicone/glass, pharmaceuticals, electrical equipment
17. Machine shops, metal platers/ heat treaters/smelters/annealers/ descalers
18. Wood preservers
19. Chemical reclamation facilities
20. Boat builders/refinishers
21. Industrial waste disposal/ impoundment areas, municipal wastewater treatment plants, landfills/dumps/transfer stations
22. Junk and salvage yards
23. Subdivisions using private wastewater disposal (individual or cluster)
24. Single-family septic systems
25. Heating oil storage (consumptive use)
26. Golf courses/parks/nurseries
27. Sand & gravel mining operations
28. Other mining operations, injection wells
29. Manure piles
30. Feed lots
31. Agricultural pesticide/ herbicide storage
32. Agricultural pesticide/ herbicide/fertilizer use

Source: State of Maine, The Planning Process for Local Ground-Water Protection, Table 2, Draft.

STATE PROGRAM SUBMITTAL

- List of categories of contamination sources
- Procedure for inventorying sources
- Procedure for refining, expanding, updating and verifying sources o contamination

STATUTE/KEY TERMS

For each State WHP Program, the State:

"...shall, at a minimum...describe a program that contains, as appropriate, **technical assistance, financial assistance,** implementation of **control measures, education, training and demonstration projects** to protect the water supply within wellhead protection areas from such contaminants."

DEVELOPMENT PHASE ACTIVITIES

Work plans should specify actions, milestones, and a schedule to:

- Evaluate existing source management programs and sources not currently controlled

- Establish and enhance management approaches

- Determine procedure for phasing

EXISTING SOURCE MANAGEMENT PROGRAMS

- Additional management efforts
- Enhance existing programs

"UNCONTROLLED" SOURCES

- Introduce new legislation
- Train industry personnel
- Provide technical and financial assistance to municipalities
- Prohibit in WHPAs
- Use methods in Statute

PHASING MANAGEMENT CONTROLS

Risk criteria:

- Hydrogeologic setting
- Type of wellhead
- Well size
- Population

STATUTE/KEY TERM

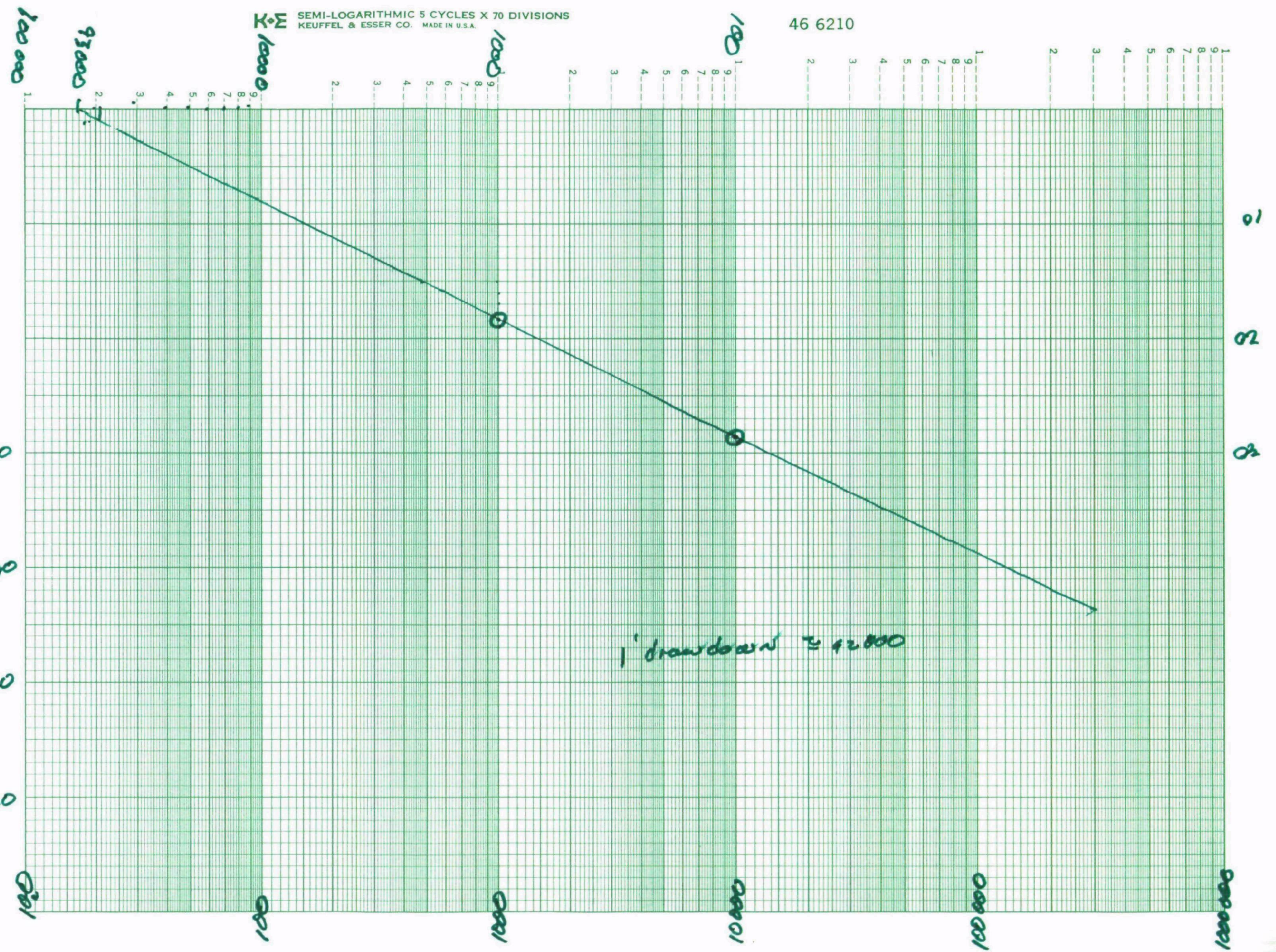
For each State WHP Program, the State:

"...shall, at a minimum...include **contingency plans** for the location and provision of alternate drinking water supplies for each public water system in the event of well or wellfield contamination by such contaminants."

STATUTE/KEY TERM

For each State WHP Program, the State:

"...shall, at a minimum...include a requirement that consideration be given to all potential sources of... contaminants within the expected wellhead area of a **new** water **well** which serves as a public water supply system."


K+E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 6210
100 000
93000
10000
1000
100
10
20
30
40
100
1000
10000
100000
1000000
1' drawdown ≈ 42,000

SDWA SUBSECTION 1428(B)

- Public Participation:
  - Technical and citizens' advisory committees
  - Notice and opportunity for public hearings

WHP PROGRAM PHASES

- Development phase
- State Program submission and EPA review
- Implementation phase

BUDGET STATUS

- STATE GRANT PROGRAM WAS AUTHORIZED IN S.D.W.A.

- CONGRESS HAS NOT APPROPRIATED FUNDS FOR W.H.P. GRANTS FOR FY 1988 AND FY 1989

- O.G.W.P. HAS FUNDS AVAILABLE FOR TECHNICAL ASSISTANCE

WOW

- S.D.W.A. STILL REQUIRES STATES TO SUBMIT AN "ADEQUATE PROGRAM" TO E.P.A. BY JUNE 1989

THIS MEANS THAT IT REALLY ISN'T A VOLUNTARY PROGRAM

EPA PROGRAM REVIEW PROCESS

- States are encouraged to submit drafts to EPA
- Procedures will vary from Region to Region
- EPA will notify State Governor of approval/ disapproval decision
- States may resubmit revised Programs within six months

GENERAL REQUIREMENTS OF WORK PLAN

- Address all six statutory Program elements plus public participation
- Identify milestones
- Provide schedule for accomplishment
- Distribute costs/personnel
- Be accompanied by a Program narrative statement

PHASING

- States may "phase-in" certain program elements to use their resources more efficiently
- Phasing is recommended principally for:
  - WHP area delineation
  - Source identification
  - Management approaches
  - Contingency plans

E.P.A. TECHNICAL ASSISTANCE EFFORTS ALREADY COMPLETED

- DELINEATION GUIDELINES
- S.D.W.A. GRANT GUIDANCE
- DECISION MAKER'S GUIDE
- GENERAL TRAINING ON WELLHEAD PROGRAM
- MODEL ASSESSMENT FOR DELINEATION
- SURFACE GEOPHYSICAL TECHNIQUES
- ANNOTATED BIBLIOGRAPHY OF W.H.P. PROGRAMS

EFFORTS IN PROGRESS

- DELINEATION TRAINING PROGRAM
- USER-FRIENDLY ANALYTICAL MODEL DEVELOPMENT
- DELINEATION T.A.D.s FOR CONFINED AQUIFERS AND FRACTURED ROCK
- SYMPOSIUM AT 28th INTERNATIONAL GEOLOGICAL CONGRESS (WASHINGTON D.C. - JULY 1989)

OTHER EFFORTS IN PROGRESS

- REGIONAL ASSISTANCE FOR STATE PROGRAM DEVELOPMENT
- NATIONAL WELLHEAD CONFERENCE
  (NEW ORLEANS, LOUISIANA - DECEMBER 1988)
- OVERVIEW OF W.H.P. MANAGEMENT STRATEGIES
- OVERVIEW OF CONTAMINATION SOURCES; FOCUS ON LIGHT INDUSTRY
- RISK ASSESSMENT AND MANAGEMENT IN W.H.P.
- APPROACHES FOR FINANCING W.H.P. IMPLEMENTATION
- CONTINGENCY PLANS; T.A.D. AND PILOT PROJECTS

1. INTRODUCTION

1.1 BACKGROUND

The Amendments to the Safe Drinking Water Act (SDWA), passed in June 1986, established the first nationwide program to protect ground-water resources used for public water supplies from a wide range of potential threats. The SDWA seeks to accomplish this goal through the establishment of State Wellhead Protection (WHP) Programs which "protect wellhead areas within their jurisdiction from contaminants which may have any adverse effect on the health of persons."

One of the major WHP elements is the determination of zones within which contaminant source assessment and management will be addressed. These zones, called Wellhead Protection Areas (WHPAs), are defined in the SDWA as "the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield." Hence, the law establishes the concept of protecting a portion of the recharge areas to these points of public drinking-water withdrawal. States are given flexibility in determining appropriate approaches to WHPA delineation, and the Environmental Protection Agency (EPA), Office of Ground Water Protection (OGWP) has prepared technical guidelines to assist on the hydrogeologic aspects of this task in the publication of "Guidelines for Delineation of Wellhead Protection Areas", June 1987. Additional guidance is available with respect to funding and implementation of a WHPA in the following OGWP's guidelines:

> "Guidelines for Applicants for State Wellhead Protection Program Assistance Funds Under the Safe Drinking Water Act" (EPA, 1987b)
>
> "Surface Geophysical Techniques for Aquifer and Wellhead Protection Delineation" (EPA, 1987c)
>
> "Model Assessment for Delineating Wellhead Protection Areas" (EPA, 1988d)

This manual was prepared to accompany the Wellhead Protection Area Delineation Training Course presented by the OGWP at regional centers during the period August to November 1988. It is the intent of this course to provide participants with an introduction to the criteria and methods used in delineating WHPAs as well as the background in ground-water flow fundamentals required to apply those methods correctly. The lecture material is supplemented with simple problem exercises that demonstrate the mechanics of the various methods and case studies that summarize actual WHPA delineation projects.

The tutorial sections of the manual are written in a style that falls between the terse outline or "bullet" format used in presentation slides and the in-depth explanations found in most textbooks. The idea is to convey, in one- or two-sentence paragraphs, the important concepts, points, and issues concerning a topic. The readers can move quickly through a topic identifying those points with which they are familiar, as well as those which are new and may require further investigation. A list of references is provided at the end of the manual (Appendix A) to direct the readers to available research materials.

Copies of the slides used in each lecture are included at the end of each section to allow participants to easily follow each lecture. These figures also serve to illustrate topics discussed in the body of the text and are referenced by slide number in the section to which they pertain.

Additional copies of this training document are available by contacting:

Office of Ground-Water Protection
U.S. Environmental Protection Agency
Washington, DC 20460

1.2 TRAINING COURSE OBJECTIVES

Wellhead Protection Area (WHPA) delineation is based on an analysis of criteria, such as radial distance, drawdown caused by pumpage, ground-water travel time, flow boundaries, or assimilative capacity in the zone surrounding the well. The criteria and thresholds define the general technical basis of the WHPA, and delineation methods are subsequently used to translate or apply these criteria to develop on-the-ground or on-the-map WHPA boundaries.

The Wellhead Protection Area Delineation Training Course was designed for those involved in delineating WHPAs or in reviewing proposed delineations. The course presents the fundamentals of ground-water flow, well hydraulics, and contaminant transport to provide the necessary technical background for the delineation process. It also covers aspects of the WHP program pertaining to wellhead nomenclature, delineation criteria and delineation methods. Hands-on exercise have been developed to lead participants through the mechanics of applying each method. To foster an appreciation for some of the complexities that can be encountered in "real world" situations, case studies are presented for a variety of different hydrogeologic settings. Case studies are also used as a basis for comparing the delineation areas produced by several different methods at a single site.

The WHPA Delineation Training Course was designed to meet the following objectives:

- Introduce the criteria and methods recommended in EPA guidelines for delineating WHPAs,

- Develop a practical understanding through instruction, examples, case studies, and hands-on exercises of the methods used to translate delineation criteria to on-the-map WHPAs,

- Introduce and evaluate various analytical and numerical tools available to implement delineation methods

PRESENTATION SLIDES

FUNDAMENTALS OF GROUND-WATER FLOW

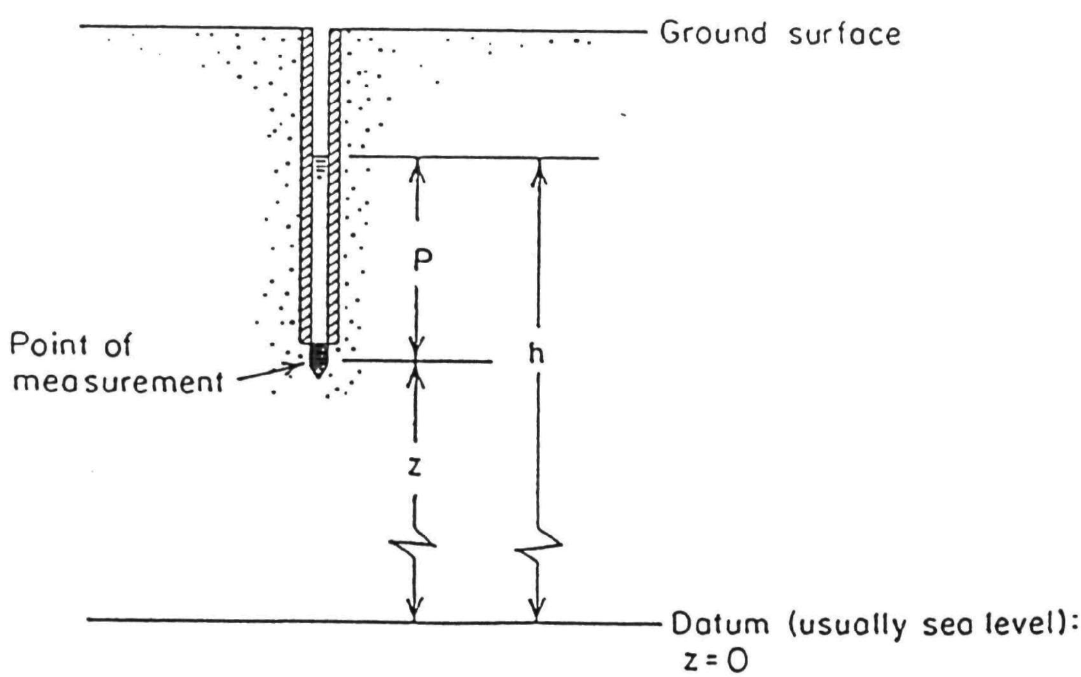
BERNOULLI'S RELATIONSHIP

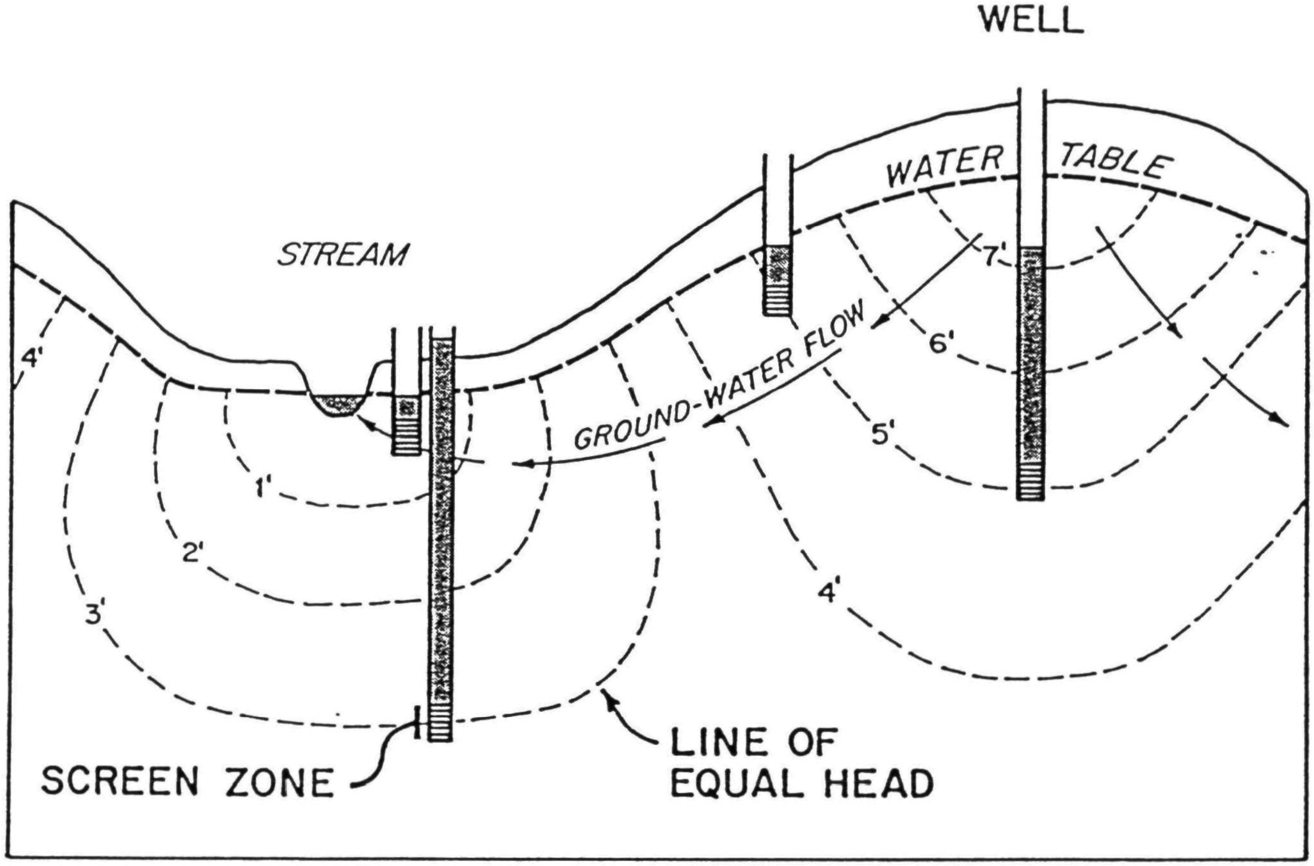
$$h = Z + P$$

where: h = hydraulic head

Z = elevation head

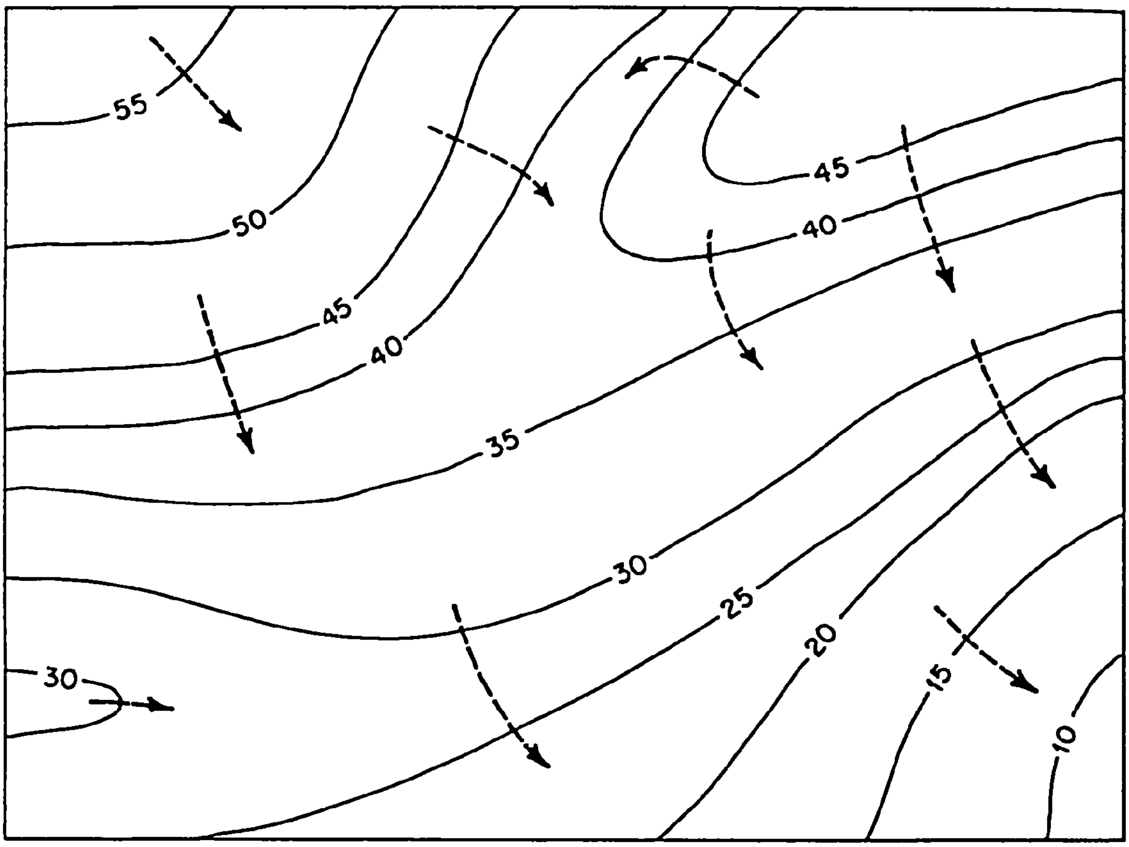
P = pressure head





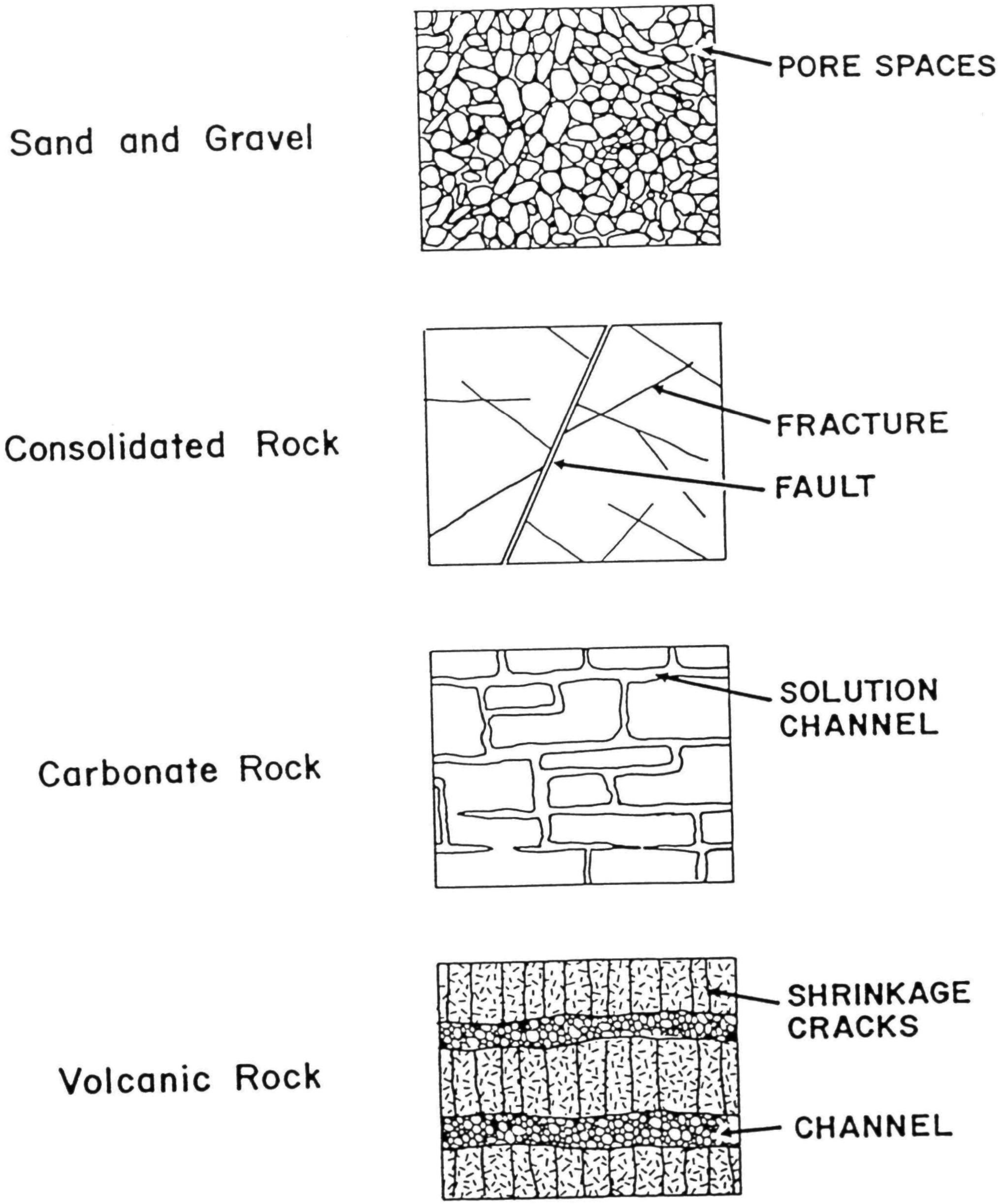
Water levels in wells controlled by hydraulic head
at the screen zone (after Fetter, 1980).

WATER TABLE



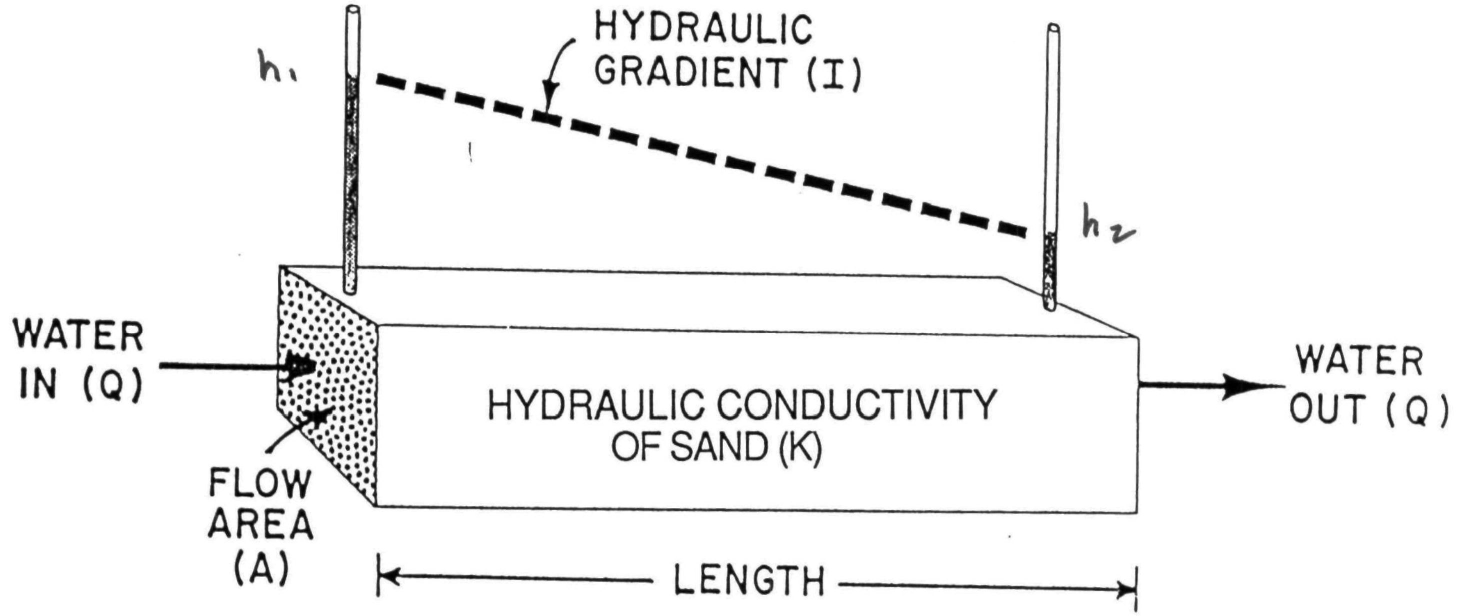
$$i = \frac{h_1 - h_2}{L} = \frac{37 - 27}{100} = 0.1$$

<- - - - - DIRECTION OF FLOW



Slide 2.05

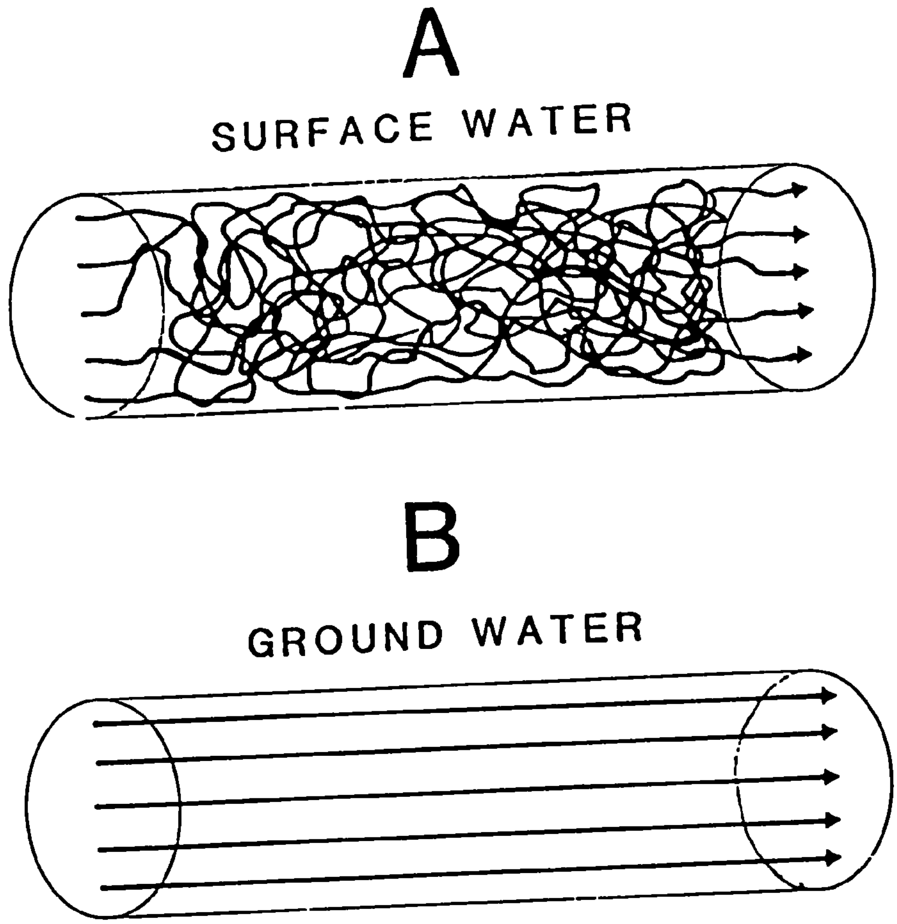
Rock texture in major aquifer types (Walton, 1970).



$$Q = KIA$$

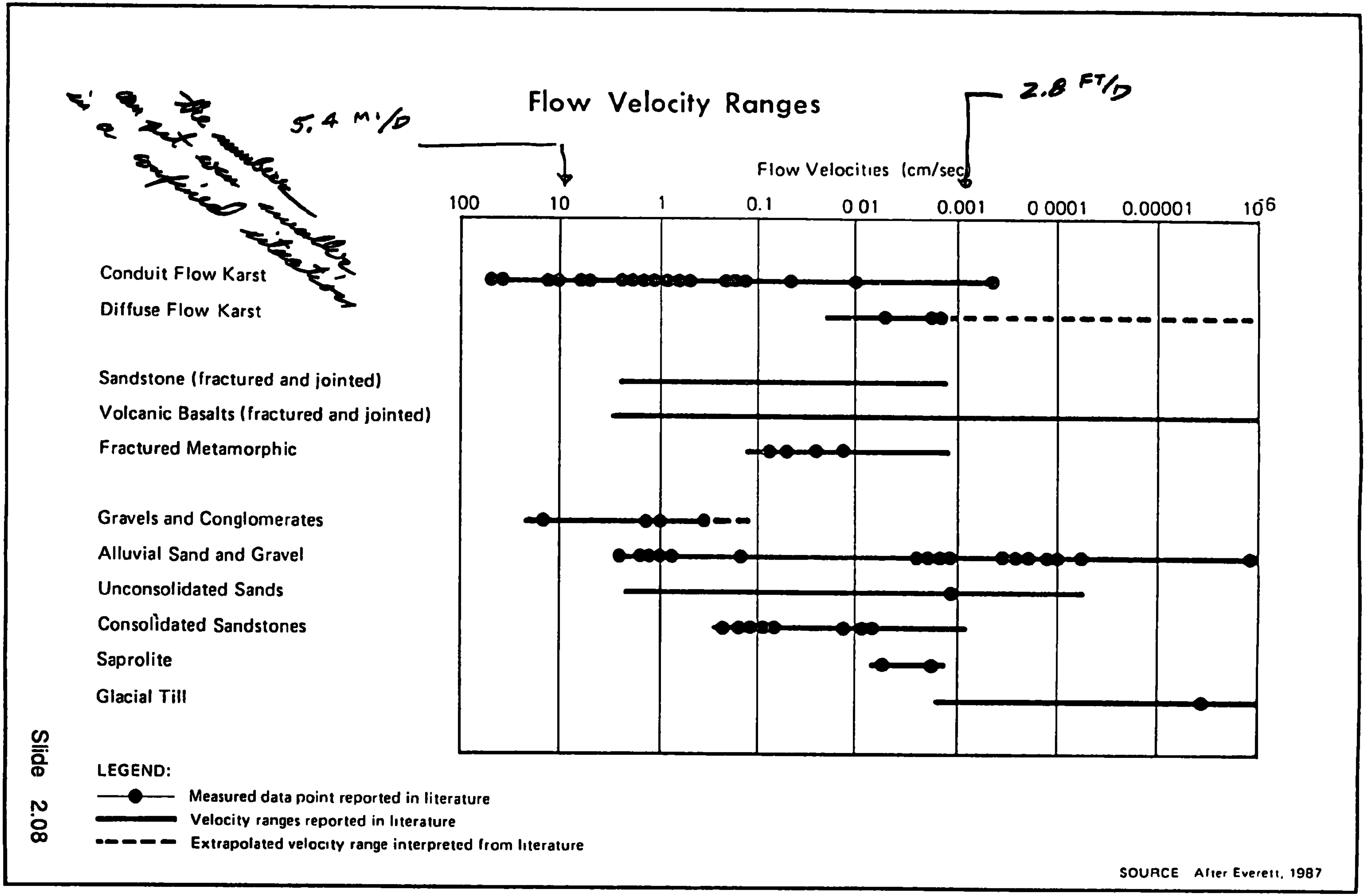
$$\text{Pore Water Velocity} = \frac{KI}{\text{porosity}}$$

Slide 2.06



A. Flow paths of molecules of water in turbulent flow.
B. Flow paths of molecules of water in laminar flow.

(Fetter, 1980).

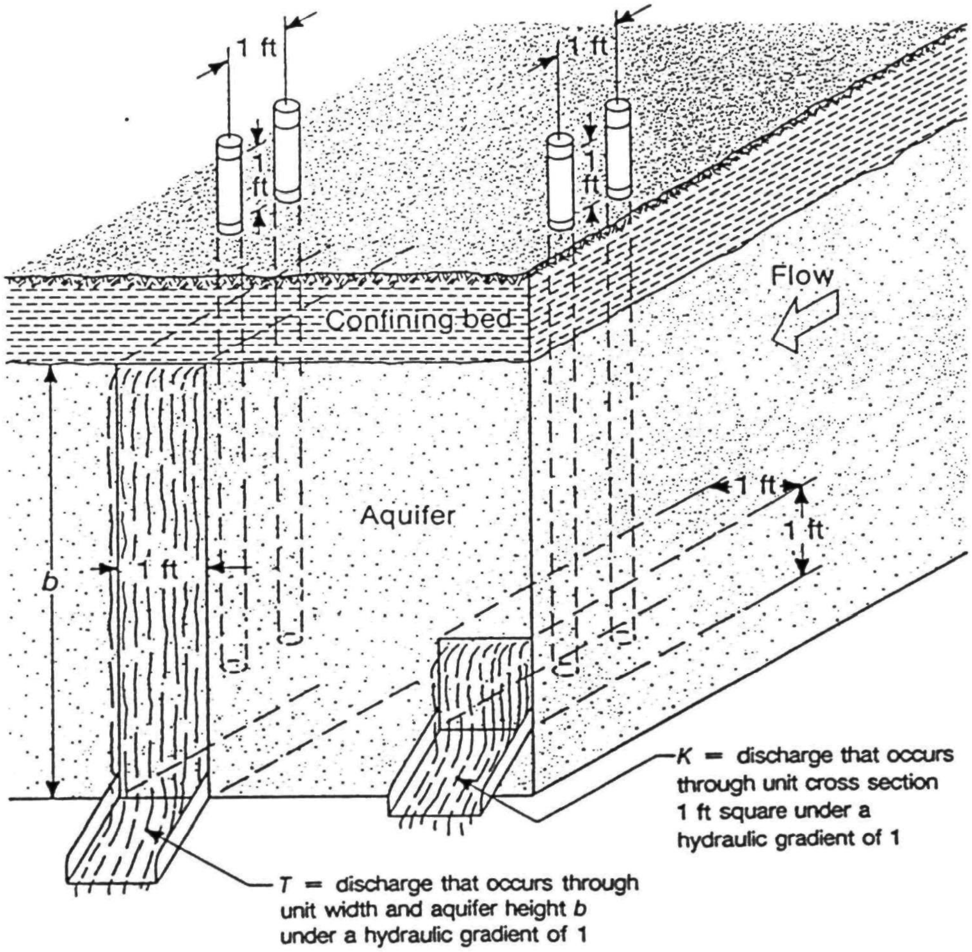


Flow Velocity Ranges
5.4 M/D
2.8 FT/D
Flow Velocities (cm/sec)
100
10
1
0.1
0 01
0.001
0 0001
0.00001
10^-6
Conduit Flow Karst
Diffuse Flow Karst
Sandstone (fractured and jointed)
Volcanic Basalts (fractured and jointed)
Fractured Metamorphic
Gravels and Conglomerates
Alluvial Sand and Gravel
Unconsolidated Sands
Consolidated Sandstones
Saprolite
Glacial Till
LEGEND:
Measured data point reported in literature
Velocity ranges reported in literature
Extrapolated velocity range interpreted from literature
SOURCE After Everett, 1987
Slide 2.08

TRANSMISSIVITY

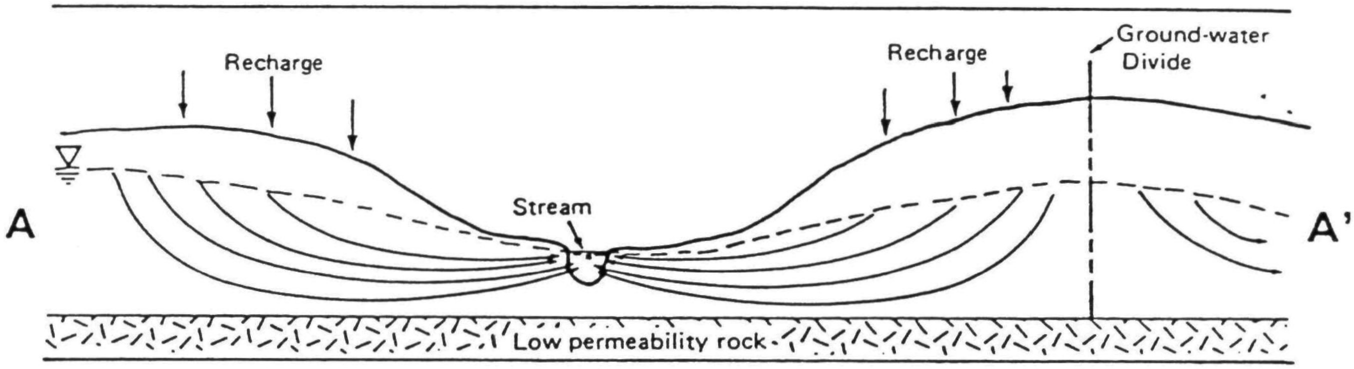
$$T = K\,b$$

$$b = \text{aquifer thickness}$$

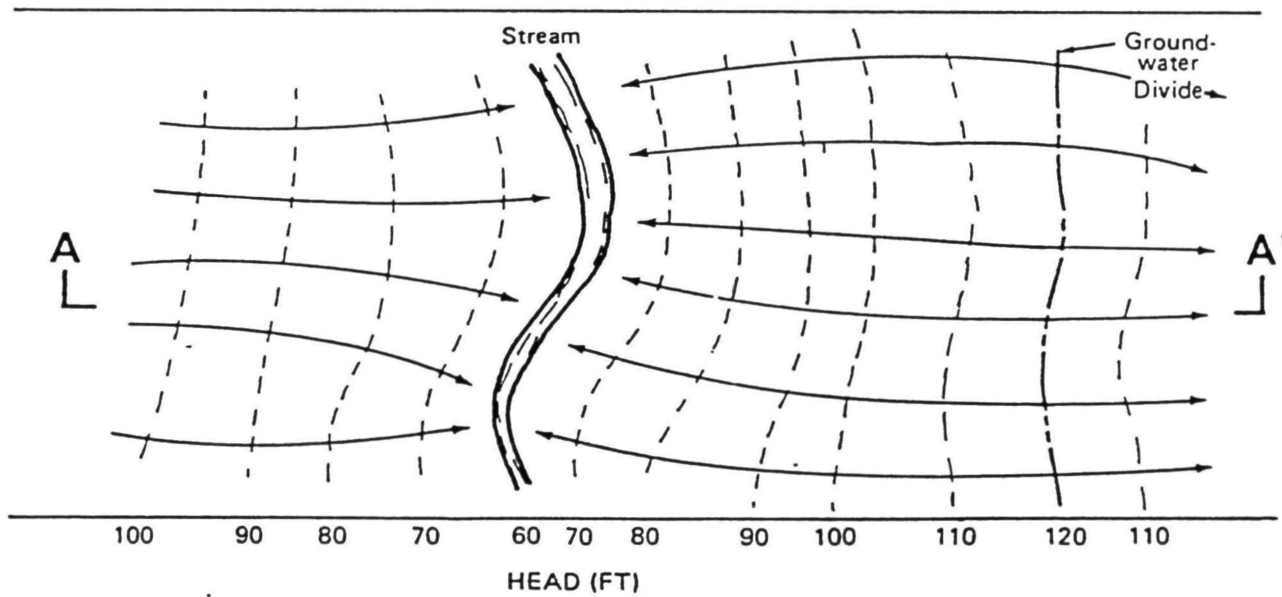


(Source: Driscoll, 1986)

Ground-water Flow System (Stream Valley) Under Natural Conditions



(a) VERTICAL



(b) PLAN VIEW--"FLOW NET"

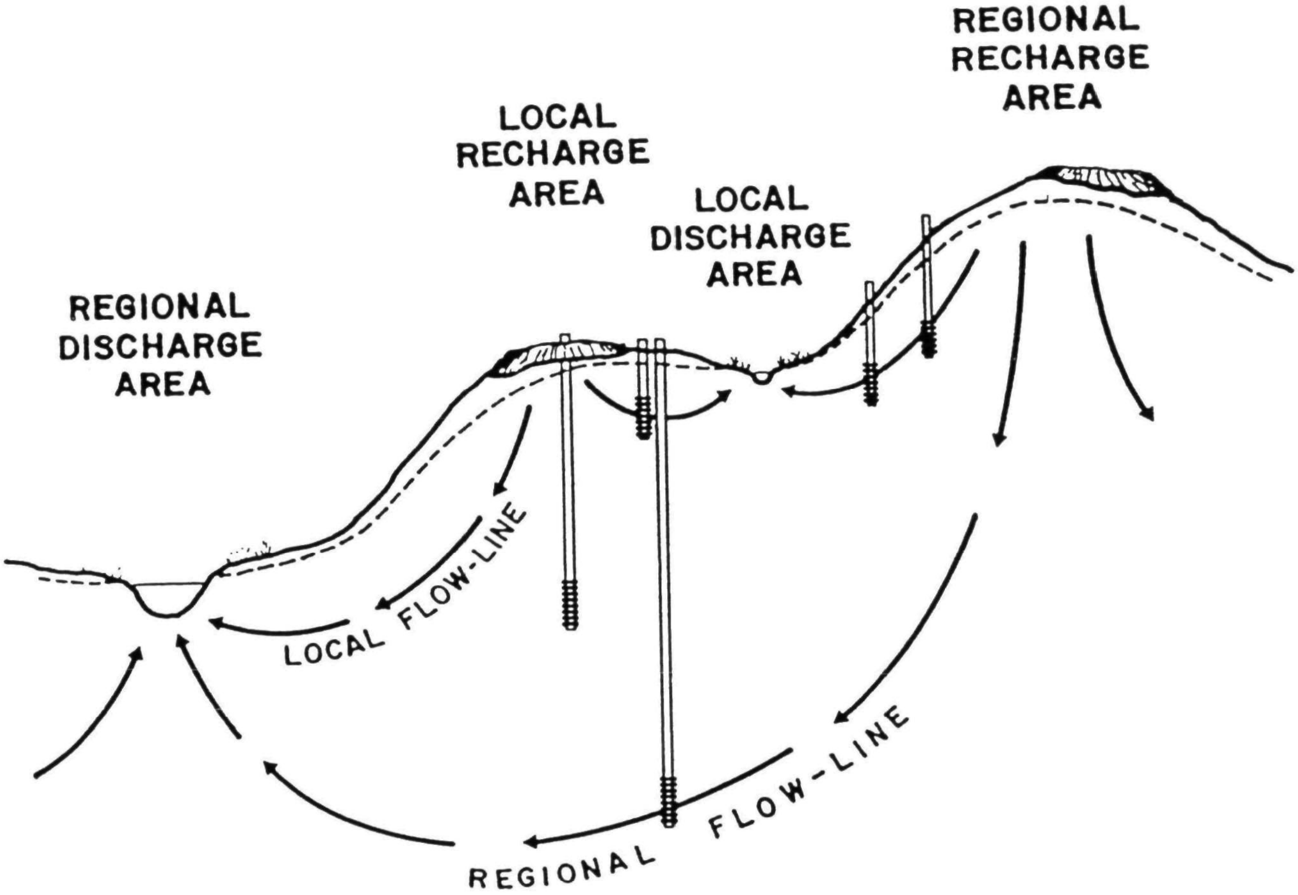
LEGEND:

- Ground-Water Divide
- Equipotential Lines
- Flow Lines
- Water Table

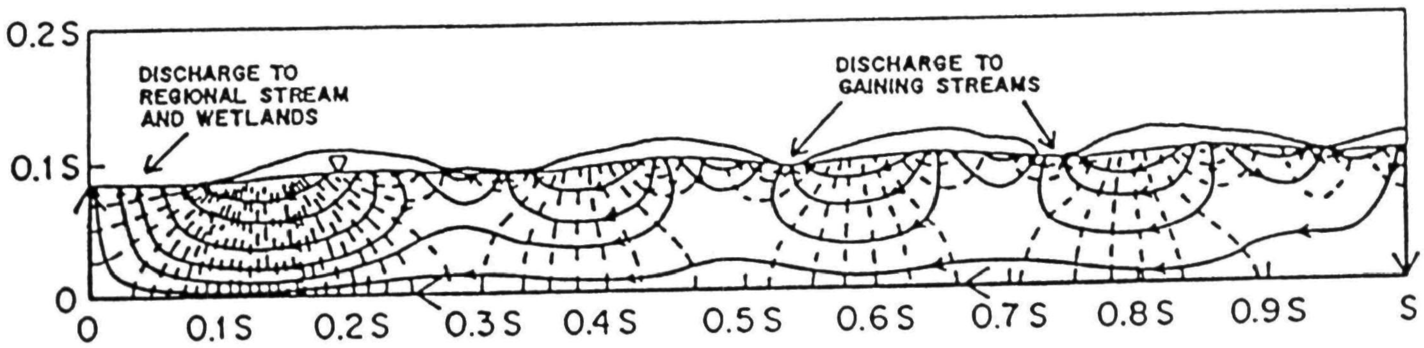
Slide 2.10

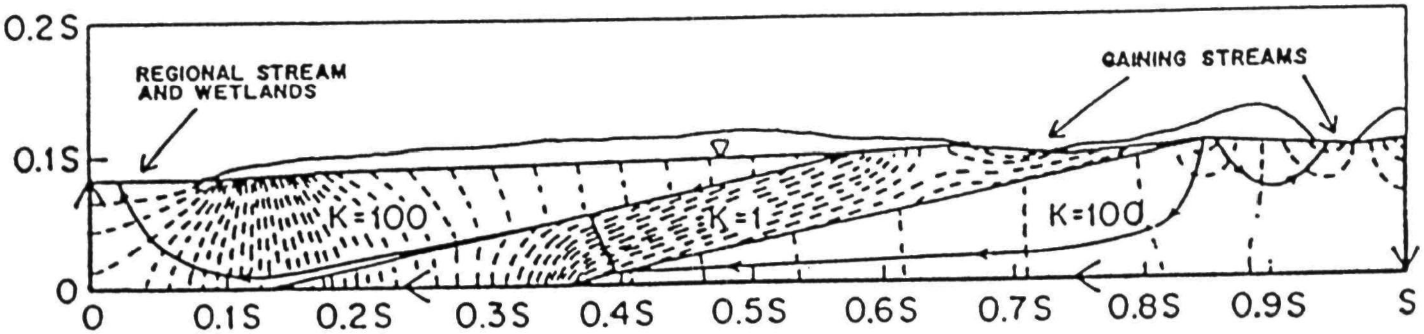
NOT TO SCALE

SOURCE: Modified from Driscoll, 1986

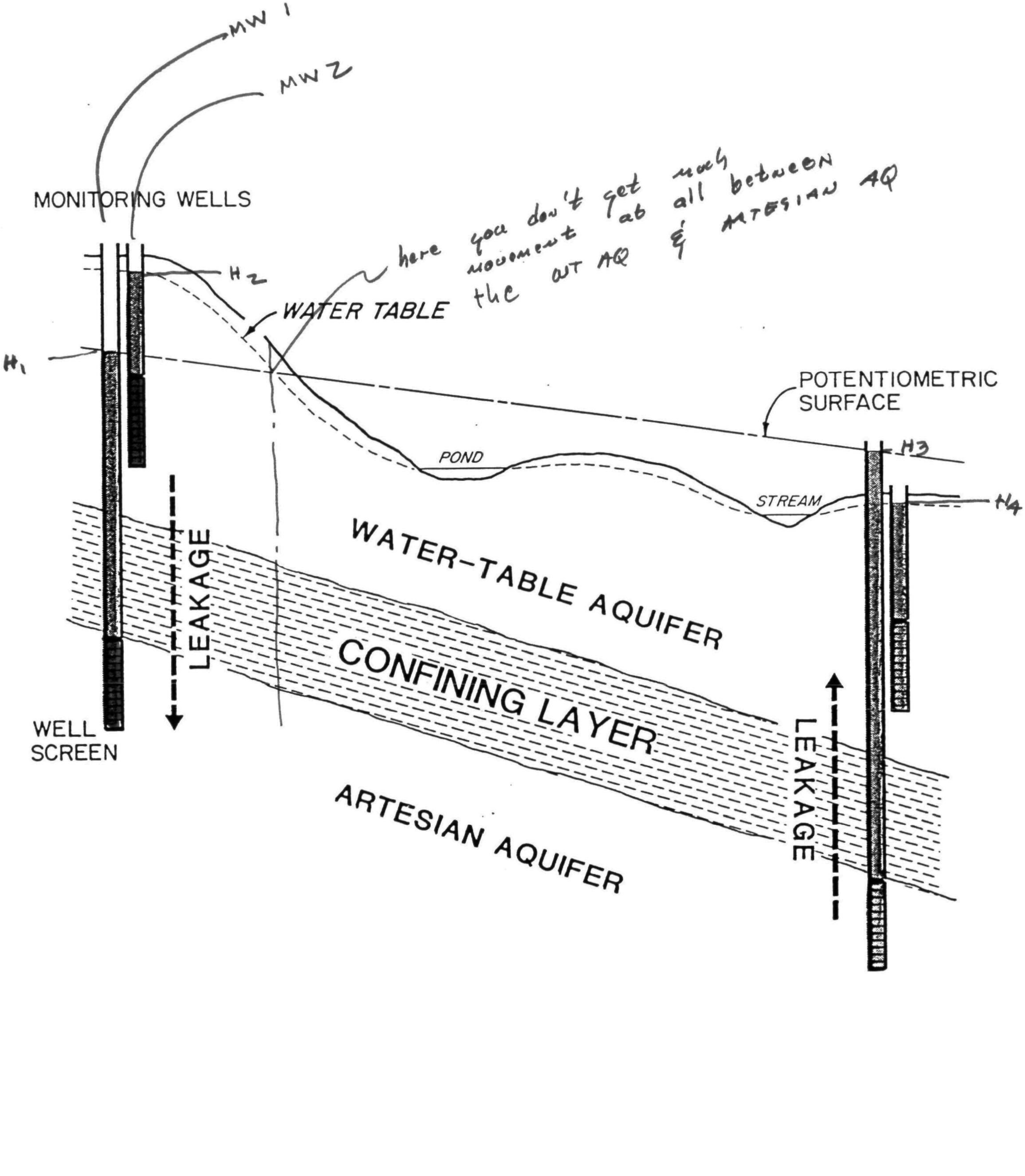


Ground-water flow pattern in a homogeneous isotropic aquifer with moderate relief.


DISCHARGE TO REGIONAL STREAM AND WETLANDS
DISCHARGE TO GAINING STREAMS
0.2S
0.1S
0
0
0.1S
0.2S
0.3S
0.4S
0.5S
0.6S
0.7S
0.8S
0.9S
S


REGIONAL STREAM AND WETLANDS
GAINING STREAMS
K=100
K=1
K=100
0.2S
0.1S
0
0
0.1S
0.2S
0.3S
0.4S
0.5S
0.6S
0.7S
0.8S
0.9S
S

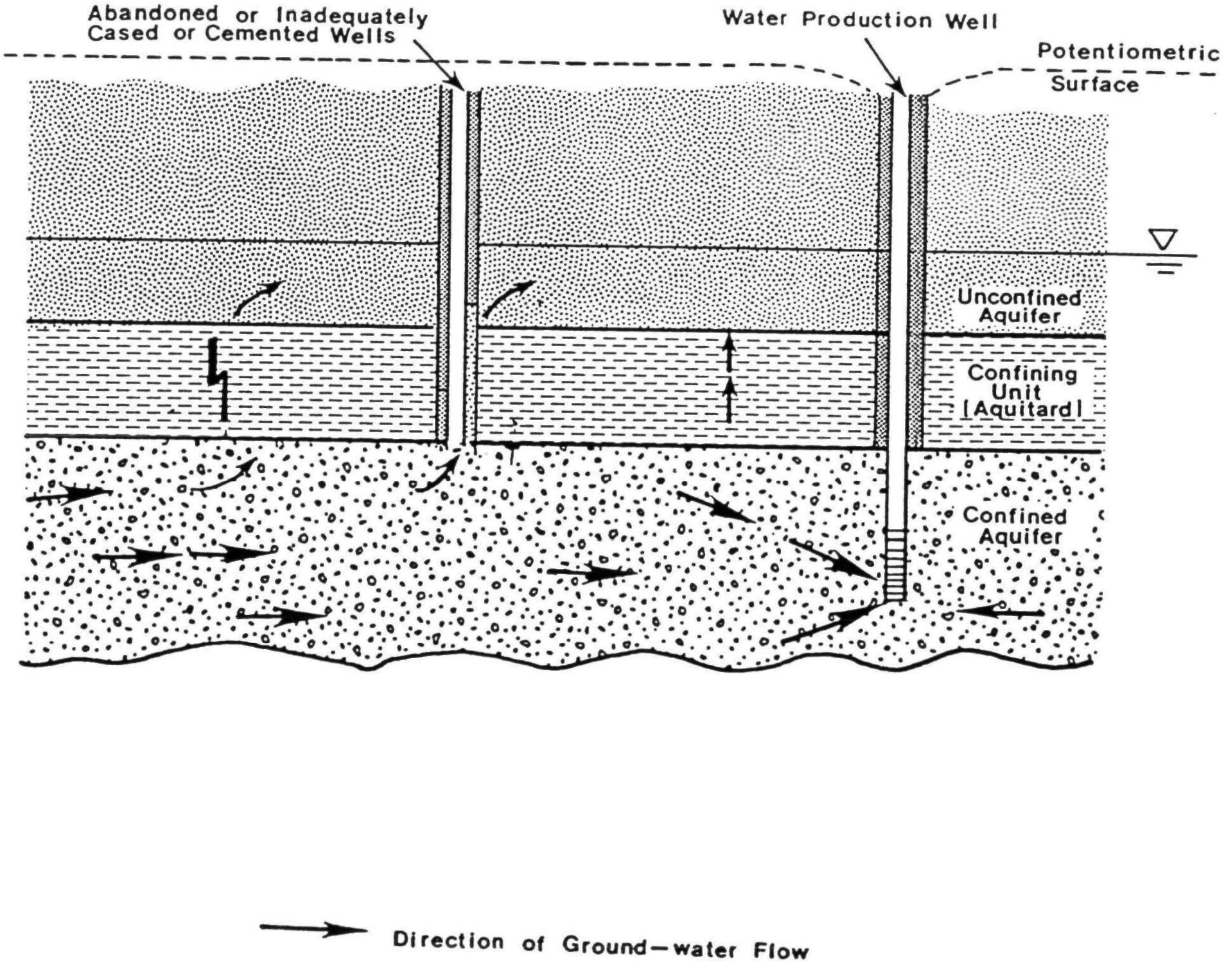
Slide 2.12



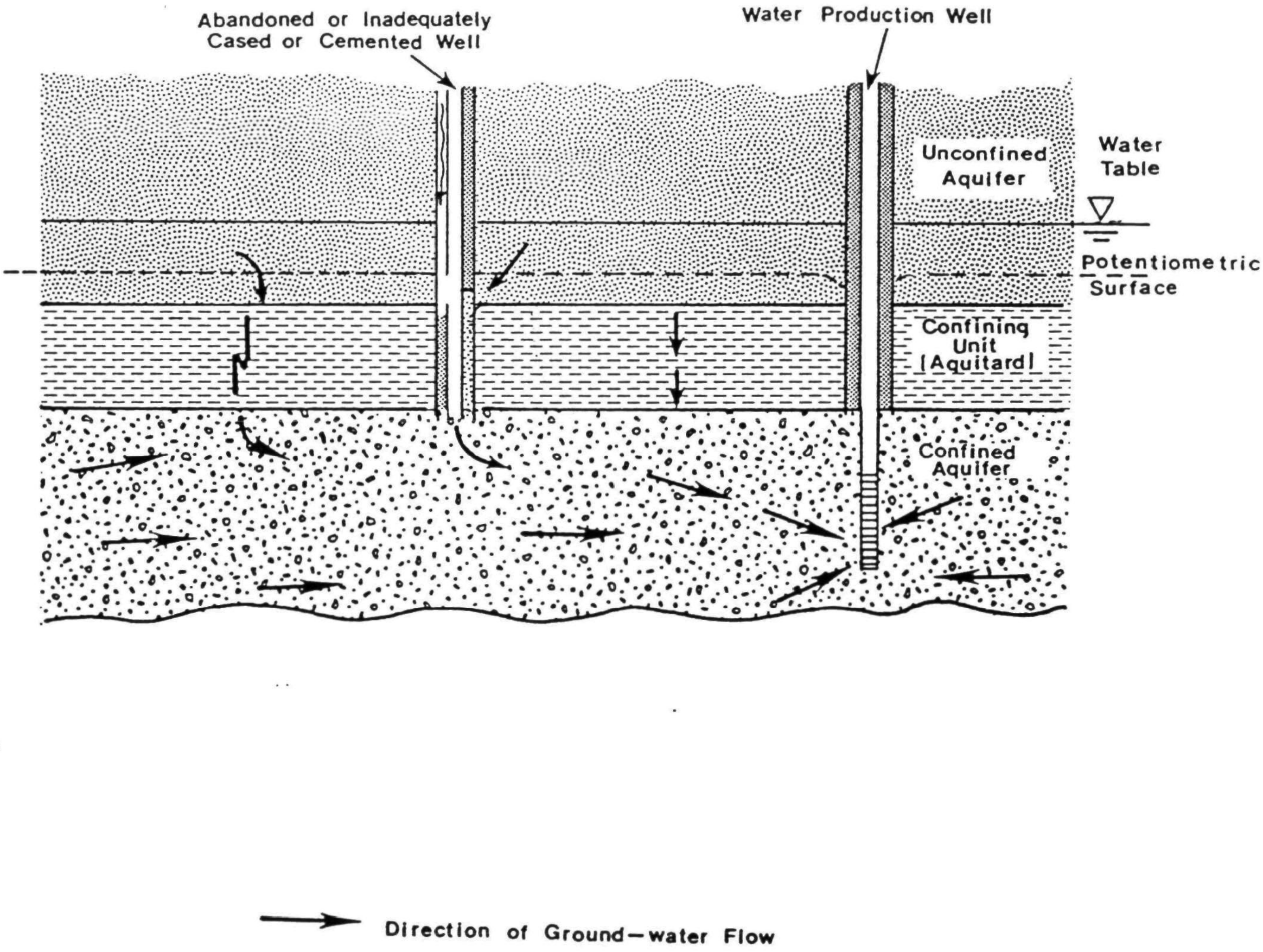
Relationships within the hydrologic system.

Slide 2.13

Confined Aquifer with Upward Leakage



Confined Aquifer with Downward Leakage



FUNDAMENTALS OF CONTAMINANT TRANSPORT

THREATS REQUIRING WHPA DELINEATION

- **DIRECT INTRODUCTION OF CONTAMINANTS IN THE IMMEDIATE WELL AREA**

- **MICROBIAL CONTAMINANTS**

- **CHEMICAL CONTAMINANTS**

OPERATIONS WITH POTENTIAL THREAT TO GROUND WATER

- GAS STATIONS/SERVICE STATIONS, TRUCK TERMINALS

- OIL PIPELINES

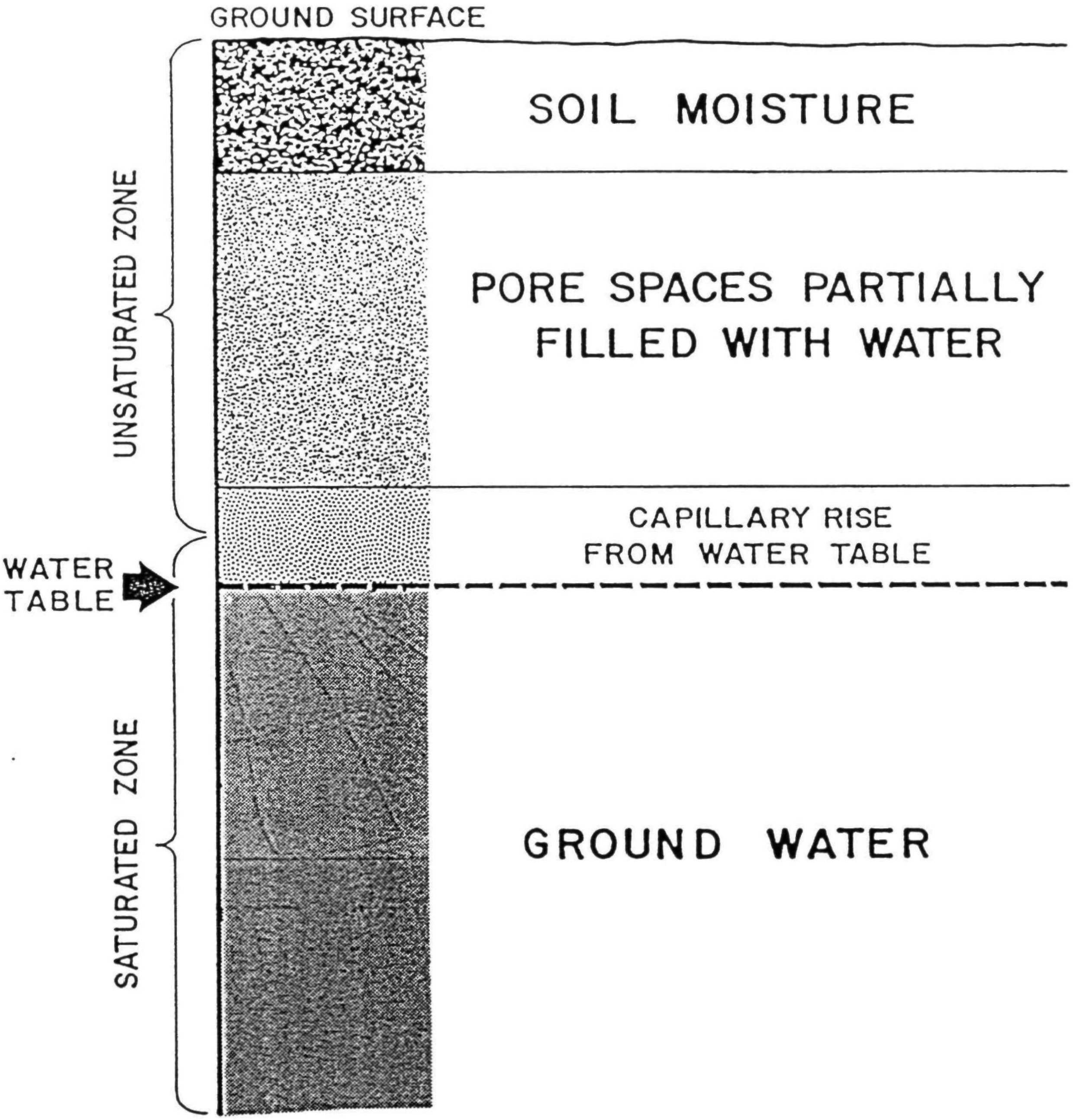
- SNOW DUMPS, RAILROAD YARDS, GRAVEYARDS, STORMWATER IMPOUNDMENT SITES

- INDUSTRIAL MANUFACTURERS: CHEMICALS, PESTICIDES/ HERBICIDES, PAPER, LEATHER PRODUCTS, TEXTILES, RUBBER, PLASTIC/FIBERGLASS, SILICONE/GLASS, ELECTRICAL EQUIPMENT, PHARMACEUTICALS

- SINGLE-FAMILY SEPTIC SYSTEMS

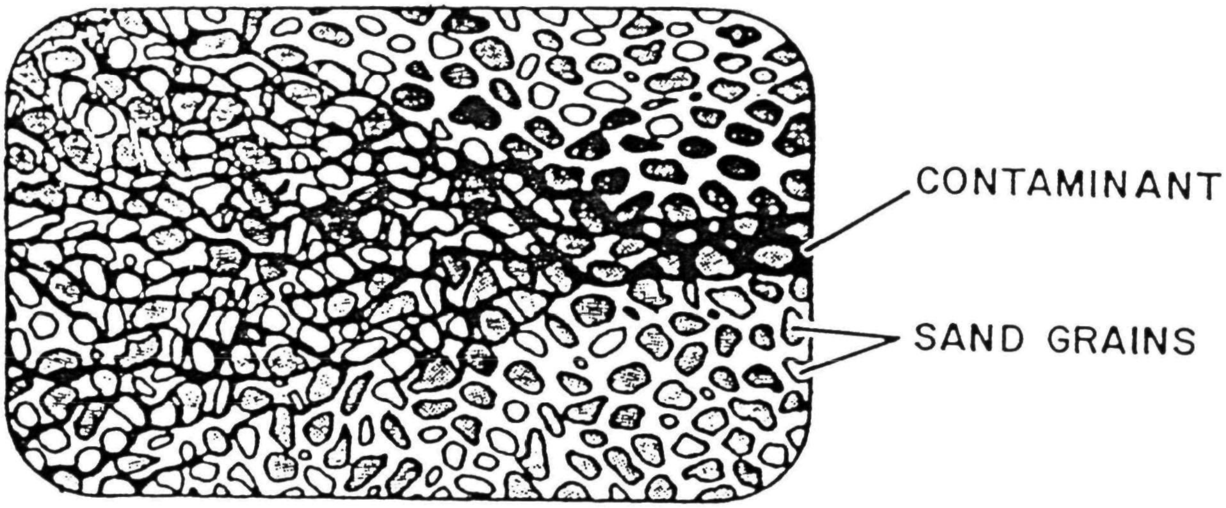
- AGRICULTURAL PESTICIDE/HERBICIDE/FERTILIZER USE

UNSATURATED AND SATURATED ZONES



(after Edward E. Johnson, Inc., 1966)

CONTAMINANT TRANSPORT IN FLOWING GROUND WATER



← DIRECTION OF GROUND-WATER FLOW

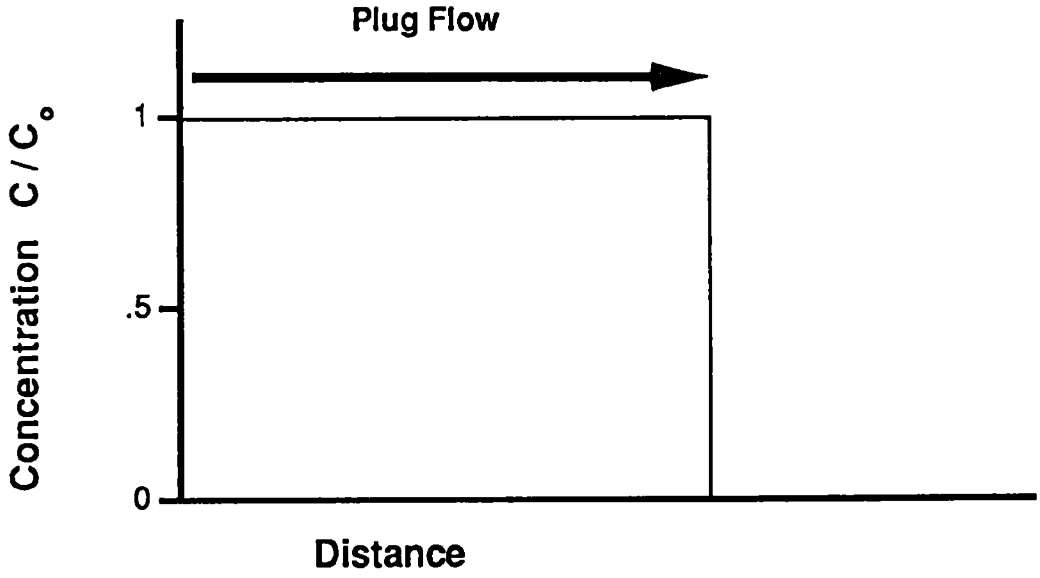
advection (move with flow)
dispersion (move around)

(Freeze and Cherry, 1979)

ADVECTION

Advection = transport by flowing ground water

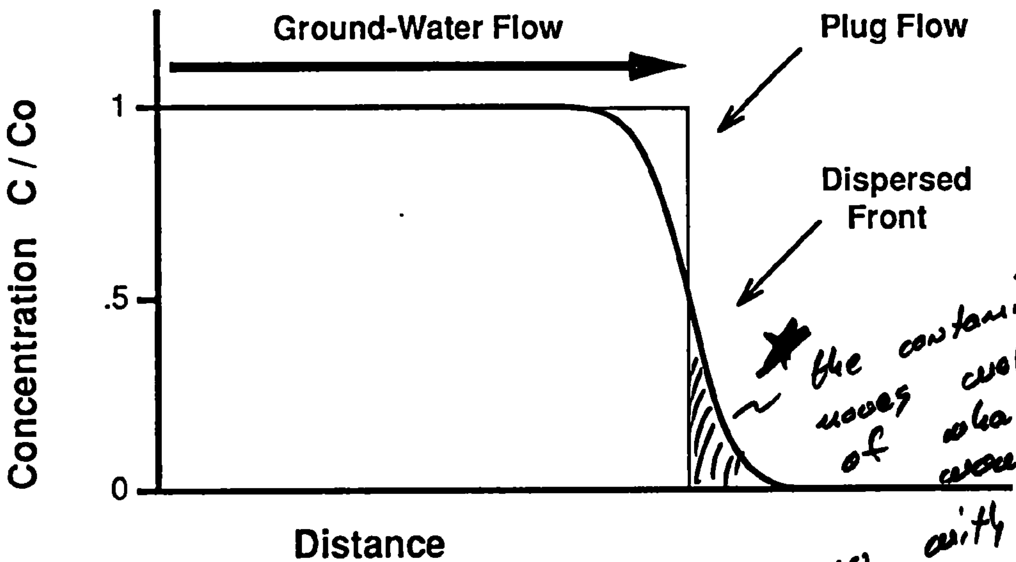
Contaminant moves at rate of ground-water flow; sharp concentration front; no spreading



DISPERSION

DISPERSION = spreading of contaminant plume

Dispersion due to mixing and diffusion spreads contaminants as they are advected; sharp concentration front is smeared



the contaminant moves well ahead of what you would pick up with "plug flow" type calculations (Darcy's law)

Hydrodynamic Dispersion

Hydrodynamic Dispersion is the sum of two processes:

Mechanical Dispersion and Molecular Diffusion

$$D^*_{ij} = D_{ij} + D_d$$

D_{ij} - Mechanical Dispersion (mixing)

$$D_{ij} = a_{ij} \; V_{ij}$$

a_{ij} - Dispersivity

V_{ij} - Pore Water Velocity

D_d - Molecular Diffusion

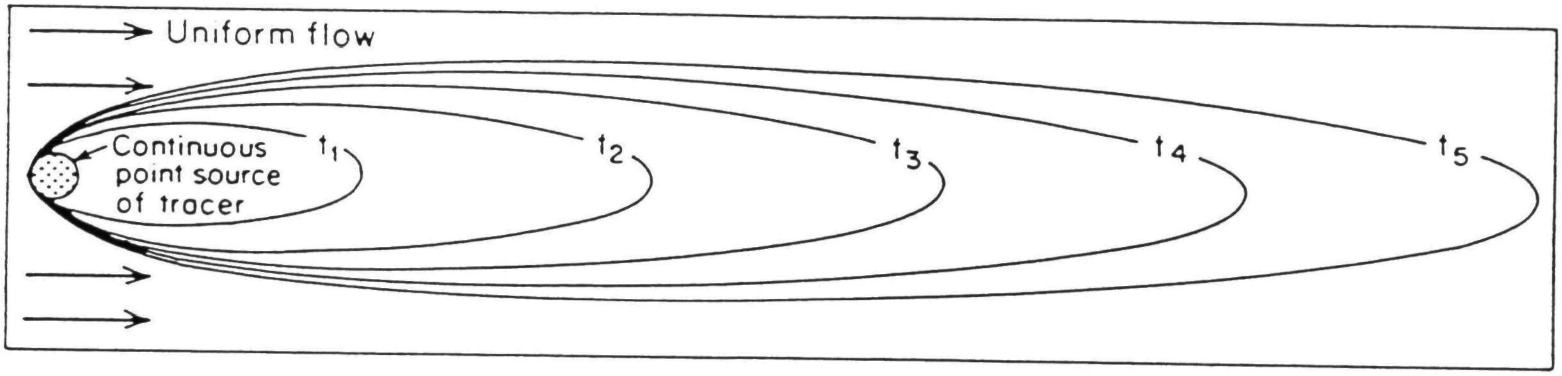
several orders of magnitude smaller than mechanical dispersion

$$D_d = D_o \tau$$

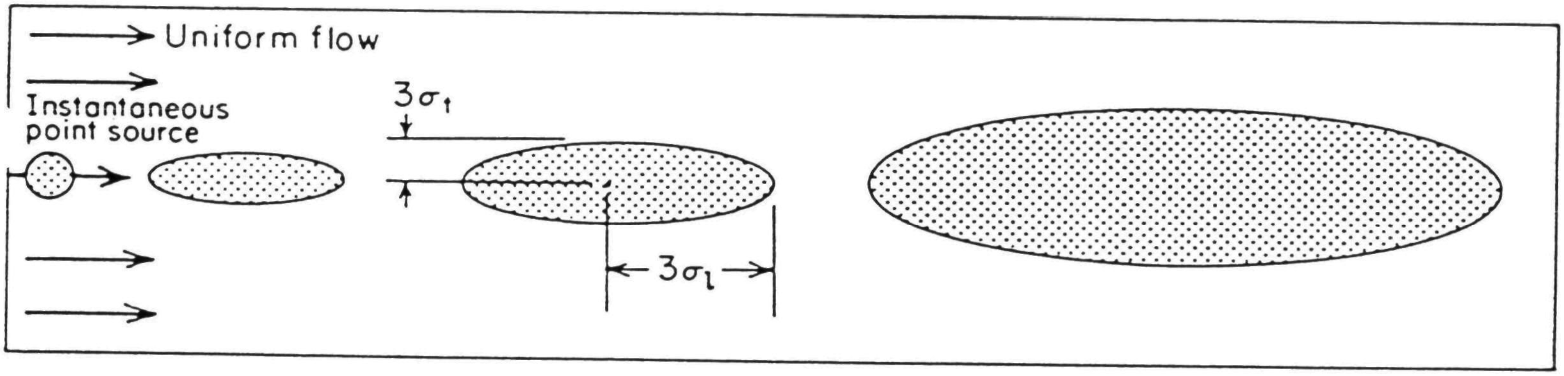
D_o - Free Water Diffusivity

τ - Tortuosity (harder to diffuse through a porous medium

Plume Formation for Continuous and Instantaneous Point Sources



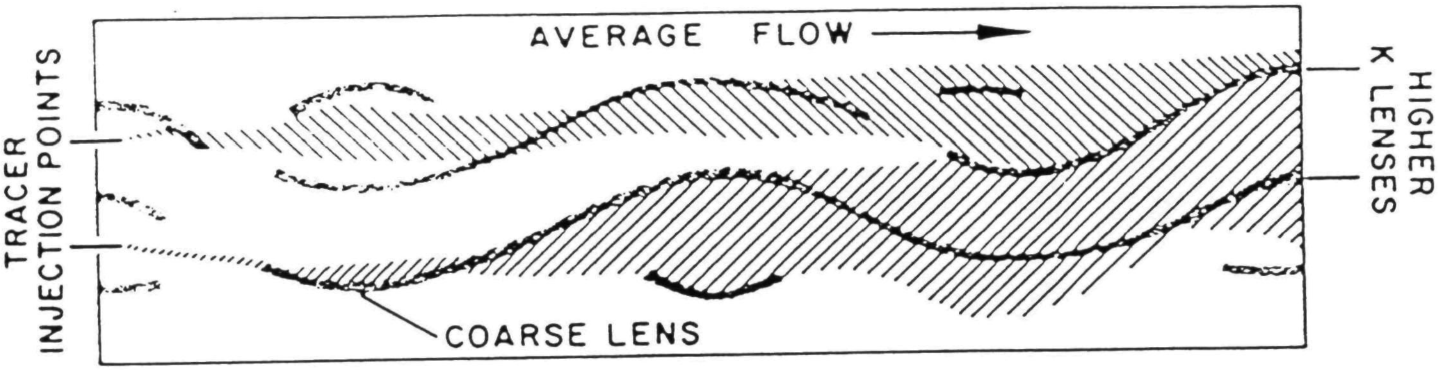
(a)



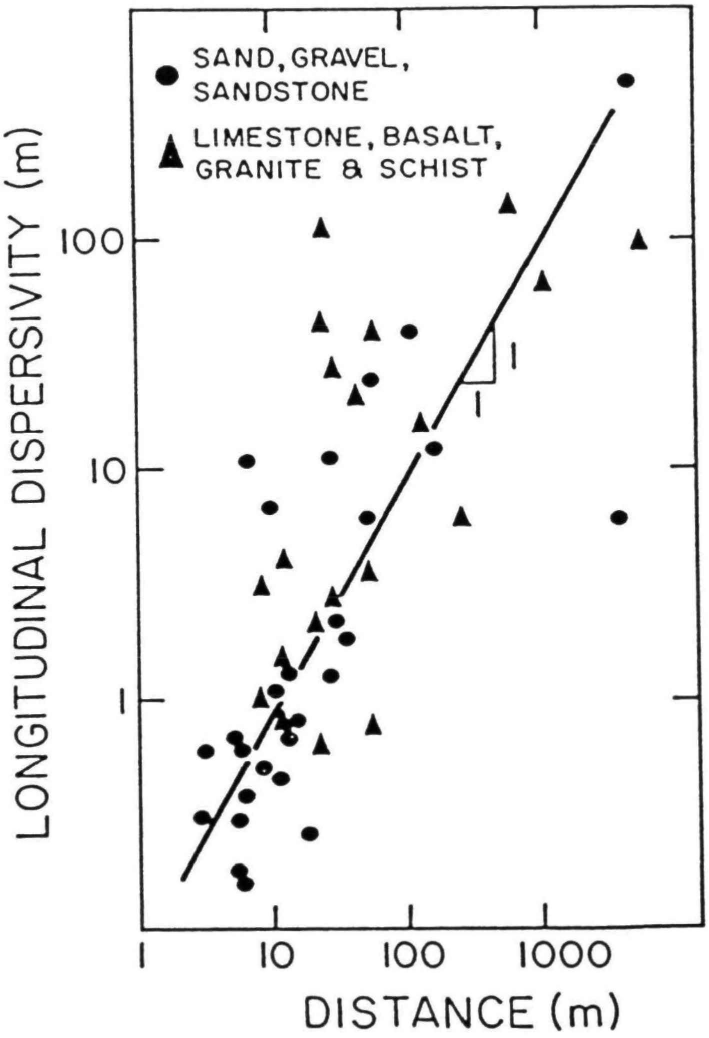
(b)

(Freeze and Cherry, 1979)

Scale-Dependence of Hydrodynamic Dispersion



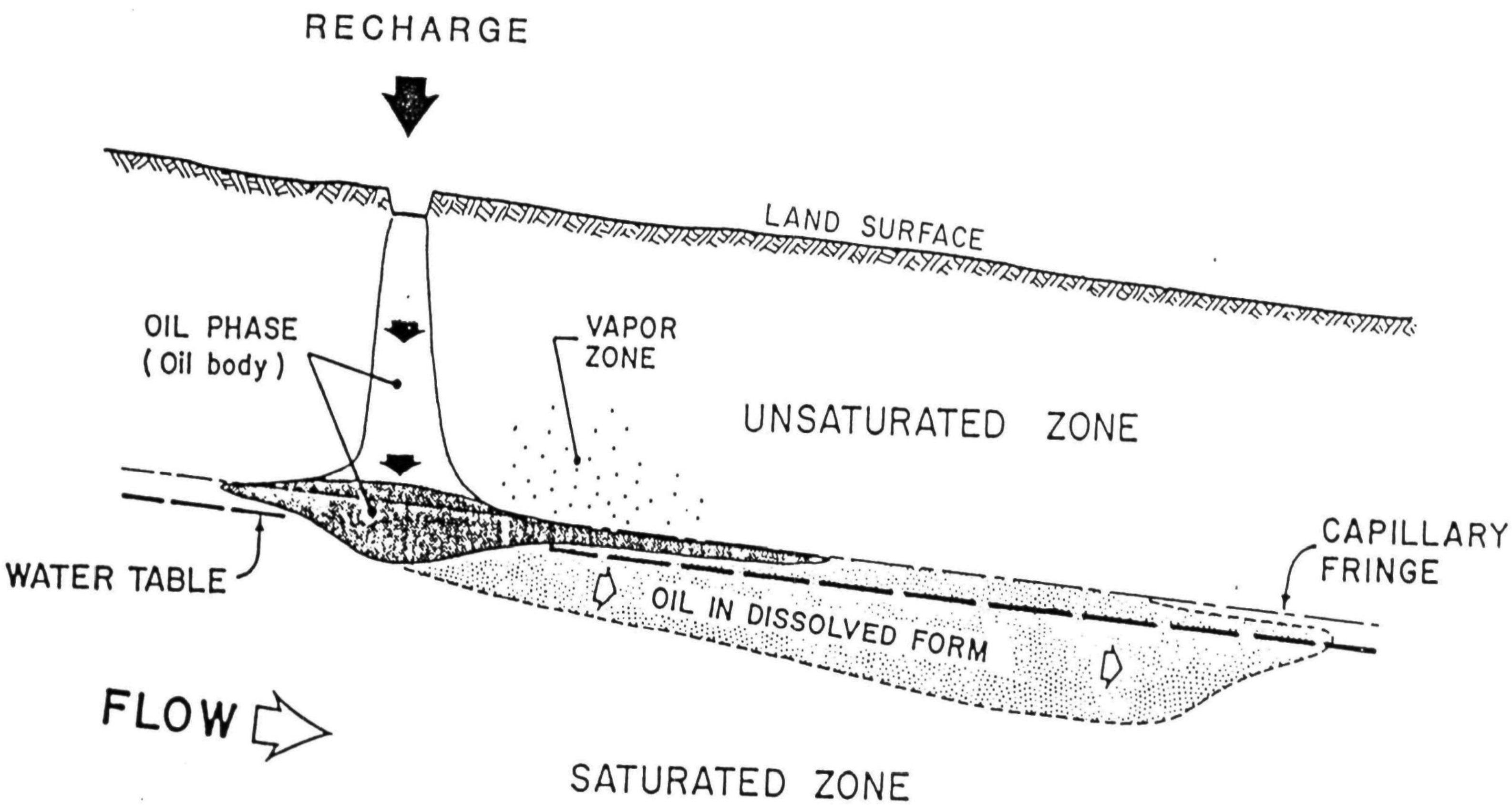
(from Skibitzkie and Robinson, 1963)



Slide 2.25

(from Lallemand-Barres and Peaudecerf, 1978)

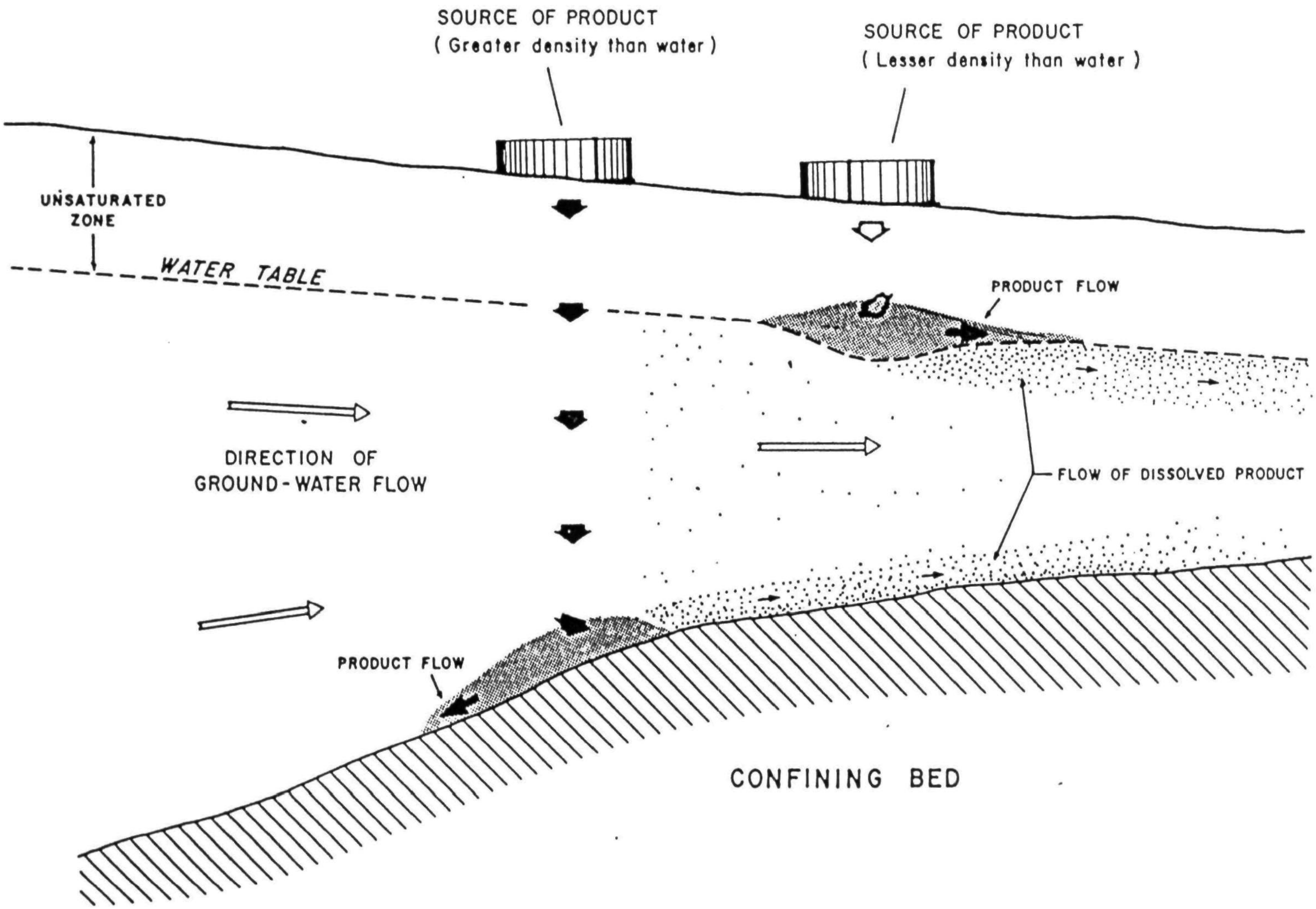
PETROLEUM PRODUCT REACHING GROUND WATER



(after Schwille, 1975)

Slide 2.26

EFFECTS OF DENSITY ON MIGRATION OF CONTAMINANTS



Slide 2.27

PREDICTING CONTAMINANT MIGRATION

ACCURATELY PREDICTING TRANSPORT OF DISSOLVED CONTAMINANTS IS DIFFICULT:

- Discontinuous discharges may produce "slugs" of contaminated water, causing wide spatial and temporal variations in water quality

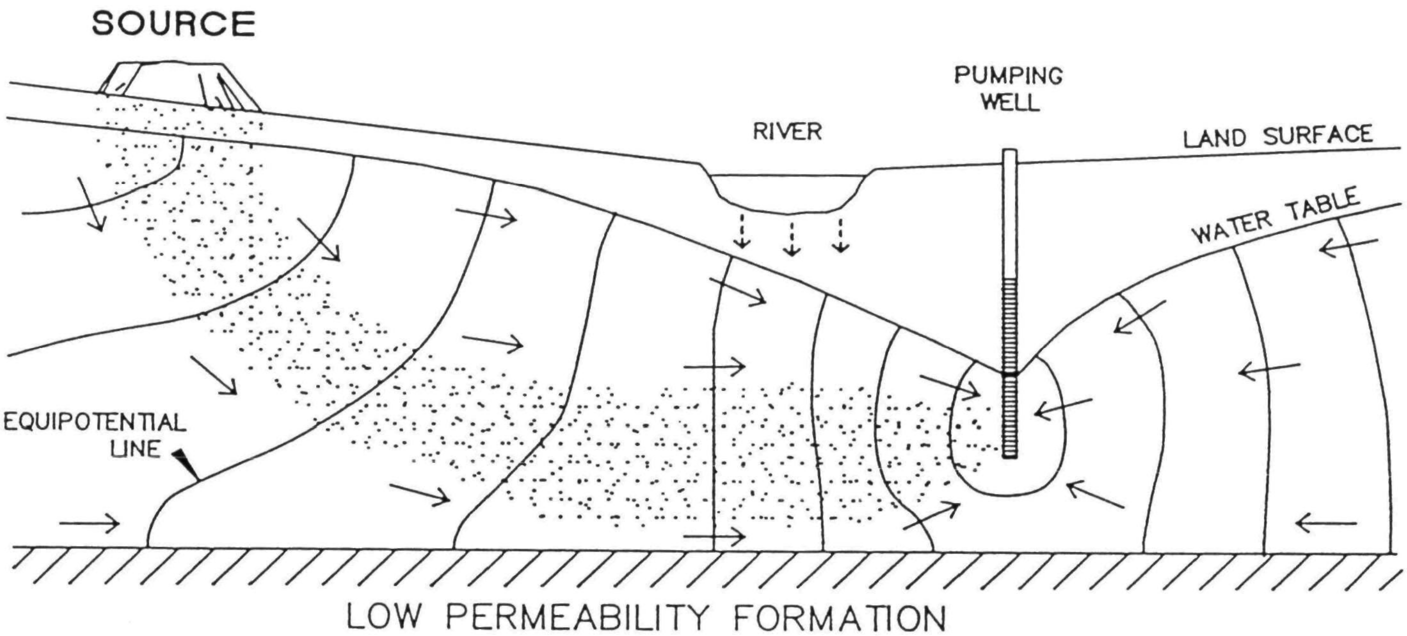
- Geochemical reactions between the contaminants and geologic materials can also cause wide fluctuations in concentration

- Computer modeling of contaminant transport processes is not as reliable as ground-water flow modeling due to greater complexities and uncertainties involved

THE PROBLEM BECOMES EVEN MORE DIFFICULT FOR CASES INVOLVING:

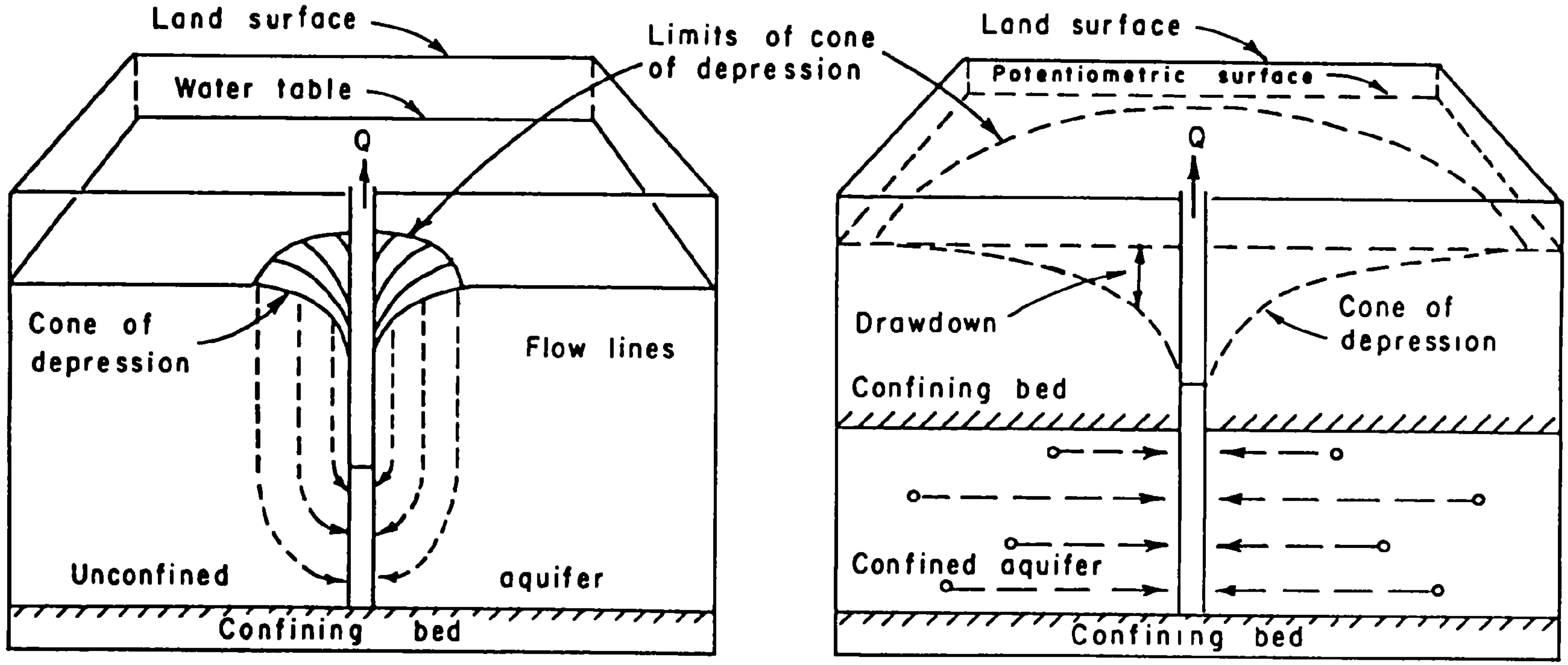
- Non-Aqueous Phase Fluids
- Density-Dependent Flow
- Degrading or Highly-Reactive Constituents
- Transport in Fractured-Rock Aquifers

FUNDAMENTALS OF WELL HYDRAULICS



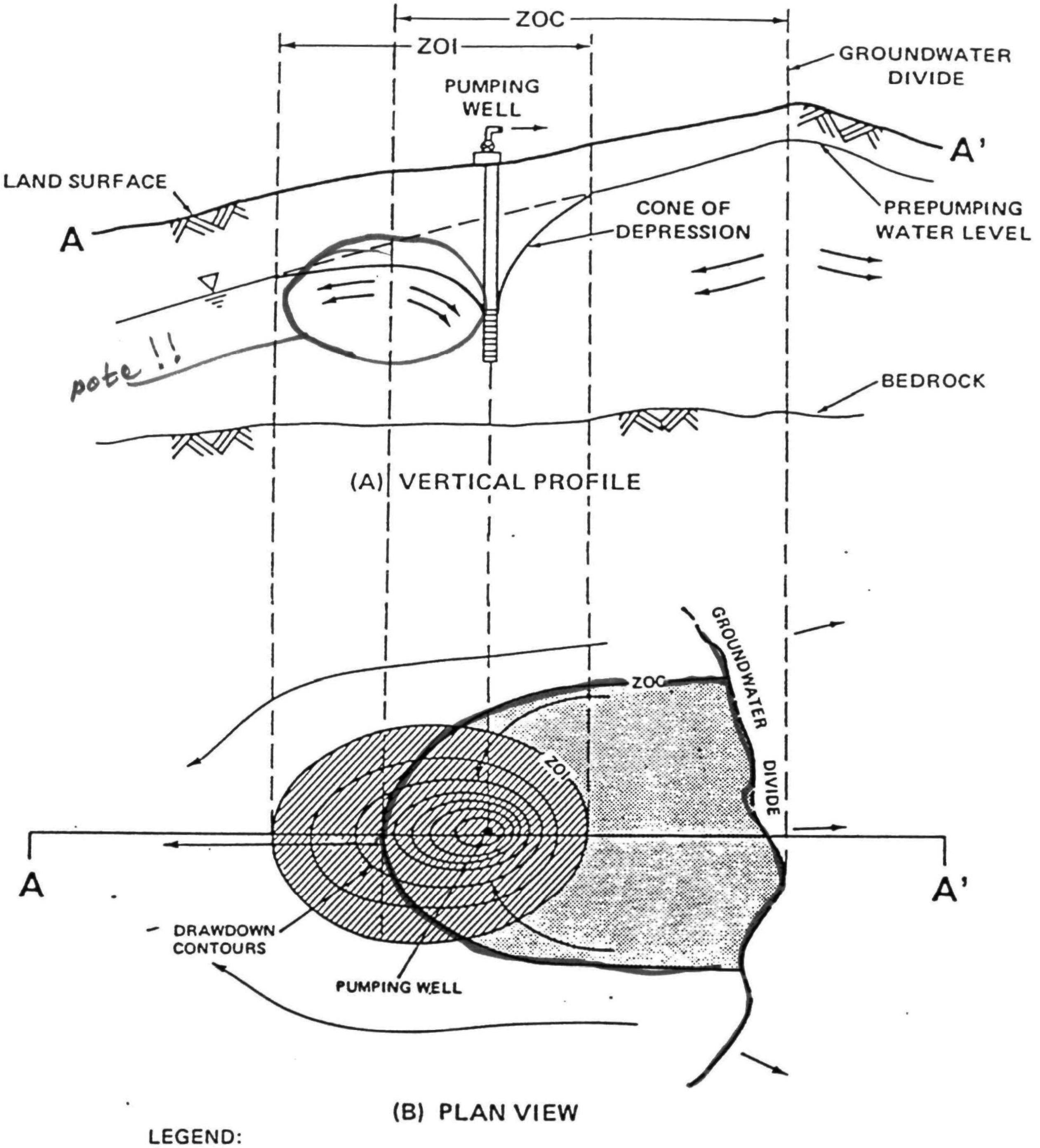
Pumpage reversing gradients under a river

CONE OF DEPRESSION



(Source: Heath, 1983)

Terminology for Wellhead Protection Area Delineation (Hypothetical Pumping Well in Porous Media)



LEGEND:

- ▽ Water table
- ——→ Ground-water Flow Direction
- • Pumping Well
- ZOI Zone of Influence
- ZOC Zone of Contribution

NOT TO SCALE

Slide 2.32

DARCY'S LAW IN RADIAL DIMENSIONS

$$Q = K I A$$

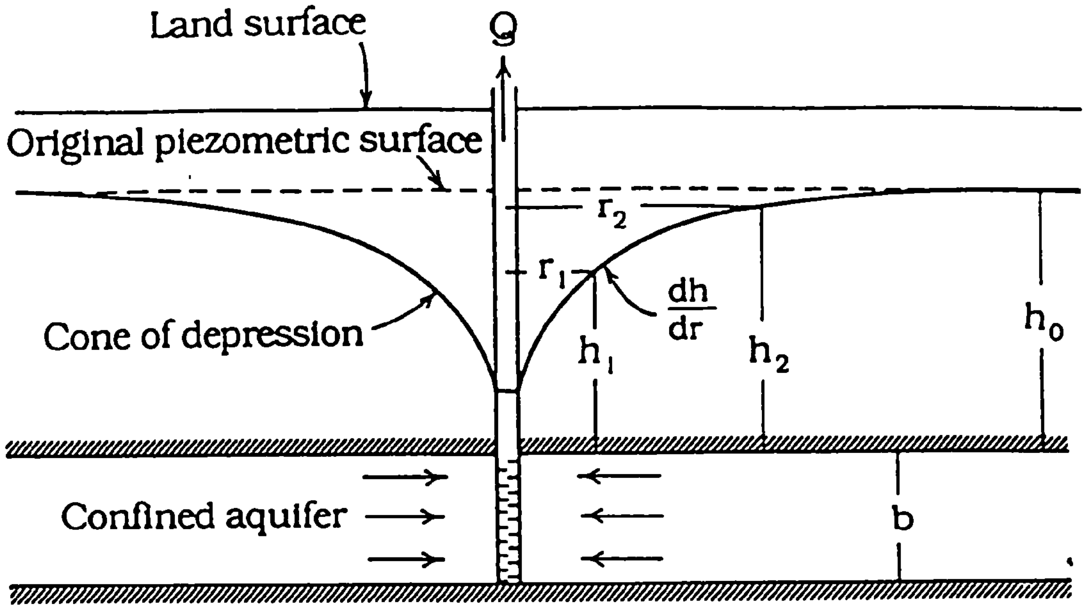
where: $A = 2\pi rb$ (area of cylinder)

$$I = \frac{dh}{dr}$$

substituting:

$$Q = 2\pi rbK \frac{dh}{dr}$$

EQUILIBRIUM FLOW TO A WELL IN A CONFINED AQUIFER



where: h_1 = hydraulic head at point nearest the well

h_2 = hydraulic head at point further from well

Q = discharge

K = hydraulic conductivity

b = aquifer thickness

r_1 = distance from well to point of h_1

r_2 = distance from well to point of h_2

EQUILIBRIUM FLOW EQUATION

Theim Equation

$$dh = \frac{Q}{2\pi bK} \frac{dr}{r}$$

$$\int_{h_1}^{h_2} dh = \frac{Q}{2\pi bK} \int_{r_1}^{r_2} \frac{dr}{r}$$

$$h_2 - h_1 = \frac{Q}{2\pi bK} \ln \frac{r_2}{r_1}$$

where: h_1 = hydraulic head at point nearest the well

h_2 = hydraulic head at point further from well

Q = discharge

K = hydraulic conductivity

b = aquifer thickness

r_1 = distance from well to point of h_1

r_2 = distance from well to point of h_2

discharge is in dist/time

no time measure in formula!!

THIEM EQUATION

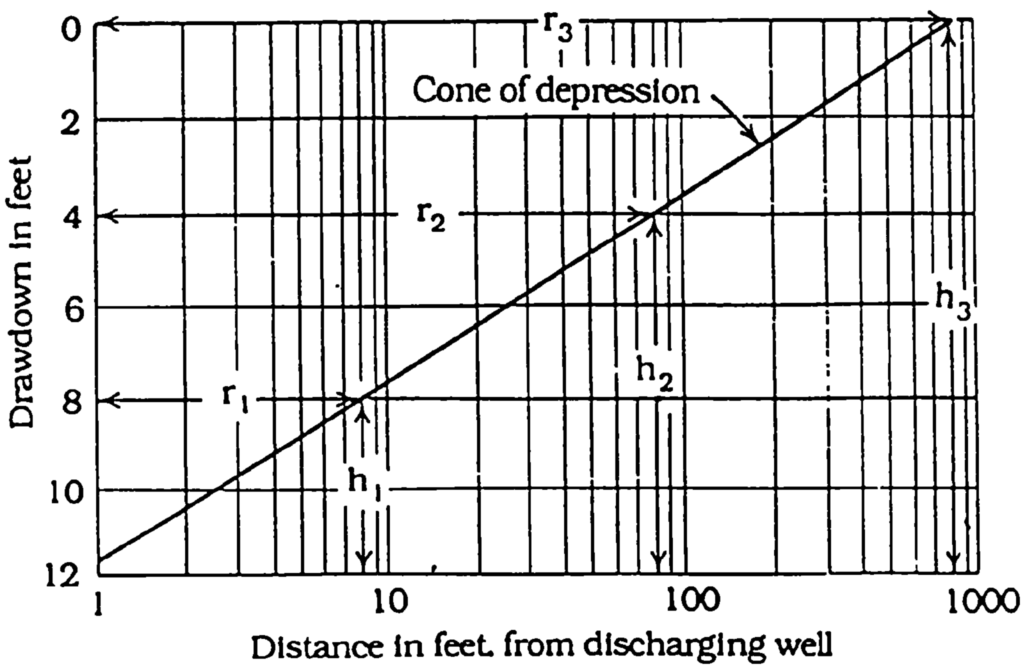
CONFINED

$$h_2 - h_1 = \frac{528\ Q\ (\log r_2/r_1)}{bK}$$

UNCONFINED

$$(h_2^2 - h_1^2) = \frac{1055\ Q\ (\log r_2/r_1)}{K}$$

DISTANCE DRAWDOWN RELATIONSHIP



distance drawdown graph

(Source: Heath, 1983)

NON-EQUILIBRIUM FLOW EQUATION

(THEIS EQUATION)

$$s = \frac{114.6Q}{T} W(u)$$

here the relationship changes over time

$$u = \frac{1.87 r^2 S}{Tt}$$

The Theis Eq. assumes T is constant, but actually T isn't the same as you pump and start "drawing" down the wtr. table

s = DRAWDOWN (feet)

Q = PUMPING RATE (gpm)

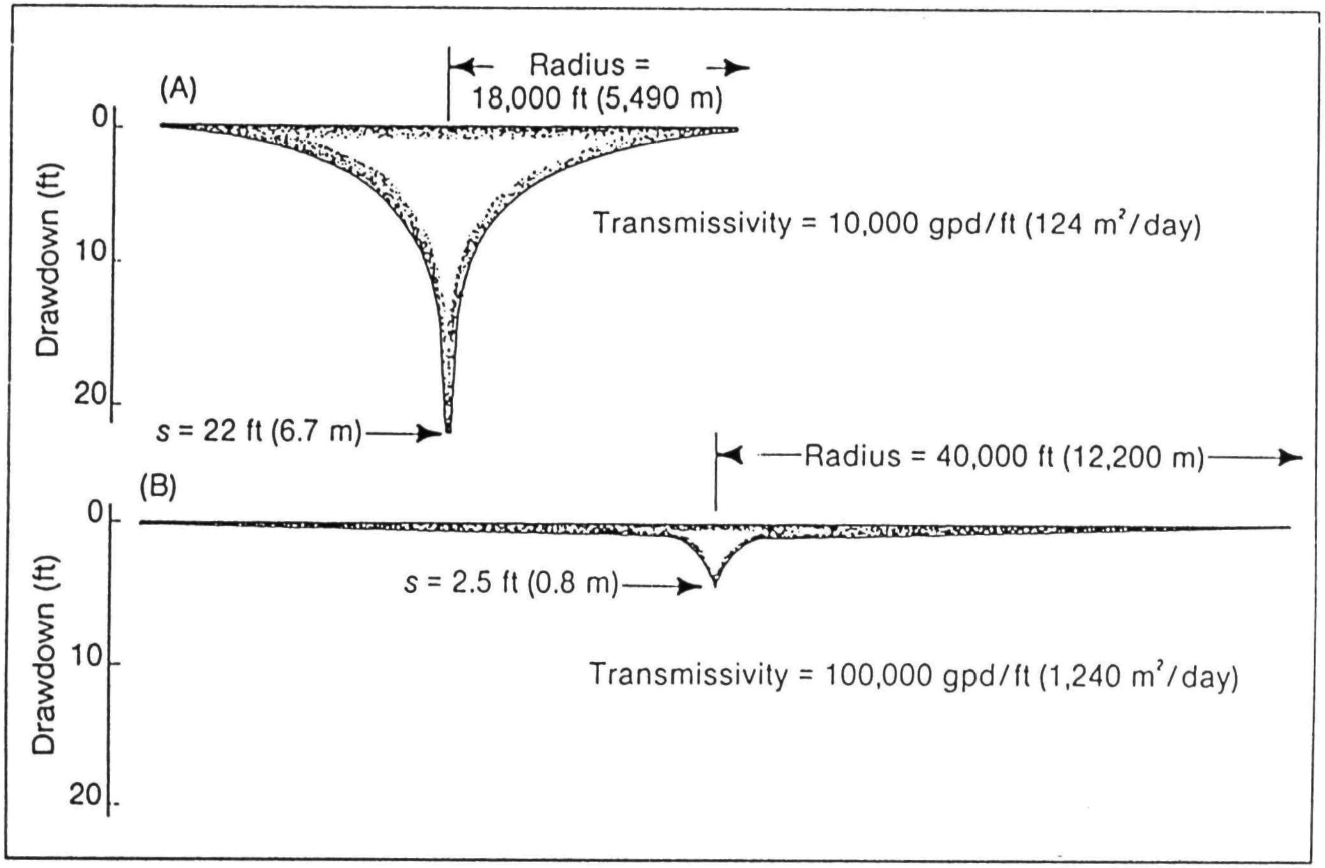
T = TRANSMISSIVITY (gpd/ft) time

S = STORAGE COEFFICIENT

r = DISTANCE FROM PUMPED WELL TO OBSERVATION WELL (ft)

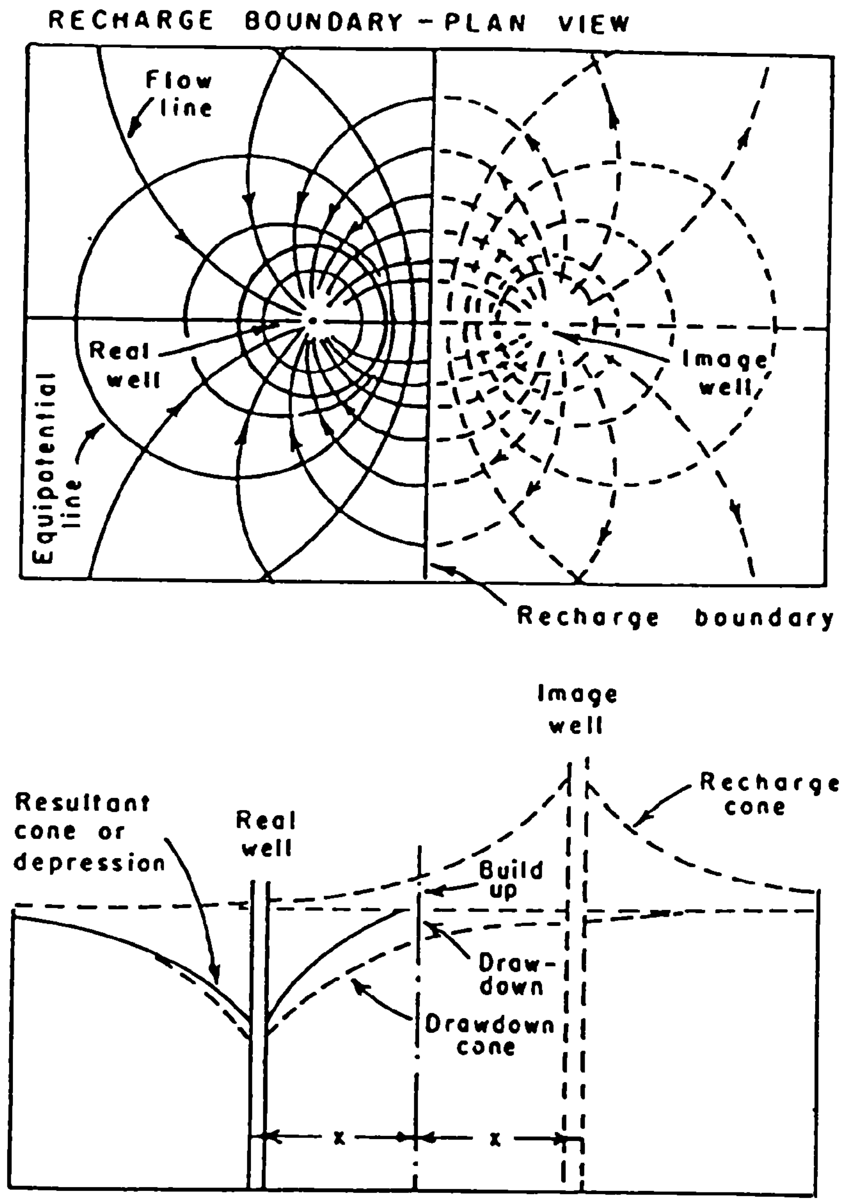
t = TIME (days)

W(u) = WELL FUNCTION (APPENDIX C)



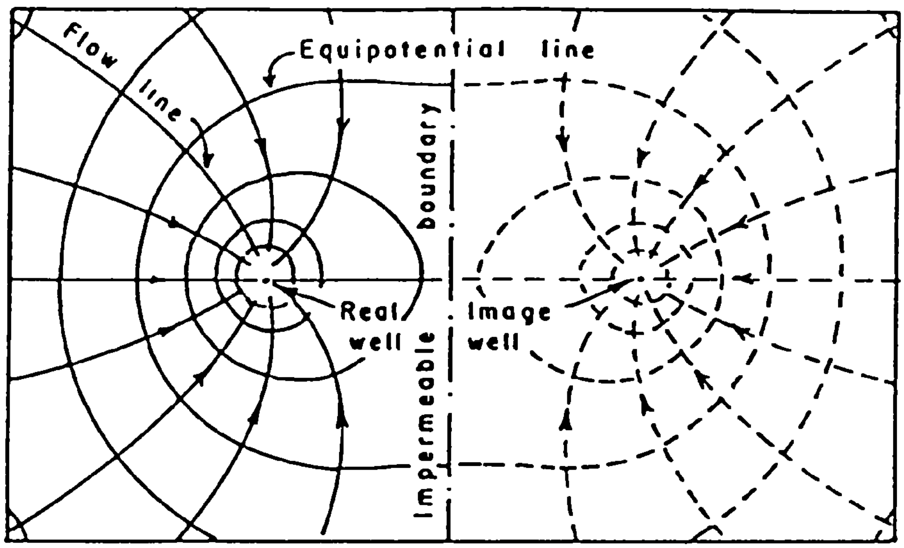
Effect of different coefficients of transmissivity on the shape, depth, and extent of the cone of depression. Pumping rate and other factors are constant. (Source: Driscoll, 1986)

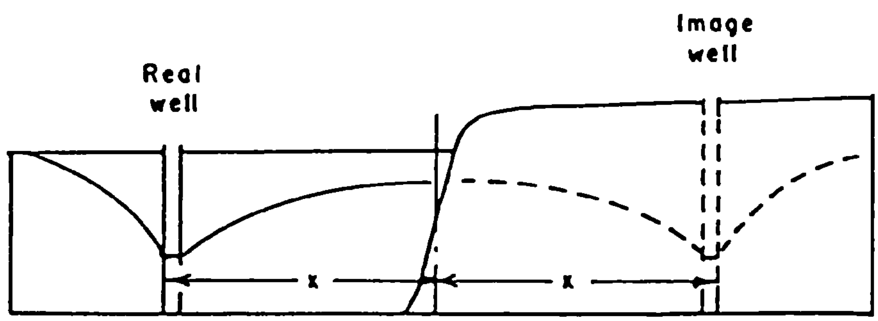
As you increase the Transmissivity, the configuration of the drawdown curve is changed



(Source: Heath, 1983)

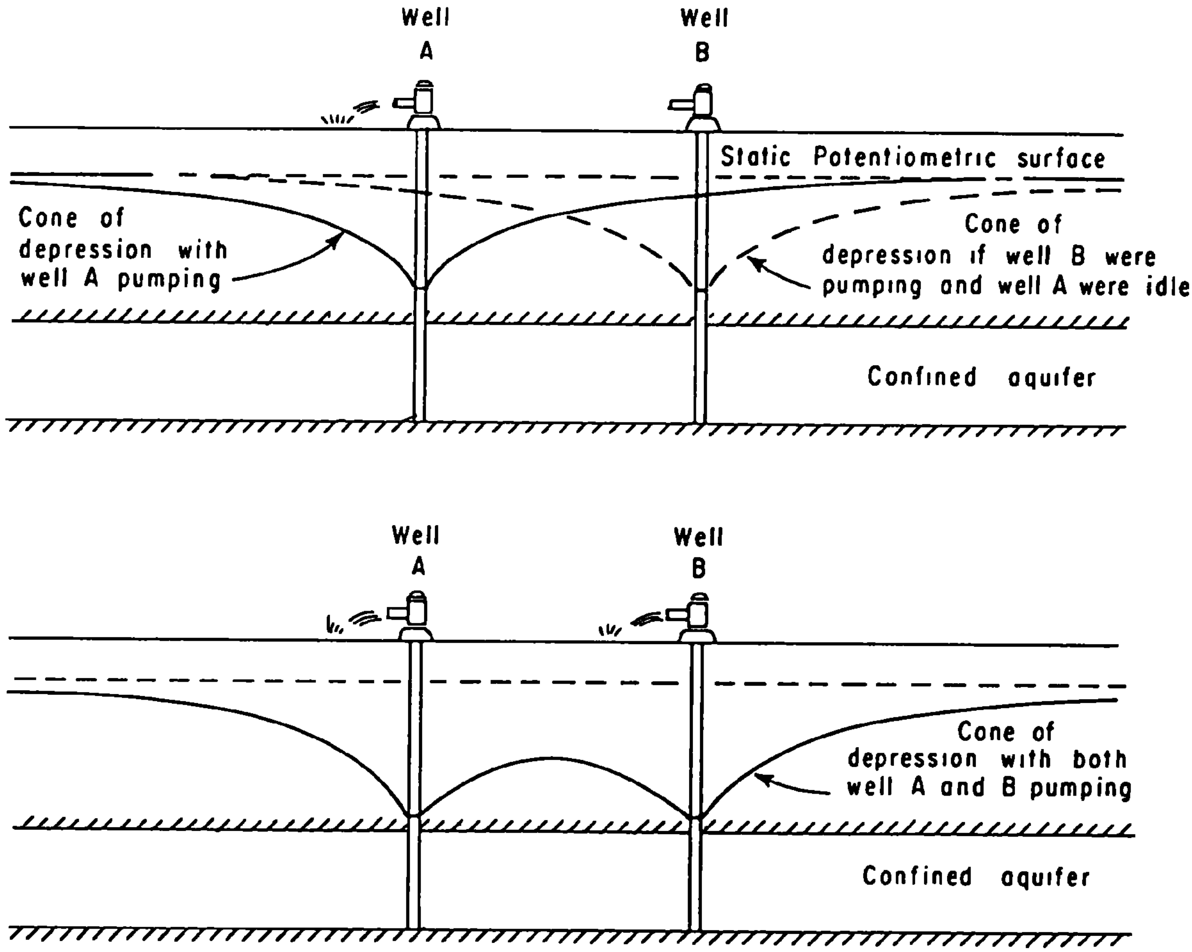
IMPERMEABLE BOUNDARY – PLAN VIEW





(Source: Heath, 1983)

Well Interference



(Source: Heath, 1983)

FUNDAMENTAL CONCEPTS EXERCISE

FUNDAMENTAL CONCEPTS EXERCISE

- WATER-SUPPLY WELL SCREENED IN SHALLOW CONFINED AQUIFER
- TRANSMISSIVITY = 10,000 GALLONS PER DAY PER FOOT
- STORAGE COEFFICIENT = .0001
- PUMPING RATE = 200 GALLONS PER MINUTE

ref slide 2.38
Appendix C

t = 100 d
one well @ 100'
" " " 1000'

EXERCISES :

✓ 1) USING THE THEIS EQUATION, ESTIMATE DRAWDOWN OBSERVED AT 100 FEET AND 1000 FEET AFTER 100 DAYS OF PUMPING

ref slide 2.38 & App C

NOTE:

CALCULATE u AND DETERMINE W(u) USING THE WELL FUNCTION TABLE IN APPENDIX C

✓ 2) PLOT THESE DRAWDOWN POINTS (DRAWDOWN ON VERTICAL, ARITHMETIC SCALE) VS. DISTANCE TO PUMPING WELL ON SEMILOG GRAPH PAPER

✓ 3) WHAT IS THE RADIUS OF THE ZONE OF INFLUENCE ?

4) AT WHAT RADIUS IS A 1 FOOT DRAWDOWN OBSERVED ?

$$s_{100} = \frac{114.6(200)\ 12.5964}{10^4} = \frac{(114.6)(2)10^2(12.6)}{10^4} = 2887.9\ 10^{-2} = 28.88'$$

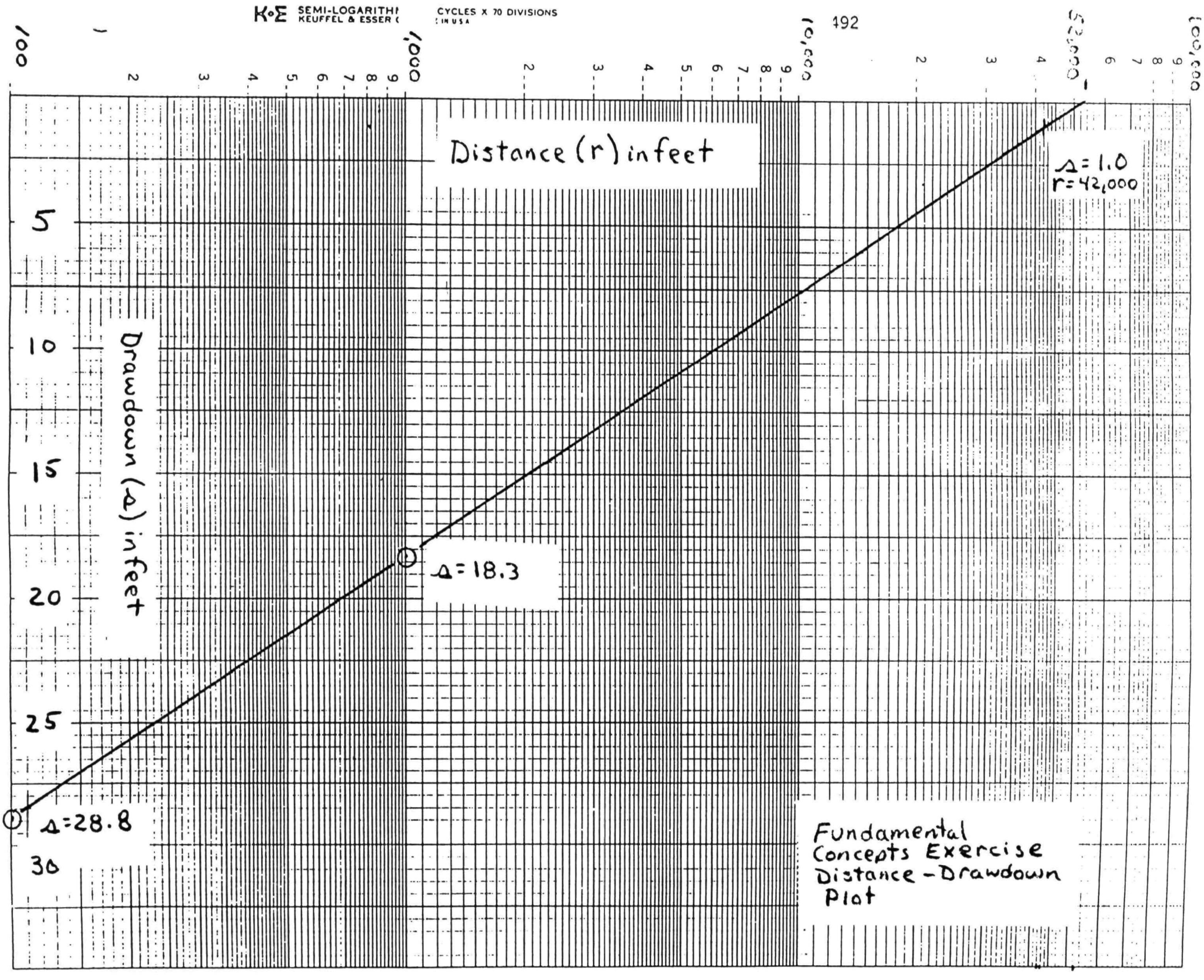
$$u = \frac{1.87(100)^2(.0001)}{(10000)(100)} = \frac{(1.87)10^4(10^{-4})}{(10^6)} = \frac{1.87}{10^8} = 1.87\ 10^{-8} < 1$$

$$Wu = 12.5964$$

$$u_{1000} = \frac{(1.87)(10^6)\ 10^{-4}}{(10^4)\ 10^2} = \frac{(1.87)10^2}{10^6} = 1.87(10^{-4})$$

$$W_u = 8$$

$$s_{1000} = \frac{114.6(200)(8)}{10^4} = \frac{18336\ 10^2}{10^4} = 18.34$$


K•E SEMI-LOGARITHMIC KEUFFEL & ESSER
CYCLES X 70 DIVISIONS
100
1,000
10,000
52,000
100,000
Distance (r) in feet
Drawdown (Δ) in feet
5
10
15
20
25
30
Δ=1.0
r=42,000
Δ=18.3
Δ=28.8
Fundamental Concepts Exercise Distance - Drawdown Plot

2. REVIEW OF FUNDAMENTAL CONCEPTS

2.1 GROUND-WATER FLOW

Bernoulli, in 1738, developed the fundamental relationship for describing ground-water energy levels (Slide 2.2).

$$h = Z + P$$

where:

- h = hydraulic head
- Z = elevation head
- P = pressure head

Ground water moves from a position of high hydraulic head to a position of low hydraulic head. For example, in a water-table aquifer, ground water will generally move from an area of high water-table elevations to an adjoining area of low water-table elevation (Slide 2.3).

The direction of ground-water flow can be determined from a contour map of water levels (equipotential lines). Flow will generally be perpendicular to the equipotential lines in the direction of decreasing hydraulic heads (Slide 2.4).

Ground-water flow occurs in the voids or pore spaces within earth materials (Slide 2.5). Porosity is commonly cataloged into primary and secondary. Primary porosity refers to the intergranular spaces while secondary porosity refers to larger non-capillary voids such as fractures or solution channels.

Ground-water flow in porous, granular media is primarily laminar. The term laminar means that molecules of water follow each other along the same flow paths, instead of crossing over to intersect and mix with other flow paths (Slide 2.7).

Laminar flow can be described by a relationship known as Darcy's law (given below).

$$Q = K \ I \ A$$

Where
- Q = discharge (L^3/T)
- K = hydraulic conductivity (L/T)
- I = hydraulic gradient, and
- A = cross-sectional area of flow (L^2)

Darcy's law can not be applied accurately where flow becomes turbulent as may be the case in settings dominated by flow in secondary porosity such as conduit karst and fractured bedrock geology.

Hydraulic conductivity (K) is a property specific to the earth material K can vary several orders of magnitude within a single geologic unit and is expressed in units such as ft/day, cm/sec, or gpd/ft^2.

Transmissivity, a term hydrogeologists commonly use to describe the hydraulic capacity of an aquifer is the product of K and the aquifer thickness (Slide 2.9).

Ground-water velocity through pore spaces (pore water velocity), V, is described by the equation:

$$V = \frac{KI}{n}$$

Where n = porosity of the medium.

Because all pores may not be interconnected (i.e., some porosity may not contribute to flow), velocity calculations should be based on the "effective" porosity. Effective porosity in aquifers is often equated with that porosity drainable under gravity (i.e., specific yield).

The velocity of ground-water flow in aquifers generally ranges from a few inches to a few feet-per-day, and is determined by the hydraulic conductivity, porosity, and hydraulic gradient.

Natural Ground-Water Flow Systems

A ground-water flow system consists of the entirety of a ground-water body extending from its recharge area to its discharge area. Boundaries of flow systems are those such as impermeable geologic boundaries, flow divides and flow lines that separate parallel flow systems (Slide 2.10).

The mass balance for a ground-water flow system estimates the mass of water entering the flow system through recharge, leaving the system through discharge, and being added to or depleted from storage within the flow system. Calculations should show that these terms are in balance (i.e., sum to zero).

Flow systems have geometries that reflect the scale of spatial variations in topography, hydrology, and earth materials (Slide 2.11). Where these variations are minor, large regional flow systems develop. Where variations are large, the result are many, small local flow systems (Slide 2.12).

Unconfined flow systems have an upper water surface (water table) that rises and falls freely. The water table may drop tens of feet during periods of extreme drought.

Recharge to a water-table aquifer occurs wherever rainfall or surface water infiltrates downward through the soil to the water table.

Recharge to an unconfined flow system, as a rule, is more rapid and of a higher magnitude compared to that of a confined aquifer.

Confined aquifers occur beneath lower permeability "confining units." The water level in a well screened into the top of a confined aquifer will rise above the bottom of the confining unit to a level referred to as the potentiometric surface (Slide 2.13).

Recharge to a confined aquifer is generally reduced compared to a non-confined aquifer. Water levels in a confined aquifer generally change less radically throughout the year than do those of an unconfined aquifer.

Confinement is a "sliding scale" between totally unconfined (water-table) settings where aquifers are in direct hydrologic connection with activities on the land surface, and well-confined settings where there is a little or no hydrologic interconnection (under current climatic and hydrogeologic conditions) between deeper aquifers tapped by public-supply wells and surficial aquifers or surface sources of pollution.

Ground-water will flow across the confining unit depending upon the hydraulic head relationships. If the hydraulic head in the confined aquifer is greater than the hydraulic head in the overlying aquifer, flow will be upward across the confining unit (Slide 2.14). This case presents a low potential for contamination of the lower aquifer in the event that the upper aquifer becomes contaminated.

Downward leakage across the confining unit will occur if the head relationships described above are reversed (Slide 2.15). However, the presence of the confining unit and its lower permeability will act to increase travel time and may also result in reduced contaminant concentration levels if contaminants should migrate across the confining unit.

The protection provided under confined conditions can be related to depth from land surface. Shallow confining conditions within 100 feet of the land surface, are generally considered less protective than deeper confining conditions. They may have approximately the same vulnerability to contamination as an unconfined aquifer.

Deep confining conditions, 300 feet or more below land surface, generally exhibit truer isolation from the surface and, therefore, provide a relatively large margin of safety. Such aquifers are typically consolidated except for in coastal plain and alluvial materials. Deeper confining units will generally have lower permeabilities.

The protective properties of a confining unit can be bypassed on account of artificial pathways such as improperly constructed wells or other man-made apertures.

Pumping of a confined unit can change the hydraulic head relationships across the confining unit in the vicinity of the well in such a way as to reverse flow directions or increase the rate of flow across the confining unit.

An assessment of the degree of confinement may be a viable component of a WHPA program. Part of the assessment may include reviews of the geologic and hydrologic relationships among aquifers, and whether or how much of the water supplied by confined wells in the State is from recent surface recharge in the immediate vicinity of the well, how much from changes in aquifer storage, how much from distant areas (representing water that recharged the aquifer hundreds to thousands of years in the past), etc.

2.2 CONTAMINANT TRANSPORT

Contaminant Threats

The delineation of WHPAs will be designed to protect wells from three general categories of threats:

- Direct introduction of contaminants in the immediate well area
- Microbial contaminants

Chemical contaminants

A basic aspect of the WHP Program is protection of the area immediately contiguous to the well (e.g., pumps, pipes, casing) from the direct introduction of contaminants near the land surface. These contaminants may originate from accidental spills, road runoff, leakage of chemicals or other incidents and are carried across the land surface to the well. These threats are avoided by "delineating" or maintaining some immediate zone around the well where access and surface runoff is controlled.

A second basic aspect of WHP is protection from microbial contamination, especially bacteria and viruses that may remain in water delivered to consumers even after treatment.

A third basic aspect is of particular importance: the broader range of threats posed by various chemical contaminants. Many of these chemicals are very persistent in the subsurface, and can theoretically traval long distances before being adsorbed by subsurface media, transformed to less harmful chemicals, diluted to non-harmful concentrations or other rendered less threatening.

WHPA programs are intended to identify sources of these threats. A list of source operations is provided in the Grants Guidelines (EPA 1987b), Exhibit 6.

Radiological contaminants may constitute a threat in areas with more waste piles, low-level radioactive waste-disposal sites, and other sources. Naturally occuring radiological threats, such as radon, are generally not considered an anthropogenic source.

Vadose Zone Movement

Contaminants originating above the saturated zone generally move vertically downward through the vadose zone to the water table (Slide 2.19).

Contaminants moving through the vadose zone may be attenuated by sorption onto soil particles, oxidation/precipitation, microbial activity, or uptake by plants.

Attenuation process in the vadose zone are much more effective than in the saturated zone. Unfortunately, these processes are difficult to characterize and model. It is difficult to account for them in transport calculations.

Saturated Zone Movement

Contaminant movement in the saturated zone is dependent in part upon the solubility, density, miscibility, and reactiveness of the constituent.

Dissolved chemicals in the saturated zone will flow with the ground water. The distribution of a dissolved chemical in the ground-water system in space and time (i.e. the shape, extent, and rate of movement of the plume) is governed by the processes of advection and hydrodynamic dispersion (Slide 2.20).

Advection refers to the movement of a dissolved chemical by the bulk mass of flowing ground water (Slide 2.21).

Hydrodynamic dispersion is a combination of plume spreading due to molecular diffusion along chemical gradients, and to mechanical mixing of the plume with surrounding waters as it moves through the pore spaces (Slide 2.22).

Dispersion is the principal factor causing dilution of the contaminants within the plume.

In most aquifers, the component of dispersion due to mechanical mixing is several orders of magnitude greater than the molecular diffusion effect.

The shape and size of the plume depends on a number of factors including the local geologic framework, local and regional ground-water flow, the type and concentration of contaminants, and variations in the rates of introduction of contaminants from the source (Slide 2.24).

Layering or intermixed zones of contrasting particle size distributions (i.e., sand stringers in a silt matrix) can accentrate dispersion (Slide 2.25).

Where ground-water flow is through fractured rock or solution cavities, predicting the migration of contaminants is orders of magnitude more complex than in the case of sand aquifers.
In opposition to advection and dispersion, several processes may inhibit the migration of contaminants including reduced solubility, adsorption, and degradation (e.g. microbial degradation, radioactive decay).

Varying levels of plume attenuation may take place depending on the complex interaction of a suite of factors including the physical and chemical properties of the geologic medium, the chemical properties of the contaminants, background chemistry of the natural ground water, flow rate, availability of oxygen, and microbial activity.

Density and miscibility of the contaminated fluids are also important factors controlling the formation and migration of a plume.

Slightly miscible fluids may flow in separate phases creating a coherent plume that mixes very little with the surrounding ground water as it migrates (Slide 2.26).

Less dense fluids may float on the surface of the water table/capillary fringe and may move in a slightly different direction from the general ground-water flow direction.

Higher density fluids tend to sink through the saturated zone eventually reaching the bottom of the aquifer where they may move in directions radically different from the overall ground-water flow direction (Slide 2.27).

Undissolved phases may give off vapors which migrate through the unsaturated zone in patterns which are unrelated to the ground-water flow system.

There can be numerous distinct plumes of contamination moving away from a site.

Lenses of sand and clay can cause other variations in plume migration due to stratification of the contaminants.

Pumping from wells can modify ground-water flow patterns and, consequently, alter the movement of a contamination plume. Contaminants within the ZOC will migrate toward the well.

Predicting Contaminant Migration

Accurately predicting the transport of dissolved contaminants is difficult; computer modeling of contaminant transport is not as reliable as ground-water flow modeling. The problem becomes more difficult where non-aqueous phase fluids, density-dependent flow, transport of chemically reactive constituents, or transport in fractured rock aquifers are involved.

Discontinuous discharges may result in "slugs" of contaminated water, causing wide spatial and temporal fluctuations in well-water quality.

Detailed monitoring of sites more than five years old has revealed fluctuations in the concentrations of some constituents while other constituents remained relatively constant. This phenomenon is caused by the solution and dissolution of certain chemicals as the plume of contamination interacts with geologic materials in its path.

In addition to the parameters required to model the flow system, transport modeling requires the hydraulic heads predicted by the flow modeling, estimates of the parameters that comprise hydrodynamic dispersion, effective porosity distribution, background water chemistry, transport properties of constituents (solubility, retardation and decay factors), strength and temporal fluctuations in waste source, and estimates of concentration initial and boundary conditions.

2.3 WELL HYDRAULICS AND AQUIFER RESPONSE TO PUMPING

The action of pumping water from a well causes a reduction in hydraulic head, commonly referred to as drawdown, in the aquifer media surrounding the well. Drawdown decreases away from the well to a point of no influence. The distance to this point is referred to as the radius of influence. Plotted in plan view, this radius is called the zone of influence (ZOI) (Slide 2.31).

In three dimensions, drawdown occurs as an inverted cone and for this reason is referred to as the cone of depression. The dimensions of the cone of depression are related to the pumping rate, duration of pumping, regional hydraulic gradient and aquifer hydraulic properties.

The area or volume of an aquifer that contributes water to a pumping well is called the zone of contribution (ZOC). Except under idealized conditions, the ZOC overlaps the ZOI but is not totally coincidental. Ideal conditions where the ZOC and ZOI are nearly identical involve highly productive water-table aquifers with nearly flat water tables (i.e., extremely low hydraulic gradients) under unpumped conditions.

Flow to a well can best be explained for an idealized confined aquifer with a single pumping well. Idealized means an infinite, horizontal aquifer of uniform thickness and possessing homogenous and isotropic hydraulic properties.

Darcy's law can be modified to account for radial flow as follows:

$$Q = K\ I\ A$$

where: $A = 2\pi rb$ (area of cylinder)

$$I = \frac{dh}{dr}$$

substituting:

$$Q = 2\pi rbK \frac{dh}{dr}$$

Differences in hydraulic head between two points on the cone of depression in a confined aquifer at equilibrium conditions (Slide 2.3) are explained as follows:

$$dh = \frac{Q}{2\pi bK} \quad \frac{dr}{r}$$

$$\int_{h_1}^{h_2} dh = \frac{Q}{2\pi bK} \int_{r_1}^{r_2} \frac{dr}{r}$$

$$h_2 - h_1 = \frac{Q}{2\pi bK} \ln \frac{r_2}{r_1}$$

where: h_1 = hydraulic head at point nearest the well
h_2 = hydraulic head at point further from well
Q = discharge
K = hydraulic conductivity
b = aquifer thickness
r_1 = distance from well to point of h_1
r_2 = distance from well to point of h_2

Referred to as the Thiem equation, this equation can be used when all dynamic conditions have reached equilibrium (i.e., Q is constant, ZOI has stabilized, and water enters the well uniformly from all directions). All flow is assumed to be horizontal, and the well is assumed to fully penetrate the aquifer.

For standard english units in log base 10, the Theim equation for confined conditions is:

$$h_2 - h_1 = \frac{528\ Q\ (\log r2/r1)}{bK}$$

For unconfined conditions (standard english units log base 10) the Thiem equation is:

$$(h_2^2 - h_1^2) = \frac{1055\ Q\ (\log r2/r1)}{K}$$

The unconfined equation looks different (hydraulic heads are squared) because of the need to account for dewatering of the aquifer near the well as a result of drawdown. The aquifer thickness, b, varies with distance to the pumping well. The result is a decrease in aquifer transmissivity as the flowing water approaches the well. Thus a greater hydraulic head loss is needed to pump an unconfined aquifer at the same Q compared to a confined aquifer.

The Thiem equation, shows that hydraulic head varies linearly with the logarithm of distance to the well (radius). Plotted on semilog paper, drawdown vs. distance occurs as a straight line. The distance-drawdown relationship for equilibrium conditions can be useful for determining WHPAs as will be explained later.

Under non equilibrium (often referred to as transient) conditions in an idealized, confined aquifer, the Theis equation, provided below, is employed to explain drawdowns in an observation well. As the well is pumped over time, drawdown in an observation well increases in a logarithmic relation as shown in the Theis curve.

$$s = \frac{114.6Q}{T} \quad W(u)$$

where s = drawdown (h_0 - h, ft)
Q = pumping rate (gal/min)
T = transmissivity (gal/day-ft)
W(u) = Theis well function

and $u = \frac{1.87r^2S}{Tt}$

where S = storage coefficient (unitless)
r = distance from pumping well to observation well (ft)
t = time (days)

$$W(u) = -0.5772 - \log_e u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} \quad . . .$$

W(u) can be read from a table after determining u (see Appendix C.).

Aquifer tests to determine hydraulic parameters involves matching a log x log plot of drawdown vs. time to the Theis type curve. A different type curve is used in nonideal conditions, such as unconfined conditions or where leakage occurs across confining layers. Corrections are needed to account for partial well penetration, aquifer boundaries, and recharge boundaries.

Leakage across a confining layer will result in a smaller ZOI and ZOC than would be calculated based solely on the pumped aquifer hydraulic properties (Slides 2.40 and 2.41).

Recharge at a boundary near the well or the presence of an impermeable (i.e., no flow boundary) will cause an asymmetric ZOI and ZOC that would be calculated based solely on the pumped aquifer hydraulic properties or will result in an asymmetric ZOI and ZOC on the pumped aquifer hydraulic properties (Slides 2.40 and 2.41).

2.4 FUNDAMENTAL CONCEPTS EXERCISE

A water supply well is screened in a shallow confined aquifer with a transmissivity of 10,000 gpd/ft^2 and storage coefficient of 1.0 X 10^{-4}. If the well is pumped at 200 gpm, how much drawdown would be observed after 100 days of pumping at distances of 100 feet and 1000 feet? This exercise will require first a calculation of u, then a tabular estimation of W(u) in order to determine drawdown, s. Values of W(u) can be found in Appendix C. After making these calculations, plot these two drawdown points vs distance to the pumping well on semilog graph paper (note drawdown should be on vertical arithmetic scale and distance to pumping well on the log scale). What is the radius of the zone of influence? At what distance (radius) is a 1 foot drawdown achieved?

2.4 FUNDAMENTAL CONCEPTS EXERCISE ANSWER

1) Calculate drawdown

a) Calculate u:

$$u = \frac{1.87\ r^2\ S}{Tt}$$

for r = 100 feet:

$$u = \frac{1.87\ (100)^2\ (0.0001)}{10{,}000\ (100)}$$

$u = 1.9 \times 10^{-6}$

W(u) = 12.6 (from table)

for r = 1000 feet:

$$u = \frac{1.87\ (1000)^2\ (0.0001)}{10{,}000\ (100)}$$

$u = 1.9 \times 10^{-4}$

W(u) = 8.0 (from table)

b) Calculate drawdown, s:

$$s = \frac{114.6\ Q}{T}\ [W(u)]$$

for r = 100 ft

$$s = \frac{114.6\ (200)\ (12.6)}{10{,}000}$$

s = 28.88 ft

for r = 1000 ft

$$s = \frac{114.6\ (200)\ (8.0)}{10{,}000}$$

s = 18.33 ft

c) Distance-drawdown plot attached

d) ZOI = 52,000 ft in radius

e) drawdown of 1 ft is at 42,000 ft

3. Elements

PRESENTATION SLIDES

WELLHEAD TERMINOLOGY

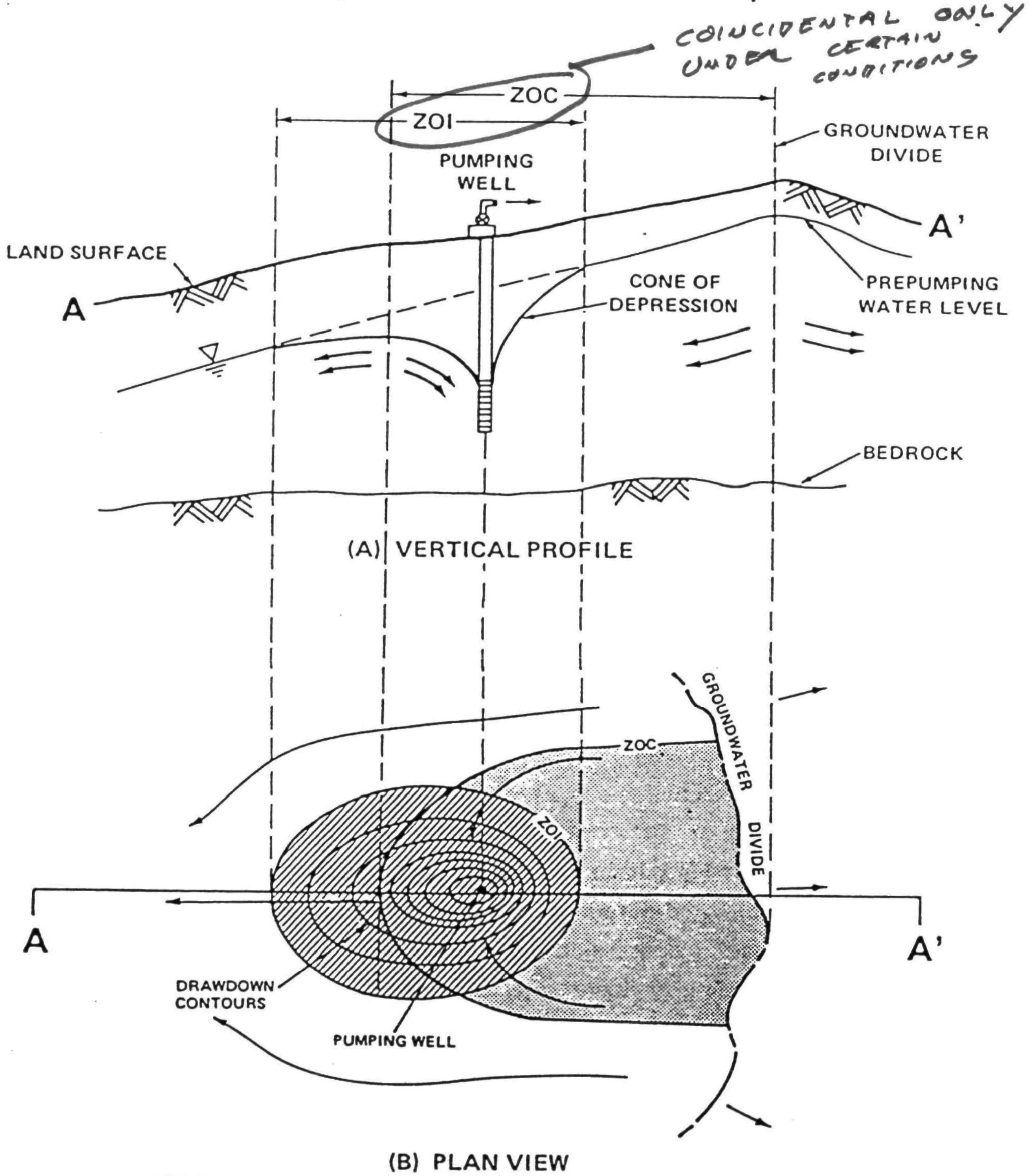
BASIC DEFINITIONS

CRITERIA — Fundamental factors affecting likelihood of contaminants reaching well

CRITERIA THRESHOLDS — Quantitative measures associated with criteria

METHODS — Technical procedures that allow criteria/ thresholds to be mapped and WHPAs therefore delineated

Terminology for Wellhead Protection Area Delineation (Hypothetical Pumping Well in Porous Media)



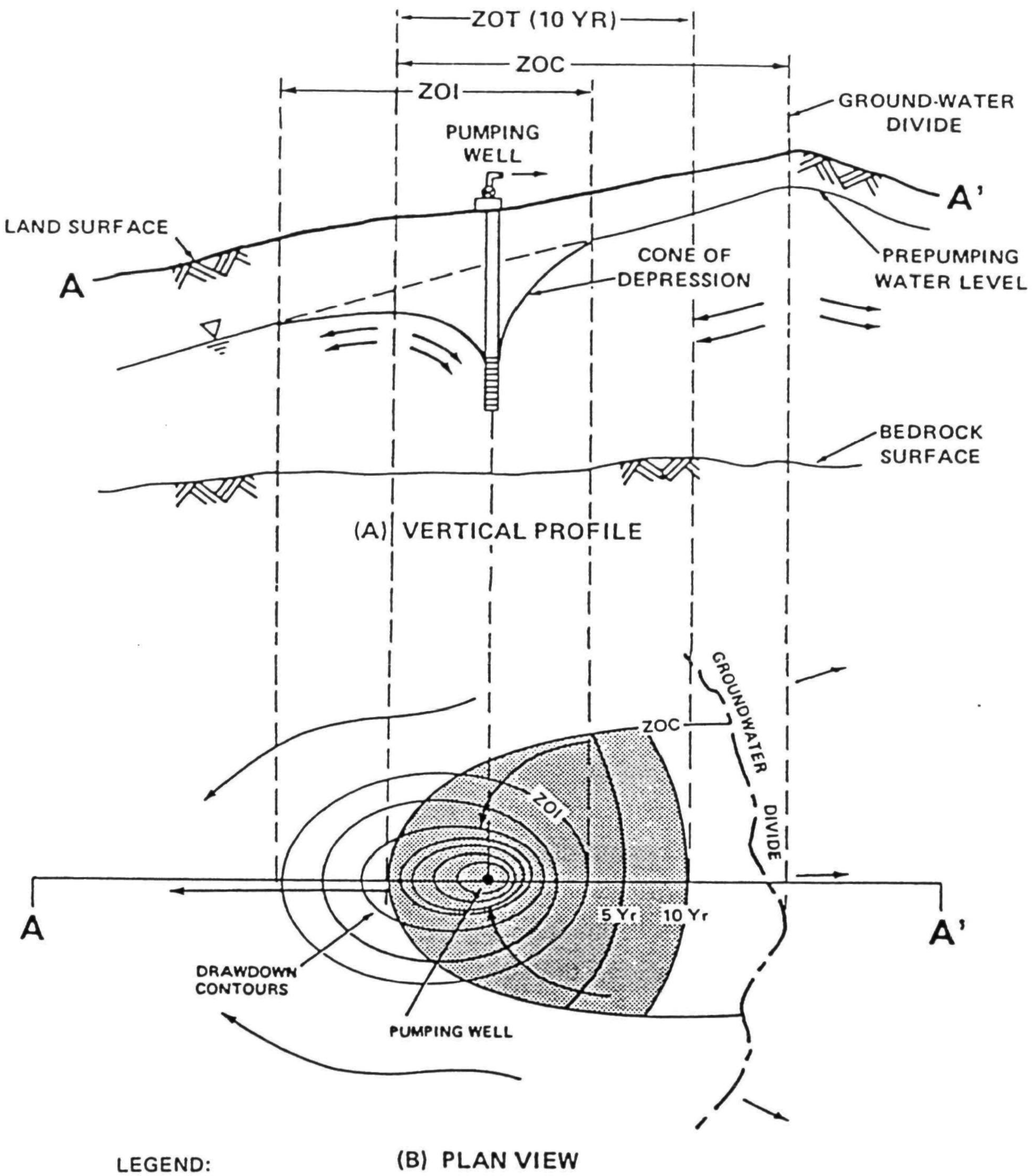
LEGEND:

- ▽ Water table
- ——→ Ground-water Flow Direction
- • Pumping Well
- ZOI Zone of Influence
- ZOC Zone of Contribution

NOT TO SCALE

Slide 3.03

Terminology for Wellhead Protection Area Delineation (Hypothetical Contaminant Transport in Porous Media)



(A) VERTICAL PROFILE

(B) PLAN VIEW

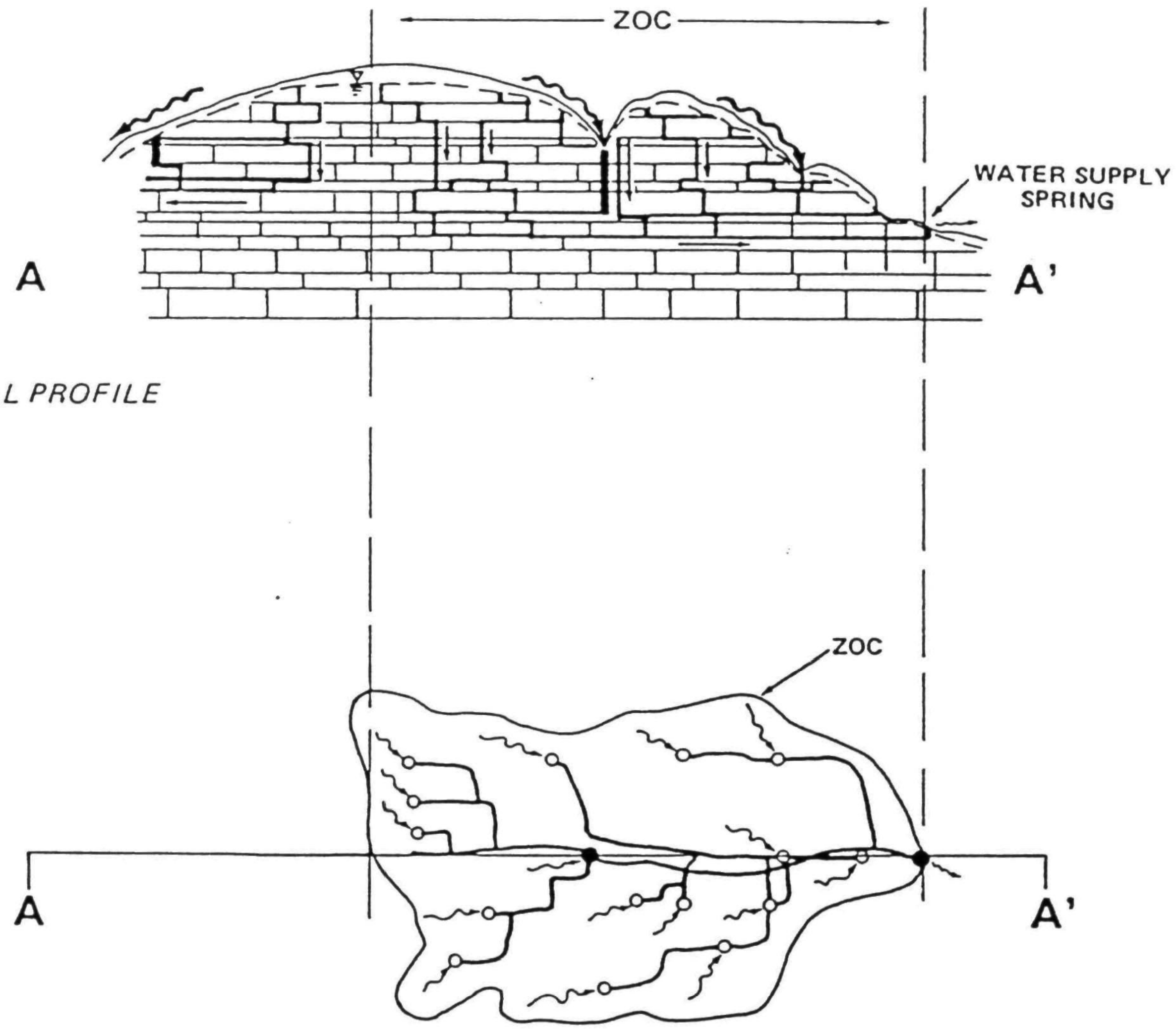
LEGEND:

- Water Table
- 10 Year Zone of Transport
- Direction of Ground-water Flow
- ZOC Zone of Contribution
- ZOI Zone of Influence
- ZOT Zone of Transport

Slide 3.04

NOT TO SCALE

Terminology for Wellhead Protection Area Delineation (Hypothetical Ground-water Basin in Mature Karst)



NOTE: The "ZOC" shown was delineated with purpose of including all principal areas contributing to the cave based on inferred surface and subsurface drainage areas.

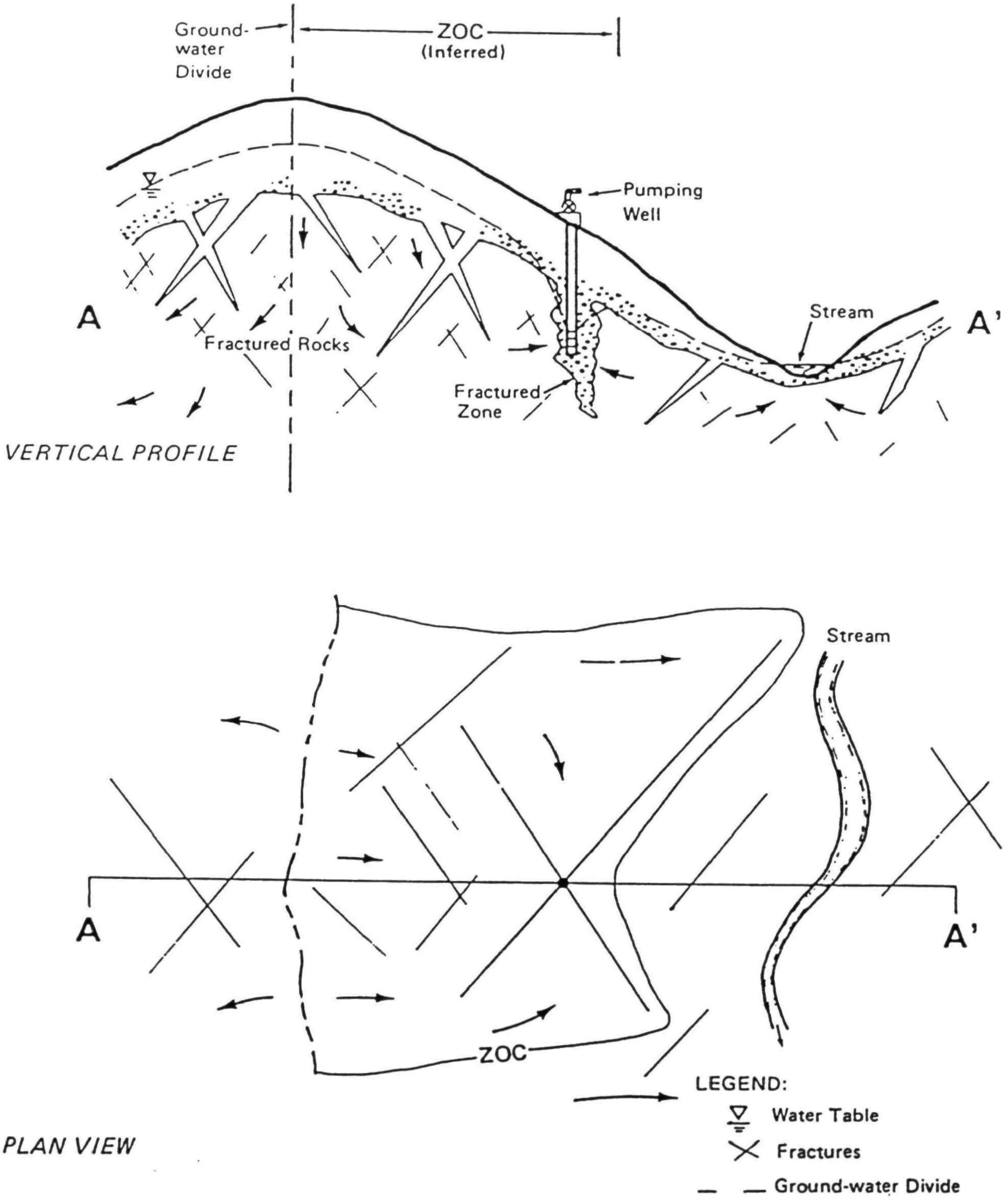
LEGEND:
- Sinkhole
- Water Supply Spring
- Surface Stream
- Conduit System
- Water Table
- Limestone

Slide 3.05

NOT TO SCALE

SOURCE: Modified from Quinlan and Ewers, 1985

Terminology for Wellhead Protection Area Delineation (Hypothetical Ground-water Basin in Fractured Rock)

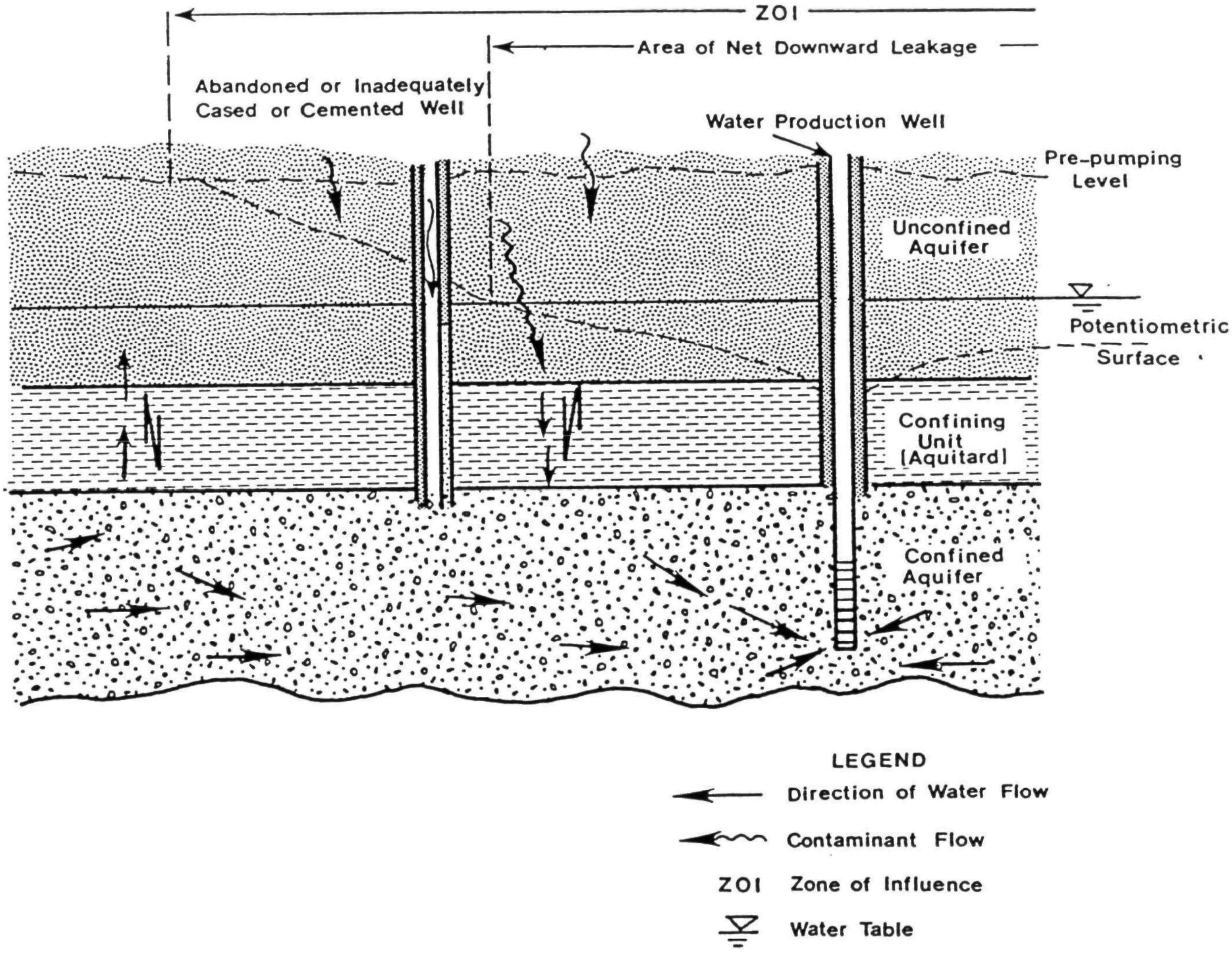


Slide 3.06

NOT TO SCALE

SOURCE: Modified from Otton, 1981

Terminology for Wellhead Protection Area Delination
[Hypothetical Confined Aquifer in Porous Media]



NOTE: ZOI is larger than area of downward leakage

WELLHEAD DELINEATION CRITERIA

(OVERVIEW)

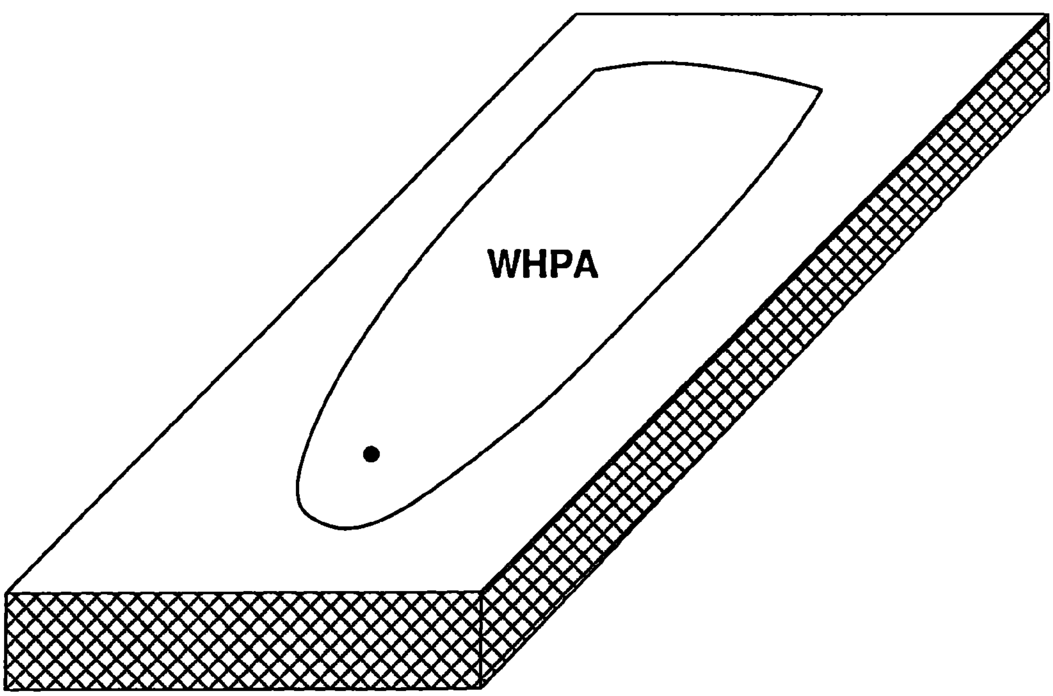
WHPA DELINEATION PROCESS

SELECT APPROPRIATE CRITERION
AND THRESHOLD (quantitative measure)
TO PROTECT WELLHEAD AREA

↓

SELECT APPROPRIATE METHOD
TO IMPLEMENT CRITERION

↓



DELINEATION CRITERIA

- DISTANCE
- DRAWDOWN
- TIME OF TRAVEL
- FLOW BOUNDARIES
- ASSIMILATIVE CAPACITY

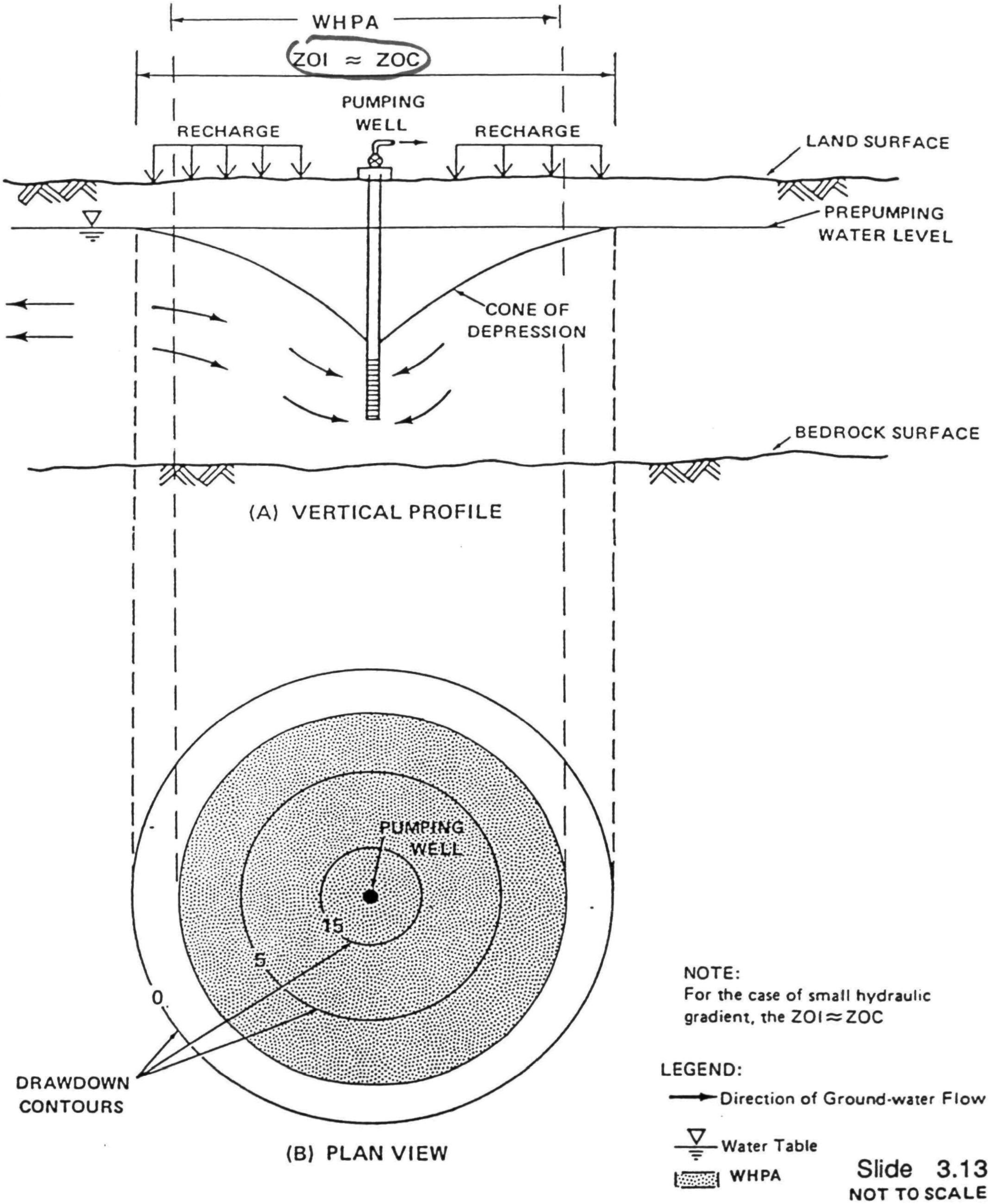
DISTANCE: COMMENTS

- Simplest, quickest and cheapest way to provide protection
- Often used as "First Step", or for microbial protection
- Accuracy depends on hydrogeologic setting
- Protectiveness depends on threshold

DRAWDOWN: COMMENTS

- Appealing since it relates directly to pumping
- Extent of geographic area (ZOI) varies from feet to miles
- May "overprotect" downgradient ✓
- May "underprotect" upgradient ✓

Aquifer with Flat Water Table and High Rainfall Conditions, Where Boundaries of ZOI and ZOC Approximately Coincide (Conceptual)



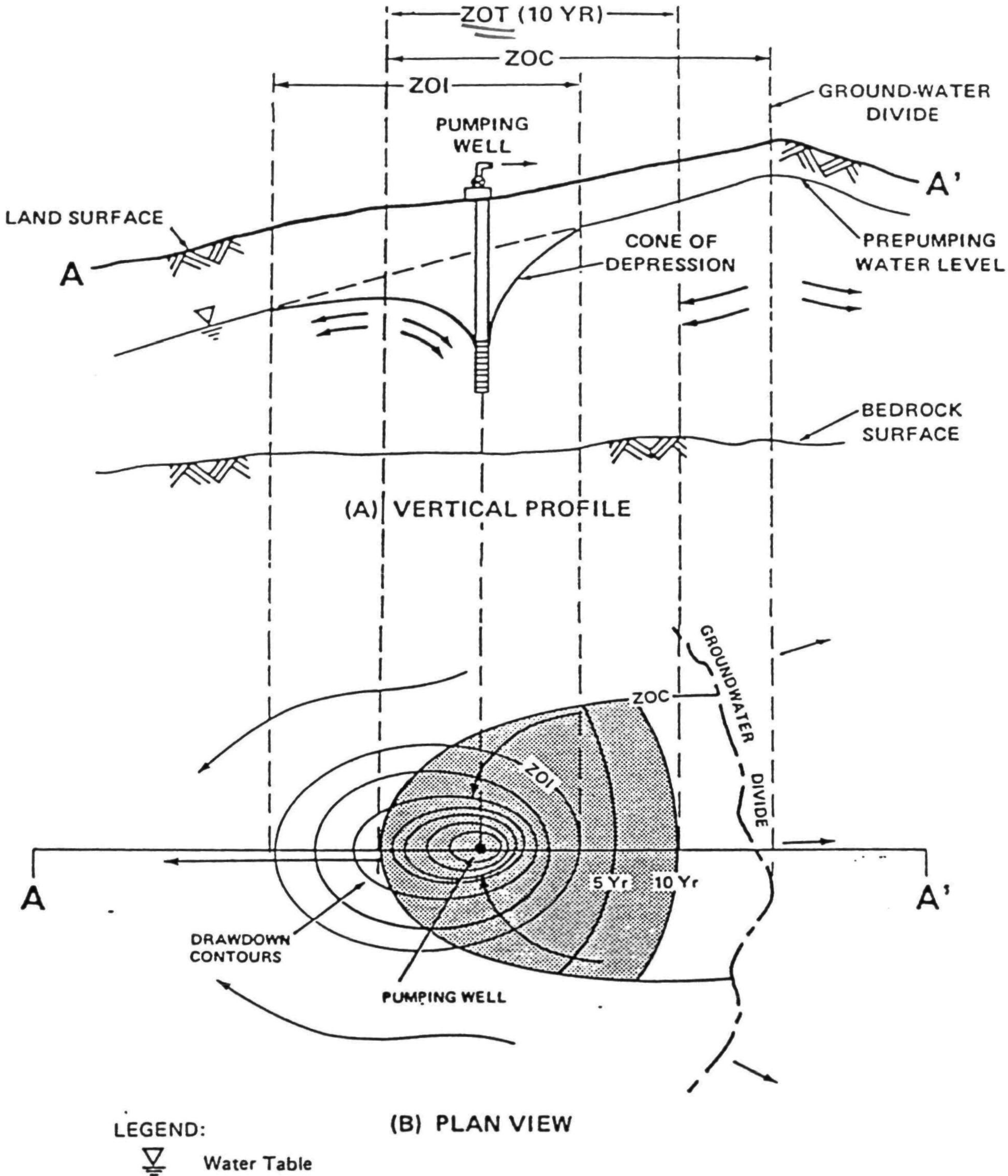
Slide 3.13
NOT TO SCALE

MORE INTEGRATED APPROACH

TIME-OF-TRAVEL: COMMENTS

- Considers physical processes and flow velocities
- Velocities within aquifers vary enormously
- Accuracy depends on method used
- Protectiveness depends on threshold

Terminology for Wellhead Protection Area Delineation (Hypothetical Contaminant Transport in Porous Media)



LEGEND:

- Water Table
- 10 Year Zone of Transport
- Direction of Ground-water Flow
- ZOC Zone of Contribution
- ZOI Zone of Influence
- ZOT Zone of Transport

Slide 3.15

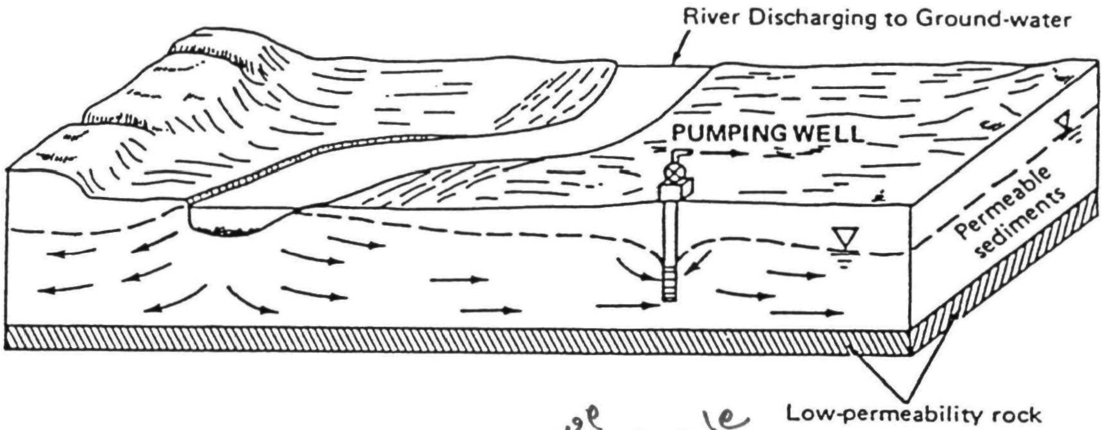
NOT TO SCALE

FLOW BOUNDARIES: COMMENTS

- Key criterion for certain aquifer types VA, MD
- Ideal for small aquifers ~ WV? Parts of PA,
- Less suited for large or deep/confined aquifers except near boundaries

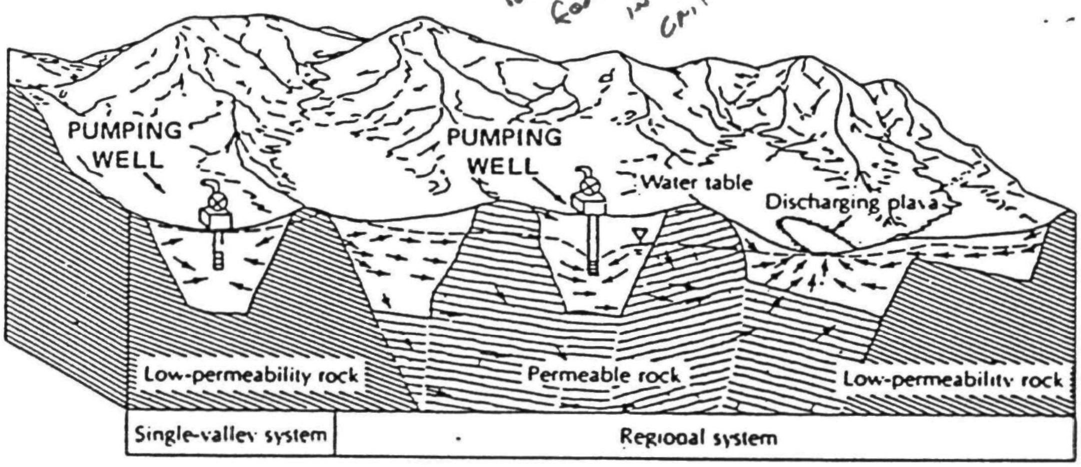
Flow Boundaries Criteria
(Conceptual)

(a)



here one should use low permeable formations as the criteria

(b)



NOTE:

(a) The ground-water divide induced by the river is an example of the type of surface feature that may be used as a physical boundary criterion [Figure (a) modified from Driscoll (1986)].

(b) The boundary between the "single valley system" and "the regional system" is an example of the type of subsurface feature that may be used as a physical boundary criterion [Figure (b) modified from Fetter (1980)].

▽ Water Table

→ Direction of Ground-water Flow

Slide 3.17

NOT TO SCALE

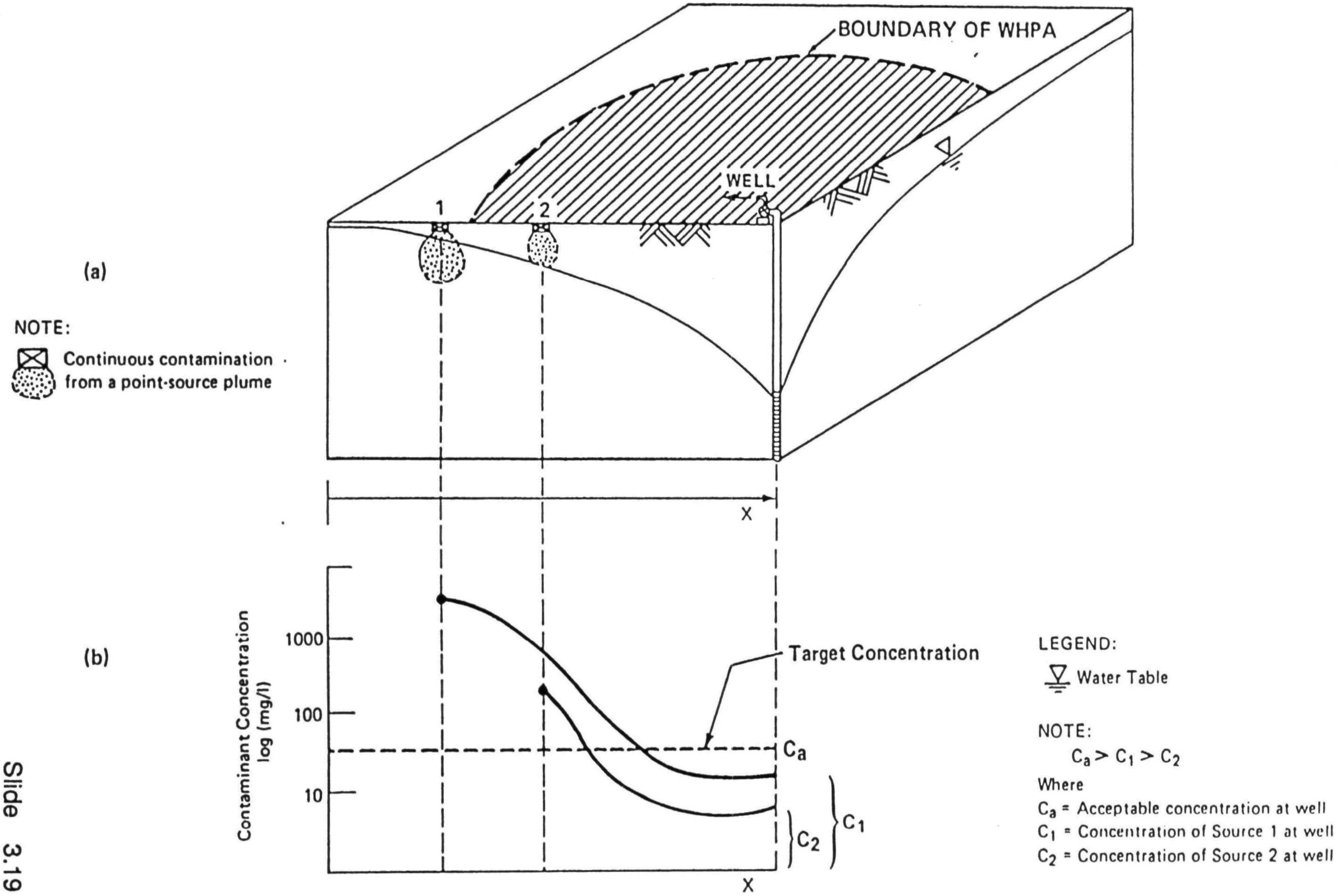
ASSIMILATIVE CAPACITY: COMMENTS

- Technically sophisticated
- Conceptual tie to management strategies
- Requires complex and expensive modeling
- No current examples for WHPAs with multiple sources

· EPA research is starting on this

· contaminant type dependent. so you could have a zol for ea. type of contaminant

Assimilative Capacity Criteria (Conceptual)



Slide 3.19

CRITERIA THRESHOLD EXAMPLES (CHEMICAL THREATS)

Distance - 1000 feet to 2 miles +

Drawdown - 0.1 to 1.0 foot

TOT - ≤ 5 to 50 years

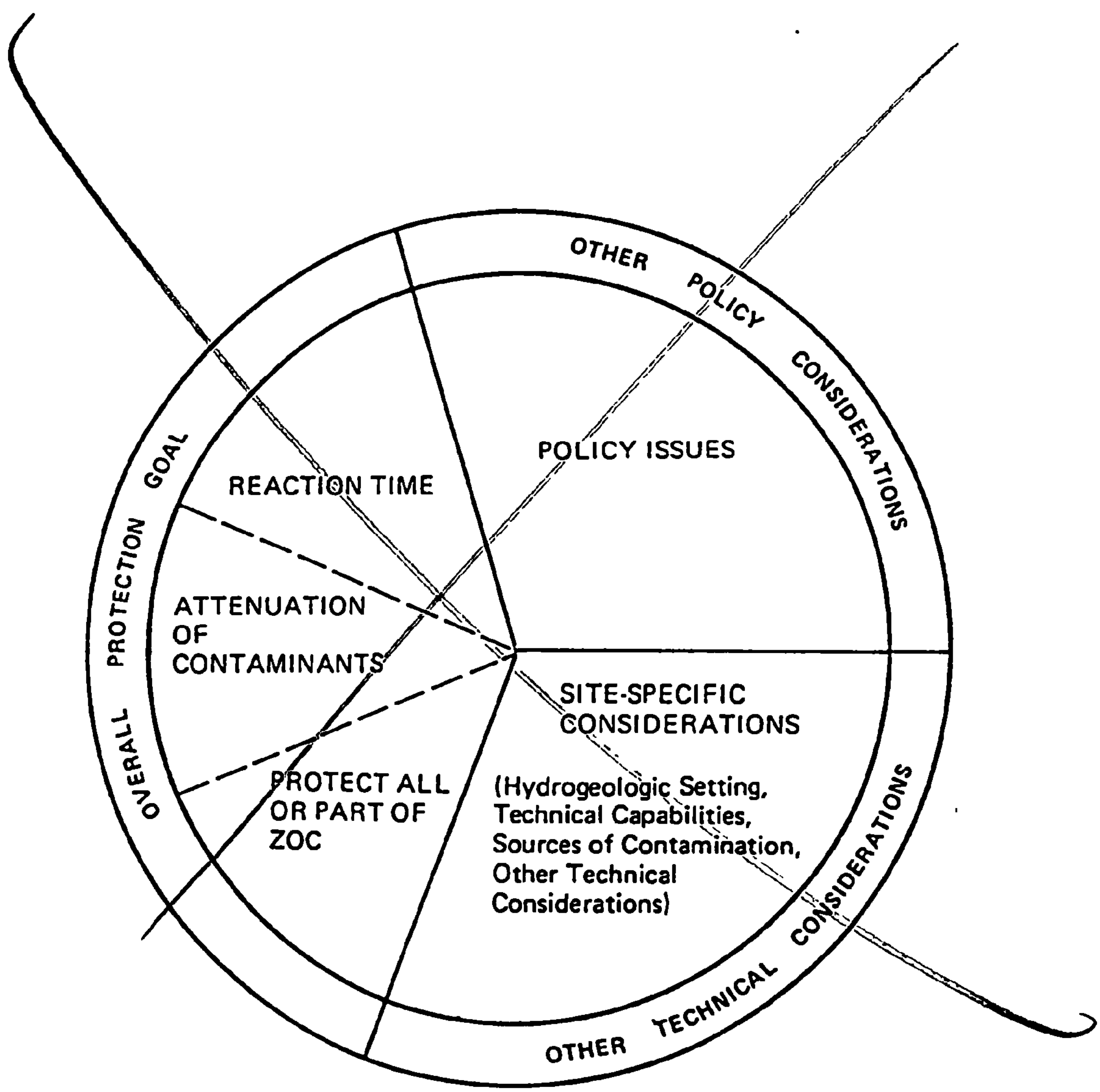
Flow Boundaries - Physical and hydrologic

Assimilative Capacity - Nitrate MCL

Relationship Between WHPA Delineation Criteria and Physical Processes

PHYSICAL PROCESS \ CRITERIA	DISTANCE	DRAWDOWN	TOT	FLOW BOUNDARIES	ASSIMILATIVE CAPACITY
ADVECTION		●	●	●	
HYDRODYNAMIC DISPERSION (MECHANICAL DISPERSION AND MOLECULAR DIFFUSION)			●		●
SOLID-SOLUTE INTERACTION (ADSORPTION, CHEMICAL REACTIONS)			●		●

Consideration Factors That May Affect Criteria Selection



WHPA GOALS

- REACTION TIME
- ATTENUATION OF CONTAMINANTS
- PROTECT ALL OR PART OF ZOC

TECHNICAL SELECTION FACTORS

- EASE OF APPLICATION
- EASE OF QUANTIFICATION
- VARIABILITY UNDER ACTUAL CONDITIONS
- EASE OF FIELD VERIFICATION
- ABILITY TO REFLECT STANDARDS
- SUITABILITY FOR LOCAL HYDROGEOLOGY
- ABILITY TO INCORPORATE PHYSICAL PROCESSES

POLICY SELECTION FACTORS

- EASE OF UNDERSTANDING
- ECONOMY OF CRITERIA DEVELOPMENT
- DEFENSIBILITY
- PHASING
- RELEVANCE TO PROTECTION GOAL

WELLHEAD DELINEATION METHODS

(OVERVIEW)

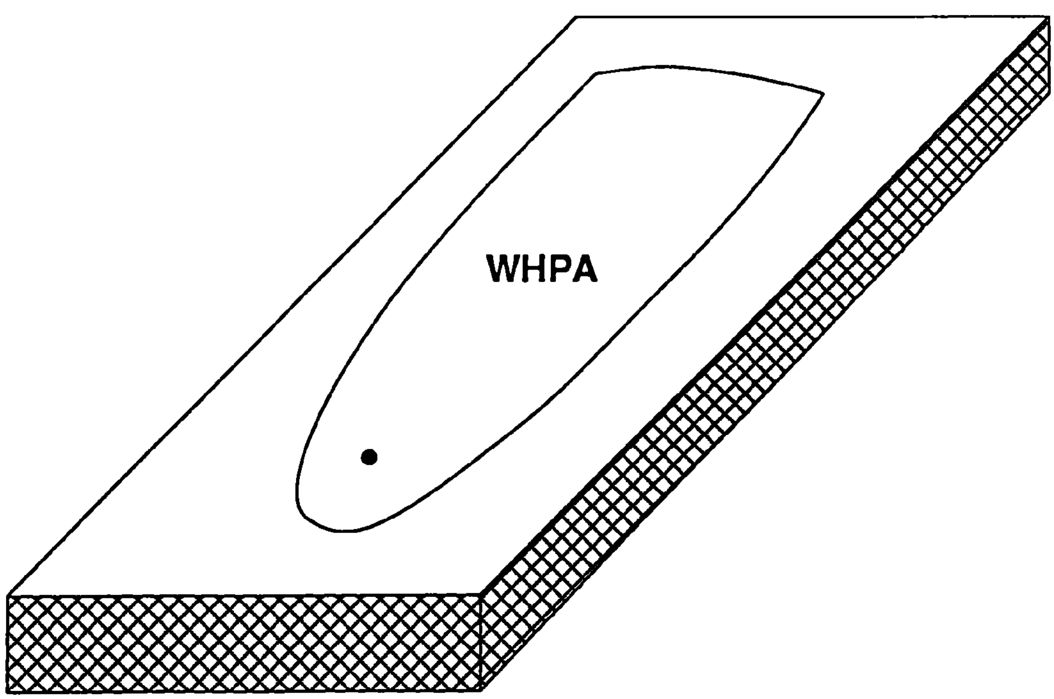
WHPA DELINEATION PROCESS

SELECT APPROPRIATE CRITERION
AND THRESHOLD
TO PROTECT WELLHEAD AREA

↓

SELECT APPROPRIATE METHOD
TO IMPLEMENT CRITERION

↓



WHPA DELINEATION METHODS

COMPLEXITY, FLEXIBILITY & COST INCREASES

1) ARBITRARY FIXED RADIUS

2) CALCULATED FIXED RADIUS

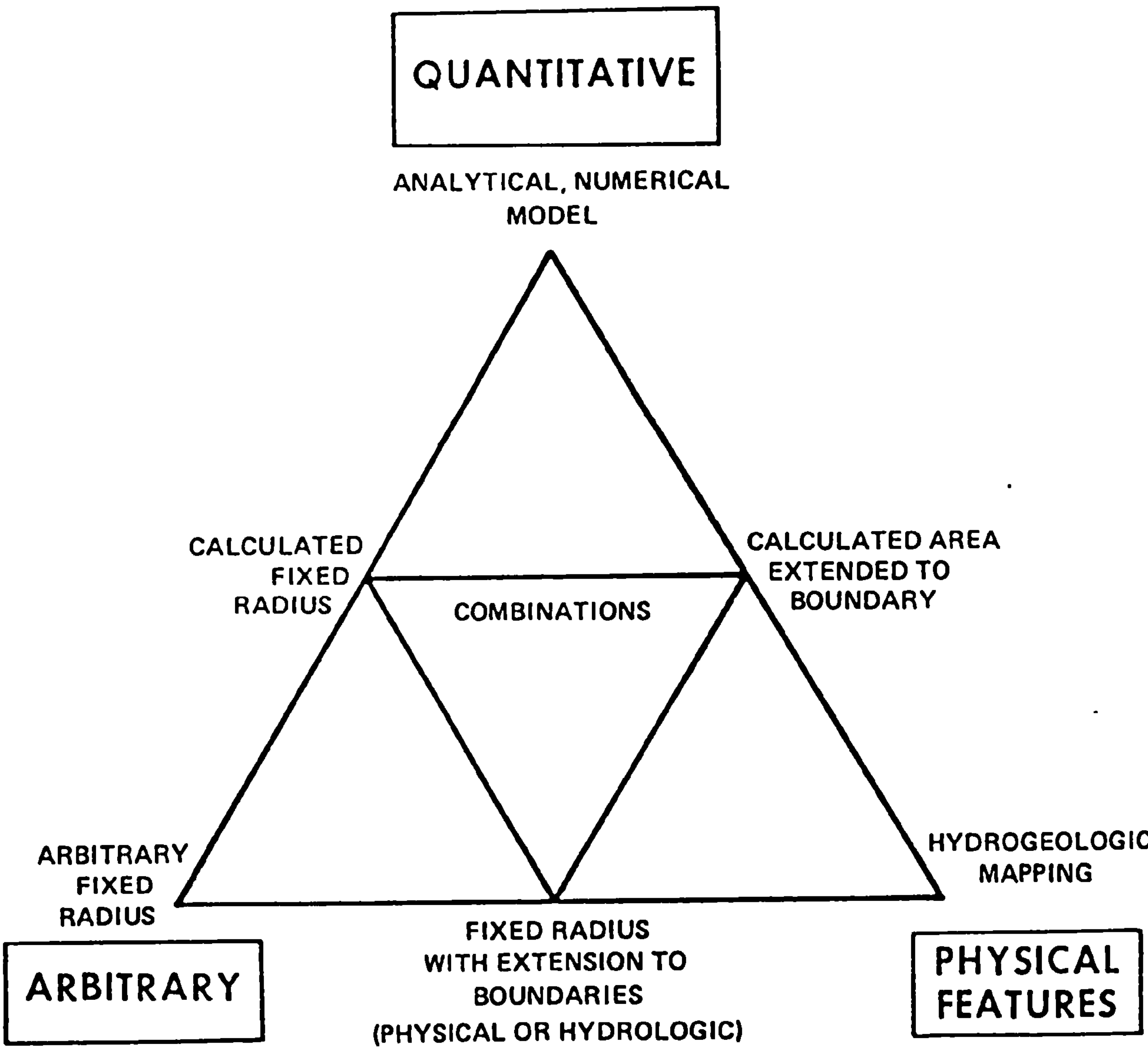
3) SIMPLIFIED VARIABLE SHAPES

4) ANALYTICAL METHODS

5) HYDROGEOLOGIC MAPPING

6) NUMERICAL FLOW / TRANSPORT MODELS

Interrelationships of WHPA Methods



Slide 3.29

METHODS DISCUSSION

- EACH RELEVANT IN SOME SETTINGS
- FIXED RADIUS QUICK AND <u>MAY</u> BE PROTECTIVE
- IMPROVEMENTS AT MODEST COST WITH:
  - CALCULATED FIXED RADIUS
  - SIMPLIFIED VARIABLE SHAPES
  - ANALYTICAL MODELING METHODS
- NUMERICAL MODELS – ACCURATE; COSTLY
- COMPARATIVE ANALYSES ENCOURAGED

METHODS VERSUS CRITERIA

METHOD \ CRITERIA	DISTANCE (L/M/H)	DRAWDOWN (L/M/H)	TOT (L/M/H)	PHYSICAL BOUNDARIES (L/M/H)	ASSIMILA-TIVE CAPACITY (L/M/H)
ARBITRARY FIXED RADIUS	H	N/A	N/A	N/A	N/A
CALCULATED FIXED RADIUS	N/A	H	H	N/A	N/A
SIMPLIFIED VARIABLE SHAPES	N/A	N/A	M	N/A	N/A
ANALYTICAL MODELS	N/A	H	H	N/A	M
NUMERICAL FLOW/ TRANSPORT MODELS	N/A	H	H	N/A	M
HYDROGEOLOGIC MAPPING	H	N/A	N/A	H	N/A

L–LOW applicability
M–MEDIUM "
H–HIGH "
N/A–NOT APPLICABLE

Slide 3.31

TECHNICAL CONSIDERATIONS INFLUENCING METHOD SELECTION

- EASE OF APPLICATION
- EXTENT OF USE
- SIMPLICITY OF DATA REQUIREMENTS
- SUITABILITY FOR HYDROGEOLOGIC SETTING
- ACCURACY

POLICY CONSIDERATIONS INFLUENCING METHOD SELECTION

- EASE OF UNDERSTANDING
- ECONOMY OF METHOD APPLICATION
- DEFENSIBILITY
- RELEVANCE TO PROTECTION GOAL

DATA REQUIREMENTS FOR WHPA METHODS

Data requirements

Application Method	K	T	Q	n	i	H	S	α	R	Hydrologic Boundaries	Aquifer Geometries
Arbitrary Fixed Radius											
Calculated Fixed Radius			X	X		X					
Simplified Variable Shapes			X		X						
Analytical Methods		X	X	X	X	X	X				
Hydrogeologic Mapping											
Numerical Models	X	X	X	X		X	X	X	X	X	X

PARAMETERS	SYMBOL	DIMENSIONS
Hydraulic Conductivity	K	L/T
Transmissivity	T	L^2/T
Pumping Rate	Q	L^3/T
Porosity	n	dimensionless
Hydraulic Gradient	i	dimensionless
Saturated Thickness	H	L
Storage Coefficient (Specific Yield)	S	dimensionless
Dispersivity	α	L
Recharge	R	L/T

Costs of Delineation Associated with Various WHPA Methods

Method	Manhours Required per Well	Level of Expertise*	Cost per Well	Potential Overhead Costs
Arbitrary Fixed Radius	1 - 5	1	$10 - 50	L
Calculated Fixed Radius	1 - 10	2	$13 - 125	L
Simplified Variable Shapes	1 - 10	2	$13 - 125	L - M
Analytical Methods	2 - 20	3	$30 - 300	M
Hydrogeologic Mapping	4 - 40	3	$60 - 600	M - H
Numerical Modeling	10 - 200+	4	$175 - 3500+	H

* Hourly wages per level of expertise assumed to be:
(based on NWWA, 1985)

1.	Non-Technical	$10.00
2.	Junior Hydrogeologist/Geologist	$12.50
3.	Mid-Level Hydrogeologist/Modeler	$15.00
4.	Senior Hydrogeologist/Modeler	$17.50

ADEQUACY OF DELINEATION

ADEQUACY OF WELLHEAD PROTECTION AREA DELINEATION

CONTENTS OF STATE SUBMITTAL

OF A WHPA

- Institutional process
- Delineation criteria and criteria thresholds
- Delineation methods
- Phasing

ADDITIONAL BACKGROUND

- Threats for WHPA delineation
  - Direct introduction of contaminants
  - Microbial contaminants
  - Chemical contaminants ← EPA IS FOCUSING ON THIS
- Confined aquifers
  - Require WHPA
  - Assess threats to confinement

INSTITUTIONAL PROCESS

for dev'g the technical aspects

- Essential for "Adequacy"
- Description – Develop and implement technical elements
- Roles – Operations and research groups
- Approach – Legal incorporation
- Coordination – Other hydrogeological efforts

CRITERIA

- Precedes method selection
- Appropriateness depends on goal, hydrogeology, policy
- Key for chemical threats
- Many adequate criteria
- May combine criteria

CRITERIA THRESHOLDS

- TOT < 5 to 10 yrs -- problem?

  justified by response approach probably requires more than 10 yr. does it come close to hydrogeological reality (sometimes a contaminant may move faster than water)

- Distance < 1000s feet -- problem? Nebraska uses a 1000.'

- More protective is preferable, if practical

  & the simple conservation is better

- Drawdown, boundaries are case-specific

- Relevant to confined aquifers

METHODS

cost = cost of doing PWS business = 1-10% of capital investment.

- Each relevant in some settings
- Fixed radius quick and may be protective
- Improvements at modest cost with calculated fixed, variable shapes, analytical
- Numerical models – accurate; costly
- May combine methods
- Comparative analyses encouraged

PHASING

- Delineate as many WHPAs as possible
- Constraints to 1989 deadline (that's the implication)
- Generic delineation possible
  - Criteria and methods (what are they)
  - Test cases (show us some test cases)
- Phase by well yield, vulnerability, contaminant sources

WORK PLANS

- Development years
  - Progress on institutional aspects
  - Progress on criteria and methods
- Implementation years
  - Adequate Program
  - Reassessments
  - Completion of delineation

3. ELEMENTS OF WHPA DELINEATION

3.1 WELLHEAD TERMINOLOGY

The following WHPA terminology is defined in the WHPA Delineation Guidelines (EPA, 1987a).

WHPA Criteria are conceptual standards that form the basis for WHPA delineation and include distances, drawdown, time of travel, assimilative capacity and flow boundaries.

WHPA Criteria thresholds are the numeric value selected for each WHPA criteria used in a delineation (e.g., a distance threshold of 1,000 feet).

Delineation Method is a technique used to translate the select critria and criteria thresholds to actual, mappable delineation boundaries.

Zone of Influence (ZOI) is the area surrounding a pumping well within which the water table or potentiometric surfaces have been changed due to ground-water withdrawal (Slide 3.3).

Zone of Contribution (ZOC) is the area surrounding a pumping well that encompasses all areas or features that supply ground-water recharge to the well (Slide 3.3).

Zone of Transport (ZOT) is the area surrounding a pumping wells, bounded by an isochrone and/or isoconcentration contour through which a contaminant may travel and reach the well (Slide 3.4).

Mature karst ground-water basins are characerterized by sinkholes, cave streams, and underground drainage. Flow is generally confined to a complex network of solution channel and cavernous conduits that is extemely difficult to infer from the surface.

An approach to delineate WHPAs in mature karst settings might be based on the boundaries of the ZOC as inferred from divides and drainage boundaries.

Fractured bedrock aquifers limit flow to wells according to the distribution and degree of interconnection that exists between fractures and with variations in rainfall recharge. Accurately determining the recharge area to a well in a fracture setting is difficult (Slide 3.5).

An assumption that the topographic divides or drainage boundaries of a fractured bedrock aquifer represent the ZOC may be the basis for WHPA delineations (Slide 3.6).

A confining layer may provide some protection for a water source. Where the dominant flow through the confining layer is toward the water-supply aquifer this should be examined as an area of concern for WHPA delineation (Slide 3.7).

Another approach to confining conditions might focus in a portion of the contributing area based upon some TOT threshold within the aquifer.

3.2 WELLHEAD PROTECTION AREA DELINEATION CRITERIA

Delineation criteria can be catalogued into five types:

- distance
- drawdown
- time of travel
- flow boundaries
- assimilative capacity

The choice of a criterion will involve consideration of both technical and nontechnical factors. Considerations for criteria selection are presented in the Wellhead Delineation Guidelines. A list of examples for the delineation criteria are also found in the Wellhead Delineation Guidelines (EPA, 1987a).

Distance Criterion

The distance criterion concept involves delineating a WHPA using a radius or horizontal dimension measured from the water supply well. The distance criterion may or may not have a technical basis. For example, individual domestic supply wells are often required to have a 100 ft to 200 ft setback to on-site septic systems based on empirical evidence concerning ground-water pollution control.

A distance-based WHPA could provide insufficient or ineffective protection in some cases. This criterion, however, is easy to implement since a uniform distance would be required from any well.

Examples include Edgartown, Massachusetts and the State of Nebraska, where fixed circles of 2,500 feet and 1,000 feet are used respectively.

Drawdown Criterion

A drawdown criterion concerns the extent to which well pumping lowers the water table of an unconfined aquifer, or the potentiometric surface of a confined aquifer. Such a criterion is related to the cone of depression or zone of influence (ZOI).

The drawdown approach is used to delineate the boundaries of the ZOI or a major portion of a ZOI. This approach works well in highly productive water-table aquifers with horizontal water tables (Slide 3.13).

Examples of drawdown criteria thresholds include Dade County, Florida where a 0.25 feet drawdown criterion threshold was used and in Palm Beach County, Florida, where 1.0 feet of drawdown was used.

The steep hydraulic gradients that result in the vicinity of a pumping well can act to accelerate contaminant migration toward the well. For this reason, the development of drawdown criterion should consider the relationship between pumping rates and contaminant migration.

Time of Travel Criterion

The time of travel (TOT) delineation criterion establishes a maximum time for a ground-water contaminant to reach a well. This approach incorporates a more comprehensive evaluation of the physical processes of contaminant transport than the previously discussed criteria (Slide 3.15).

Most time of travel methods have been developed based on the physical process of advective transport and have not considered the movement of specific contaminants. Generally speaking, contaminants move at velocities slower than the effective transport of water molecules.

At lower velocities, physical processes such as hydrodynamic dispersion should be considered because of their potential to cause a contaminant to reach a well sooner than would be predicted using advective, Darcian TOT calculations. Detailed discussions concerning dispersion and contaminant transport are found in Anderson (1984), Bear (1979) and Fried (1975).

Ground-water flow velocities under natural settings vary considerably and are related to the types of aquifer media (i.e., porosity and hydraulic conductivity). The highest flow rates can be found in karst and fractured rock flow settings. In such settings the time of travel approach may not be appropriate.

A maximum velocity or maximum travel time for contaminants to reach a well is considered a conservative approach in that the numerous factors operating along the contaminant flow path to reduce, disperse or dilute the maximum concentration provide for an additional level of safety.

Dade County Florida, as an example, employs two TOT criteria thresholds. A 100 day TOT Zone is delineated for control of entering viruses and a 210 day TOT is delineated to represent the longest drought on record.

Flow Boundaries

Physical or hydraulic boundaries of an aquifer or ground-water flow system can be used effectively to delineate the bounds of the maximum potential zone of contribution (ZOC). The physical limits of an aquifer, and a fixed regional ground-water divide are examples of flow boundaries (Slide 3.17).

Flow boundary criteria may be very appropriate for flow settings such as conduit karst and fractured bedrock aquifers.

Flow divides, particularly those associated with gaining streams may not always be shown to be appropriate flow boundaries for purposes of WHPA delineation. For this reason, a thorough technical evaluation may be necessary.

A flow boundary criterion can be especially useful for small aquifers where travel times from the boundaries may be very brief, or where the zone of influence is rapidly affected by proximity to the physical limits of the aquifer.

Physical boundaries to aquifers have been employed as criterion to delimit WHPAs in Vermont, Massachusetts and Florida.

Assimilative Capacity

The assimilative capacity criterion for WHPA delineation may apply a range of processes that attenuate contaminant concentrations within a ground-water flow system. However, no known examples of this approach to delineate WHPA has been uncovered.

The concept is to allow such processes to work providing that contaminant levels reach acceptable levels before they reach a well. Contaminant concentrations that exceed standards at some distance away from the well, may attenuate as they migrate to acceptable levels at the well screen (Slide 3.19).

The existence and magnitude of attenuation processes are directly linked to the contaminants and aquifer properties. They are not easily modelled or quantitatively determined. Site specific data for specific contaminants would be needed in order to use this approach.

Specific standards for the various contaminants may also have to be developed if such standards do not exist.

<u>Criteria Selection Considerations</u>

Three major considerations for selecting WHPA delineation criteria involve the overall protection goal, technical considerations, and policy considerations. Detailed discussion of these considerations is provided in WHPA Delineation Guidelines.

Three general goals for ground-water protection in the vicinity of wellheads involve the following:

- reaction time -- to provide a remedial action zone to protect wells from unexpected contaminant releases,
- attenuation of contaminants -- attenuate the concentrations of specific contaminants to desired levels at the time they reach the wellhead, and
- protect all or part of ZOC -- provide a well field management zone in all or a major portion of the existing or potential recharge area of the well.

Generally the criteria can be matched up to the specific criteria goals as follows:

- the remedial action zone goal is consistent with a TOT criterion,
- the zone for attenuation goal implies an assimilative capacity criterion or possibly a TOT criterion, and
- the wellfield management area goal is consistent with a distance-drawdown or flow boundaries criteria.

Six technical factors have been identified for evaluating the appropriateness of each wellhead delineation criterion. A table with matrix cells designed for assisting in such an evaluation is provided in the WHPA Delineation Guidelines.

The technical merits of a criterion depend on the degree to which the criterion incorporates those processes affecting ground-water flow and contaminant transport, and the suitability of the criterion for the local hydrogeologic condition. A criterion such as drawdown, which considers only the physical processes may have less technical merit than a time of travel criterion which encompasses a more complete range of processes explaining contaminant transport.

Technical factors are as follows:

- <u>ease of application</u>. How easily can a technical user apply the criteria. The more technically demanding criteria require more advanced and specialized user abilities. Does the implementing agency have such abilities on staff?

- <u>ease of quantification</u>. The suitability of a criterion for use in guidelines of regulations may be directly influenced by the ease to which a numerical value can be placed or derived. The distance and time of travel criterion are easily expressed in numerical form. Others are not.

- <u>variability under actual conditions</u>. Which hydraulic conditions are expected to change (e.g., increased pumping rates)? The criterion selected would most likely need to allow for such variations. For example, the time of travel criterion allows the user to modify the size of the WHPA to reflect an anticipated increase in pumping rates.

- <u>ease of field verification</u>. The most appropriate criterion would be one that could be calculated in the office and accurately verified in the field. For example, in a porous media aquifer, it is much more difficult to verify calculated travel times than it is drawdowns.

- <u>ability to reflect ground-water quality standards</u>. Where a protective goal to attenuate concentrations of constituents is established, the delineation criterion would be expected to be related to the ability of the ground-water flow system to achieve the water-quality standard given the expected contaminant levels. If little is known concerning the behavior/attenuation of specific contaminants, then a less quantitative delineation criterion would be more appropriate.

- suitability for a given hydrogeologic setting. As discussed previously, selected criterion are more appropriate in some hydrogeologic settings than others.

- ability to incorporate physical processes. Selection of a criterion should include consideration of whether the physical processes controlling contaminant transport are incorporated with the selected criterion.

Policy Considerations

Five policy considerations for choosing a WHPA Criterion have been identified. A table with a decision matrix is provided in the WHPA Delineations Guidelines as an aid for making the policy evaluation. Policy considerations are as follows:

- ease of understanding. The ease with which the general public can understand the criterion may be a significant measure of its utility.

- economy of criteria development. The cost of developing the various criteria can vary substantially. Generally criteria that are more complex will require a more highly trained staff for implementation.

- defensibility. WHPA delineation criteria that are clearly defined and defensible against potential challenges in litigation will be most acceptable to enforcement and permitting authorities. The more technically defensible criteria will be favored.

- usefulness for implementing phasing. Where a state prefers to initiate their WHPA program in phases, the first or interim stage might favor a less costly, more easily implemented criterion. More sophisticated criteria would be applied in later phases as appropriate.

- relevance to protection goal. The degree to which a criterion allows for the attainment of the protective goal or goals will be a decisive factor in the selection process.

3.3 WELLHEAD PROTECTION AREA DELINEATION METHODS

Once an appropriate Wellhead Protection Area (WHPA) delineation criterion and threshold have been decided upon (see previous section), a method must be selected to implement the criterion. In some cases, multiple protection zones may be defined around a water-supply well or wellfield using different thresholds for the same criterion. This would require the use of a single method for repeated calculations. In cases where multiple zones are delineated using different criteria, several methods may be applied to the same site.

Six methods have been identified in the WHPA Delineation guidance document (EPA 1987a) as having been used to delineate protection areas. These methods, listed in order of increasing cost and sophistication, are:

Arbitrary Fixed Radius Method - involves determination of simple circular protection areas; size often based on expert judgment.

Calculated Fixed Radius Method - similar to arbitrary fixed radius method, but some properties of the hydrogeologic system and well pumping rate incorporated in determination of size of circle.

Simplified Variable Shapes Method - incorporate more hydrogeologic information in the initial development stages but, once developed, it is as easy to apply as the fixed radius method.

Analytical Modeling Methods - involve the solution of simplified ground-water flow and transport equations using calculators or computers, and are based on a simplified representation of the aquifer system.

Hydrogeologic Mapping Methods - use geologic and geophysical techniques to determine flow system properties and to identify flow boundaries.

Numerical Modeling Methods - similar to analytical modeling methods but more powerful and flexible; often incorporate data collected using hydrogeologic mapping methods.

The methods are discussed in Chapter 4 of the Delineation Guidelines (EPA, 1987a). Also the remainder of this training manual is devoted to descriptions of the methods, discussions of their advantages and disadvantages, case studies illustrating their use in WHPA delineation studies, and exercises designed to familiarize the reader with the practical aspects of applying the various models.

Method Selection Considerations

Selection of a WHPA delineation method is somewhat constrained once the desired delineation criterion has been selected in that the method must be suitable to map the criterion. Choice of method is tied less to the protection goal than to accuracy of the delineation desired and the financial resources available for delineation. Several technical and policy considerations that may influence method selection are discussed fully in the Delineation Guidelines (EPA, 1987a) and summarized below.

Technical Considerations:

Extent of Use. How commonly is the method used?

Simplicity of Data. What data are required for the application of method. Is the data site-specific or regional? Are the financial resources to fund the necessary data collection available? Is the data available through previous work or reports and, if so, does the data need to be updated?

Suitability for a Given Hydrogeologic Setting. An important consideration is whether or not the analytical method is suitable for the hydrogeologic setting of interest. It is necessary to evaluate the ability of an analytical model to incorporate, or be adopted to incorporate, the hydrogeologic characteristics of a site such as variable aquifer parameters, boundary conditions, and the effects of hydraulic sources and sinks.

Accuracy. Perhaps the most important consideration. To what degree do the results accurately compare to actual field conditions?

Policy Considerations:

Ease of Understanding. Can the principles underlying the method be understood by nontechnical personnel?

Economy of Application. Higher relative costs can inhibit the use of one method over another. Costs that may contribute to implementation expense include those for data acquisition, professional labor, computer time, graphics, and reporting.

Defensibility. Enforcement and permitting regulations and procedures require that the boundaries of a WHPA be well defined and defended against potential challenges and litigation by parties affected by the delineation. Does the method used to delineate a WHPA have the scientific basis to withstand such challenges?

Relevance to Protection Goal. In general, WHPA delineation will reflect the overall policy/protection goal of a State program. Selecting a method relevant to this goal is the key factor in program success.

4. Fixed Radii & Simp.
Variable Shapes

ARBITRARY FIXED RADIUS METHOD

WHPA DELINEATION METHODS

1) ARBITRARY FIXED RADIUS

2) CALCULATED FIXED RADIUS

3) SIMPLIFIED VARIABLE SHAPES

4) ANALYTICAL METHODS

5) HYDROGEOLOGIC MAPPING

6) NUMERICAL FLOW / TRANSPORT MODELS

ARBITRARY FIXED RADIUS METHOD

MAKE THEM BIG (2-3 MI)

DESCRIPTION

Circle of specified radius is drawn around a well or wellfield

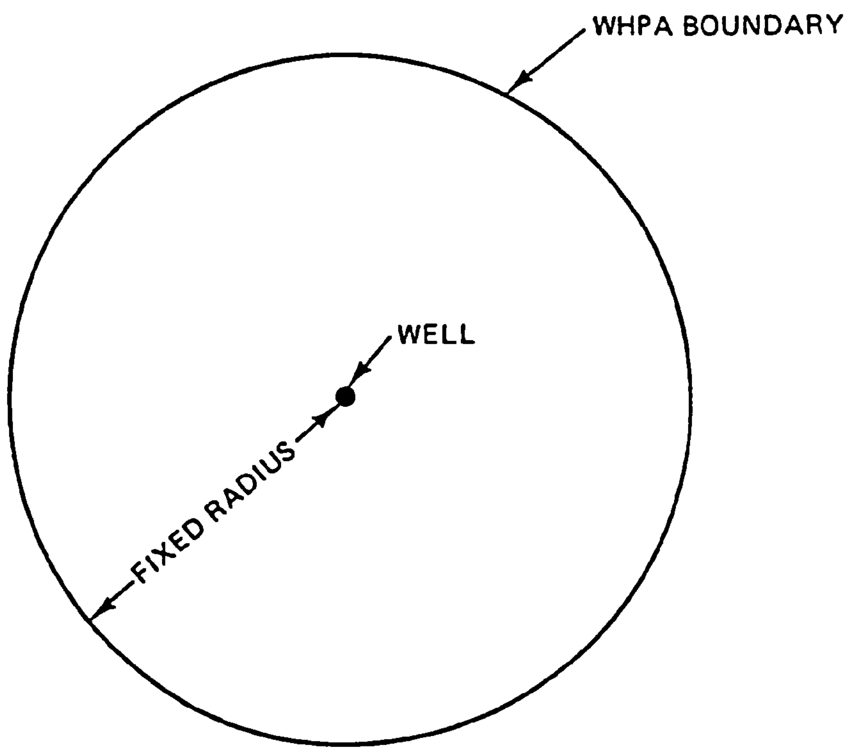
ADVANTAGES

- simple, fast, inexpensive way to apply the distance criterion
- easily mapped and verified in the field
- suitable for physical or microbial threats, or as a temporary measure in early stages of WHPA delineation

DISADVANTAGES

- does not take site-specific hydrogeological data into account, and may therefore overprotect or underprotect depending on hydrogeology
- low defensibility

METHODS: ARBITRARY FIXED RADIUS



Slide 4.04

NOT TO SCALE

ARBITRARY FIXED RADIUS METHOD CASE STUDY

- STATE OF FLORIDA

- PROPOSED LAW REQUIRES A ZONE WITH 200-FOOT RADIUS TO BE DELINEATED FOR PUBLIC WATER-SUPPLY WELLS WITH WITHDRAWALS IN EXCESS OF 100,000 GALLONS PER DAY

- PROTECTION ZONE IS TO RESTRICT ANY ACTIVITIES THAT COULD CONTAMINATE THE GROUND WATER

ARBITRARY FIXED RADIUS METHOD CASE STUDY

- STATE OF MASSACHUSSETTS

- AQUIFER LAND ACQUISITION PROGRAM REQUIRES DELINEATION OF A WHPA WITH 400-FOOT RADIUS FOR PUBLIC WATER- SUPPLY WELLS

- AREA TO SERVE AS THE FIRST OF THREE ZONES DESIGNED TO CONTROL LAND USE AROUND WATER-SUPPLY WELLS

ARBITRARY FIXED RADIUS METHOD USED TO DELINEATE WHPA (ZONE 1) AT FRANKLIN, MA

CALCULATED FIXED RADIUS METHOD

WHPA DELINEATION METHODS

1) ARBITRARY FIXED RADIUS

2) CALCULATED FIXED RADIUS

3) SIMPLIFIED VARIABLE SHAPES

4) ANALYTICAL METHODS

5) HYDROGEOLOGIC MAPPING

6) NUMERICAL FLOW / TRANSPORT MODELS

CALCULATED FIXED RADIUS METHOD

DESCRIPTION

Circle with radius ~~specified by time-of-travel criterion~~ is drawn around well or wellfield

ADVANTAGES

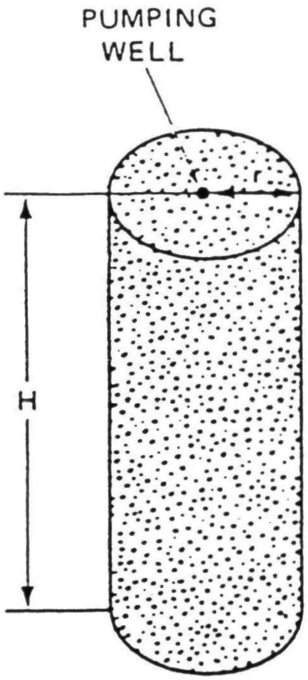
- simple to apply, easily mapped and verified
- requires limited amount of data, but provides more accurate coverage
- good tie to TOT criterion

DISADVANTAGES

- less accurate in many situations because it does not account for hydrogeological factors that influence contaminant transport

METHODS: CALCULATED FIXED RADIUS

concept is that the wtr comes from outside a cylinder



$$r = \sqrt{\frac{Q\,t}{\pi\, n\, H}} = 1138 \text{ ft}$$

WHERE

Q = Pumping Rate of Well = 694.4 gpm = 48,793,668 ft^3/yr

n = Aquifer Porosity = 0.2

H = Open Interval or Length of Well Screen = 300 ft

t = Travel Time to Well (5 Years)

(Any consistent system of units may be used.)

$$Q\,t = n\,\pi\,H\,r^2$$

$Q\,t$ — VOLUME PUMPED

$n\,\pi\,H\,r^2$ — VOLUME OF CYLINDER modified by aquifer porosity

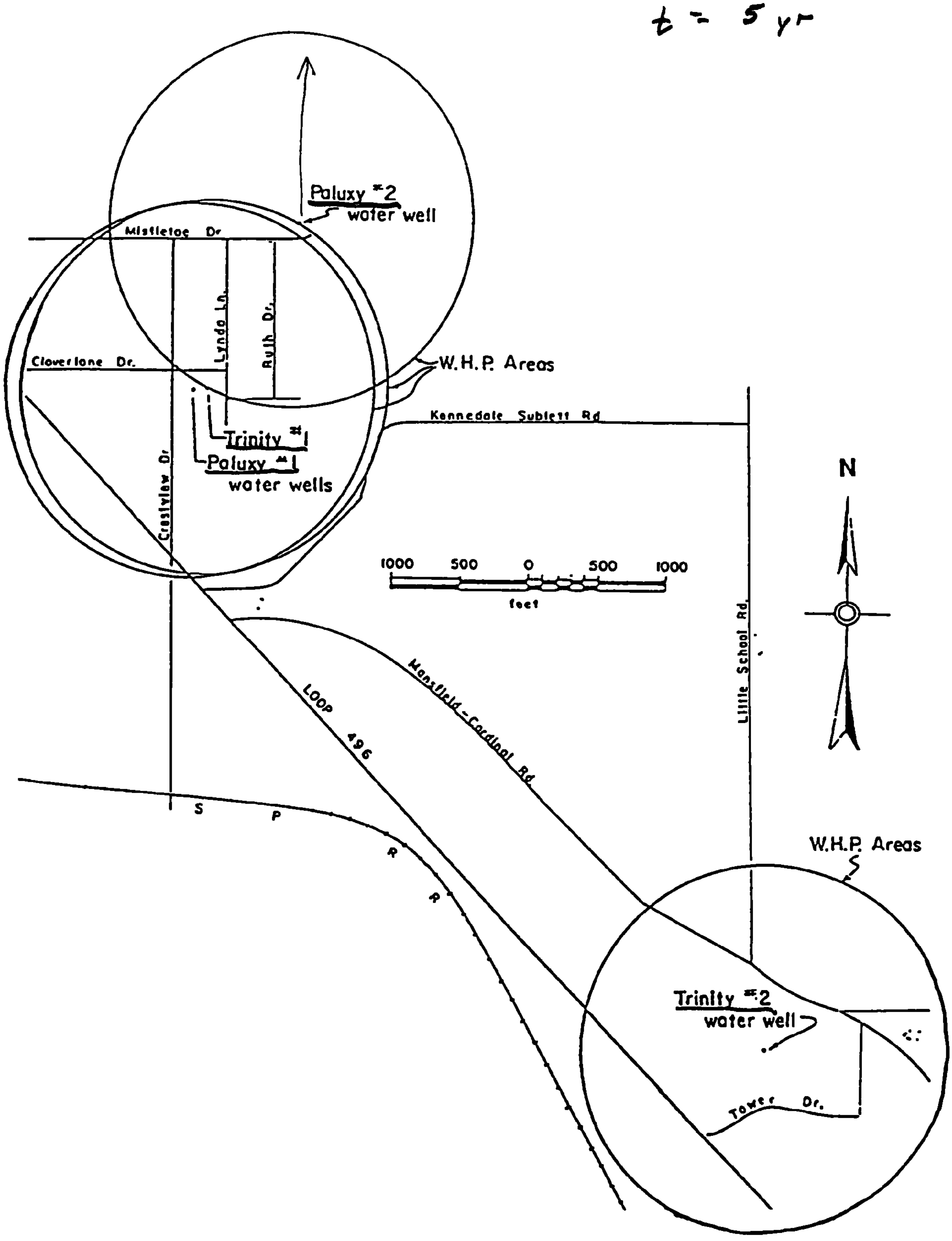
CALCULATED FIXED RADIUS EXERCISE

CALCULATED FIXED RADIUS EXERCISE

- KENNEDALE, TEXAS

- FOUR PUBLIC WATER-SUPPLY WELLS LOCATED IN CONFINED AQUIFER

- VOLUMETRIC FLOW EQUATION AND FIVE YEAR TOT CRITERION THRESHOLD USED TO DELINEATE WHPAS



CITY OF KENNEDALE WELLHEAD PROTECTION AREAS

Slide 4.14

CITY OF KENNEDALE PUMPING AND WATER-WELL DATA

WELL	SCREEN LENGTH		PUMPING RATE
Paluxy #1	80 ft	600	4,520,788.8 ft^3/yr
Paluxy #2	80 ft		2,966.123 ft^3/yr
Trinity #1	175 ft	707	13,756,858.3 ft^3/yr
Trinity #2	175 ft		28,953,048.1 ft^3/yr

Aquifer Porosity = .25 Time of Travel = 5 years

Solutions:

Paluxy #1 $$r = \left[\frac{(4,520,789\ ft^3/yr)\ (5\ yr)}{\pi\ (.25)(80\ ft)} \right]^{1/2} = 600\ ft$$

Paluxy #2 $$r = \left[\frac{(2,966,123\ \ ft^3/yr)\ (5\ yr)}{\pi\ (.25)(80\ ft)} \right]^{1/2} = 486\ ft$$

Trinity #1 $$r = \left[\frac{(13,756,858\ ft^3/yr)\ (5\ yr)}{\pi\ (.25)(175\ ft)} \right]^{1/2} = 707\ ft$$

Trinity #2 $$r = \left[\frac{(7,581,805\ ft^3/yr)\ (5\ yr)}{\pi\ (.25)(175\ ft)} \right]^{1/2} = 525\ ft$$

SIMPLIFIED VARIABLE SHAPES METHOD

WHPA DELINEATION METHODS

1) ARBITRARY FIXED RADIUS

2) CALCULATED FIXED RADIUS

3) SIMPLIFIED VARIABLE SHAPES

4) ANALYTICAL METHODS

5) HYDROGEOLOGIC MAPPING

6) NUMERICAL FLOW / TRANSPORT MODELS

SIMPLIFIED VARIABLE SHAPES METHOD

DESCRIPTION

Delineation using "standardized forms" generated with analytical methods, with flow boundaries and TOT used as criteria

ADVANTAGES

- if the "standardized forms" have previously been developed for the region, delineation is fast, requires limited site - specific data and little technical expertise

- offers more refined analysis than the fixed-radii methods, with only a moderate increase in cost

one set of std. shapes; state-wide applying

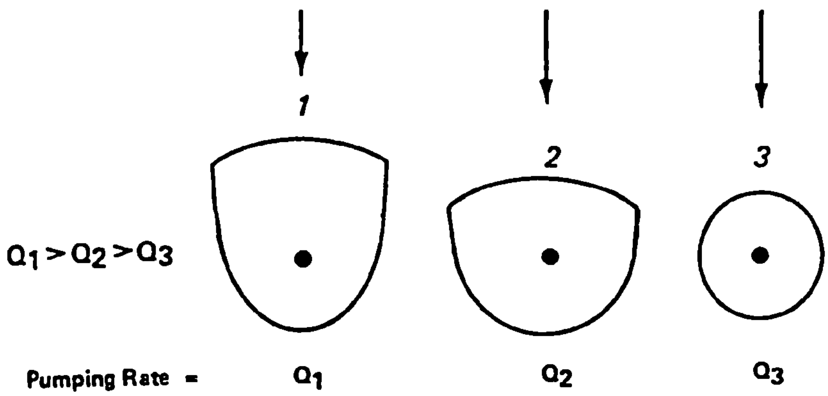
DISADVANTAGES

- this method results in inaccurate delineation if site conditions depart from local hydrogeological trends

- if "standardized forms" have not already been developed in the region in which the site is located, the cost of generating the forms ~~is~~ may be considerable as it requires significant site-specific data collection

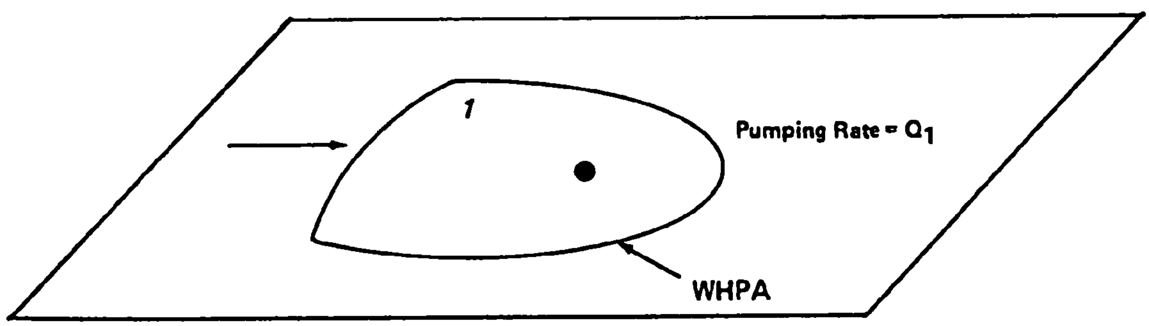
WHPA Delineation Using Simplified Variable Shapes Method

STEP 1: DELINEATE STANDARDIZED FORMS FOR CERTAIN AQUIFER TYPE



- Various standardized forms are generated using analytical equations using sets of representative hydrogeologic parameters.
- Upgradient extent of WHPA is calculated with TOT equation; downgradient with uniform flow equation.

STEP 2: APPLY STANDARDIZED FORM TO WELLHEAD IN AQUIFER TYPE



- Standardized form is then applied to well with similar pumping rate and hydrogeologic parameters.

LEGEND:

● Pumping Well

↓ Direction of Ground-water Flow

Slide 4.20

NOT TO SCALE

4. FIXED RADII AND SIMPLIFIED VARIABLE SHAPES METHODS

4.1 INTRODUCTION

The fixed radius methods are the simplest class of WHPA delineation techniques. The methods involve defining a circular area, centered on the well or wellfield, within which the ground-water supply is to be protected.

The method used to establish the radius of the circular area distinguishes the two techniques. The arbitrary radius is based on very generalized hydrogeologic considerations or expert judgement. The resulting circle is then circumscribed about a well or wellfield without explicitly considering site-specific aquifer properties or pumping rate. The calculated fixed radius method considers pumping rate and incorporates some information about the aquifer in determining the size of the delineated circle.

Simplified variable shapes are developed using more sophisticated analytical techniques, but once the standard set of shapes has been computed they are applied as simply as are the circles used in the fixed radii methods. The following sections describe each method, advantages and disadvantages, and field cases in which the methods have been used to delineate WHPAs.

4.2 ARBITRARY FIXED RADIUS METHOD

Description

The arbitrary fixed radius method is the simplest method used to delineate WHPAs. It involves drawing a circle of specified radius around a well being protected (Slide 4.4). The radius selected to delineate a WHPA may be arbitrarily selected. It may be based on state or local regulations, very generalized hydrogeologic considerations, and/or professional judgement. For example, the radius selected could be based on distances previously chosen using different delineation methods in similar hydrogeologic settings.

Advantages

The arbitrary fixed-radius method is an inexpensive and simple way to apply the distance criterion. It can be completed quickly, is easily verified in the field, and requires little technical expertise. This method can be adopted as a temporary measure in the early stages of a particular WHP program until a time when a more sophisticated approach can be adopted and/or more detailed hydrogeologic data are available. The approach can be adequately protective if large distance thresholds are chosen, thus, compensating somewhat for its lack of hydrogeologic precision.

Disadvantages

Due to the lack of scientific basis for choosing a specific radius, there is much uncertainty in the application of the arbitrary fixed radius method. This is especially true in areas where the hydrogeology is anisotropic and heterogeneous, and in areas where flow boundaries are located. As a result, this method may tend to over- or under-protect well recharge areas. This can lead to increased costs of purchasing land to be included in a WHPA, and to insufficient protection of the zone of contribution of a well. In addition, the lack of technical justification for the distance criterion gives application of the arbitrary fixed radius method low defensibility.

Example

In the State of Florida, as part of a proposed law to protect public water supplies that have an average daily ground-water withdrawal of at least 100,000 gallons, an area with a 200-foot radius is to be delineated (Slide 4.5). The area is established to restrict any activities that could contaminate the ground water.

As part of the Aquifer Land Acquisition Program in Massachusetts, the State uses the arbitrary-fixed radius method to delineate the first of three zones designed to control land use in areas surrounding public water-supply wells (see Case Study B.5). The area consists of a circle with a 400-foot radius that is off-limits to activities that could possibly contaminate the ground water (Slides 4.6 and 4.7).

4.3 CALCULATED FIXED RADIUS METHOD

Description

Delineating a WHPA using the calculated fixed radius method involves drawing (mapping) a circle with a radius specified by, for example, a TOT criterion threshold. The radius is calculated using an analytical equation based on the volume of ground water that will be drawn to a production well in the specified time (Slide 4.11). The time period is one that will allow for cleanup of contaminants threatening the well, or allows for adequate dilution or dispersion of contaminants.

The analytical equation used to calculate the radius of the WHPA depends on the data available. For example, if the effective porosity of the aquifer is known, a simple volumetric equation is used. If pumping-test data are available for an unconsolidated, unconfined aquifer, the radius is determined using the Theis equation.

Advantages

This method is relatively quick and inexpensive compared to the more complicated delineation methods. It requires little technical expertise and allows for the delineation of a number of WHPAs in a short period of time. The calculated fixed radius method requires more funds than the arbitrary fixed radius method because it requires more hydrogeologic data, but it provides greater accuracy and is just as simple to map.

Disadvantages

The calculated fixed radius method may be inaccurate in many situations because it does not account for hydrogeologic factors that influence contaminant transport such as aquifer anisotropy and heterogeneity, and the presence of flow boundaries.

Example

The Florida Department of Environmental Regulations requires that Zone II of a WHPA be defined as a circle of a radius calculated using the volumetric equation with a 5 year time-of-travel criterion (see Case Study B.4). The volumetric equation:

$$Qt = n\pi Hr^2$$

or

$$r = \left[\frac{Qt}{n\pi H}\right]^{\frac{1}{2}}$$

where,

Q = well pumping rate (ft^3/yr)
n = aquifer porosity
H = open interval (ft)
t = travel time to well (yrs)
r = WHPA radius (ft)

4.4 CALCULATED FIXED RADIUS EXERCISE

Background

The Texas Water Commission (TWC) delineated WHPAs for four public water-supply wells in the City of Kennedale, Texas (Slide 4.14). The TWC selected a 5 year time-of-travel as the threshold criterion, and the calculated fixed radii method was chosen to delineate the WHPAs. The volumetric flow equation was used to calculate the radius of each WHPA and an additional buffer zone was added to each calculated radius, bringing the WHPA to a quarter mile radius.

Hydrogeologic Setting

The City of Kennedale derives its water from the Trinity Aquifer, which is comprised of two water-producing units, the Paluxy and Twin Mountains Formations. The two zones are separated by a confining unit, the Glen Rose Formation. The entire aquifer is under confined conditions, lying under 600 feet of marl, clay, and limestone.

The regional ground-water velocity within the Trinity Aquifer is estimated to be 2 to 3 feet per year. In the vicinity of Kenndale, where extensive pumping has lowered the piezometric surface and induced larger hydraulic gradients, ground water may be moving 200 to 300 feet per year towards the pumping centers.

Problem

The hydrogeologic and pumping data used in calculating the radii are provided in Slide 4.15. Using the volumetric flow equation,

$$r = \left[\frac{Qt}{n \pi H} \right]^{\frac{1}{2}}$$

where,

r = protection area radius (ft)
Q = pumping rate of well (ft^3/yr)
t = time of travel (years)
n = porosity of aquifer
H = length of well screen (ft)

Calculate the radius for each well.

4.5 SIMPLIFIED VARIABLE SHAPES METHOD

Description

The simplified variable shapes method for WHPA delineation provides an alternative to the more simplistic fixed radii methods and the more complex analytical methods. It provides a middle ground between these two types of methods in that its development incorporates analytical methods while its implementation is similar to that of the fixed radii methods.

In the simplified variable shapes method, "standardized forms" (Slide 4.20) are generated using analytical methods, such as the uniform flow equation (see Section 5.4), with both flow boundaries and TOT used as criteria. This method attempts to simplify implementation by selecting a few representative shapes from the large array of potential possibilities. The appropriate "standardized form" is selected for hydrogeologic conditions similar to those found at the wellhead. The standardized form is then oriented around the well according to ground-water flow patterns. The variable shapes are calculated by first computing the distance to downgradient and lateral extents of the ground-water flow boundaries around a pumping well, and then using a TOT criterion to calculate the upgradient extent. Standardized forms for various criteria are calculated for different sets of hydrogeologic conditions. Input data for the creation of the standardized shapes include basic hydrogeologic parameters and well pumping rates.

Advantages

Advantages of the simplified variable shapes method are that it can be easily implemented once the shapes of the standardized forms are calculated, and that it requires a relatively small amount of field data. In addition, relatively little technical expertise is required to do the actual delineations. Generally, the only information required to apply the shapes to a particular well or well field, once the standardized forms are delineated, are the well-pumping rate, material type, and the direction of ground-water flow. This method offers a more refined analysis than the fixed radius method, with only a modest increase in cost; significant data collection is required (compared to calculated fixed radii) in order to obtain the set of representative hydrogeologic parameters needed to calculate the shapes of the standardized forms and to determine the overall ground-water flow velocities.

Disadvantages

The simplified variable shapes method may not be accurate in areas with many geologic heterogeneities and complex hydrologic boundaries. If flow directions near a well differ from those inferred from regional or subregional assessments, erroneous coverage and insufficient protection result.

Example

An example in which the simplified variable shapes method was used to delineate the highly prolific chalk aquifer in Southern England can be found in "Guidelines for Delineation of Wellhead Protection Areas" (U.S. EPA, 1987a).

ANALYTICAL DRAWDOWN METHODS

WHPA DELINEATION METHODS

1) ARBITRARY FIXED RADIUS

2) CALCULATED FIXED RADIUS

3) SIMPLIFIED VARIABLE SHAPES

4) ANALYTICAL METHODS — DRAWDOWN

5) HYDROGEOLOGIC MAPPING

6) NUMERICAL FLOW / TRANSPORT MODELS

ANALYTICAL DRAWDOWN METHODS

DESCRIPTION

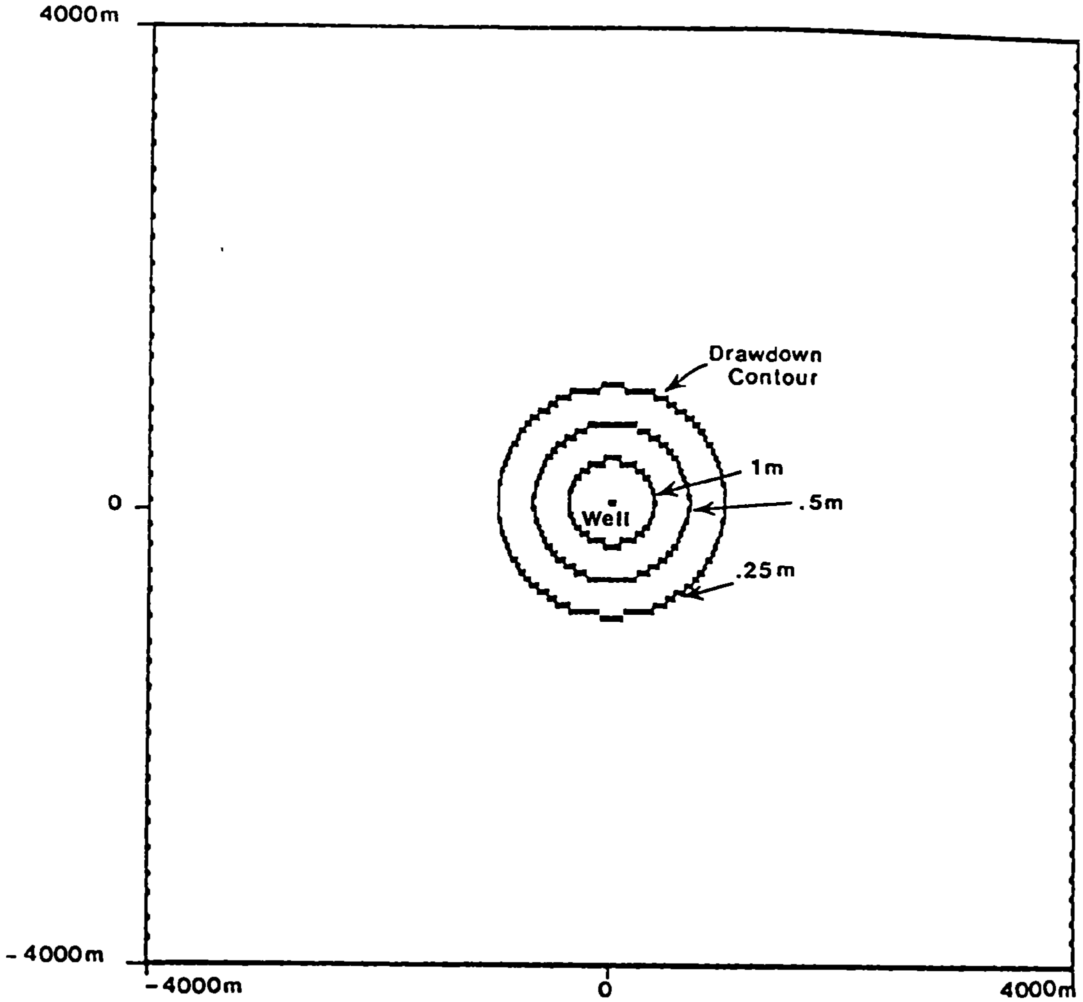
Delineation of a WHPA based on specified value of drawdown criterion

ADVANTAGES

- delineation based on site-specific hydrologeological data
- these methods provide accurate coverage in cases when the ZOI of a well is similar to the ZOC (i.e. , flat water-table conditions)

DISADVANTAGES

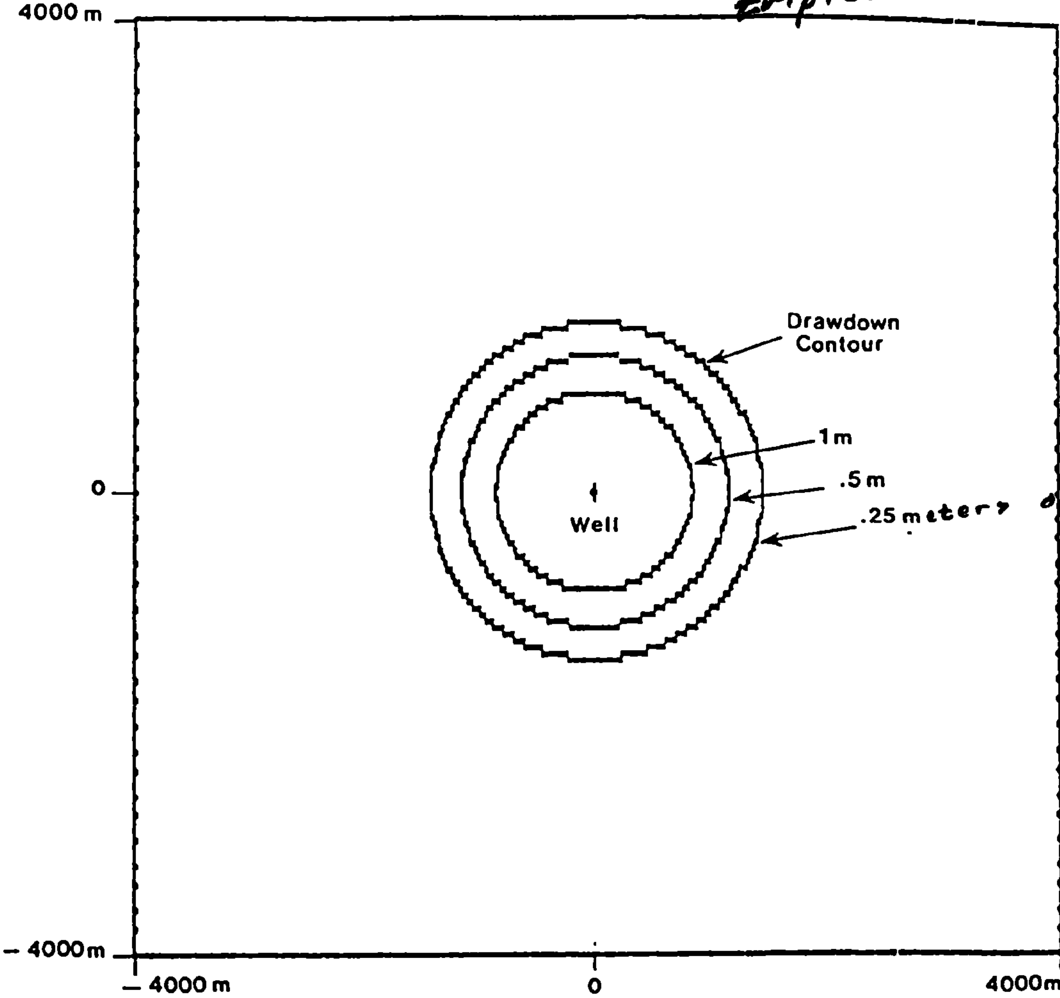
- these methods may be inaccurate in sloping water-table and anisotropic conditions, where the ZOI of a well does not closely resemble the ZOC
- may overprotect downgradient, and underprotect upgradient



LOW PUMPING RATE

- Pumping rate = 1500 m^3/day
- Transmissivity = 250 m^2/day
- Storage coefficient = .1
- Maximum drawdown = 8.8m
- Duration of pumping = 180 days

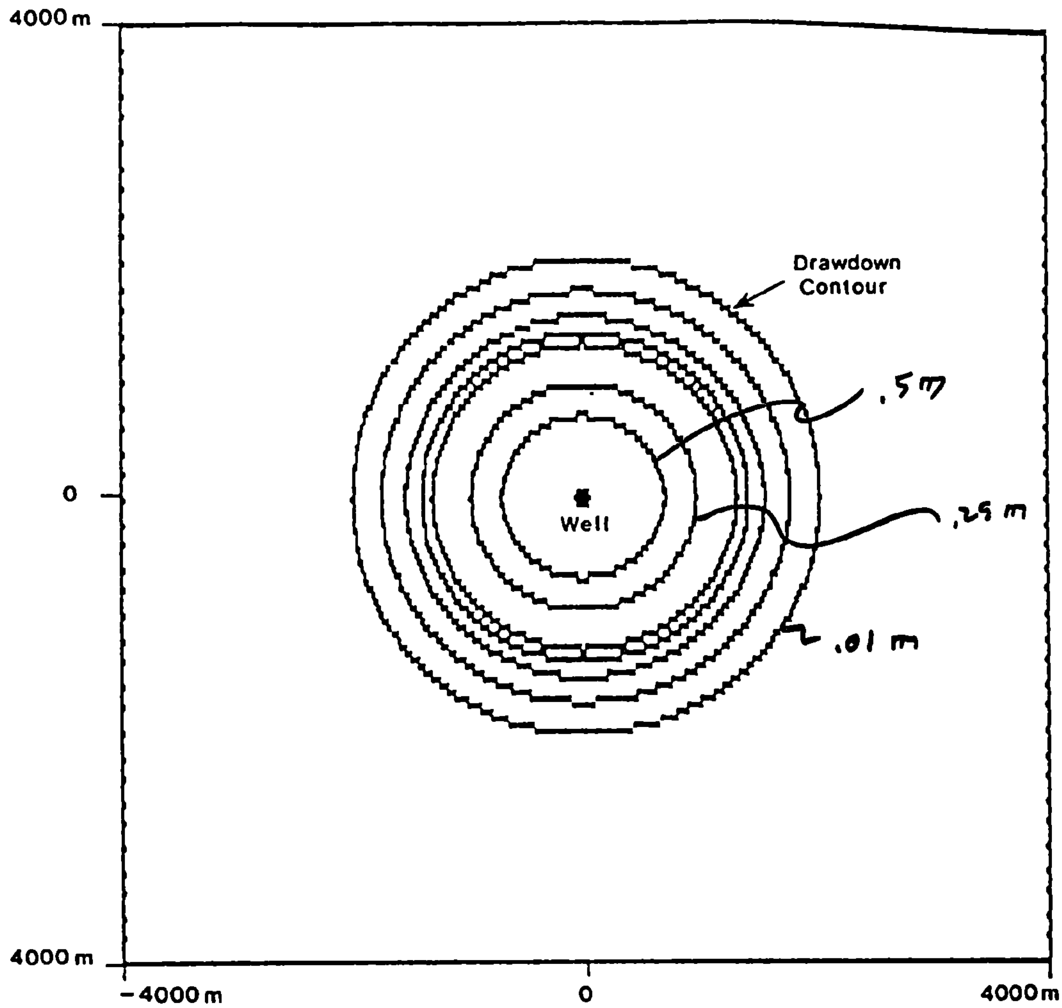
here the pumping rate is tripled.



harder the pumping rate the larger the ZOI

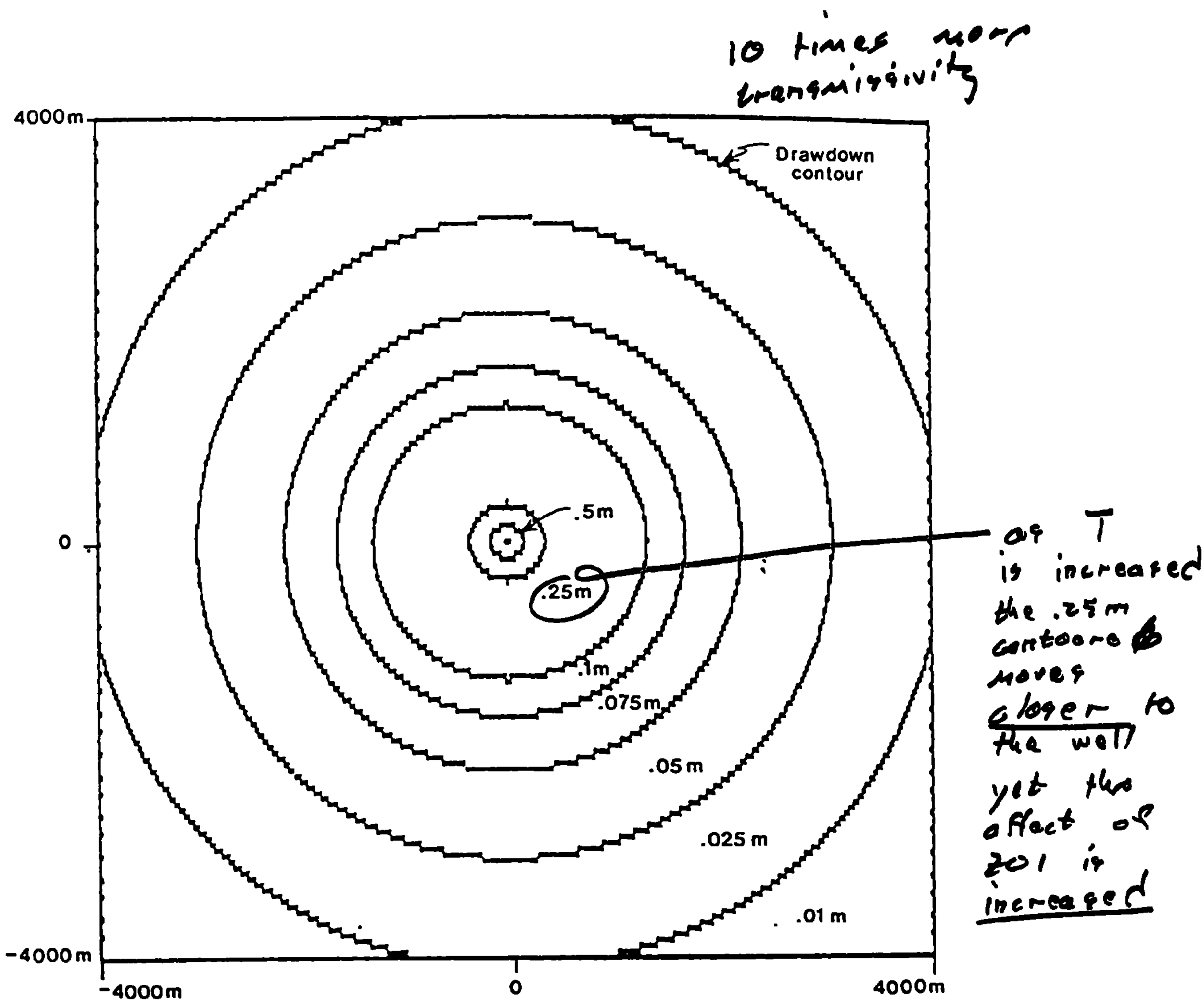
HIGH PUMPING RATE

- Pumping rate = 4500 m^3/day
- Transmissivity = 250 m^2/day
- Storage coefficient = .1
- Maximum drawdown = 26.4m
- Duration of pumping = 180 days



LOW TRANSMISSIVITY

- Pumping rate = 1500 m^3/day
- Transmissivity = 200 m^2/day
- Storage coefficient = .1
- Maximum drawdown = 10.87m
- Duration of pumping = 180 days
- Drawdown contours: .01m, .025m, .05m, .075m, 1m, .25m, .5m



HIGH TRANSMISSIVITY

- Pumping rate = 1500 m^3/day Q remains constant
- Transmissivity = 2000 m^2/day
- Storage coefficient = .1
- Maximum drawdown = 1.22m
- Duration of pumping = 180 days

DRAWDOWN METHOD EXAMPLE
OAKLEY, KANSAS ref Appendix B

AQUIFER DESCRIPTION

- Unconfined Aquifer
- Calcareous Sandstone with some clay, silt, gravel, cobbles and boulders
- Transmissivity (T) = 20,000 gpd/ft
- Storativity (S) = .12
- Gradient (I) = 10 ft/mile to the east

MODEL DESCRIPTION

- Two Dimensional Finite Difference Model
- 50 x 50 Grid
- Node Spacing = 660 feet spacing of the grid
- Program locates point at which 0.05 feet of drawdown is achieved
- Variable Pumping Rate of wells is averaged out over one year

RESULTS

Program calculated 0.05 feet of drawdown at a radius of 10, 500 ft

THEIS EQUATION

note how this compares with the more sophisticated model Oakley, Ka. d.d.

$$s = \frac{114.6\,Q}{T}\,W(u)$$

$$u = \frac{1.87\,r^2 S}{Tt}$$

s= drawdown (feet) know what we want.
Q= pumping rate (gpm)
T= Transmissivity (gpd/ft)
S= Storage Coefficient
r= distance from pumped well to observation well (ft)
t= time (days) = 360 d.
W(u)= Well Function (Appendix C)

so we can rearrange the Theis eq & solve for r

INPUT DATA:

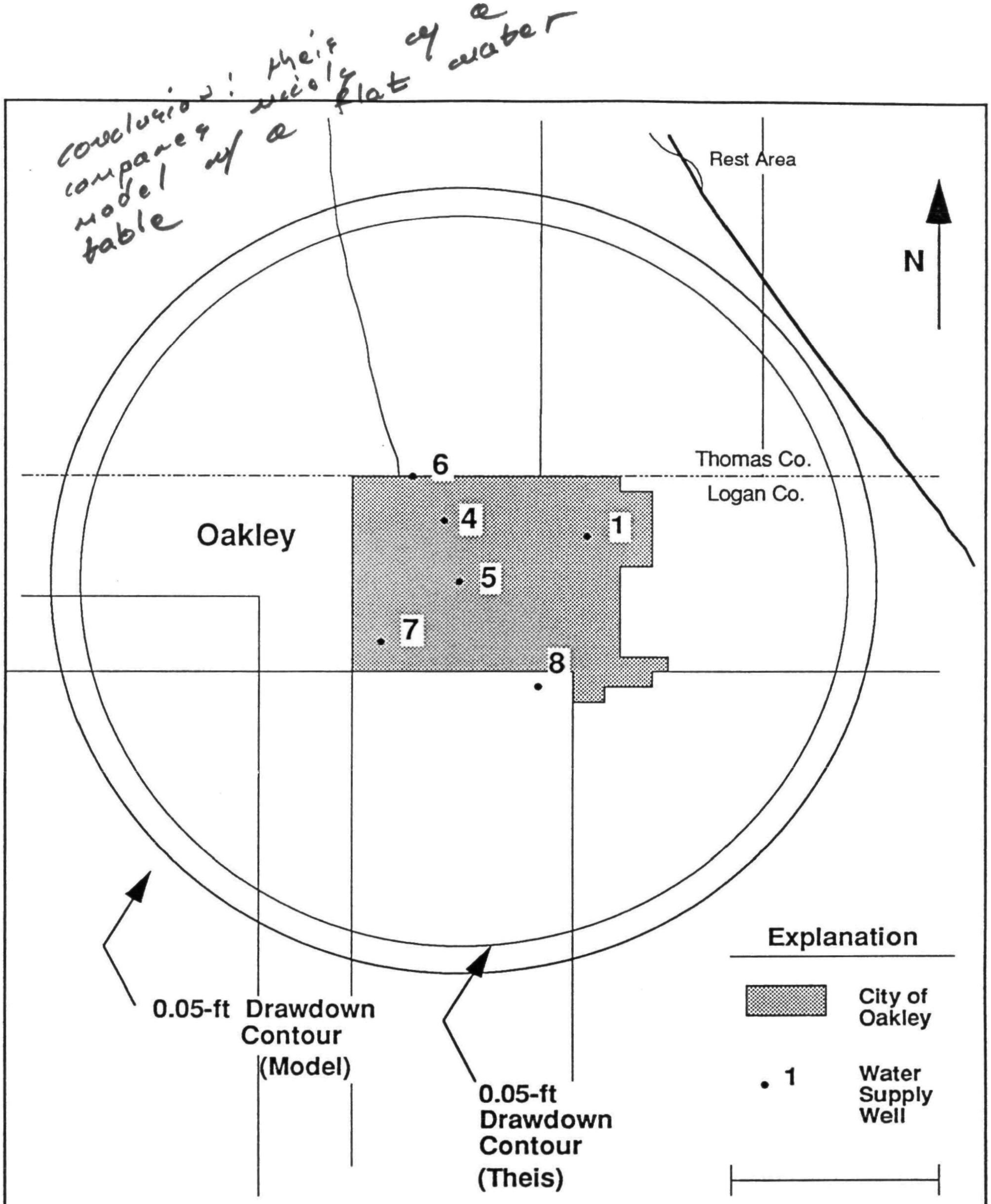
Q = 676 gpm
T = 20,000 gpd/ft
S = .12

Use the Theis Equation, and iterate to find the 0.05 ft drawdown point.

1. Guess a value of r
2. Calculate u for that radius
3. Read W(u) from Appendix C
4. Calculate drawdown from Theis Equation
5. Estimate a new raduis that will yield a drawdown closer to .05 ft
6. Go to step 2.
7. Repeat until you reach a radius that yields a drawdown of 0.05 ft.

RESULTS

Theis equation calculated 0.05 feet of drawdown at 9,880 feet from center of wellfield



For another method:
THWELLS - Paul van der Heijde

DRAWDOWN COMPARISON FOR OAKLEY, KANSAS

ANALYTICAL TIME-OF-TRAVEL METHODS

as a general rule of thumb you want to shoot for drawdown of 0.1' to 1.0'

WHPA DELINEATION METHODS

1) ARBITRARY FIXED RADIUS

2) CALCULATED FIXED RADIUS

3) SIMPLIFIED VARIABLE SHAPES

4) ANALYTICAL METHODS — TIME-OF-TRAVEL

5) HYDROGEOLOGIC MAPPING

6) NUMERICAL FLOW / TRANSPORT MODELS

what happens w/ an anisotropic aquifer: T is one value in one direction but diff in another direction (changing conductivity or transmissivity, depending upon direction)

ANALYTICAL TIME - OF - TRAVEL METHODS

DESCRIPTION

WHPA delineation based on the maximum time for a contaminant to reach a well based on regional ground-water advection patterns and velocities

ADVANTAGES

- these methods incorporate varying amounts site - specific hydrogeological data
- considers physical processes and flow velocities

DISADVANTAGES

- increased data requirements result in increased costs

TIME OF TRAVEL METHOD CASE STUDY
Brookings County, South Dakota

Brookings County, South Dakota

- Water supply wells draw water from Big Sioux Aquifer
- ZOCs determined for wells; no WHPAs delineated
- TOT equation used to define upgradient extent of ZOC
- Five year and ten year TOT distances computed
- Darcy's Law used to compute TOT distance based on regional flow 1gradient (effect of pumping well was neglected)

EQUATION

Darcy's Law (pore water velocity)

$$v = \frac{Ki}{n}$$

K= Hydraulic Conductivity
n= porosity
i= hydraulic gradient

Velocity Definition

$$v = \frac{x}{t}$$

x= distance
t= time (time of travel in this case) in days

Final Equation

$$x = vt = \frac{Kit}{n}$$

TIME OF TRAVEL METHOD CASE STUDY
Brookings County, South Dakota (Cont.)

Bruce Well # 1: Aquifer Data

- Aquifer Material: Unconsolidated glacial outwash (sand , gravel)
- Aquifer Thickness: 11 feet
- Aquifer Porosity: 0.20
- Hydraulic Conductivity: 670 ft/day
- Hydraulic Gradient: 0.0017 – this assumes you don't have a pumping well. This is just the natural gradient. Therefore, this isn't as conservative

5 Year TOT Distance:

$$x = \frac{Kit}{n} = \frac{(670 \text{ ft/day})(0.0017)(1825 \text{ days})}{0.20}$$

= 10,393 feet ≈ 2 miles

10 Year TOT Distance:

$$x = \frac{Kit}{n} = \frac{(670 \text{ ft/day})(0.0017)(3650 \text{ days})}{0.20}$$

= 20,786 feet ≈ 4 miles

TIME OF TRAVEL METHOD CASE STUDY
Oakley, Kansas

Oakley, Kansas

- Water-supply wells draw water from Ogallala Formation
- 2 Types of WHPAs delineated –

  Overall wellfield protection area: 0.05 ft drawdown contour (shown in previous page) } less stringent restrictions

  Individual well protection area: 180-day time-of-travel distance } more stringent restrictions
  This way to establish another (2nd) zone for a 2nd level of protection

- 180-day time-of-travel distance computed using Darcy's Law for pore velocity based on gradient across short sections of aquifer moving radially outward from well (effect of pumping well considered) Thus changing the gradient each time.
- Aquifer Data: (this is just one well)

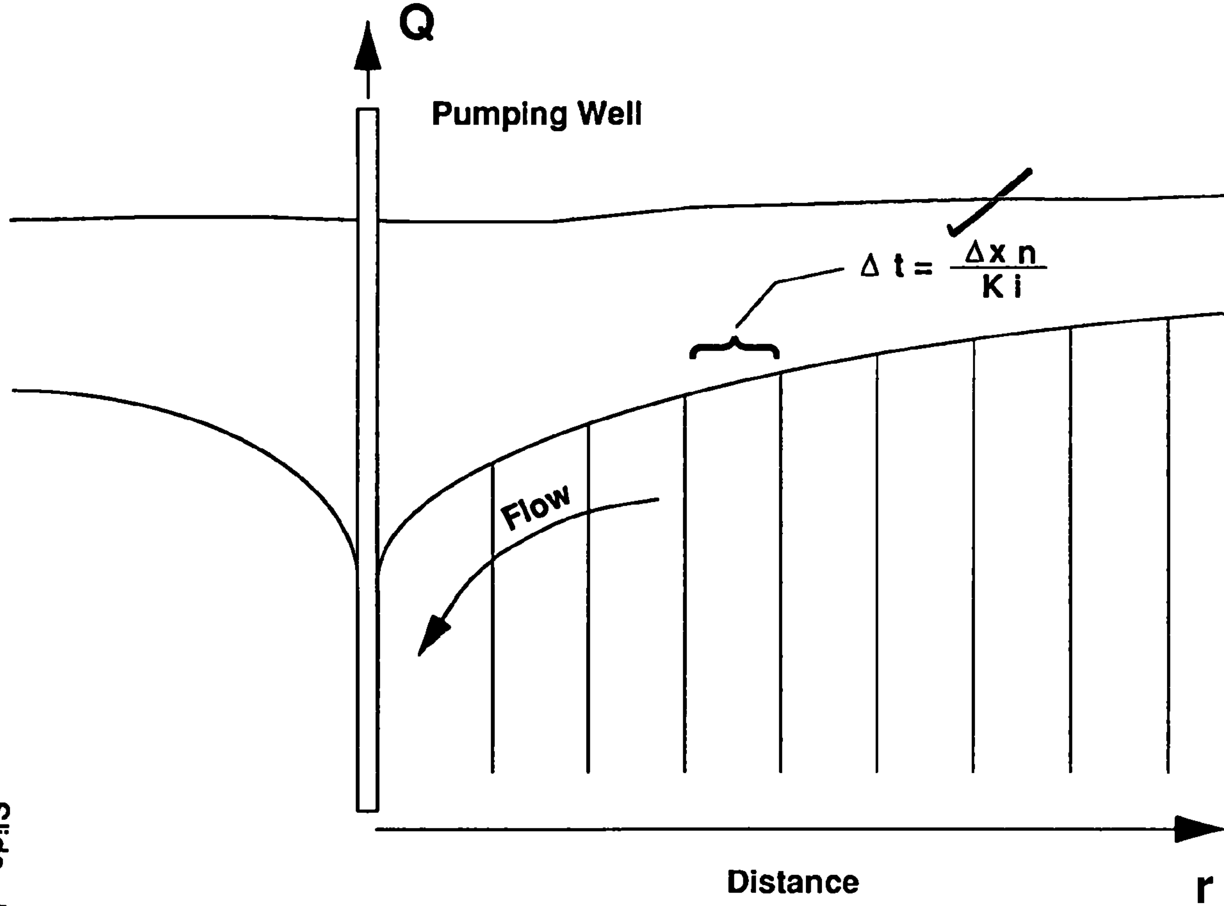
  $T = 20{,}000$ gpd/ft $K = 235$ gpd/ft^2

  $S = 0.12$ $n = 0.15$

  $Q = 300{,}000$ gp~~m~~d ~~(208.3 gpm)~~ $t = 365$ days

  $i = 0.002$

DARCY'S LAW APPROACH TO TOT CALCULATION INCORPORATING EFFECTS OF PUMPING WELL



1. Radial distance outward from well is divided into segments and Darcy's Law TOT equation is solved for each segment.

2. Times for successive segments are summed moving outward from the well until selected TOT threshold is reached.

TIME OF TRAVEL METHOD CASE STUDY
Oakley, Kansas (Cont.)

Theis

$$U = \frac{1.87\,S}{T\,t}\,r^2 = \frac{(1.87)(0.12)}{(20{,}000\ \text{gpd/ft}^2)(365\ \text{days})}\,r^2$$

$$U = (3.07 \times 10^{-8})\,r^2$$

go to table

$$s = \frac{114.6\,Q}{T}\,W(u) = \frac{(114.6)(208.3\ \text{gpm})}{20{,}000\ \text{gpd/ft}^2}\,W(u)$$

$$s = 1.194\,W(u)$$

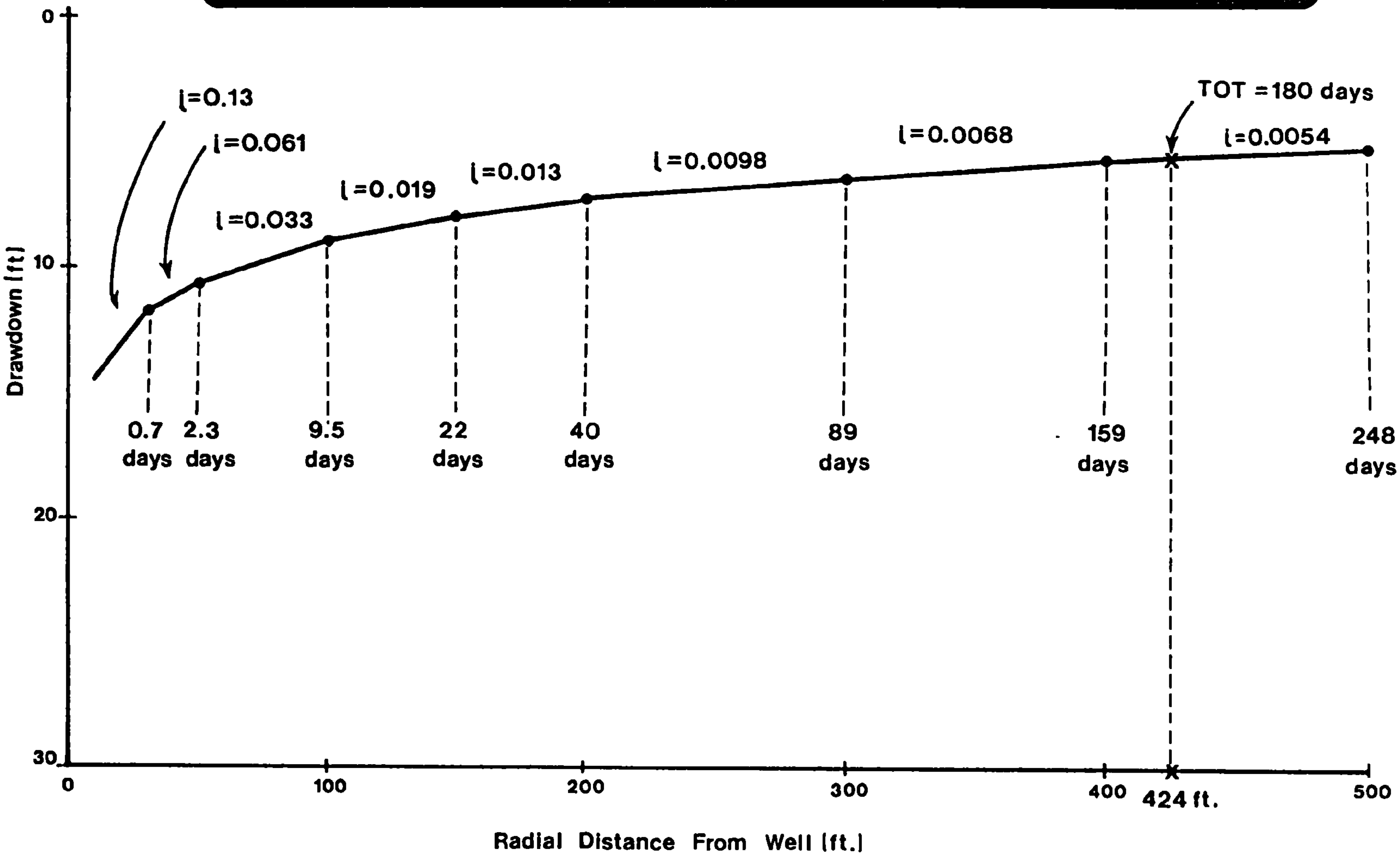
$$v = \frac{\Delta x}{\Delta t} = \frac{K\,i}{n}$$

$$\Delta t = \frac{\Delta x}{v} = \frac{\Delta x\,n}{K\,i} = \frac{(0.15)}{(31.4\ \text{ft/day})}\,\frac{\Delta x}{i}$$

$$\Delta t = (4.77 \times 10^{-3})\,\frac{\Delta x}{i}$$

r (ft)	s (ft)	Δ s (ft)	Δ x (ft)	i	Δ t (days)	Σ t (days)
10	14.46					
30	11.83	2.63	20	0.13	0.74	0.74
50	10.62	1.21	20	0.061	1.6	2.34
100	8.96	1.66	50	0.033	7.2	9.54
150	8.00	0.96	50	0.019	12.5	22.0
200	7.33	0.67	50	0.013	18.4	40.4
300	6.35	0.98	100	0.0098	48.7	89.1
400	5.67	0.68	100	0.0068	70.1	159
500	5.13	0.54	100	0.0054	88.3	248

TIMES-OF-TRAVEL FOR INDIVIDUAL DISTANCE SEGMENTS COMPUTED USING DARCY'S LAW



Slide 5.19

ANALYTICAL ZONE OF CONTRIBUTION METHODS

WHPA DELINEATION METHODS

1) ARBITRARY FIXED RADIUS

2) CALCULATED FIXED RADIUS

3) SIMPLIFIED VARIABLE SHAPES

4) ANALYTICAL METHODS —
ZONE-OF-CONTRIBUTION

5) HYDROGEOLOGIC MAPPING

6) NUMERICAL FLOW / TRANSPORT MODELS

ANALYTICAL ZONE OF CONTRIBUTION METHODS

"RESCU" computer program

DESCRIPTION

Involves delineating recharge areas and subsurface regions through which water that is eventually pumped from the well flows

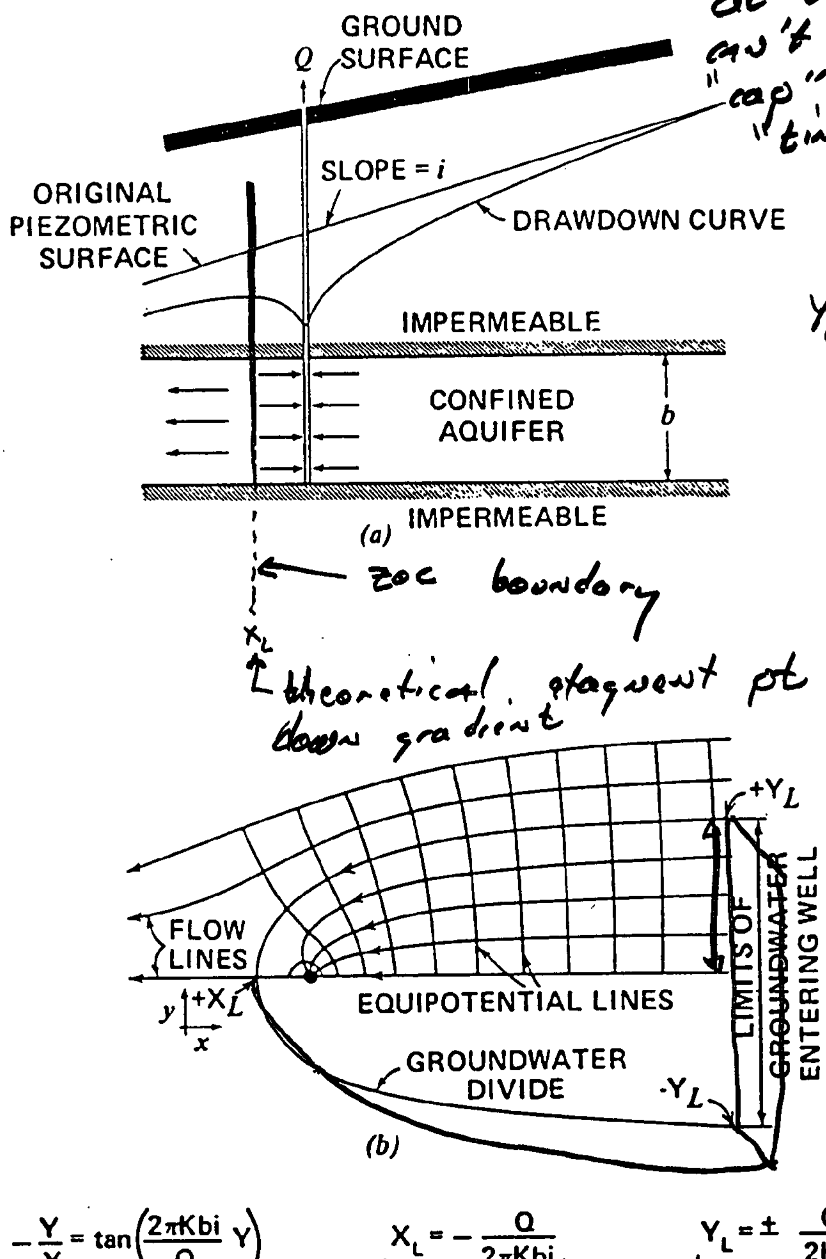
ADVANTAGES

- incorporate a number of site-specific hydrogeological parameters
- provide excellent protection of water supply
- the most accurate of the analytical methods

DISADVANTAGES

- implementation of these methods can be costly due to the significant amount of hydrogeological data required
- mapping of topographic divides, recharge areas, and flow boundaries required

WHPA Delineation Using the Uniform Flow Analytical Model



$$-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q} Y\right)$$

UNIFORM-FLOW EQUATION

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

DISTANCE TO DOWN-GRADIENT NULL POINT

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

BOUNDARY LIMIT

LEGEND:

- ● Pumping Well

Where:
Q = Well Pumping Rate
K = Hydraulic Conductivity
b = Saturated Thickness
i = Hydraulic Gradient
π = 3.1416

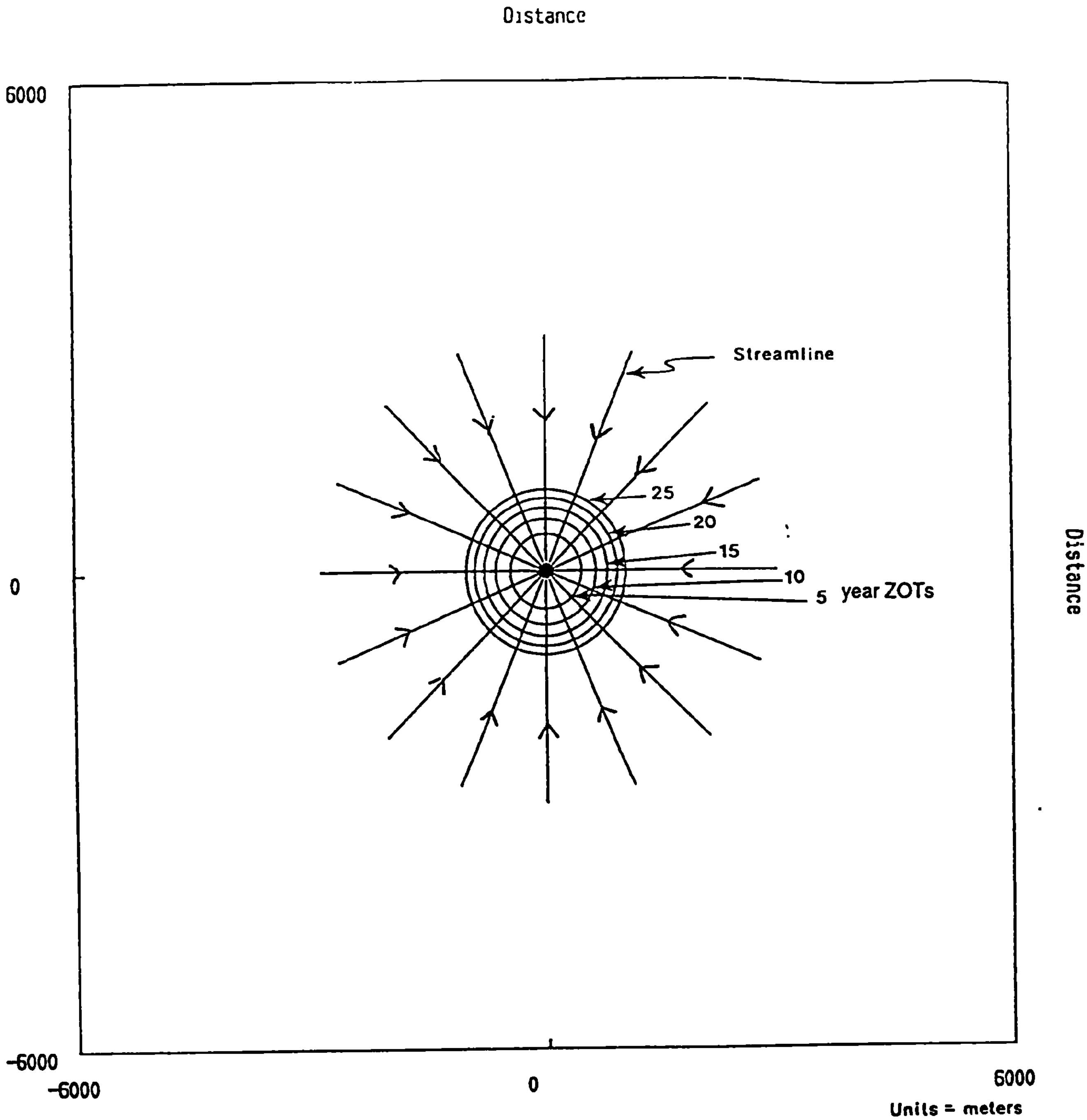
Slide 5.23

SOURCE: Todd, 1980 — also see another ref. in appendix

NOT TO SCALE

no time element in equation. It assumes a steady state so actually Y_L would be at ∞ which you can't do so you "cap" it with a "time-of-travel"

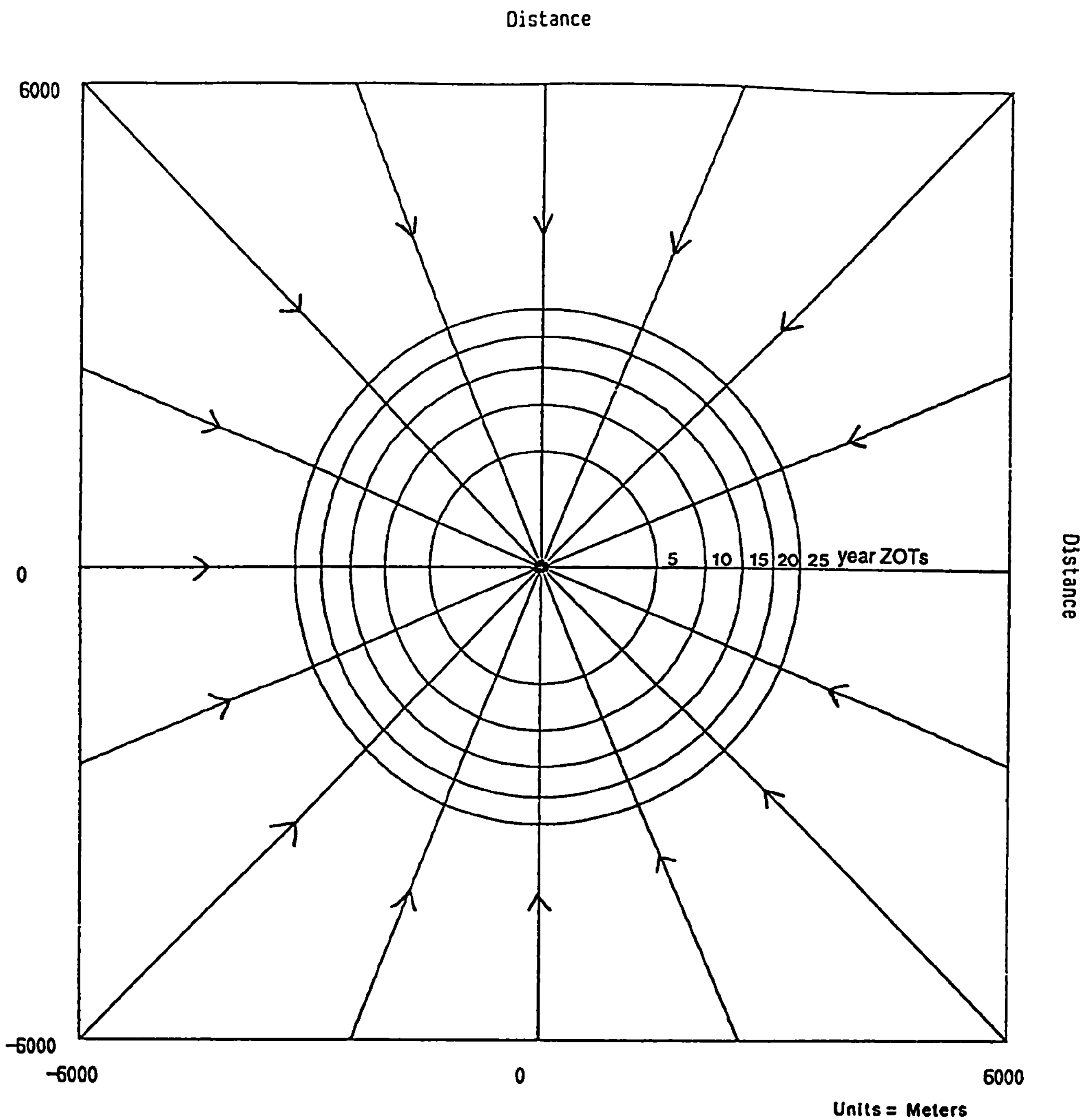
Y_L = dist from ℄ well flow gradient to the outer limits of ZOC



EXAMPLE 1 LOW PUMPING RATE, HORIZONTAL WATER TABLE

DATA

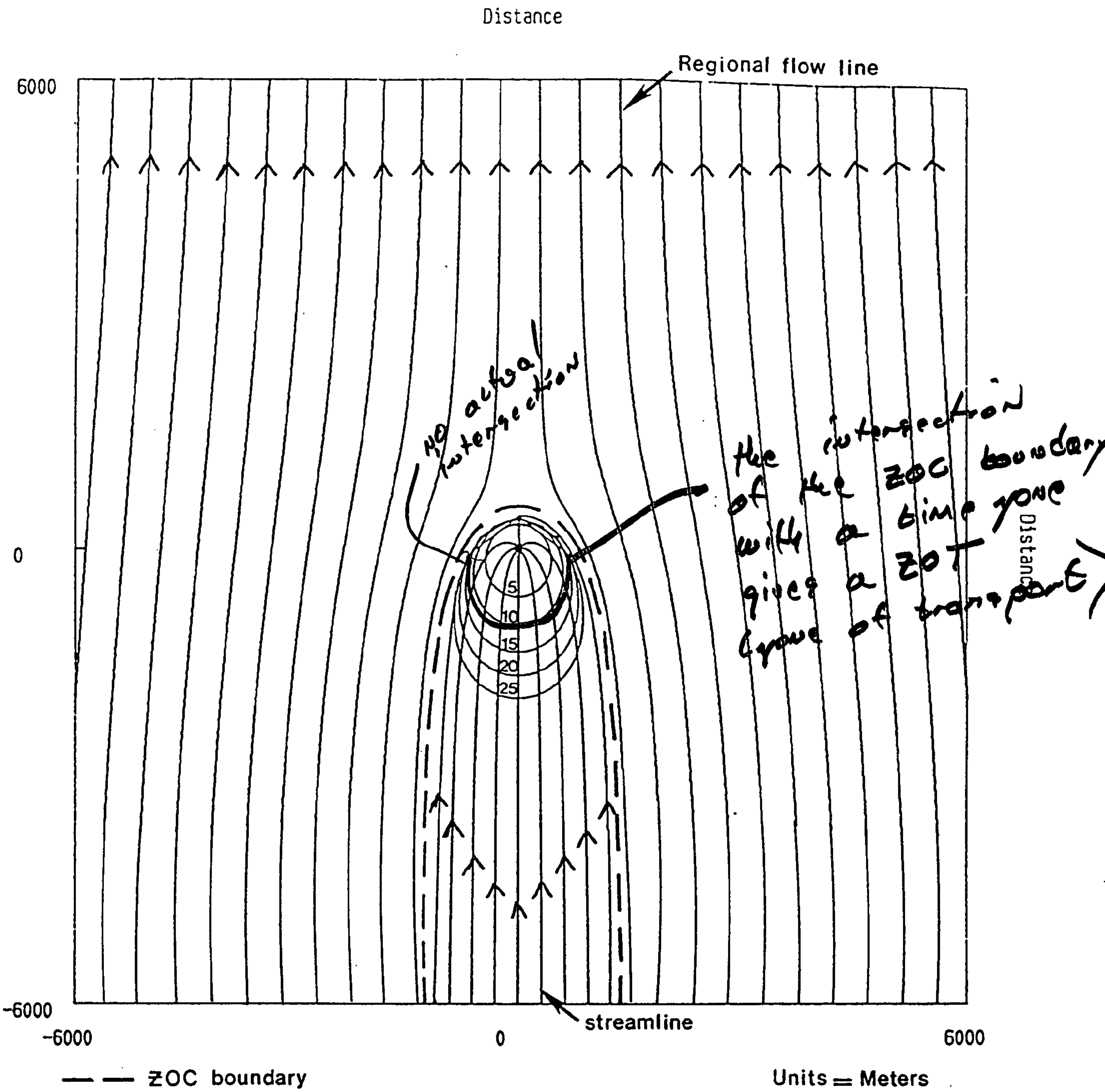
- PUMPING RATE = 15 CUBIC METERS PER HOUR
- REGIONAL HYDRAULIC GRADIENT = 0



EXAMPLE 2 HIGH PUMPING RATE, HORIZONTAL WATER TABLE

DATA

- PUMPING RATE = 150 CUBIC METERS PER HOUR
- REGIONAL HYDRAULIC GRADIENT = 0

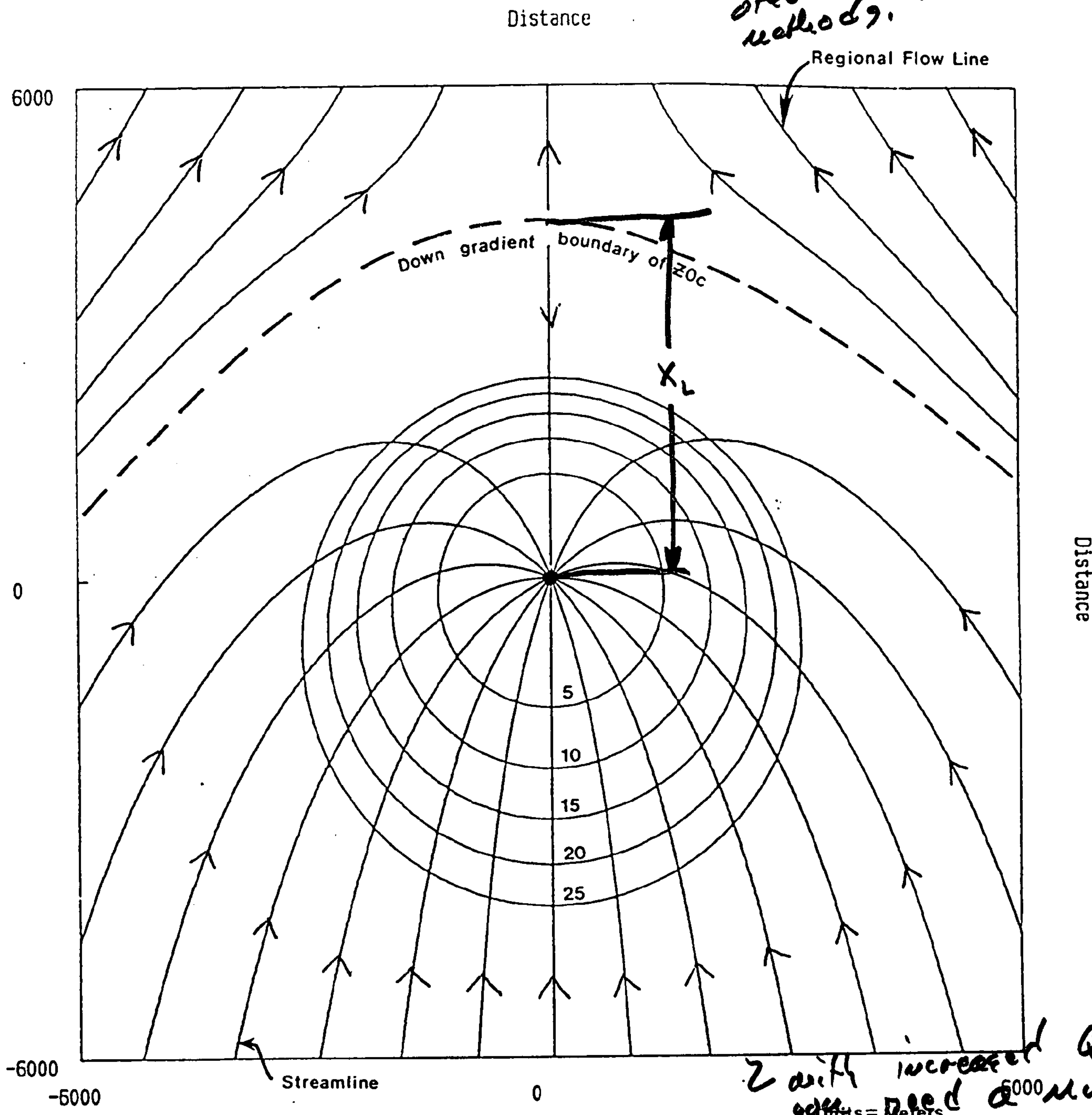


EXAMPLE 3 LOW PUMPING RATE, MODERATELY SLOPING WATER TABLE

DATA

- PUMPING RATE = 15 CUBIC METERS PER HOUR
- REGIONAL HYDRAULIC GRADIENT = .05
- REGIONAL FLOW IS FROM BOTTOM TO TOP OF FIELD

This ignores dispersion like all other analytical methods.



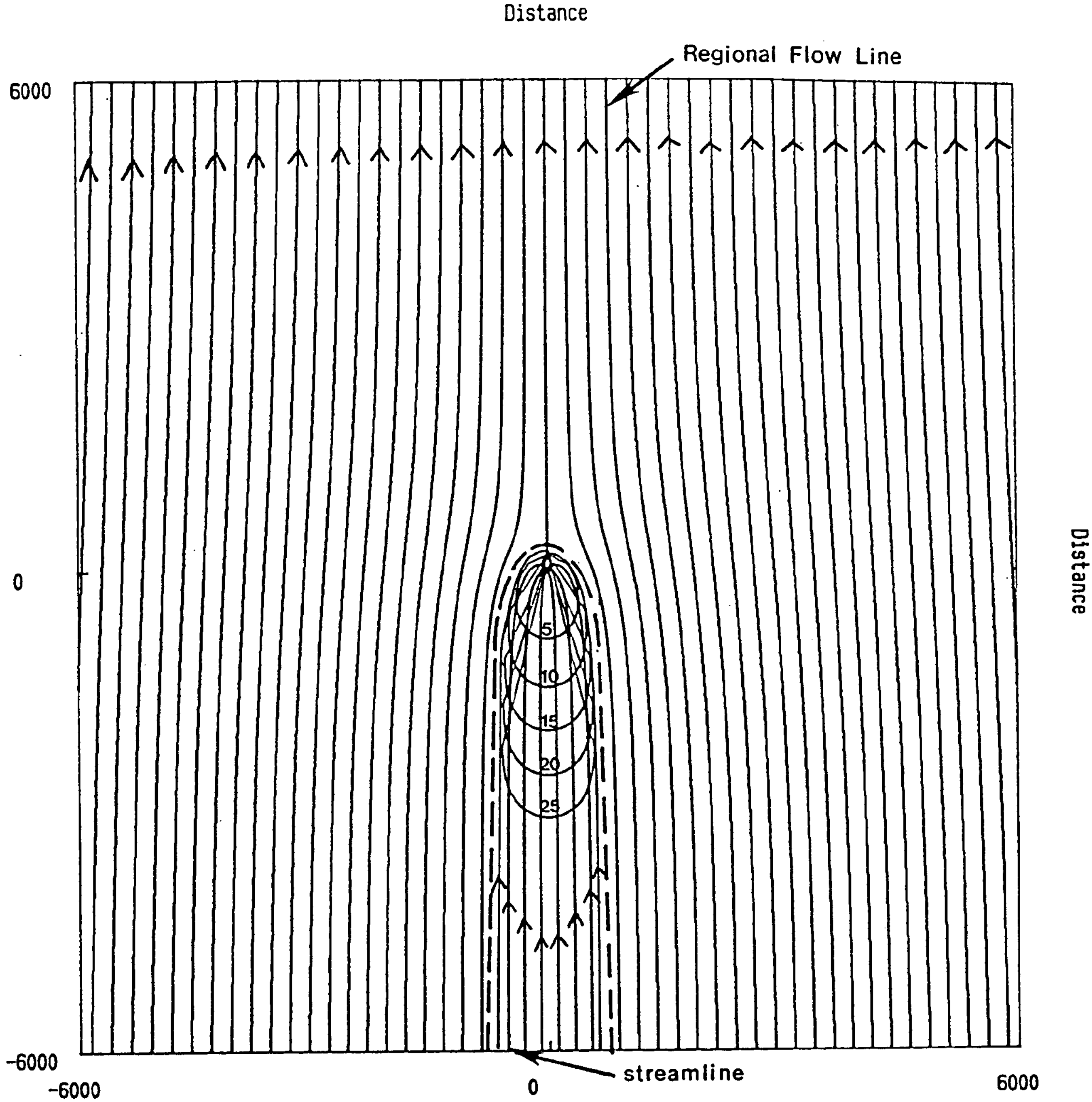
2 with increased Q you need a much larger aquifer area to supply that well

<u>EXAMPLE 4</u> <u>HIGH PUMPING RATE</u>, MODERATELY SLOPING WATER TABLE

<u>DATA</u>

- PUMPING RATE = 150 CUBIC METERS PER HOUR
- REGIONAL HYDRAULIC GRADIENT = .05
- REGIONAL FLOW IS FROM BOTTOM TO TOP OF FIELD

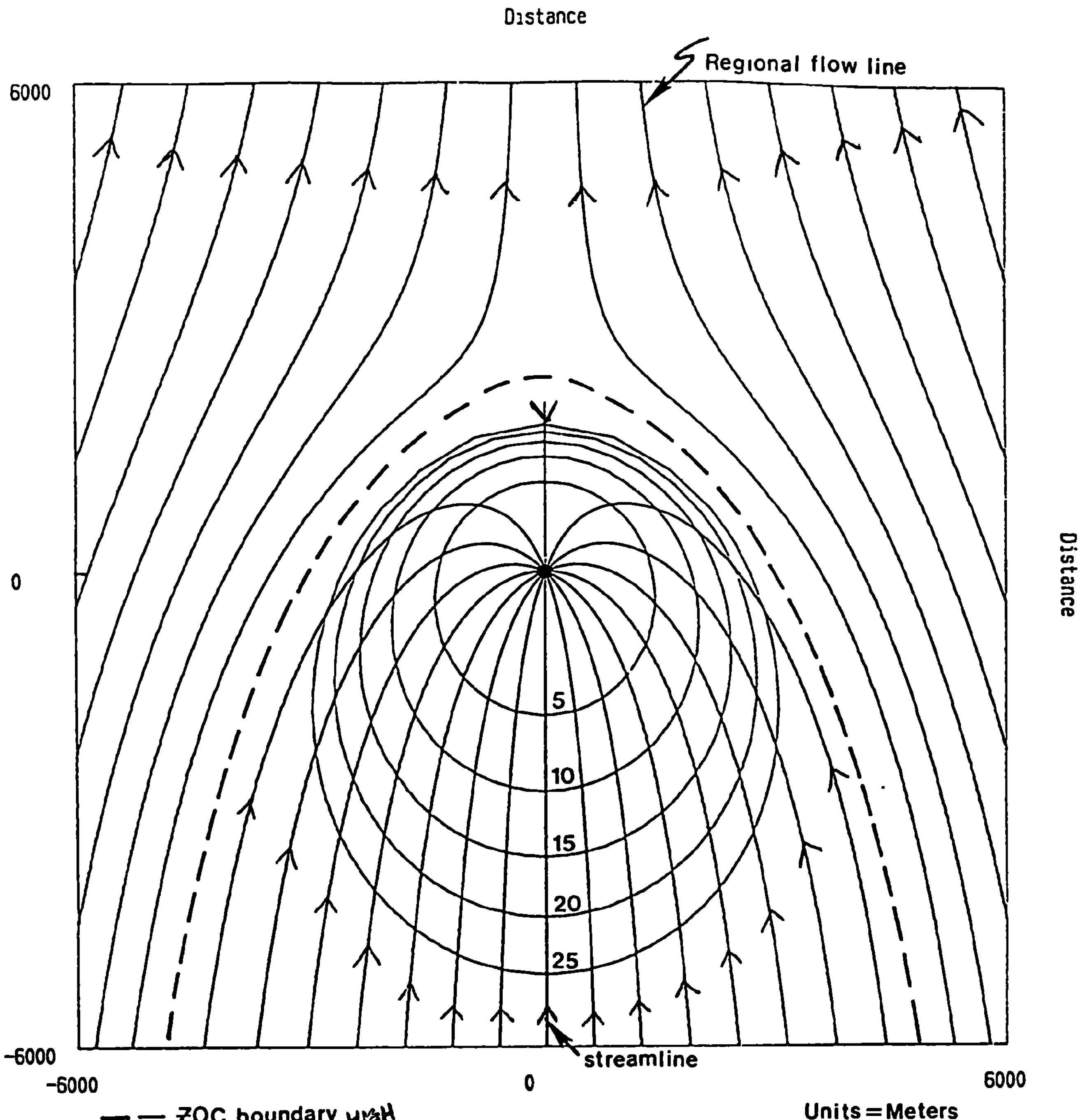
Slide 5.27



EXAMPLE 5 **LOW PUMPING RATE, STRONGLY SLOPING WATER TABLE**

DATA

- PUMPING RATE = 15 CUBIC METERS PER HOUR
- REGIONAL HYDRAULIC GRADIENT = .1
- REGIONAL FLOW IS FROM BOTTOM TO TOP OF FIELD



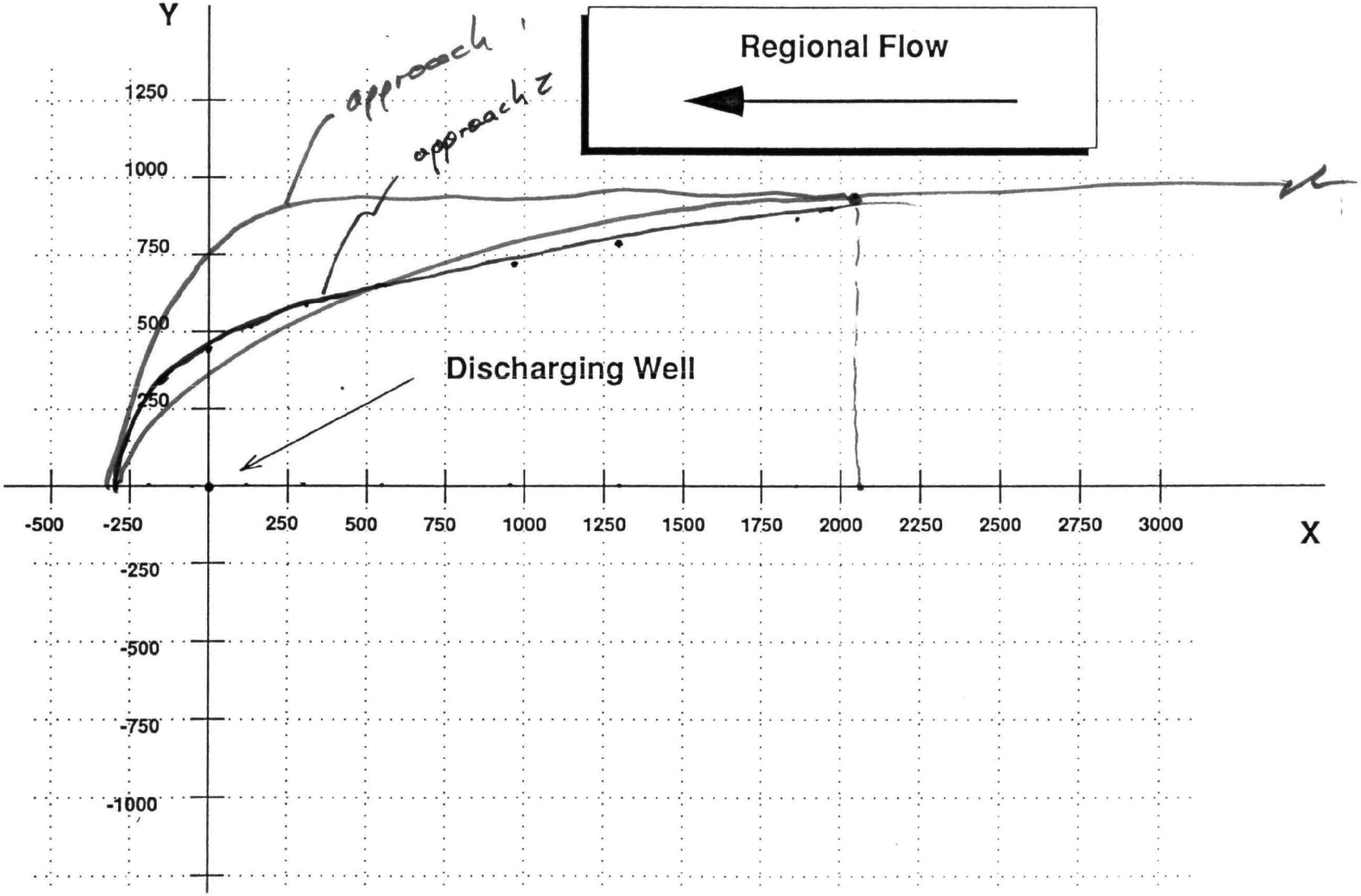
EXAMPLE 6 ~~LOW~~ HIGH PUMPING RATE, STRONGLY SLOPING WATER TABLE

DATA

- PUMPING RATE = 150 CUBIC METERS PER HOUR
- REGIONAL HYDRAULIC GRADIENT = .1
- REGIONAL FLOW IS FROM BOTTOM TO TOP OF FIELD

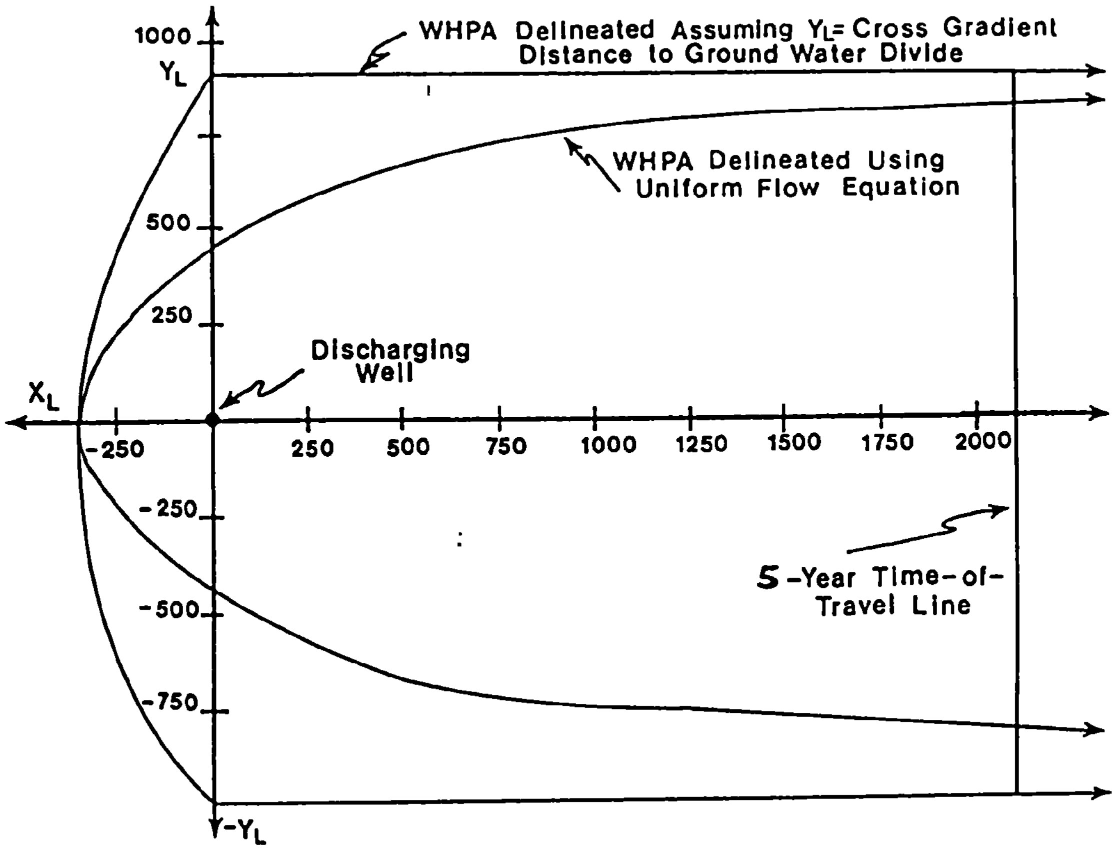
ANALYTICAL METHODS EXERCISE

ANALYTICAL METHODS EXERCISE



Slide 5.31

SOLUTION TO ANALYTICAL METHODS EXERCISE



5. ANALYTICAL METHODS

5.1 INTRODUCTION

Analytical methods are the most common delineation methods used when, in more complex hydrogeologic settings, greater accuracy is necessary than can be obtained from the previous methods. These methods can define ground-water flow boundaries and contaminant transport dynamics through the use of equations representing flow in simple aquifer systems. These methods are often completed with the aid of computers.

Analytical methods require the input of various hydrogeologic parameters such as aquifer transmissivity and porosity, hydraulic gradient, hydraulic conductivity, and saturated thickness of the aquifer. Costs of using analytical methods to delineate WHPAs are relatively low, but implementation costs can be high if site-specific hydrogeologic data must be developed for each WHPA. If sufficient information is not available through pertinent local or hydrogeologic reports, data collection may involve site studies, including test-well drilling and pump tests.

The analytical methods explained in this section of the course include calculating drawdown in a well using the Theis equation (hand calculation) determining an appropriate area using a volumetric flow equation with a TOT criterion and a zone of contribution determination with a TOT criterion. The first and last of these can be simplified by the use of appropriate computer models which is also discussed. For applicable ground-water computer models for the criteria and analytical and numerical methods, consult the OGWP document, model assessment for delineating WHPAs (EPA, 1988).

<u>Advantages</u>

Most hydrogeologists and civil engineers can understand the methods and apply them correctly. Also, because these methods take into account site-specific hydrogeologic parameters, they provide more accurate representations of the actual hydrogeologic settings than previous methods.

<u>Disadvantages</u>

The methods use models that generally do not take into account hydrologic boundaries, aquifer heterogeneities, and non-uniform rainfall or evapotranspiration.

5.2 ANALYTICAL DRAWDOWN METHODS

Description

These analytical methods involve delineation of a WHPA based on a specified threshold value of the drawdown criterion. These values vary from hundredths of a foot in small aquifers where the zone of influence (ZOI) is not areally extensive and the maximum drawdown is small to several feet in regional aquifers. Analytical methods that calculate drawdown, when applied properly, can provide accurate descriptions of the ZOI of a well. Accordingly, these methods should be employed when delineation of a WHPA based on the ZOI of a well is appropriate (i.e., horizontal water-table conditions).

Example

The equation most commonly used to calculate drawdown in homogeneous, isotropic confined aquifers is the Theis equation. The form of the Theis equation used to compute drawdown is (Driscoll, 1986):

$$s = \frac{114.6\ Q\ W(u)}{T}$$

where,

- s = drawdown, in ft, at any point in the vicinity of a well discharging at a constant rate
- Q = pumping rate, in gpm
- T = coefficient of transmissivity of the aquifer, in gpd/ft
- W(u) = is read "well function of u" and represents an exponential integral

In the W(u) function, u is equal to:

$$u = \frac{1.87 r^2 S}{Tt}$$

where,

- r = distance, in ft, from the center of a pumped well to a point where the drawdown is measured
- S = coefficient of storage (dimensionless)
- T = coefficient of transmissivity, in gpd/ft
- t = time since pumping started, in days

Values of W(u) for computed values of u can be obtained from the Well Function table in Appendix C.

Many computer programs have been designed to solve the Theis equation and calculate drawdown. One such program, THWELLS (van der Heijde, 1987), will be used here to demonstrate the effects of aquifer transmissivity and well-pumping rate, all other factors the same, on the size of a WHPA delineated on the basis of the ZOI of a well. THWELLS was developed to calculate head drawdown or buildup at any location in a confined aquifer due to the summation of discharge (pumping) or recharge (injection) of up to 100 wells.

Data input includes the number of wells, aquifer transmissivity and storage coefficient, the x and y coordinates of pumping or injection wells, discharge or recharge rate, and duration of pumping. Effects of no-flow or constant head line boundaries can be simulated using image-well theory. The program outputs the drawdown or buildup at any location (x,y) in the aquifer as a result of each individual well and the sum of all effects. The program has options for determination of head response at a particular time, both presented in tabular and graphic format.

Slides 5.4 through 5.7 are examples of THWELLS graphic output to a dot matrix printer. The figures show, in plan view, contours of drawdown around a single pumping well. Slides 5.4 and 5.5 show the effect of low and high pumping rates, respectively, on the size of the ZOI. Other factors equal, the size of a WHPA will increase with increasing pumping rate.

Slides 5.6 and 5.7 show the effect of low and high transmissity, respectively, on the size of the ZOI and the configuration of the water table. Other factors equal, the size of a WHPA may either increase or decrease with increasing transmissivity depending on the drawdown threshold chosen to delineate the WHPA. For example, in Slides 5.6 and 5.7, the 0.25m drawdown contour moves closer to the well for the case of higher transmissivity which would result in a smaller WHPA (if 0.25m were the criterion threshold). However, the 0.01m drawdown contour moves farther from the well, which would result in a larger WHPA. The data used in each THWELLS run and the important points of comparison among the four cases are summarized below:

SLIDES 5.4 and 5.5

DATA

- transmissivity = 250 square meters per day
- storage coefficient = .1
- contours are .25 meters, .5 meters, 1 meter
- pumping rate in Figure 5.1.1 is 1500 cubic meters per day
- pumping rate in Figure 5.1.2 is 4500 cubic meters per day
- maximum drawdown in Figure 5.1.1 is 8.8 meters
- maximum drawdown in Figure 5.1.2 is 26.4 meters

NOTE:

- similar contours are found at greater distances from well in Figure 5.1.2
- ratio of maximum drawdowns is equal to ratio of pumping rates. Pumping rate is directly proportional to drawdown in Theis equation
- a well pumping at a greater rate, all other factors the same, has a larger ZOI and will require a larger WHPA to protect the well if a threshold value of the drawdown criterion is the basis of delineation

SLIDES 5.6 and 5.7

DATA

- pumping rate = 1500 cubic meters per day
- storage coefficient = .1
- 8000 meter x 8000 meter field
- drawdown contours are .01 meters, .025 meters, .05 meters, .075 meters, .1 meters, .25 meters, .5 meters
- maximum drawdown in Figure 5.1.3 is 10.87 meters
- maximum drawdown in Figure 5.1.4 is 1.22 meters
- aquifer transmissivity in Figure 5.1.3 is 200 square meters per day
- aquifer transmissivity in Figure 5.1.4 is 2000 square meters per day

NOTE:

- all other factors the same, wells in aquifers of higher transmissivity will create a lower maximum drawdown. Transmissivity and drawdown are inversely proportional in the Theis equation
- all other factors the same, wells in aquifers with higher transmissivities will have a larger ZOI (but delineated WHPAs may be larger or smaller depending on selected threshold value of drawdown criterion)
- wells in aquifers with high transmissivities generally have a long and flat cone of depression, while wells in low transmissivity aquifers generally have a short and steep cone of depression

A second example is provided showing a comparison between a WHPA delineated for a wellfield in Oakley, Kansas using a numerical model and the same WHPA delineated using the Theis analytical equation (Slide 5.9). A drawdown threshold of 0.05 ft was used to delineate the WHPA. The numerical model results placed the WHPA boundary at a radius of approximately 11,500 ft from the center of the wellfield. The Theis solution agreed well with the numerical model, computing the 0.05 ft contour at a radial distance of approximately 9,900 ft from the center of the wellfield (Slide 5.10).

5.3 ANALYTICAL TIME-OF-TRAVEL METHODS

Description

Analytical methods that can be used to delineate WHPAs based on the Time of Travel (TOT) criterion calculate the travel time required for a contaminant to reach a pumping well. This is usually done through the reverse-tracking of a particle using predicted regional ground-water advection patterns and velocities. The mapped distance from the well to the outer edge of the WHPA is the product of the average ground-water velocity times the TOT criterion threshold specified by the pertinent regulations. TOT analytical methods incorporate varying degrees of site-specific hydrogeologic information and vary greatly in terms of their complexity. Some of the types of data that are likely to be required to implement these methods are aquifer porosity, hydraulic conductivity, regional flow gradient, aquifer transmissivity and storativity, and pumping and injecting rates.

An example of a simple analytical method that can be used with the TOT criterion is the volumetric flow equation. This equation determines the aquifer volume required to yield the volume of water removed from the aquifer in a period equal to the TOT criterion threshold. This method requires aquifer porosity and pumping-rate data, as well as the open interval of the well.

Examples

The first example (Slides 5.14 and 5.15) illustrates the use of Darcy's Law to compute pore water flow velocity and TOT distance. The method has been used in a number of WHPA delineations including a project in Brookings County, South Dakota (Case Study B.1). The method, as employed here, uses the regional gradient (i) to compute flow velocity and does not take into account the effects of the pumping well. Distances were computed for 5-yr and 10-yr TOT thresholds.

The second example (Slides 5.16 to 5.19) is based on a method used to delineate small 180-day TOT zones ground individual wells in an Oakley, Kansas wellfield (Case Study B.3). More limiting use restrictions were to apply to these smaller protection zones within the larger WHPA for the entire wellfield. The Theis equation is used to compute the drawdown curve with radial distance from a well. This radial distance is then subdivided into short segments (Slide 5.17), and Darcy's law is applied to each segment to compute pore-water velocity and TOT. Travel times for individual segments are summed, moving radially outward from the well, until the cumulative TOT equal 180 days (Slides 5.18 and 5.19).

Another analytical method that incorporates the TOT criterion is the analytical transport model RESSQ. An introduction to the model and some example runs are included in the following section of zone-of-contribution methods.

5.4 ANALYTICAL ZONE OF CONTRIBUTION METHODS

Description

A desirable way to ensure protection of a water-supply well is to protect the land surface and the subsurface regions that contribute water to the water supply. This region of the flow system is called the zone of contribution, or ZOC. The ZOC includes all recharge areas and subsurface regions through which water flows to the pumping well. To determine the entire ZOC of a well or wellfield requires an understanding of the well hydraulics of the system as well as hydrogeologic mapping of topographic divides, recharge areas, and no-flow boundaries.

One method of defining the ZOC involves the use of the uniform flow equation to determine the stagnation point downgradient from a well and the width of the upgradient zone that contributes flow to the well. This method is discussed in greater detail in the Delineation Guidelines (EPA, 1987a, p. 4-14).

The stagnation point or downgradient null point marks the distance beyond which flow in the aquifer will not be drawn into the well under the influence of pumping. The boundary limits of the ZOC in the direction upgradient from the well define the width of aquifer (given its depth, conductivity, and prevailing regional (gradient) required to supply flow to the discharging well. These concepts are summarized in Slide 5.23. The equations employed in this method will be explained further in the hands-on exercise in Section 5.5, "Analytical Methods Exercise."

The sizes of ZOCs can vary greatly. In the case of small production wells operating in prolific, horizontal water-table aquifers, the ZOC can be an area with a radius of tens-of-feet. In the case of a larger well field, the ZOC can extend miles from the well field and, in the case of the confined aquifers not necessarily be contiguous with the well field. Because in some cases it is unrealistic to set aside such large areas to serve as WHPAs, the entire ZOC of a well is not normally chosen as the WHPA. Instead, in such cases, the ZOC is combined with a TOT criterion threshold and the portion of the ZOC that contributes flow to the well within that time period serves as the WHPA. These zones of transport (ZOT) are identified by contours of equal travel time (isochrones).

RESSQ - WHPA Delineation Using Flow Boundary and TOT Criteria

Many analytical methods can be used to delineate WHPAs on the basis of ZOTs. One such method is the computer model RESSQ (Javandel, et al, 1984). RESSQ, a semi-analytical model, is designed to calculate two-dimensional contaminant transport by the processes of advection and adsorption in homogeneous, isotropic, confined, and steady-state flow-field aquifers.

To run RESSQ, the following input data are required: aquifer thickness, porosity, pumping/injection rates, regional pore water velocity, direction of regional flow, injection contaminant concentration, and the adsorption capacity of the rock matrix.

The model produces tabular and graphic output. The tabular output lists the final destinations and arrival times of streamlines as well as a contaminant concentration profile over time for production wells receiving contamination. The graphic output displays the location of production/injection wells, with streamlines plotted to depict the flow field. Time-of-travel fronts may also be displayed.

The user specifies the number of streamlines leaving each well, the time periods for which the contaminant fronts are plotted, and the total time of simulation. The ability to calculate and display chosen time fronts makes RESSQ an excellent tool for TOT delineation applications.

The following hypothetical situations were developed using RESSQ in order to demonstrate the effects of pumping rates and regional hydraulic gradients on the ZOTs of a well. The examples were developed assuming an isotropic, homogeneous, confined aquifer with no assimilative capacity, and saturated thickness of 10m. Hydraulic conductivity (K) is 100 m/yr, and effective porosity (n) is 0.1. Six cases were developed to illustrate the relationship between regional gradient and pumping rate in determining the size at the ZOT. Three regional gradients were selected from horizontal to fairly steep (0, 0.05, 0.1) and, for each gradient, the flow field was computed for low and high pumping rates (15 m^3/hr, 150 m^3/hr). Changes in the regional hydraulic gradient were effected by changing the regional pore-water velocity. Hydraulic gradient and pore-water velocity are related by the equations:

$$V = \frac{q}{n} = \frac{Ki}{n}$$

where,

v = pore-water velocity (m/yr)
q = average (regional) ground-water velocity (m/yr)
n = porosity of aquifer = .1
K = hydraulic conductivity = 100 m/yr
i = hydraulic gradient (dimensionless)

By keeping the values of K and n constant, the desired hydraulic gradient was obtained by entering the corresponding pore-water velocity value into the model.

The time fronts in each example are plotted for 5, 10, 15, 20, and 25 years. Note the acceleration as flow approaches the pumping well (i.e., greater distances traversed in successive 5-yr intervals as flow moves toward well).

The data used in each RESSQ run and the important points of comparison among the six runs are summarized below:

RESSQ EXAMPLES

EXAMPLE 1: LOW PUMPING RATE, HORIZONTAL WATER TABLE
(Slide 5.24)

DATA

- pumping rate = 15 m^3/hr
- regional hydraulic gradient = 0

SHOWS

- ground-water velocity increases as the water approaches pumping center due to increased hydraulic gradient
- straight pathlines, approach well radially
- all ZOCs circular with this method of calculations

NOTE

- ideal conditions for use of calculated fixed radius method
- method can be applied with high accuracy

EXAMPLE 2: HIGH PUMPING RATE, HORIZONTAL WATER TABLE
(Slide 5.25)

DATA

- pumping rate = 150 m^3/hr
- regional hydraulic gradient = 0

SHOWS

- increased radius of WHPA for a given TOT
- ground-water velocity increases slightly as water approaches pumping center due to increase hydraulic gradient
- straight pathlines, approach well radially
- all ZOCs circular

NOTE:

- ideal conditions for calculated fixed radius method
- method can be applied with high accuracy

EXAMPLE 3: LOW PUMPING RATE, MODERATE WATER-TABLE GRADIENT (Slide 5.26)

DATA

- pumping rate = 15 m^3/hr
- regional hydraulic gradient = .05
- regional hydraulic gradient flows from bottom to top of page

SHOWS

- ZOCs highly skewed in upgradient direction
- stagnation point clearly marked
- ground-water velocities greatly accelerated within 5 year TOT boundary

NOTE:

- application of calculated fixed radius for WHPA leads to erroneous coverage - under coverage if downgradient radius is chosen, over coverage if upgradient radius is chosen
- under these conditions, CFR method is inappropriate, analytical methods should be used to increase accuracy of delineation
- ZOC is increasingly skewed with increased TOTs.

<u>EXAMPLE 4</u>: HIGH PUMPING RATE, MODERATE WATER-TABLE GRADIENT (Slide 5.27)

DATA

- pumping rate = 150 m^3/hr
- regional hydraulic gradient = .05
- regional hydraulic gradient flows from bottom to top of page

SHOWS

- pathlines curve slightly (within 25 year TOT limits) as approach well
- ZOC skewed slightly in upgradient direction - degree of skew increases with increasing TOT

NOTE

- in the case of a well with a high pumping rate in an aquifer with a moderate hydraulic gradient, ZOCs are nearly circular for TOTs of 5 to 10 years
- under these conditions, the calculated fixed radius methods is appropriate if applied with 5 and 10 year TOTs. Application to TOTs beyond 10 years results in increased erroneous coverage

EXAMPLE 5: LOW PUMPING RATE, HIGH WATER-TABLE GRADIENT
(Slide 5.28)

DATA

- pumping rate = 15 m^3/hr
- regional hydraulic gradient = .1
- regional hydraulic gradient flows from bottom to top of field

SHOWS

- ZOC is almost entirely upgradient of pumping center

NOTE

- under these conditions, the calculated fixed radius method results in unacceptable coverage and error

EXAMPLE 6: HIGH PUMPING RATE, HIGH WATER-TABLE GRADIENT (Slide 5.29)

DATA

- high pumping rate: 150 m^3/hr
- regional hydraulic gradient = .1
- regional hydraulic gradient flows from bottom to top of field

SHOWS

- a high pumping rate reduces the effect of a large gradient within the 5 yr TOT, but the ZOCs for the remaining time fronts are skewed such that the calculated fixed radius method would provide an unsatisfactory WHPA delineation for TOTs greater than 5 years

NOTE

- calculated fixed radius is unacceptable delineation method if applied under such conditions with TOTs greater than 5 years

5.5 ANALYTICAL METHODS EXERCISE

The purpose of this exercise is to employ two analytical methods to define the boundary of a WHPA. The uniform flow equation is used to define the boundary of the aquifer zone contributing flow to a pumping well. Darcy's law is then used to computer a time-of-travel distance that defines the upgradient extent of the WHPA for a specified TOT criterion.

Two approaches to applying these methods are presented. The first approach is based on a method applied in Brookings County, South Dakota (see Case Study B.1). The approach requires only three calculations to define the WHPA.

The second approach involves generating a better approximation to the zone-of-contribution (ZOC) by using the uniform flow equation repeatedly to compute many points along the flow boundary. At the completion of the exercise, compare the WHPAs delineated using these two approaches.

$\cot\theta = \frac{1}{\tan\theta}$

Approach 1

1) For this exercise, use equations from the Uniform Flow Analytical Model and the following data:

Q = 46, 170 ft^3/day,
i = .001
b = 110 ft
K = 228 ft/day

$X_L = \frac{Q}{2\pi Kbi} = \frac{46170}{2\pi(228)(110)(10^{-3})} = 243$

$Y_L = \frac{Q}{2Kbi} = \frac{46170}{2(228)(110)\,10^{-3}} = 920 \times (2) = 1840$

to compute
  a) Distance to the downgradient null point, X_L
  b) Maximum width of influx zone, $2Y_L$

2) Use the relationship, V=Ki/n, to calculate the distance to the 5-year time-of-travel line. Porosity = .20. $V = \frac{(228)(10^{-3})}{.2} = 1.14$

3) Plot (using graph paper provided, Slide 5.31) the shape of the ZOC; assume Y_L is the cross-gradient distance to the ground-water divide. Then draw the 5-year time-of-travel line as the upgradient boundary of ZOC to create a 5-year zone-of-transport (ZOT).

$d_{5y} = v(t) = (1.14)(5)365 = 2080.5$

Approach 2

1) Again using the uniform flow equations, compute the X and Y coordinates of points along the ground-water divide for Y = 800, 762, 734, 674, 587, 514, 440, and 293.

Hint: the uniform flow equation along the ground-water divide reduces to:

$$X = -Y \cot (Y/-X_L)$$

where cotangent is in radians

$X_{800} = 800 \cot\left(\frac{800}{293}\right) =$ 1894
$X_{762} =$ 1268
$X_{734} =$ 993
$X_{674} =$ 602
$X_{587} =$ 271
$X_{514} =$ 95
$X_{440} =$ -31
$X_{293} =$ -188

2) Use the points generated in #2 above, the value for X_L computer in Approach 1, #1 and the 5-year time-of-travel line computed in Approach 1, #2 to delineate the WHPA produced using the uniform flow equations and a 5-year time-of-travel criterion threshold.

Part 3

1) How do the WHPAs delineated using the two approaches compare?

SOLUTIONS:

Approach 1

1a) $$X_L = \frac{-Q}{2\pi Kbi} = \frac{46{,}170 \text{ ft}^3/\text{day}}{2\pi(228 \text{ ft/day})(110 \text{ ft})\ (.001)}$$

$$X_L = -293 \text{ ft}$$

1b) $$Y_L = \pm \frac{Q}{2Kbi} = \pm \frac{46{,}170 \text{ ft}^3/\text{day}}{2(228 \text{ ft/day})(110 \text{ ft})(.001)}$$

$$Y_L = \pm 920 \text{ ft}$$

2) $$V = \frac{Ki}{n} = \frac{(228 \text{ ft/day})(.001)}{.20} = 1.139 \text{ ft/day}$$

Distance to 5-year TOT line = (velocity)(1825 days) = 2,079 ft

3) See Graph (Slide 5.32)

Approach 2

1) Using $X = -Y \cot (Y/-X_L)$

for Y = 762: X = (-762 ft) cot (762 ft/293 ft)
= 1268 ft

X (ft)	Y (ft)
1834	800
1268	762
982	734
606	674
269	587
93	514
-31	440
-188	293

2) See Graph (Slide 5.32)

Part 3

The simpler approach used in Brookings County, SD is also more conservative (i.e., it protects a large area). For the aquifer conditions presented here, the two approaches agree well.

6. Mapping

PRESENTATION SLIDES

HYDROGEOLOGIC MAPPING METHODS

WHPA DELINEATION METHODS

1) ARBITRARY FIXED RADIUS

2) CALCULATED FIXED RADIUS

3) SIMPLIFIED VARIABLE SHAPES

4) ANALYTICAL METHODS

5) HYDROGEOLOGIC MAPPING

6) NUMERICAL FLOW / TRANSPORT MODELS

HYDROGEOLOGIC MAPPING METHODS

DESCRIPTION

Delineation of WHPAs by mapping TOT and flow boundary criteria using geological observations, geophysical data, and dye-tracing methods

ADVANTAGES

- well suited to hydrogeologic settings dominated by near-surface flow boundaries, as are found in many glacial and alluvial aquifers with high flow velocities, and to highly anisotropic aquifers

DISADVANTAGES

- require specialized expertise in geologic and geomorphic mapping
- require significant judgement on what constitute likely flow boundaries
- less suited to delineatind WHPAs in large or deep aquifers

HYDROGEOLOGIC MAPPING

- **Flow System Boundaries:**
  - **Recharge**
  - **Impermeable**
  - **Flow Divides**

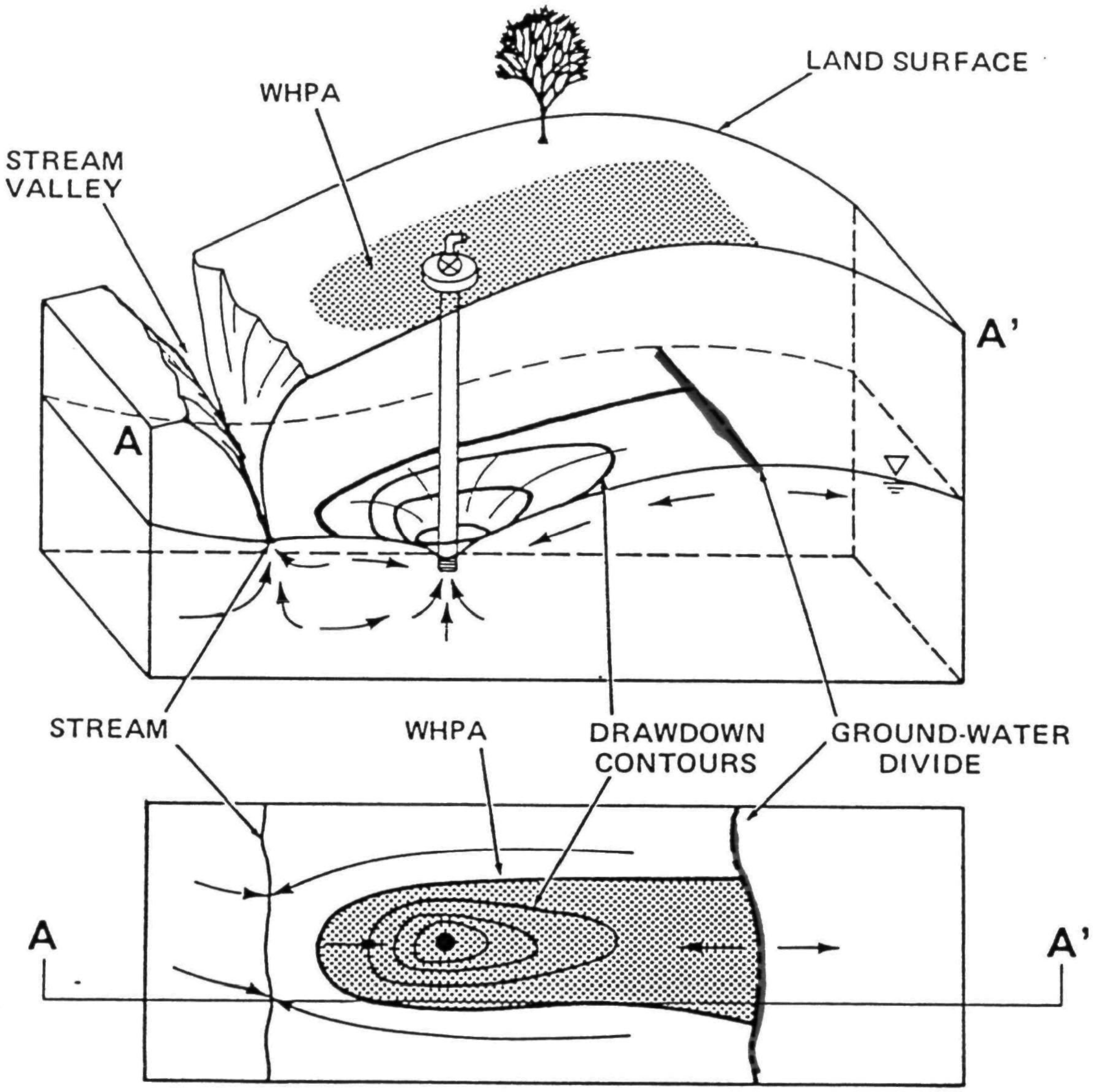
- **Conduit Flow Paths**

you can map recharge areas as well

MAPPING TECHNIQUES

- GENERAL GEOLOGIC MAPPING
  - TOPOGRAPHY
  - WATER LEVELS
  - WATER QUALITY
  - GEOLOGIC CONTACTS
  - LINEAMENT ANALYSIS (photographic)
  - AQUIFER TESTS
- GEOPHYSICS
- DYE TRACING
- AGE ASSESSMENT (TRITIUM)

WHPA Delineation Using Hydrogeologic Mapping
(Use of Ground-water Divides)

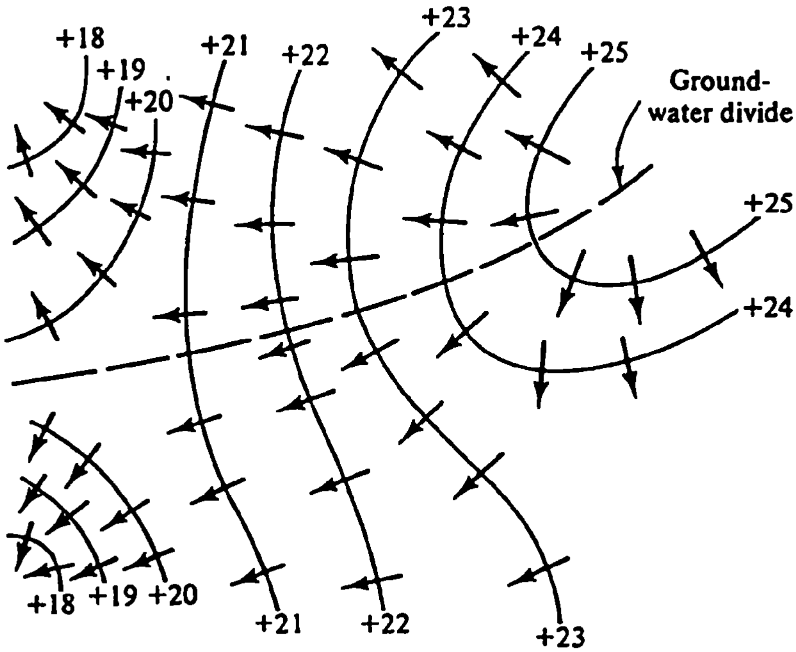


LEGEND:

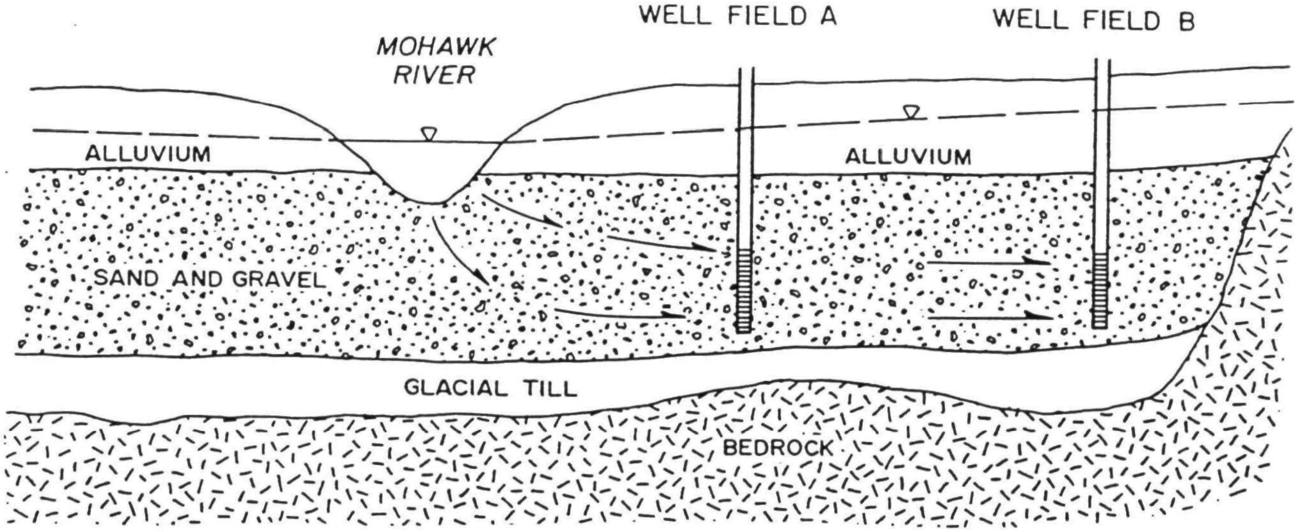
- Water Table
- Pumping Well
- Ground-water Divide
- Direction of Ground-water Flow
- WHPA

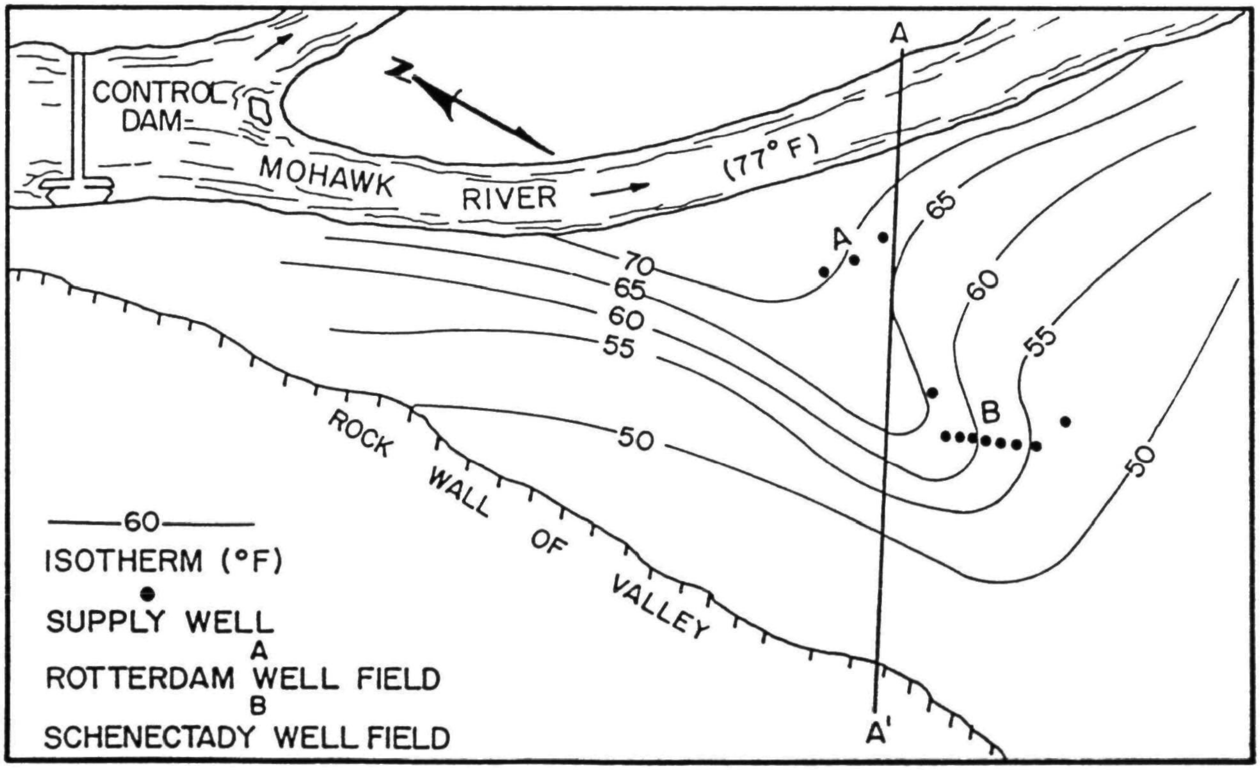
Slide 6.06

GROUND-WATER DIVIDE



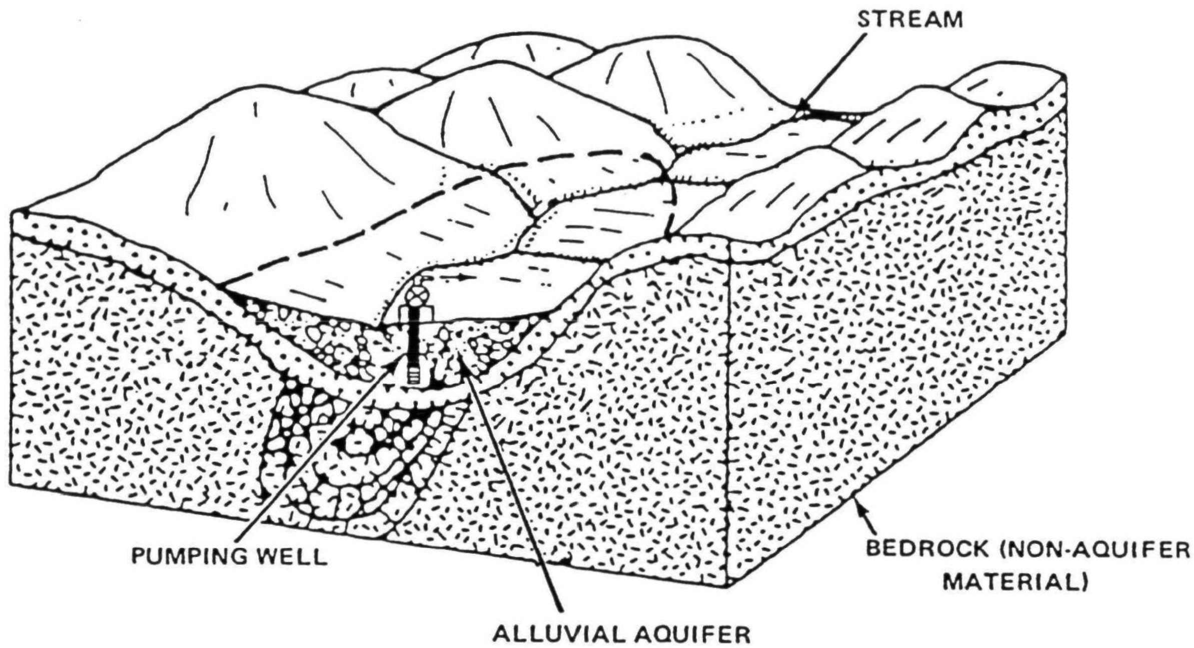
WATER QUALITY MAPPING: MOHAWK RIVER BASIN, NEW YORK





(Source: Heath & Trainer, 1968)

WHPA Delineation Using Hydrogeologic Mapping (Use of Geologic Contacts)

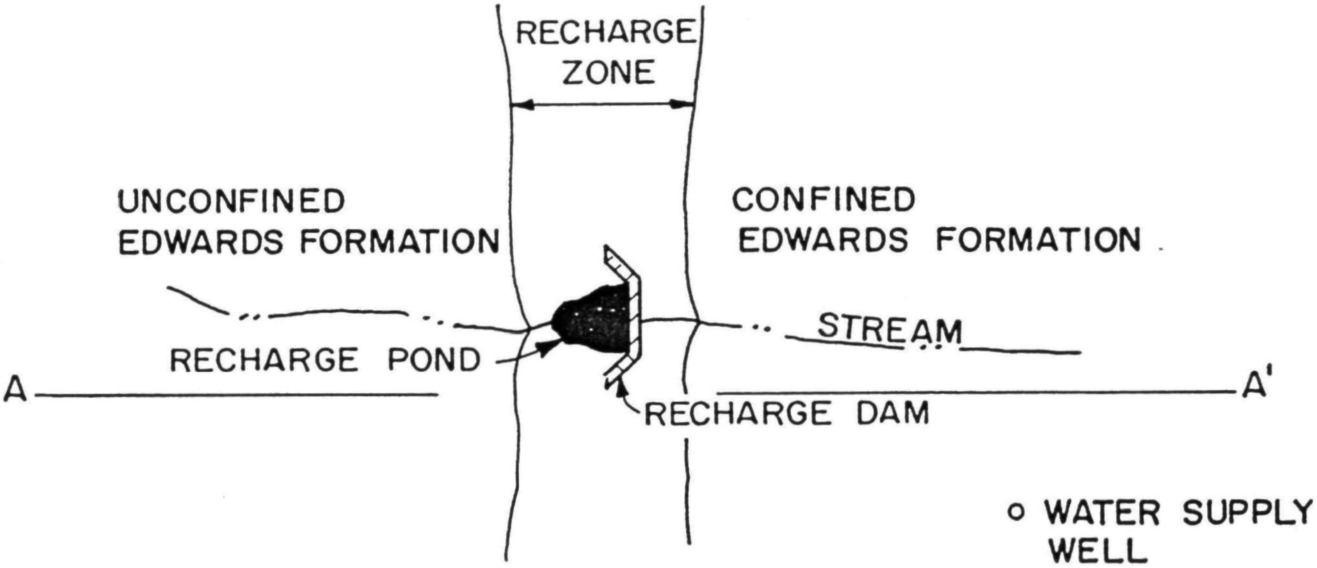


— — — Primary WHPA Boundary Drawn as Contact Between Aquifer and Non-Aquifer Material

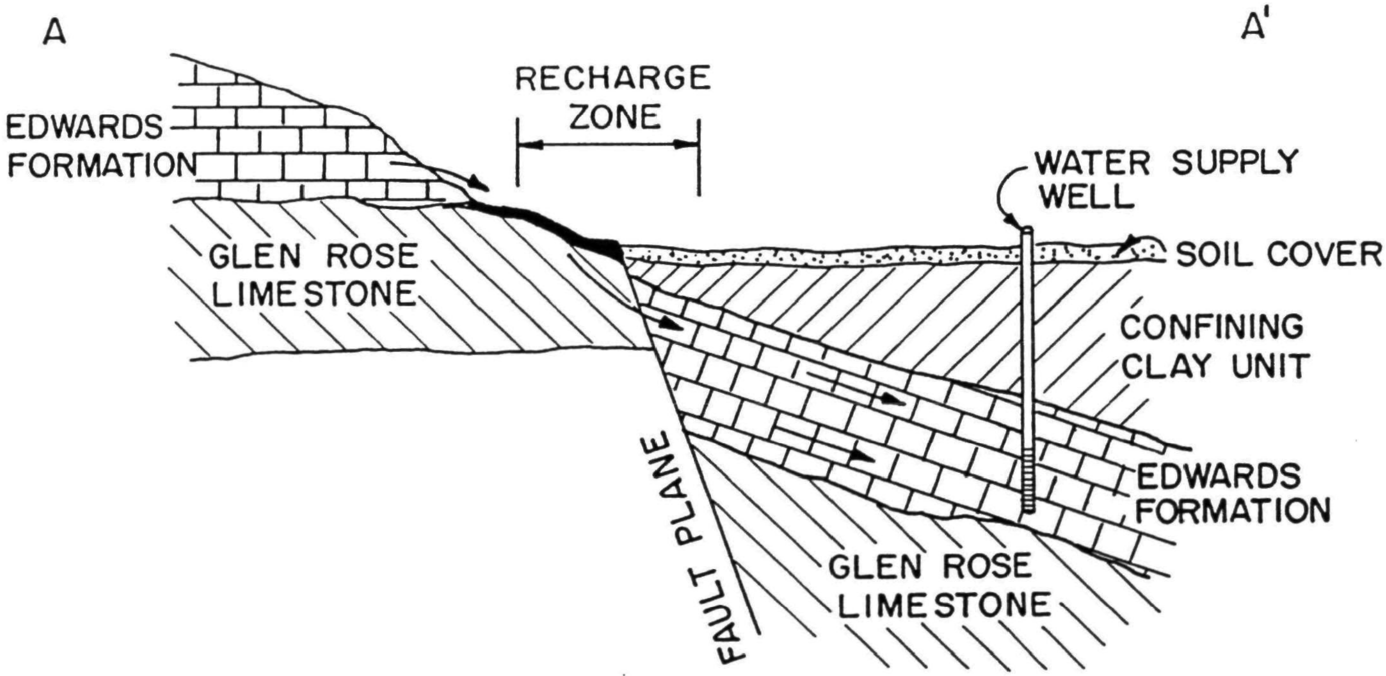
NOTE: A secondary protection zone could be delineated based on the larger area of recharge derived from surface runoff, and inferred from topography and basin boundaries.

Slide 6.09
NOT TO SCALE

GEOLOGIC CONTACT MAP: EDWARDS AQUIFER, TEXAS



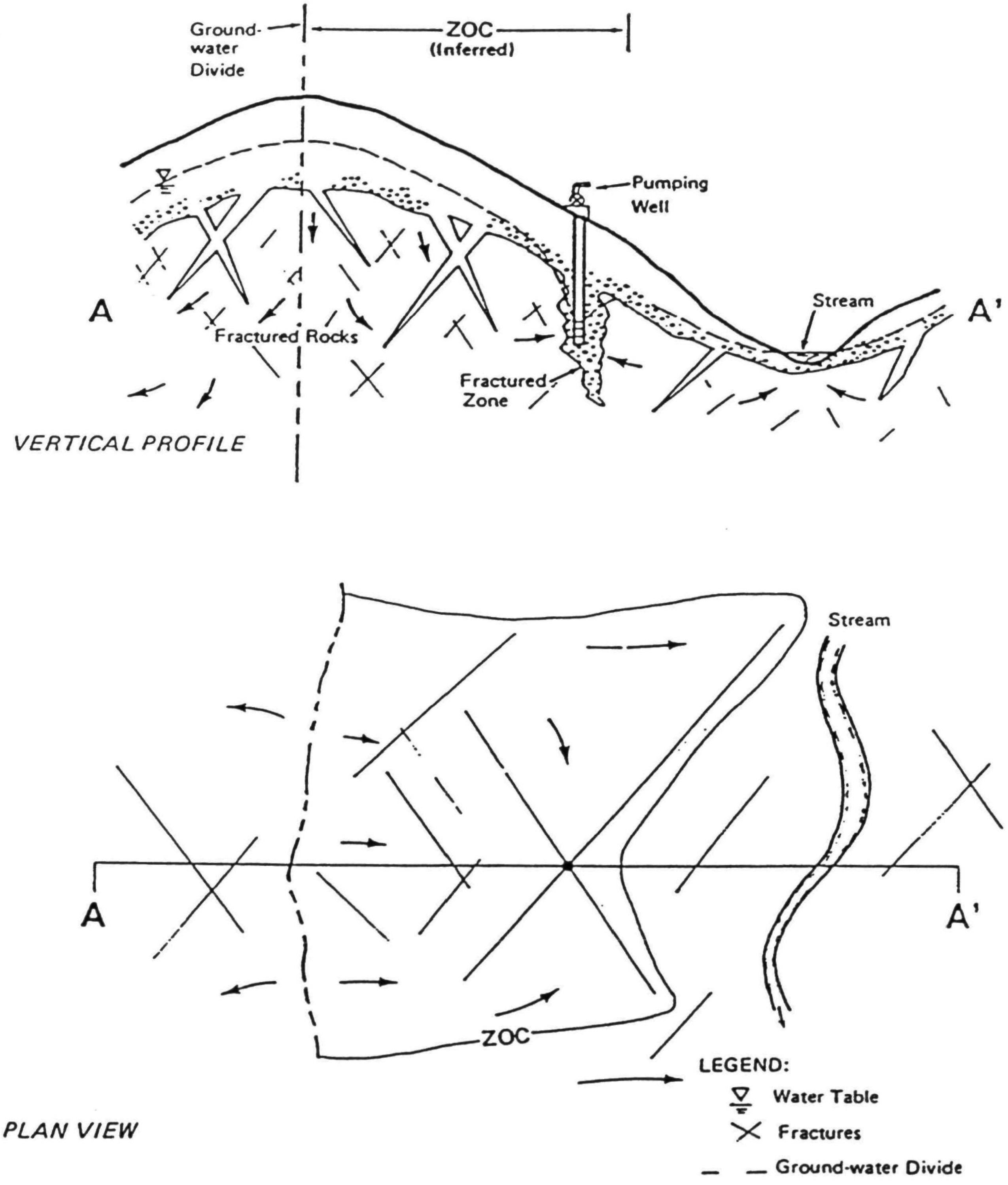
PLAN



CROSS-SECTION

Slide 6.10

Terminology for Wellhead Protection Area Delineation (Hypothetical Ground-water Basin in Fractured Rock)



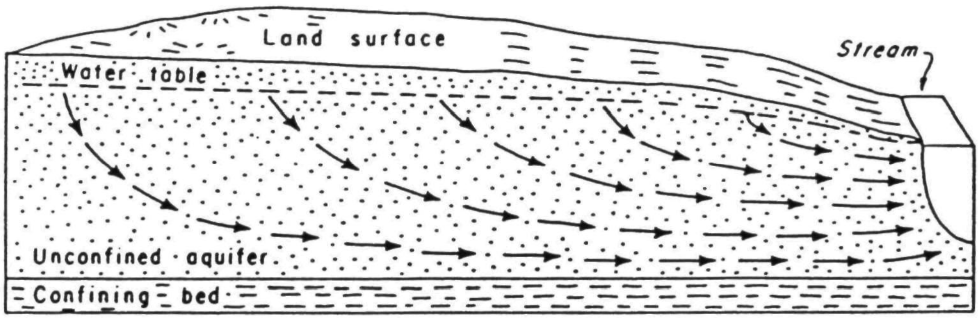
Slide 6.11

SOURCE: Modified from Otton, 1981

NOT TO SCALE

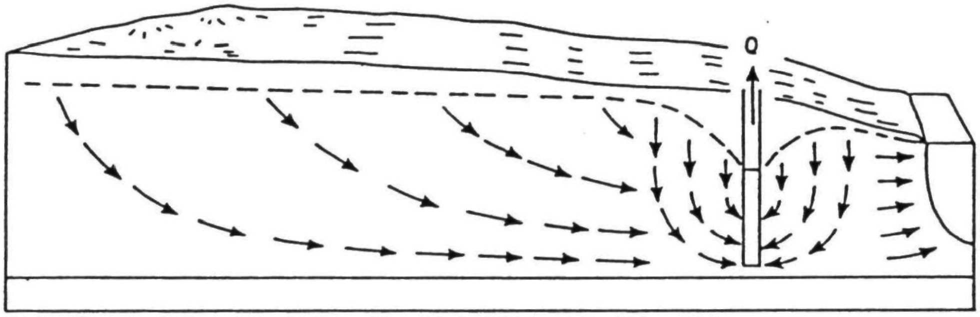
AQUIFER TEST DETERMINATION

OF AQUIFER BOUNDARIES



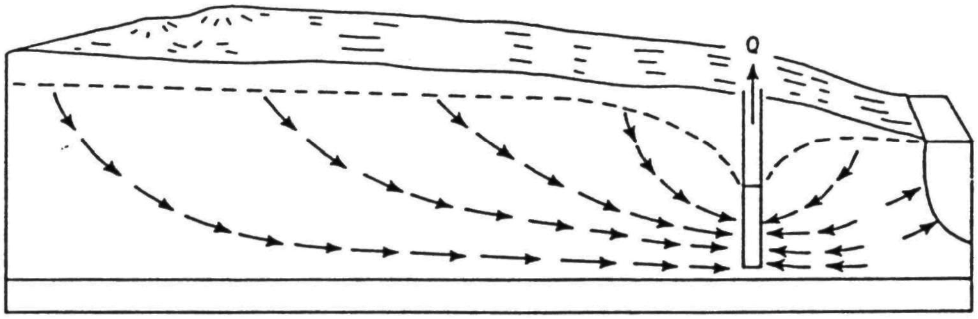
t = o

Discharge (D) = Recharge (R)



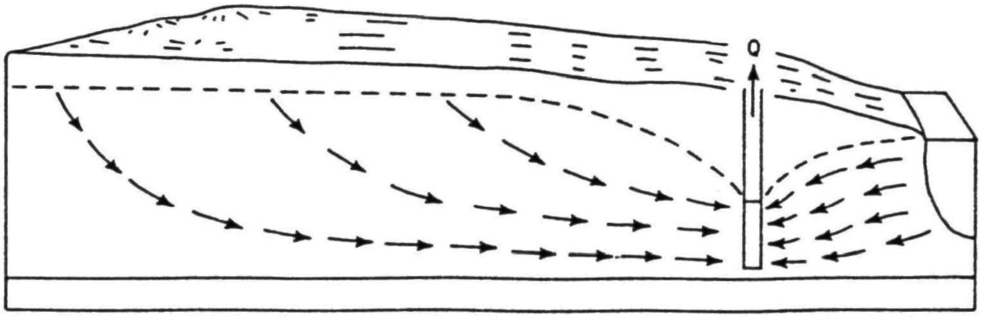
t = 1 hr.

Withdrawal (Q) = Reduction in storage (△s)



t = 6 hrs.

Withdrawal (Q) = Reduction in storage (△s) + Reduction in discharge (△D)



t = 24 hrs.

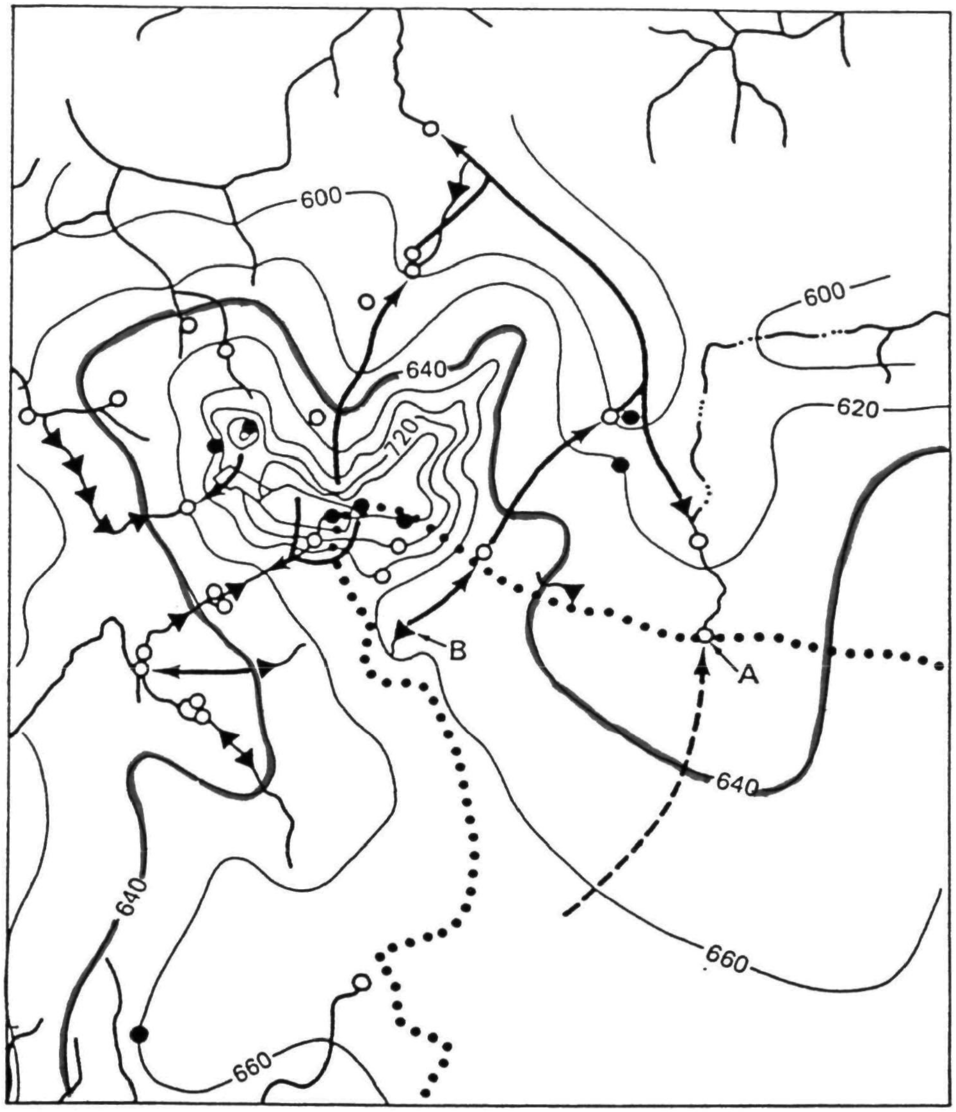
Withdrawal (Q) = Reduction in discharge (△D) + Increase in recharge (△R)

(Source: Heath, 1983)

GEOPHYSICAL METHODS

- Elastic-seismic
- Electrical
- Density-Gravimetric
- Magnetic

WHPA Delineation Using Hydrogeologic Mapping: Dye Tracing (Example From Kentucky)



600 Potentiometric surface
Traced flow route
Sinking spring
Spring-fed stream
Intermittent stream
Sinking stream
Inferred ZOC of spring A based on mapping of potentiometric surface
A Municipal water supply spring
Inferred direction of ground-water flow

Sinking stream B was found to not be in ZOC of spring A, although this would be inferred from potentiometric surface.

Modified from Quinlan and Ewers, 1985

Slide 6.14
NOT TO SCALE

AGE ASSESSMENT

- EVALUATION OF LEAKINESS OF CONFINING STRATA

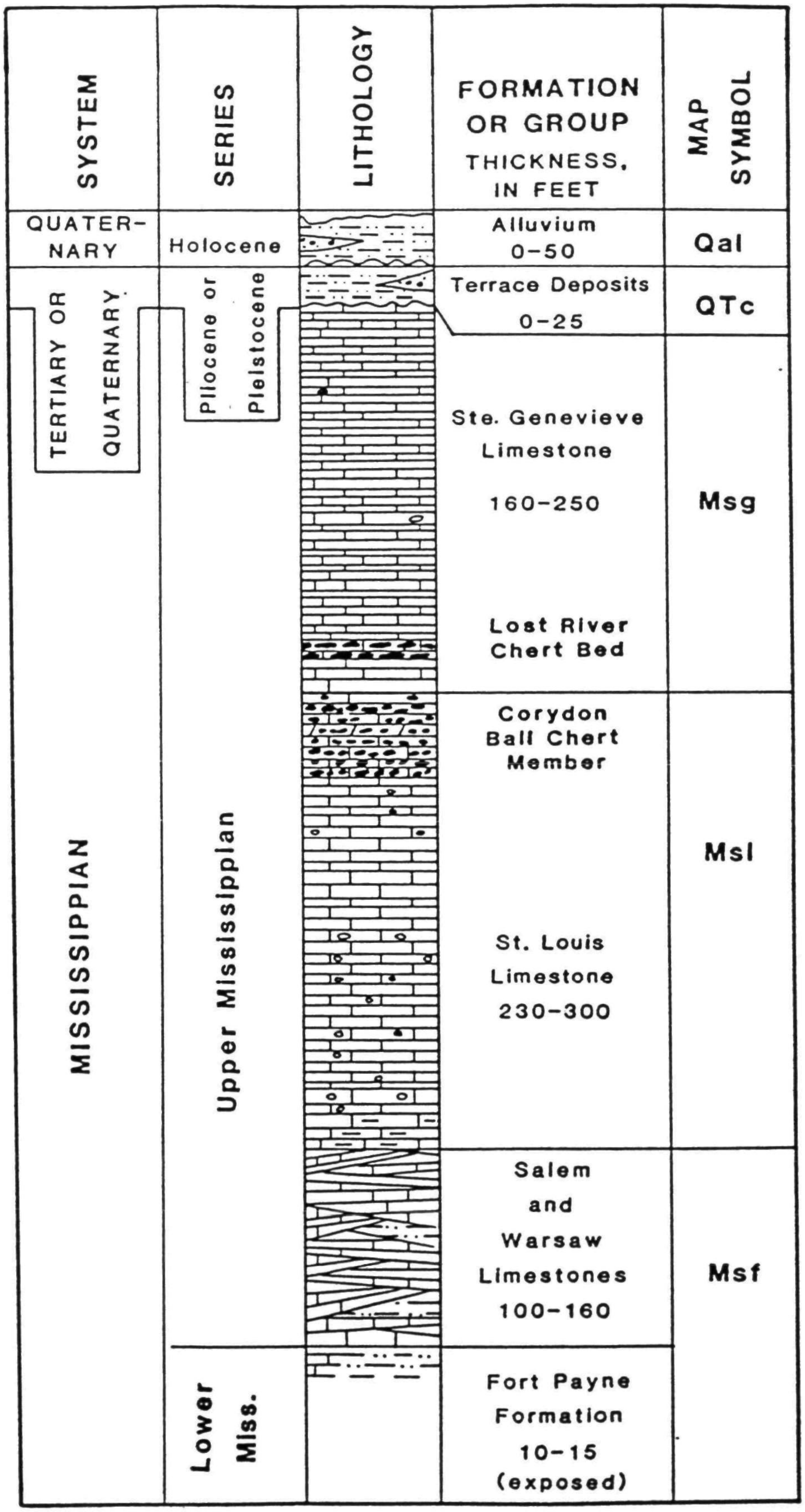
- TRACERS

  - TRITIUM
  - TRICHLOROFLUOROMETHANE (CCl_3F)

MAPPING CASE STUDY AND EXERCISE

MAPPING EXERCISE SETTING

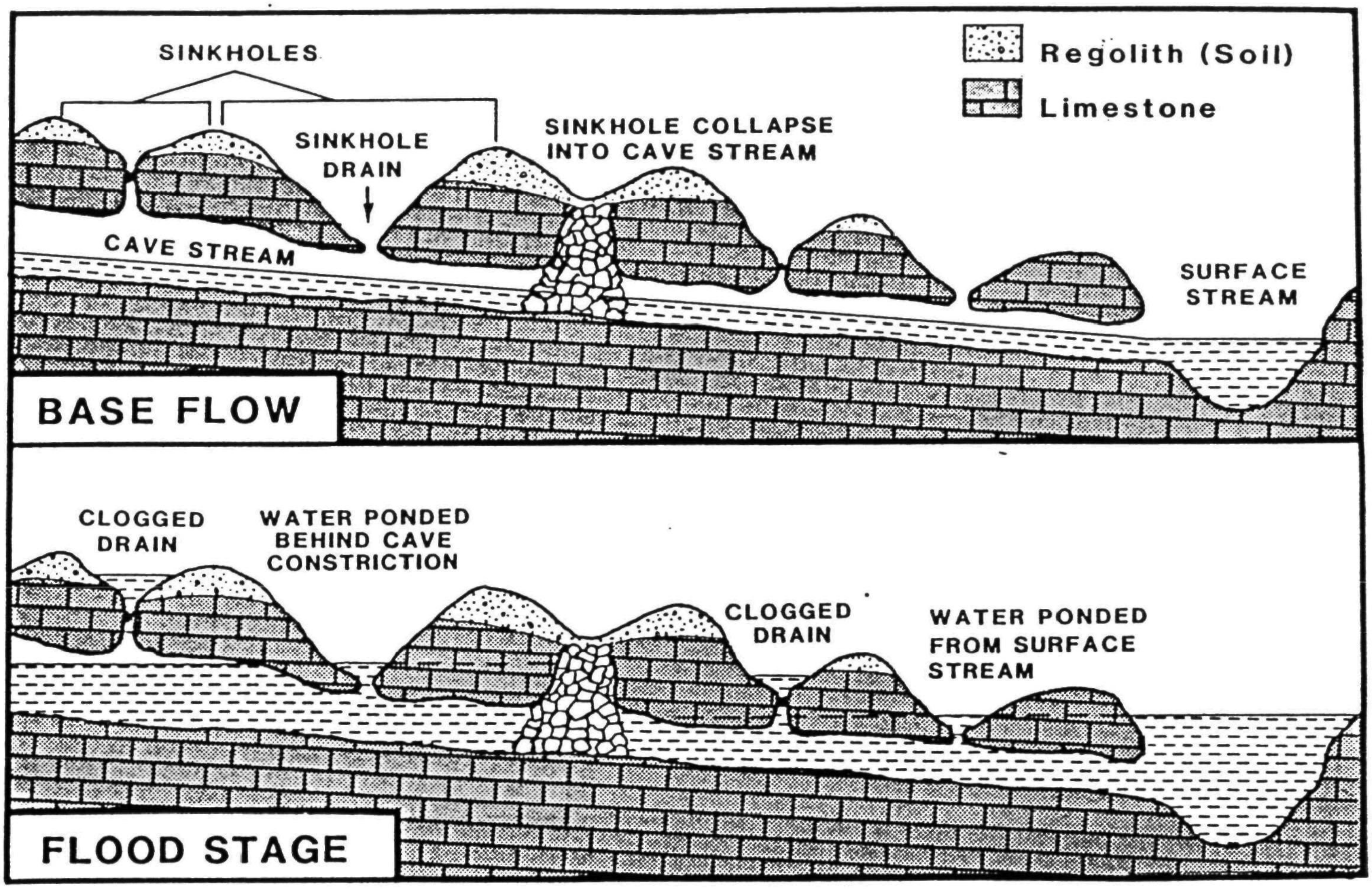
- BOWLING GREEN, KENTUCKY
- PUBLIC WATER SUPPLY DERIVED FROM UNCONFINED KARST AQUIFER
- WHPA DELINEATION STUDY CURRENTLY IN PROGRESS
- DYE-TRACER STUDIES COMPLETED TO DEFINE FLOW ROUTES
- FLOW VELOCITY STUDIES COMPLETED FOR SOME MAJOR FLOW ROUTES



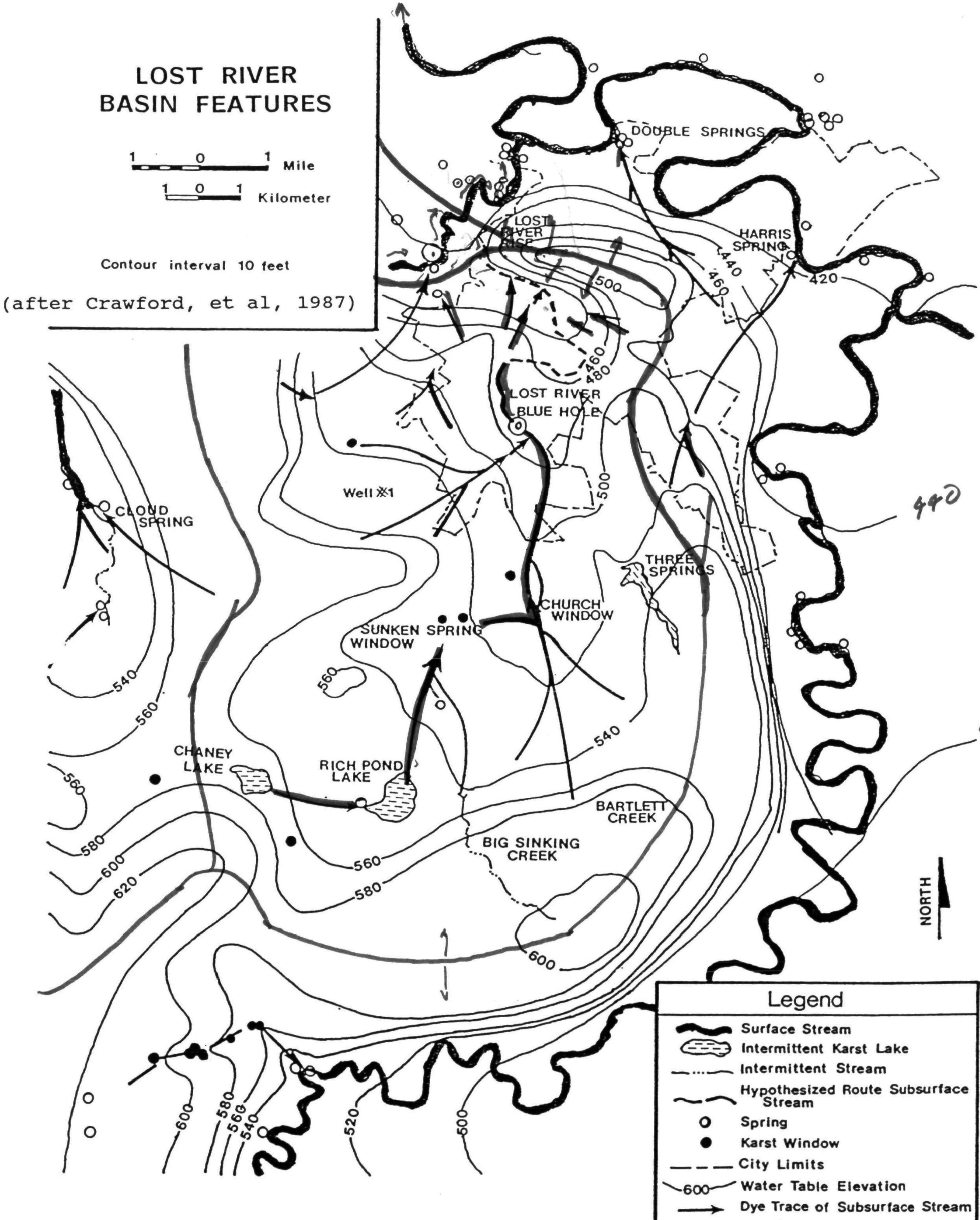
Stratigraphic Column for the Bowling Green area.
Source: modified from McGrain and Sutton (1973).

Slide 6.18

LOST RIVER BASIN HYDROLOGY

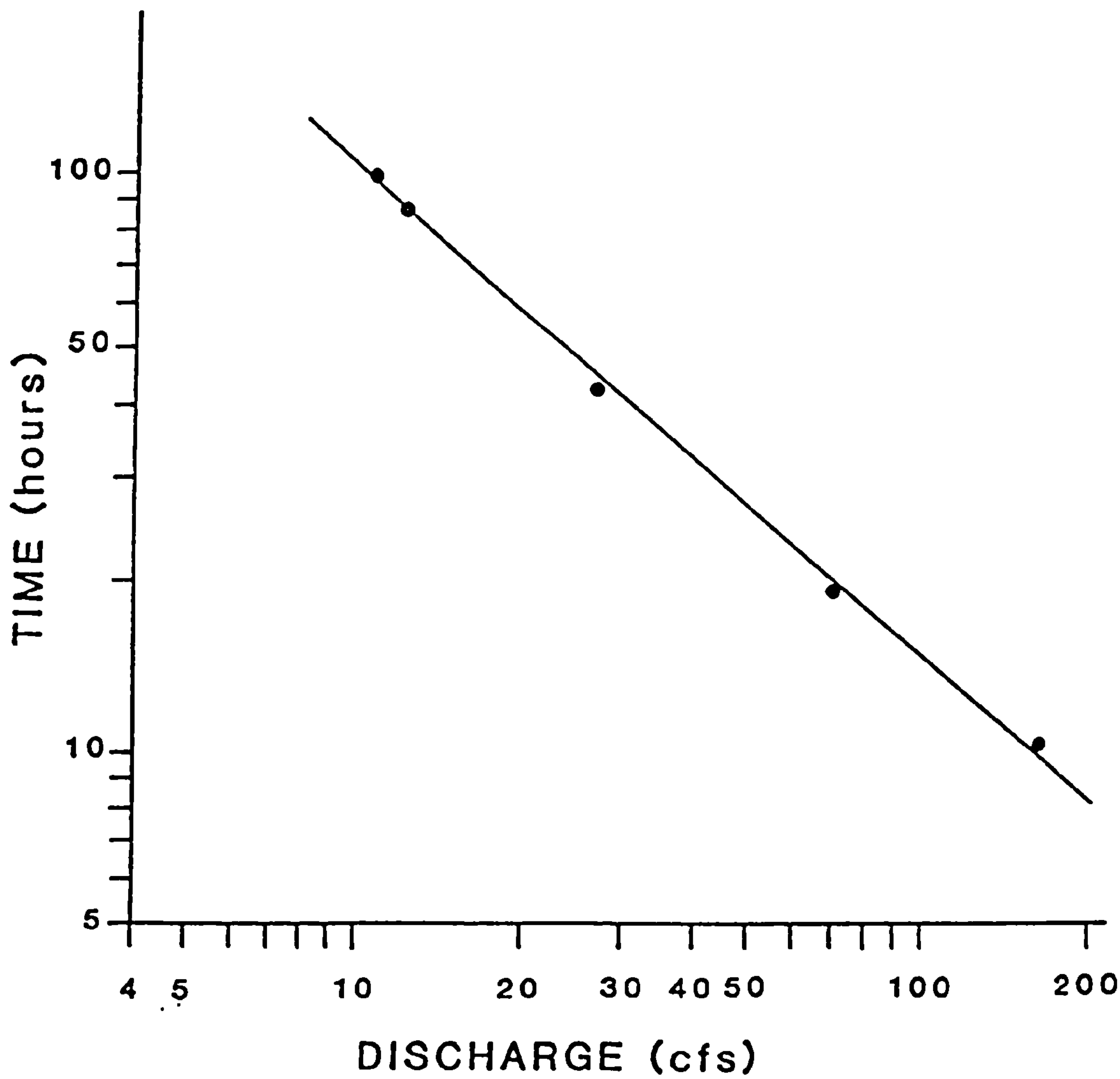


(after Crawford, et al, 1987)


LOST RIVER
BASIN FEATURES
1 0 1 Mile
1 0 1 Kilometer
Contour interval 10 feet
(after Crawford, et al, 1987)
DOUBLE SPRINGS
LOST RIVER RISE
HARRIS SPRING
420
440
460
500
460
480
LOST RIVER BLUE HOLE
Well ※1
CLOUD SPRING
500
440
THREE SPRINGS
CHURCH WINDOW
SUNKEN SPRING WINDOW
560
540
560
480
540
CHANEY LAKE
RICH POND LAKE
560
BARTLETT CREEK
BIG SINKING CREEK
580
600
620
560
580
600
NORTH
600
580
560
540
520
500
Legend
Surface Stream
Intermittent Karst Lake
Intermittent Stream
Hypothesized Route Subsurface Stream
Spring
Karst Window
City Limits
600
Water Table Elevation
Dye Trace of Subsurface Stream
Subsurface Stream Flowing through Mapped Cave

Slide 6.20

Blue Hole to Rise



TIME OF ARRIVAL OF TRACER vs. DISCHARGE

(after Crawford, et al, 1987)

HYDROGEOLOICAL MAPPING EXERCISE

WHPA CRITERIA: FLOW BOUNDARIES

THRESHOLD: BOUNDARIES OF BASIN

METHOD: MAPPING WATER LEVELS AND GROUND-WATER DIVIDES

USING DYE TRACER INFORMATION AND WATER-LEVEL MAP DETERMINE BOUNDARIES OF THE GROUND-WATER FLOW BASIN TO LOST RIVER RISE SPRINGS

GROUP EXERCISE

(MAPPING AND ANALYTICAL METHODS)

GROUP EXERCISE

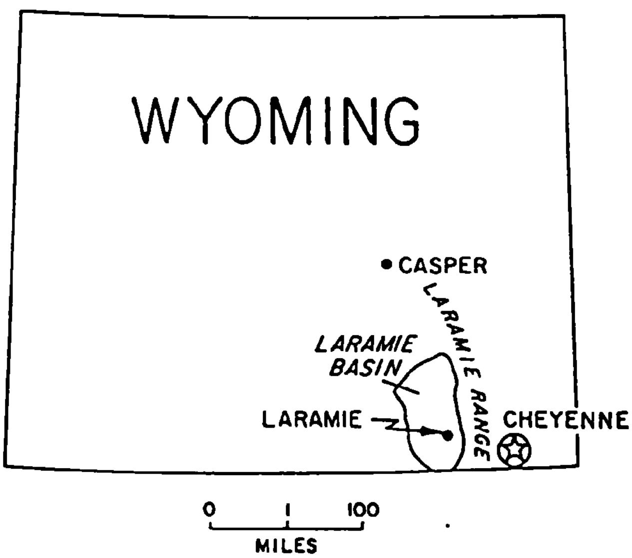
- LARAMIE BASIN WYOMING

r = 10800

- 3 SCENARIO'S
  - UNCONFINED, POROUS MEDIA

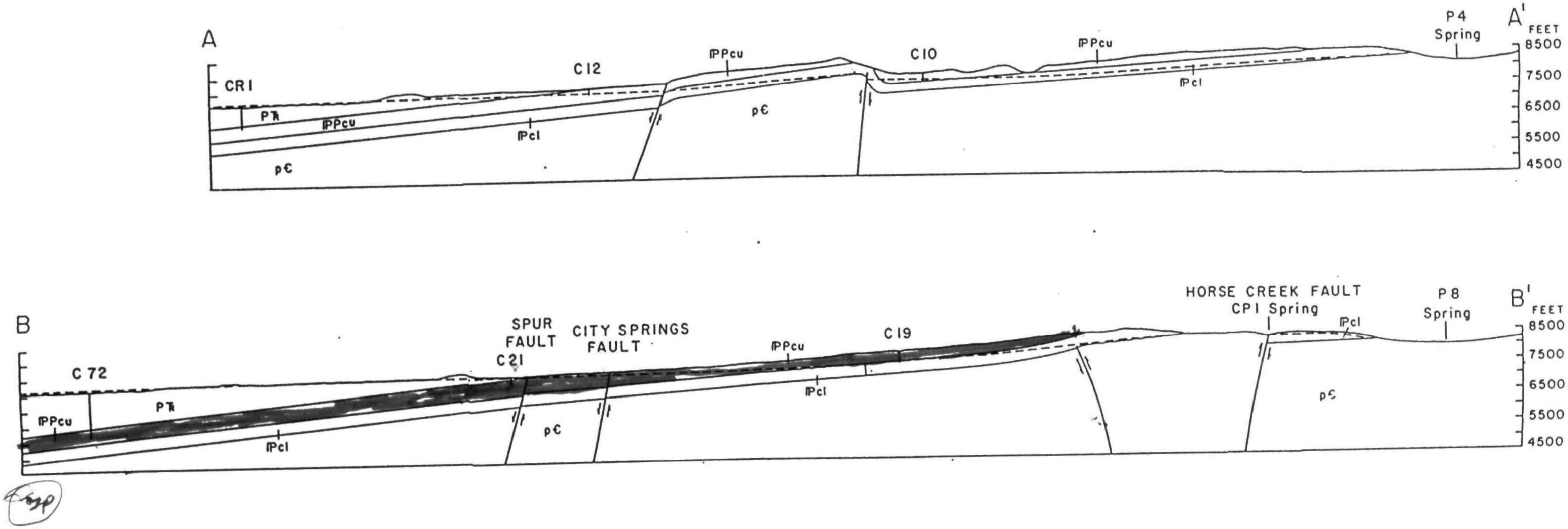
    i = .075

  - CONFINED, POROUS MEDIA
  - FRACTURED ROCK, UNCONFINED
- EXERCISE FORMAT
  - GROUPS OF 4 TO 5
  - PRESENTATION OF HYDROGEOLOGIC SETTING
  - ASSISTANCE DURING EXERCISE
  - SUMMARY FOR EACH SCENARIO

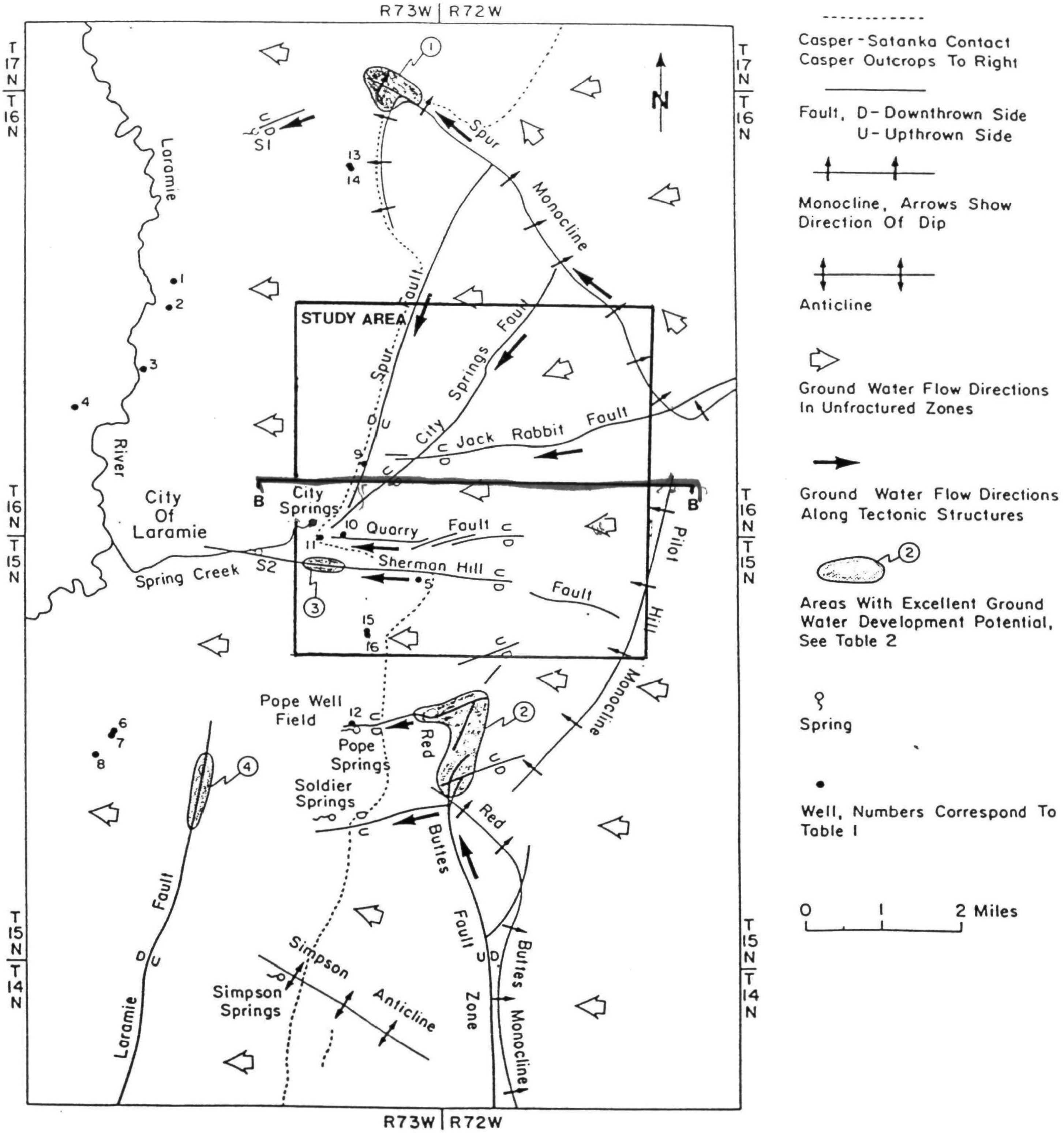


Location of the Laramie Basin and Laramie

Geologic cross sections, Laramie area, Albany County, Wyoming.



Slide 6.26



Locations of tectonic structures, selected wells and springs, and ground-water flow directions in the vicinity of Laramie, Wyoming.

4000 $\frac{8}{2\ 1/2}$ 12,800′ = 2.42 SM

Slide 6.27

4000 $\frac{21}{2\ 1/2}$ 33,600 = 6.36 SM

A = (6.36) 2.42 = 15.4 SM

EXERCISE I: UNCONFINED POROUS MEDIA (SCENARIO I)

WHPA CRITERIA: TOT

THRESHOLD: 5 YEAR

METHODS: A. CALCULATED FIXED RADIUS (VOLUMETRIC FLOW EQUATION)

B. UNIFORM FLOW ANALYTICAL MODEL WITH PORE WATER VELOCITY EQUATION

INPUT PARAMETERS:

WELL = C40

K = 0.70 FT/D

b = 200 FT

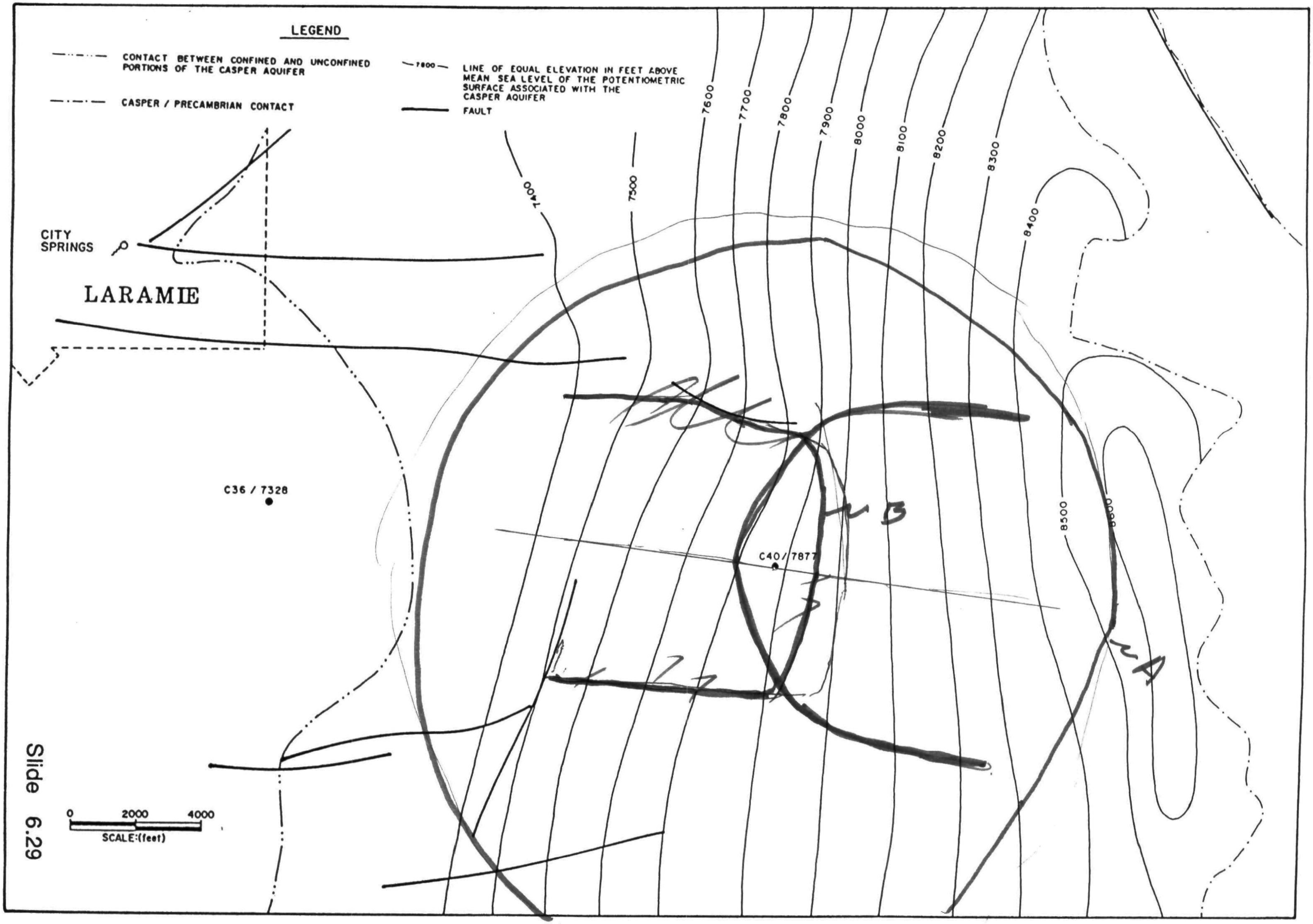
S = 0.001

Q = 1×10^5 FT^3/DAY

n = 0.01

H = 50'

EXERCISE I & II WORKSHEET



Slide 6.29

EXERCISE II: CONFINED POROUS MEDIA (SCENARIO 2)

WELL C36

WHPA CRITERIA: TOT

THRESHOLD: 5 YEAR

METHODS: A. CALCULATED FIXED RADIUS (VOLUMETRIC FLOW EQUATION)

$A = \frac{Q}{\ldots} = 4.2 \times 10^{8}\ FT^2 \approx 15\ Mi^2$

B. UNIFORM FLOW ANALYTICAL MODEL WITH PORE WATER VELOCITY EQUATION

- USE WHPAs FROM EXERCISE I AS SIMPLIFED SHAPES FOR WELL C36
- EVALUATE VALIDITY OF WHPAs FROM EXERCISE I IF DRAWN AROUND WELL C38

(i.e., DO CONFINING CONDITIONS PRESENT AT C38 ALLOW FOR REINTERPRETATION OF WHPA BOUNDARIES?)

NOTE: DEPTH TO AQUIFER IS 300 FT

EXERCISE III: FRACTURED ROCK AQUIFER (SCENARIO 3)

CITY SPRINGS

WHPA CRITERIA: FLOW BOUNDARIES

THRESHOLD: ZOC

METHODS: HYDROGEOLOGIC MAPPING

INPUT PARAMETERS:

K = 0.7 FT/D

b = 200 FT

S = 0.01

Q = 1×10^6 GAL/DAY

n = 0.20

RECHARGE =1.4 IN/YEAR

HINT: PERFORM MASS BALANCE
Q = RECHARGE RATE X RECHARGE AREA

$Q = KIA$

$A = b \times L$ $\quad b = \frac{I}{KA}$

$Q = TiL$

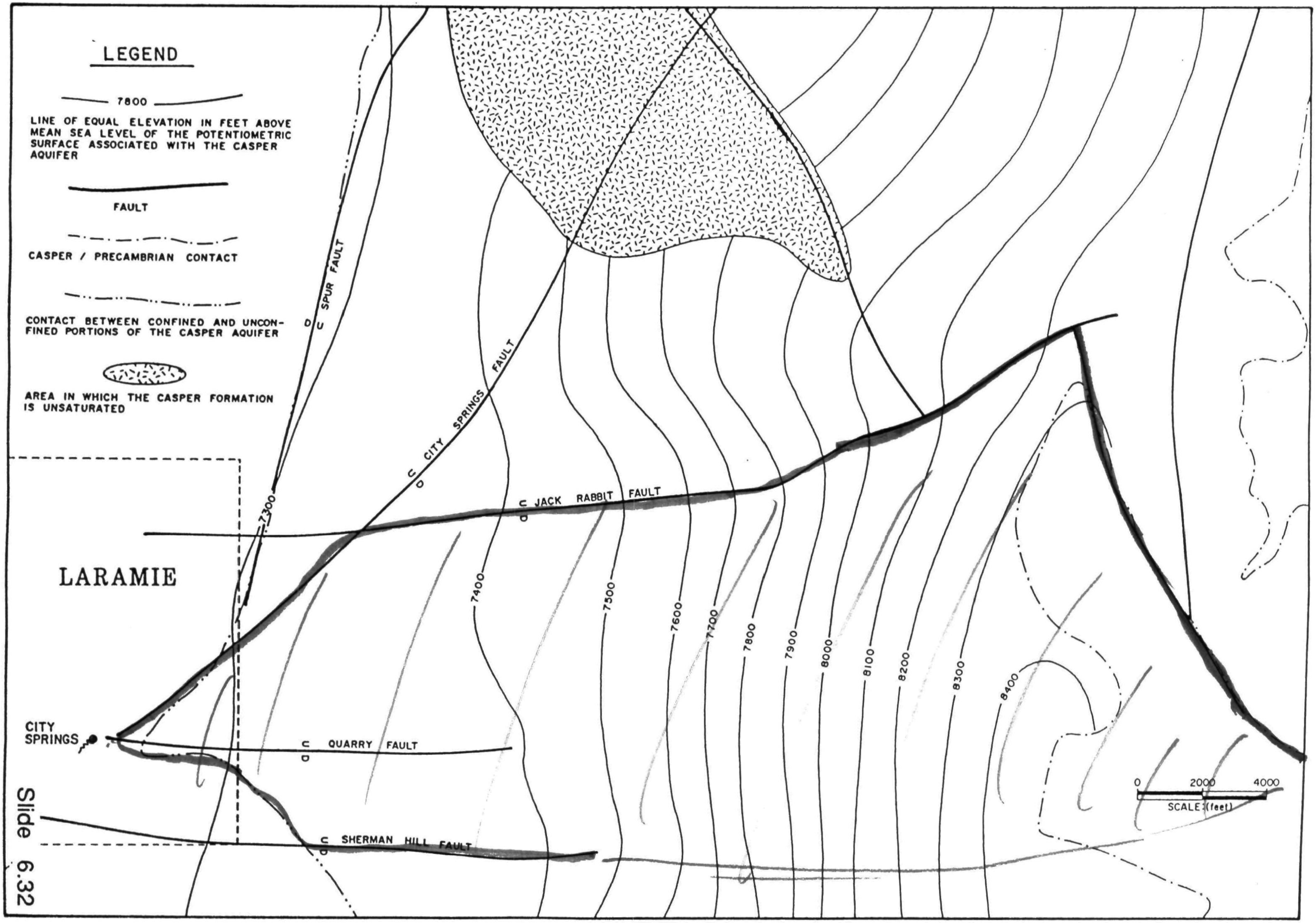
$L = \frac{Q}{Ti}$

$A = \frac{Q}{h} = \frac{10^6}{3\ 10^2} = \frac{1}{3}\ 10^4 = .34 \times 10^4 = 3400\ FT^2$

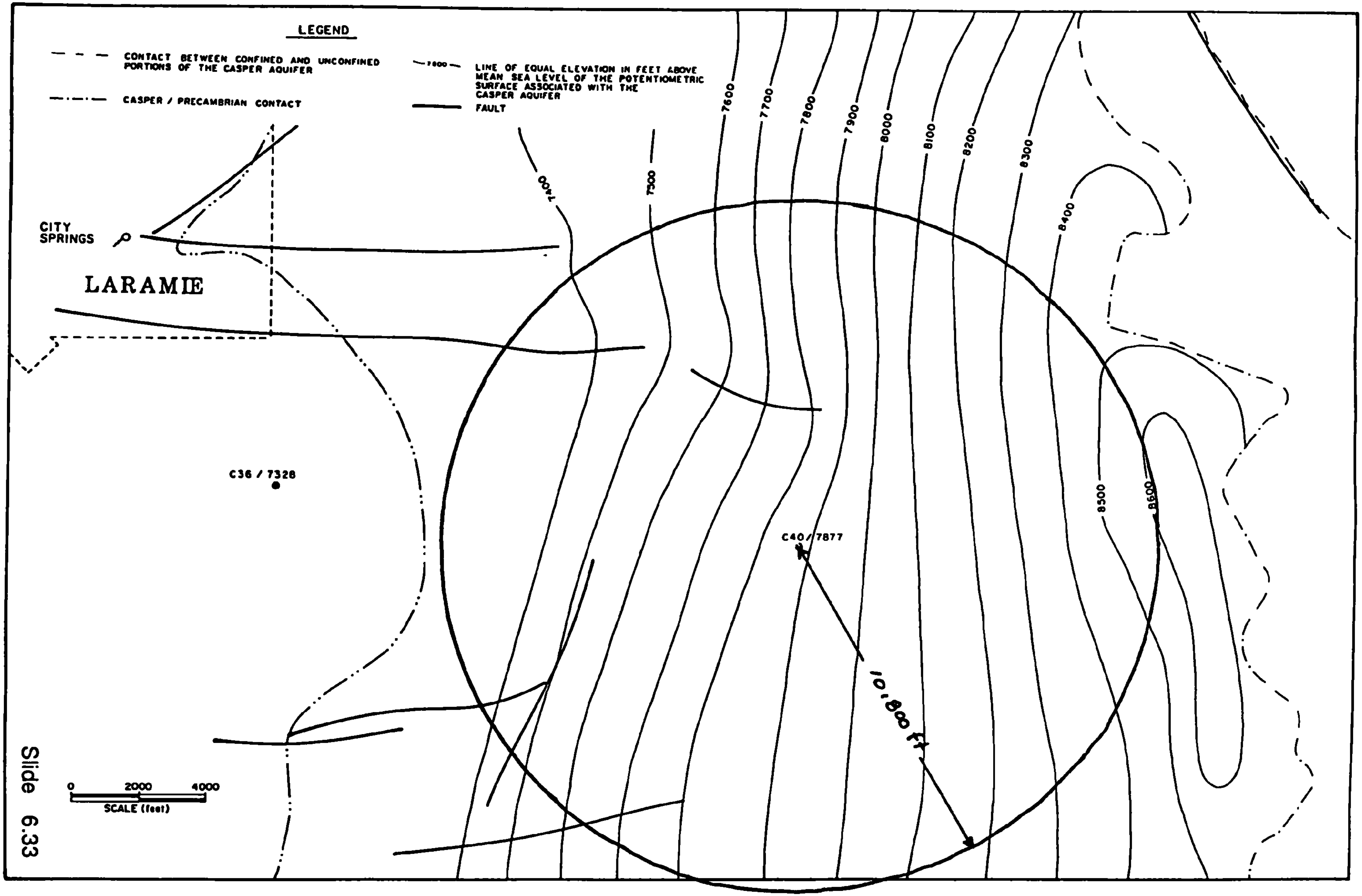
$\frac{(365)\ 10^6}{\frac{1.4}{12}} = A = \frac{12\,(365)}{7.48\,(1.4)}\ 10^6 = 418 \times 10^6\ FT^2$

$= 15$ sq mi

EXERCISE III WORKSHEET

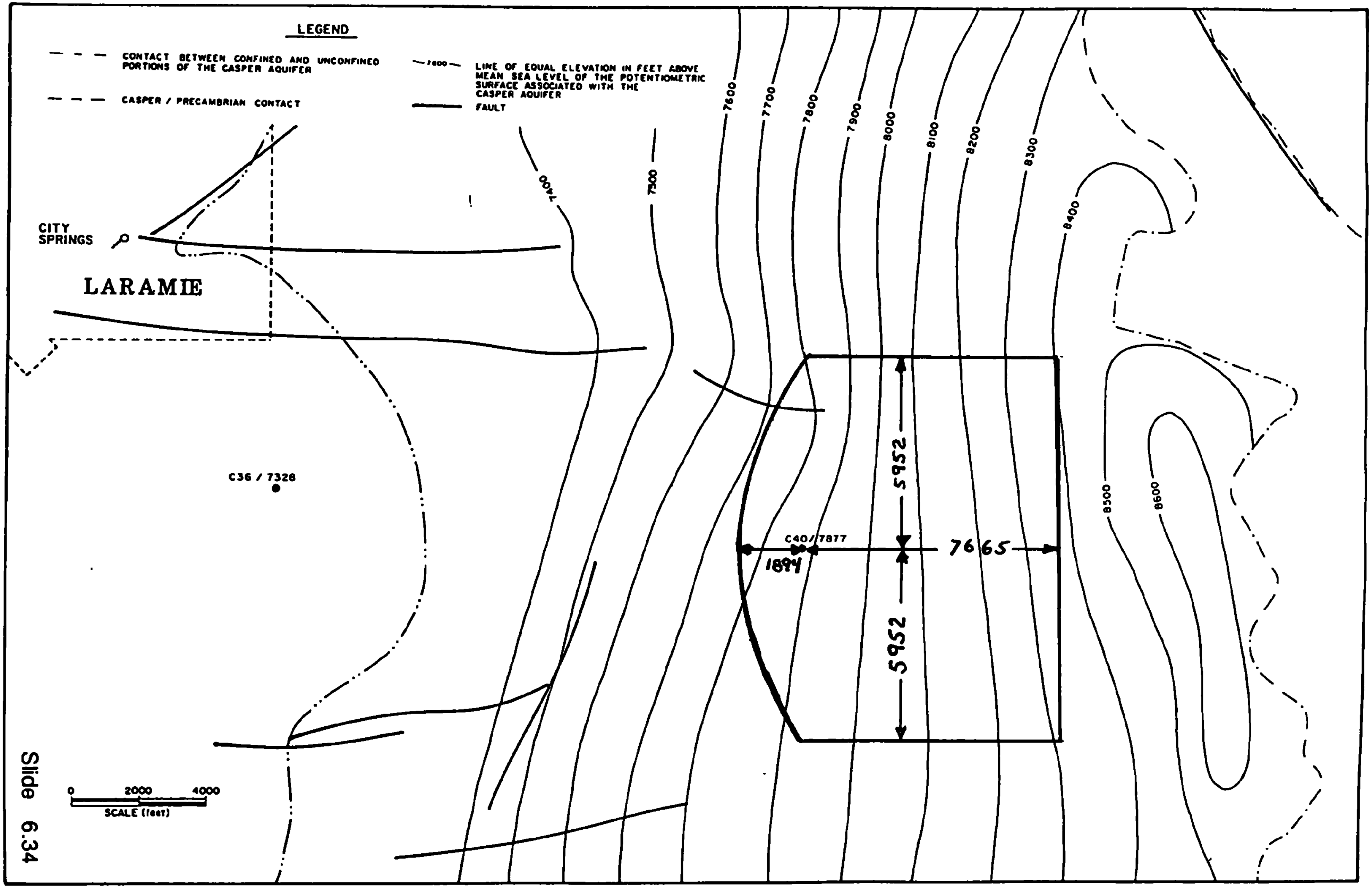


EXERCISE IA: CALCULATED FIXED RADIUS, VOLUMETRIC FLOW SOLUTION



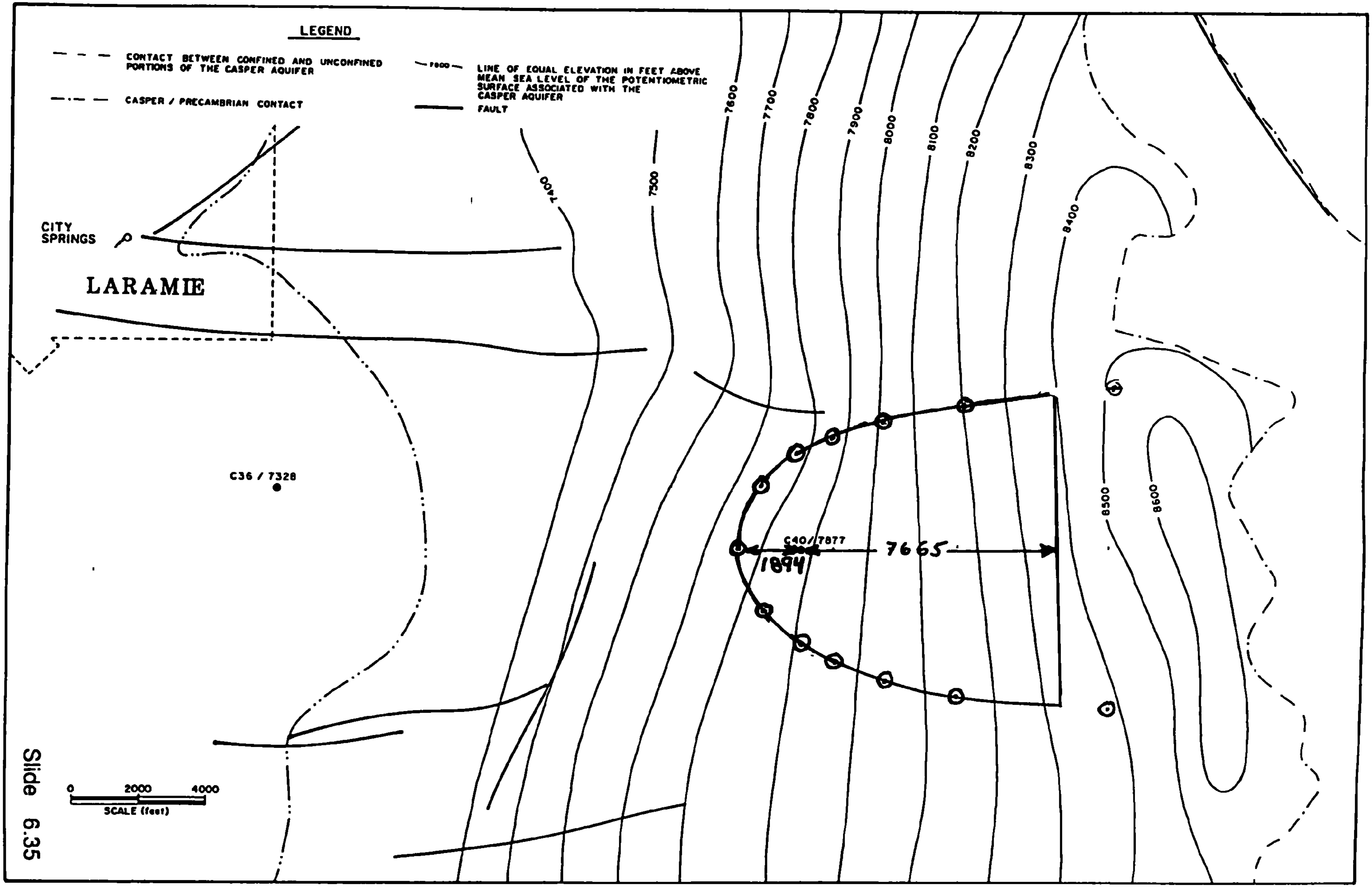
Slide 6.33

EXERCISE IB: UNIFORM FLOW ANALYTICAL FLOW MODEL SOLUTION

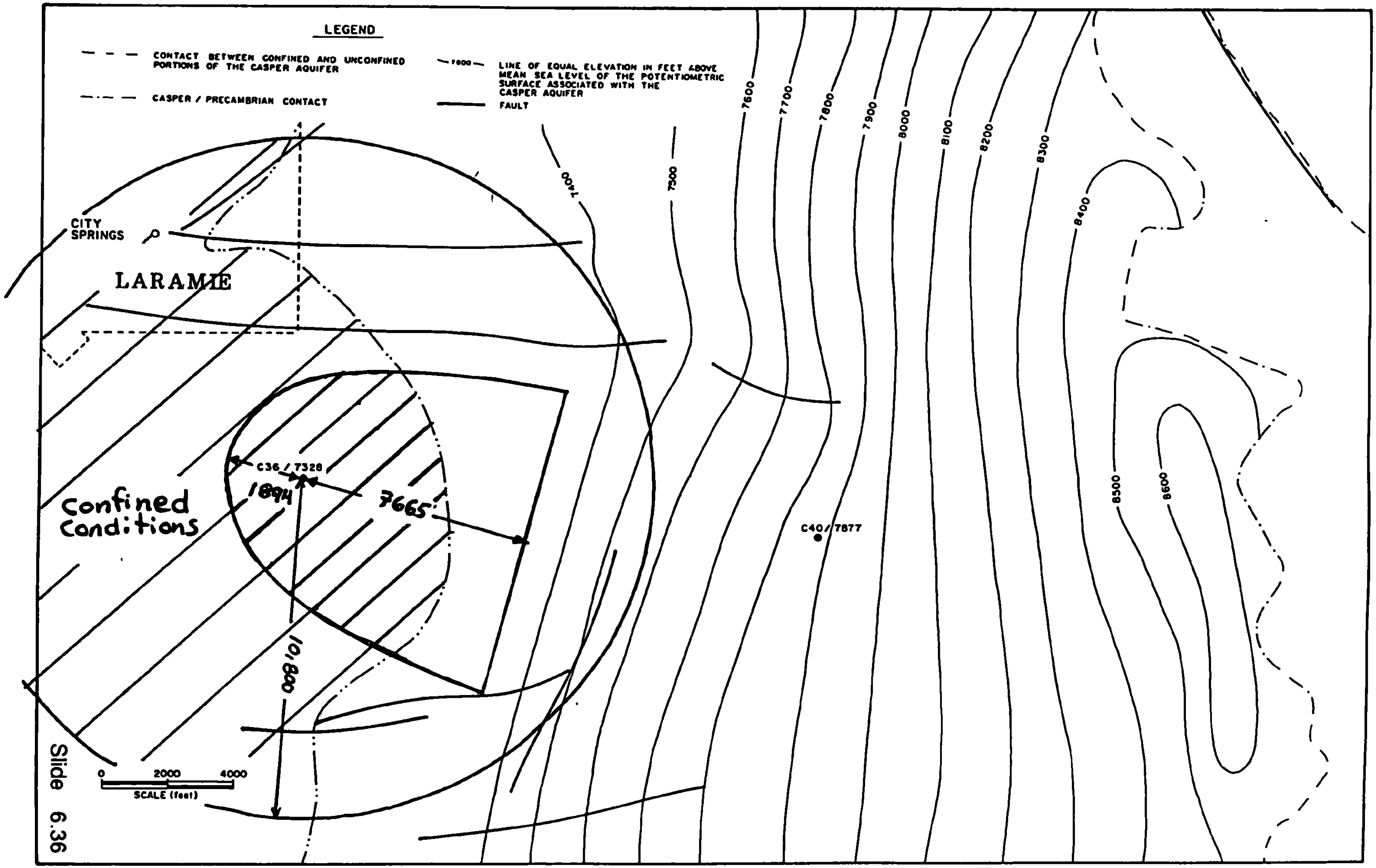


Slide 6.34

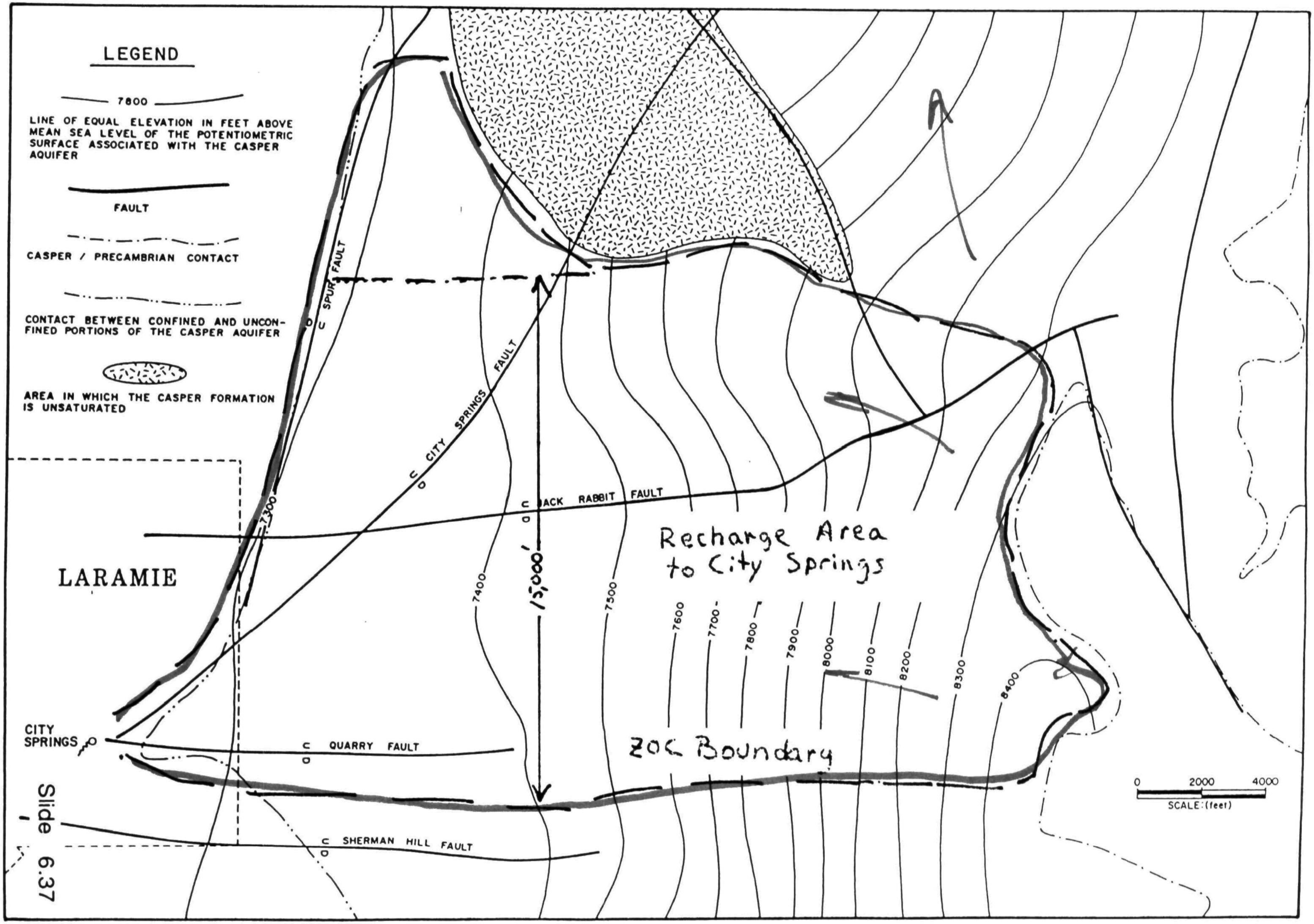
EXERCISE IB: UNIFORM FLOW ANALYTICAL FLOW MODEL SOLUTION



EXERCISE IIA: SIMPLIFIED VARIABLE SHAPES SOLUTION



EXERCISE III: RECHARGE AREA AND DARCY'S LAW SOLUTION



6. HYDROGEOLOGIC MAPPING METHODS

6.1 INTRODUCTION

In the hierarchy of WHPA delineation methods, hydrogeologic mapping methods are categorized above analytical methods and below numerical flow and transport modeling methods in terms of sophistication and cost.

Hydrogeologic techniques used in field investigations provide site-specific data and a detailed characterization of the aquifer. In this sense, the methods provide a more accurate representation of flow boundaries and aquifer features than do simple analytical techniques which often require simplifying assumptions (e.g., infinite boundaries).

Field mapping and data collection methods, however, cannot integrate the aquifer data into a comprehensive picture of the flow characteristics and expected time-response of the aquifer as can numerical flow and transport models.

Advantages

Hydrogeologic mapping is well suited to hydrogeologic settings dominated by near-surface flow boundaries, as are found in many glacial and alluvial aquifers with high flow velocities, and to highly fractured anisotropic aquifers, such as fractured bedrock and conduit-flow karst.

Disadvantages

The method requires specialized expertise in geologic and geomorphic mapping, plus significant judgment on what constitutes likely flow boundaries. This method is also less suited to delineating WHPAs in large or deep aquifers.

6.2 OVERVIEW OF HYDROGEOLOGIC MAPPING METHODS

Hydrogeologic mapping techniques can be employed to locate physical features for WHPA boundaries. Features such as ground-water flow system boundaries and principle flow conduits can in many circumstances be mapped.

Flow system boundaries, which can be mapped by various methods, are of three types:

- Impermeable boundaries,
- Ground-water flow divides, and
- Recharge boundaries

thologic changes can present a barrier to flow where an aquifer is in contact with less permeable material, such as bedrock or fine-grained deposits. Ground water divides often coincide with topographic divides and act as an upgradient limit of a ground-water basin. Recharge boundaries, such as streams or other surface water bodies, can act as a flow boundary in shallow aquifers which are in good hydraulic connection with the surface waters.

In many hydrogeologic settings, flow boundary, and TOT criteria can be mapped using geological, geophysical, and dye-tracing methods.

General Geological Mapping Methods

General geological methods include mapping of features such as topography, water levels, water-quality geologic contacts, and lineaments. Aquifer water-quality tests will also provide information on boundaries and the degree of confinement.

In simple cases, where topographic divides may safely be assumed to reflect ground-water divides, ground-water basins can often be quickly delineated using existing topographic maps (Slide 6.6).

.. more accurate definition of the ground-water basin can be developed from water level data from across the basin. Water levels can be plotted and contoured to determine the location of ground-water divides, as well as flow directions within the basin (Slide 6.7).

Water-quality data can be used to delineate the zone of contribution in some circumstances. For example, infiltering river water with a higher temperature can be traced to a well field (Slide 6.8).

Mapping of geologic contacts which act as flow boundaries can be accomplished using various geological data sources. A survey of published data may reveal geologic maps of the study area, which show geologic contacts at the surface and often include cross-sections illustrating the geologic relationships at depth (Slide 6.9).

Drilling logs are also a good source of subsurface information. Geomorphic features, such as escarpments and valleys, are often controlled by and therefore indicative of the underlying geology.

All geophysical techniques have certain limitations and their own particular advantages. The choice of a method depends on the hydrogeologic setting, the depth to be investigated, the desired quality of resolution and resources available for funding.

Dye-Tracing Methods

Principle flow conduits can be mapped in karst and fractured bedrock aquifers through the use of dye tracing techniques. After ground-water drainage basin divides have been delineated from topographic and water-table information, dye tracing can be used to define ground-water flow patterns, as well as to quantify flow rates.

Tracing studies involve the injection of a dye or some other tracer into the ground water through a sinkhole or other viaduct and monitoring suspected downgradient springs or discharge areas. Where the tracer is detected, the injection point is proven to be within the Zone of Contribution (ZOC) to the monitoring point (Slide 6.14).

The length of time for the tracer to appear is related to the flow rate. Flow rates may be related to the spring discharge rate. For a given path, TOT usually decreases as discharge rate increases.

Age Assessment (Tritium)

An assessment of tritium levels in confined aquifers can be used to determine age. Higher levels may indicate short residence time and leakiness of the confining strata.

Another anthropogenic compound, trichlorofluoromethane (CCl_3 F) has been used as tracer for determining leakage into confined aquifers. CCl_3 F is subject to sorption phenomena that affect its concentration in ground water (Russell and Thompson, 1983).

6.3 MAPPING EXERCISE

The mapping exercise involves a public water-supply spring in an unconfined karst aquifer in Kentucky. The Bowling Green, Kentucky area presented has been studied in great detail as part of an ongoing karst hydrology research program. A wellhead delineation study is in progress. Additional information is provided in a case study found in Appendix B.

HYDROGEOLOGIC SETTING

The study area surrounding Bowling Green is underlain by carbonate rocks of Mississippian Age, predominately the Ste. Genevieve Limestone, with the St. Louis and Girkin Limestones occurring in minor portions of the study area (Slide 6.18). The entire area is a mature karst terrane, exhibiting typical land form features associated with karst, such as sinkholes, sinking streams, and springs (Slide 6.19).

Solution enhancement of fractures and joints in the rock has created large subterranean conduits through which ground water can flow at high velocities. Such conduit flow can be several orders of magnitude higher than diffuse flow which occurs through intergranular pore space.

Flow patterns of ground water in karst aquifers can differ greatly from those in granular aquifers due to flow through channels. Furthermore, flow patterns within a single aquifer may change significantly between normal and high-flow conditions, because storm water can fill underground conduits, causing overflow to run off into channels which normally contain no water. These factors make the prediction of ground water flow direction difficult.

Flow rates between the major karst features (i.e., lakes, sinks, spring, and windows) were established as part of a study. Table 6.1 provides travel time data between selected points. Note that TOT is dependent upon the stage or water levels in the cave streams. Even at low stage, however, TOT across the basin is in the order of days.

METHOD AND CRITERIA SELECTION

Because conduit flow in mature karst aquifers generally does not follow ground-water flow patterns associated with porous media aquifers, using methods of wellhead protection based on simple shapes or analytical flow equations is unlikely to result in delineation of an effective WHPA.

For example, calculating a fixed radius based on the volumetric flow equation, or trying to determine the radial distance at which a certain drawdown occurs may be meaningless if a well receives some of its water from a solution cavity which has its origin a mile or more outside of the calculated zone of contribution. Also, large supplies of water are collected at springs, which must also be protected, but which cannot be evaluated using analytical equations derived for discharging wells.

For this reason, hydrogeologic mapping lends itself as the most useful tool in delineating both WHPAs and protection areas for springs in mature karst aquifers.

The first step in defining areas to protect wells and springs used for public water supply is to determine the boundaries of the ground water basin in which the spring or well is located. The ground water basin in a karst aquifer is defined as the entire area which drains to a spring or set of springs.

Delineation of the ground water basin can be accomplished through mapping of the potentiometric surface to determine general flow directions, coupled with dye-flow or other tracing techniques to better define flow routes.

Ideally, both the potentiometric surface map and the tracing should be done for normal and high-flow (storm event) conditions. Having defined the ground water basin and the general flow patterns within the basin, the next step involves determination of the contributing area for an individual well or spring by examining the flow patterns and potentiometric surface upgradient of the water supply.

Depending on the proximity of the well to the boundary of the ground-water basin and on flow rates as determined through dye-tracing, an appropriate delineation criteria may be time of travel (TOT) or flow boundaries. The ground water divide would be appropriate for a well located near the edge of the basin.

EXERCISE

Using the attached worksheet map delineate the boundaries if the ground-water basin (ZOC) supplying the springs at Lost River Rise. (Hint: determine location of ground-water divide). Shown on the worksheet mao are water-level contours, dye-trace study results and the location of important hydrologic features.

TABLE 6.1
TRAVEL TIMES IN HOURS IN THE LOST RIVER BASIN
(From Crawford, et. al., 1987)

BLUE HOLE TO RISE

Date of Trace	Initial stage (feet)	Qi cfs	Centroid stage (feet)	Qc cfs	Time of first arrival hrs.	Time of centroid hrs.
11/7/82	---	12.4	---	12.4	68.0	87.64
9/22/83	6.35	9.2	6.67	10.8	80.5	98.56
3/30/84	7.49	145	7.55	160	10.0	10.33
6/18/84	6.65	70	6.66	70	16.5	19.57
7/18/84	6.01	29	5.97	27	32.5	42.5

BIG SINKING CREEK TO RISE

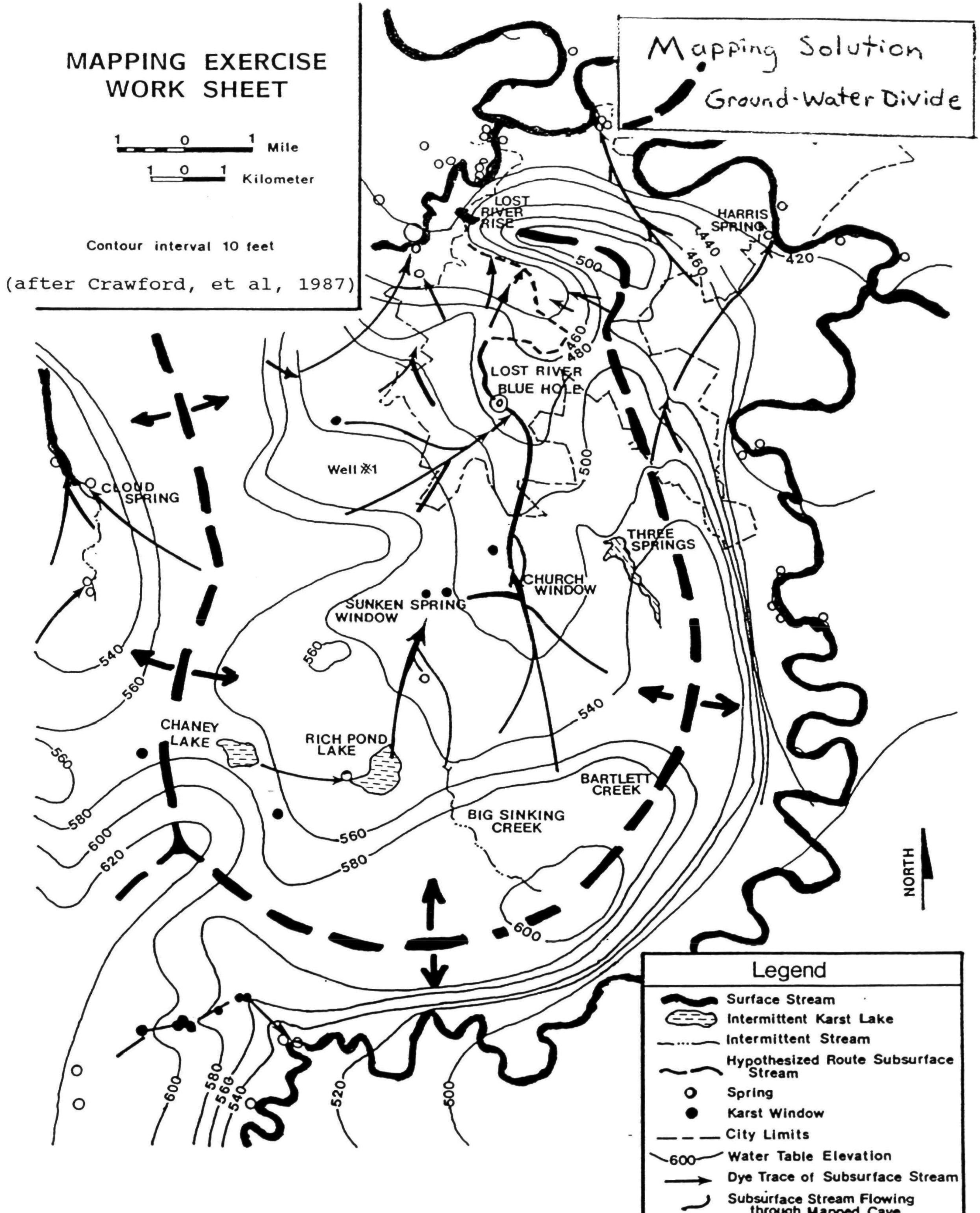
Date of Trace	Initial stage (feet)	Qi cfs	Centroid stage (feet)	Qc cfs	Time of first arrival	Time of centroid
11/7/82	---	12.4	----	12.4	185	224
3/30/84	7.39	130	7.4	138	29.5	32.7
4/18/84	6.85	47	6.87	50	48.5	54.7
6/18/84	6.8	70	6.66	70	39.25	47.6
7/18/84	5.89	25	5.88	25	83	102

BIG SINKING CREEK TO BLUE HOLE

Date of Trace	Initial stage (feet)	Qi cfs	Centroid stage (feet)	Qc cfs	Time of first arrival	Time of centroid
3/30/84	6.11	127	6.05	120	19.5	20.8
4/18/84	5.25	63	5.23	63	27.5	32.2
*6/1/84	5.86	105	5.86	105	18.5	22.01
7/18/84	2.9	25	2.57	17	43	54

* Trace started when Big Sinking Creek ponded.

Results of quantitative dye traces.



MAPPING EXERCISE
WORK SHEET
1 0 1 Mile
1 0 1 Kilometer
Contour interval 10 feet
(after Crawford, et al, 1987)
Mapping Solution
Ground-Water Divide
LOST RIVER RISE
HARRIS SPRING
440
460
420
500
460
480
LOST RIVER BLUE HOLE
Well ※1
CLOUD SPRING
THREE SPRINGS
CHURCH WINDOW
SUNKEN SPRING WINDOW
560
540
560
CHANEY LAKE
RICH POND LAKE
540
BARTLETT CREEK
BIG SINKING CREEK
560
580
600
620
560
580
600
NORTH
600
580
560
540
520
500
Legend
Surface Stream
Intermittent Karst Lake
Intermittent Stream
Hypothesized Route Subsurface Stream
Spring
Karst Window
City Limits
600 Water Table Elevation
Dye Trace of Subsurface Stream
Subsurface Stream Flowing through Mapped Cave

6.4 GROUP EXERCISE

The Laramie basin in Wyoming is used as the setting for these exercises (Slide 6.25, 6.26, and 6.27). A case study describing regional and local geology and hydrology is provided in Appendix B.

Three scenarios have been constructed each with a separate set of problems. Some of the parameter values presented are ficticious.

SCENARIOS

Scenario 1. Wells located in an unconfined, porous media aquifer.

In the Laramie area, the parts of the Casper aquifer between major tectonic structures can be treated as an unconfined/porous media aquifer at the scale of a water-supply well or well field. The wellhead protection area criteria distance, drawdown, time of travel, and flow boundaries, are applicable to delineating a protection area for a well located in an unconfined porous- media aquifer.

Delineation methods that use a fixed radii, simplified shapes, analytical flow equations, or numerical models can be used to define a protection area around a well or a spring in this type of setting.

Delineation methods that take into consideration site-specific hydrogeologic conditions (i.e. analytical methods and numerical methods) will define an area for protection that is somewhat more realistic than the simpler methods that generate a standard area.

Senario 2. Wells located in a confined, porous media aquifer with a nearby recharge area.

Another portion of the Casper Aquifer in the Laramie area is confined. The degree of confinement is such that most recharge occurs in a nearby unconfined portion of the aquifer. A confining unit separating a porous media aquifer from the ground surface provides some protection to the water source. Therefore, for those cases where the recharge area is in close proximity to the well, it may be appropriate to map the recharge area as the WHPA, rather than mapping an area immediately surrounding the well. This decision would depend on two factors.

1. The distance of the recharge area from the well, and the time it would take a contaminant released in the recharge area to arrive at the well.

2. The degree to which the overlying confining unit protects the aquifer. The protective capacity of the confining unit depends, in part, on the presence of fractures, improperly abandoned wells, and the vertical gradient across the confining bed. If a number of fracture zones or other conduits are present it may be appropriate to map the area around the well as a WHPA as well as all or relevant parts of the recharge area.

<u>Scenario 3</u>. Wells and Springs located in close proximity to a fracture zone.

Fractured-rock aquifers share many characteristics with conduit karst aquifers. Fracturing has created conduits through which ground water can flow at high velocities. Velocities in fractured rocks however do not usually match the velocity found in karst aquifers because fracture openings have not been enlarged to the same extent by dissolution.

Fractured-rock aquifers generally have relatively little storage capacity in the pore space of the aquifer, compared to that in porous, granular aquifers. A fracture zone capable of significant water supply is usually the result of storage from the matrix rock being discharged to the fracture system in significant quantities. This is the case with the Casper aquifer near Laramie.

Because of the rapid, preferred flow through the fracture zone, the most appropriate WHPA delineation criteria are probably hydrogeologic mapping of the area supplying the fracture zone or zone of contribution (ZOC), combined with a time-of-travel (TOT) calculation to determine a reasonable WHPA.

EXERCISES

Exercise I. Wells located in an unconfined porous media aquifer. (Scenario 1 - Slide 6.29)

Using the following aquifer parameters and a TOT criteria threshold of 5 years, delineate a WHPA around the pumping well No. C40 using the techniques of a) Calculated Fixed Radii (Volumetric Flow Equation), b) Uniform Flow Analytical Model. Use a TOT calculation to delineate the upgradient extent of the WHPA. Be careful to take into consideration any hydrogeologic boundaries that may exist.

K = .70 ft/d
b = 200 ft
S = .01
Q = 1×10^5 ft^3/day
n = .01
H = 50'

Exercise II. Wells located in a confined porous media aquifer with a nearby recharge area (Scenario 2).

a. Use the WHPAs generated in Exercise I as simplified variable shapes appropriate for the Casper aquifer in the Laramie Basin. Position both shapes as WHPAs for Well C36.

b. Evaluate the validity of WHPAs delineated in Exercise I if they were drawn around Well No. C36. Do the confining conditions present at C36 allow for a reinterpretation of WHPA boundaries?

Exercise III. Wells & Springs located in close proximity to a fracture zone (Scenario 3).

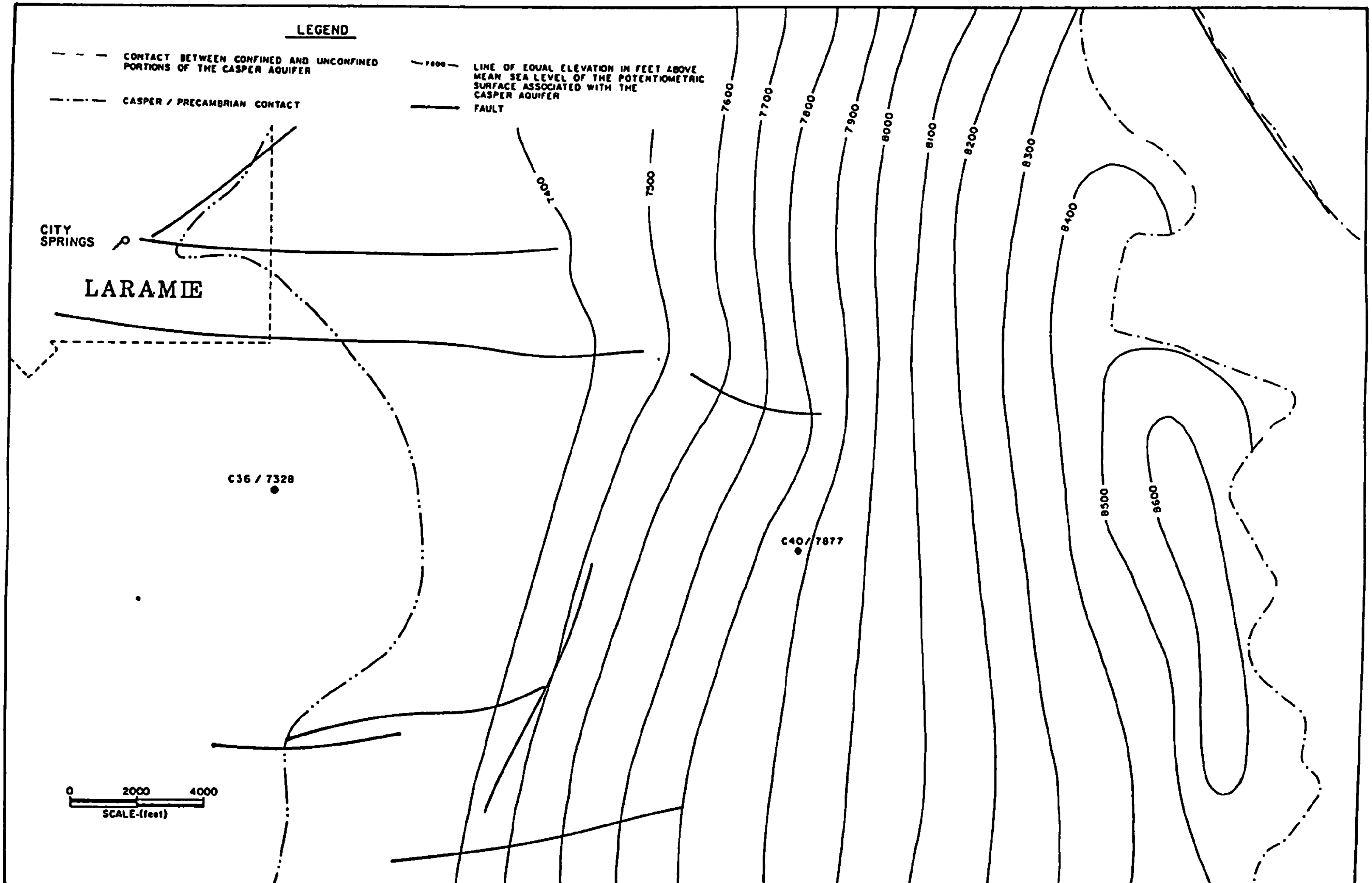
Using the aquifer parameters given below and the map given in Exercise I delineate the most appropriate WHPA for City Springs by:

a. Mapping the area that supplies water to the fault zones associated with the spring.

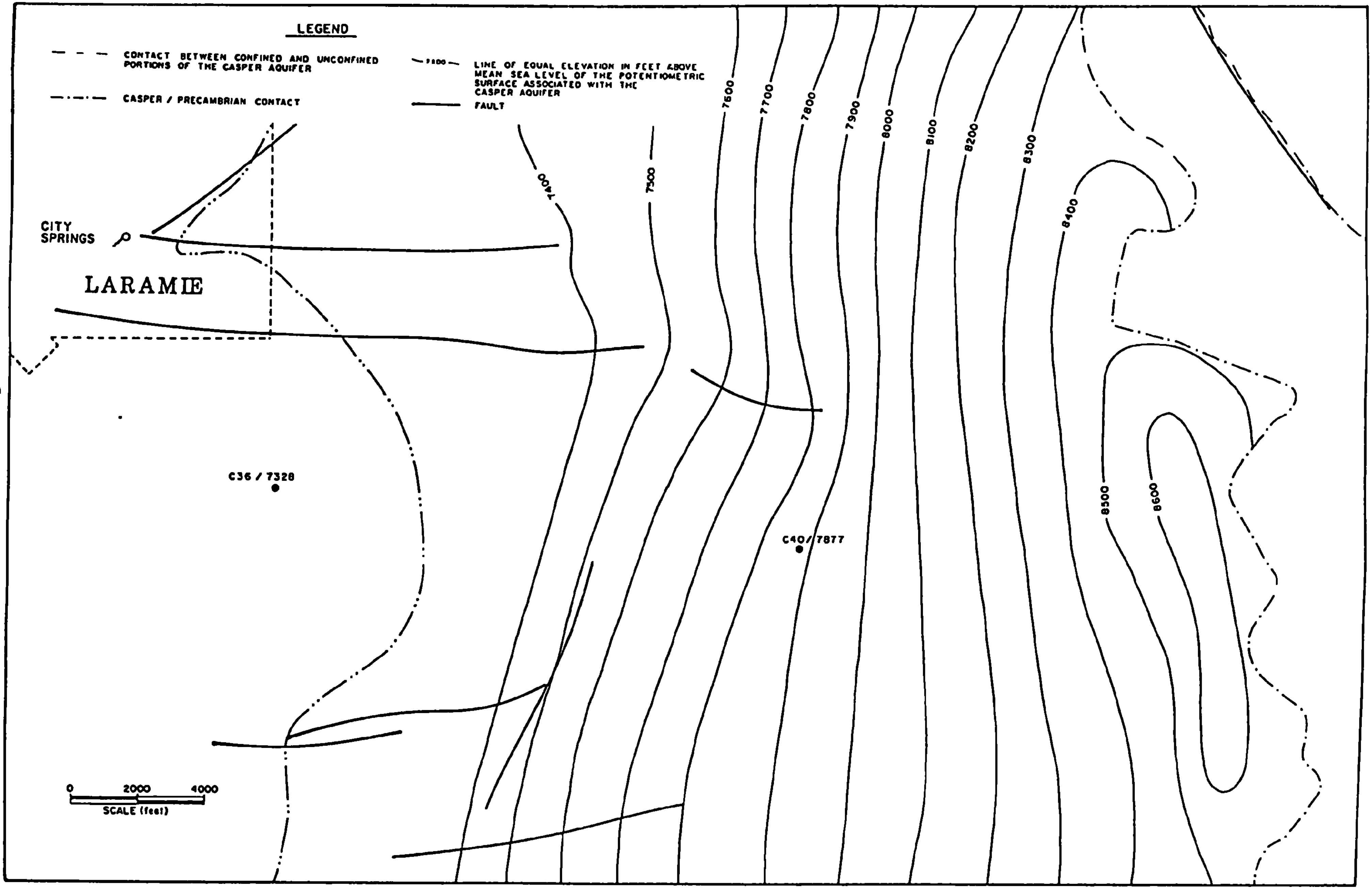
K = .7 ft/day
b = 200 ft
S = .01
Q = 1×10^6 gal/day
n = .2
recharge rate = 1.4 in/yr

Hint: Perform a mass balance on the water discharging at the spring with water collected in the recharge area of the spring.

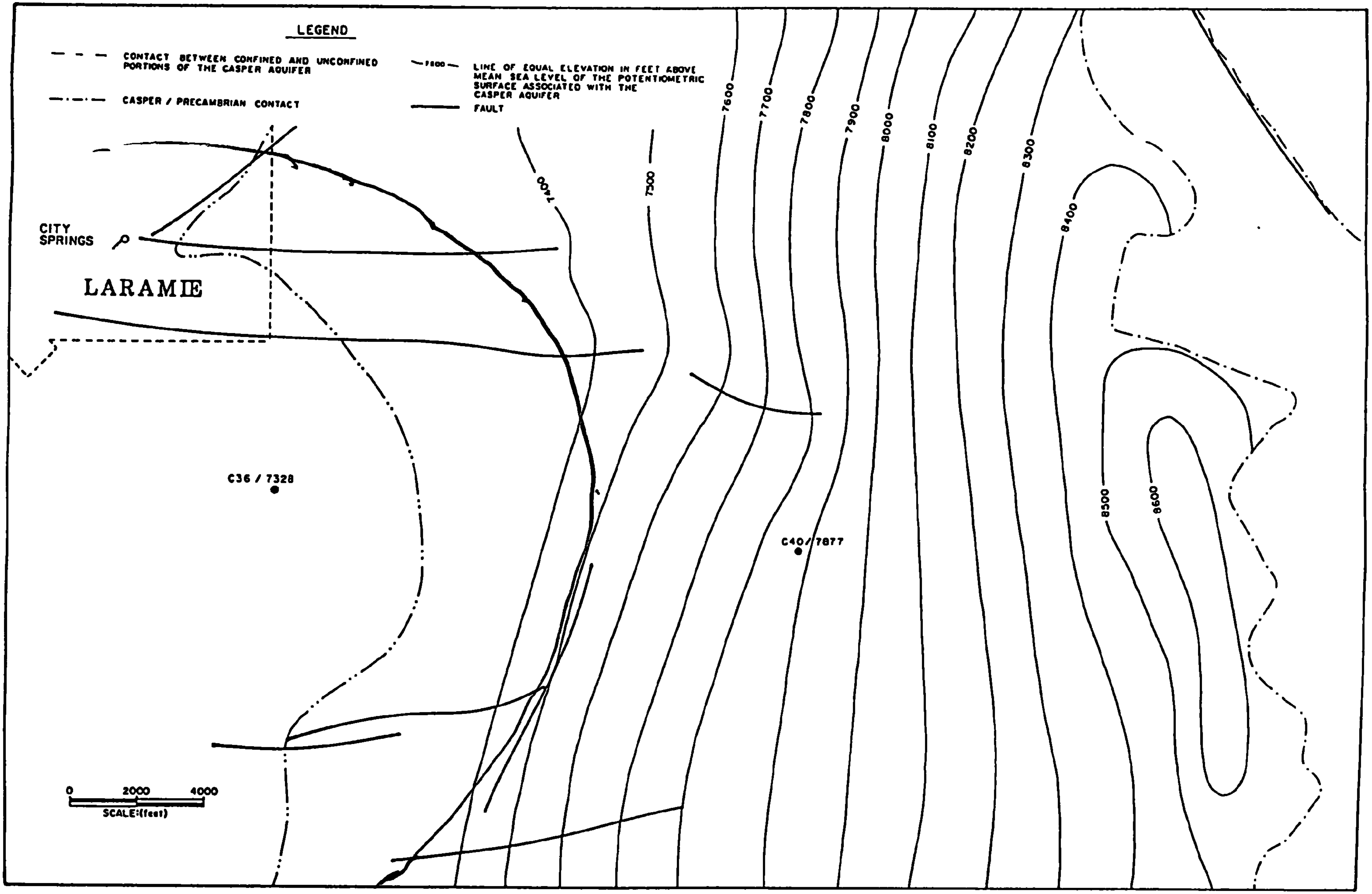
EXERCISE I & II WORKSHEET



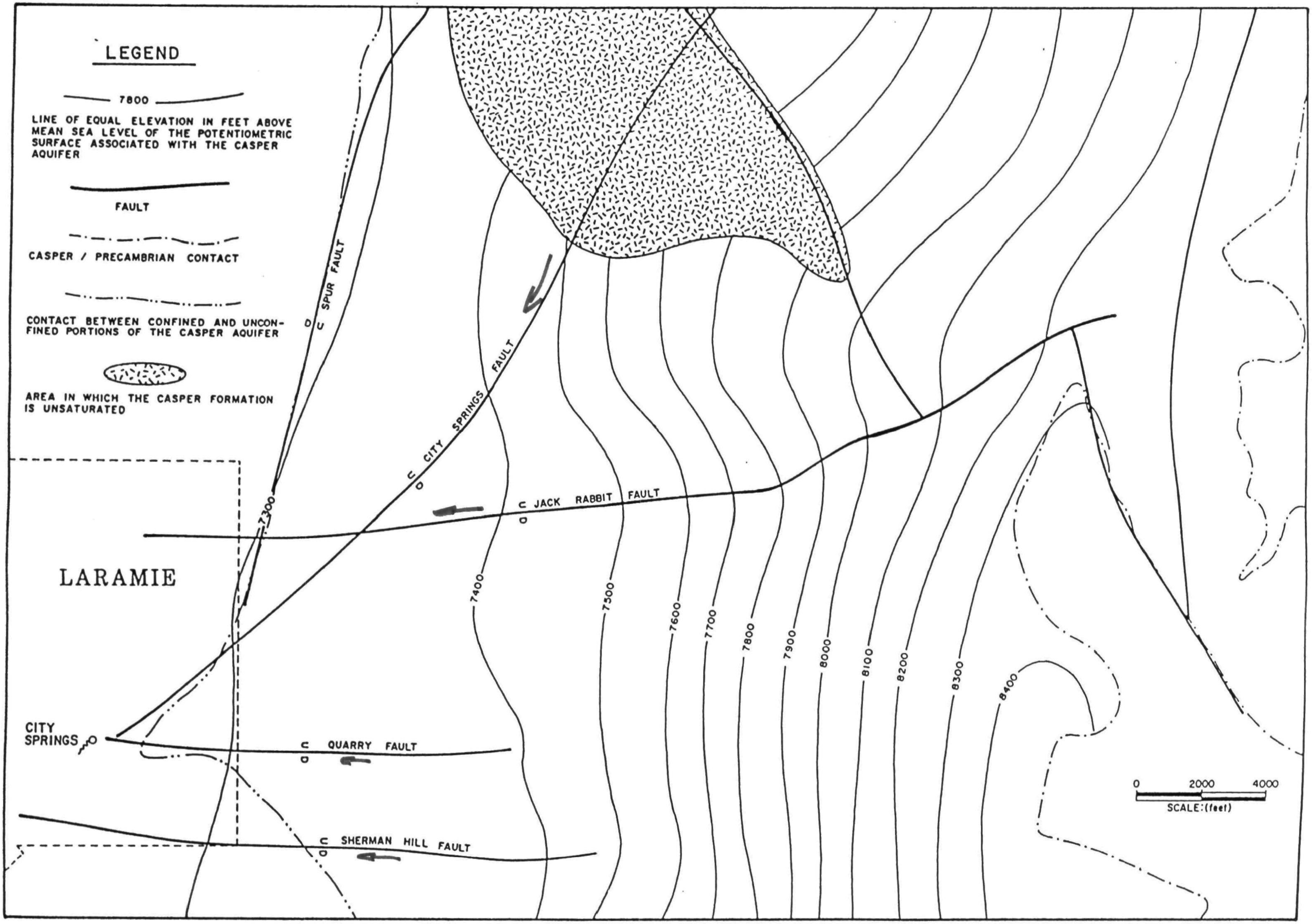
EXERCISE I & II WORKSHEET



EXERCISE I & II WORKSHEET



EXERCISE III WORKSHEET



6.4 GROUP EXERCISE ANSWER

Exercise I. Wells located in an unconfined porous media aquifer

Aquifer parameters given are:

K = .70 ft/day
b = 200 feet
t = 5 years = 1825 days
S = 0.01
Q = $1\text{x}10^5$ ft^3/day
n = .01
H = 50 feet

Aquifer parameters that need to be calculated:

i = 0.06 (estimated from the potentiometric map)

$$v = \frac{Ki}{n} = \frac{(.70 \text{ ft/day})(.06)}{.01} = 4.2 \text{ ft/day}$$

Method A: Calculated Fixed Radius using the Volumetric Flow Equation

$$r = \sqrt{\frac{Qt}{\pi n H}} = \sqrt{\frac{(1\text{x}10^5 \text{ ft}^3\text{/d})(1825\text{d})}{\pi(.01)(50 \text{ ft})}} = 10779 \text{ ft}$$

= 2.04 miles

Slide 6.33 shows the fixed radius WHPA.

Method B: Uniform Flow Analytical Model

Distance to down-gradient null point

$$X_L = -\frac{Q}{2\pi kbi} = \frac{1\text{x}10^5 \text{ ft}^3\text{/d}}{2\pi\ (.70 \text{ ft/d})(200 \text{ ft})(.06)} = -1894 \text{ ft}$$

1625 ft

Boundary Limit

$$Y_L = \pm\frac{Q}{2kbi} = \pm\frac{1\text{x}10^5 \text{ ft}^3\text{d}}{2(.70 \text{ ft/d})(200 \text{ ft})(.06)} = \pm 5952 \text{ ft}$$

± 4762 ft

Uniform-Flow Equation

$$-\frac{Y}{X} = \text{Tan}\ \frac{2\pi kbi}{Q}\ Y$$

, this equation reduces

to: $x = -y \cot (y/-X_L)$

X	Y
-1131	±2000
-640	±2500
-39.5	±3000
995.6	±3500
2403	±4000
4681	±4500
9116	±5000

Distance to 5-year TOT line = (velocity)(3650 days)

= (4.2 ft/d)(3650 days) = 7665 ft = 1.45 mi

Slides 6.34 and 6.35 show WHPAs for the uniform flow equation solution.

Exercise II.

a. Slide 6.36 shows the positioned WHPA shapes

b. In this exercise a portion of the WHPA, close to the well, is confined while another more distant portion is unconfined. In some cases, it may be argued that the confined portion of the aquifer should be eliminated from the WHPA. The confining unit must be able to provide sufficient protection to the underlying aquifer so that a contaminant release at the surface could not make its way to the aquifer. A confined aquifer that is deeper than 300 feet and does not have fractures or other conduits present in the confining unit is mentioned in the Delineation Guidelines as being relatiely isolated. The confining unit in the vicinity of Well C-36 is approximately 300-feet thick and there is no indication of the presence of fractures or other conduits.

Exercise III. Map recharge area for a City Springs

Two different methods can be used to map the recharge area

Method A. Use the recharge rate of 1.4 in/year and calculate the area needed to supply a discharge rate of 1 x 10^6 gal/day.

Recharge rate = 1.4 in/year = .117 ft/yr

Discharge rate =

$$1 \times 10^6 \text{ gal/day} \times \frac{1.337 \times 10^{-1} \text{ ft}^3}{\text{gal}} \times \frac{365 \text{ days}}{\text{year}}$$

$$= 4.9 \times 10^7 \text{ ft}^3/\text{year} =$$

$$\text{Area} = \frac{\text{Discharge rate}}{\text{Recharge rate}} = \frac{4.9 \times 10^7 \frac{\text{ft}^3}{\text{year}}}{.117 \frac{\text{ft}}{\text{year}}} = 4.2 \times 10^8 \text{ ft}^2$$

AREA = 15.0 miles^2

The recharge area is interpreted to lie between faults leading to spring and upgradient aquifer boundary as shown in Slide 6.37.

Method B

Using Darcy's law

$$Q = KIA$$

where A = bxL, then if T=Kxb
by substitution and rearrangement

$$Q = TiL$$

$$L = \frac{Q}{Ti}$$

K = .7 ft/day

i = .06

b = 200 ft

$$Q = 1 \times 10^6 \text{ gal/day} \times \frac{1.337 \times 10^{-1} \text{ ft}^3}{\text{gal}} = 1.3 \times 10^5 \frac{\text{ft}^3}{\text{day}}$$

$$T = Kb = \frac{.7\ ft}{day} \times (200\ ft) = 140\ ft^2/day$$

$$L = \frac{1.3 \times 10^5\ ft^3/day}{(140\ ft^2/day)\ (.06)} = 1.5 \times 10^4\ ft = 3.0\ mi$$

L = 3.0 miles

The zone contributing to fracture flow using Darcy's law is shown in Slide 6.37.

7. Numerical

PRESENTATION SLIDES

NUMERICAL MODELING METHODS

WHPA DELINEATION METHODS

1) ARBITRARY FIXED RADIUS

2) CALCULATED FIXED RADIUS

3) SIMPLIFIED VARIABLE SHAPES

4) ANALYTICAL METHODS a numerical method in which you have to make simplifying solutions

5) HYDROGEOLOGIC MAPPING

6) NUMERICAL FLOW / TRANSPORT MODELS

here you don't have to make simplifying assumptions

NUMERICAL MODELING METHODS

DESCRIPTION

Delineation of WHPAs using computer models that approximate ground-water flow and/or transport equations numerically

ADVANTAGES

- have the potential to be very accurate (however, always check them over to see if they make sense)
- can be applied to nearly all types of hydrogeologic settings
- can simulate dynamic aspects of ther hydrogeologic system that affect WHPA size and shape

DISADVANTAGES

- costs of implementation are relatively high compared to other methods
- considerable expertise in hydrogeology and modeling is required to use numerical methods
- misuse of model can lead to innacurate results
- limitations on grid spacing and density make numerical models less suitable than analytical methods in assessing drawdowns close to pumping wells (you average conditions within each cell of the grid. Thus, the larger the cell the more inaccurate, especially close to those wells with dramatic drawdown)

NUMERICAL GROUND-WATER FLOW AND CONTAMINANT TRANSPORT MODELING

- SIMPLY ANOTHER HYDROGEOLOGIC TOOL

- FORCES INTEGRATION OF AVAILABLE DATA INTO A CONSISTENT ANALYSIS

- PROVIDES QUANTITATIVE FRAMEWORK FOR SYSTEM ANALYSIS UNDER CHANGED CONDITIONS

- ALLOWS BETTER UNDERSTANDING OF COMPLEX FLOW SYSTEMS

TYPES OF GROUND-WATER MODELS

CONCEPTUAL

- DESCRIPTION OF KEY AQUIFER FEATURES; BASIS FOR OTHER TYPES OF MODELS

PHYSICAL (SAND TANK)

- NON-SCALED
- HYDRAULICALLY-SCALED

ANALOG *(based on physical properties that are analogous to GW flow)*

- PHYSICAL ANALOG
  - VISCOUS FLOW (HELE-SHAW)
  - ELASTIC MEMBRANE
- ELECTRIC ANALOG
  - CONDUCTIVE PLATE
  - RESISTOR-CAPACITOR CIRCUIT

MATHEMATICAL *(most common type)*

- ANALYTICAL
  - CLOSED-FORM
  - SEMI-ANALYTICAL
  - ANALYTICAL ELEMENT
- NUMERICAL
  - FINITE DIFFERENCE *} most commonly used*
  - FINITE ELEMENT
  - BOUNDARY INTEGRAL

ANALOGIES TO GROUND-WATER FLOW

VARIABLE	GROUND WATER	ELECTRICITY	HEAT
Potential	Head, h	Voltage, V	Temperature, T
Quantity transported	Volume discharge rate	Electrical charge	Thermal conductivity
Physical property of medium	Hydraulic conductivity	Electrical conductivity	Thermal conductivity
Relation between potential and flow field	Darcy's law $q = -K \text{ grad } h$ where q is specific discharge	Ohm's law $i = -\sigma \text{ grad } V$ where i is electrical current	Fourier's law $q = -K \text{ grad } T$ where q is heat flow
Storage quantity	Specific storage, S_s	Capacitance, C	Heat capacity, C_v

(Modified from Wang and Anderson, 1979)

Finite-Difference and Finite-Element Discretization Schemes

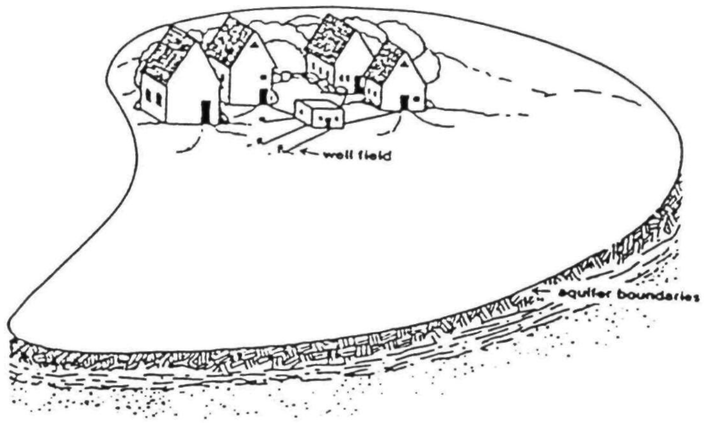
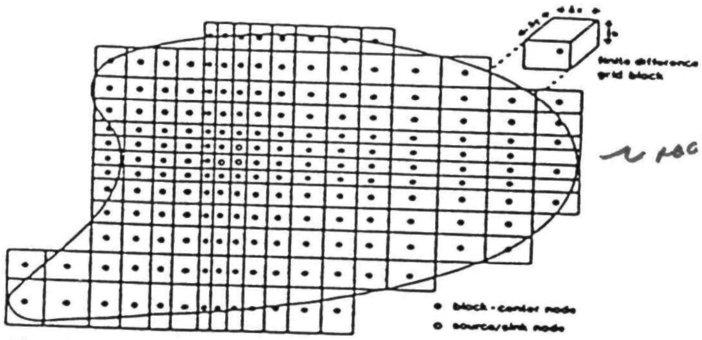
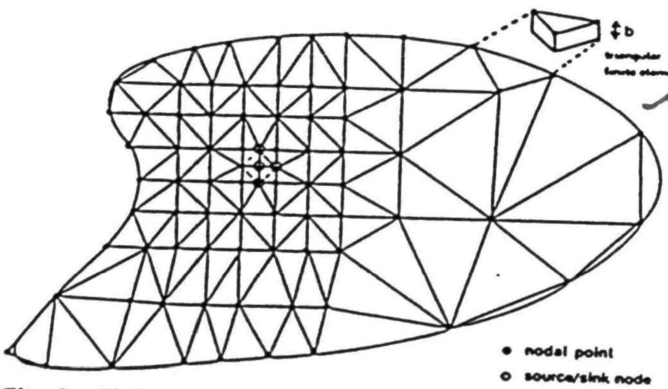


Fig. 4a. Map view of aquifer showing well field and boundaries.



~ rectangular

Fig. 4b. Finite-difference grid for aquifer study, where Δx is the spacing in the x-direction, Δy is the spacing in the y-direction and b is the aquifer thickness.

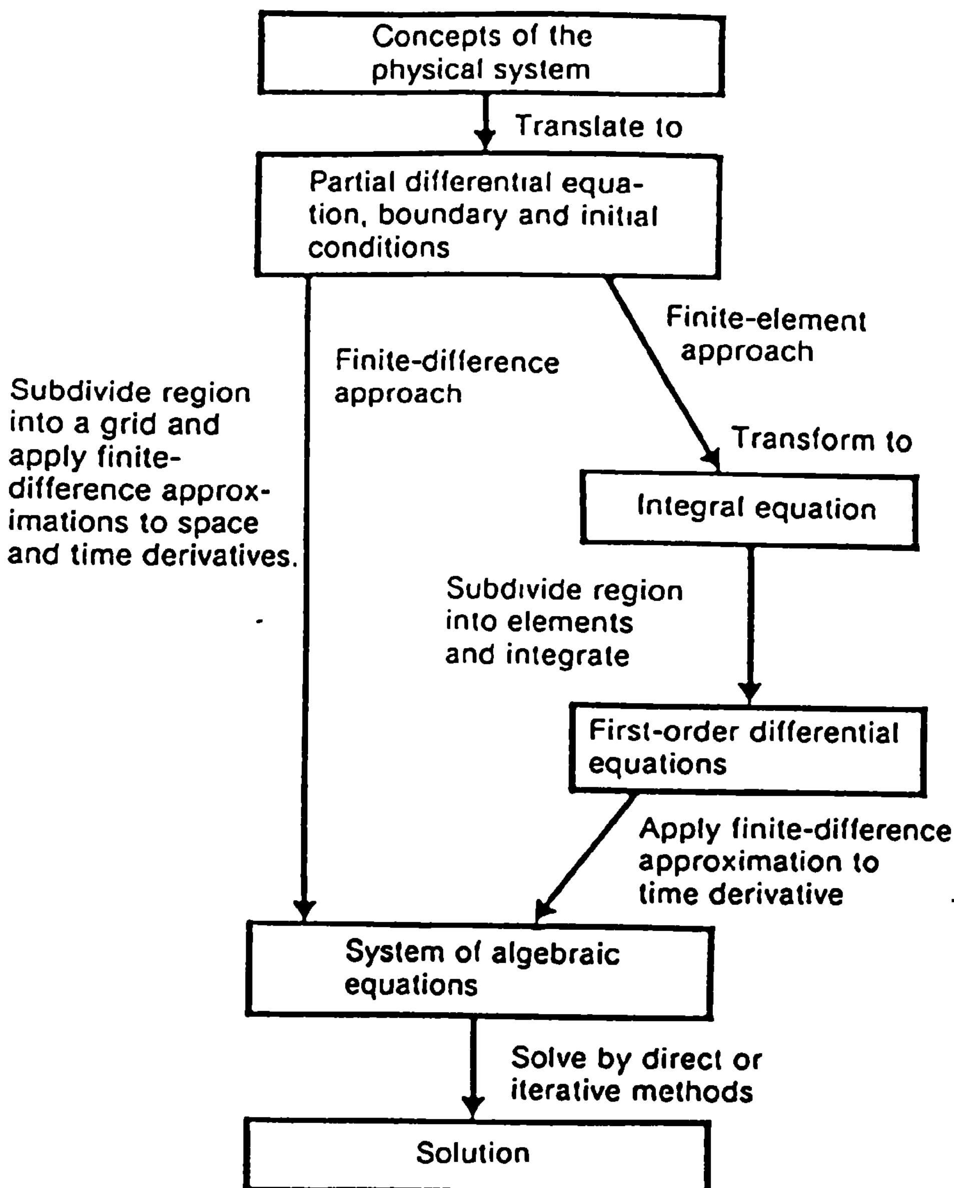


~ any polygonal shape

(Mercer and Faust, 1981)

Fig. 4c. Finite-element configuration for aquifer study where b is the aquifer thickness.

Models Developed by Finite-Difference and Finite-Element Methods

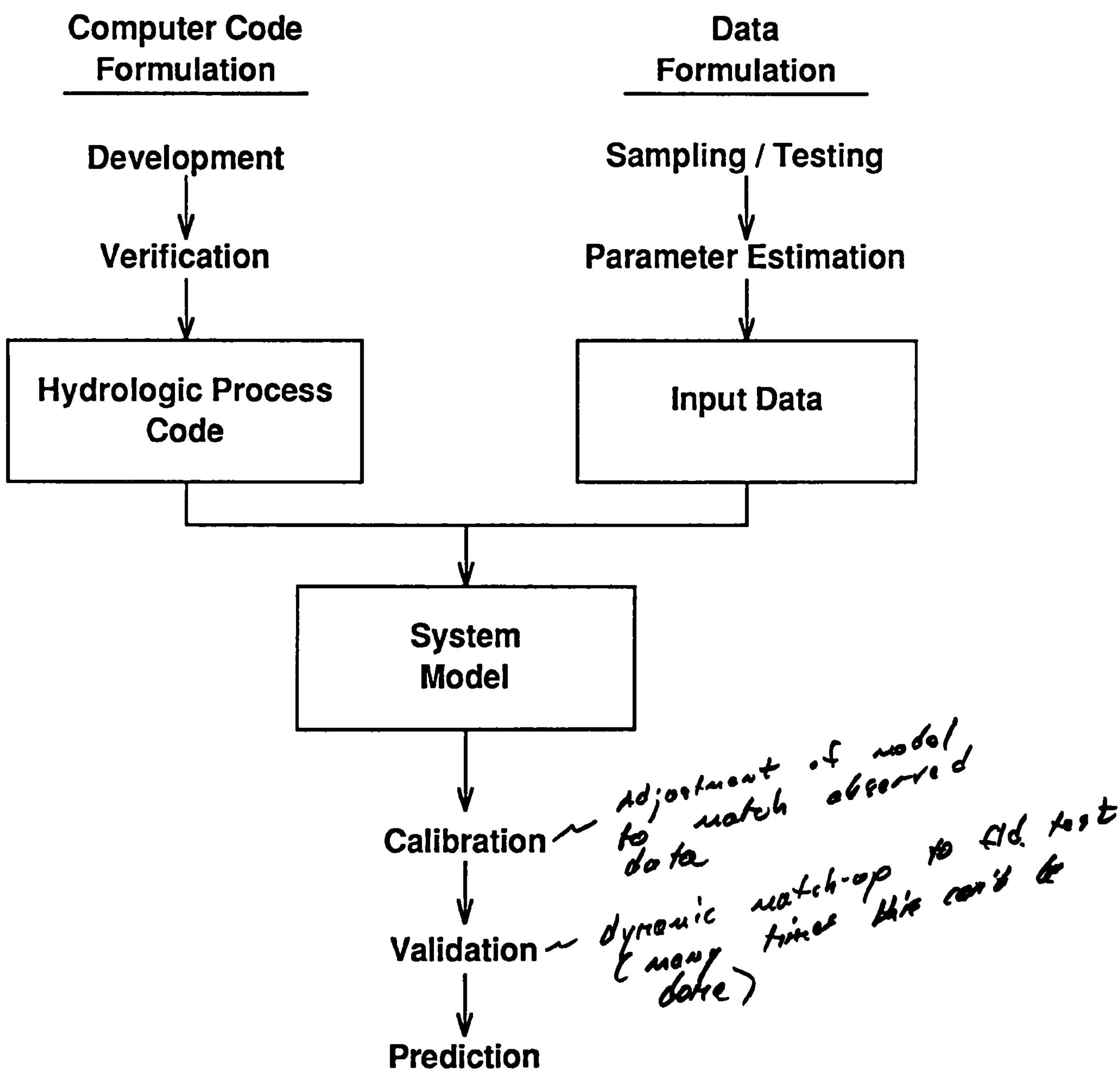


(Mercer and Faust, 1981)

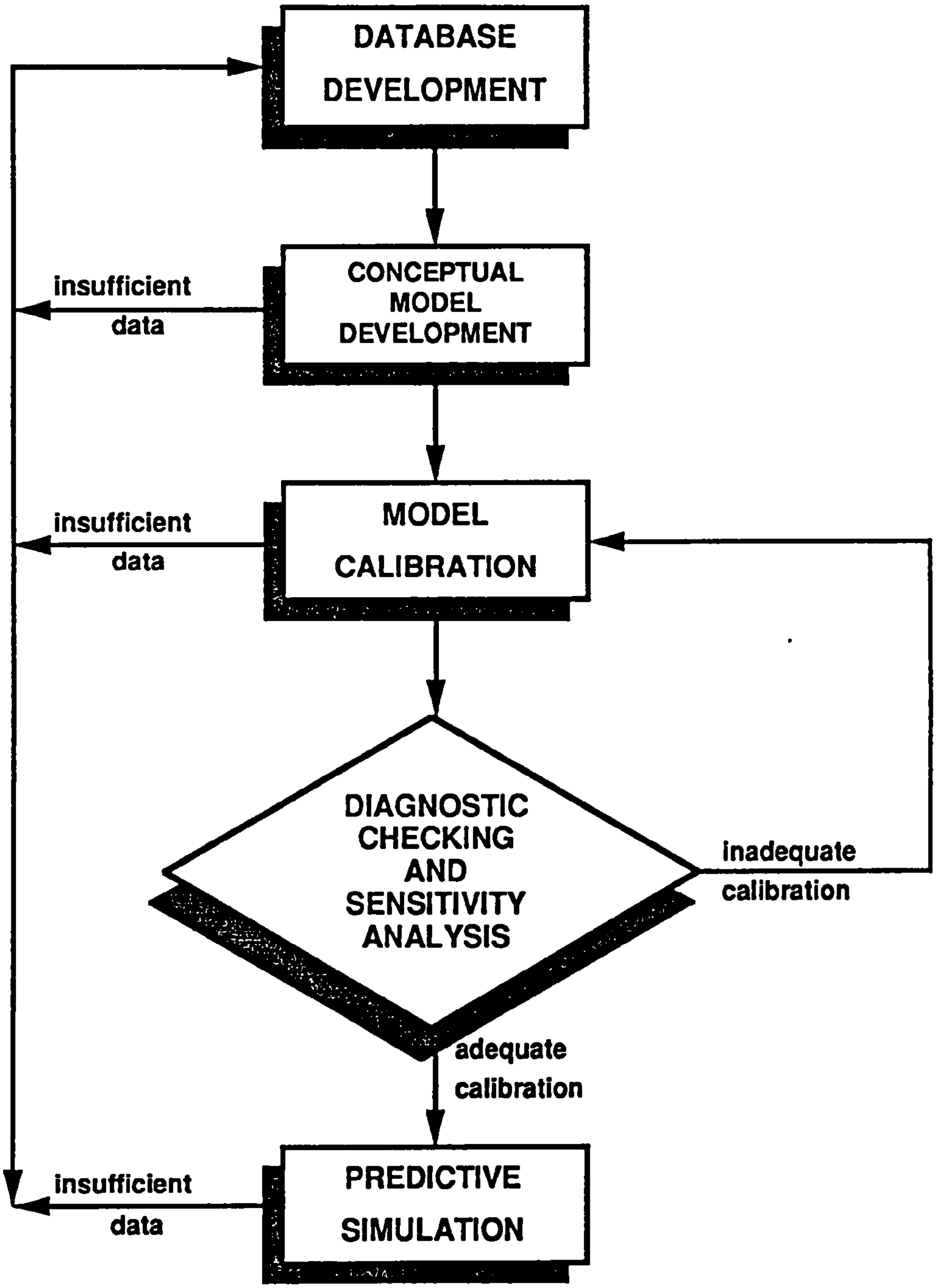
STEPS IN DEVELOPMENT AND APPLICATION OF A HYDROLOGIC COMPUTER MODEL

computer program

Definition: MODEL = CODE + DATA



ITERATIVE MODEL-BUILDING PROCEDURE



DATA REQUIREMENTS FOR PREDICTIVE MODELING OF GROUND-WATER FLOW AND SOLUTE TRANSPORT

1. PHYSICAL FRAMEWORK

A. GROUND-WATER FLOW

- HYDROGEOLOGIC MAP SHOWING BOUNDARIES AND BOUNDARY CONDITIONS
- TOPOGRAPHIC MAP SHOWING SURFACE-WATER BODIES
- WATER-TABLE MAP
- BEDROCK CONFIGURATION MAP
- SATURATED THICKNESS MAP
- TRANSMISSIVITY MAP SHOWING AQUIFER AND BOUNDARIES
- SPECIFIC STORAGE MAP OF AQUIFER
- TRANSMISSIVITY AND SPECIFIC STORAGE MAP OF CONFINING BED
- RELATION OF SATURATED THICKNESS TO TRANSMISSIVITY
- HYDRAULIC CONNECTION OF STREAM AND AQUIFER

B. SOLUTE TRANSPORT (IN ADDITION TO ABOVE)

- PARAMETERS THAT COMPRISE HYDRODYNAMIC DISPERSION
- EFFECTIVE POROSITY DISTRIBUTION
- NATURAL CONCENTRATION OF SOLUTE IN GROUND WATER
- FLUID DENSITY VARIATIONS AND RELATIONSHIP TO CONCENTRATION
- HYDRAULIC HEAD DISTRIBUTION (TO COMPUTE VELOCITIES)
- BOUNDARY CONDITIONS FOR CONCENTRATION

DATA REQUIREMENTS FOR PREDICTIVE MODELING (CONTINUED)

2. STRESSES ON SYSTEM

A. GROUND-WATER FLOW

- TYPE AND EXTENT OF RECHARGE AREAS
- SURFACE-WATER DIVERSIONS
- GROUND-WATER PUMPAGE (IN TIME AND SPACE)
- STREAMFLOW (IN TIME AND SPACE)
- PRECIPITATION AND INFILTRATION

B. SOLUTE TRANSPORT (IN ADDITION TO ABOVE)

- SOURCES AND STRENGTHS OF CONTAMINANT SOURCES
- STREAM-FLOW QUALITY
- WATER-QUALITY OF PRECIPITATION

3. OTHER FACTORS

A. GROUND-WATER FLOW AND TRANSPORT

- ECONOMIC WATER-SUPPLY INFORMATION
- LEGAL AND ADMINISTRATIVE RULES
- ENVIRONMENTAL FACTORS
- PLANNED CHANGES IN WATER AND LAND USE

(ADAPTED FROM MOORE, 1979)

TYPICAL NUMERICAL MODELING ANALYSES APPLICABLE TO WHPA DELINEATION

- FLOW SYSTEM CHARACTERIZATION
  - HYDRAULIC HEADS
  - DRAWDOWN DUE TO PUMPING
  - FLOW BOUNDARIES
  - RECHARGE / DISCHARGE
  - SOURCES / SINKS

- VELOCITY FIELD ASSESSMENT
  - FLOW PATTERNS
  - PARTICLE VELOCITIES
  - TIME OF TRAVEL

- CONTAMINANT TRANSPORT ANALYSIS
  - FATE AND TRANSPORT
  - ARRIVAL TIME

SUMMARY OF COMPUTER MODELS FOR WHPA DELINEATION

- REVIEW CONDUCTED FOR OGWP BY IGWMC

- 64 COMPUTER MODELS REVIEWED

- OF THE 64 MODELS:
  - 27 ARE GROUND-WATER FLOW MODELS
  - 37 ARE SOLUTE TRANSPORT MODELS

  AND
  - 51 ARE NUMERICAL MODELS
  - 13 ARE ANALYTICAL MODELS

- REPORT PRESENTS:
  - DESCRIPTION
  - AVAILABILITY
  - USABILITY
  - RELIABILITY

Source: Model Assessment for Delineating Wellhead Protection Areas, Office of Ground-Water Protection, EPA, 1988.

MODEL SELECTION CONSIDERATIONS

MAJOR CRITERIA IN SELECTING A MODEL FOR A SITE-SPECIFIC WHPA DELINEATION ARE:

- THAT THE MODEL BE SUITABLE FOR THE INTENDED USE
- THAT THE MODEL BE RELIABLE & USEABLE (USER FRIENDLY)
- THAT THE MODEL CAN BE APPLIED EFFICIENTLY

Source: Model Assessment for Delineating Wellhead Protection Areas, Office of Ground-Water Protection, EPA, 1988.

CHECKPOINTS FOR REVIEWING

A GROUND-WATER MODELING STUDY

CHECKPOINTS FOR REVIEWING A GROUND-WATER MODELING STUDY

INITIAL READING OF MODELING REPORT (1st scan of report)

PURPOSE

Sets tone for review

Aids in evaluation of:
~~appropriateness of selected modeling technique, reasonableness of simplifying assumptions, and interpretation of results~~

A simple goal should only require a simple model or a simple technique

HYDROGEOLOGIC SETTING

Aids in evaluation of:
soundness of conceptual model,
reasonableness of parameter ranges,
appropriateness of selected computer code

QUANTITY AND QUALITY OF DATA

Provides basis for reviewing technical approach

CONCEPTUAL MODEL (this should be in there)

Preliminary check for technical soundness

COMPUTER CODE

Preliminary judgement regarding appropriate selection

RESULTS

Preliminary judgement regarding success of application; note problem areas so that possible sources of error can be identified during detailed review

CHECKPOINTS FOR REVIEWING A GROUND-WATER MODELING STUDY (Cont.)

DETAILED REVIEW OF MODELING REPORT

PURPOSE

Is purpose clearly stated?

Consistent with regulatory requirements of model application?

HYDROGEOLOGIC SETTING

Boundary Conditions

Regional and local settings described in sufficient detail?

Strong regional or local controls?

Aquifer boundaries well-defined?

Recharge and discharge areas identified?

Distinctive aquifer features (layering, confining beds, fractures)?

Unusual features requiring simplifying assumptions?

* INPUT DATA   THIS IS A QA/QC CHECK

Data collection procedures followed correctly?

Field and lab test results interpreted correctly?

Significant data gaps requiring simplifying assumptions?

Will data gaps require "expert judgement" data estimates?

Will assumptions or data estimates be verifiable?

CHECKPOINTS FOR REVIEWING A GROUND-WATER MODELING STUDY (Cont.)

CONCEPTUALIZATION

Is conceptual model complete and technically sound?

Conflicts between conceptual model and field data?

CALIBRATION

THIS ANOTHER QA/QC COMPONENT ?

Is computer code used for model calibration identified?

Is code in public domain (widely used, tested, and accepted)?

(YOU TEND TO BE ON SAFER GROUND IF YOU USE A WIDELY USED, TESTED & ACCEPTED MODEL)

Were and code modifications thoroughly tested?

Is selected code appropriate for aquifer system?

Is model area clearly identified on a map?

Are starting parameter estimates presented?

Are code operation parameters presented and discussed?

Are simplifying assumptions clearly identified?

Is final calibration run completely described?

Is match with calibration targets acceptable?

Are final parameter values reasonable?

SENSITIVITY ANALYSIS

Were sensitivity analyses performed?

Are sensitivity analyses described clearly and completely?

Does model respond too greatly to changes in parameters?

Does model respond too little to changes in parameters?

IS THERE A MASS BALANCE ?

check of boundary conditions

CHECKPOINTS FOR REVIEWING A GROUND-WATER MODELING STUDY

DIAGNOSTIC CHECKING

Reasonableness of model checked against factors other than calibration targets?

Are discrepancies explainable and acceptable?

PREDICTION

Are predictive simulations described in sufficient detail?

Number and range of runs sufficient to meet objectives?

Does range dangerously exceed calibration range?

Is data pre- and post-processing clearly described?

INTERPRETATION

Are results presented and interpreted clearly?

Is interpretation consistent with conceptual model?

Are results presented with appropriate qualifying statements regarding data limitations, simplifying assumptions, and limited scope and intent of modeling study?

DOCUMENTATION

Is entire modeling study documented so as to be understandable?

Is study documented sufficiently to support intended purpose?

Are complete records available if more detailed review required?

Is version of source code used in study available?

Are computer copies of final calibration runs available?

Are computer copies of predictive simulations available?

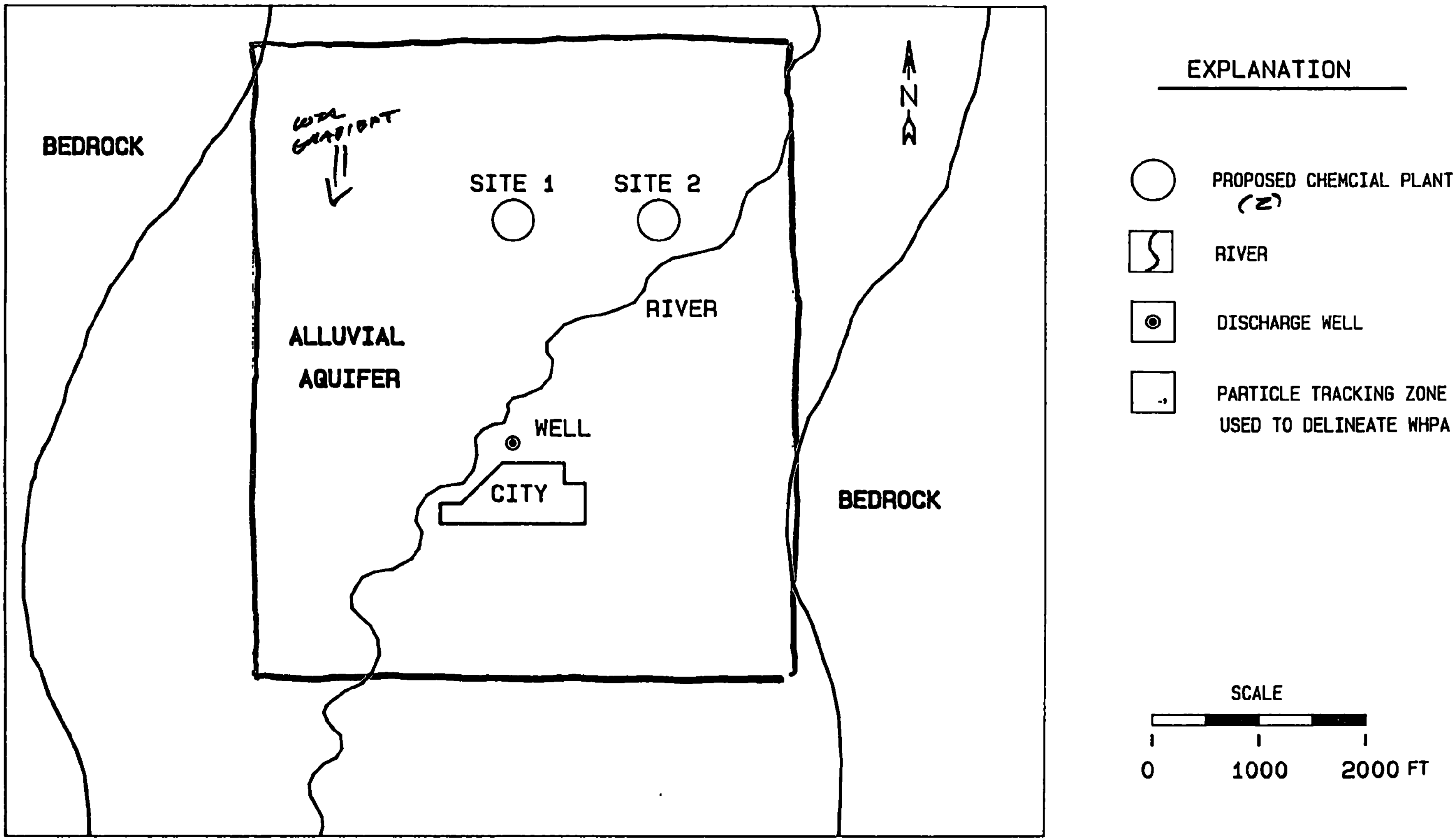
NUMERICAL MODELING

HYPOTHETICAL CASE STUDY

HYPOTHETICAL NUMERICAL MODELING CASE STUDY

- SINGLE PUMPING WELL IN TYPICAL VALLEY-FILL AQUIFER
- DELINEATE WHPA WITH 1000-DAY BUFFER WITHIN ZOC
- AQUIFER DATA:

AQUIFER MATERIAL	Glacial outwash (sand, gravel)
AQUIFER THICKNESS	200 ft
VALLEY WIDTH	7,500 ft
AQUIFER POROSITY	0.25
HYDRAULIC CONDUCTIVITY (AQUIFER ASSUMED ISOTROPIC)	100 ft/day
HYDRAULIC GRADIENT	0.005
PUMPING RATE	133,700 cfd (1 mgd)



SITE MAP FOR HYPOTHETICAL VALLEY-FILL AQUIFER.

Slide 7.23

HYPOTHETICAL NUMERICAL MODELING CASE STUDY
(CONTINUED)

APPROACH 1

- TREAT AQUIFER AS HOMOGENEOUS
- IGNORE RIVER AND RECHARGE

A) USE ANALYTICAL SOLUTION FOR ZOC AND TOT (RESSQ)

RESSQ INPUT DATA:

AQUIFER THICKNESS	61 m
AQUIFER POROSITY	0.25
PORE WATER VELOCITY	223 m/yr (2 ft/day)
TIME OF TRAVEL	2.74 yr (1000 days)
PUMPING RATE	158 m^3/hr (1 mgd)

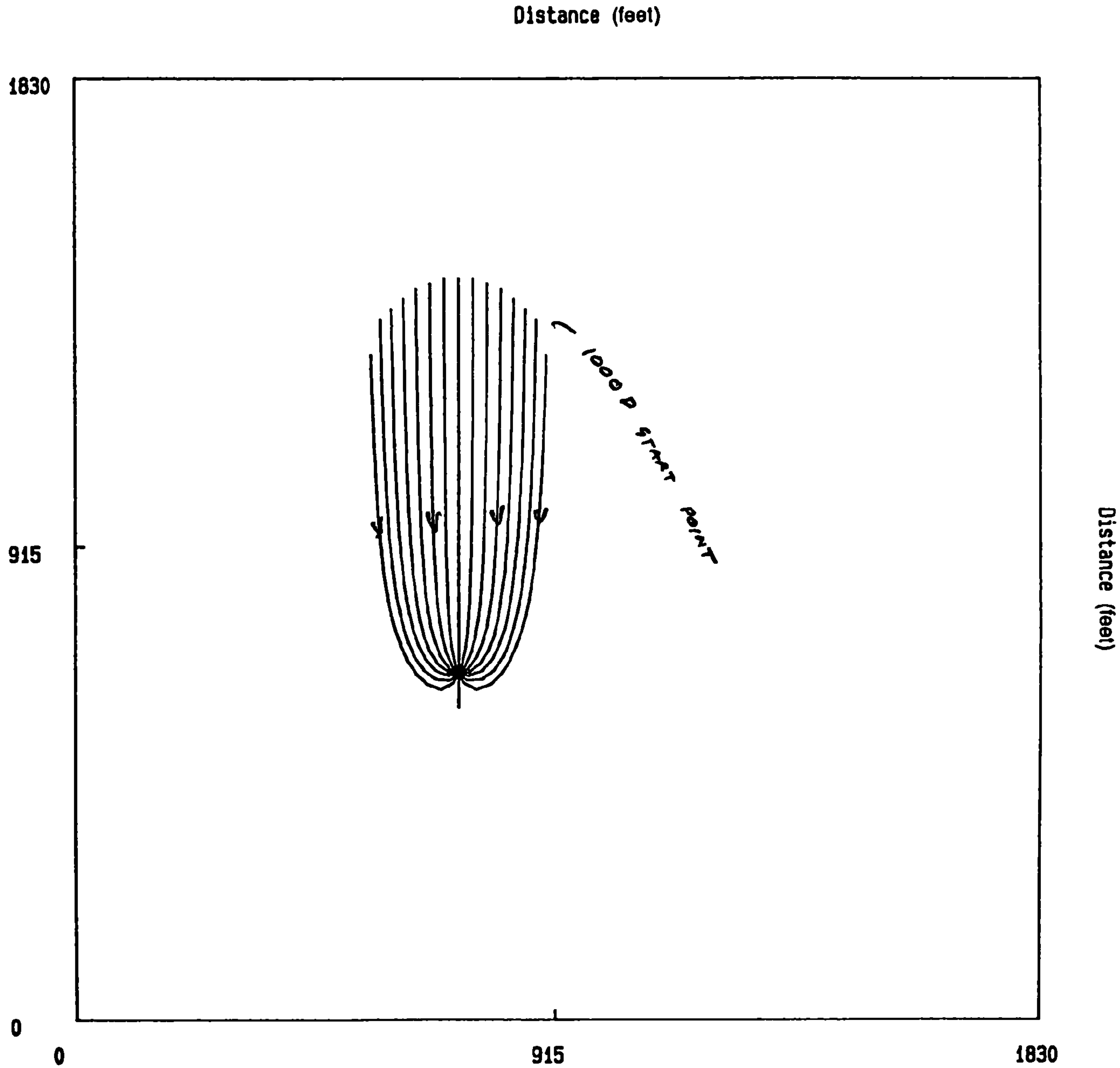
B) CHECK RESULTS WITH FINITE-DIFFERENCE MODEL (MODFLOW) AND PARTICLE-TRACKING CODE (GWPATH)

MODFLOW INPUT DATA:

AQUIFER THICKNESS	200 ft
HEAD ON NORTH BOUNDARY	2,000 ft
HEAD ON SOUTH BOUNDARY	1,960 ft
CELL WIDTH IN X-DIRECTION	200 ft
CELL WIDTH IN Y-DIRECTION	200 ft
HYDRAULIC CONDUCTIVITY	100 ft/day
PUMPING RATE	133,700 cfd

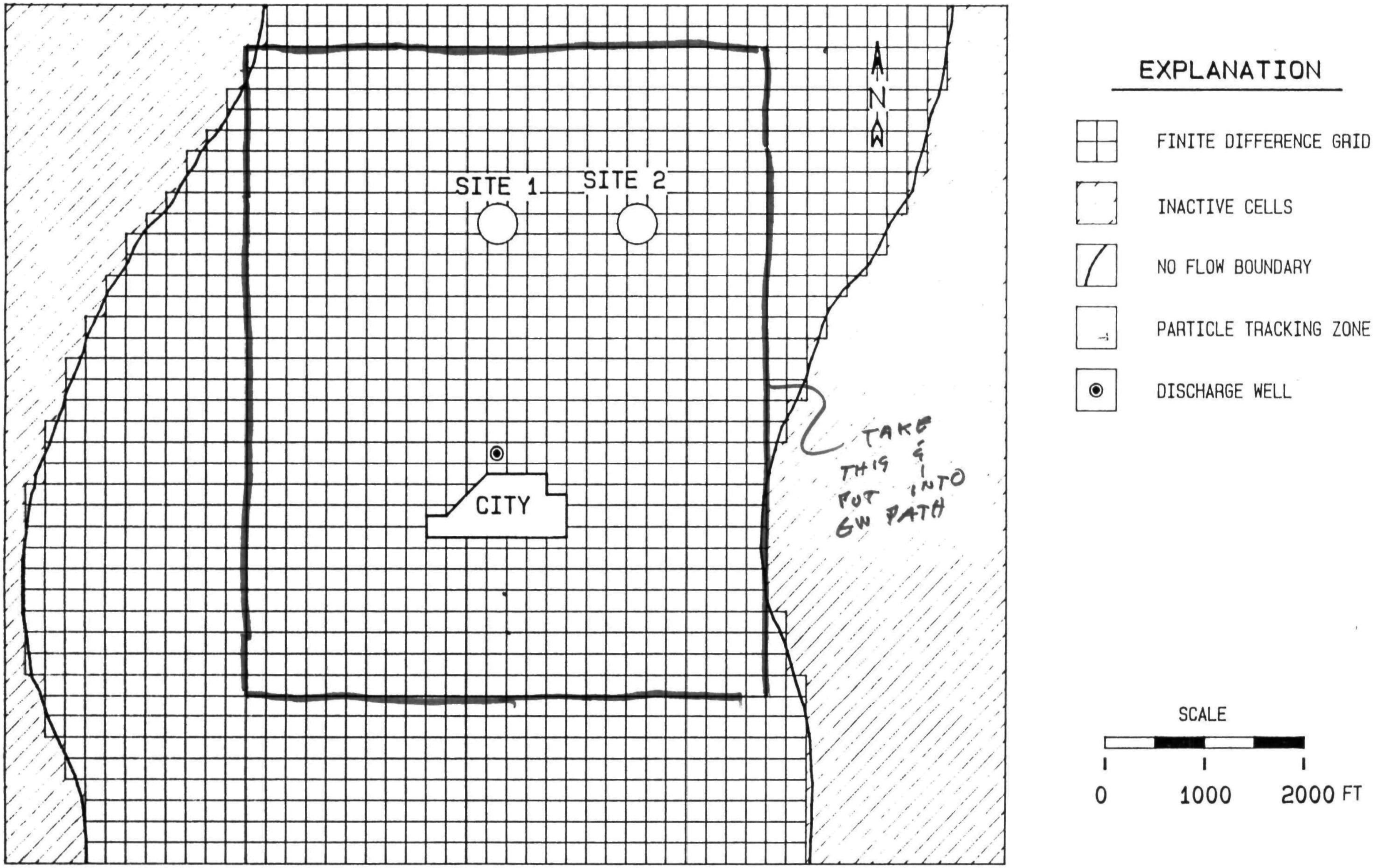
GWPATH INPUT DATA:

AQUIFER POROSITY	0.25



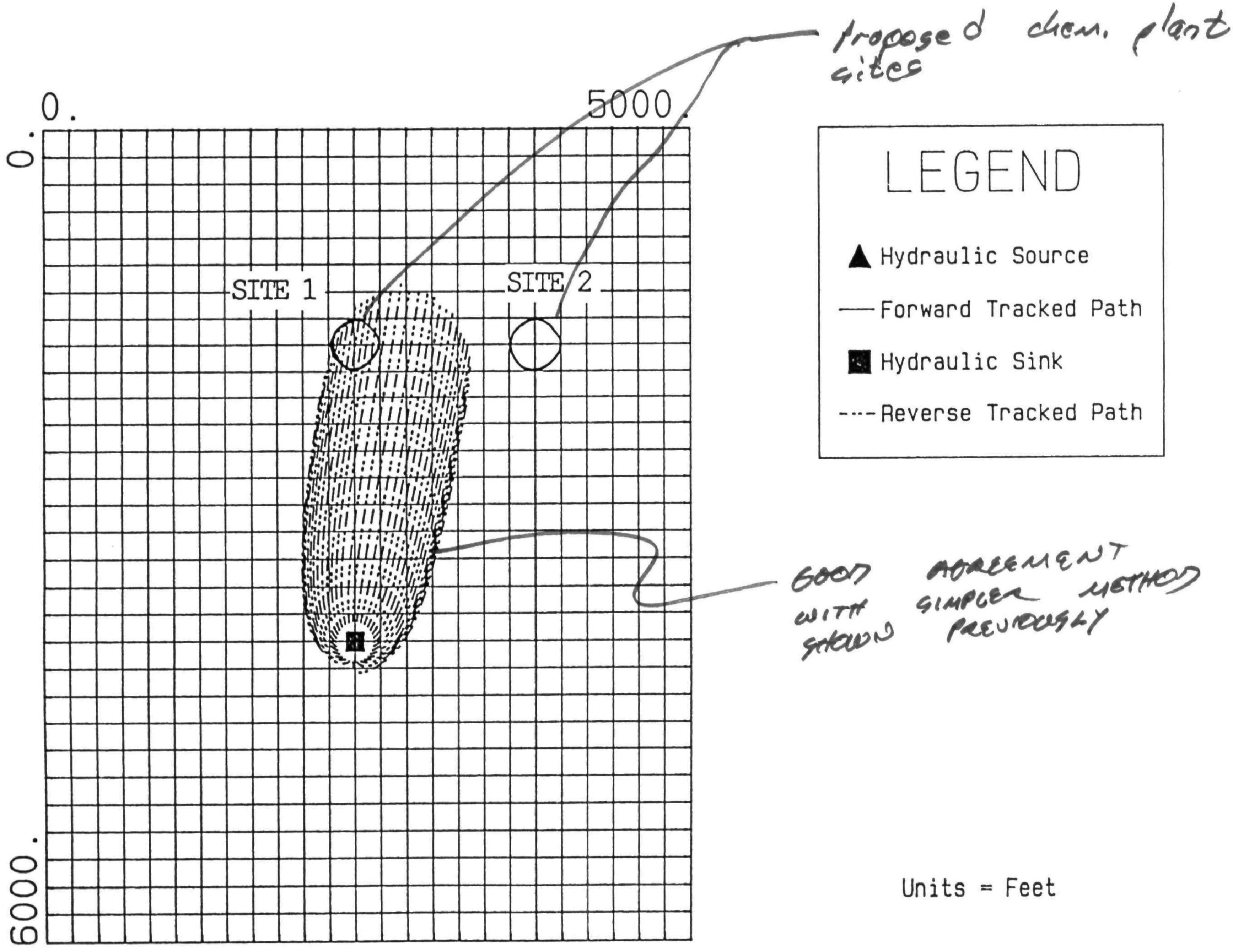
ZONE OF CONTRIBUTION TO PUMPING WELL COMPUTED USING RESSQ.

Slide 7.25



FINITE-DIFFERENCE GRID FOR HYPOTHETICAL VALLEY-FILL AQUIFER FOR CASE OF HOMOGENEOUS AQUIFER.

Slide 7.26



Slide 7.27

ZONE OF CONTRIBUTION TO PUMPING WELL COMPUTED USING GWPATH FOR CASE OF HOMOGENEOUS AQUIFER.

HYPOTHETICAL NUMERICAL MODELING CASE STUDY
(CONTINUED)

APPROACH 2

- TREAT AQUIFER AS HOMOGENEOUS
- INCLUDE EFFECTS OF RIVER AND RECHARGE
- USE FINITE-DIFFERENCE MODEL (MODFLOW) AND PARTICLE-TRACKING CODE (GWPATH)

* NO CONDUCTIVITY IN RIVER BED GIVEN

MODFLOW INPUT DATA: (SAME AS APPROACH 1)

AQUIFER THICKNESS	200 ft
HEAD ON NORTH BOUNDARY	2,000 ft
HEAD ON SOUTH BOUNDARY	1,960 ft
CELL WIDTH IN X-DIRECTION	200 ft
CELL WIDTH IN Y-DIRECTION	200 ft
HYDRAULIC CONDUCTIVITY	100 ft/day
PUMPING RATE	133,700 cfd

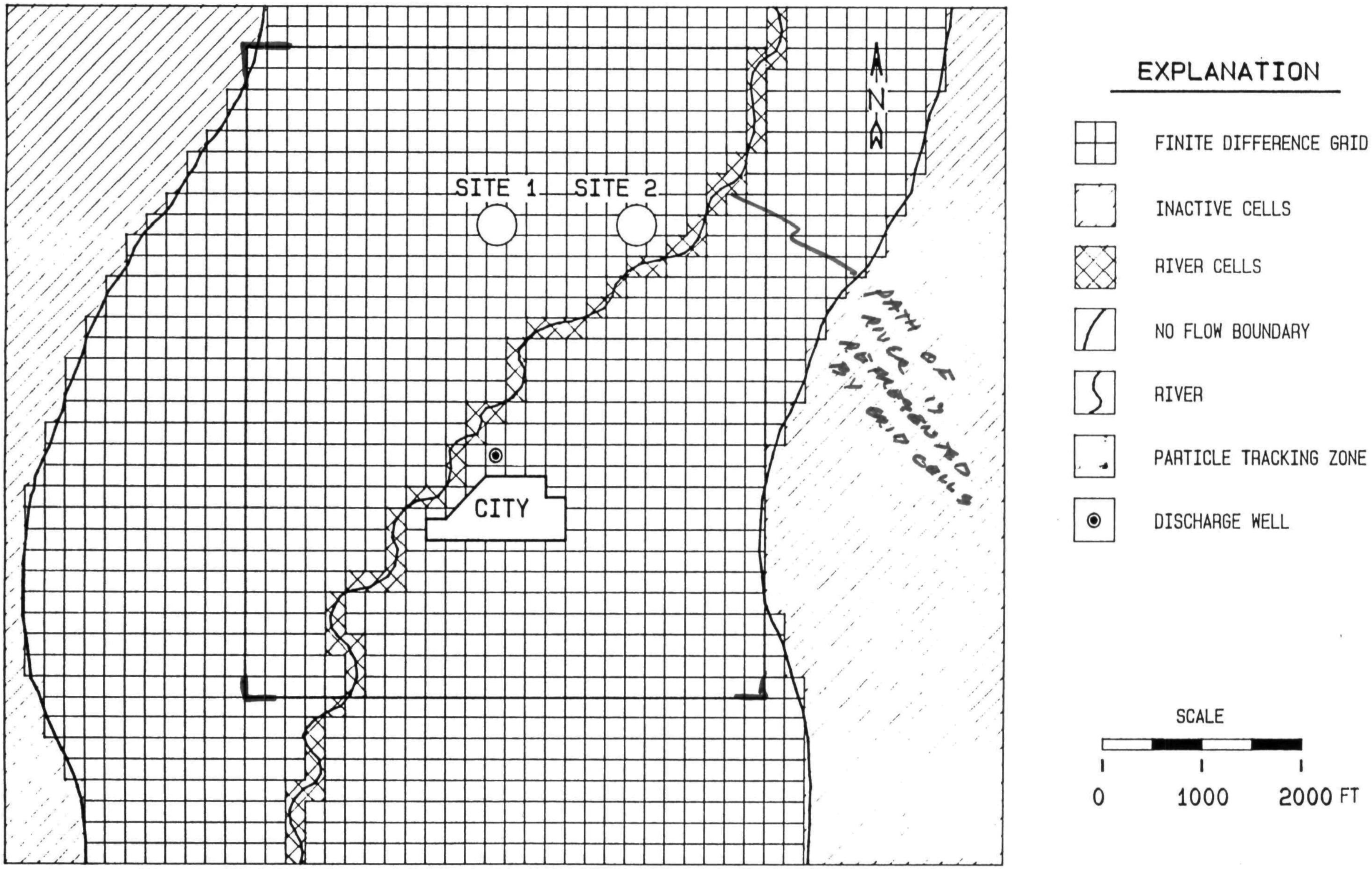
PLUS

53 RIVER CELLS *	
AREAL RECHARGE	1.5 ft/yr

because the conductivity is so high there is a recharge to the river from the aquifer which overcomes the disch from ~~aquifer~~ river to aquifer around the well.

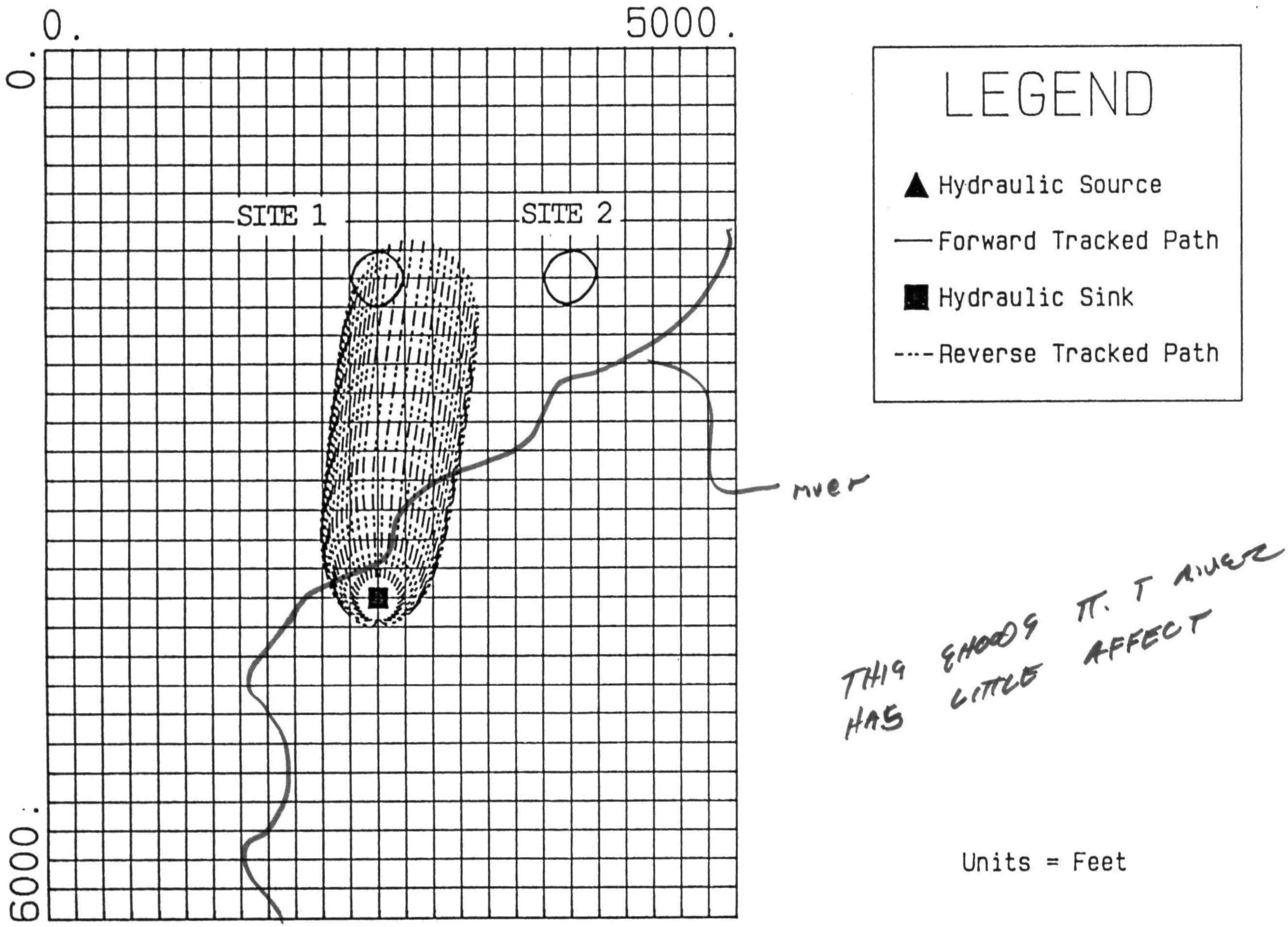
GWPATH INPUT DATA: (SAME AS APPROACH 1)

AQUIFER POROSITY	0.25



FINITE-DIFFERENCE GRID FOR HYPOTHETICAL VALLEY-FILL AQUIFER FOR CASE OF HOMOGENEOUS AQUIFER WITH RIVER AND RECHARGE.

Slide 7.29



Slide 7.30

ZONE OF CONTRIBUTION TO PUMPING WELL COMPUTED USING GWPATH
FOR CASE OF HOMOGENEOUS AQUIFER WITH RIVER AND RECHARGE.

HYPOTHETICAL NUMERICAL MODELING CASE STUDY
(CONTINUED)

APPROACH 3

- INCLUDE EFFECTS OF HETEROGENEITIES (CLAY PLUGS)
- IGNORE EFFECTS OF RIVER AND RECHARGE
- USE FINITE-DIFFERENCE MODEL (MODFLOW) AND PARTICLE-TRACKING CODE (GWPATH)

MODFLOW INPUT DATA: (SAME AS APPROACH 1)

AQUIFER THICKNESS	200 ft
HEAD ON NORTH BOUNDARY	2,000 ft
HEAD ON SOUTH BOUNDARY	1,960 ft
CELL WIDTH IN X-DIRECTION	200 ft
CELL WIDTH IN Y-DIRECTION	200 ft
HYDRAULIC CONDUCTIVITY	100 ft/day
PUMPING RATE	133,700 cfs

PLUS

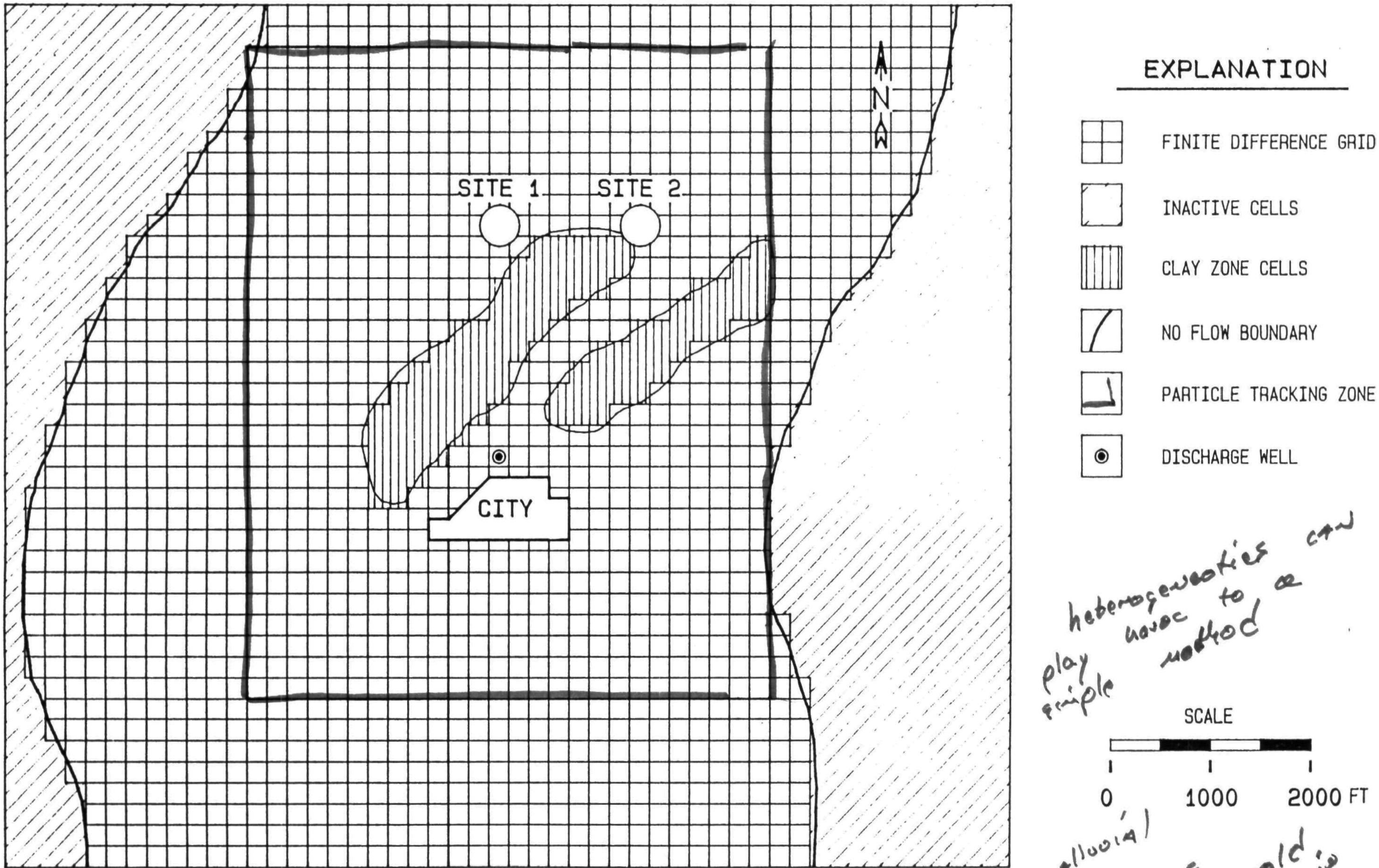
HYDRAULIC CONDUCTIVITY OF CLAY PLUG ZONES	10 ft/day

GWPATH INPUT DATA: (SAME AS APPROACH 1)

AQUIFER POROSITY	0.25

PLUS

POROSITY OF CLAY PLUGS	0.40

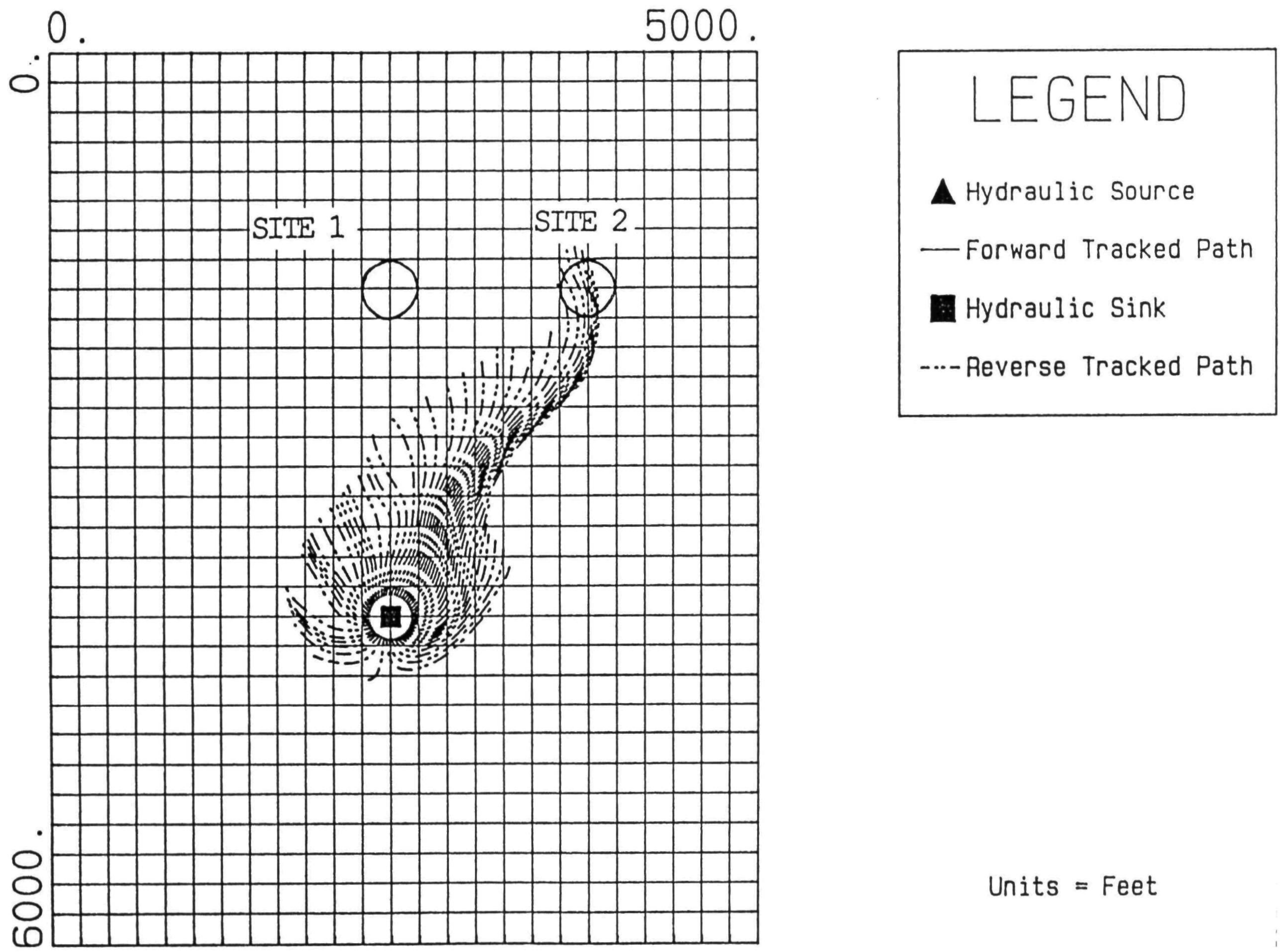


heterogeneities can play havoc to a simple method

FINITE-DIFFERENCE GRID FOR HYPOTHETICAL VALLEEY-FILL AQUIFER FOR CASE OF NONHOMOGENEOUS AQUIFER (CLAY ZONES).

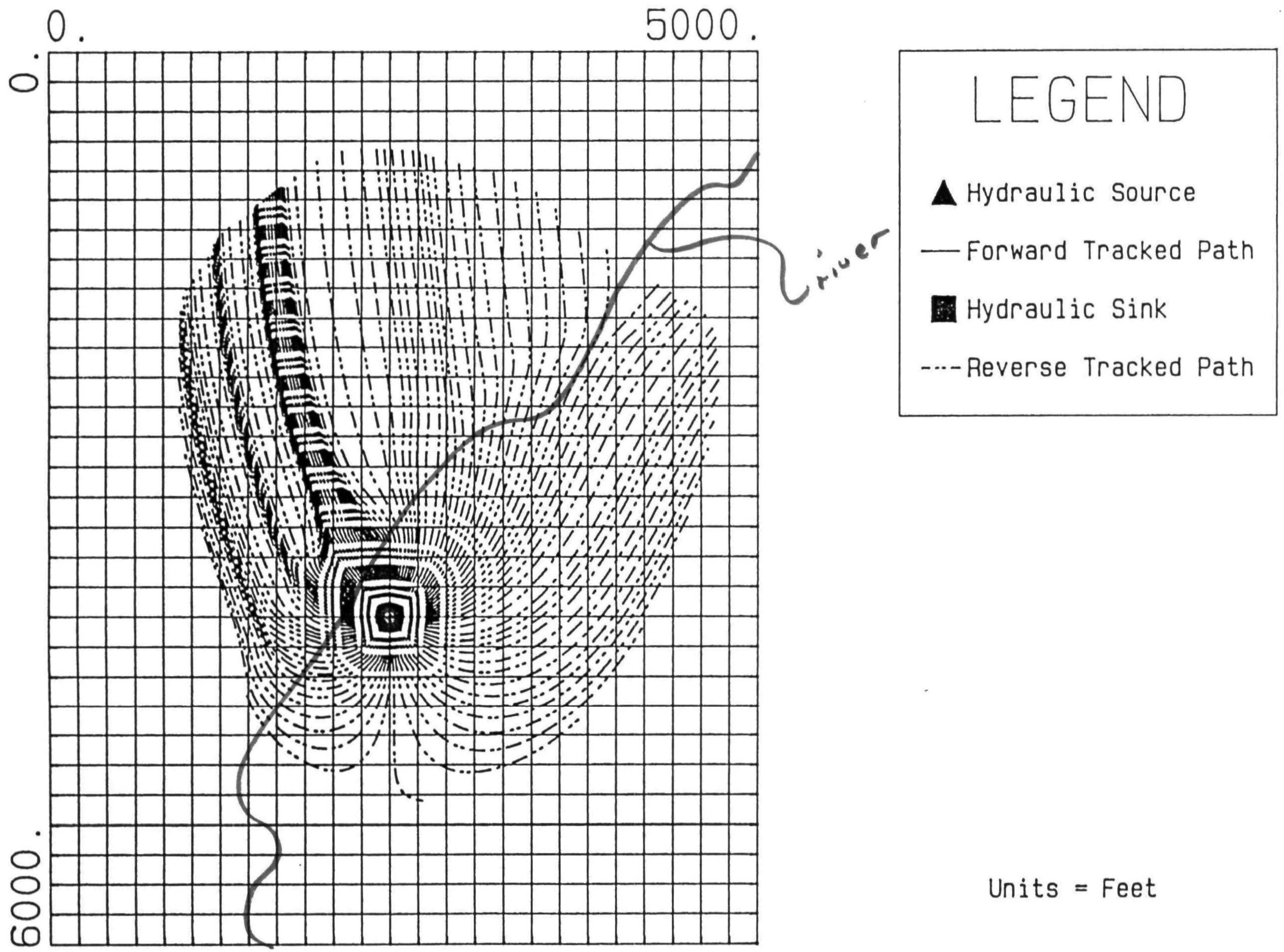
for alluvial zones small changes in conductivity could make big changes in the outcome

Slide 7.32



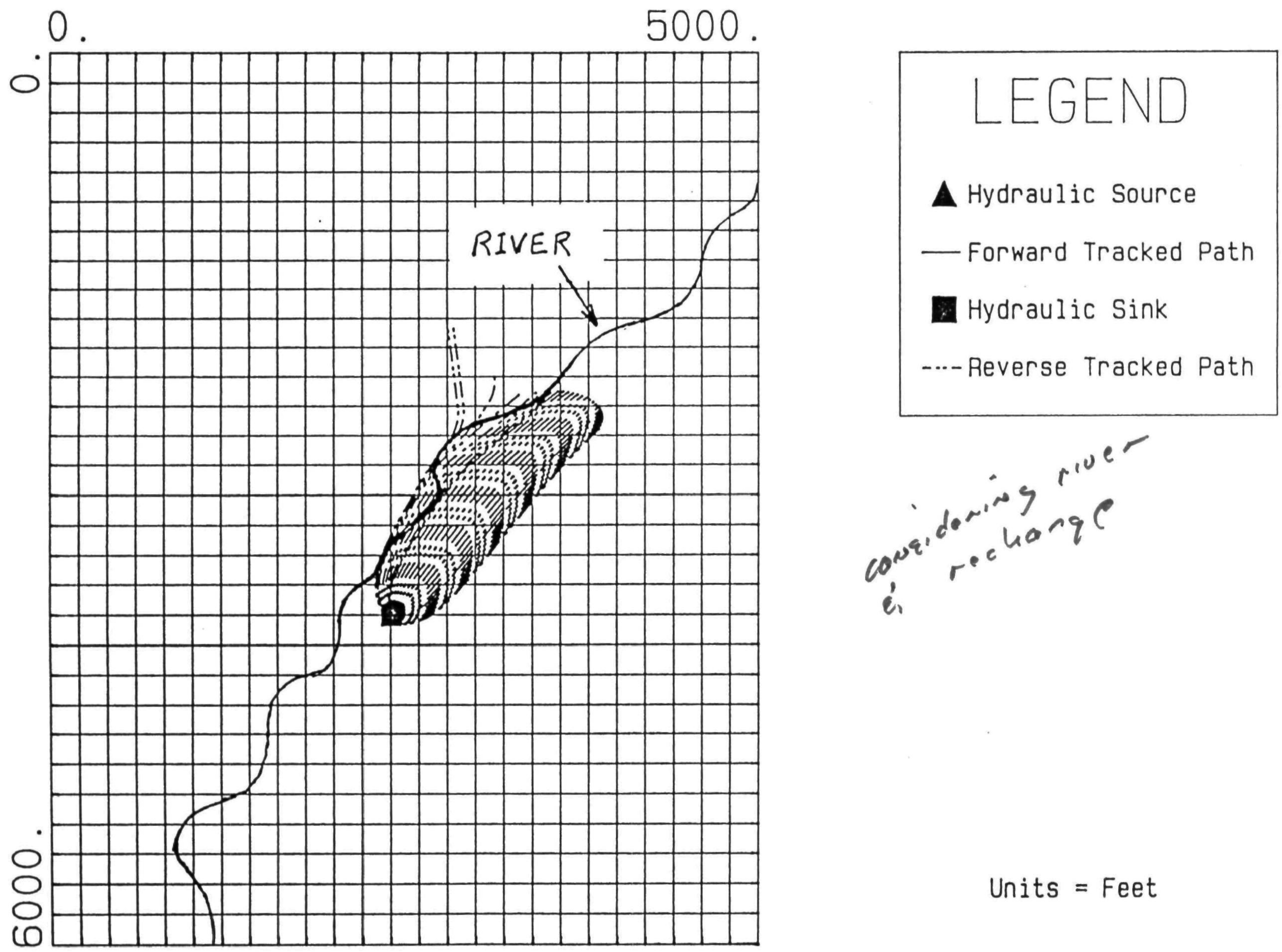
Slide 7.33

ZONE OF CONTRIBUTION TO PUMPING WELL COMPUTED USING GWPATH FOR CASE OF NONHOMOGENEOUS AQUIFER (CLAY ZONES).



Slide 7.34

ZONE OF CONTRIBUTION TO PUMPING WELL COMPUTED USING GWPATH
FOR CASE OF AQUIFER CONDUCTIVITY REDUCED BY FACTOR OF 10.



Slide 7.35

ZONE OF CONTRIBUTION TO PUMPING WELL COMPUTED USING GWPATH
FOR CASE OF PUMPING WELL DISCHARGE REDUCED BY FACTOR OF 10.

NUMERICAL MODELING CASE STUDY

FRANKLIN, MASSACHUSETTS

NUMERICAL MODELING CASE STUDY
FRANKLIN, MASSACHUSETTS

- CITY OF FRANKLIN PROPOSED NEW WATER SUPPLY WELL
- DEQE REQUIRES DELINEATION OF THREE ZONES AROUND WELL

ZONE I	Immediate area within 400 ft of well
ZONE II	Area which supplies water to well under severe conditions (180 days pumping at design rate with no recharge)
ZONE III	Area beyond Zone II from which surface water and ground water drains into Zone II

- NUMERICAL MODEL DEVELOPED TO DELINEATE ZONE II
- AQUIFER DATA:

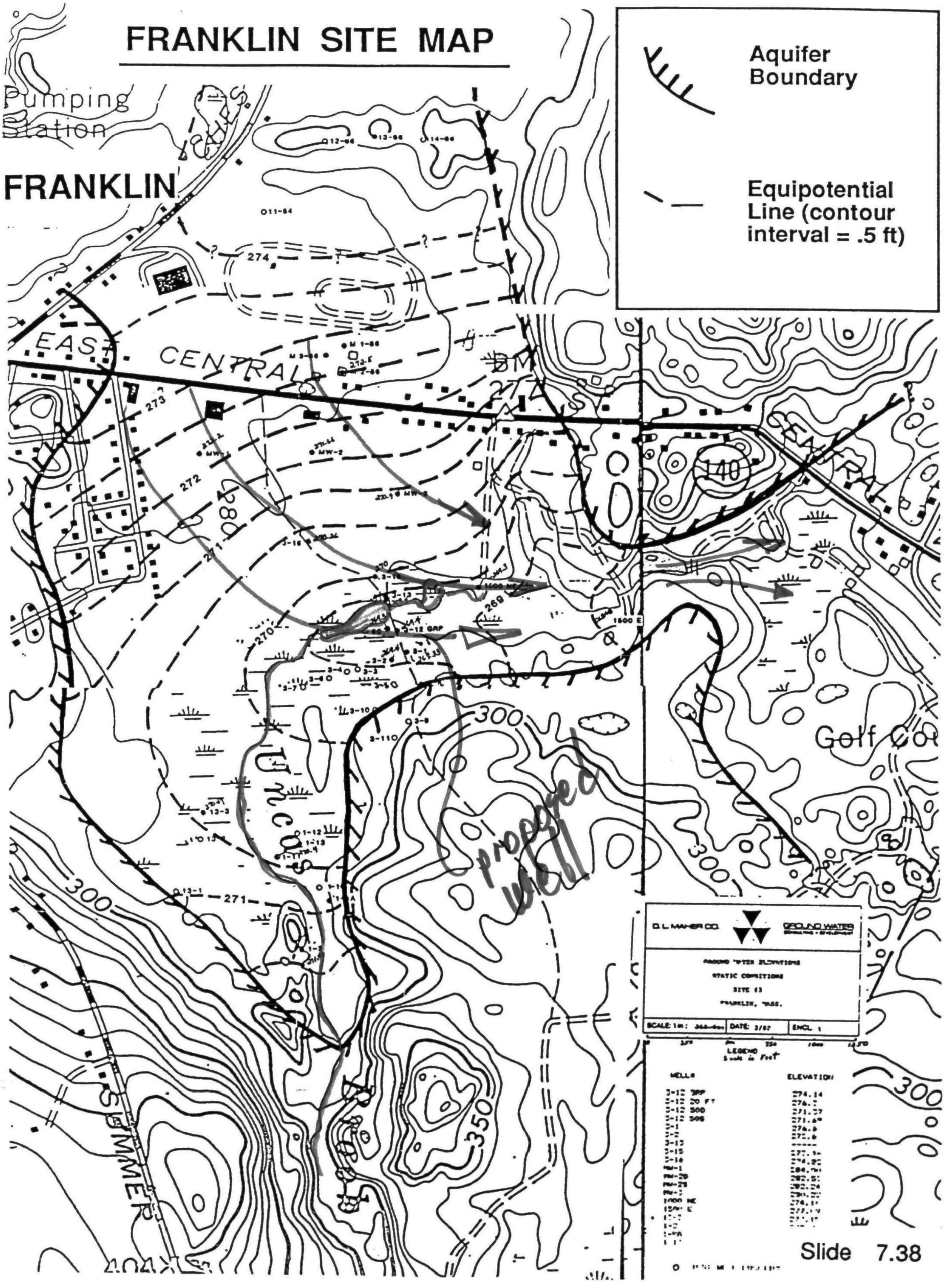
AQUIFER MATERIAL	Glacial outwash (sand, silt, clay)
AQUIFER THICKNESS	43 ft at valley center
VALLEY BOUNDARIES	bounded by bedrock on all sides except for narrow neck to East
AQUIFER TRANSMISSIVITY (ASSUMED ISOTROPIC)	150,000 gpd/ft near well 50,000 gpd/ft near boundaries
HYDRAULIC GRADIENT	0.001 to the East
STORATIVITY	0.02

RECHARGE FROM PRECIPITATION

STREAM ACTS AS CENTRAL DISCHARGE POINT

STREAM MAY ALSO PROVIDE RECHARGE DURING PUMPING

FRANKLIN SITE MAP



Slide 7.38

NUMERICAL MODELING CASE STUDY
FRANKLIN, MASSACHUSETTS (CONT.)

- THREE-DIMENSIONAL FINITE-DIFFERENCE MODEL DEVELOPED

- MODFLOW CODE SELECTED BECAUSE OF ITS ABILITY TO SIMULATE IMPORTANT AQUIFER FEATURES:

    MULTI-LAYERED AQUIFER

    IRREGULAR BOUNDARIES

    HETEROGENEITY WITHIN LAYERS

    INTERACTION WITH SURFACE WATER

    AREAL RECHARGE

    PARTIALLY PENETRATING WELL

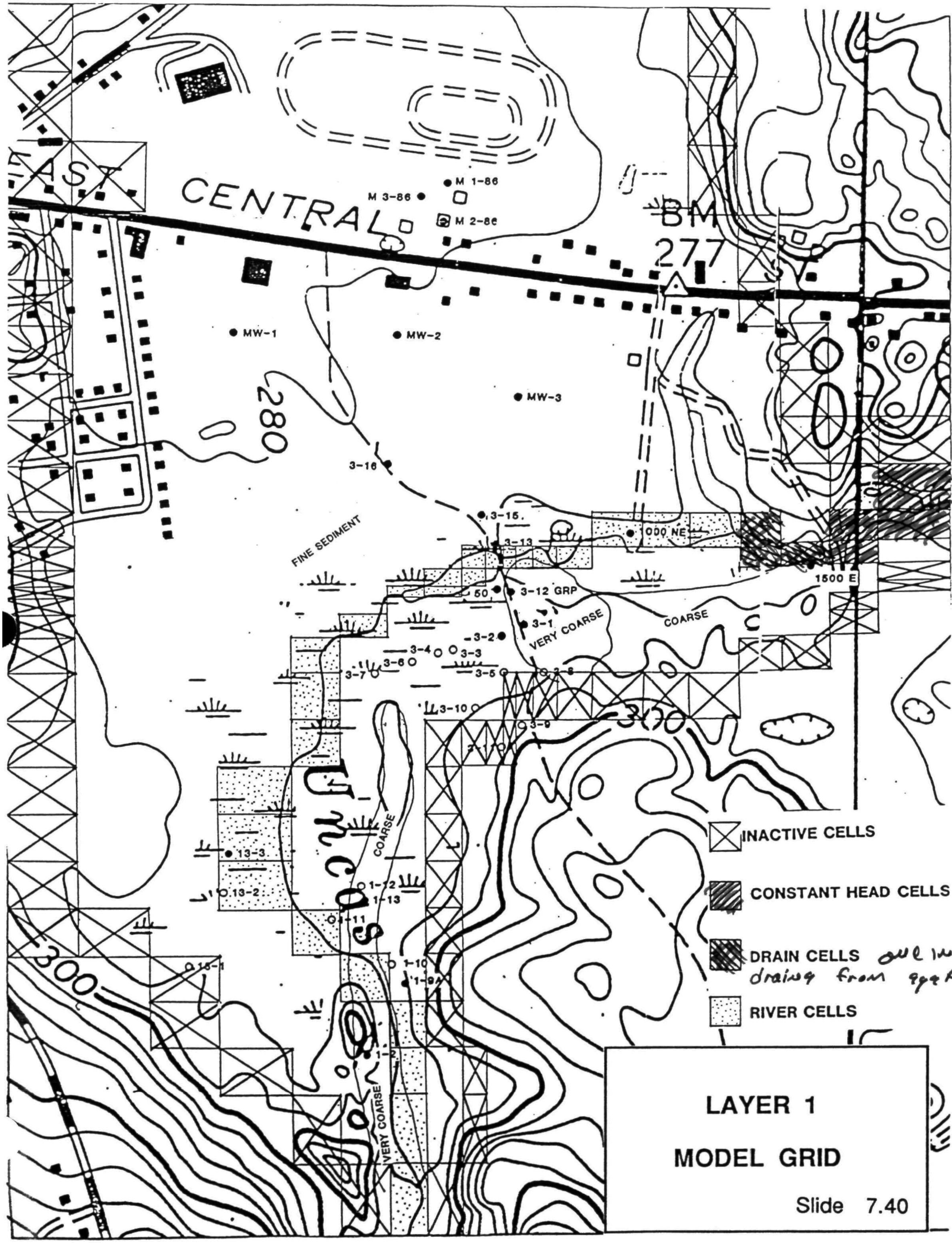
- MODEL SETUP:

    3-D Model (2 layers, 21 columns, 27 rows)

    Graded grid (50 ft near well, 400 ft near boundaries)

    No-flow boundaries around entire aquifer, except for narrow discharge zone to east

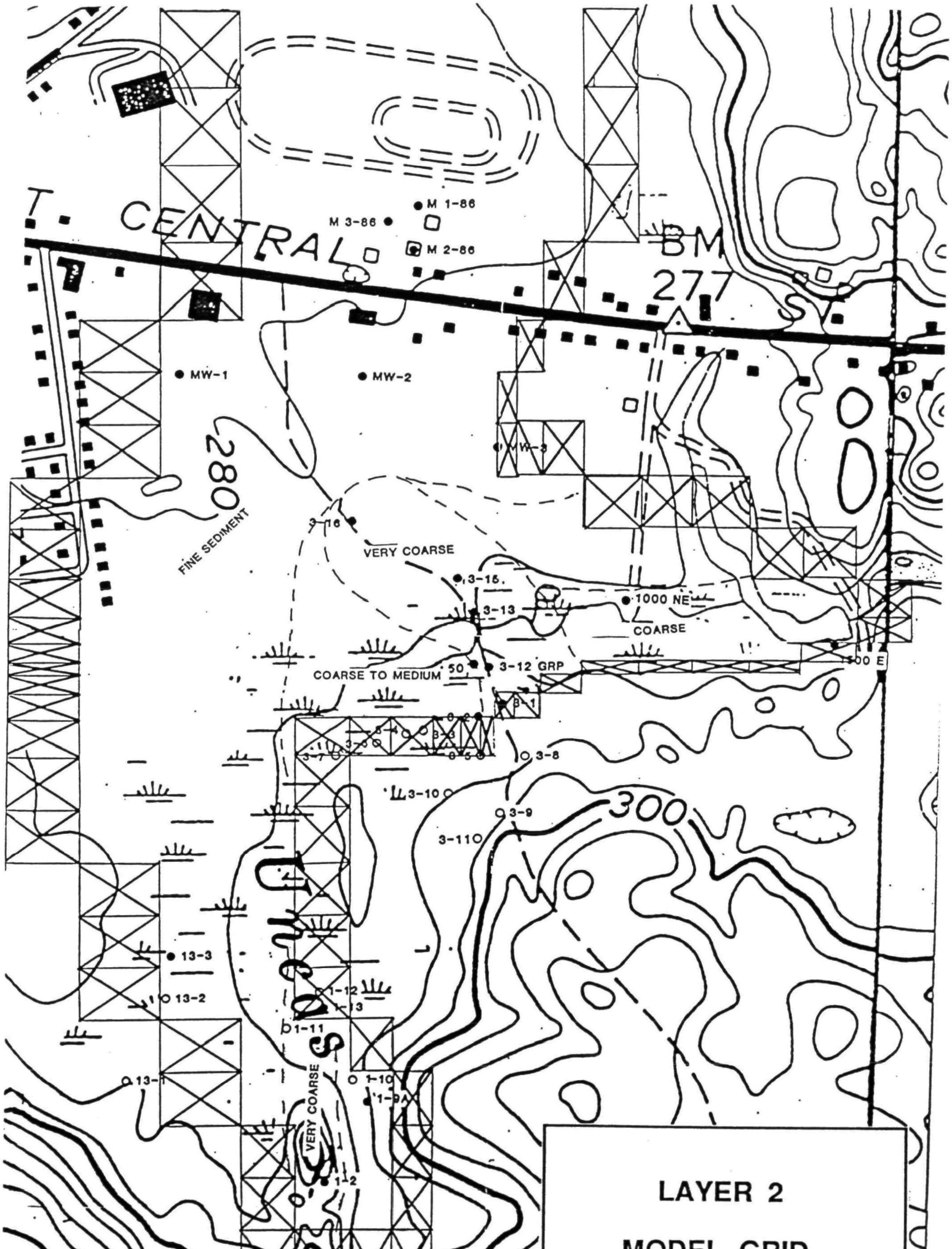
    Constant heads at eastern boundary to establish gradient that produced eastward flow



LAYER 1

MODEL GRID

Slide 7.40



LAYER 2

MODEL GRID

Slide 7.41

NUMERICAL MODELING CASE STUDY
FRANKLIN, MASSACHUSETTS (CONT.)

- **DATA COLLECTION:**

  20 boreholes drilled and logged

  15 of the boreholes converted to observation wells

  5-day pumping test conducted

  Estimates of transmissivity and storativity determined using Jacob's straight-line method and Theis curve-matching technique

- **MODEL CALIBRATION:**

  STEP 1 - Calibrate to static conditions

  Input aquifer parameters, recharge and discharge rates

  Parameters adjusted in both layers until good match with observed heads and good water balance achieved

  STEP 2 - Calibrate to pumping test conditions

  Start with calibrated model from Step 1

  Discharge rate of 350 gpm set in pumping well cells

  Parameters adjusted until model output matched observed data satisfactorily

NUMERICAL MODELING CASE STUDY FRANKLIN, MASSACHUSETTS (CONT.)

- **PREDICTIVE SIMULATION:**

  Stress period set to 180 days; recharge was eliminated.

  Four scenarios simulated:

  SCENARIO 1 - Stream ignored; lower specific yield

  Simulation failed after 120 days; excessive dewatering of upper layer of model

  SCENARIO 2 - Stream ignored; higher specific yield

  Simulation failed after 120 days; excessive dewatering of upper layer of model

  SCENARIO 3 - Stream modeled lower specific yield

  Simulation showed all ground water within valley would flow toward well

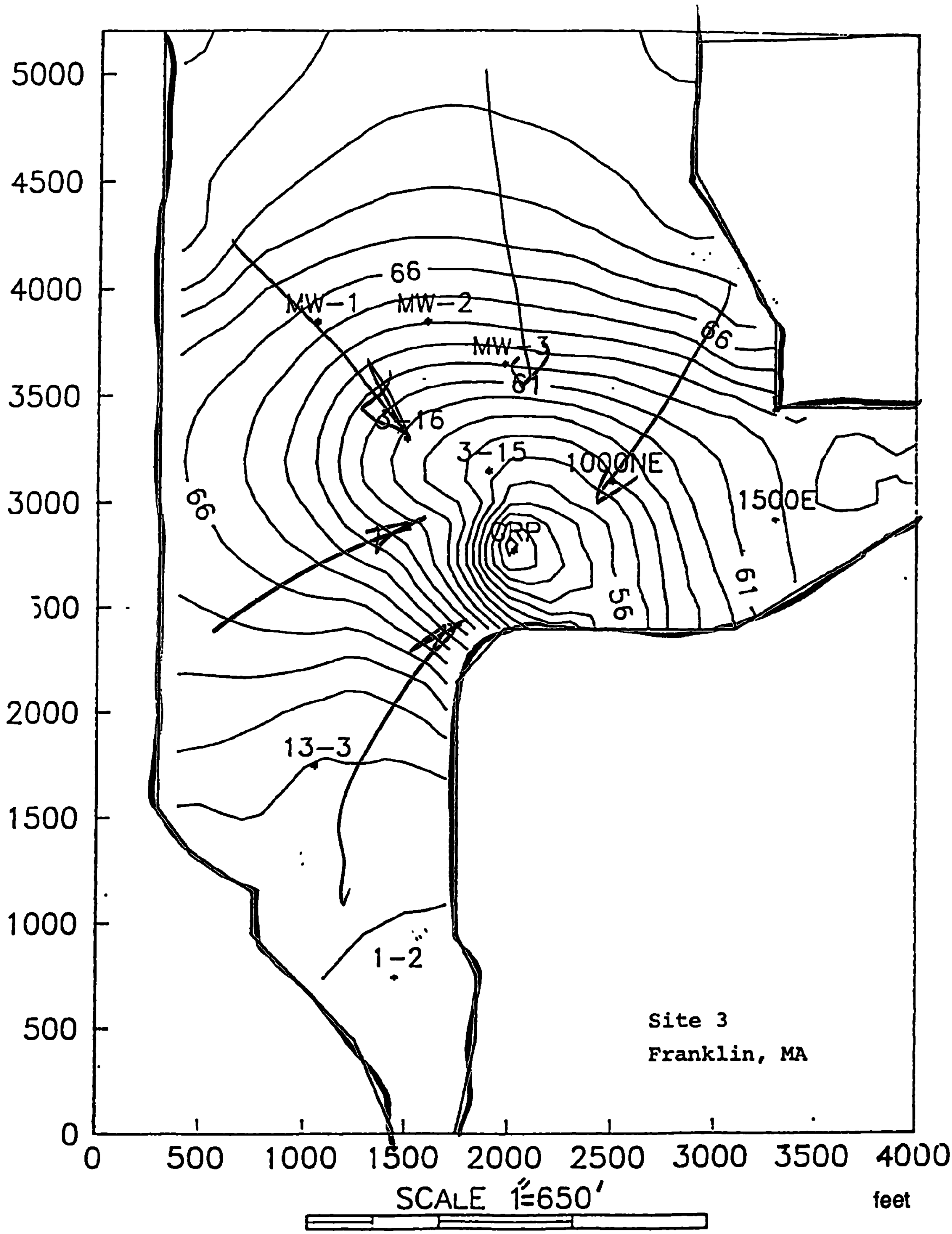
  SCENARIO 4 - Stream modeled lower specific yield

  Simulation showed all ground water within valley would flow toward well

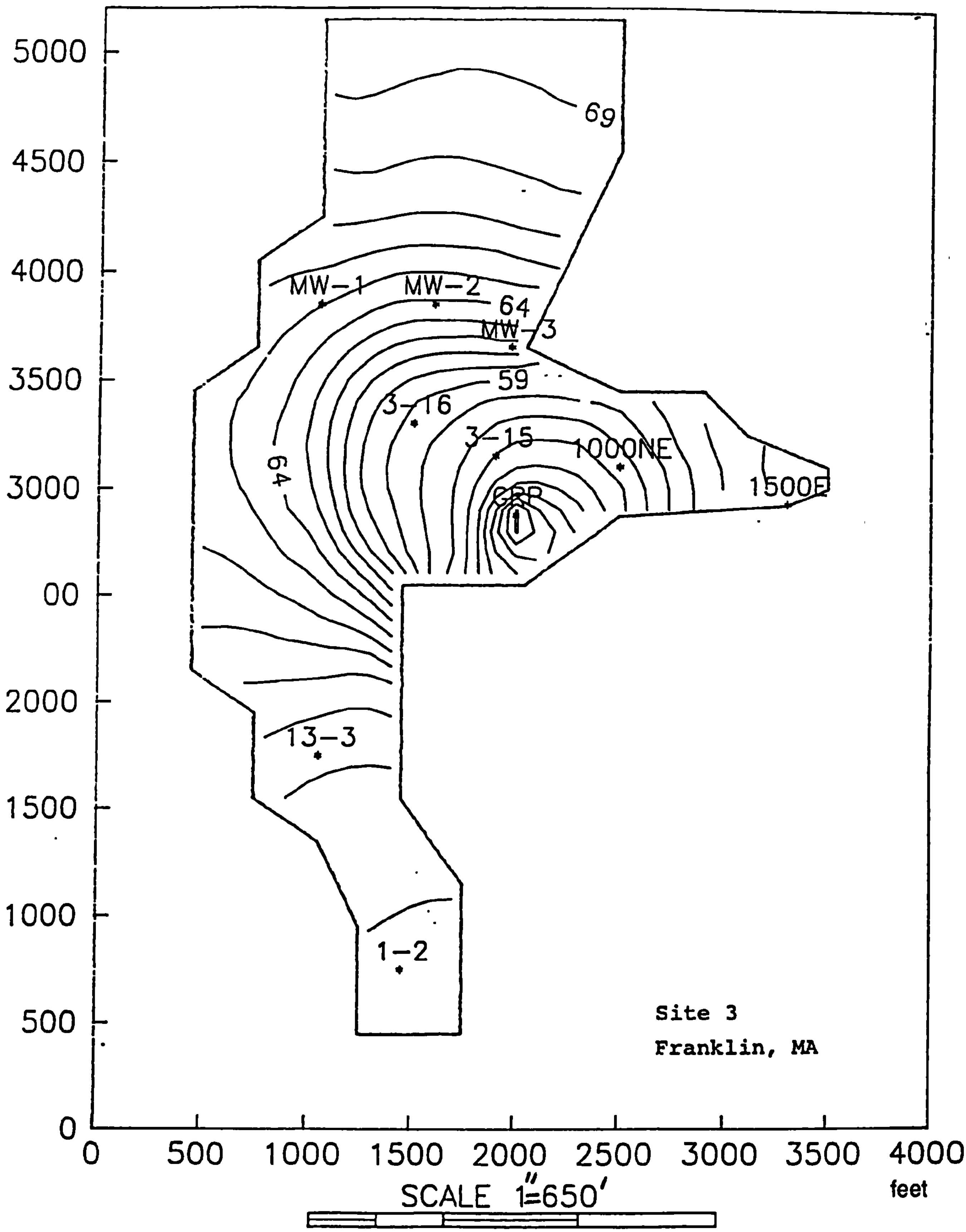
- **RESULTS OF STUDY:**

  Zone II delineated as entire valley in which well is located.

MODEL RESULTS AFTER 180-DAY PUMPING PERIOD: LAYER 1

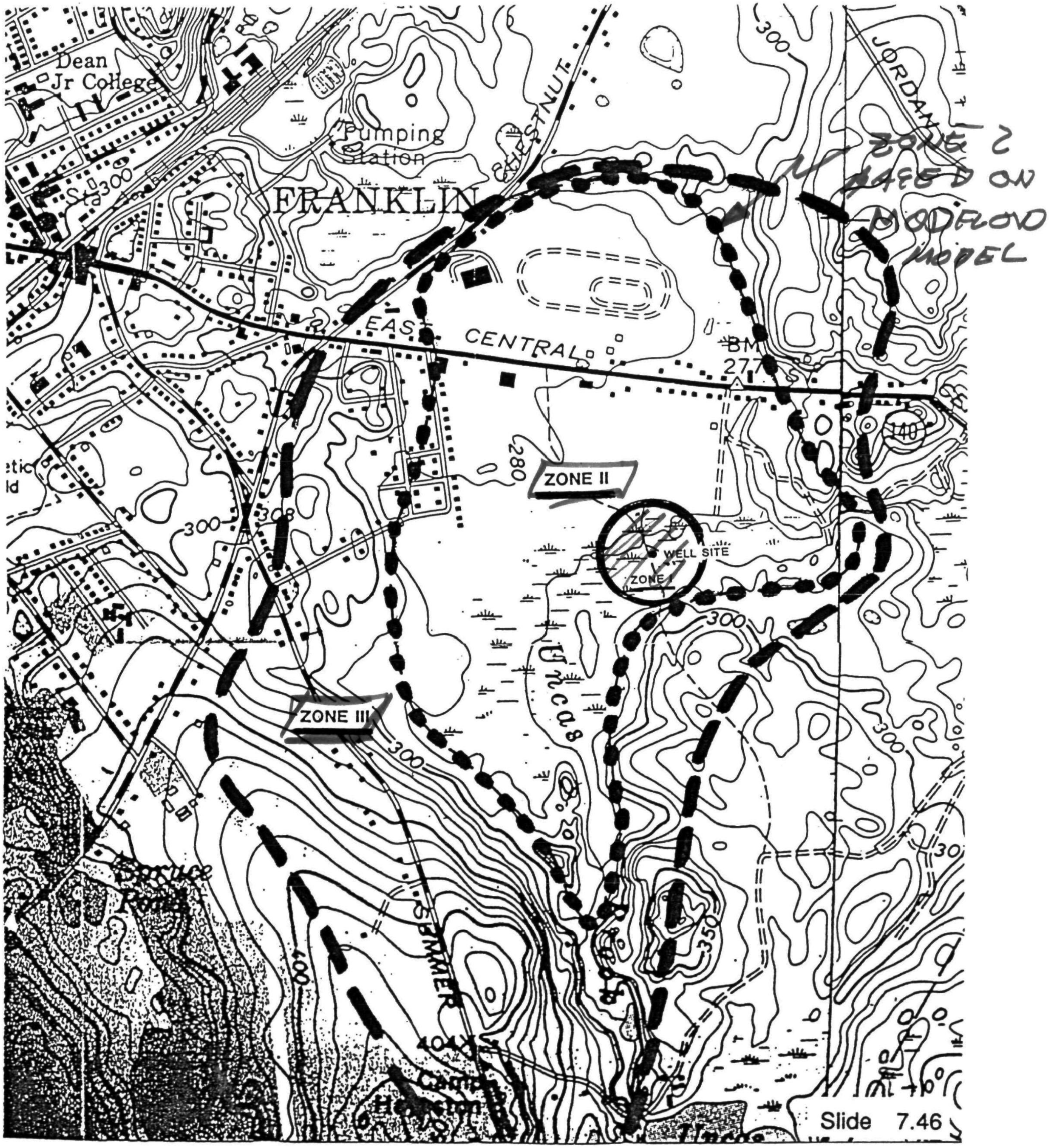


MODEL RESULTS AFTER 180-DAY PUMPING PERIOD: LAYER 2



Slide 7.45

WHPA ZONES DELINEATED FOR FRANKLIN, MASSACHUSETTS SITE



7. NUMERICAL MODELING METHODS

7.1 INTRODUCTION

Numerical methods of modeling ground-water flow and contaminant transport lie at the upper end of the spectrum of WHPA delineation methods in terms of sophistication, data requirements, and cost.

Numerical methods of simulating flow and transport produce computer models similar to those developed using analytical methods. Numerical models, however, are capable of dealing with more complex hydrogeologic systems and time-varying pumping rates.

Numerical modeling methods can be used to map criteria such as drawdown, flow boundaries, and TOT. This is typically accomplished in a two-step procedure with a flow model being used to generate a hydraulic head field, and a particle-tracking or solute-transport code used to aid in outlining the WHPA.

Sixty-four models (51 of them numerical, 13 analytical) applicable to WHPA delineation were reviewed for OGWP by the International Ground-Water Modeling Center (Model Assessment fo Delineating Wellhead Protection Areas, EPA, 1988). The report summarizes features and assesses availability, usability, and reliability of each model.

Major criteria in selecting a model for a site-specific WHPA delineation are: 1) that the model be suitable for the intended use, 2) that the model be reliable, and 3) that the model can be applied efficiently (EPA, 1988).

7.2 FUNDAMENTAL CONCEPTS OF NUMERICAL MODELING

Types of Models

The four basic types of ground-water flow models (Slide 7.5) are conceptual, physical, analog, and mathematical. Mathematical models offer the most sophisticated predictive capability, and among mathematical modeling techniques, numerical models are the most powerful. After a brief introduction to the four types of models, the remainder of this section focuses on numerical modeling techniques.

Conceptual Models

Conceptual models represent (in a descriptive sense) the fundamental features and properties of the flow system.

Conceptual models may be based on professional judgement and previous experience with similar hydrogeologic settings, but the incorporation of field data will produce a more detailed and complete conceptualization of the hydrogeologic system.

Conceptual models form the basis for all other types of modeling, and the importance of formulating a correct conceptual model as a first step to more advanced modeling cannot be overemphasized.

Physical Models

Physical models use the process of porous media flow to represent the actual flow conditions. Sand tank models of ground-water seepage are a common example.

Analog Models

Analog models can be of two types: physical analogs or electric analogs.

Physical analog models use a physical process that behaves in the same fashion as flow through a porous medium to mimic flow conditions. Parallel plate viscous flow (Hele-Shaw) models and elastic membrane models are some common examples.

Electric and heat analog models use the mathematical similarity between equations governing conductance of energy through solids and flow of fluid through a confined aquifer to represent aquifer conditions.

Mathematical Models

Mathematical models of ground-water flow solve equations governing porous media flow subject to constraints imposed by aquifer geometry, boundary conditions, and initial conditions.

Mathematical models can be set-up, run, and changed much more quickly and economically than analog models. They can also represent a wider range of aquifer conditions.

The equation being solved reflects the complexity of the conceptualized flow system (i.e. simplifying assumptions result in simpler equations to solve).

Mathematical models are of two types: analytical and numerical.

Analytical models are based on exact mathematical solutions to simpler equations representing idealized aquifer conditions. The method gives highly accurate solutions to a less accurate representation of the real flow system.

Numerical models are based on numerical approximations to more complex equations and boundary conditions. The method gives slightly less accurate solutions to a more accurate representation of the flow system.

Analytical models (e.g. Theis solution, uniform flow equation) are often algebraic equations that can be solved on a hand calculator.

Numerical solution techniques involve the simultaneous solution of hundreds or thousands of equations and usually require a digital computer.

Analytical models usually require only a few input parameters and the form of the equation being solved makes it easy to see the manner in which the parameters affect the solution.

Numerical require large amounts of data describing aquifer heterogeneities, location and nature of model boundaries, and locations and strengths of sources and sinks within the model domain. A sensitivity analysis is usually required to determine the effects of given parameters on model response.

Numerical Modeling

Numerical models can be used to simulate steady-state or transient ground-water flow systems. Steady-state systems do not change with time; for example, a regional model designed to represent average annual water levels. Transient systems vary with time; for example, an aquifer system undergoing drawdown as the result of one or more pumping wells.

There are several types of numerical techniques employed in ground-water flow modeling including finite difference methods, finite element methods, and boundary integral element methods. Of these modeling methods, finite difference methods and finite element methods are the most widely used, with finite difference models being the most popular.

Finite difference and finite element methods break-up (discretize) the flow domain into a set of grid blocks or mesh cells (Slide 7.7). Equations are written for computational nodes located at the corners or centers of the blocks which, when solved, yield the value of hydraulic head at that location in the flow field (Slide 7.8).

Transient problems require the discretization of time as well. Initial conditions are specified, and the entire aquifer problem is solved at each of many short time steps to produce the solution at some later time.

A 50-column by 20-row finite difference grid would result in 1000 simultaneous equations. Solution of such large sets of matrix equations requires high-speed computers, especially if a large number of time steps is required.

Numerical models are very powerful tools due to the wide range of problems that can be treated.

Numerical models can be used to simulate aquifer conditions for steady-state and transient cases, incorporating numerous aquifer layers and other heterogeneities, with a variety of different boundary conditions, for any specified initial conditions, with multiple sources and sinks.

Approach to Numerical Modeling

A numerical model should be viewed as a quantitative tool available to the hydrogeologist to aid in the analysis of ground-water problems (Slide 7.4).

An aquifer model consists of two components: the computer code (program) that embodies the mathematical model of the physical process, and the site-specific data that allow the model developer to set-up the code to represent that particular aquifer system (Slide 7.9).

When selecting a code for model development it is wise to choose a model that has been thoroughly tested and widely accepted within the ground-water computer modeling field so that, when results are presented, the code itself is not called into question. This is especially important in studies used in support of license or permit applications, or in court cases.

Numerical modeling is useful for preliminary studies preceding field investigations (i.e. can assist in directing field data collection activities).

A numerical model can be used at any point in an investigation to test the current conceptualization of the system, and to aid in the estimation of aquifer parameters based on available data.

A numerical ground-water model provides a framework within which to integrate or synthesize collected data, to aid in interpretation of field results.

Numerical models are useful for the prediction of system response at later times for the current set of hydrogeologic conditions, or to predict aquifer response to changed conditions.

The three most common misuses of models are overkill, inappropriate prediction, and misinterpretation.

To avoid overkill, the type and complexity of model developed for a particular problem should be based on the quantity and quality of available data and on the purpose of the modeling investigation.

Complex numerical models developed from a sparse data base may appear impressive, but the necessary incorporation of a large number of unsubstantiated assumptions may produce unreliable model predictions.

Inappropriate prediction results from the application of a model to predict aquifer conditions that are beyond the capabilities of the code (program) or far outside the range of conditions that the model was developed to handle.

Misinterpretation can result from a lack of conceptual understanding of the specific system model, which can result in improper utilization of the model, or an inability to relate model results to the true system. Even worse is no interpretation; blind faith acceptance of model results.

Application of Numerical Models

Any application of a numerical model to a hydrogeological problem should follow a set of well-defined steps: data review, conceptual model development, code selection, model calibration, diagnostic checking, sensitivity analysis, and predictive simulation (Slide 7.10).

Data for the aquifer system to be modeled should be compiled and evaluated by checking for completeness and quality. Obvious data gaps or contradictions should be cause for concern. Numerical models require a large site-specific data base in order to yield accurate results (Slides 7.11 and 7.12).

Formulation of an accurate conceptual model of the system is probably the most important step. If it is wrong, the numerical model, with all its sophistication, will be wrong as well.

Codes should be evaluated against the objectives of the study, and the quantity of available data. The features of the selected code should match the features of the conceptualized flow system, and the data requirements of the code should be consistent with the existing data base.

Calibration involves adjustment of model parameters until a satisfactory agreement is obtained between computed heads and the heads at selected calibration targets (usually water levels in wells). Transient calibration matches the history of response of the aquifer system.

Diagnostic checking involves a "reality check" to see if the calibrated model makes sense; aquifer parameters should be within reasonable ranges, the water budget for the aquifer should match hydrologic observations, and areas at some distance from calibration targets should be checked to be sure the water table does not breach land surface.

Sensitivity analyses identify the parameters that exert the greatest influence on model response by varying each parameter by a fixed relative amount (e.g. 10 % or 50%) and recording the change in the response variable (e.g. head). - Additional data collection focusing on the most sensitive parameters may greatly improve model performance.

After the model has been calibrated, checked, and run through a set of sensitivity trials it may be used with some confidence to make predictions. Predictions are often the ultimate goal of the modeling study, but they should not be attempted without careful attention to the preceding steps.

Advantages

This method has the potential to be very accurate, can be applied to nearly all types of hydrogeologic settings, and can simulate dynamic aspects of the hydrogeologic system that affect WHPA size and shape.

Disadvantages

Costs are high relative to other methods, and considerable expertise in hydrogeology and modeling is required to use the method. The cost may be warranted where a high degree of accuracy is desired.

Due to limitations on model grid spacing and density, numerical models are less suitable than numerical methods in assessing drawdowns close to pumping wells. For this reason, WHPA delineation in some European countries in recent years has focused on combining analytical methods for the near-field and numerical models for the bulk of the protection area.

7.3 CHECKPOINTS FOR REVIEWING A MODELING STUDY

A report describing the application of a numerical model to a hydrogeological investigation should be reviewed in two steps: an initial reading to grasp intent and content of report, and a detailed review to closely examine approach, assumptions, and technical issues.

Initial Reading

First establish the purpose of the model application. This will detemine the level at which certain factors should be evaluated in the review including appropriateness of selected modeling technique, reasonableness of simplifying assumptions, and interpretation of results.

Review the section describing the hydrogeologic setting being modeled. This will provide a basis for assessing the soundness of the conceptual model, reasonableness of parameter ranges, and appropriateness of the selected computer code.

Briefly review the quantity and quality of available data. This will permit evaluation of appropriateness of the selected code.

Skim the conceptual model section checking for completeness and judging basic agreement with the aquifer setting and field data.

Identify the code being used and form a preliminary opinion as to its appropriateness for the particular application.

Read the salient points in the results and interpretation section to determine the degree of success of the application. Problem areas should be noted so that possible sources of error can be identified during the detailed review.

Detailed Review

The detailed review of a model application should be conducted by moving through the following series of topics and addressing the listed questions, items, or issues. The following are questions that should be considered in the detailed review.

Purpose

Is the purpose clearly stated?

Is the purpose, as stated, consistent with the regulatory requirements the model application was developed to address?

Hydrogelogic Setting

Is the regional setting (geology, climate, surface and subsurface hydrology) described in sufficient detail?

Is the local setting (geology, climate, surface and subsurface hydrology) described in sufficient detail?

Are there any strong regional controls on the local setting?

Are there any strong local controls?

Are aquifer boundaries well-defined?

Are recharge and discharge areas identified?

Are there any distinctive aquifer features (layering, confining zones, fractures)?

Are there any unusual system features (regional, local, aquifer)?

Will these unusual features require simplifying assumptions to yield a tractable problem?

Data

Were data on which the model is based collected correctly?

Were field or laboratory tests interpreted correctly?

Were any data reduction or parameter estimation procedures performed correctly?

Are there any data gaps?

Will data gaps require simplifying assumptions?

Will data gaps require parameter estimates based solely on professional judgement?

Are data gaps serious enough to preclude a reasonable attempt at model development?
Do data gaps require assumptions or parameter estimates that are not testable or verifiable?

Conceptualization

Is the conceptual model of the hydrogeologic system complete enough for the purposes of the study?

Is the conceptualization sound?

Are there conflicts between the conceptual model and available evidence from field data?

Calibration

Is the code used for model development and calibration identified?

Is the code in the public domain (or readily available), and is it widely-used, well-tested, and widely-accepted?

If the code has been modified in any way, are these modifications clearly described and have they been thoroughly tested?

If the code is proprietary, is its selection justified on technical grounds, and has the code been thoroughly tested?

Is the selected code appropriate for the system being modeled?

Are the code theory and features described?

Is a description provided of the governing equations being solved?

Is the area being modeled clearly identified on a map?

Are the starting values of hydraulic parameters and boundary conditions clearly stated?

Are any other time-stepping or code operation parameters presented and discussed?

Are simplifying assumptions (due to lack of field data or the nature of the study) used during model setup clearly identified?

Are any special simplifying assumptions required to make the selected code work in this particular case clearly identified and justified?

Are results of the final calibration run completely presented and discussed?

Is agreement between model results and calibration targets good enough given hydrogeologic conditions, model scale, and purpose of the study?

Are any discrepancies between calibrated heads and target values satisfactorily explained and justified?

Are parameter values, boundary conditions, and other features of the calibrated model reasonable and within acceptable ranges?

Does it appear that individual parameters or, sometimes more importantly combinations of parameters, have been deliberately skewed within their range of reasonable values to produce a desired or predetermined result?

Sensitivity Analyses

Were sensitivity analyses performed on the calibrated model to test for robustness and to identify the most sensitive parameters?

Are the results of sensitivity analyses presented in an understandable form?

Do the sensitivity analyses indicate that model calibration indicators (usually some measure of residuals between calculated and target heads) deteriorate rapidly with only small changes in model parameters?

Do sensitivity analyses indicate that the model does not respond to changes in parameter values, indicating some overriding control on the system?

Diagnostic Checking

Was the reasonableness of the calibrated model checked against factors (e.g. aquifer water mass balance) other than the calibration targets?

Does the model, although calibrated well, not compare well with these other factors?

Does the model, with noted discrepancies between computed values and calibration targets, match well with the bulk of field observations and water budget estimates?
Are there justifiable explanations for calibration discrepancies that would allow the model to be used satisfactorily for the purpose of the study?

Prediction

Are all predictive simulations conducted for the study described in sufficient detail (model setup, input data, output data, graphical presentation of results)?

Are the number and range of the predictive simulation model runs sufficient to meet the objectives of the study?

Does the range of runs dangerously exceed the range of conditions used during model calibration?

Is all pre- and post-processing of data clearly described? (It is important to know which results are attributable to the selected code and which are attributable to data manipulation during post-processing.)

Interpretation

Are model results presented and interpreted clearly in non-technical language?

Is the interpretation of model results consistent with the conceptual model of the system?

Is the interpretation consistent with the simplicity or complexity of the model? (It is incorrect to interpret model predictions in light of features that are not even incorporated in the model.)

Are model results presented with qualifying statements that reflect the limitations of the data, the simplifications inherent in the model, and the limited scope and intent of the modeling study?

Documentation

Is the entire modeling study documented sufficiently to be understandable to the reviewer?

Is the modeling study documented sufficiently to support its intended use (permit application, litigation support, etc.)? Are complete records of the modeling investigation available for more detailed review if required?

Is the version of the source code used to develop the model available?

Are printed and machine readable copies of the final calibration run available?

Are printed and machine readable copies of all predictive simulation runs available?

7.4 NUMERICAL MODEL CASE STUDIES

Numerical modeling has been used to delineate Wellhead Protection Areas (WHPAs) at many sites around the country including several described in the case studies included in this manual (Appendix B). The first example presented in this section, however, is a hypothetical "case study" designed to illustrate the use of a numerical model in delineating a WHPA. A comparison is made between the numerical model results and those obtained using a simple analytical solution. Emphasis is placed on the flexibility of the numerical approach and the ease with which hydrogeologic complexity can be treated and various assumptions can be tested.

A second case study is described in which a numerical model was applied to an actual site near Franklin, Massachusetts to delineate a WHPA for the aquifer. The case provides a good example of the data collection, model calibration, and predictive simulation steps.

A third case study involving numerical modeling at a site in Palm Beach County, Florida is not discussed in detail in this section due to the length and complexity of the case. A summary of the study, however, is provided in Appendix B (Case Study B.4). Ground-water flow and transport models were used to delineate WHPAs based on TOT and drawdown criteria. Of special interest is the fact that advective transport travel-time zones were augmented by a factor of 25 percent to account for dispersion effects. This represents a more sophisticated approach than simple particle tracking techniques.

7.4.1 <u>NUMERICAL MODELING CASE STUDY 1</u>:

HYPOTHETICAL NUMERICAL MODELING CASE STUDY

The following hypothetical study was developed to demonstrate the advantages of numerical modeling methods in delineating WHPAs for complex hydrogeologic settings. While the site and the data are fictitious, the aquifer setting and the parameter values used in the demonstration are representative of real-world values.

A WHPA is to be delineated for a water-supply well in a typical valley-fill aquifer (Slide 7.22). The protection area is to provide a 1,000-day travel-time buffer within the aquifer zone that contributes flow to the well. The results of the study will have implications for two sites currently being considered for a new chemical plant. Three technical experts are hired to delineate the WHPA, and each decides to take a very different approach to analyzing the site.

The aquifer setting (Slide 7.23) is a broad valley oriented north-south and filled to a depth of 200 feet with sand and gravel outwash. Aquifer tests indicate a hydraulic conductivity of 100 feet per day (ft/day), and water level measurements in wells throughout the valley show a regional flow gradient of 0.005 to the south. The average porosity of the aquifer material is 0.25.

The small river running through the valley carries an average discharge of 1,500 cubic feet per second (cfs). A single water supply well, located in the center of the study area near the river, is pumped at a rate of 133,700 cfs (1 million gallons per day). For the purposes of this demonstration, the well is assumed to draw water from the entire thickness of the aquifer.

The town being supplied by the well is located south of the well as shown on the map (Slide 7.23), and the proposed chemical plant sites are located about 3,000 ft north of town and 2,000 ft north of the well.

Approach 1

Expert 1 decided to take a simple approach, treating the predominantly sand and gravel material filling the valley bottom as a homogeneous aquifer (Slide 7.24). He also assumed that the river had little effect on the flow system, and he ignored it in his modeling. He applied the analytical computer model RESSQ to the study site using the following data:

Aquifer thickness	61 m (200 ft)
Porosity	0.25
Pore velocity	223 m/yr (2 ft/day, computed using Darcy's law)
Flow direction	South
Time of travel	2.74 yr (1000 days)
Pumping rate	158 m^3/hr (133,700 cfs)

The zone contributing ground-water to the supply well within a 1,000-day time-of-travel distance (Slide 7.25) shows an area about 350 ft wide and 850 ft long extending north of the well.

To check his work, he constructed a simple finite difference model (Slide 7.26) of the aquifer system and pumping well using the MODFLOW code (McDonald and Harbaugh, 1984). He used the following data:

Aquifer thickness	200 ft
Constant head on north boundary	2,000 ft
Constant head on south boundary	1,960 ft
(these heads produce a regional gradient of 0.005)	
Cell width in x-direction	200 ft
Cell width in y-direction	200 ft
Hydraulic conductivity	100 ft/day
Pumping rate	133,700 cfs

Although the problem setup is the same, generating the input data set for MODFLOW took considerably more time than the 7-line data file required for RESSQ. After computing the hydraulic heads in the flow field using MODFLOW, he used the particle tracking code GWPATH (Shafer, 1987) to determine the zone contributing water to the well within 1,000 days. GWPATH requires a rectangular computational domain, so data from the MODFLOW grid cells within the large bold rectangle shown on Figure 1 were used for the particle tracking study. He used the head field generated by MODFLOW as input to GWPATH and assumed a porosity of 0.25. The results of this analysis (Slide 7.27) were almost identical to the RESSQ model. Because flow does not move directly south in the valley, but follows the broad S-shape of the valley, the WHPA is oriented very slightly north-east. The size of the WHPA, however, is almost exactly the same as that generated by RESSQ.

In this simple case there seemed to be little advantage in using the more sophisticated finite-difference model over the simple analytical solution. The finite-difference model took longer to setup and gave almost exactly the same results.

As a result of the protection area defined by his WHPA delineation study, Expert 1 recommended Site B for the new chemical plant.

Approach 2

Expert 2 decided to account for surface hydrology in his analysis to delineate the WHPA (Slide 7.28). He obtained the elevation of the water level in the river and the elevation of the riverbed at numerous points along its course through the study area. He also obtained records that showed an average annual rainfall in the area of 54 inches, and estimated that 18 inches of that amount infiltrated every year to recharge the ground water system. Since the analytical model RESSQ cannot treat areal recharge or surface water bodies, he developed a MODFLOW model of the aquifer. He used the same data shown in Approach 1, with 53 grid blocks representing river cells (Slide 7.29), and a recharge of 18 in/yr.

His delineated area (Slide 7.30) does not differ significantly from those of Approach 1. The moderate amount of recharge is transmitted through the highly conductive aquifer without significantly altering the hydraulic head field established by the regional flow regime.

For this set of aquifer conditions, the regional flow is moving southward beneath the river, and the zone contributing flow to the well is relatively unaffected by the presence of the river and the introduction of recharge. In other words, the river is not acting as a flow boundary. For this case, the results match well with those computed by the analytical solution employed in RESSQ.

This may not always be the case. Rivers may act as flow boundaries depending on the properties of the aquifer, regional flow conditions, rate of recharge, and rate of pumping (see section below entitled Additional Considerations).

Based on his study, Expert 2 also recommended Site B for the new chemical plant.

Approach 3

Expert 3 decided to incorporate subsurface geology into his delineation study (Slide 7.31). From well borings in the area, he determined that large zones of low-permeability material (clay plugs) were located on either side of the river in the vicinity of the pumping well. Since analytical solutions cannot treat a nonhomogeneous aquifer, he constructed a MODFLOW model of the system (Slide 7.32). Testing revealed that the hydraulic conductivity of the clay material was 10 ft/day and its porosity was 0.40. He neglected the river and recharge, and constructed his model using the same MODFLOW data set used in Approach 1. In this case, however, he included low permeability blocks (10 ft/day) to represent the clay zones. He used GWPATH to perform particle tracking on the resulting head field, with a porosity of 0.25 for the sand and gravel material and 0.40 for the clay plugs.

The WHPA he delineated (Slide 7.33) was much different from those generated in the other approaches. The clay plugs had two effects on the flow system. First, they diverted regional flow from the north so that is could only reach the well within 1,000 days through a narrow section of the aquifer oriented northeast-southwest between the clay plugs. In addition, it restricted flow toward the well in the area just west of the well, causing greater drawdown and a broader zone of contribution directly around the well.

His findings were reported to the appropriate agencies in time to ensure that Site A was selected for the new chemical plant. A toxic spill at the plant, were it located at Site B, would have traveled directly to the water supply well within 1,000 days.

ADDITIONAL CONSIDERATIONS

Permeability contrasts (like clay plugs) are not the only ground-water flow system features that can alter the size and orientation of a WHPA. The orientation of the WHPA can be altered significantly from that predicted from an examination of the regional gradient, even in a homogeneous aquifer.

As an example, consider the MODFLOW model constructed in Approach 2 above. If a similar model were constructed with a hydraulic conductivity of 10 ft/day instead of 100 ft/day, the resulting 1,000-day travel time WHPA (developed using GWPATH for particle tracking) would be much larger (compare Slides 7.34 and 7.30). The quantity of flow moving toward the well under the regional gradient of 0.005 is greatly reduced, and the well requires a much broader zone of contribution to receive the 133,700 cfs being withdrawn. The influence of areal recharge and the resulting flow toward the river is evidenced in the refraction of the particle paths, but the well is drawing water from both sides of the river. The river does not act as a flow boundary for the flow system in the vicinity of the pumping well.

If, however, the pumping rate is reduced by a factor of ten to 13,370 cfs, the effect of recharge and flow toward the river exerts a greater influence on the ground-water flow system than does the pumping well. The zone of contribution is largely confined to the region south of the river (Slide 7.35). The river bounds the zone of contribution on the north, and the axis of the WHPA is oriented northeast in much the same manner as it was when flow to the well was being controlled by the low permeability zones (see Approach 3 above).

This demonstrates that many factors, and the balance of strengths among those factors, must be taken into account to accurately delineate a WHPA in a complex hydrogeologic flow system. The U. S. Geological Survey Open File Report 86-543 (Morrissey, 1987) provides an excellent discussion and numerous modeling examples of the effects of recharge and rivers on the contributing areas of wells located near rivers.

7.4.2 NUMERICAL MODELING CASE STUDY 2:

NUMERICAL MODEL APPLIED TO A MASSACHUSETTS AQUIFER

The Massachusetts Department of Environmental Quality Engineering (DEQE) required that three zones be delineated around a proposed water supply well in Franklin, Massachusetts. The case study is presented in detail in Appendix B, with only the numerical modeling application designed to delineate one of the zones discussed here.

The intermediate zone around the well is to encompass the land area which supplies ground water to a pumping well under the most severe recharge and pumping conditions. In the Franklin case, a computer simulation was deemed necessary to delineate this zone. The finite-difference ground-water flow code MODFLOW (McDonald and Harbaugh 1984) was selected because its features permitted an accurate representation of the complex hydrogeologic system surrounding the well.

The aquifer is a glacial outwash deposit of sands, silts, and clays with a maximum thickness of 43 feet at the valley center. The aquifer is bounded on all sides by bedrock valley walls or glacial till except for a narrow zone to the east that connects the aquifer to an adjacent valley (Slide 7.38). Flow is to the east under a gradient of about 0.001. Transmissivity ranges from about 150,000 gpd/ft near the well to 50,000 gpd/ft near the boundaries of the aquifer. Storativity was approximately 0.02.

A three-dimensional model (2 layers, 21 columns, 27 rows) was constructed with a grid spacing graded from 50 feet near the water supply well to 400 feet near the aquifer boundaries. No-flow boundaries were set around the entire aquifer except for a narrow discharge zone to the east (Slides 7.40 and 7.41). Constant heads at this point established a gradient that produced eastward flow.

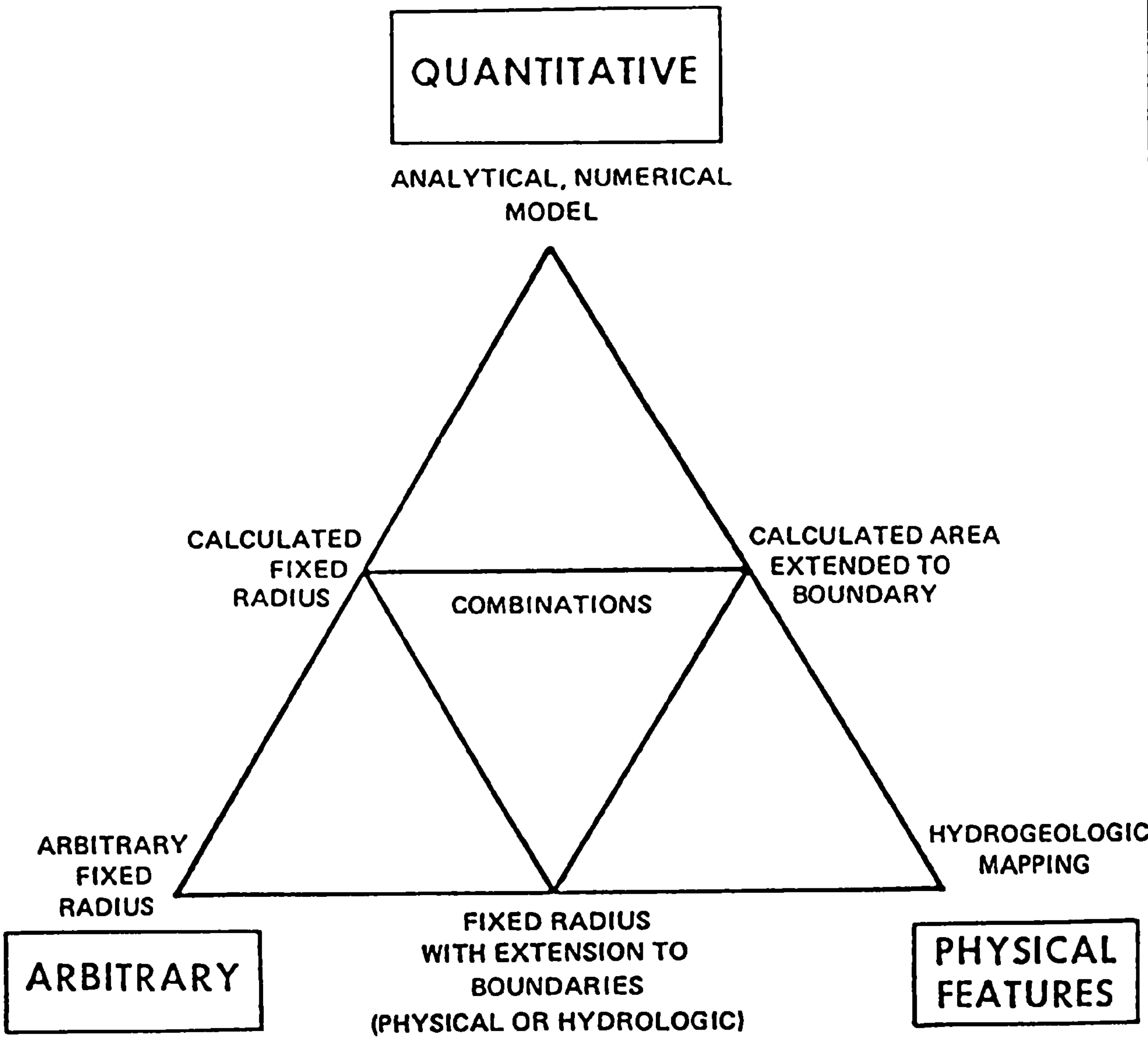
The model was first calibrated for non-pumping conditions, and then for conditions simulating the pumping of wells under conditions simulating pumping tests previously conducted to estimate aquifer parameters.

Following calibration, predictive simulations were conducted for the severe pumping conditions required by DEQE regulations. Four scenarios were simulated: high and low aquifer storativity ignoring recharge from a surface stream, and high and low storativity incorporating the effects of the stream in the model using the river simulation package.

The simulations with no recharge from the stream failed due to excessive dewatering of model cells. The simulations with stream recharge predicted that, for both values of storativity, all flow within the valley would be toward the well (Slides 7.44 and 7.45). Zone II was delineated as the entire valley in which the well was situated (Slide 7.46).

COMPARATIVE ANALYSES

Interrelationships of WHPA Methods



WHPA Comparative Analysis
What is Accuracy?

Too Small < Accurate < Too Large

	Too Small	Accurate	Too Large
RESULTS:	Underprotection	Preservation of Quality	Overprotection
PROBLEMS:	Quality Degradation		Implementation

Slide 8.03

Relationship Between WHPA Delineation Methods and Criteria

CRITERIA / METHOD	DISTANCE (L/M/H)	DRAWDOWN (L/M/H)	TOT (L/M/H)	PHYSICAL BOUNDARIES (L/M/H)	ASSIMILA-TIVE CAPACITY (L/M/H)
ARBITRARY FIXED RADIUS	H	N/A	N/A	N/A	N/A
CALCULATED FIXED RADIUS	N/A	H	H	N/A	N/A
SIMPLIFIED VARIABLE SHAPES	N/A	N/A	M	N/A	N/A
ANALYTICAL MODELS	N/A	H	H	N/A	M
NUMERICAL FLOW/ TRANSPORT MODELS	N/A	H	H	N/A	M
HYDROGEOLOGIC MAPPING	H	N/A	N/A	H	N/A

L–LOW
M–MEDIUM
H–HIGH
N/A–NOT APPLICABLE

Slide 8.04

COMPARATIVE ANALYSIS:

KENNEDALE, TEXAS

PURPOSE OF CASE STUDY 1

- COMPARATIVE STUDY INVOLVING DRAWDOWN AND TIME-OF-TRAVEL CRITERIA

- ILLUSTRATES IMPORTANCE OF BALANCE BETWEEN PROTECTIVE AND IMPLEMENTABLE DELINEATION

- ILLUSTRATES IMPORTANCE OF UNDERSTANDING AQUIFER SYSTEM MECHANICS AND WATER SOURCE TO THE WELL

- HYDROGEOLOGIC SETTING

  - 4 WELLS IN TRINITY AQUIFER

  - PUMPING 70,000 - 280,000 GPD PER WELL

  - 1.1 MGD COMBINED PUMPAGE FOR 1988

  - TWO PRIMARY PRODUCTION ZONES

    PALUXY
    TWIN MOUNTAINS

  - 600-FT CONFINING MATERIALS

REGIONAL HYDROGEOLOGIC BOUNDARIES

RECHARGE AREA 20 MILES WEST

- DIRECT INFILTRATION IN OUTCROP AREA
- RECHARGE RATE 1 IN/YR

VELOCITY ESTIMATES

- RANGE 1-2 FT/YR TO 200 FT/YR

WHPA CRITERIA AND METHODS

- CRITERIA
  - DRAWDOWN (5-FOOT CONTOUR)
  - TOT (5-YEAR TRAVEL TIME)

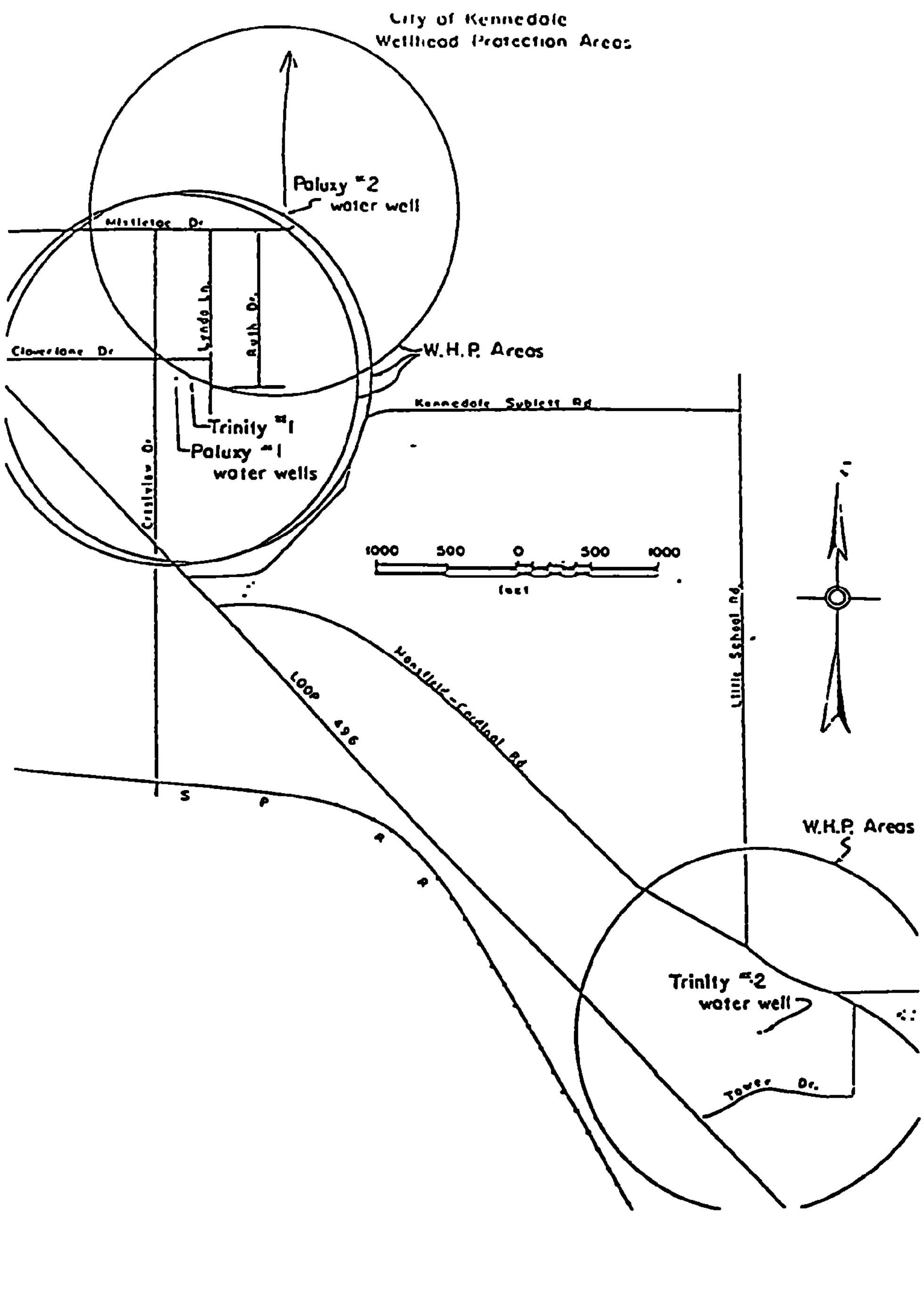
- METHODOLOGY
  - CALCULATED FIXED RADIUS USING THE VOLUMETRIC FLOW EQUATION

$$r = \sqrt{\frac{Qt}{n \pi H}}$$

  - ADDED AN ADDITIONAL BUFFER ZONE

- DRAWDOWN MODEL RESULTS YIELD UNREALISTIC AREA USING 5-FOOT DRAWDOWN CRITERION THRESHOLD

WELLHEAD PROTECTION AREAS



- CALCULATED RADII FOR ALL WELLS LESS THAN 800 FEET
- WHPA ESTABLISHED AT 1,320 FEET

COMPARATIVE ANALYSIS:

BROOKINGS COUNTY, SOUTH DAKOTA

PURPOSE OF CASE STUDY 2

- COMPARATIVE STUDY OF HYDROGEOLOGIC MAPPING AND ANALYTICAL METHODS
- ILLUSTRATES THE IMPORTANCE OF GROUND-WATER AND SURFACE-WATER RELATIONSHIPS AND AQUIFER SYSTEM BOUNDARIES
- USES MULTIPLE ZONE DELINEATION WITH 1-FOOT DRAWDOWN CRITERIA

HYDROGEOLOGIC SETTING

. BIG SIOUX AQUIFER

- UNCONSOLIDATED SANDS AND GRAVELS OF GLACIAL OUTWASH ORIGIN

- DEPOSITED ON IMPERMEABLE TILL, OR BEDROCK

- UNCONFINED CONDITIONS

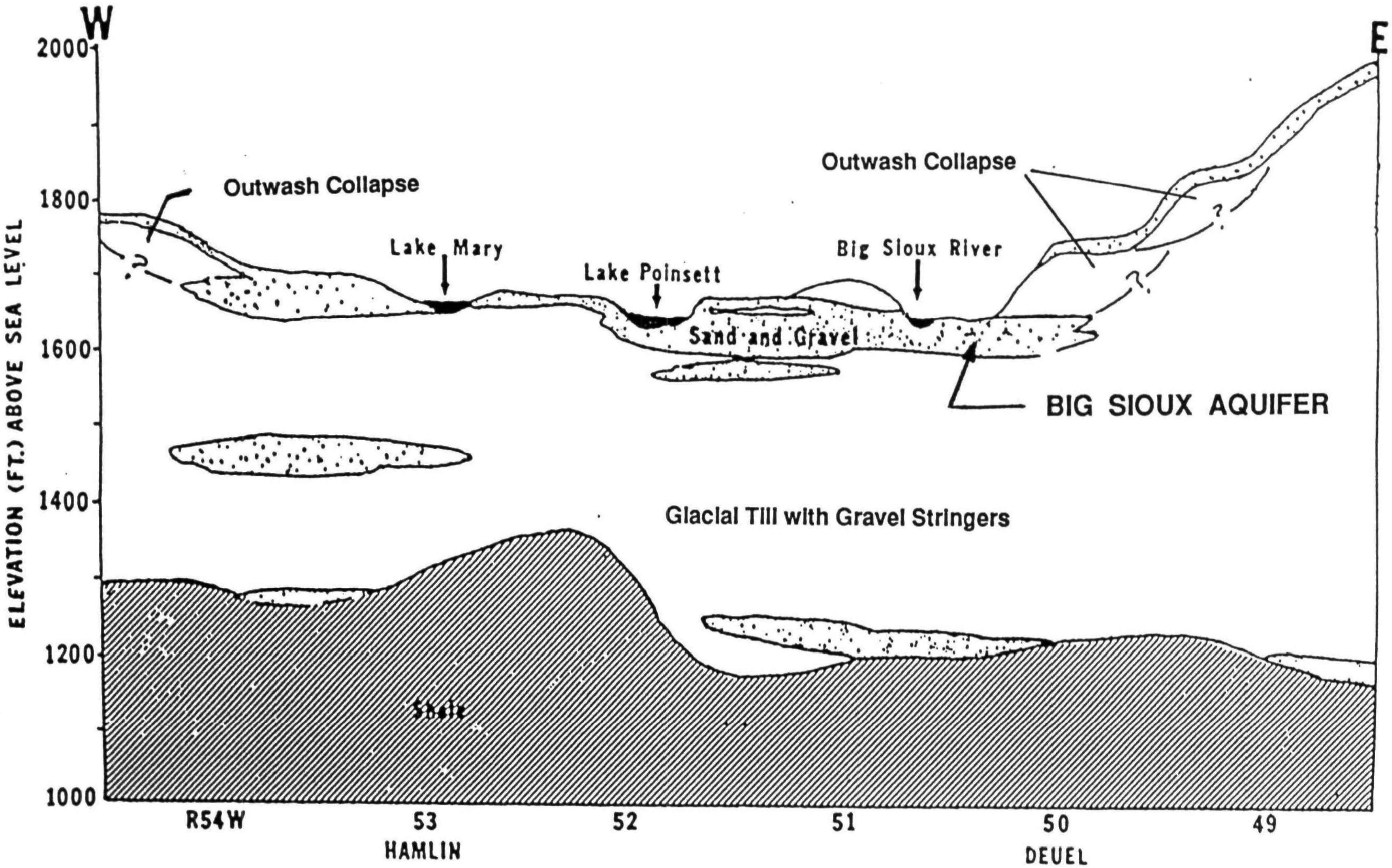
$n = .20 - .35$

$K = 20 - 20{,}000$ gpd/ft^2

$b = 20 - 60$ ft

. WELL YIELDS AS MUCH AS 1000 GPM

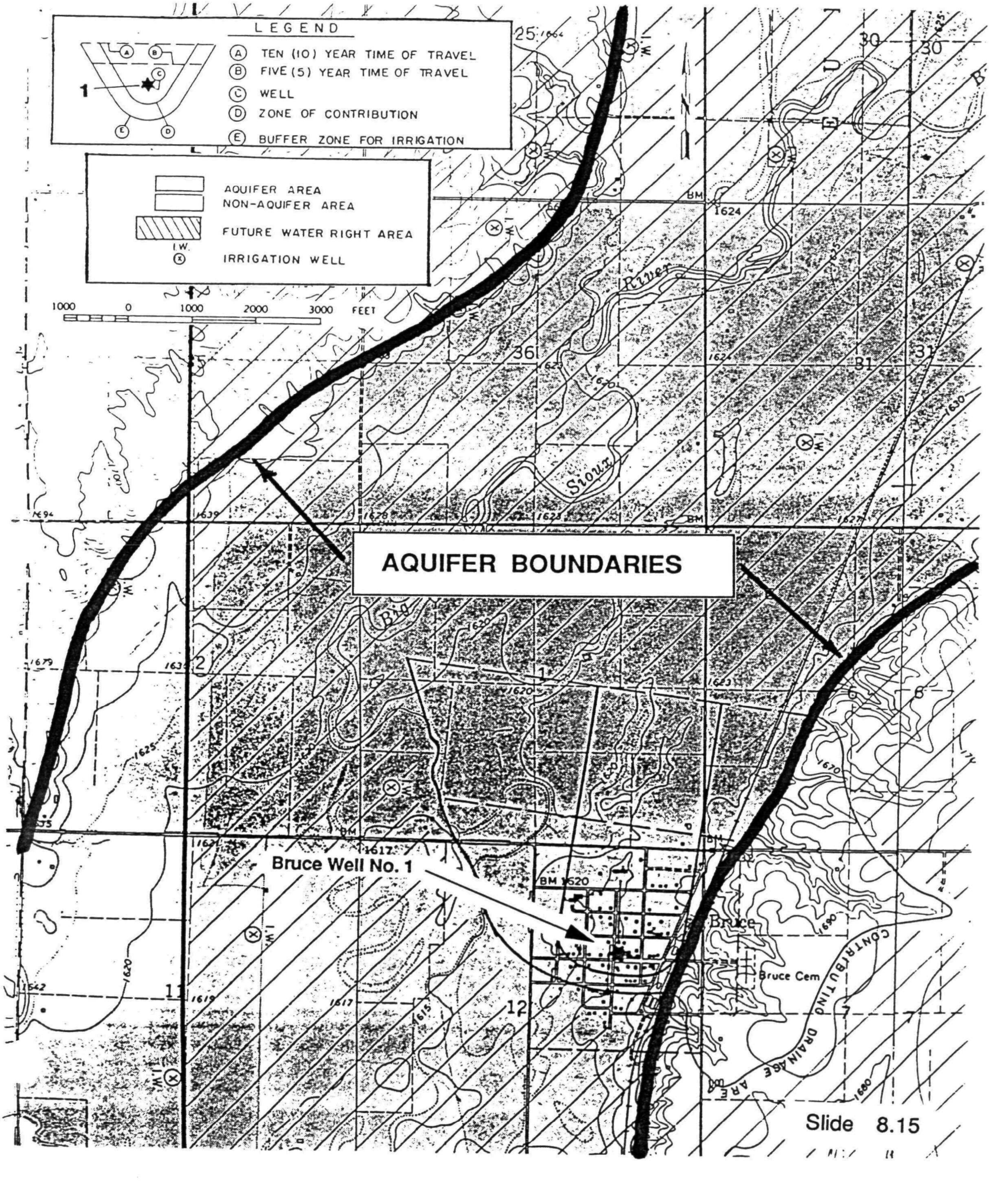
. INDUCED INFILTRATION IMPORTANT ROLE



GEOLOGIC CROSS-SECTION OF BIG SIOUX BASIN

Slide 8.14

BRUCE WELL NO. 1 SETTING



Slide 8.15

ANALYTICAL ZONE OF TRANSPORT METHOD

- SOLVE UNIFORM FLOW EQUATION
  - KEY POINTS ON THE UPGRADIENT DIVIDE
  - ESTIMATE DOWN-GRADIENT/CROSS GRADIENT
  - LOCATE UPGRADIENT TOT EXTENT
- DELINEATE WHPA

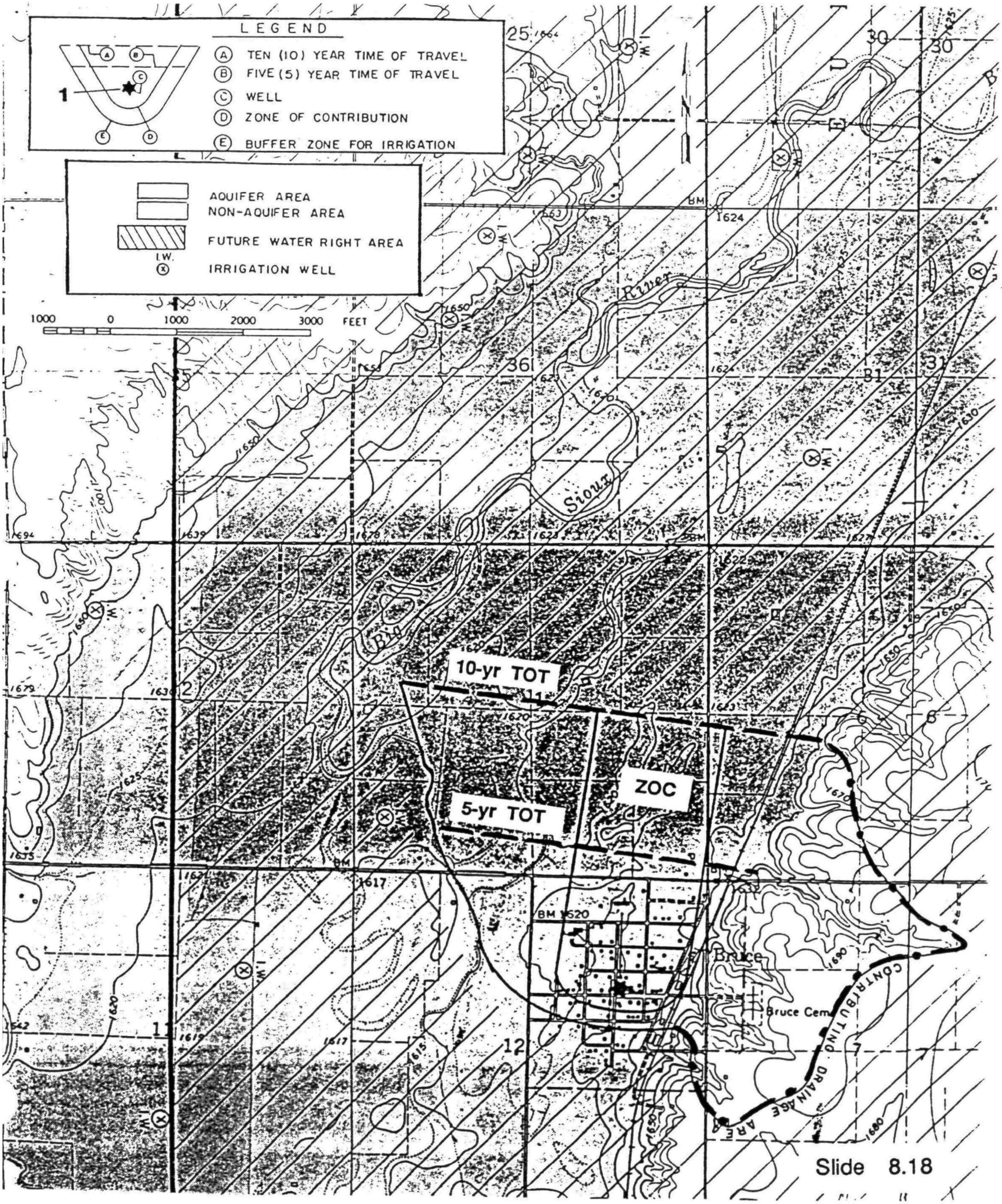
HYDROGEOLOGIC BOUNDARY EFFECTS

. ADJUST THE ZOC AT INTERSESCTION WITH THE AQUIFER BOUNDARY

. DELINEATE CONTRIBUTING DRAINAGE AREA

. SIMILAR ADJUSTMENT FOR IRRIGATION WELLS

ZONE OF TRANSPORT METHOD RESULTS



Slide 8.18

THEIS ANALYTICAL METHOD

- EMPLOY DRAWDOWN CRITERION
- DRAWDOWN THRESHOLD = 1 FOOT
- THWELLS COMPUTER CODE

  T = 55, 128 gpd/ft

  S = 0.20

  Q = 120 gpm

  t = 20 years

- GOOD MATCH BETWEEN THEIS AND SIMPLIFIED VARIABLE SHAPES BUT DOES NOT CONSIDER BOUNDARY EFFECTS

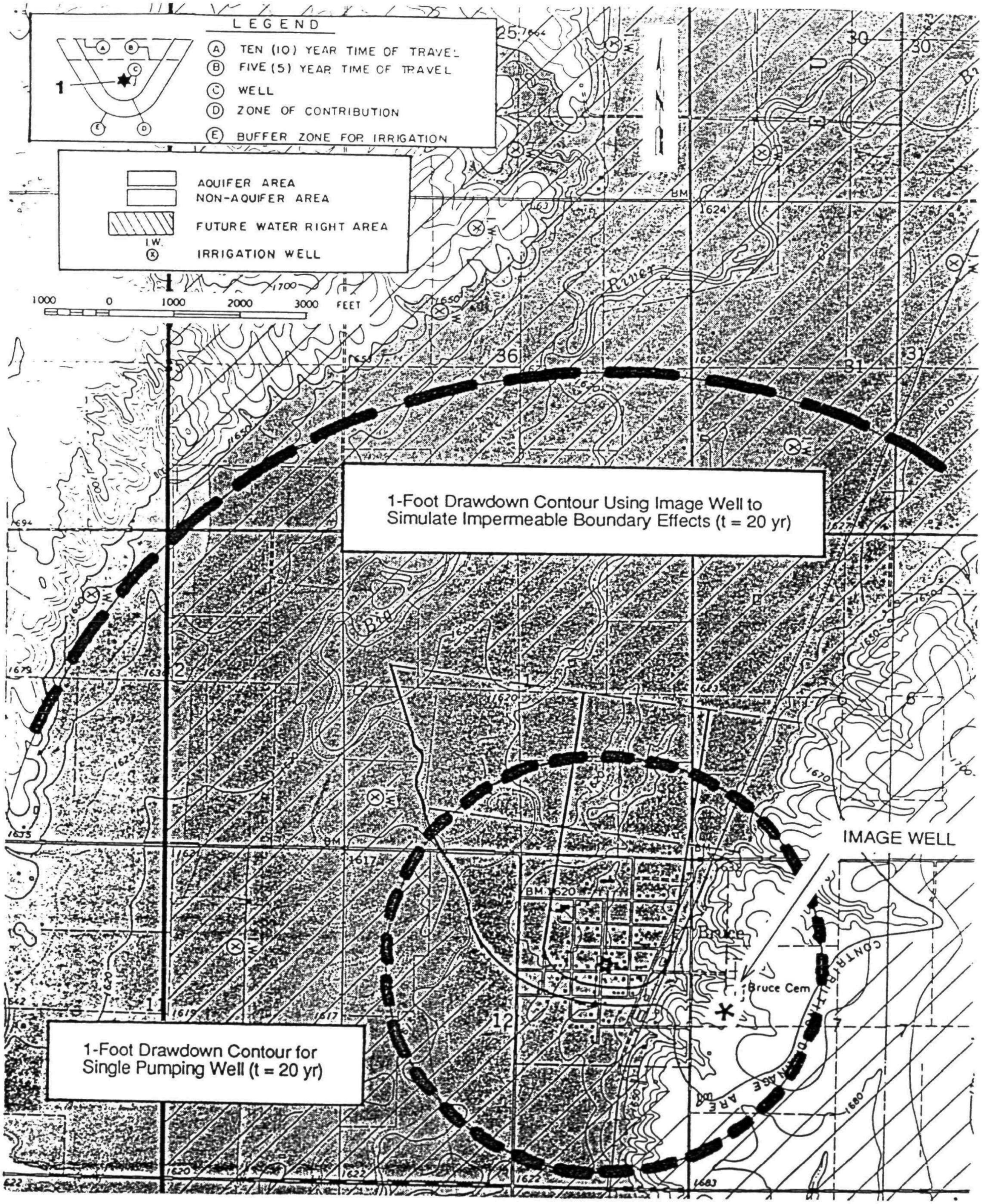
THEIS - IMAGE WELL

- BARRIER BOUNDARY EFFECTS RESULT IN GREATER DRAWDOWN THAN IN INFINITE AQUIFER

- ACCOUNT FOR BARRIERS THROUGH THE USE OF IMAGE WELL THEORY
  - THEIS EQUATION WITH MULTIPLE PUMPING WELLS
  - APPLY LAW OF SUPERPOSITION

- PLACE PUMPING WELL (FICTITIOUS IMAGE WELL) AT THE SAME DISTANCE FROM THE BARRIER AS THE REAL WELL

- USE THWELLS



Comparative analysis between Theis drawdown method and WHPA delineation methods applied at Bruce Well #1, Brookings County, South Dakota.

COMPARATIVE ANALYSIS

CYPRESS CREEK WELLFIELD, FLORIDA

PURPOSE OF CASE STUDY 3

- COMPARISON OF SEVERAL MODELING APPROACHES USING TIME-OF-TRAVEL CRITERION

- THREE APPROACHES CONSIDERED

  - VOLUME BALANCE (CALCULATED FIXED RADIUS)
  - RANDOM WALK
  - METHOD OF CHARACTERISTICS

- CYPRESS CREEK WELLFIELD

- IMPORTANT TO UNDERSTAND SUBTLE DIFFERENCES IN NUMERICAL MODEL APPROACHES

HYDROGEOLOGIC PARAMETERS

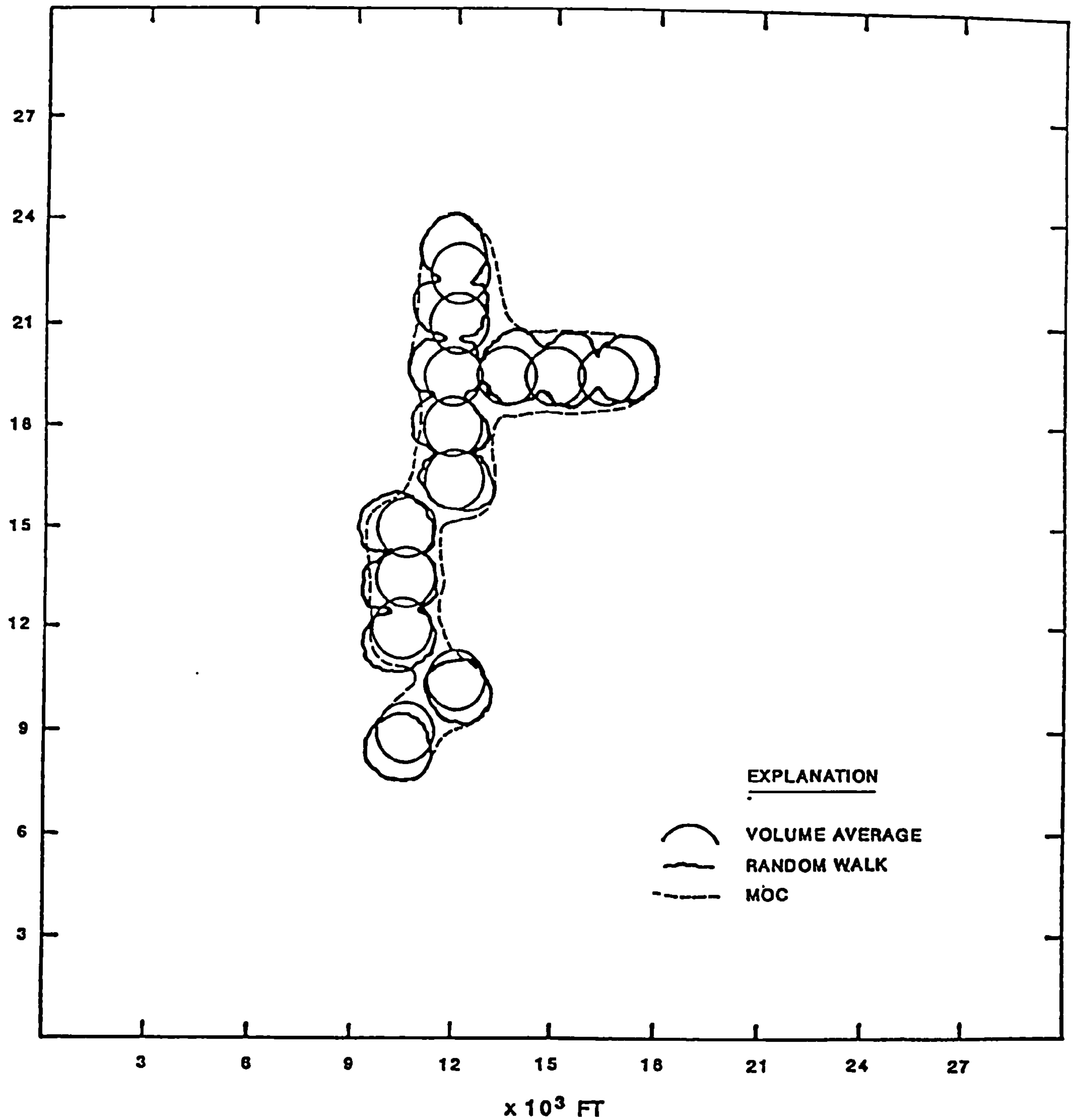
- CYPRESS CREEK WELLFIELD

  T = 400,000 gpd/ft
  b = 500 ft
  L = 0.01 gpd/ft^3
  Q = 2.3 MGD/WELL (13 WELLS)
  D = .000001

- COMPUTER TIME OF TRAVEL FROM LOCATIONS IN AQUIFER TO WELLS

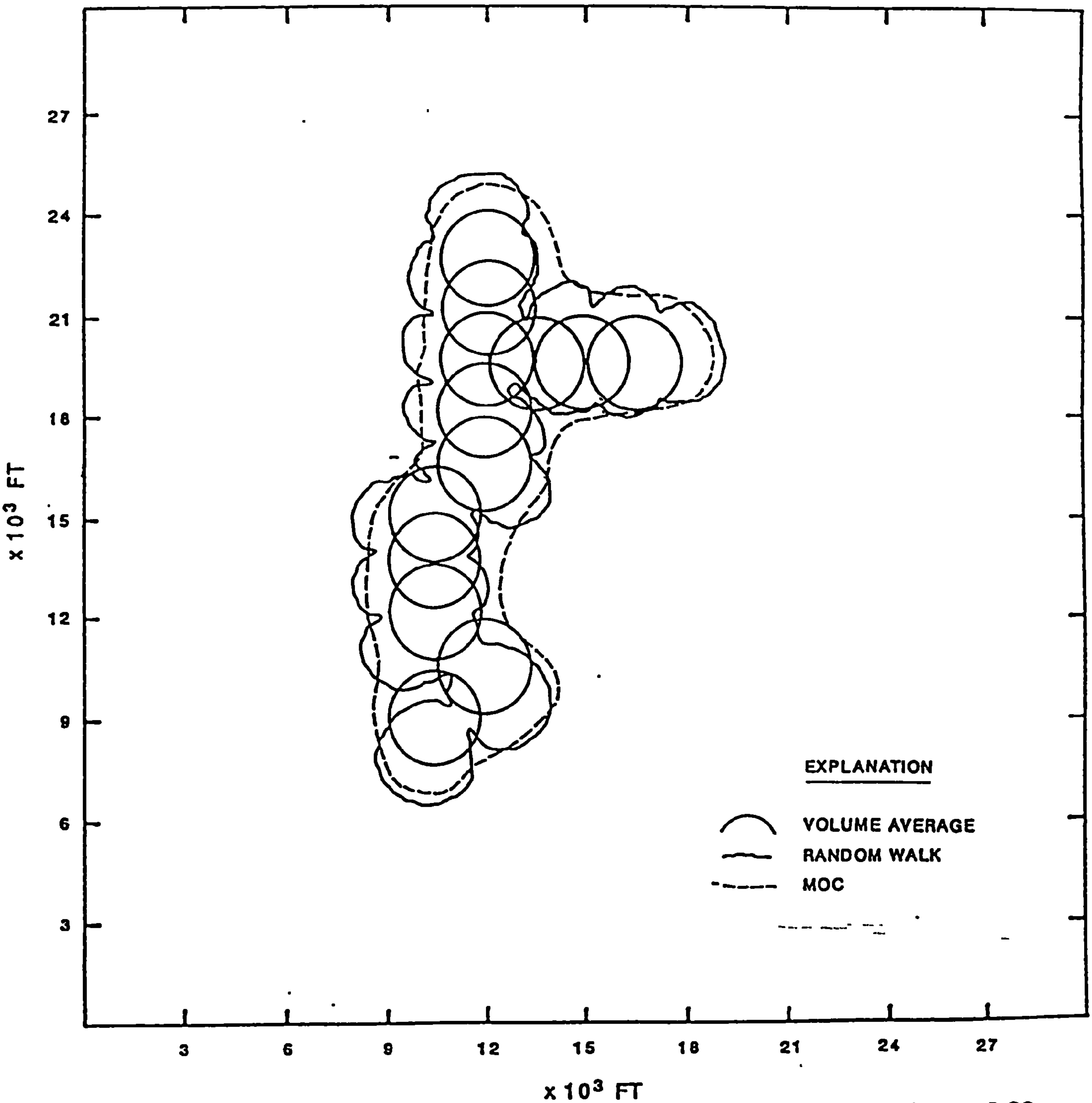
- RESULTS REPORT SEQUENCE OF TRAVEL DISTANCE FOR 2-YEAR, 5-YEAR, 10-YEAR TIME

2 - YEAR TRAVEL DISTANCE



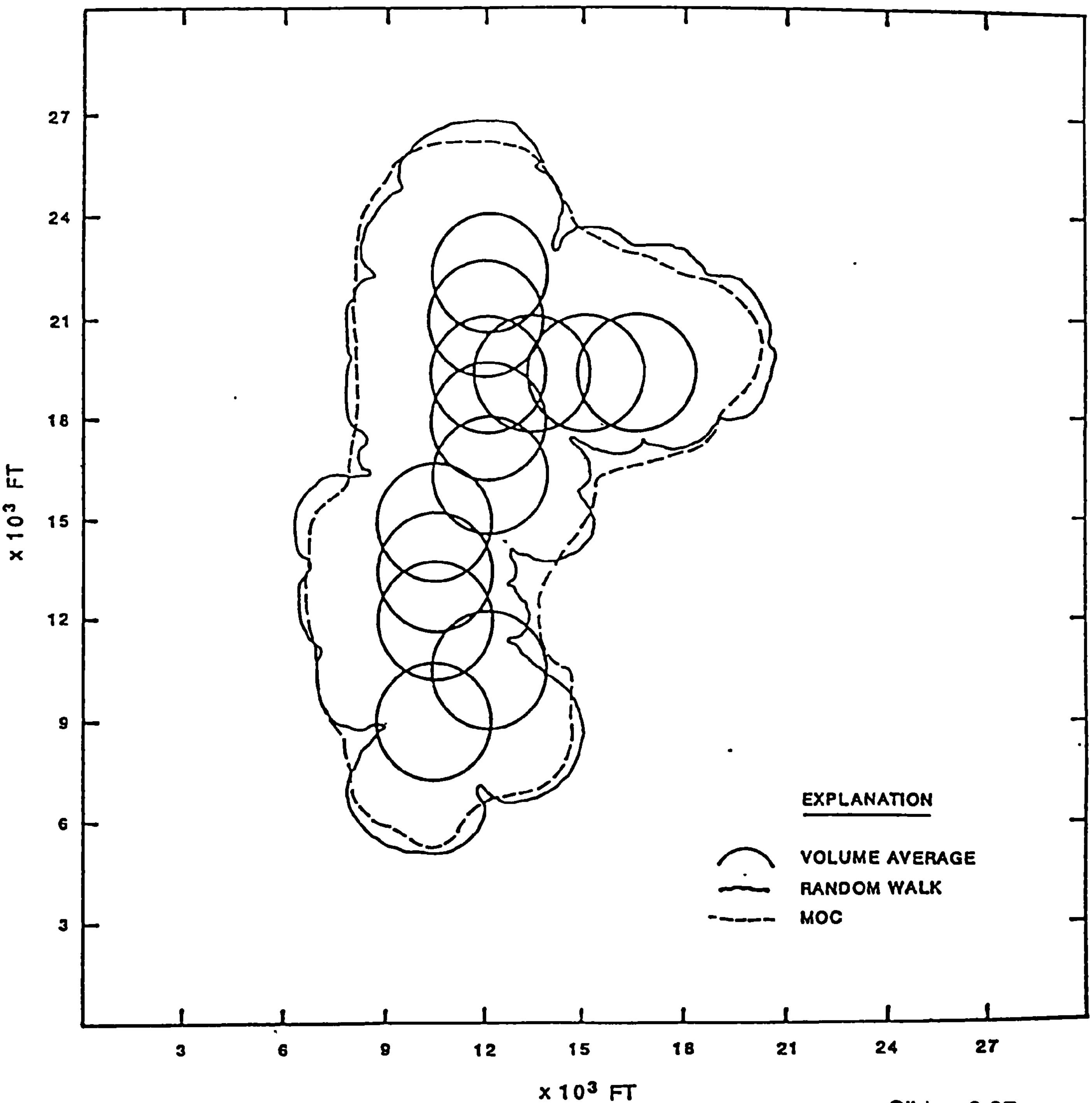
Slide 8.25

5 - YEAR TRAVEL DISTANCE



Slide 8.26

10 - YEAR TRAVEL DISTANCE



Slide 8.27

COMPARISON SUMMARY

- VOLUME BALANCE INTRODUCES GREATER ERROR WITH TIME
  - TRAVEL DISTANCE CONTOURS DO NOT CONSIDER OTHER WELLS
  - 70% OVERLAP AT 10 YEARS
- NUMERICAL MODELS EXHIBIT SUBTLE DIFFERENCES
  - AVERAGING SCHEMES OF FORMULATION
  - GRID RESOLUTION EFFECTS
- MODEL SELECTION CONSIDERATIONS
  - AVAILABILITY OF DATA
  - COMPUTER FACILITIES
  - AQUIFER SYSTEM COMPLEXITY
  - CODE FORMULATION, CHARACTERISTICS

8.0 COMPARATIVE ANALYSIS CASE STUDIES

8.1 INTRODUCTION

At least six methods are available for use in delineating Wellhead Protection Areas (WHPAs). These methods span a broad range of cost and complexity. It is valuable, prior to designing a WHPA delineation study, to examine comparative analysis test cases in which several methods are applied to the same location.

Such studies may be used to assess a number of factors related to WHPA delineation. Comparison of a WHPA accurately delineated with a sophisticated method against WHPAs delineated with simpler methods permit assessment of the "safety factors" supposedly incorporated in the simple methods. Similarly, a favorable comparison between simple and sophisticated methods may indicate that the sophisticated methods are not worth the extra cost. Comparative analyses may also be used to assess the impact of different criteria thresholds selected for a given site.

The following case studies have been selected to illustrate the use of several methods at a single site. Where appropriate, the suitability of the methods applied is discussed.

8.2 COMPARATIVE ANALYSIS CASE STUDY 1:

COMPARISON OF DRAWDOWN AND TIME-OF-TRAVEL CRITERIA

In October, 1987 the City of Kennedale, Texas requested that the Texas Water Commission (TWC) establish wellhead protection criteria for their public water supply system. The case study is presented in greater detail in Appendix B. The material pertinent to the comparison of two different criteria for the same system of wells is summarized here.

The City of Kennedale derives its water from the Trinity Aquifer which is confined beneath 600 feet of limestone, marl, and clay. TWC first developed a computer model of drawdown in the confined aquifer using pumping data for the period 1952 to 1987. The zone of influence (ZOI) was defined in this case as the 5-foot drawdown contour. Results of the modeling study showed that the 5-foot drawdown contour was located at a distance of 20 miles from the Kennedale wells, encompassing an area that engulfed Fort Worth and extended into two other counties.

It was decided that this large zone of influence would not be appropriate. Water moved very slowly through the confined aquifer, and a zone of over 1,200 square miles would be unnecessarily overprotective. It was reasoned that the distance required for a 5-year time-of-travel to the wells would provide for sufficient attenuation of any contaminants.

The calculated fixed radius method was used to delineate the WHPA for each well based on pumping data during the previous two years. Calculated radii for all wells were less than 800 feet. A buffer zone was added to the calculated radii and the WHPA for each was established as the zone within a one-quarter mile (1,320 ft) radius of each well (Slide 8.10).

The large difference in areas between the two methods described above results from the nature of the aquifer. Pressure phenomena (i.e. reduction in piezometric surface of 5 ft in this case) can extend to great distances from wells in confined aquifers. This is true even for relatively low pumping rates and low flow velocities through the aquifer.

8.3 COMPARATIVE ANALYSIS CASE STUDY 2:

COMPARATIVE ANALYSIS USING THEIS SOLUTION

The Brookings, South Dakota case study (Appendix B) describes a project in which a modified simplified variable shapes method was used to delineate a Wellhead Protection Area (WHPA) for the Big Sioux Aquifer, an alluvial valley-fill aquifer (Slides 8.14 and 8.15). Hydrogeologic mapping of topographic divides was also used to define the small drainage catchments flanking the aquifer that have the potential to introduce contaminants in a short time through surface water runoff (Slide 8.18). This second method was used to delineate a buffer zone surrounding the inner zone that had been delineated by the simplified variable shapes analysis. The reader is referred to Appendix B for a detailed description of the aquifer setting and the methods used.

To compare a third method with the two actually used in the Brookings case study, an example was developed using the Theis well hydraulics equation. The drawdown criterion with a threshold of 1 foot was selected to delineate the hypothetical WHPA. The computer code THWELLS (van der Heijde, 1987) was used to solve the Theis equation for a single pumping well and plot the 1-foot drawdown contour. The following data for the well identified as Bruce Well 1 were derived from the case description in Appendix B, and a pumping time of 20 years was assumed:

Transmissivity	55,128 gpd/ft
Storage coefficient	0.20
Pumping rate	120 gpm

After 20 years of pumping, the 1-foot drawdown contour is located at a radial distance of approximately 3,300 feet from the well. The area encompassed by this contour is shown on Slide 8.21.

The WHPA delineated using the Theis equation, while over-protecting slightly south of the well, appears to match the actual delineated WHPA fairly well, but this is deceiving. The Theis equation assumes an infinite aquifer, which causes the 1-foot drawdown contour to extend several thousand feet into the bedrock material forming the valley wall. This is, of course, unrealistic. While the Theis-delineated area appears to match well, it is actually matching a zone that was added based on geologic mapping and surface water runoff considerations; not on aquifer hydraulics considerations.

The Theis solution would have been applicable for a well located in the center of the valley, but valley wall effects are important for wells located along the edge of the aquifer. One solution to this problem uses an image well located on the opposite side of the valley wall from the pumping well. An image well is a fictitious well, pumping at the same rate as the real well, and added to the system to represent the effects of an impermeable boundary (i.e. the valley wall). The Theis equation for drawdown is solved for each well and the solutions summed to provide the drawdown surface for the two-well system.

THWELLS is capable of solving the Theis equation for multiple pumping wells. The solution obtained for each well is added, according to the method of superposition, to yield the final solution. A calculation was performed with an image well located 2,000 ft from Bruce Well #1 and pumping at the same rate as the real well. The valley wall is located midway between the two wells. After 20 years, the one-foot drawdown contour in the aquifer is located at a radial distance of 9,450 feet from Well #1, extending to the far valley wall (Slide 8.21).

This computation assumes that the Theis equation applies accurately to this shallow unconfined aquifer and that the aquifer is infinite in extent. Both of these assumptions probably introduce significant error into this simple calculation. Nonetheless, the exercise serves to demonstrate the effort of an impermeable boundary on the drawdown calculation.

8.4 COMPARATIVE ANALYSIS CASE STUDY 3:

COMPARATIVE ANALYSIS OF TRAVEL-TIME MODELS

In July of 1986, the Florida West Coast Regional Water Supply Authority (WCRWSA) commissioned a study (Geraghty & Miller, 1986) to demonstrate the use of various modeling approaches to determine solute travel times in areas affected by water supply wells. The study was developed for a wellfield deemed to be representative of those in the region. Proposed wellhead protection legislation for the State of Florida would potentially affect privately owned land surrounding wellfields and the ability for water supply authorities to acquire land. WCRWSA was interested in determining the complexity, costs, and limitations of alternative modeling approaches.

The Cypress Creek wellfield was selected for the study area, and field parameters and well locations used in the investigation were obtained from a WCRWSA report on the Cypress Creek field. The following parameters were used as needed in each of the example models:

Transmissivity (Tx and Ty)	400,000 gpd/ft
Aquifer thickness (b)	500 ft
Leakance (L)	0.01 gpd/ft3
Pumping rate (Q)	2.3 mgd/well
Number of wells	13
Dispersivity (D)	0.000001

Three models were investigated for computing the travel time of particles moving from discharge points in the aquifer to pumping wells in the wellfield. In the first and most simple method, it was assumed that all water discharged from a pumped well is removed from the soil volume inscribed by a cylinder with the well at its center, a height equal to the aquifer thickness, and an effective pore volume equal to the discharge volume. This is the familiar "calculated fixed radius method" described in the WHPA Delineation Guidelines (EPA 1987a).

Two numerical models were also developed with dispersion set at or near zero (advection-only solute transport), which permitted comparison of the numerical results with the simpler calculated radius method. One numerical model used the microcomputer version of the Random Walk solute transport code (Prickett et al. 1981). The model was developed with the assumption of zero leakance between the aquifer and underlying units.

The third model was developed using the Method of Characteristics (MOC) solute transport code (Konikow and Bredehoeft 1978). The model incorporated a small leakance representative of conditions at the Cypress Creek site. This leakance in the numerical model was expected to have little effect on the results. Preliminary calculations based on the hydraulics of a single pumping well showed that, even with a head differential of 100 feet between the aquifer and underlying layers (an unrealistically high amount), the computed travel distance would be changed by a factor of less than 0.001 (0.1 percent).

Plots of the 2-year, 5-year, and 10-year travel distances (Slides 8.25, 8.26, and 8.27, respectively) were generated for the three models to permit a graphical comparison of the results. The contours of Model 1 show a series of 13 overlapping circular contours. Each contour represents the travel distance that would exist had none of the other wells been present. Since two wells cannot extract water from the same cylindrical soil volume, the volume error associated with this approach is simply the amount of circle overlap. Overlap is minimal for the 2-year travel distance and increases to nearly 70 percent for the 10-year travel distance. Additional error is introduced by not accounting for the deviation from strict radial flow caused by nearby wells.

The contours for the two numerical models are quite close as could be expected. In both cases, dispersion was set at or close to zero. Leakance was incorporated into the MOC model. However, as expected it had negligible effect on the computed travel-time distances.

The main difference between the two numerical models is caused by differences in resolution due to grid refinement and differences associated with the averaging schemes. The Random Walk model utilizes an 11 by 11 node grid, with a node spacing of 3,000 feet., while the MOC model utilizes a 20 by 20 node grid with a node spacing of 1,500 feet. Discretization error associated with the choice of grid spacing will therefore be higher with the Random Walk model. The difference in the graphical representation of the travel time contours is largely due to the averaging scheme associated with the MOC model. Particles are associated with a particular node in the grid if they fall within the square area which surrounds the node and bisects the distance from it to adjacent nodes. In the Cypress Creek example, the averaging scheme encompasses an area of 1,500 by 1,500 ft. The Random Walk model tracks particles at 100-ft intervals and plots their positions directly. This results in a better defined plume.

It should be noted that the models developed for this investigation did not consider many factors which would affect travel distance contours around a well or wellfield, including regional flow gradient, hydrodynamic dispersion, or retardation of the moving solute due to adsorption onto soil material. When regional flow is considered, for example, the area delineated around the well becomes elongated and its center is offset from the well in the direction of flow.

The cost of estimating travel times largely depends on the availability of data, computer facilities and degree of model resolution desired. The volume balance (calculated radius) approach is the least expensive. The only aquifer parameter required is the effective porosity, and the calculation is simple.

The two numerical models used in this study are of approximately equal complexity and require essentially the same data inputs. The version of Random Walk used in this study could not handle leakance, but a version is available that adds that feature. The cost of purchasing, installing and testing each model is on the order of $500. The labor costs required to set up each model with site specific data and appropriate boundary conditions and to perform a sufficient number of simulations to be confident in the results can range from $5,000 to $50,000. Additional complexities of the aquifer system or the type of information required from the model would place a study at the high end of this range.

For example, the study described here was designed to compare modeling approaches and not to delineate precise defensible boundaries. On the course grid spacing of 1,500 by 1,500 ft well locations were only approximated. A variable mesh grid would be needed to accurately model the well locations, and a finer grid would be required to more accurately delineate the plume boundary. Consideration of spatially varying hydraulic properties, the inclusion of chemical transport properties, and more complex boundary conditions might also be required. In order to be legally defensible, these factors would have to be considered and would involve additional model setup and testing costs and additional expenses in obtaining the required data.

A. References

APPENDIX A:

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REFERENCES

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APPENDIX B:

CASE STUDIES

APPENDIX B: CASE STUDIES

The following case studies present actual Wellhead Protection Area (WHPA) delineation cases, or in the case of two studies, sites for which WHPAs may eventually be delineated. Table B-1 lists the cases, their status (WHPA delineation completed or in progress) and the criteria and methods employed or demonstrated in each.

Cases were provided by regional offices of the Environmental Protection Agency (EPA), and an attempt was made to present cases for a range of hydrogeologic settings and a variety of delineation methods. The case studies provided here are synopses of the material supplied by EPA regional offices, and every effort was made to accurately report the methods and results of each case. Selection of these cases in no way implies a preferential endorsement of the criteria and methods used for WHPA delineation in these studies. No opinion is offered concerning the appropriateness of the criteria and methods for the sites to which they were applied, and no attempt was made to correct errors in implementation and/or reporting of the various methods used.

TABLE B-1
SUMMARY OF WHPA DELINEATION CASE STUDIES

CASE STUDY/ LOCATION	STATUS	CRITERIA	WHPA DELINEATION METHOD
1. Brookings Co. South Dakota	In Progress	-- time of travel -- flow boundaries	-- uniform flow equation -- hydrogeologic mapping (to define hydrogeologic boundaries)
2. Kennedale, Texas	Completed	-- time of travel	-- calculated fixed radii
3. Oakley, Kansas	Completed	-- time of travel -- drawdown	-- numerical model -- Darcy's law velocity equation
4. Palm Beach County, Florida	Completed	-- time of travel -- drawdown	-- numerical flow model -- numerical transport model
5. Franklin, Massachusetts	Completed	-- distance -- flow boundaries	-- fixed radii -- numerical model -- hydrogeological mapping
6. Bowling Green, Kentucky	In Progress	-- time of travel -- flow boundaries	-- hydrogeologic mapping

B.1 CASE STUDY: BROOKINGS COUNTY, SD

INTRODUCTION

Brookings County in South Dakota undertook a comprehensive mapping program in 1987 as an initial step in developing Wellhead Protection Areas (WHPAs). The county first identified all public municipal and rural water supply wells. Available information was used to characterize the Big Sioux aquifer, which is almost entirely unconfined in the county (see Figure 1). The uniform flow equation was then used to generate conservative estimates of the zone of contribution (ZOC) to each well. This zone was amended with a buffer zone for irrigation wells, and modified where hydrogeologic boundaries bisected the calculated ZOC.

PROGRAM OBJECTIVES

The goal of the Wellhead Protection program in Brookings County was to identify and map zones of contribution to public water supply wells. Although official WHPAs have not yet been delineated for the wells studied in this investigation, it is expected that the ZOCs mapped will be adopted as WHPAs when it is decided what activities will be regulated, and how the ordinance will be enforced.

HYDROGEOLOGIC SETTING

Most public water supply wells in Brookings County draw water from the Big Sioux aquifer, a sequence of unconsolidated glacial outwash overlain by minor amounts of alluvial sand and gravel. Much of the aquifer data used in the study (Table 1) was obtained from the South Dakota Department of Water and Natural Resources (DWNR). The saturated thickness of the aquifer ranges from 20 to 40 feet, but reaches as much as 60 to 80 feet in parts of Brookings County (DWNR, 1987). The aquifer is almost entirely unconfined, with exceptions in areas where younger glacial till has covered the aquifer as a result of outwash collapse. Glacial till also forms an impermeable boundary beneath the aquifer (see Figure 2). Where the aquifer is not bounded by till, it is in contact with less permeable Precambrian or Cretaceous rock. Figure 3 illustrates the general stratigraphic relationships of geologic units in and around the Big Sioux aquifer.

Wells in the Big Sioux can yield over 1,000 gpm because of its water-bearing properties. Porosity ranges from 20 to 35 percent, which is typical of glacial outwash deposits. Values of hydraulic conductivity vary from 20 to 2.0×10^4 gal/day/ft^2; and the specific yield is estimated at 15 to 20 percent (DWNR, 1987).

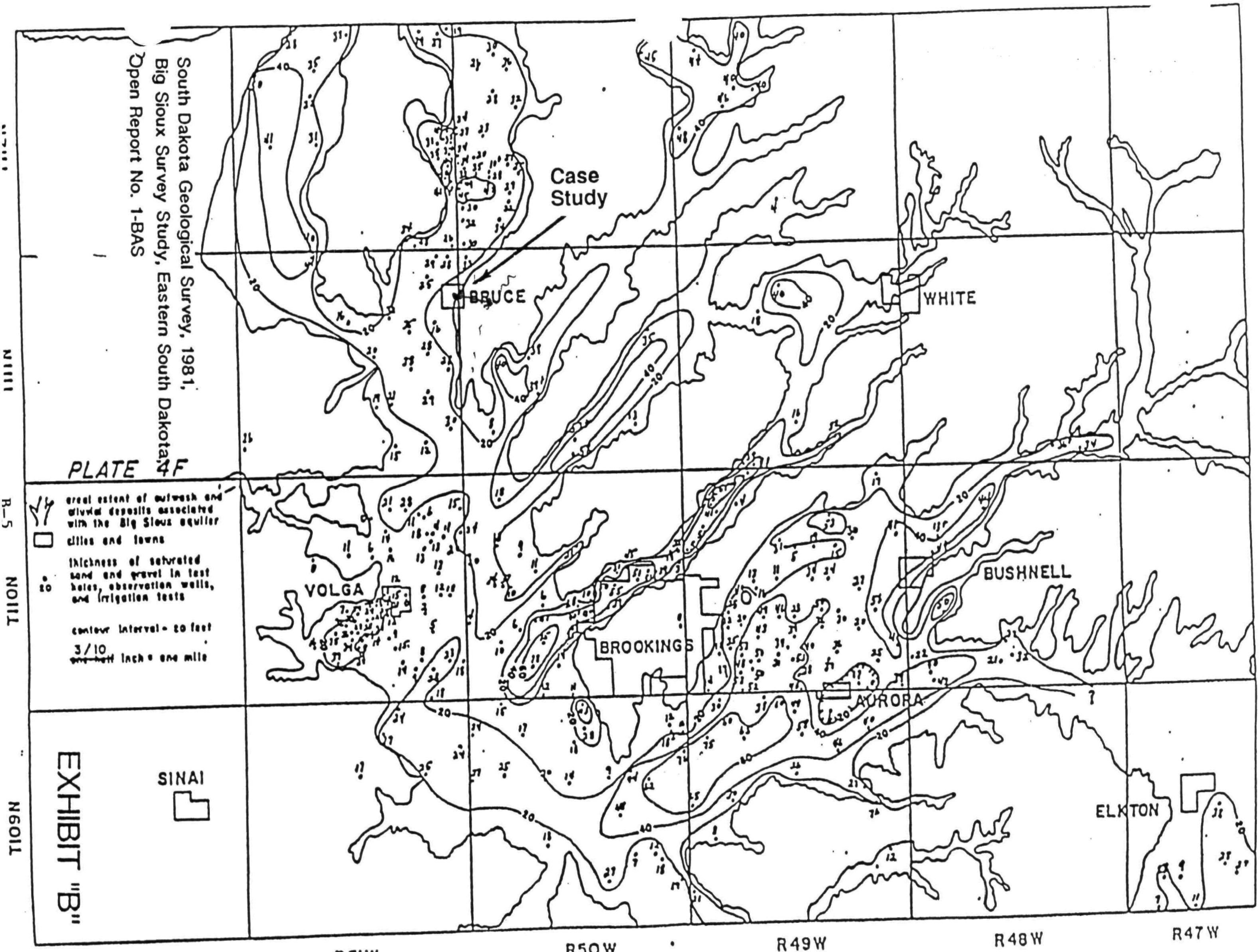


FIGURE 1. BROOKINGS COUNTY SATURATED THICKNESS

TABLE 1-SUMMARY OF DATA USED IN EVALUATIONS

WATER SUPPLY	WELL NUMBER	CAPACITY (GPM)	"Q" (CF/D)	SAT THK "b" (FT)	HYD COND "K" (FT/D)	HYD GRAD "i" (FT/FT)
AURORA	1	90	17325.00	20.00	670.00	0.0019
BRKNGS-E	1	1000	192500.00	63.00	670.00	0.0013
	2	1400	269500.00	63.00	670.00	0.0013
	3	1400	269500.00	63.00	670.00	0.0013
BRKNGS-N	3	840	161700.00	37.33	587	0.0015
	4	690	132825.00	47.33	587	0.0015
	5	255	49087.50	37.33	587	0.0015
	6	570	109725.00	37.33	587	0.0015
	7	610	117425.00	37.33	587	0.0015
	8	490	94325.00	37.33	587	0.0015
	9	750	144375.00	37.33	587	0.0015
B-D-K RWS	1	300	57750.00	34	615	0.0013
(BRUCE)	2	250	48125.00	34	571	0.0013
	3	225	43312.50	34	706	0.0013
	4	350	67375.00	34	582	0.0013
B-D RWS	1	110	21175.00	20.83	600	0.0017
	2	110	21175.00	21	600	0.0017
BRUCE	1	120	23100.00	11	670	0.0017
ELKTON	1	90	17325.00	8	600	0.0023
	2	125	24062.50	31	600	0.0023
VOLGA	2	120	23100.00	17	480	0.0029
	3	150	28875.00	16	480	0.0029
	4	120	23100.00	15	480	0.0029
	5	185	35612.50	30	300	0.0033
	6	185	35612.50	30	300	0.0033
(FUTURE)	7	185	35612.50	30	300	0.0033
WESTERN ESTATES	1	388	74690.00	18	533	0.0017

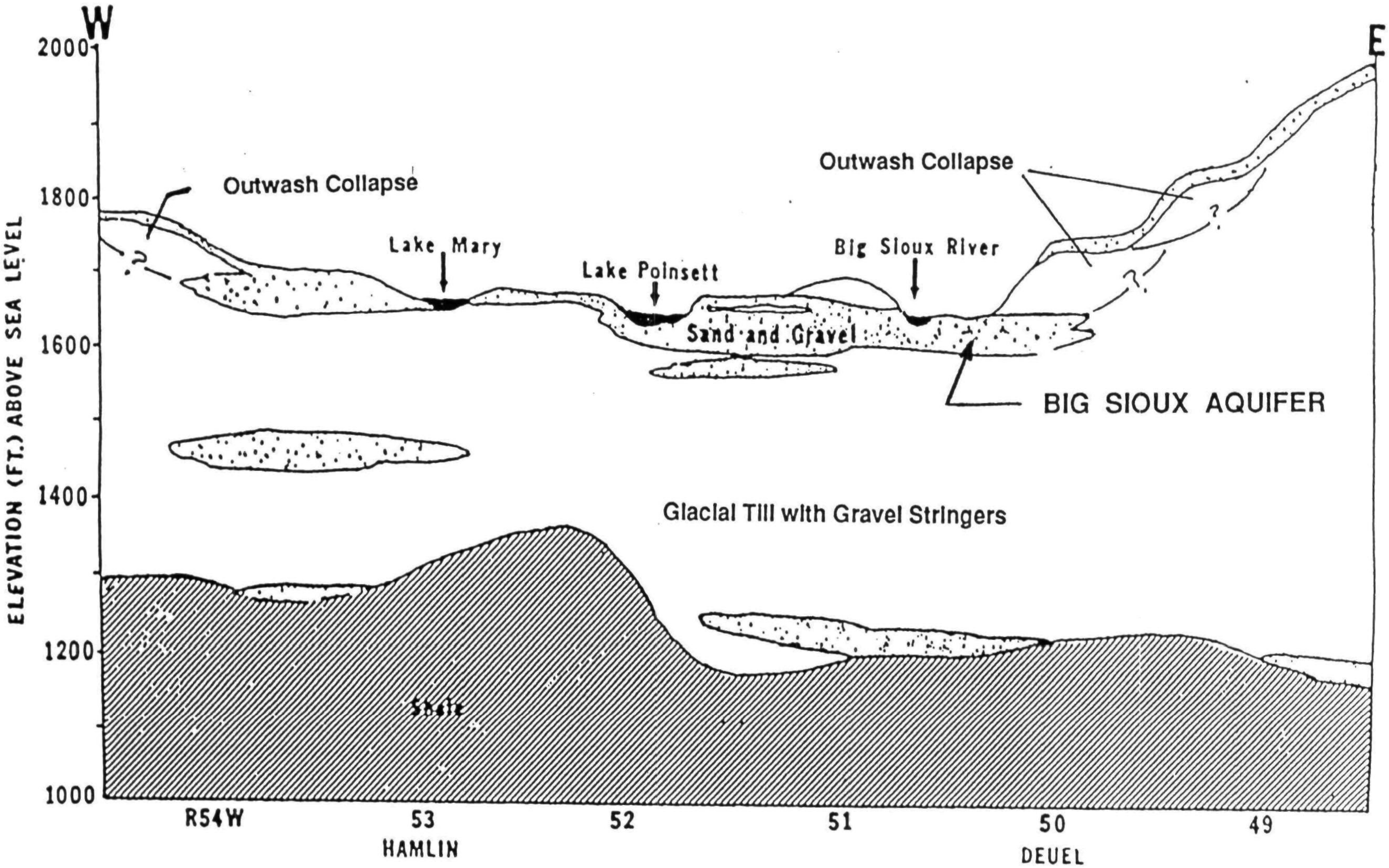
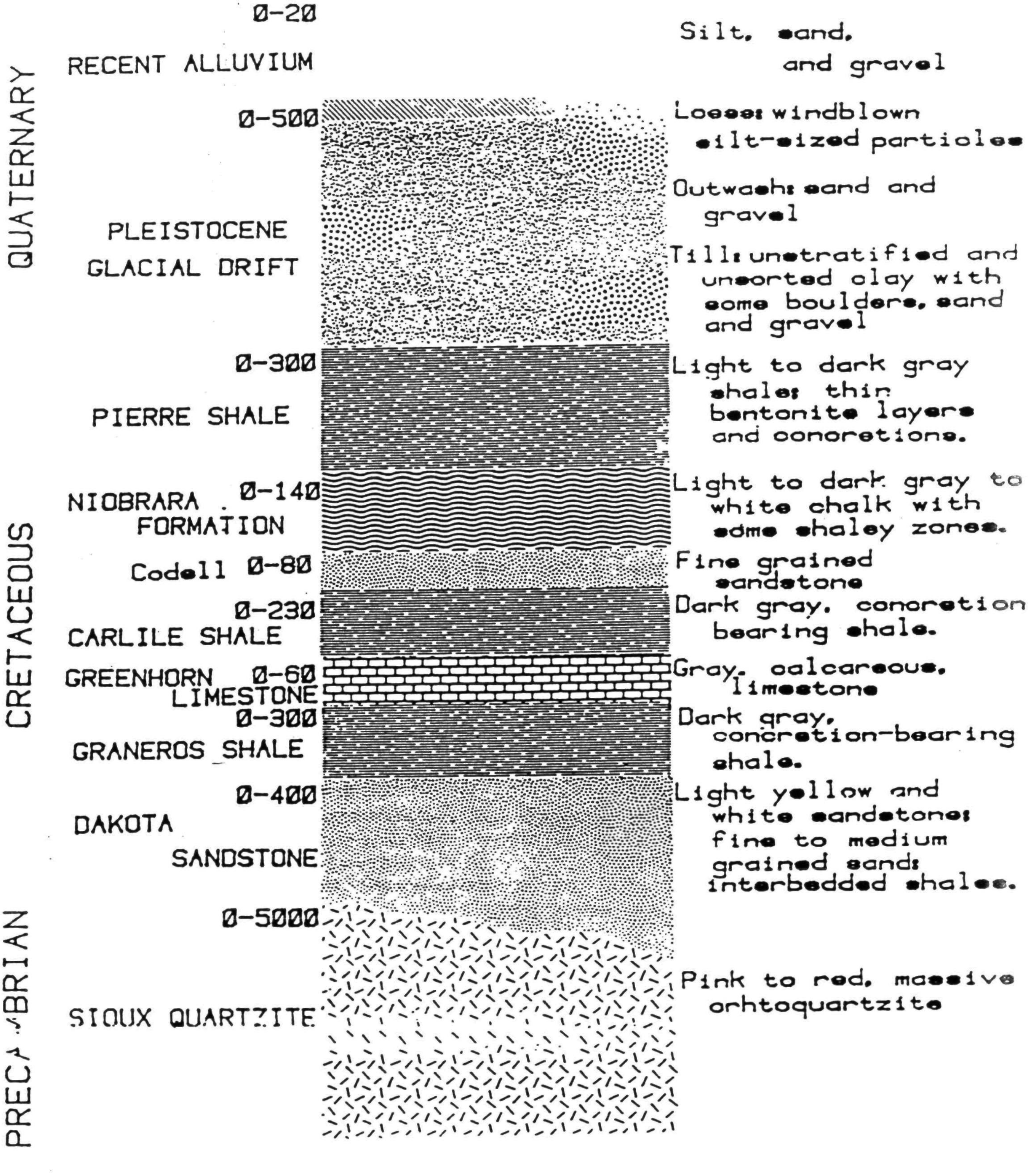


FIGURE 2. GEOLOGIC CROSS-SECTION OF BIG SIOUX BASIN

FIGURE 3. GENERALIZED STRATIGRAPHIC COLUMN BIG SIOUX RIVER BASIN



As an unconfined aquifer, the Big Sioux derives its recharge from infiltration of precipitation and seepage from surface-water bodies. Quick response of water levels to recharge events indicates that the aquifer is unconfined and in good hydraulic connection with the surface. This is an important consideration in terms of ground-water protection, as contaminants can quickly leach into the aquifer through the highly permeable sediments above the water table.

METHOD AND CRITERIA SELECTION

In order to identify the entire ZOC, the criteria selected were the flow boundaries, and a time-of-travel criterion for the upgradient limit. Because the County wanted to delineate WHPAs using only available data a simplified method of approximating the flow boundaries was used. The method was adapted from work done in Southern England and described in "Guidelines for Delineation of Wellhead Protection Areas", published by EPA, as the simplified variable shapes method.

The technique involves solving the uniform flow equation to yield key points on the no-flow boundary or ground-water divide produced by the pumping well; using the resultant values to estimate a conservative ZOC down-gradient and cross-gradient of the well; and using a TOT equation to define an upgradient extent of the ZOC. The equations derived from the uniform flow equation are:

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

and $$Y_L = \pm \frac{Q}{2\pi Kbi}$$

where,

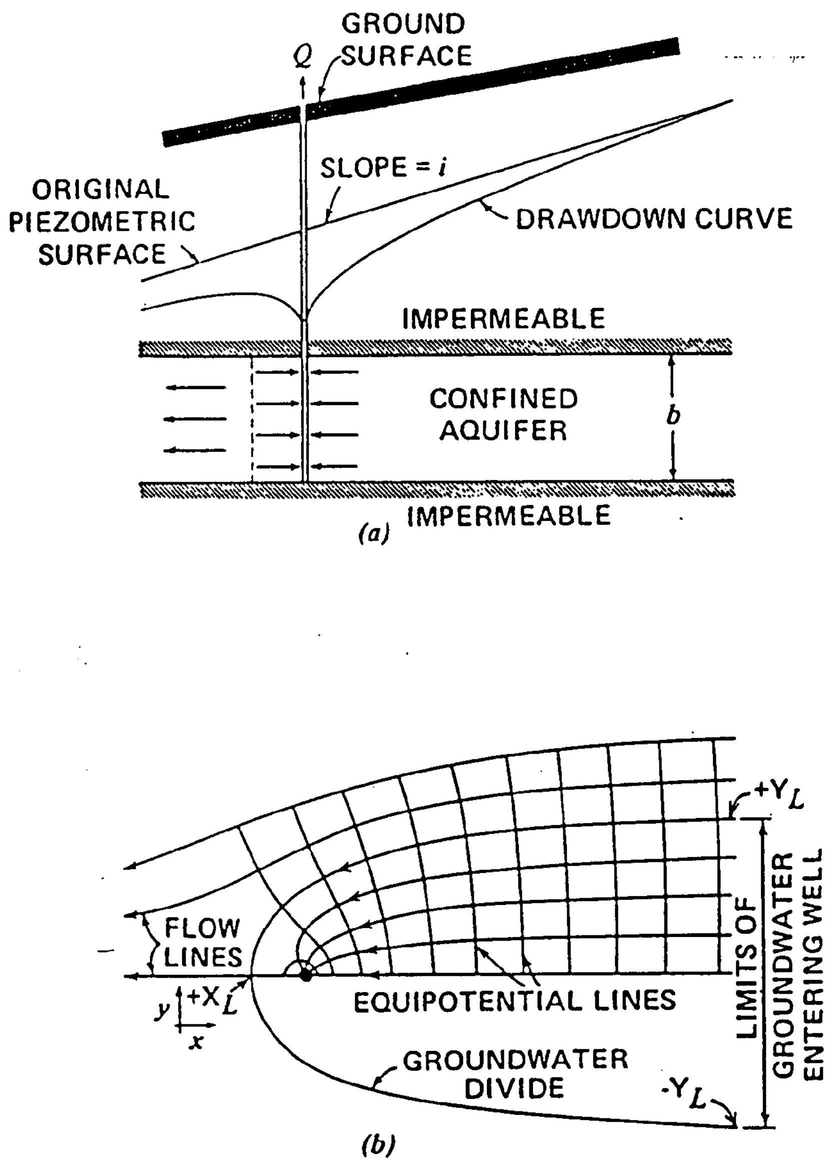
X_L = distance to the down-gradient null point beyond which ground water is not drawn back towards the well

Y_L = maximum perpendicular distance to the ground-water divide from a line extending directly upgradient of the well

Q = pumping rate
K = hydraulic conductivity
b = saturated aquifer thickness
i = hydraulic gradient

FIGURE 4.

WHPA Delineation Using the Uniform Flow Analytical Model



$$-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q}Y\right)$$

UNIFORM-FLOW EQUATION

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

DISTANCE TO DOWN-GRADIENT NULL POINT

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

BOUNDARY LIMIT

LEGEND:

- ● Pumping Well

Where:
Q = Well Pumping Rate
K = Hydraulic Conductivity
b = Saturated Thickness
i = Hydraulic Gradient
π = 3.1416

SOURCE: Todd, 1980

NOT TO SCALE

The physical meaning of the equations is illustrated in Figure 4. The values used in the equations were taken from existing records and are presented in Table 1.

The Y_L value calculated using the uniform flow equation actually represents the distance to an asymptote which the ground-water divide approaches at an infinite distance upgradient of the well. However, to avoid calculating the coordinates of a series of points along the curve, the Y_L distance was assumed to be the cross-gradient distance to the ground-water divide from the well. This results in the configuration shown in Figure 5, which is more conservative than the actual ground-water divide.

Because the uniform-flow equation assumes an infinite upgradient extent of the ZOC, another method must be used to define the upgradient extent of the WHPA. For the wells in Brookings County, calculated distances were based on 5-year and 10-year travel times. The velocity of ground-water movement was computed as

$$V = Ki$$

The distance was then simply

$$r = Vt \quad \text{where } t = \text{travel time}$$

(Note: The method of computing flow velocity shown above differs from the method recommended in the WHP Guidance document. The recommended method incorporates the effect of aquifer porosity which results in higher computed flow velocities, and larger WHPAs.)

Hydrogeologic boundaries were also taken into consideration in delineating the ZOC. Where a hydrogeologic boundary such as a stream, an aquifer boundary or a ground-water divide intersected the calculated ZOC, such a boundary was designated as the extent of the ZOC, and "upgradient" areas were excluded from consideration.

For additional protection, a buffer zone was developed to protect against the effect of irrigation wells. This buffer zone was determined by a method developed in Colorado, where the following relationships apply:

1. The downgradient extent of the buffer zone is twice the distance from the well to the downgradient null point.

2. The cross-gradient distance from the well to the buffer zone is twice the distance from the well to the Y_L distance.

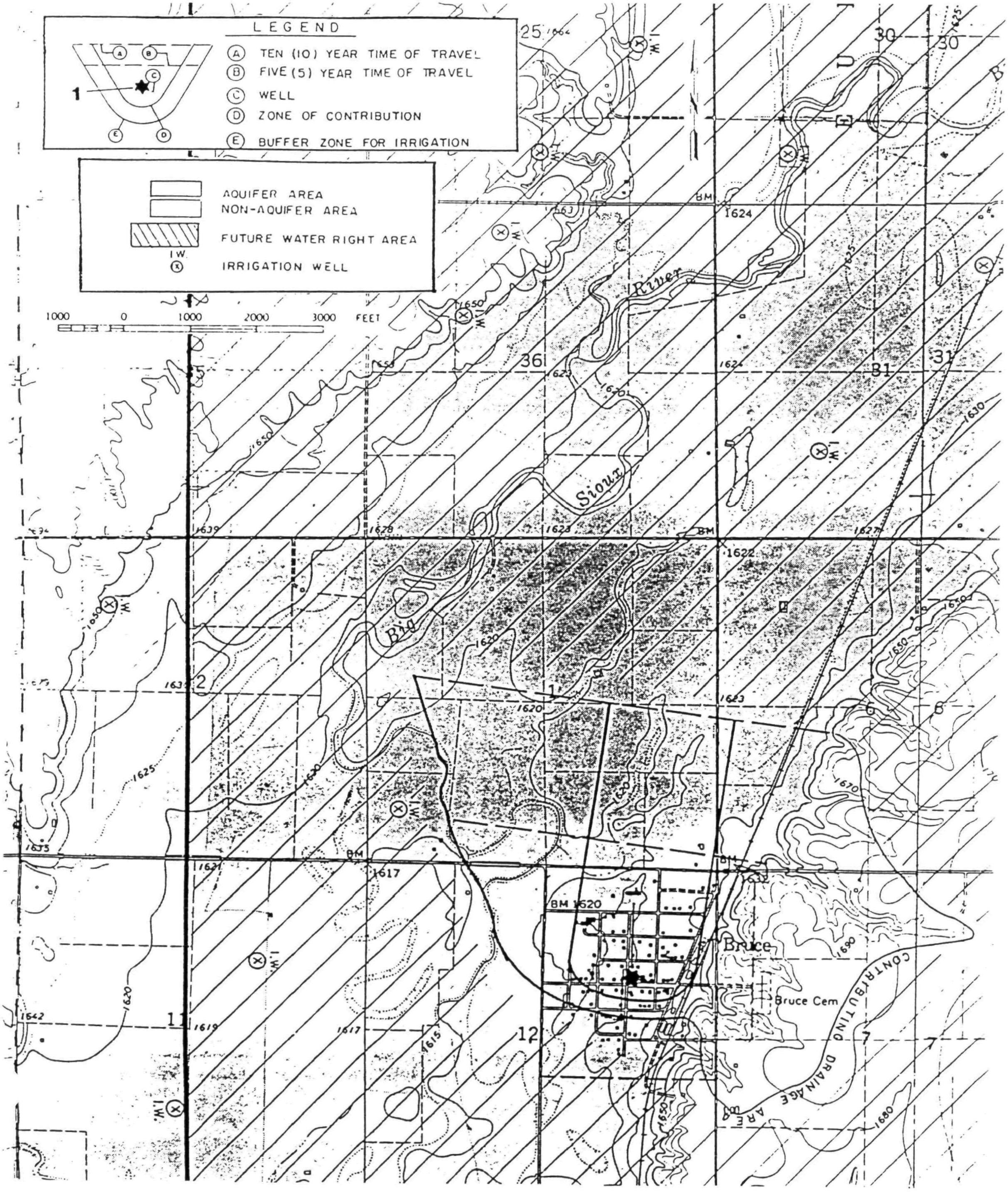
3. The buffer zone in the upgradient direction extends beyond the original delineate boundary an additional 50 feet for every 100 feet of distance upgradient of the well.

Finally, where the ZOC or buffer zone was intersected by an aquifer boundary, an area was delineated outside of the aquifer as a contributing drainage area. Based on topography, this area represents the area from which degraded surface water could quickly enter the ZOC of a well through surface runoff.

RESULTS

A total of 10 ZOCs have been delineated for 26 wells in Brookings County. An example of a completely delineated ZOC and buffer zone, with contributing drainage area is shown in Figure 5.

Fig. 5 ZOC and Buffer Zone For Bruce Well No. 1.



B.2 CASE STUDY: KENNEDALE, TEXAS

INTRODUCTION

The City of Kennedale, in Tarrant County, Texas is located approximately 15 miles southeast of Fort Worth (see Figure 1). In October of 1987 the City requested that the Texas Water Commission establish wellhead protection criteria for their public water supply system. The Commission used available information supplied by Kennedale to delineate wellhead protection areas for each of five municipal wells using the calculated fixed radius method described in EPA's WHPA Guideline document.

PROGRAM OBJECTIVES

In developing groundwater protection goals for the City of Kennedale, the Texas Water Commission examined potential sources of groundwater quality degradation and grouped them according to their origin. The three major groups were:

1) Problems that originate on the land surface

2) Problems that originate in the ground above the water table.

3) Problems that originate in the ground below the water table.

A more complete list of identified potential sources is given in Table 1.

Attention was focused primarily on the third group of sources, because the 600 feet of confining beds above the aquifer were considered substantial protection to the Kennedale wells. Any source of contamination originating near the surface would be greatly diluted and attenuated before reaching the confined aquifer. Nor was a protection strategy developed for the recharge area. The long distance and slow regional movement of ground water was considered to provide a sufficient buffer for diluting contaminants.

HYDROGEOLOGIC SETTING

The City of Kennedale derives its water from the Trinity Aquifer, which is comprised of two water-producing zones, the Paluxy and Twin Mountains Formations; and a confining unit, the Glen Rose Formation, which separates the two. The entire aquifer system is under confined conditions in the Kennedale

FIGURE 1. KENNEDALE, TEXAS SITE MAP

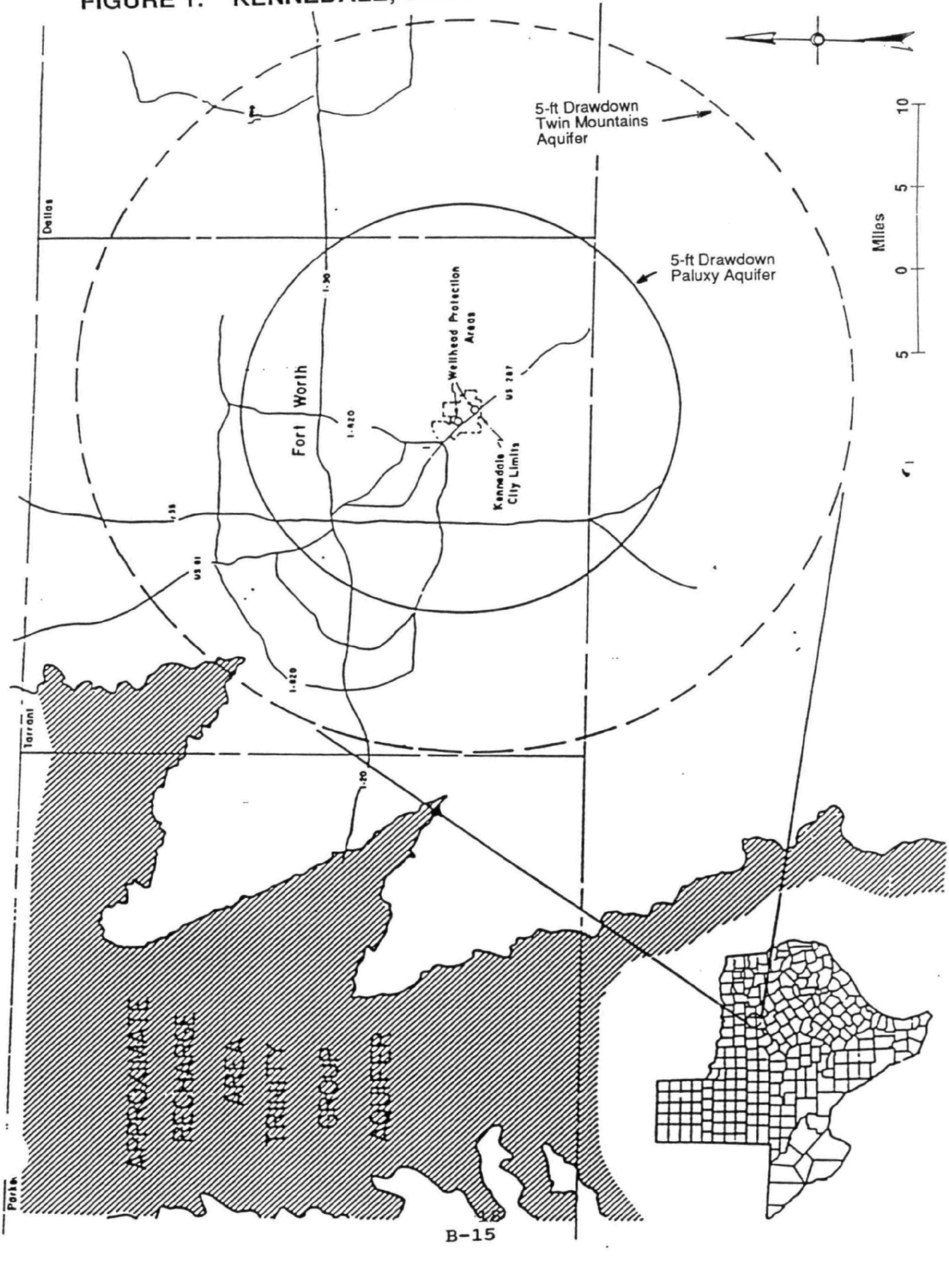


TABLE 1

Sources of Ground Water Quality Degradation

Ground Water Quality Problems that Originate on the Land Surface

1. Infiltration of polluted surface water
2. Land disposal of either solid or liquid wastes
3. Stockpiles
4. Dumps
5. Disposal of sewage and water-treatment plant sludge
6. De-icing salt usage and storage
7. Animal feedlots
8. Fertilizers and pesticides
9. Accidental spills
10. Particulate matter from airborne sources

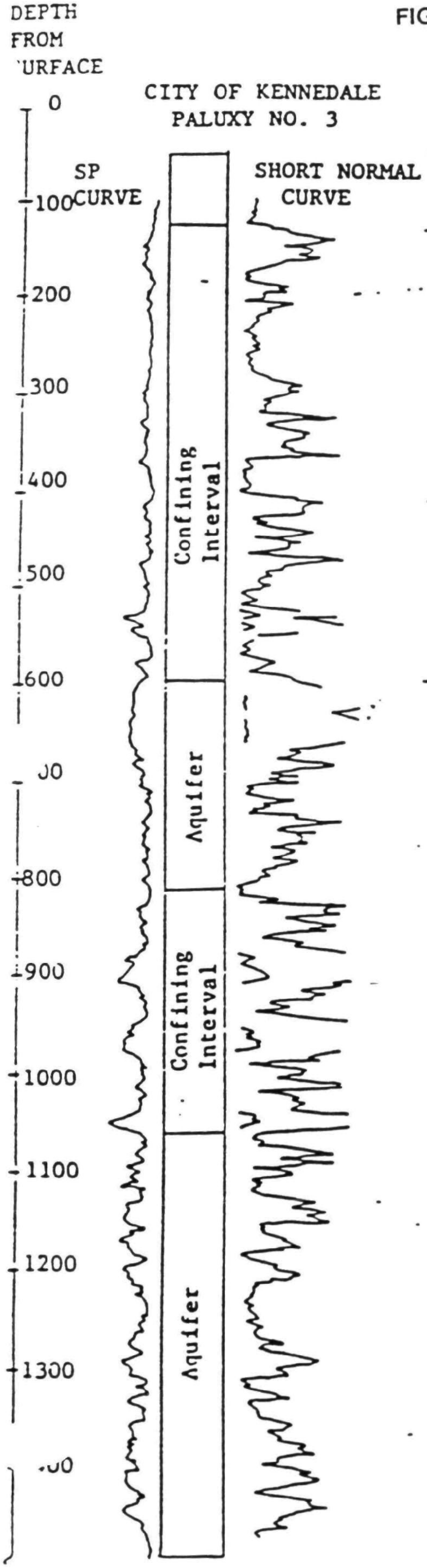
Ground Water Quality Problems that Originate in the Ground Above the Water Table

1. Septic tanks, cesspools, and privies
2. Holding ponds and lagoons
3. Sanitary landfills
4. Waste disposal in excavations
5. Leakage from underground storage tanks
6. Leakage from underground pipelines
7. Artificial recharge
8. Sumps and dry wells
9. Graveyards

Ground Water Quality Problems that Originate in the Ground Below the Water Table

1. Waste disposal in well excavations
2. Drainage wells and canals
3. Well disposal of wastes
4. Underground storage
5. Secondary recovery
6. Mines
7. Exploratory wells
8. Abandoned wells
9. Water-supply wells
10. Ground-water development

FIGURE 2. STRATIGRAPHIC UNITS



GROUP	UNIT	CHARACTER OF ROCKS
Woodbine		Medium to coarse sand, clay, and some lignite
Washita	Mainstreet Lm.	Fossiliferous limestone, marl, and clay
	Weno Lm. Pawpaw Fm.	
	Denton Clay	
	Fort Worth Fm.	
	Duck Creek Fm.	
	Kiamichi Fm.	
Fredericks-burg	Goodland Lm.	
	Walnut Fm.	
Trinity	Paluxy Fm.	Fine sand, sandy shale, and shale
	Glen Rose Formation	Limestone, marl, shale, and anhydrite
	Twin Mountains Fm.	Fine to coarse sand, shale, clay and basal gravel

area, lying beneath 600 feet of limestone, marl, and clay. A summary of the stratigraphic relationships is presented in Figure 2.

Recharge to the Trinity aquifer occurs primarily through infiltration in the outcrop area, located about 20 miles west of the city and covering over 600 square miles. The rate of recharge is estimated at one inch per year distributed over the outcrop area. Regionally, ground water within the Trinity aquifer is moving at an estimated rate of one to two feet per year toward the east. In the vicinity of Kennedale, where heavy pumping has lowered the piezometric surface and thereby steepened the hydraulic gradient, ground water may be moving at a rate of 200 to 300 feet per year towards pumping centers.

CRITERIA AND METHOD SELECTION

Before selecting an appropriate method for WHPA delineation, the Texas Water Commission (TWC) examined available data on supply well construction, discharge rates, and hydrogeologic properties of the Trinity aquifer. Using a computer drawdown model, the TWC simulated the drawdown for the period 1952 to 1987, and mapped the 5-foot drawdown contour interval for both the Paluxy and Twin Mountains aquifers. The area within the approximately 20-mile radius to the 5-foot drawdown was considered the zone of influence of the Kennedale wells (Figure 1). Due to the long pumping period considered and the hydrogeologic properties of the aquifer, the resultant zone of influence was very large, encompassing Fort Worth and extending into two other counties.

It was decided that the large zone of influence of those wells would not be appropriate, since the slow groundwater velocities in the area would also offer protection from subsurface sources of contamination in the zone of influence through attenuation of pollutants. A five-year time of travel was selected as the criteria, and a calculated fixed radius was chosen as the method to delineate the WHPAs. The radius which encompassed the 5-year TOT distance was calculated according to the volumetric flow equation,

$$r = \sqrt{\frac{Qt}{n \pi H}}$$

where

r = radius
Q = pumping rate
t = travel time
n = porosity
H = length of screen

RESULTS

The final WHPA delineation included an additional buffer zone which was added to the calculated radius, rounding the WHPA up to a one-fourth mile radius for each well. The values used in calculating the radii are given in Table 2. The mapped WHPAs are shown in Figure 3.

TABLE 2

HYDROGEOLOGIC DATA USED TO CALCULATE WELLHEAD PROTECTION AREAS FOR KENNEDALE, TEXAS

Well ID	Porosity	Screen Length	FY 1986 (in gallons)	FY 1987 (in gallons)	TOTAL (in gallons)
Paluxy #1	.25	80 ft.	25,954,700	41,676,300	67,631,000
Paluxy #2	.25	80 ft.	18,220,300	26,152,900	44,363,200
Paluxy #3	.25	80 ft.	--	--	--
Trinity #1	.25	175 ft	103,017,700	102,784,900	205,802,600
Trinity #2	.25	175 ft	59,725,700	53,698,100	113,423,800

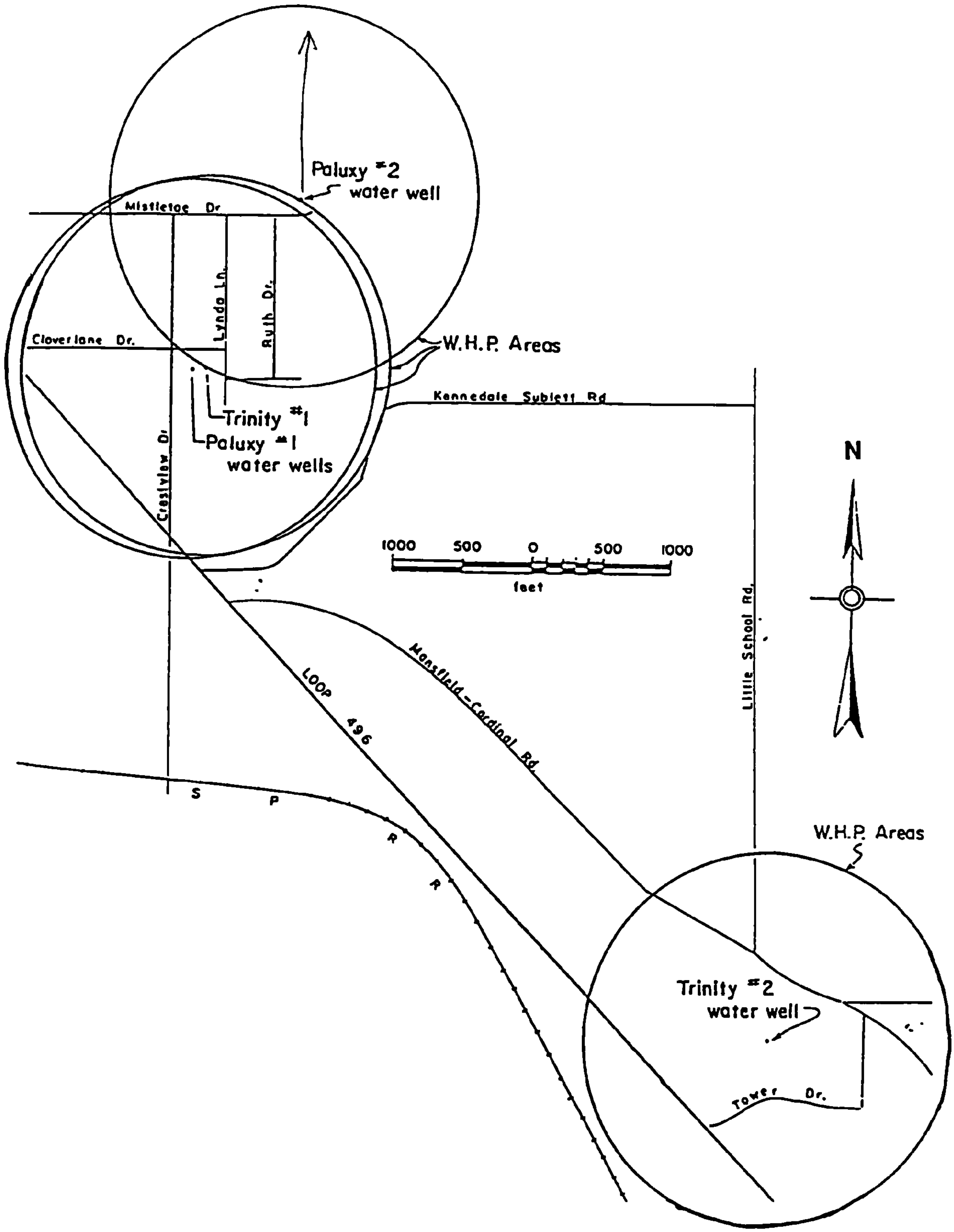


FIGURE 3. CITY OF KENNEDALE WELLHEAD PROTECTION AREAS

B.3 CASE STUDY: OAKLEY, KANSAS

INTRODUCTION

In response to Section 1428 of the Safe Drinking Water Act Amendment of 1986, the city of Oakley, Kansas initiated a Wellhead Protection program for its municipal water supply wells. The City, in consultation with the Northwest Kansas Groundwater Management District, decided to use a numerical flow model to generate the area of influence, cone of depression, and time of travel for each pumping well. The numerical model also offers Oakley the capability of varying pumpage rates and grid spacing and the opportunity to refine the Wellhead Protection Areas (WHPAs) with time.

PROGRAM OBJECTIVES

It was decided by the City management to delineate two WHPAs: an overall protection area for the well field and a secondary protection area. The overall protection area represents the 0.05 foot drawdown area of the Oakley well field after pumping. The secondary protection area includes the area around an individual well within a 180 day time of travel (TOT) distance. More stringent regulations would be applied to the activities in the secondary protection area around individual wells.

HYDROGEOLOGIC SETTING

The Oakley, Kansas public water supply wells are screened in the Ogallala Formation. The Ogallala Formation is an unconfined aquifer composed chiefly of calcareous sandstone cōntaining clay, silt, gravel, cobbles, and boulders of Tertiary age. It is cemented by calcium carbonate to various degrees. A mature drainage system was developed upon the underlying bedrock formations before deposition of the Ogallala formation. Determination of the width and depth of the principal valleys of that system is important in delineation of areas of greatest saturated thickness. Some of these channels provide a medium for storage and transmission of ground water. In the vicinity of Oakley, these channels generally trend northeast. The ground-water gradient (i) is 10 feet per mile, and the flow direction is inferred to be eastward. The saturated thickness of the Ogallala Formation in the vicinity of Oakley, Kansas is approximately 120 feet.

Pump test data obtained from wells located approximately six miles from Oakley gave the following aquifer parameters:

$T = 20{,}000$ gpd/ft
$S = .12$
$K = 235$ gpd/ft^2
$i = 0.002$

METHOD AND CRITERIA SELECTION

The "Basin Aquifer Simulation Model" by T.A. Prickett and C.G. Lonnquist of the Illinois State Water Survey was chosen to delineate the WHPAs. The two-dimensional numerical flow model, capable of outputting the area of influence, cone of depression, and TOTs was modified by the Northeast Kansas Ground Water Management District to simulate water table conditions.

Various assumptions were made because of the model chosen, limitations of the data, and the hydrogeologic conditions in the study area. The assumptions are as follows:

1) The zone of influence (ZOI) and the zone of contribution (ZOC) are considered the same because the water table is nearly level in the area and the pumping regime is relatively small.

2) The aquifer parameters calculated for a well six miles from the study area are similar to those found in the WHPA.

3) The total pumpage, for a year, was withdrawn in equal daily increments over the year. In fact, 70 percent of Oakley's total withdrawals are typically taken in the four months from June through September. This allows some degree of recovery to take place during the remaining eight months.

The area around Oakley was represented by a 50 x 50 model grid with node spacing of 660 feet in both the x and y directions. A recharge boundary was induced along the west side of the grid by assigning an artificially high storage value of 3.0×10^{12}, and a discharge of 25,410 gallons per day (gpd) was applied on the east side of the grid to induce horizontal flow in the model equivalent to the natural flow resulting from the regional gradient of 0.002.

TABLE 1

MONTHLY PUMPING RATES FOR OAKLEY, KANSAS WATER SUPPLY WELLS
(based on 3 year average)

Well No.	Pumping Rate (gpd)
1	36,256
4	144,267
5	173,719
6	58,403
7	257,366
8	303,570

Because of the relative simplicity of the hydrogeology in the area, it was possible to compare drawdown obtained with the numerical method against an analytical solution to the same problem. The numerical model was run assuming 720,000 GPD was pumped for 75 days from the center mode. These same values were then input into the Theis equation and the results compared. The result of the numerical model was in close agreement with that obtained in the Theis equation. The model was then considered calibrated.

A three year history of monthly pumping rates from all Oakley wells was used to estimate discharge values at the nodes representing pumping wells. Pumping rates used in the program are shown in Table 1. Because this version of the model requires constant pumpage, the wells were assumed to have pumped their total annual amount in equal daily increments. The model was run for twelve, 30-day time steps in order to account for one year of pumping. Since Oakley's total annual withdrawals are not actually pumped in equal daily increments, it was assumed that a single year's pumpage would closely enough approximate the results of pumping the well field for longer periods of time in order to identify the overall area of influence.

In order to obtain TOT outputs, the program locates the radius at which the Theis equation computes 0.5 feet of drawdown; segments that radius into equal increments of width w with each increment approaching but not exceeding 10 feet; determines head differences across each increment; calculates velocity and travel time through each increment (starting at the well and extending outward) and sums the travel times. Pore velocity was calculated using Darcy's law and dividing the darcian flux velocity by the aquifer porosity.

RESULTS

Figure 1 shows the overall WHPA as generated by the model. It represents the 0.05 feet influence area of the Oakley well field after pumping their total historical amounts from their six wells in equal daily increments for one years time. The radius of the WHPA is approximately 11,500 ft.

Figure 2 shows the secondary WHPAs around each of Oakley's public water supply wells. The secondary WHPAs include the area within a 180-day TOT distance from each well.

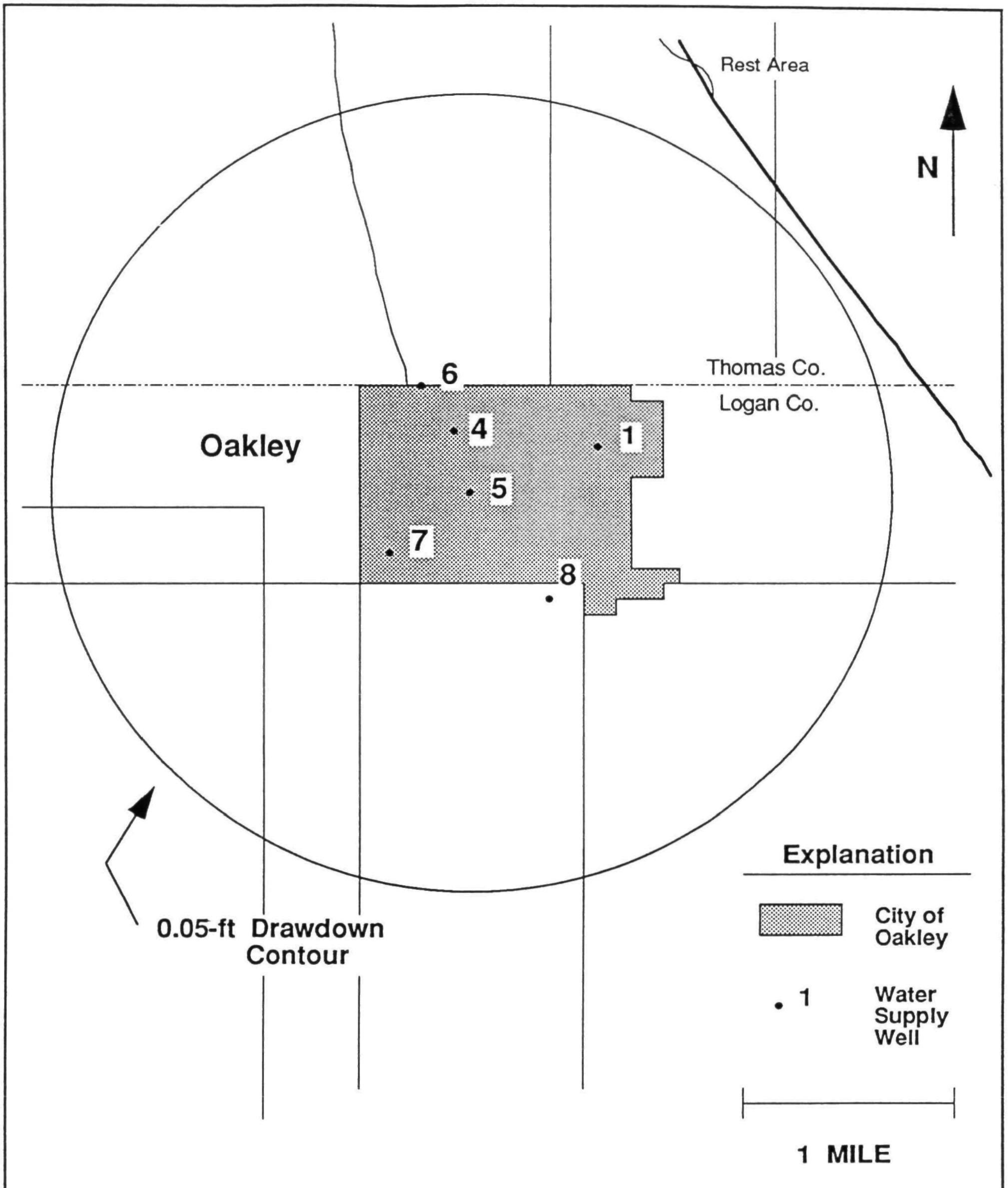
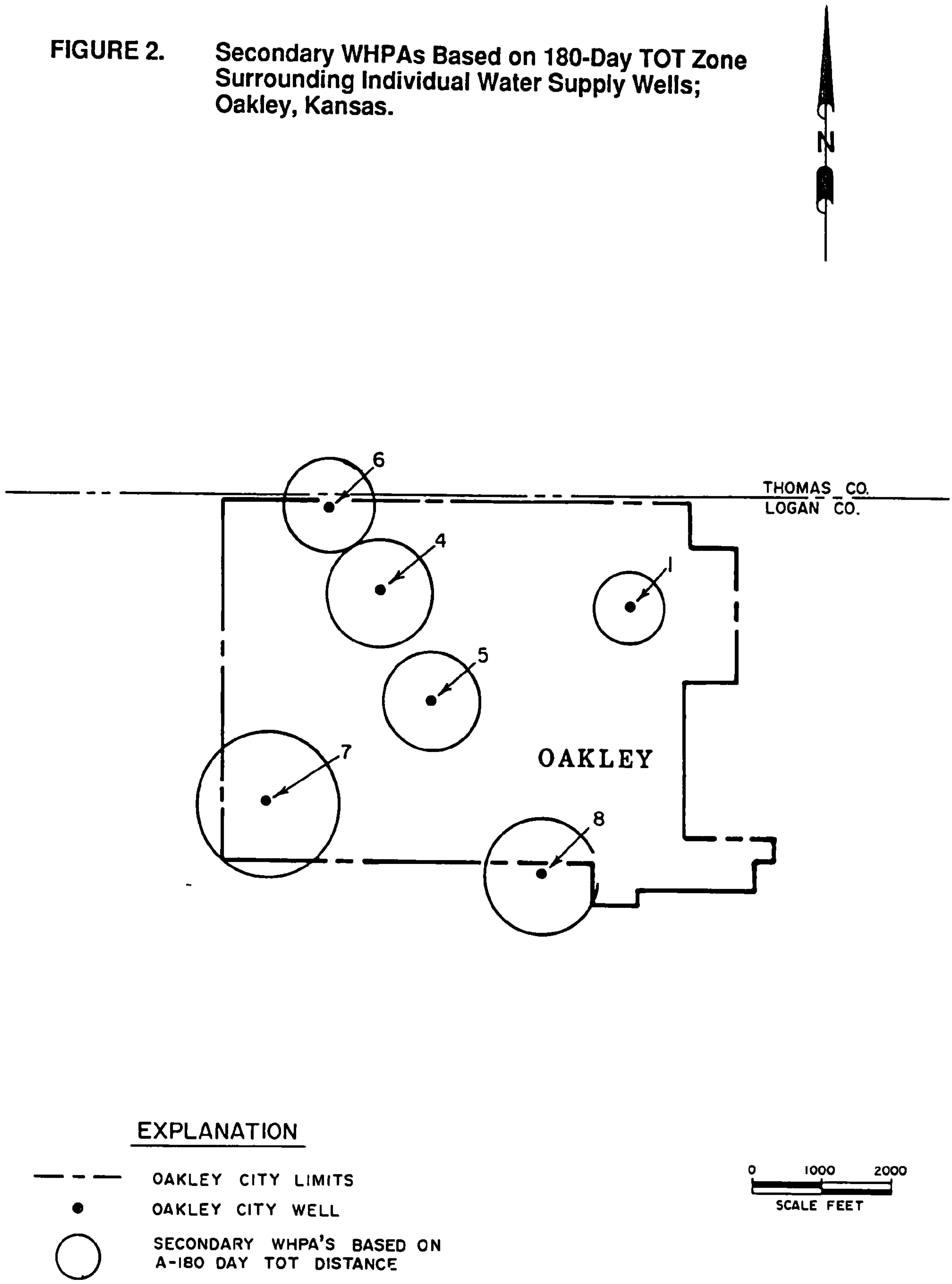


Figure 1. WHPA for Wellfield at Oakley, Kansas Based on 0.05-ft Drawdown Threshold.

FIGURE 2. Secondary WHPAs Based on 180-Day TOT Zone Surrounding Individual Water Supply Wells; Oakley, Kansas.



B.4 CASE STUDY: PALM BEACH COUNTY, FLORIDA

INTRODUCTION

Aquifer protection programs were initiated in South Florida in late 1979. In late 1981 the EPA approved and funded a Wellhead Protection Program for Dade, Broward and Palm Beach Counties. This project, known as the "State Biscayne Aquifer Project", was developed by the Florida Department of Environmental Regulations. The program consisted of three phases: developing time of contaminant travel contours around well fields, identifying sources of contamination within these contours, and developing well field protection ordinances.

Counties in Florida have the authority to write their own local rules that specify the types of information needed and acceptable methods for Wellhead Protection Area (WHPA) delineation. Palm Beach County, located along the east coast north of Miami, developed an ordinance requiring that a WHPA be delineated for each well or well field, and that the delineation criteria be time of travel (TOT) and/or drawdown. The criteria threshold values are as follows:

Zone I -- 30 day TOT
Zone II -- 210 day TOT
Zone III -- 500 day TOT or 1-foot drawdown contour, whichever extends farthest from the well/well field

Because the size of the WHPAs change with a change in pumping rate, the WHPAs are to be updated periodically as ground-water development continues. The following case study illustrates how the program was applied in the County.

PROGRAM OBJECTIVE

The objective of the wellhead delineation program for Palm Beach County was to define, by computer simulation, contaminant travel time (distance) zones. For the Ordinance, it was determined that a 30-day (Zone I), 210-day (Zone II) and a 500-day or one-foot drawdown contour (Zone III) would be most appropriate. The outer boundary of Zone III was marked by the 500-day TOT or one-foot contour whichever extended farthest from the well field. The one-foot contour zone was defined as an area where the difference in steady-state water-level elevations between 1984 levels and predicted year 2010 levels equals or exceeds one foot. Table 1 provides pumping rates for selected well fields.

TABLE 1. NUMBER OF WELLS AND PUMPING RATES FOR SELECTED WELLFIELDS YEARS 1984 AND 2010

WELLFIELD	No. OF WELLS	1984 PUMPAGE RATES (CFS)	1984 PUMPAGE RATES (MGD)	No. OF WELLS	2010 PUMPAGE RATES (CFS)	2010 PUMPAGE RATES (MGD)
1 TEQUESTA	4	0.97	0.63	4	4.18	2.70
2 JUPITER	22	8.35	5.40	34	31.99	20.67
3 SEACOAST WOOD	14	11.03	7.13	14	28.62	18.50
4 SEACOAST LILAC	6	1.44	0.93	6	6.19	4.00
5 SEACOAST RICHARD	8	3.04	1.97	8	5.80	3.75
6 SEACOAST DIXIE	9	1.55	1.00	9	5.80	3.75
7 RIVERA BEACH	23	11.20	7.24	26	18.95	12.25
8 MANGONIA	4	0.62	0.40	5	2.94	1.90
9 CONSOLIDATED	2	0.30	0.19	3	0.54	0.35
10 CENTURY	3	1.46	0.94	3	2.17	1.40
11 MEADOWBROOK	2	1.26	0.81	3	4.64	3.00
12 PBC #1	7	0.45	0.29	7	12.38	8.00
13 PBC #2	7	0.85	0.55	17	21.66	14.00
14 PBC #3	7	2.71	1.75	11	12.38	8.00
15 PBC #8	9	9.36	6.05	28	49.51	31.99
16 PBC #9	13	9.12	5.89	13	20.67	13.36
17 ROYAL PALM BEACH	5	1.12	0.72	7	5.38	3.48
18 ACME	11	2.22	1.43	11	12.69	8.20
19 PALM SPRINGS	11	6.81	4.40	15	9.28	6.00
20 ATLANTIS	5	0.95	0.61	5	2.07	1.34
21 LAKE WORTH	12	10.12	6.54	12	14.70	9.50
22 LANTANA	4	2.89	1.87	4	3.71	2.40
23 MANALAPAN	11	1.12	0.72	11	2.94	1.90
24 BOYNTON BEACH	21	12.18	7.87	40	61.89	39.99
25 VILLAGE OF GOLF	3	0.39	0.25	3	0.60	0.39
26 DELRAY BEACH	22	17.30	11.18	24	35.59	23.00
27 HIGHLAND BEACH	3	1.80	1.16	3	4.64	3.00
28 BOCA RATON	51	44.77	28.93	51	89.57	57.88
29 PRATT WHITNEY	6	1.51	0.97	7	1.89	1.22
TOTAL		166.87	107.83		473.37	305.89

HYDROGEOLOGIC SETTING

The sediments that underlie Palm Beach County consist of unconsolidated sands, loose- to well-cemented limestones, moderately indurated sandstones, coquina, and sparry clay lenses. These sediments are Pleistocene in age and are considered part of the Pamlico Sands and the Anastasia Formation.

The surficial aquifer in Palm Beach County is the saturated portion of these sediments. It is characterized by large variations in the spatial distribution of porosity and permeability. Along the eastern part of the county, a zone of high secondary permeability is known to occur. The secondary permeability is attributed to dissolution of calcareous cementing material by circulating ground water. Western Palm Beach County does not exhibit these extensive zones of secondary porosity and permeability.

The surficial aquifer in Palm Beach County varies from west to east, ranging from 140 feet in the west to more than 320 feet thick along the Atlantic Coastline. Aquifer thickness can be determined with data shown on Figures 1 and 2. While Figure 1 shows the elevation of the water table, representing the top of the aquifer, Figure 2 shows variations in the elevation of the base of the surficial aquifer.

Figure 3 shows the inferred distribution of aquifer transmissivity in the eastern part of the County. Variations in both transmissivity and specific yield of wells in the surficial aquifer are related to variations in thickness and the presence of primary and/or secondary permeability. Within the thickest zones of secondary permeability, transmissivity ranges from 100,000 to 2 million gpd/ft. Lower values, between 50,000 and 100,000 gpd/ft, were reported for areas along the coast, and in the western half of the county (Figure 2). Values reported for specific yield were also highly variable, although a constant value of 0.2 was utilized in the model.

Recharge estimates for the area range from 6 to 12 inches per year (in/yr). Recharge to the aquifer is accomplished through infiltration of rain waters and leakage from numerous canals. Leakage from canals tends to reduce the amount of drawdown observed in the vicinity of pumping centers, and thus reduces the areal extent of their zone of influence. This has the additional effect of increasing travel time, which decreases the size of WHPAs delineated on the basis of TOT calculations.

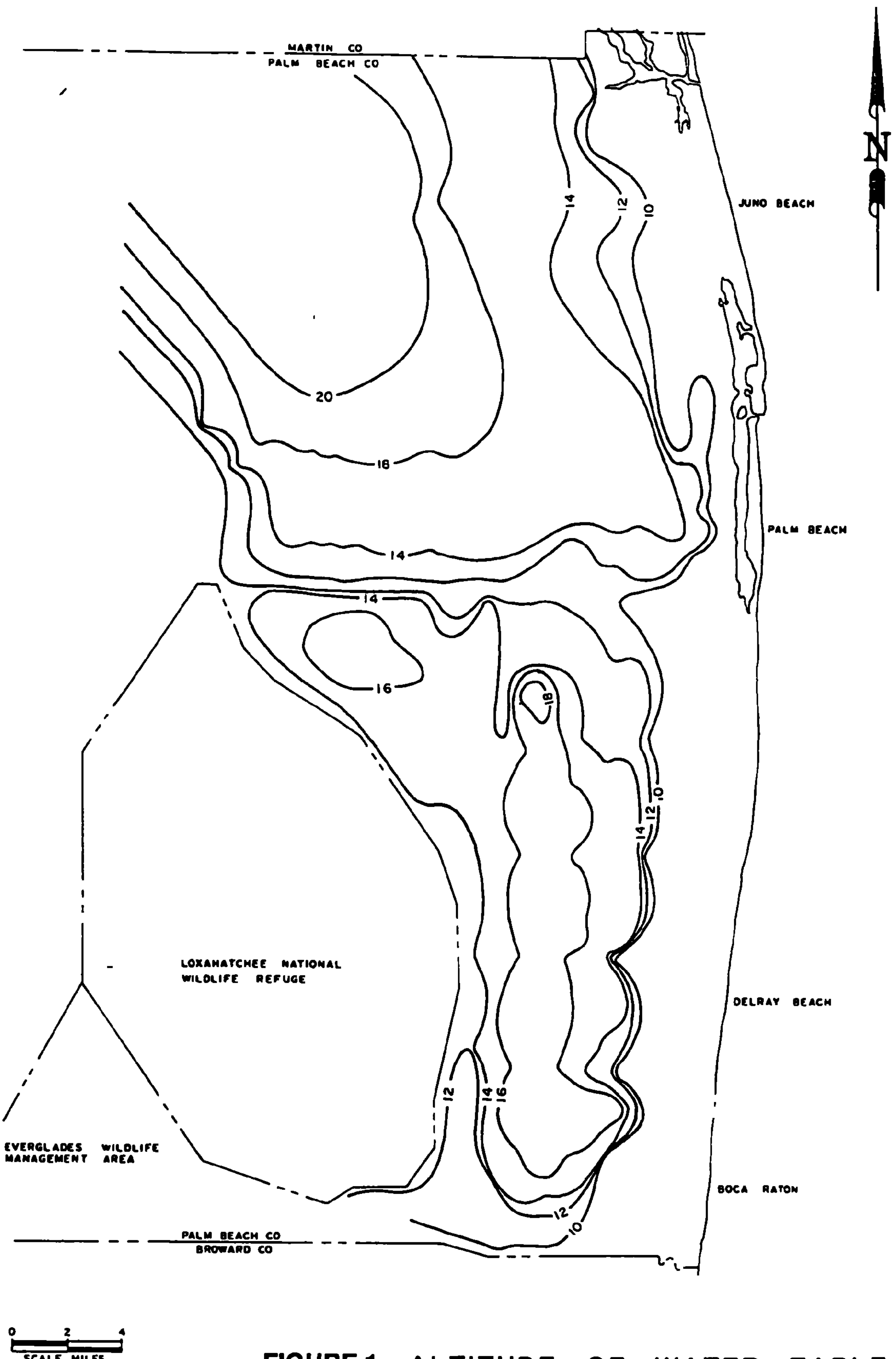


FIGURE 1. ALTITUDE OF WATER TABLE
SURFICIAL AQUIFER
PALM BEACH COUNTY, FLORIDA

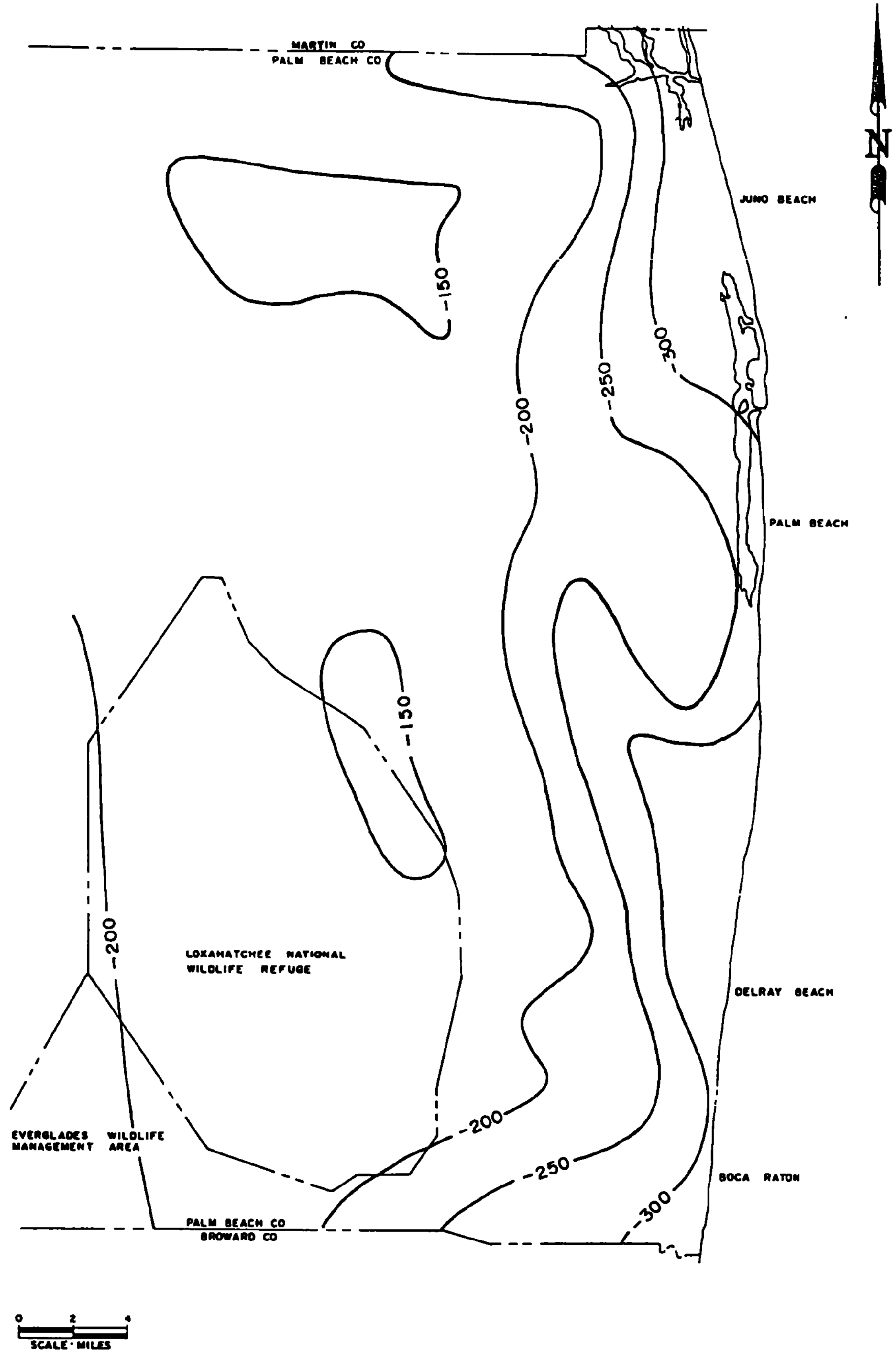


FIGURE 2. ELEVATION OF BASE OF SURFICIAL AQUIFER SYSTEM

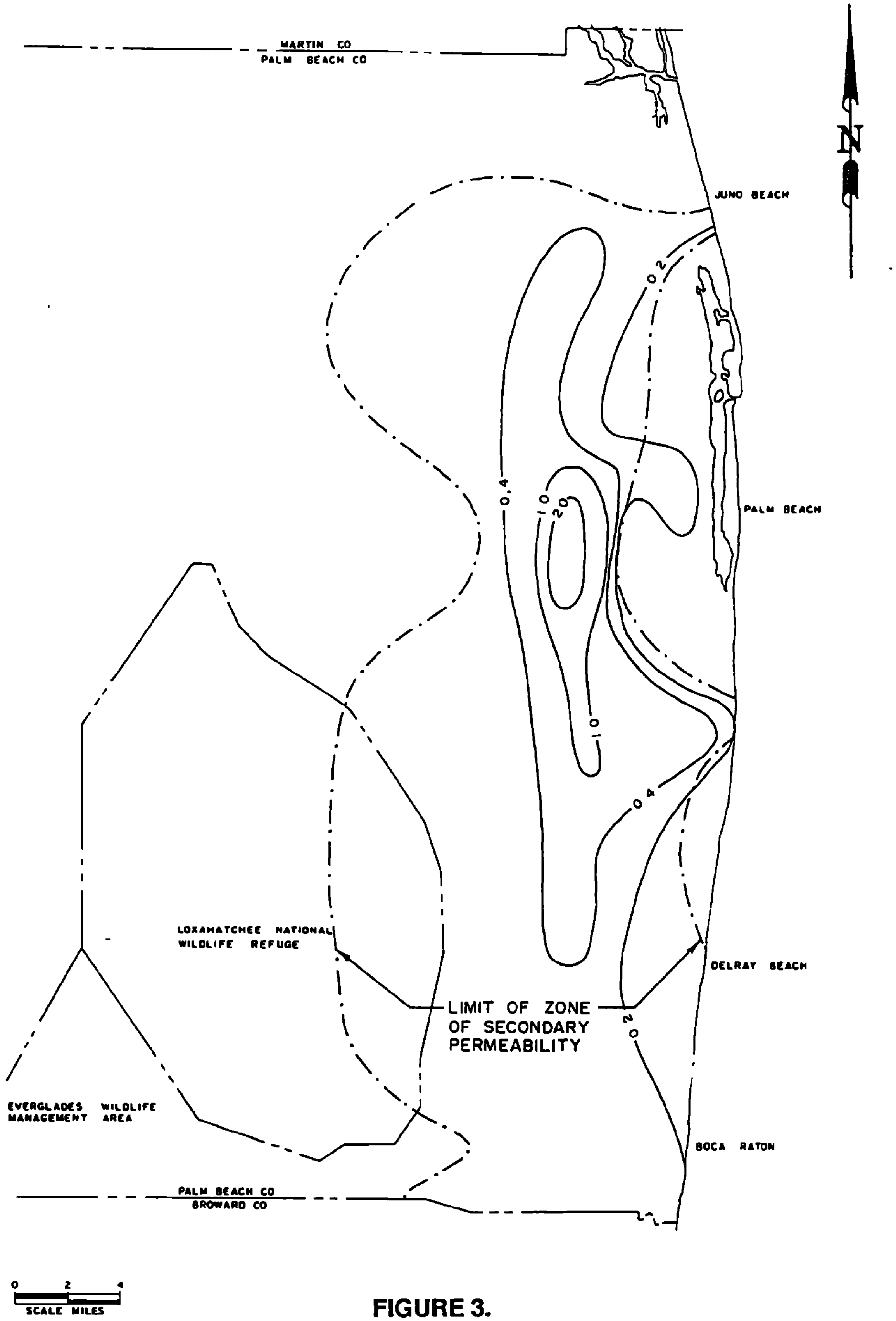


FIGURE 3.

TRANSMISSIVITY MAP OF EASTERN PALM BEACH COUNTY

NOTE. TRANSMISSIVITY VALUES IN MILLIONS OF GALLONS PER DAY PER FOOT

DELINEATION METHOD SELECTION

A numerical model, based on a three-dimensional, finite-difference computer code developed by the U.S. Geological Survey, was used to delineate the WHPAs. A numerical simulation model was selected because of the complex and dynamic hydrogeologic conditions that occur in the area. In addition, once a numerical model is calibrated, it can be utilized to model other hydrologic conditions such as new sources of ground-water supply, different contamination problems, and to predict future drawdowns. The computer methodology required to generate the WHPAs involved a two step procedure:

1. First the hydraulic head distribution over the model area had to be simulated and compared to available head data. The McDonald and Harbaugh (1984) "Modular Three-Dimensional Finite Difference Ground-Water Flow Model" (MODFLOW) was used for this computation by constructing a two-dimensional model of the aquifer system.

2. The second step involved using the hydraulic head values obtained from Step 1 as input into a mass transport program to generate the travel time (distance) zones. Because MODFLOW does not contain a solute transport routine, a separate particle-tracking program, which is a variation of Prickett's "Random Walk" technique, was chosen to perform Step 2. In order to account for contaminant attenuation factors such as dispersion and dilution, the model augments the time interval in question by a factor of 25 percent.

In summary, the generation of travel-time plots involves the following sequence of events:

1. Compute hydraulic heads
2. Compare to known heads and adjust model inputs
3. Recompute heads with "calibrated" model
4. Calculate ground-water velocities
5. Generate and advance particles through flow field
6. Track particles into well-field areas
7. Delineate WHPAs based on particle travel times

RESULTS

Inputs required by the model include transmissivity, specific yield, aquifer recharge, aquifer thickness, and total pumpage of the wellfield. In addition, leakage from all the major canals was input into the model and adjusted as part of the calibration process. Finally, the established hydrological boundaries for the modeling area were selected (whenever possible) to reflect actual flow boundary conditions.

The ground-water flow regime was simulated by setting up two grid systems of square cells for the northern (220 x 136 grid) and the southern (220 x 256 grid) part of the county. Both grids have the same cell dimensions of 528 feet on a side.

Table 2 provides a range of WHPA dimensions determined for the travel-distance zones and one-foot drawdown contour for each well field. Figure 4 shows that, in general, WHPAs in the southern part of the county are smaller than those in the north. This is attributed to the large number of canals in the south and the greater recharge of water from them caused by local pumpage. Under similar pumping rates, the smaller canal recharge in the north results in greater stress and increased drawdowns in the aquifer.

TABLE 2.

APPROXIMATE EXTENT OF TRAVEL-DISTANCE ZONES AND ONE FOOT CONTOUR

WELLFIELD NUMBER / NAME	2010 # OF WELLS	ZONE 1 RANGE (FT)	ZONE 2 RANGE (FT)	ZONE 3 RANGE (FT)	1 FT CONTOUR RANGE (FT)
1 Tequesta	4	50 / 90	270 / 350	550 / 670	n/a
2 Jupiter	34	10 / 800	40 / 2590	100 / 3240	700 / 1300
3 Seascoast (Hood)	14	50 / 170	440 / 840	1050 / 1520	650 / 1300
4 Seacoast (Lilac)	6	20 / 120	50 / 500	175 / 600	0 / 750
5 Seacoast (Richard)	8	50 / 200	220 / 600	400 / 960	250 / 7000
6 Seacoast (Dixie)	9	50 / 200	700 / 900	1050 / 1600	2000 / 3000
7 Riviera	26	25 / 230	75 / 1150	175 / 1710	750 / 4500
8 Mangonia	5	50 / 175	425 / 625	750 / 1050	1000 / 4000
9 Consolidated	3	35 / 75	50 / 150	85 / 375	n/a
10 Century	3	40 / 300	110 / 1700	200 / 2500	n/a
11 Meadowbrook	3	225 / 275	1550 / 1700	3100 / 3900	n/a
12 PBC #1	7	25 / 220	600 / 1150	690 / 1875	2500 / 4500
13 PBC #2	17	25 / 160	150 / 630	460 / 1060	250 / 3000
14 PBC #3	11	50 / 175	300 / 850	730 / 1360	700 / 1300
15 PBC #8	28	35 / 370	280 / 1620	425 / 3270	700 / 2800
16 PBC #9	13	10 / 180	40 / 830	375 / 1570	500 / 2000
17 Royal Palm Beach	7	75 / 220	600 / 1190	700 / 1520	900 / 1500
18 ACME	11	40 / 75	120 / 370	260 / 640	1000 / 2500
19 Palm Springs	15	50 / 100	250 / 675	500 / 1000	n/a
20 Atlantis	5	40 / 50	120 / 300	200 / 550	n/a
21 Lake Worth	12	10 / 300	275 / 1200	1350 / 1900	1700 / 5000
22 Lantana	4	50 / 100	250 / 600	500 / 1150	n/a
23 Manalapan	11	25 / 50	50 / 225	100 / 750	n/a
24 Boynton	40	25 / 400	225 / 1450	450 / 2550	1200 / 10500
25 Village of Golf	3	50 / 75	100 / 1150	125 / 2050	n/a
26 Delray	24	25 / 300	575 / 1400	750 / 2250	900 / 9000
27 Highland	3	10 / 130	250 / 700	600 / 1100	1500 / 1900
28 Boca Raton	51	25 / 250	100 / 1400	200 / 2350	1500 / 5500
29 Pratt & Whitney	7				n/a

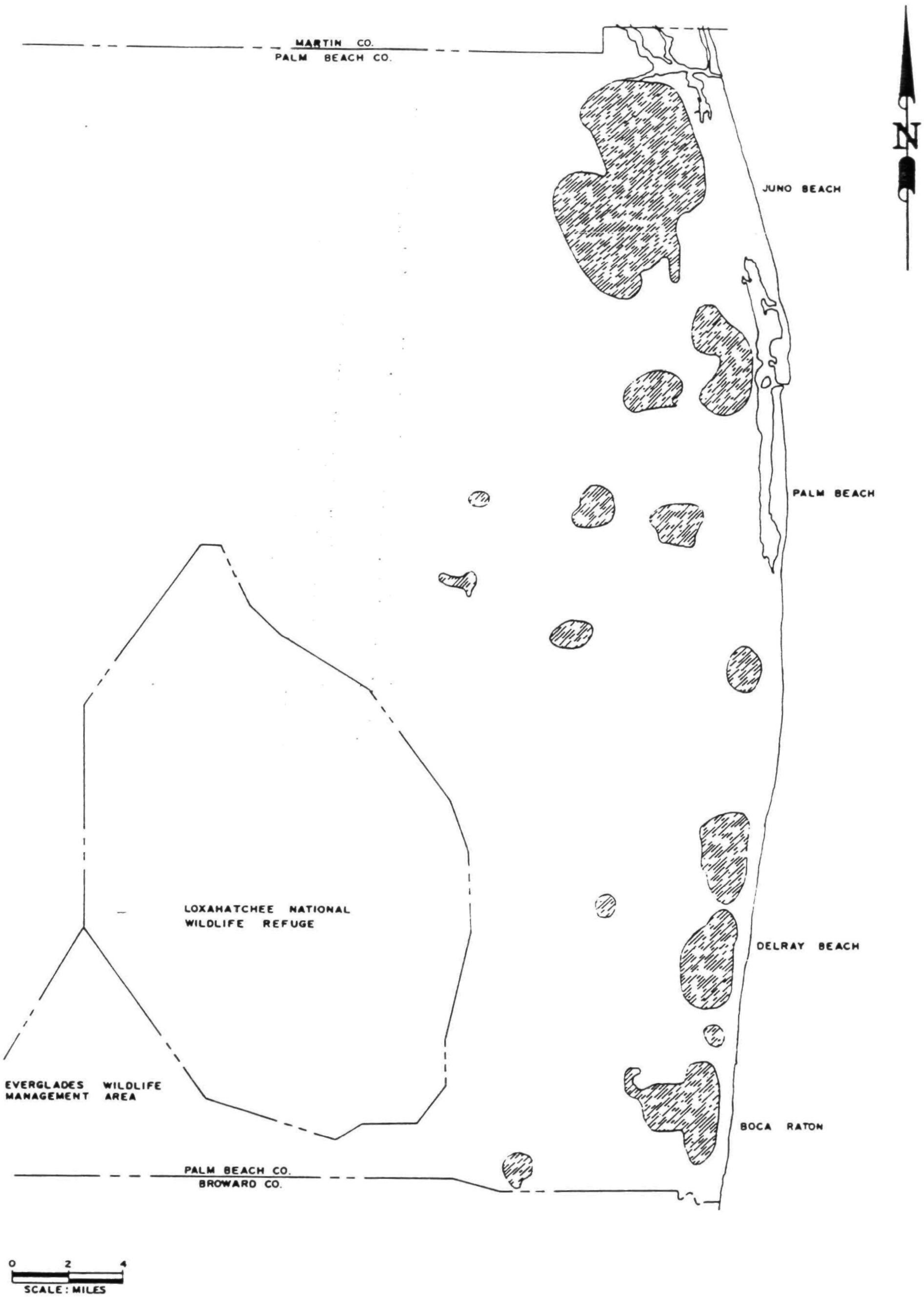


FIGURE 4. ONE-FOOT CONTOUR ZONE
EASTERN PALM BEACH COUNTY

B.5 CASE STUDY: FRANKLIN, MASSACHUSETTS

INTRODUCTION

In Massachusetts, the Department of Environmental Quality Engineering (DEQE) has developed a standard procedure to be followed by municipalities seeking to develop new wells for water supply. In addition to a survey of all wells in the area of interest, a survey of potential sources of pollution; and a description of the aquifer, the zone of contribution to the proposed well must be delineated.

The DEQE recognizes three zones around a well, in which varying degrees of ground water protection are practiced. The zones are defined as:

Zone I -The immediate area which lies within 400 ft of the well.

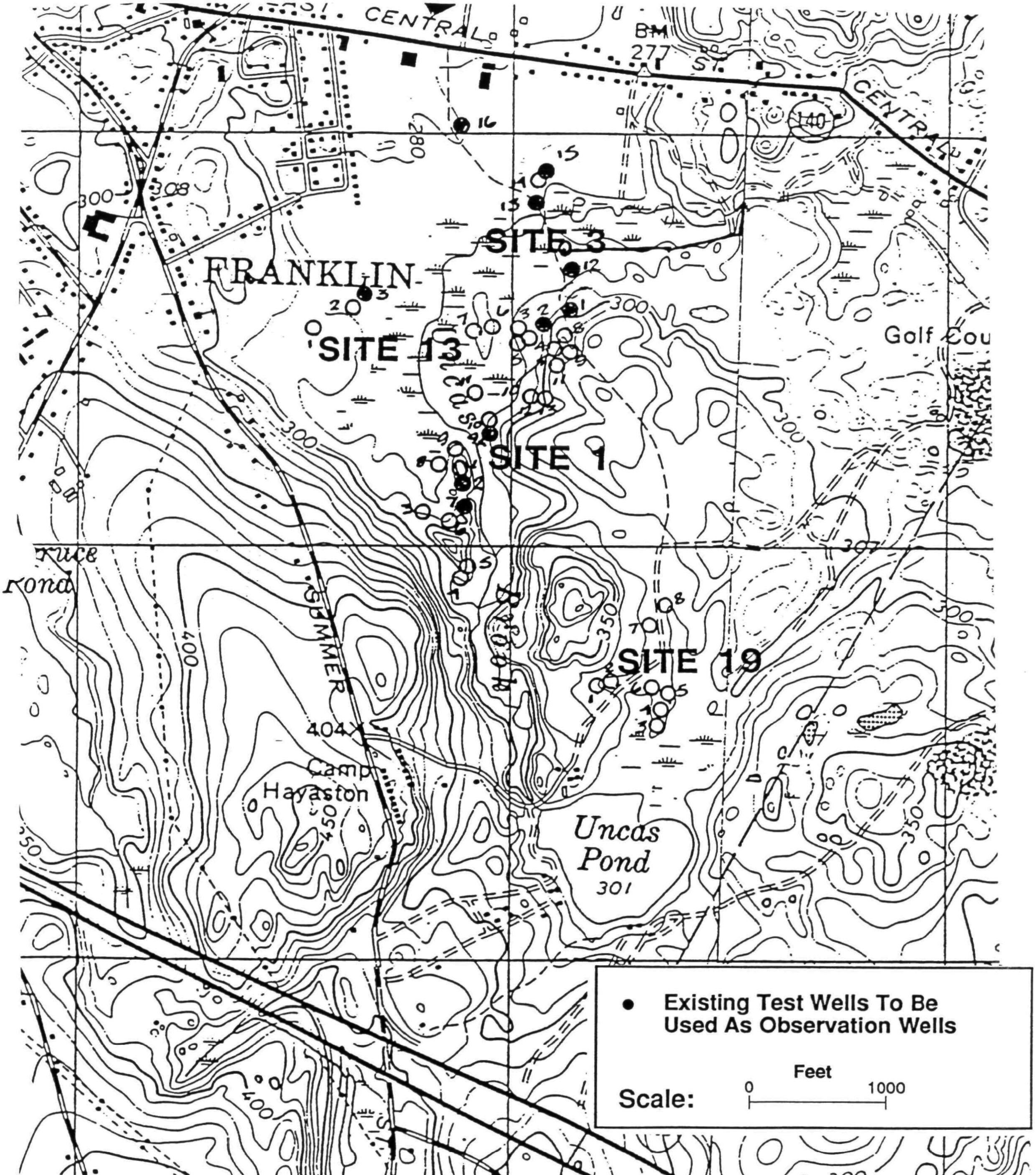
Zone II-The land area which supplies ground water directly to a pumping well under the most severe recharge and pumping conditions. The baseline condition is considered to be 180 days of pumping at design rate without recharge to the aquifer.

Zone III-The land area beyond zone II from which surface water and/or ground water drains into Zone II.

Zone II is the most difficult of the three to delineate, so the State DEQE has set forth guidelines for the acceptable methods of Zone II delineation. As a minimum effort, a 5-day pump test must be performed, and drawdown and recovery data must be collected from an appropriate number of observation wells. Information on aquifer parameters inferred from the pump test data is then used to predict the extent of Zone II as defined above. If the aquifer has a complex configuration or heterogeneous composition, and simple analytical techniques cannot accurately reflect the behavior of the aquifer under pumping conditions, then a numerical simulation of the aquifer is required.

In the case of Franklin, Massachusetts (see Figure 1), such a computer simulation was deemed necessary. Following a preliminary survey of existing data, which included published reports and logs of nearby wells, a field investigation was undertaken to better define the area's hydrogeology. Approximately 20 boreholes were drilled and logged, 15 of them being converted to observation wells. Results of this investigation and the pump test indicated spatial variation in aquifer parameters which would require numerical simulation for proper evaluation of Zone II.

FIGURE 1. FRANKLIN, MASSACHUSETTS SITE MAP



WELLHEAD PROTECTION OBJECTIVES

The City of Franklin's purpose in initiating the study was to determine the zones of contribution to their proposed supply well as defined by the Massachusetts DEQE. These three zones around a water supply well have been established to offer varying degrees of protection to the ground water from potential sources of contamination. Zone I protects the area immediately surrounding the well. Zone II includes any area which directly contributes water to a pumping well. Zone III is designated in order to protect all areas from which surface or ground water drains into Zone II.

HYDROGEOLOGIC SETTING

The site of the proposed Franklin water supply well is located in an alluvial valley of glacial origin. The aquifer is composed of interstratified sands, silts, and gravels, of glacio-fluvial origin and is bounded by bedrock and glacial till. Thickness of the valley sediments reaches a maximum of 43 feet in the central region of the valley and decreases to as little five feet near the valley walls. The stratigraphy is not homogeneous. In the area surrounding the test well, very coarse sands and gravels were encountered from the surface to the base of the valley. To the north and west, the sediments thin rapidly and are overlain by fine sand and silt.

Under static, non-pumping conditions, ground water flows toward the center of Uncas Brook and out the valley through a narrow neck of the aquifer, which connects it to another valley (Figure 2). Regionally, the general flow is to the east toward the discharge point, under a hydraulic gradient of .001 to .002. Transmissivities determined from the 5-day pump test using Jacob's straight line approximation method and the Theis curve-matching technique ranged from 145,000 to 188,000 gpd/ft for nearby observation wells, and from 45,000 to 77,000 gpd/ft for outer wells. Values for storativity ranged from .018 to .035.

METHOD AND CRITERIA SELECTION

The three zones of contribution to a supply well, as defined by the DEQE, lend themselves to delineation by certain criteria and methods. By definition, Zone I encompasses the area within 400 feet of the well, an arbitrary fixed radius with a distance criteria. Zone III, the land area from which ground water or surface water drains into Zone II, is best delineated by mapping of topographic

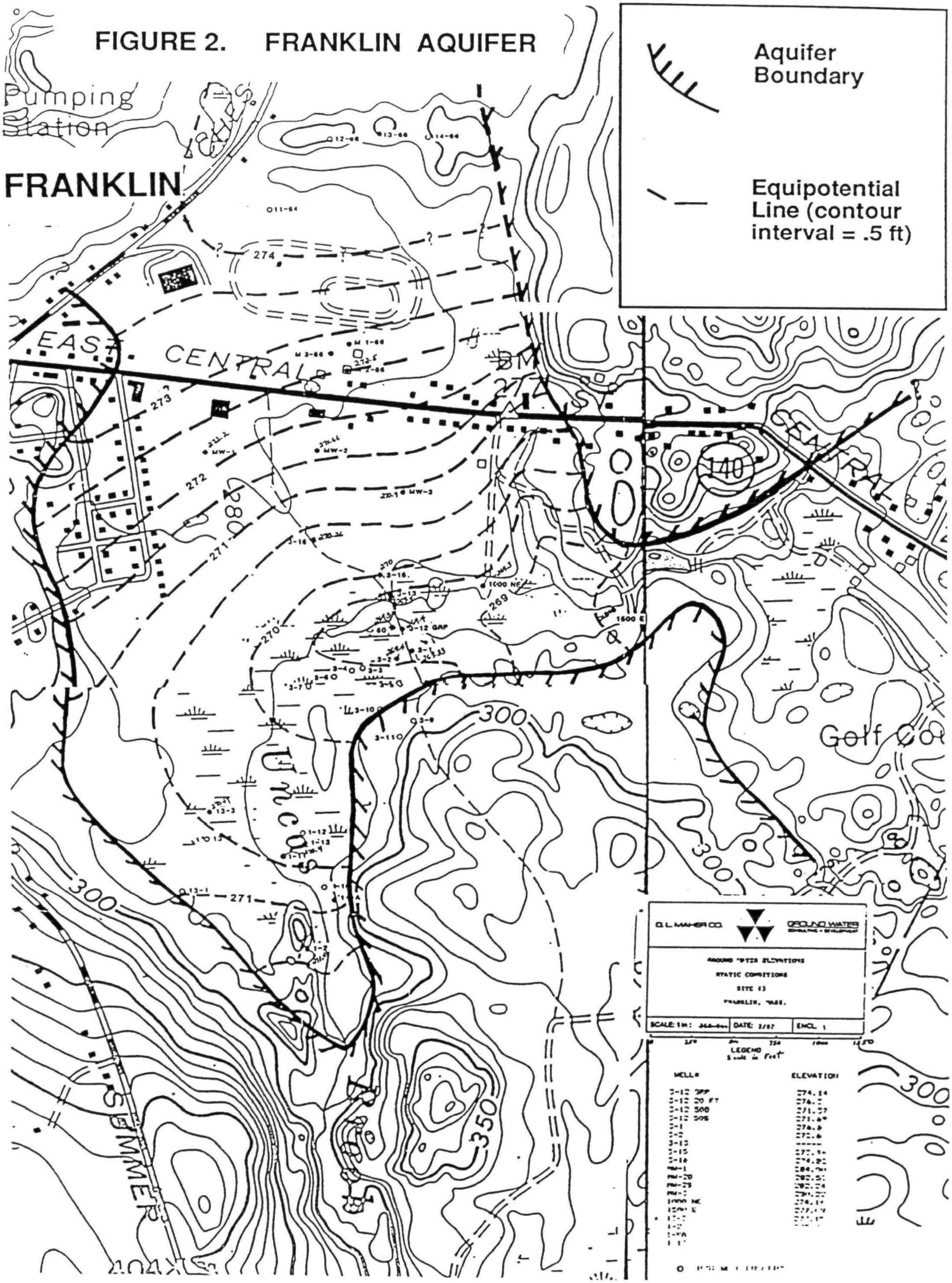


FIGURE 2. FRANKLIN AQUIFER

and hydrogeologic divides, which are basically flow boundaries.

Zone II is the most difficult to determine, being defined as the area which supplies water directly to a pumping well. Little latitude was given to Franklin in choosing a method and a criteria, as the DEQE requires that data from a 5-day pump test to be used to project what the zones of contribution will be after 180 days of pumping at the design rate without recharge to the aquifer. In addition, the DEQE requires the use of a computer simulation of the aquifer if aquifer conditions are too complex for a simple analytical solution.

Because of the complexity of the hydrogeologic setting, a numerical model was chosen to simulate ground-water flow under the required pumping and recharge conditions. The computer software package, MODFLOW (Modular Three-Dimensional Finite Difference Ground-Water Flow Model) was selected because of its ability to simulate certain phenomena recognized at the site, such as a multilayered aquifer, irregular boundaries, heterogeneity within layers, interaction with surface water, a partially penetrating well and areal recharge.

Model Description

The model simulated the ground-water flow regime by a two layer, non-uniform grid of 21 columns by 27 rows (Figures 3.A and 3.B). The grid spacing increased from 50 feet near the pumping center to 400 feet near the model boundaries. Aquifer boundaries (till or bedrock) were simulated by inactive cells. Constant heads were assigned to cells east of the "bottle neck" to drive flow in that direction. Initial heads in the aquifer model were assigned according to water table elevations throughout the area.

In order to calibrate the model, it was necessary to first simulate non-pumping conditions. Recharge and discharge rates and aquifer parameters were input to the model. Values for aquifer parameters were derived from the results of previous test drilling and the pumping test. Parameters for both layers of the model were modified until simulated heads matched observed aquifer heads and a balanced water budget was achieved.

Further calibration was needed to ensure that the model would accurately simulate pumping conditions. A discharge rate of 350 gpm was set in the cells representing the discharging wells and several runs were made. Output from the model was compared to data collected during the pump

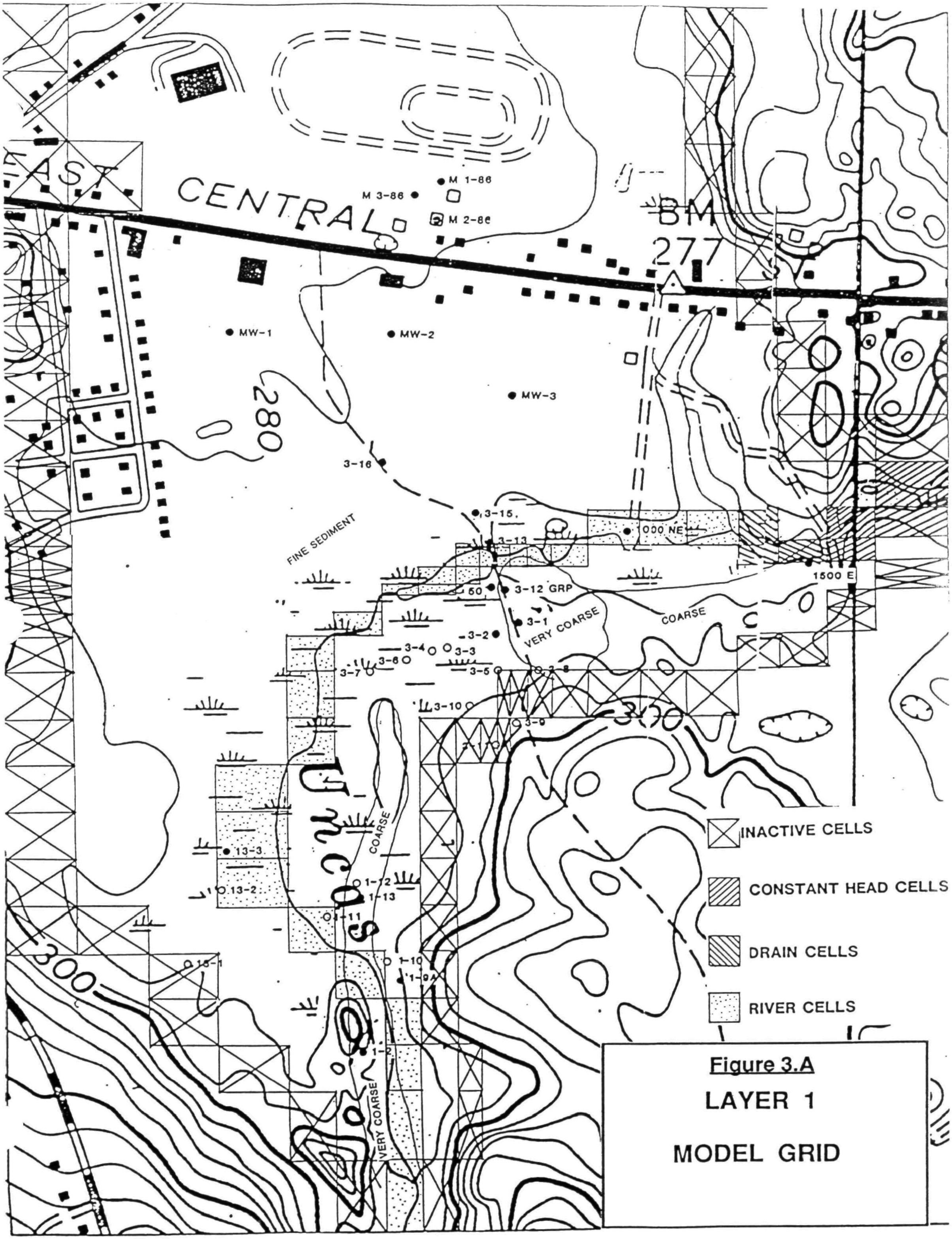


Figure 3.A

LAYER 1

MODEL GRID

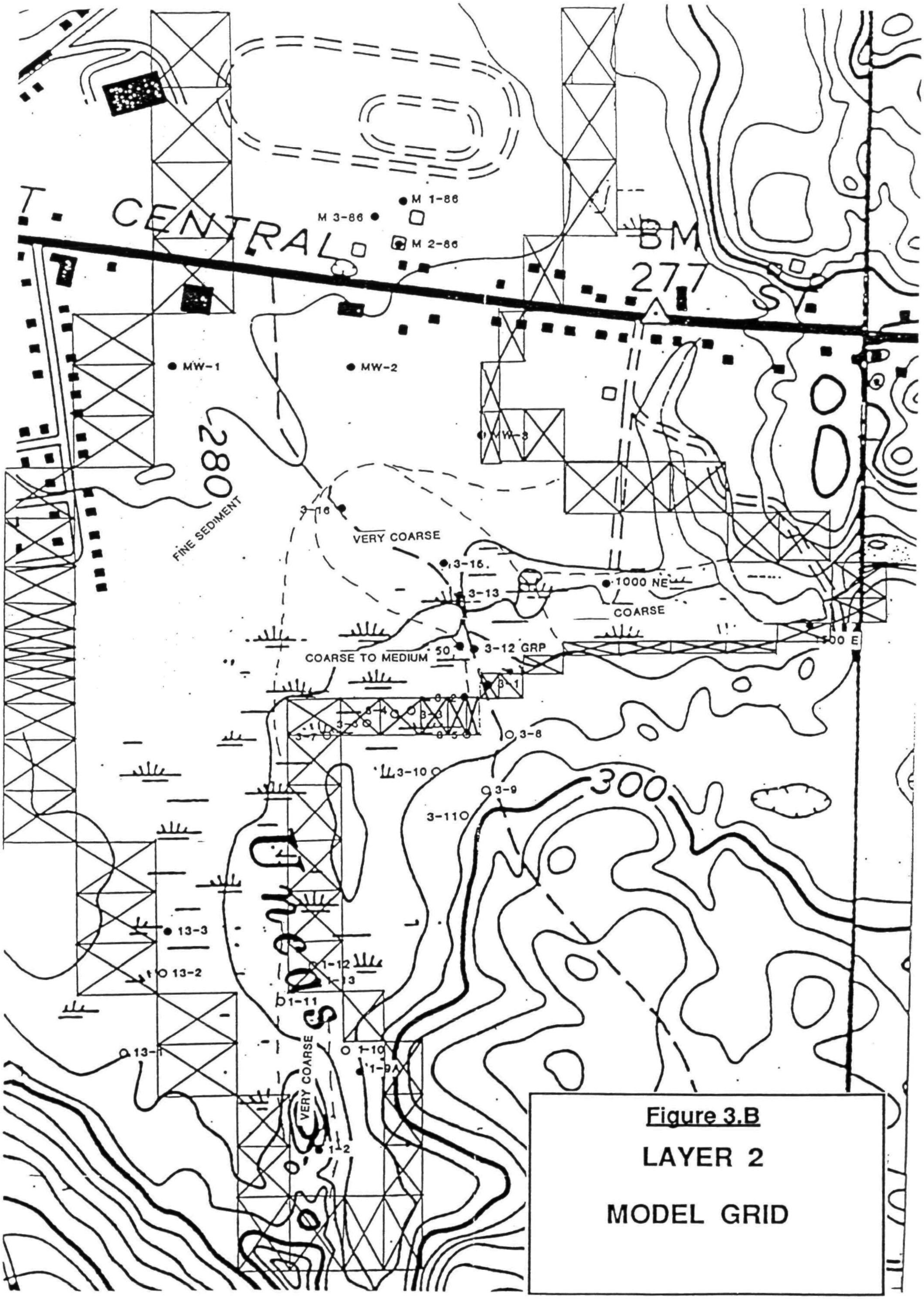


Figure 3.B

LAYER 2

MODEL GRID

Figure 4.A MODEL RESULTS AFTER 180-DAY PUMPING PERIOD: LAYER 1

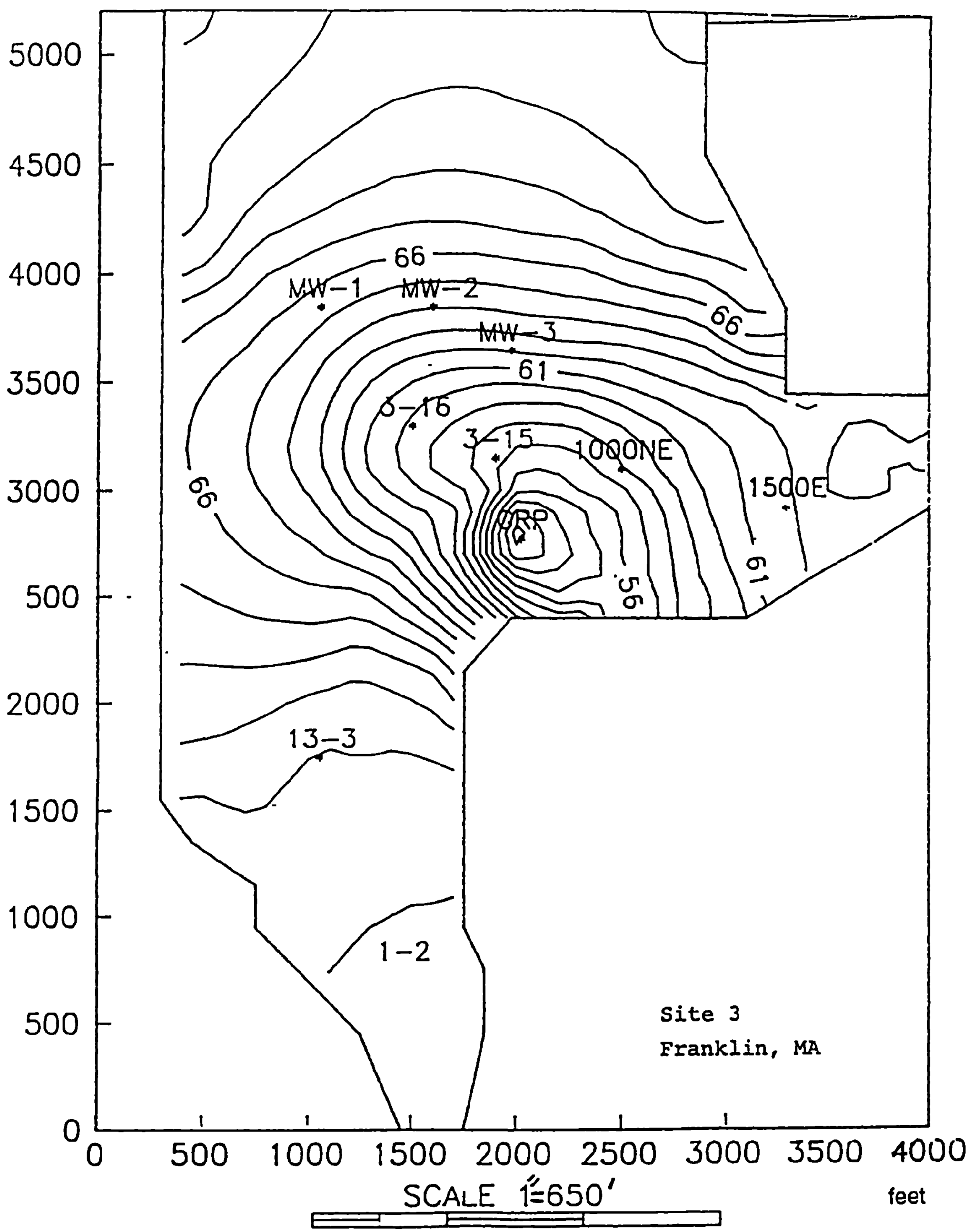
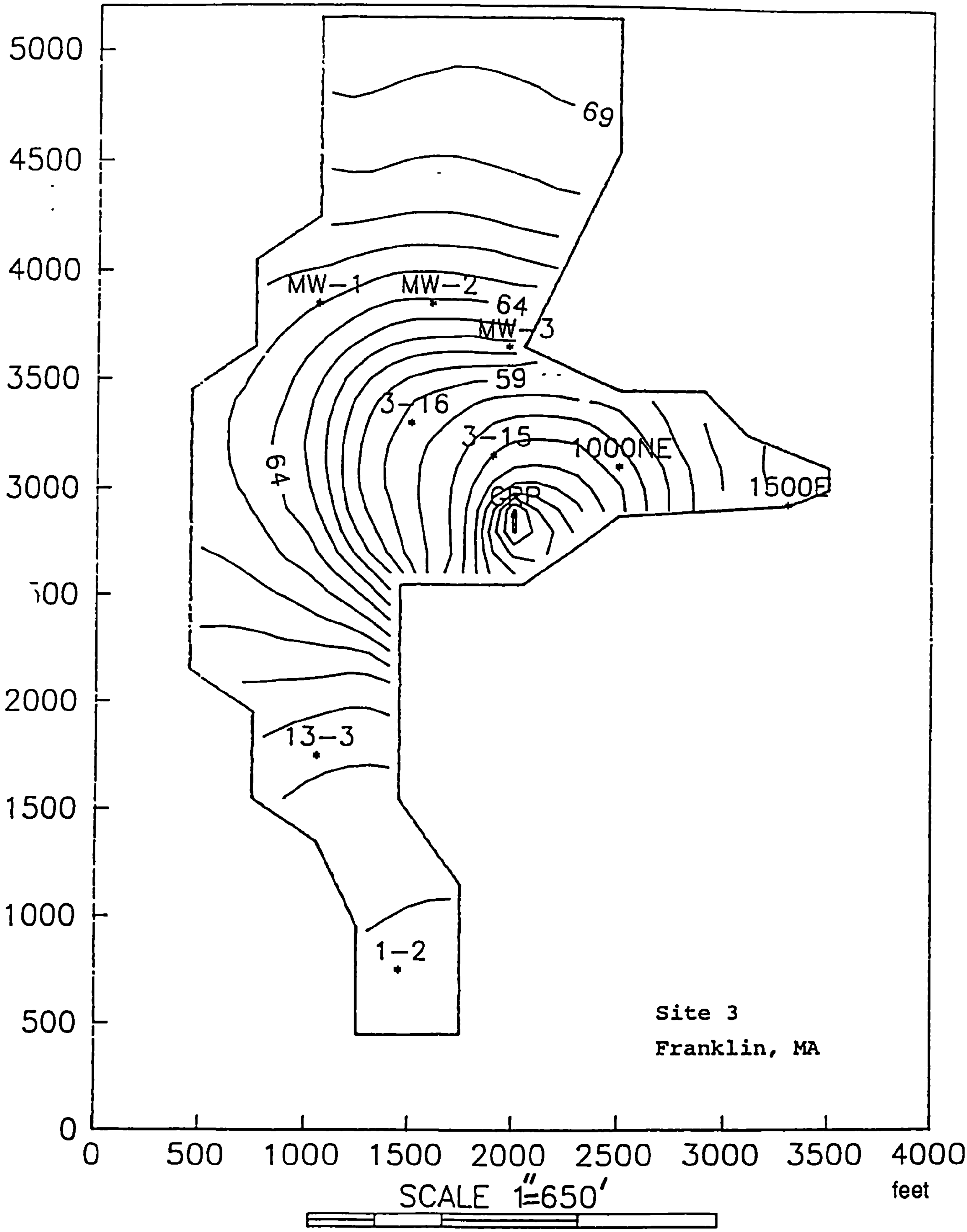


Figure 4.B MODEL RESULTS AFTER 180-DAY PUMPING PERIOD: LAYER 2



test, and adjustments were made to certain parameters until model output matched the observed data satisfactorily.

Following calibration, the model was ready to be used to simulate the required pumping conditions. In determining the extent of Zone II, the land area directly contributing water to the well, the stress period was set to 180 days and the areal recharge was eliminated. Four scenarios were run in order to analyze variations in size of the area. In two runs, the influence of the surface stream was ignored and the specific yield was modified slightly. The same modifications for specific yield were again made in two runs in which the river simulation package was used.

RESULTS

The simulation attempts in which the stream was ignored failed after a period of 120 days due to excessive dewatering in the upper layer. Both of the other model runs predicted that all ground-water flow within the entire valley would be toward the well. Figures 4.A and 4.B shows the model's prediction of ground-water elevations after 180 days of pumping.

As a result of the model simulation, Zone II was delineated as the entire valley in which the well is situated. (See Figure 5). Zone III, also shown in Figure 5, extends to the topographic divide which bounds the Uncas Brook watershed.

Figure 5.

WHPA ZONES DELINEATED FOR FRANKLIN, MASSACHUSETTS SITE

B.6 CASE STUDY: BOWLING GREEN, KENTUCKY

INTRODUCTION

In the Bowling Green, Kentucky area (Figure 1), water for public supply is obtained from both springs and wells in a mature unconfined karst aquifer. Currently, a study is in progress to address the problem of ground-water protection, which will include the delineation of Wellhead Protection Areas (WHPAs). While no actual WHPAs have been defined, the problem is similar to determining the zone of contribution (ZOC) to a spring. Much work has been done in the area on defining ground-water basins and general flow routes using dye-tracing techniques. Such information is useful in determining the ZOC to a well or spring. The material presented below has been summarized from a report on the hydrogeology of the Bowling Green area prepared by Crawford, et. al. (1987).

HYDROGEOLOGIC SETTING

The study area (Figure 2) surrounding Bowling Green is underlain by carbonate rocks of Mississippian Age, predominately the Ste. Genevieve Limestone, with the St. Louis and Girkin Limestones occurring in minor portions of the study area (Figures 3 and 4). The entire area is a mature karst terrain, exhibiting typical land form features associated with karst, such as sinkholes, sinking streams, and springs. Solution enhancement of fractures and joints in the rock has created large subterranean conduits through which ground water can flow at high velocities (Figure 5). Such conduit flow can be several orders of magnitude higher than diffuse flow which occurs through intergranular pore space.

Flow patterns of ground water in karst aquifers can differ greatly from those in granular aquifers due to flow through channels. Furthermore, flow patterns within a single aquifer may change significantly between normal and high-flow conditions, because storm water can fill underground conduits, causing overflow to run off into channels which normally contain no water. These factors make the prediction of ground water flow direction difficult.

METHOD AND CRITERIA SELECTION

Because conduit flow in mature karst aquifers generally does not follow ground-water flow patterns associated with porous media aquifers, using methods of wellhead protection based on simple shapes or analytical flow equations is unlikely to result in delineation of an effective WHPA. For

LOCATION OF BOWLING GREEN AND LOST RIVER KARST GROUNDWATER BASIN, WARREN COUNTY, KENTUCKY

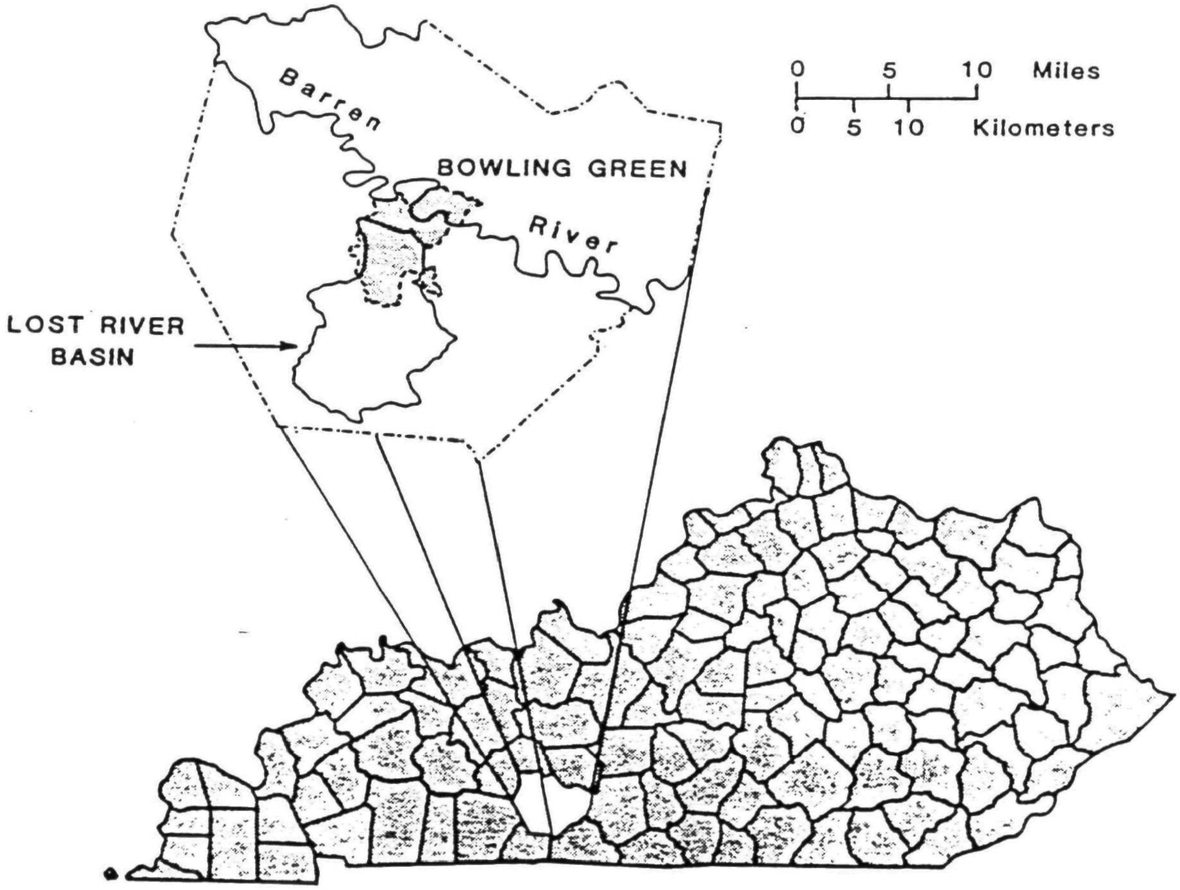


FIGURE 1. Location of the Lost River Groundwater Basin, Warren County, Kentucky.

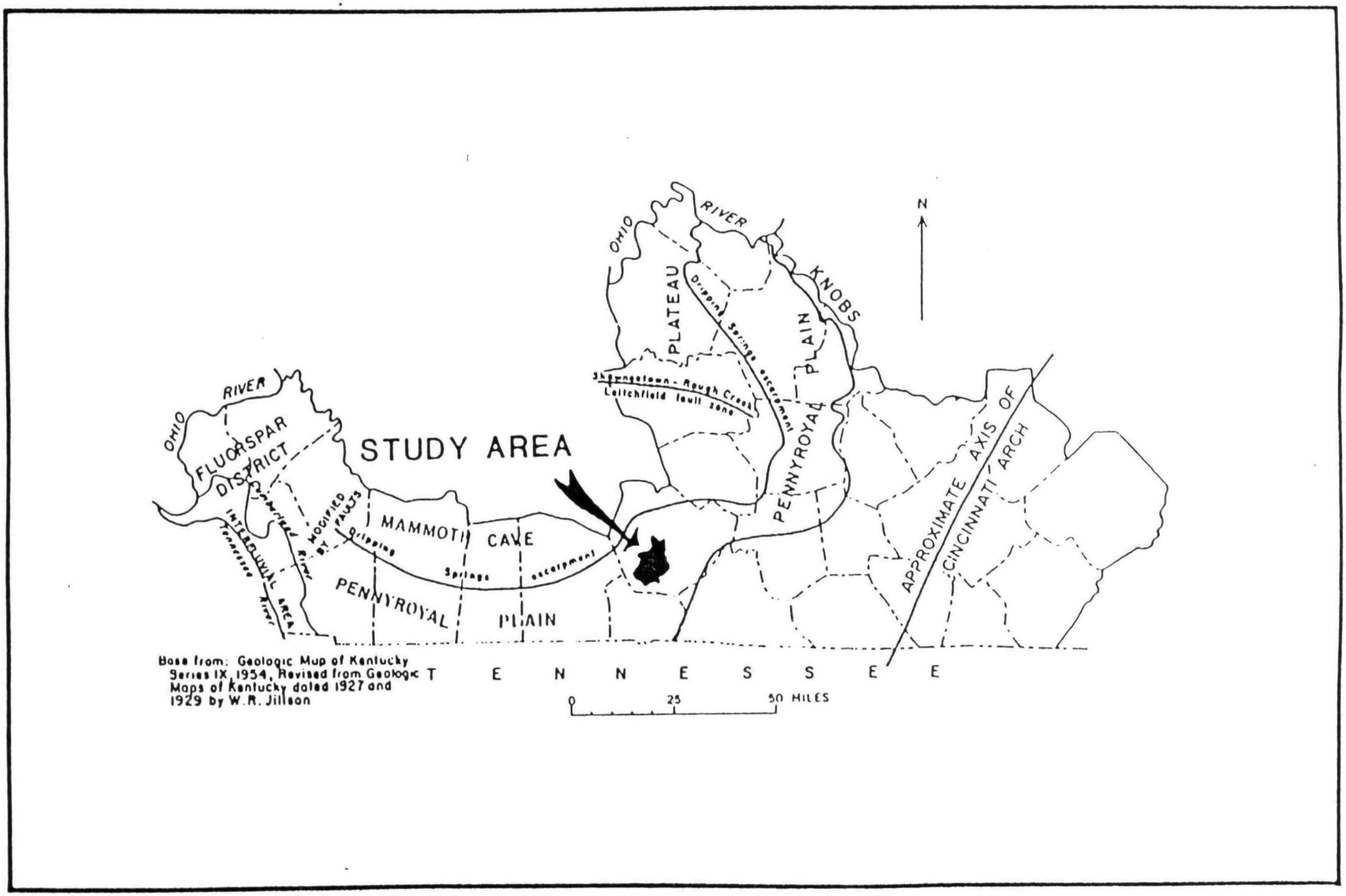


FIGURE 2. Location of the study area with respect to regional physiographic setting.

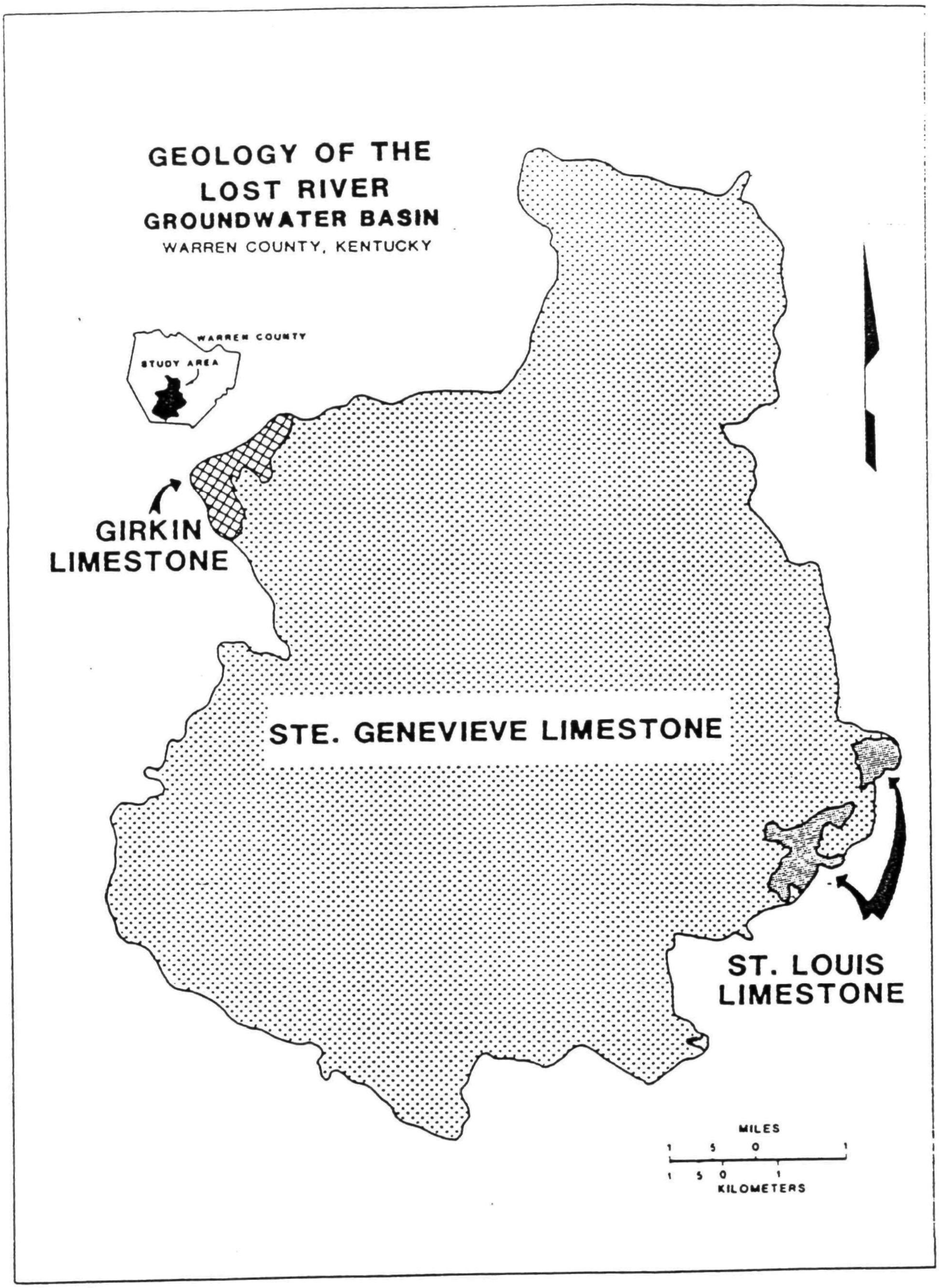


FIGURE 3. **Geology of the Lost River Groundwater Basin.**

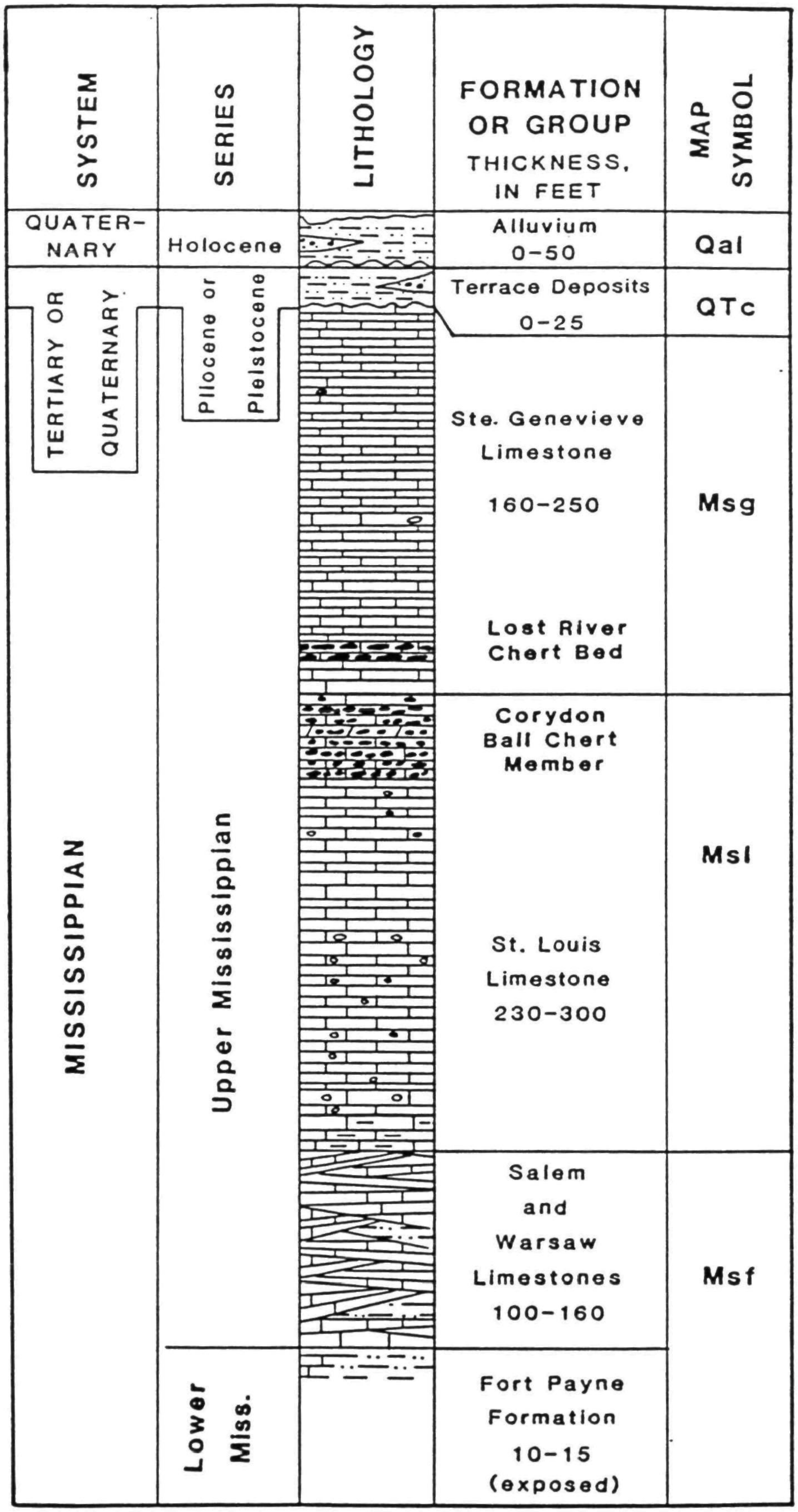


FIGURE 4. Stratigraphic Column for the Bowling Green area. Source: modified from McGrain and Sutton (1973).

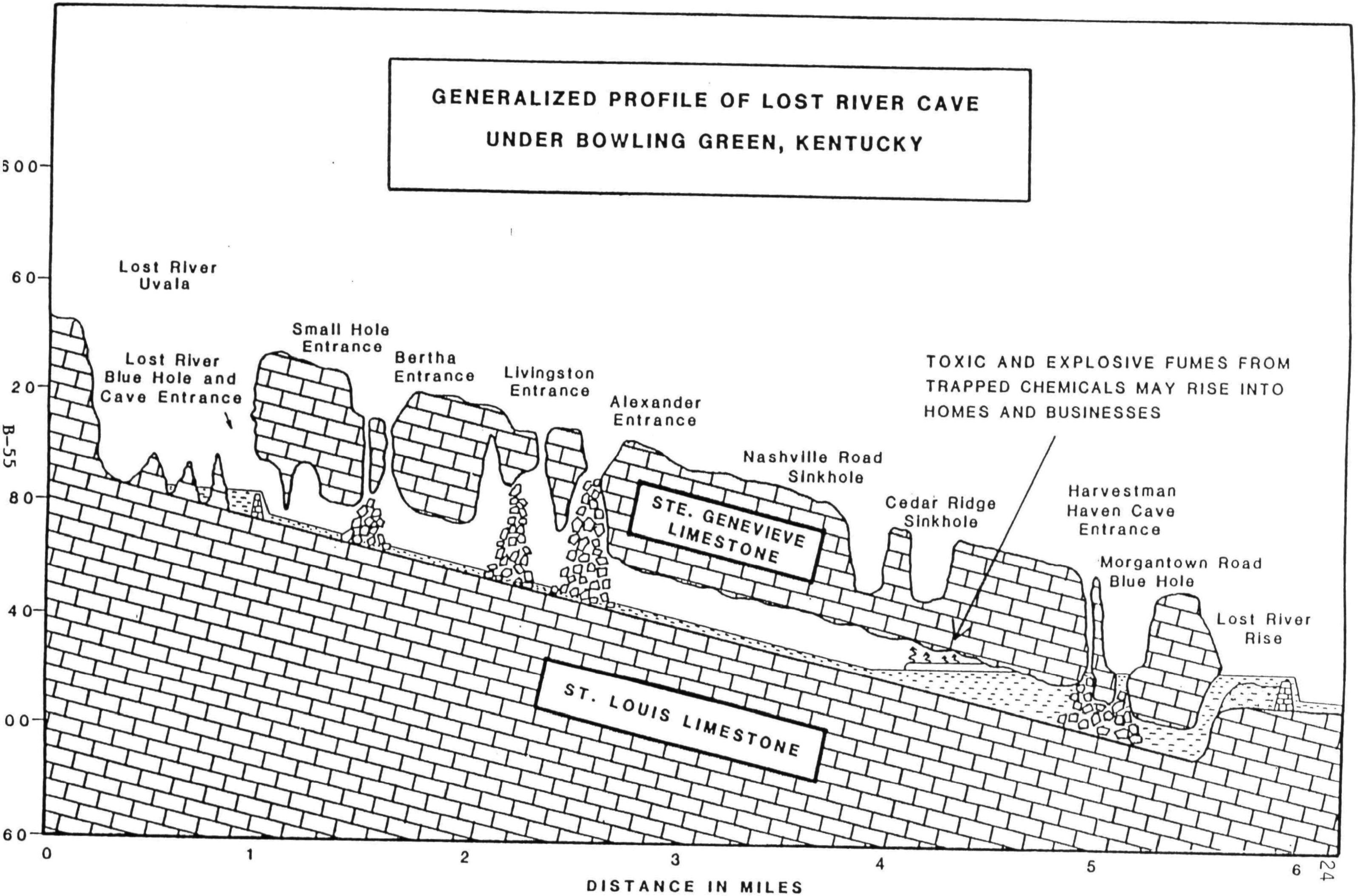


FIGURE 5. Generalized profile of the Lost River.

example, calculating a fixed radius based on the volumetric flow equation, or trying to determine the radial distance at which a certain drawdown occurs may be meaningless if a well receives some of its water from a solution cavity which has its origin a mile or more outside of the calculated zone of contribution. Also, large supplies of water are collected at springs, which must also be protected, but which cannot be evaluated using analytical equations derived for discharging wells. For this reason, hydrogeologic mapping lends itself as the most useful tool in delineating both WHPAs and protection areas for springs in mature karst aquifers.

The first step in defining areas to protect wells and springs used for public water supply is to determine the boundaries of the ground water basin in which the spring or well is located. The ground water basin in a karst aquifer is defined as the entire area which drains to a spring or set of springs. Delineation of the ground water basin can be accomplished through mapping of the potentiometric surface to determine general flow directions, coupled with dye-flow or other tracing techniques to better define flow routes. Ideally, both the potentiometric surface map and the tracing should be done for normal and high-flow (storm event) conditions.

Figure 6 shows the potentiometric surface and subsurface flow routes mapped for the Lost River Basin south of Bowling Green. This information and topographic data that aided in identifying surface-water flow divides were used to delineate the boundary of the hydrogeologic system (Figure 7).

Having defined the ground water basin and the general flow patterns within the basin, the next step involves determination of the contributing area for an individual well or spring by examining the flow patterns and potentiometric surface upgradient of the water supply. Depending on the proximity of the well to the boundary of the ground-water basin and on flow rates as determined through dye-tracing, an appropriate delineation criteria for the upgradient extent of the WHPA may be time of travel (TOT) or flow boundaries.

The ground-water divide forming the boundary of the basin would be appropriate and easy to implement if the well or spring were located near the edge of the basin. However, for a well located near the center or at the mouth of a large basin, enforcing a WHPA that extends to the boundary of the basin may be difficult.

In such a case, a TOT criterion may be considered to delineate the upgradient boundary. The problem with this approach in a conduit-flow karst system is that velocities are often so high that time-of-travel distances are too short

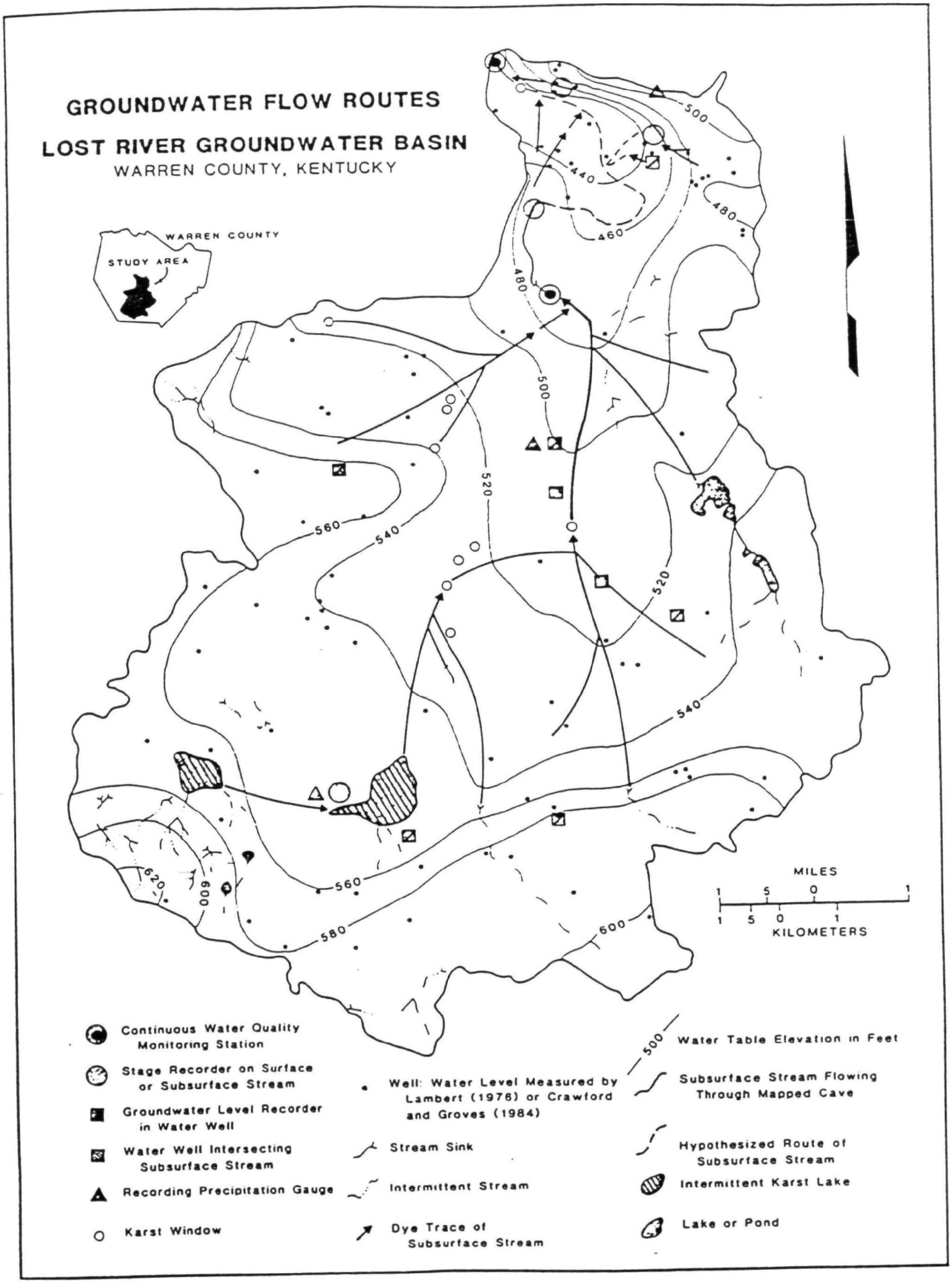


FIGURE 6. Groundwater flow routes of the Lost River Groundwater Basin.

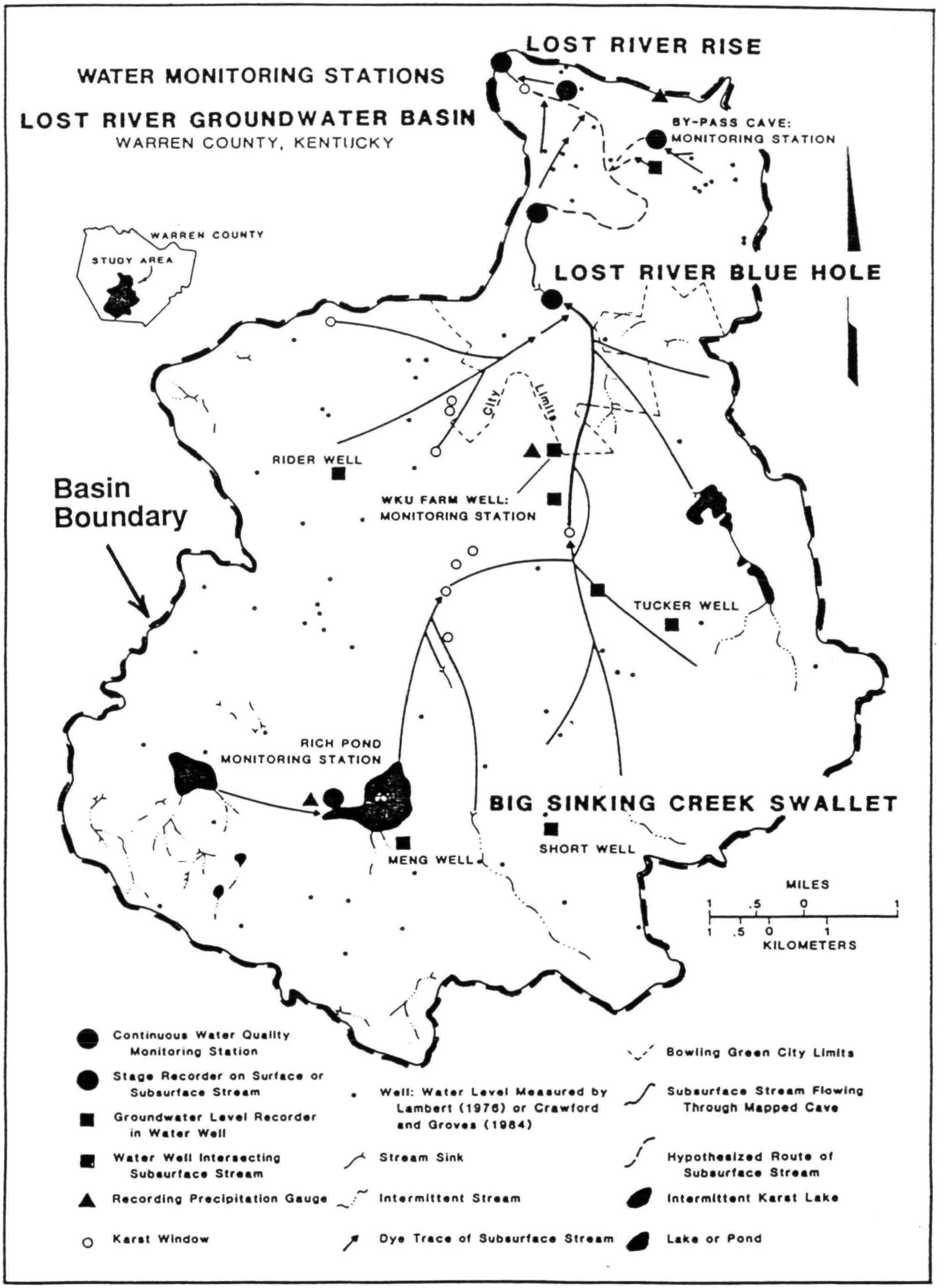


FIGURE 7. Lost River Groundwater Basin, showing routes of dye traces of subsurface streams.

to provide an adequate buffer. Data from the Lost River Basin (Table 1 and Figure 8) indicate that subsurface flow moves from Big Sinking Creek in the headwater region of the basin to Lost River Rise at the mouth (a distance of approximately 10 miles, see Figure 7) in 1 to 10 days, depending on flow conditions.

Due to the unique nature of karst ground-water flow systems, special care must be taken in selecting the criterion, threshold, and method used to delineate a WHPA.

REFERENCE

Crawford, N.C., C.G. Groves, T.P. Feeney and. B.J. Keller, 1987, Hydrogeology of the Lost River Karst Ground-Water Basin, Warren County, Kentucky, prepared for Kentucky Natural Resources and Environmental Protection Cabinet Division of Water Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky.

BLUE HOLE TO RISE

Date of Trace	Initial stage (feet)	Qi cfs	Centroid stage (feet)	Qc cfs	Time of first arrival	Time of centroid
11/7/82	———	12.4	———	12.4	68.0	87.64
9/22/83	6.35	9.2	6.67	10.8	80.5	98.56
3/30/84	7.49	145	7.55	160	10.0	10.33
6/18/84	6.65	70	6.66	70	16.5	19.57
7/18/84	6.01	29	5.97	27	32.5	42.5

BIG SINKING CREEK TO RISE

Date of Trace	Initial stage (feet)	Qi cfs	Centroid stage (feet)	Qc cfs	Time of first arrival	Time of centroid
11/7/82	———	12.4	————	12.4	185	224
3/30/84	7.39	130	7.4	138	29.5	32.7
4/18/84	6.85	47	6.87	50	48.5	54.7
6/18/84	6.8	70	6.66	70	39.25	47.6
7/18/84	5.89	25	5.88	25	83	102

BIG SINKING CREEK TO BLUE HOLE

Date of Trace	Initial stage (feet)	Qi cfs	Centroid stage (feet)	Qc cfs	Time of first arrival	Time of centroid
3/30/84	6.11	127	6.05	120	19.5	20.8
4/18/84	5.25	63	5.23	63	27.5	32.2
*6/1/84	5.86	105	5.86	105	18.5	22.01
7/18/84	2.9	25	2.57	17	43	54

* Trace started when Big Sinking Creek ponded.

TABLE 1. Results of quantitative dye traces.

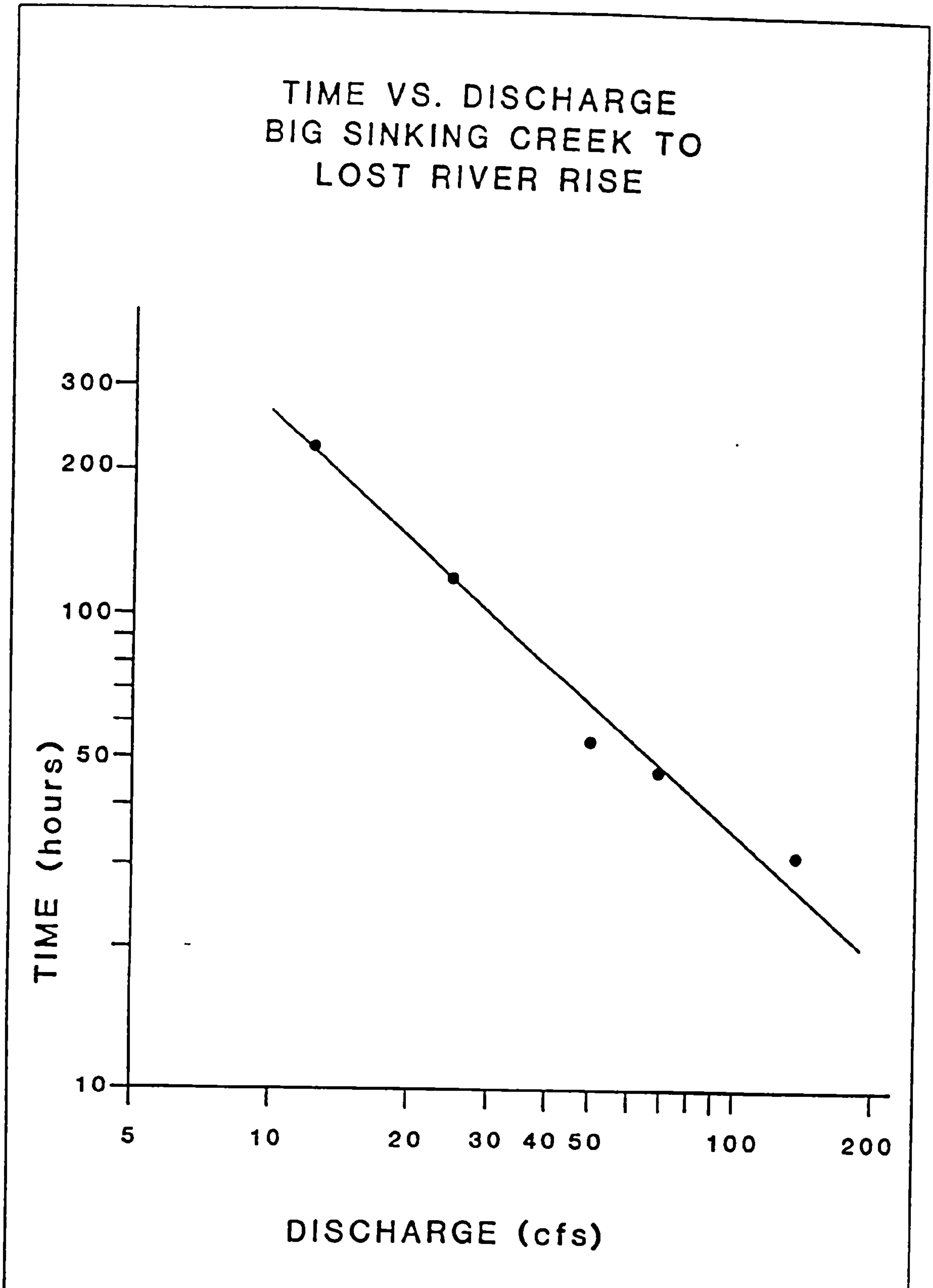


FIGURE 8. Time vs. Discharge: Big Sinking Creek to Lost River Rise.

C. Well Function

APPENDIX C:

VALUES OF WELL FUNCTION

APPENDIX C.

Values of *W(u)* Corresponding to Values of *u* for Theis Nonequilibrium Equation

N \ u	N×10⁻¹⁵	N×10⁻¹⁴	N×10⁻¹³	N×10⁻¹²	N×10⁻¹¹	N×10⁻¹⁰	N×10⁻⁹	N×10⁻⁸	N×10⁻⁷	N×10⁻⁶	N×10⁻⁵	N×10⁻⁴	N×10⁻³	N×10⁻²	N×10⁻¹	N
1.0	33.9616	31.6590	29.3564	27.0538	24.7512	22.4486	20.1460	17.8435	15.5409	13.2383	10.9357	8.6332	6.3315	4.0379	1.8229	0.2194
1.1	33.8662	31.5637	29.2611	26.9585	24.6559	22.3533	20.0507	17.7482	15.4456	13.1430	10.8404	8.5379	6.2363	3.9436	1.7371	1860
1.2	33.7792	31.4767	29.1741	26.8715	24.5689	22.2663	19.9637	17.6611	15.3586	13.0560	10.7534	8.4509	6.1494	3.8576	1.6595	1584
1.3	33.6992	31.3966	29.0940	26.7914	24.4889	22.1863	19.8837	17.5811	15.2785	12.9759	10.6734	8.3709	6.0695	3.7785	1.5889	1355
1.4	33.6251	31.3225	29.0199	26.7173	24.4147	22.1122	19.8096	17.5070	15.2044	12.9018	10.5993	8.2968	5.9955	3.7054	1.5241	1162
1.5	33.5561	31.2535	28.9509	26.6483	24.3458	22.0432	19.7406	17.4380	15.1354	12.8328	10.5303	8.2278	5.9266	3.6374	1.4645	1000
1.6	33.4916	31.1890	28.8864	26.5838	24.2812	21.9786	19.6760	17.3735	15.0709	12.7683	10.4657	8.1634	5.8621	3.5739	1.4092	08631
1.7	33.4309	31.1283	28.8258	26.5232	24.2206	21.9180	19.6154	17.3128	15.0103	12.7077	10.4051	8.1027	5.8016	3.5143	1.3578	07465
1.8	33.3738	31.0712	28.7686	26.4660	24.1634	21.8608	19.5583	17.2557	14.9531	12.6505	10.3479	8.0455	5.7446	3.4581	1.3098	06471
1.9	33.3197	31.0171	28.7145	26.4119	24.1094	21.8068	19.5042	17.2016	14.8990	12.5964	10.2939	7.9915	5.6906	3.4050	1.2649	05620
2.0	33.2684	30.9658	28.6632	26.3607	24.0581	21.7555	19.4529	17.1503	14.8477	12.5451	10.2426	7.9402	5.6394	3.3547	1.2227	04890
2.1	33.2196	30.9170	28.6145	26.3119	24.0093	21.7067	19.4041	17.1015	14.7989	12.4964	10.1938	7.8914	5.5907	3.3069	1.1829	04261
2.2	33.1731	30.8705	28.5679	26.2653	23.9628	21.6602	19.3576	17.0550	14.7524	12.4498	10.1473	7.8449	5.5443	3.2614	1.1454	03719
2.3	33.1286	30.8261	28.5235	26.2209	23.9183	21.6157	19.3131	17.0106	14.7080	12.4054	10.1028	7.8004	5.4999	3.2179	1.1099	03250
2.4	33.0861	30.7835	28.4809	26.1783	23.8758	21.5732	19.2706	16.9680	14.6654	12.3628	10.0603	7.7579	5.4575	3.1763	1.0762	02844
2.5	33.0453	30.7427	28.4401	26.1375	23.8349	21.5323	19.2298	16.9272	14.6246	12.3220	10.0194	7.7172	5.4167	3.1365	1.0443	02491
2.6	33.0060	30.7035	28.4009	26.0983	23.7957	21.4931	19.1905	16.8880	14.5854	12.2828	9.9802	7.6779	5.3776	3.0983	1.0139	02185
2.7	32.9683	30.6657	28.3631	26.0606	23.7580	21.4554	19.1528	16.8502	14.5476	12.2450	9.9425	7.6401	5.3400	3.0615	9849	01918
2.8	32.9319	30.6294	28.3268	26.0242	23.7216	21.4190	19.1164	16.8138	14.5113	12.2087	9.9061	7.6038	5.3037	3.0261	.9573	01686
2.9	32.8968	30.5943	28.2917	25.9891	23.6865	21.3839	19.0813	16.7788	14.4762	12.1736	9.8710	7.5687	5.2687	2.9920	.9309	01482
3.0	32.8629	30.5604	28.2578	25.9552	23.6526	21.3500	19.0474	16.7449	14.4423	12.1397	9.8371	7.5348	5.2349	2.9591	.9057	01305
3.1	32.8302	30.5276	28.2250	25.9224	23.6198	21.3172	19.0146	16.7121	14.4095	12.1069	9.8043	7.5020	5.2022	2.9273	8815	.01149
3.2	32.7984	30.4958	28.1932	25.8907	23.5881	21.2855	18.9829	16.6803	14.3777	12.0751	9.7726	7.4703	5.1706	2.8965	8583	.01013
3.3	32.7676	30.4651	28.1625	25.8599	23.5573	21.2547	18.9521	16.6495	14.3470	12.0444	9.7418	7.4395	5.1399	2.8668	8361	008939
3.4	32.7378	30.4352	28.1326	25.8300	23.5274	21.2249	18.9223	16.6197	14.3171	12.0145	9.7120	7.4097	5.1102	2.8379	.8147	007891
3.5	32.7088	30.4062	28.1036	25.8010	23.4985	21.1959	18.8933	16.5907	14.2881	11.9855	9.6830	7.3807	5.0813	2.8099	7942	006970
3.6	32.6806	30.3780	28.0755	25.7729	23.4703	21.1677	18.8651	16.5625	14.2599	11.9574	9.6548	7.3526	5.0532	2.7827	.7745	006160
3.7	32.6532	30.3506	28.0481	25.7455	23.4429	21.1403	18.8377	16.5351	14.2325	11.9300	9.6274	7.3252	5.0259	2.7563	7554	005448
3.8	32.6266	30.3240	28.0214	25.7188	23.4162	21.1136	18.8110	16.5085	14.2059	11.9033	9.6007	7.2985	4.9993	2.7306	.7371	004820
3.9	32.6006	30.2980	27.9954	25.6928	23.3902	21.0877	18.7851	16.4825	14.1799	11.8773	9.5748	7.2725	4.9735	2.7056	.7194	004267
4.0	32.5753	30.2727	27.9701	25.6675	23.3649	21.0623	18.7598	16.4572	14.1546	11.8520	9.5495	7.2472	4.9482	2.6813	.7024	003779
4.1	32.5506	30.2480	27.9454	25.6428	23.3402	21.0376	18.7351	16.4325	14.1299	11.8273	9.5248	7.2225	4.9236	2.6576	6859	003349
4.2	32.5265	30.2239	27.9213	25.6187	23.3161	21.0136	18.7110	16.4084	14.1058	11.8032	9.5007	7.1985	4.8997	2.6344	6700	002969
4.3	32.5029	30.2004	27.8978	25.5952	23.2926	20.9900	18.6874	16.3848	14.0823	11.7797	9.4771	7.1749	4.8762	2.6119	6546	002633
4.4	32.4800	30.1774	27.8748	25.5722	23.2696	20.9670	18.6644	16.3619	14.0593	11.7567	9.4541	7.1520	4.8533	2.5899	6397	002336
4.5	32.4575	30.1549	27.8523	25.5497	23.2471	20.9446	18.6420	16.3394	14.0368	11.7342	9.4317	7.1295	4.8310	2.5684	6253	002073
4.6	32.4355	30.1329	27.8303	25.5277	23.2252	20.9226	18.6200	16.3174	14.0148	11.7122	9.4097	7.1075	4.8091	2.5474	6114	001841
4.7	32.4140	30.1114	27.8088	25.5062	23.2037	20.9011	18.5985	16.2959	13.9933	11.6907	9.3882	7.0860	4.7877	2.5268	5979	.001635
4.8	32.3929	30.0904	27.7878	25.4852	23.1826	20.8800	18.5774	16.2748	13.9723	11.6697	9.3671	7.0650	4.7667	2.5068	5848	001453
4.9	32.3723	30.0697	27.7672	25.4646	23.1620	20.8594	18.5568	16.2542	13.9516	11.6491	9.3465	7.0444	4.7462	2.4871	5721	001291
5.0	32.3521	30.0495	27.7470	25.4444	23.1418	20.8392	18.5366	16.2340	13.9314	11.6289	9.3263	7.0242	4.7261	2.4679	5598	001148
5.1	32.3323	30.0297	27.7271	25.4246	23.1220	20.8194	18.5168	16.2142	13.9116	11.6091	9.3065	7.0044	4.7064	2.4491	5478	001021

Appendix C Continued

N \ n	$N\times10^{-15}$	$N\times10^{-14}$	$N\times10^{-13}$	$N\times10^{-12}$	$N\times10^{-11}$	$N\times10^{-10}$	$N\times10^{-9}$	$N\times10^{-8}$	$N\times10^{-7}$	$N\times10^{-6}$	$N\times10^{-5}$	$N\times10^{-4}$	$N\times10^{-3}$	$N\times10^{-2}$	$N\times10^{-1}$	N
5 2	32.3129	30 0103	27.7077	25.4051	23.1026	20 8000	18.4974	16 1948	13.8922	11 5896	9 2871	6 9850	4.6871	2 4306	5362	0009086
5.3	32.2939	29 9913	27.6887	25 3861	23.0835	20.7809	18 4783	16.1758	13 8732	11.5706	9.2681	6 9659	4 6681	2 4126	5250	0008086
5.4	32.2752	29.9726	27.6700	25.3674	23.0648	20 7622	18.4596	16.1571	13 8545	11 5519	9.2494	6.9473	4 6495	2 3948	.5140	0007198
5.5	32.2568	29 9542	27.6516	25.3491	23.0465	20 7439	18 4413	16 1387	13.8361	11.5336	9 2310	6 9289	4 6313	2 3775	.5034	0006409
5.6	32.2388	29.9362	27.6336	25.3310	23 0285	20.7259	18.4233	16 1207	13 8181	11 5155	9.2130	6 9109	4 6134	2 3604	4930	0005708
5.7	32.2211	29.9185	27.6159	25 3133	23.0108	20.7082	18 4056	16.1030	13 8004	11.4978	9 1953	6.8932	4 5958	2 3437	4830	0005085
5.8	32.2037	29.9011	27.5985	25.2959	22.9934	20.6908	18 3882	16 0856	13.7830	11 4804	9.1779	6 8758	4.5785	2 3273	4732	0004532
5 9	32.1866	29.8840	27.5814	25.2789	22.9763	20 6737	18.3711	16 0685	13.7659	11.4633	9.1608	6.8588	4.5615	2 3111	4637	0004039
6.0	32.1698	29.8672	27.5646	25.2620	22.9595	20.6569	18.3543	16 0517	13.7491	11.4465	9 1440	6 8420	4.5448	2 2953	4544	0003601
6 1	32.1533	29.8507	27.5481	25 2455	22.9429	20.6403	18.3378	16.0352	13.7326	11 4300	9.1275	6.8254	4 5283	2 2797	.4454	.0003211
6 2	32.1370	29.8344	27.5318	25.2293	22.9267	20.6241	18.3215	16.0189	13.7163	11.4138	9.1112	6.8092	4.5122	2 2645	.4366	0002864
6.3	32.1210	29.8184	27.5158	25.2133	22.9107	20.6081	18.3055	16.0029	13.7003	11.3978	9 0952	6 7932	4.4963	2 2494	.4280	0002555
6 4	32.1053	29.8027	27.5001	25.1975	22.8949	20.5923	18.2898	15.9872	13.6846	11.3820	9.0795	6.7775	4.4806	2.2346	.4197	.0002279
6.5	32.0898	29.7872	27.4846	25.1820	22.8794	20.5768	18.2742	15.9717	13.6691	11.3665	9.0640	6.7620	4.4652	2 2201	.4115	0002034
6.6	32.0745	29.7719	27.4693	25.1667	22.8641	20.5616	18.2590	15.9564	13.6538	11.3512	9.0487	6.7467	4.4501	2.2058	.4036	.0001816
6.7	32.0595	29.7569	27.4543	25.1517	22.8491	20.5465	18.2439	15.9414	13.6388	11.3362	9.0337	6.7317	4.4351	2.1917	.3959	.0001621
6 8	32.0446	29.7421	27.4395	25.1369	22.8343	20.5317	18.2291	15.9265	13.6240	11.3214	9 0189	6.7169	4.4204	2 1779	.3883	0001448
6 9	32.0300	29.7275	27.4249	25.1223	22.8197	20 5171	18.2145	15.9119	13.6094	11.3068	9.0043	6.7023	4.4059	2 1643	.3810	0001293
7.0	32.0156	29.7131	27.4105	25.1079	22.8053	20.5027	18.2001	15.8976	13 5950	11 2924	8.9899	6.6879	4.3916	2.1508	.3738	0001155
7.1	32.0015	29.6989	27.3963	25.0937	22.7911	20.4885	18.1860	15.8834	13.5808	11.2782	8.9757	6 6737	4.3775	2 1376	3668	0001032
7 2	31.9875	29.6849	27.3823	25.0797	22.7771	20.4746	18.1720	15.8694	13.5668	11.2642	8.9617	6.6598	4 3636	2 1246	3599	00009219
7.3	31.9737	29.6711	27.3685	25.0659	22.7633	20.4608	18.1582	15.8556	13 5530	11.2504	8 9479	6 6460	4.3500	2.1118	3532	00008239
7.4	31.9601	29.6575	27.3549	25.0523	22.7497	20.4472	18.1446	15.8420	13.5394	11.2368	8.9343	6 6324	4.3364	2 0991	.3467	00007364
7.5	31.9467	29.6441	27.3415	25.0389	22.7363	20.4337	18.1311	15 8286	13.5260	11 2234	8 9209	6 6190	4 3231	2 0867	3403	00006583
7.6	31.9334	29.6308	27.3282	25.0257	22.7231	20.4205	18.1179	15.8153	13.5127	11.2102	8.9076	6.6057	4.3100	2.0744	.3341	00005886
7 7	31.9203	29.6178	27.3152	25.0126	22.7100	20.4074	18.1048	15.8022	13.4997	11.1971	8 8946	6 5927	4.2970	2 0623	.3280	.00005263
7.8	31.9074	29.6048	27.3023	24.9997	22.6971	20.3945	18.0919	15.7893	13 4868	11.1842	8 8817	6 5798	4.2842	2.0503	.3221	00004707
7.9	31.8947	29.5921	27.2895	24.9869	22.6844	20.3818	18.0792	15 7766	13.4740	11.1714	8 8689	6 5671	4 2716	2 0386	.3163	00004210
8.0	31 8821	29.5795	27.2769	24.9744	22.6718	20.3692	18 0666	15 7640	13.4614	11 1589	8 8563	6.5545	4 2591	2 0269	.3106	00003767
8 1	31.8697	29.5671	27.2645	24 9619	22.6594	20 3568	18 0542	15.7516	13.4490	11.1464	8 8439	6 5421	4.2468	2 0155	3050	00003370
8 2	31 8574	29.5548	27.2523	24.9497	22.6471	20 3445	18 0419	15 7393	13 4367	11.1342	8 8317	6 5298	4.2346	2 0042	2996	.00003015
8.3	31.8453	29.5427	27.2401	24.9375	22 6350	20.3324	18.0298	15 7272	13 4246	11.1220	8 8195	6 5177	4 2226	1 9930	2943	00002699
8.4	31.8333	29.5307	27.2282	24.9256	22.6230	20 3204	18 0178	15 7152	13 4126	11 1101	8 8076	6 5057	4 2107	1 9820	2891	00002415
8.5	31.8215	29.5189	27.2163	24.9137	22.6112	20 3086	18 0060	15 7034	13.4008	11 0982	8.7957	6 4939	4 1990	1 9711	.2840	00002162
8 6	31.8098	29.5072	27.2046	24.9020	22.5995	20.2969	17.9943	15 6917	13 3891	11 0865	8.7840	6 4822	4 1874	1 9604	2790	00001936
8 7	31.7982	29.4957	27.1931	24.8905	22 5879	20 2853	17.9827	15.6801	13 3776	11 0750	8 7725	6 4707	4 1759	1 9498	2742	00001733
8 8	31.7868	29.4842	27.1816	24 8790	22.5765	20 2739	17 9713	15.6687	13 3661	11 0635	8 7610	6 4592	4.1646	1 9393	2694	00001552
8 9	31.7755	29.4729	27.1703	24 8678	22.5652	20 2626	17.9600	15.6574	13 3548	11 0523	8 7497	6 4480	4 1534	1 9290	2647	00001390
9.0	31.7643	29.4618	27.1592	24.8566	22.5540	20 2514	17 9488	15.6462	13 3437	11 0411	8 7386	6 4368	4 1423	1 9187	2602	00001245
9 1	31.7533	29 4507	27.1481	24 8455	22.5429	20.2404	17.9378	15 6352	13 3326	11 0300	8 7275	6 4258	4.1313	1 9087	2557	00001115
9.2	31.7424	29.4398	27.1372	24 8346	22.5320	20 2294	17 9268	15 6243	13 3217	11 0191	8 7166	6 4148	4 1205	1 8987	2513	.000009988
9 3	31.7315	29.4290	27.1264	24.8238	22.5212	20 2186	17.9160	15.6135	13.3109	11.0083	8 7058	6 4040	4.1098	1 8888	2470	000008948
9 4	31.7208	29.4183	27.1157	24.8131	22.5105	20.2079	17.9053	15.6028	13.3002	10 9976	8 6951	6 3934	4.0992	1 8791	2429	.000008018
9.5	31.7103	29.4077	27.1051	24 8025	22.4999	20.1973	17.8948	15.5922	13.2896	10.9870	8 6845	6 3828	4.0887	1.8695	2387	000007185
9.6	31.6998	29.3972	27 0946	24 7920	22.4895	20.1869	17.8843	15.5817	13 2791	10 9765	8 6740	6 3723	4.0784	1.8599	.2347	000006439

Appendix C Continued

N \ u	$N \times 10^{-15}$	$N \times 10^{-14}$	$N \times 10^{-13}$	$N \times 10^{-12}$	$N \times 10^{-11}$	$N \times 10^{-10}$	$N \times 10^{-9}$	$N \times 10^{-8}$	$N \times 10^{-7}$	$N \times 10^{-6}$	$N \times 10^{-5}$	$N \times 10^{-4}$	$N \times 10^{-3}$	$N \times 10^{-2}$	$N \times 10^{-1}$	N
9.7	31.6894	29.3868	27.0843	24.7817	22.4791	20.1765	17 8739	15 5713	13 2688	10.9662	8.6637	6 3620	4.0681	1 8505	2308	000005771
9.8	31.6792	29.3766	27.0740	24.7714	22.4688	20 1663	17.8637	15 5611	13 2585	10 9559	8 6534	6 3517	4.0579	1 8412	2269	000005173
9.9	31.6690	29.3664	27.0639	24.7613	22 4587	20 1561	17.8535	15 5509	13.2483	10 9458	8 6433	6 3416	4 0479	1.8320	2231	000004637

NOTE See page 218 for Theis equation and definitions of terms.

Values of $W(u)$ for u between 1 × 10 [15] and 1 × 10 [1] computed by R G Kazmann assisted by M M Evans U S Geological Survey values for u between 1 × 10 and 9 9 adapted from Tables of Exponential and Trigonometric Integrals.

From Water Supply Paper 887, U.S. Geological Survey, 1942

D. Conversions

APPENDIX D:

TABLE OF UNITS CONVERSION FACTORS

UNIT CONVERSION TABLE

	MULTIPLY	BY	TO OBTAIN
Length	ft mile	.3048 1.609	m km
Area	ft^2 mi^2	.00920 2.590	m^2 km^2
Volume	ft^3 gallon	.02832 .003785	m^3 m^3
Velocity	ft/sec	.3048	m/sec
Discharge	ft^3/sec gal/min	.02832 6.039×10^{-5}	m^3/sec m^3/sec
Hydraulic conductivity	ft/sec gal/day/ft^2	.3048 4.720×10^{-7}	m/sec m/sec
Permeability	ft^2	.09290	m^2
Transmissivity	ft^2/sec gal/day/ft	.09290 1.438×10^{-7}	m^2/sec m^2/sec

Instructor: Charlie

LIST OF PARTICIPANTS

U.S. ENVIRONMENTAL PROTECTION AGENCY

WELLHEAD PROTECTION AREA DELINEATION TRAINING COURSE

Fairfax, Virginia
August 23 - 25, 1988

PARTICIPANT NAME	AFFILIATION	ADDRESS	AREA CODE AND TELEPHONE NUMBER
Dale Albeck	Broome Co. Health Dept. N.Y.S.	1 Wall Street Binghamton, NY 13901	607/772-2887
Greg Anderson	Maryland MDE-Water Supply	201 W. Preston Street Baltimore, MD 21201	301/225-6368
Bill Balfour	VA Water Control Board	2111 N. Hamilton Richmond, VA 23230	804/367-6345
Seymour Bayuk	Dept. of Utilities	7409 BNA Blvd., NW Glen Burnie, MD 21061	301/760-7740
Phil Cherry	DE Dept. of Natural Resources	89 Kings Highway Dover, DE 19901	302/736-4793
Gary Chirlin	Chirlin & Assoc., Inc.	18 Anamosa Ct. Rockville, MD 20855	301/258-0220
Bob Dundas	DE Dept. of Natural Resources	89 Kings Highway Box 1401 Dover, DE 19901	302/736-4793
Jeff Featherstone	DE River Basin Comm.	25 St. Police Dr. West Trenton, NJ 08628	609/883-9500
Karen Fitzmaurice	Univ. of KY	148 Walton Ave. 233 Mining and Mineral Research Building Lexington, KY 40508	606/255-4649
Richard Fox	Joint Conserv. Committee	Box 254, Harrisburg, PA 17120	717/787-7570
Jim Gerhart	U.S.G.S.	208 Carroll Bldg. 8600 Lasalle Rd. Towson, MD 21204	301/828-1535

PARTICIPANT NAME	AFFILIATION	ADDRESS	AREA CODE AND TELEPHONE NUMBER
Keith Harner	Dover Township	2480 West Canal Rd. Dover, PA 17315	717/292-3634
✓ Don ~~Klintz~~ Kunty	WV Health Dept.	1800 Washington St., E Charleston, WV 25305	304/348-2981
Cindy Kranz	EPA	1 Wall St. ~~Binghamton, NY 13901~~	215/597-8399
Ben Lacy	EPA	841 Chestnut St. Phil., PA 19107	215/597-9058
Jill Larson	EPA	Headquarters	202/245-3716
✓ Joseph Lee	DER	PA DER, BCEC 2nd Floor Exec. House Harrisburg, VA 17120	717/787-9561
✓ Ron Lilly	Lord Fx. Planning Dist. Comm.	103 E. Sixth St. Front Royal, VA 22630	703/635-4146
Paula Luborsky	EPA	841 Chestnut St. Phil., PA 19107	215/597-2786
Larry Mata	EPIC	P.O. Box 1575-EPA Vint Hill Farms Station Warrenton, VA 22186	703/349-8995
Cristina Morrison	EPA	Headquarters	202/475-7057
David Nelms	U.S.G.S.	3600 W. Broad St. Room 606 Richmond, VA 23230	804/771-2427
✓ Robert Paul	WV Health Dept.	1800 Washington ST., E Charleston, WV 25305	304/348-2981
Linda Silversmith	League of Women Voters of Maryland	260 New Mark Esp. Rockville, MD 20850	301/294-0566
Mary Sitton	EPA	P.O. Box 1575 Vint Hill Farms Station Warrenton, VA 22186	703/349-8975
Ron Slotkin	Broome Co. Health Dept. N.Y.S	1 Wall St. Binghamton, NY 13901	607/772-2887

PARTICIPANT NAME	AFFILIATION	ADDRESS	AREA CODE AND TELEPHONE NUMBER
Bob Thranson	EPA	Headquarters	202/382-7103
Mary Tieman	Cong. Research Service	1507 Baltimore Rd. Alexandria, VA 22308	202/282-5937
Tom Wall	EPA	401 M St., NW Permits Div. (EN-330) Washington, DC 20460	202/475-9515
Ava Nelson Zandi	EPA	841 Chestnut St. Phil., PA 19107	215/597-9388

SOFTWARE DEMONSTRATED DURING WELLHEAD PROTECTION AREA DELINEATION TRAINING COURSE

THWELLS

Source: International Ground Water Modeling Center
Holcomb Research Institute
Butler university
Indianapolis, IN 46208

Phone: (317) 283-9458 Contact: Stan Williams

Use: Drawdown calculations (Theis solution)

Cost: $50

RESSQ

Source: International Ground Water Modeling Center
Holcomb Research Institute
Butler university
Indianapolis, IN 46208

Phone: (317) 283-9458 Contact: Stan Williams

Use: Zone of Contribution, Zone of Transport (Analytical)

Cost: $100

GWPATH

Source: Illinois State Water Survey
2204 Griffith Dr.
Champaign, IL 61820-7495

Phone: (217) 333-6775 Contact: John Shafer

Use: Particle Tracking, Zone of Transport (Numerical)

Cost: $125