LECTURE 9

PUMP-AND-TREAT SYSTEMS

Pump and Treat Technology

Goals:

1. Hydraulic containment of contaminated ground water

   Prevent contamination from spreading to uncontaminated areas

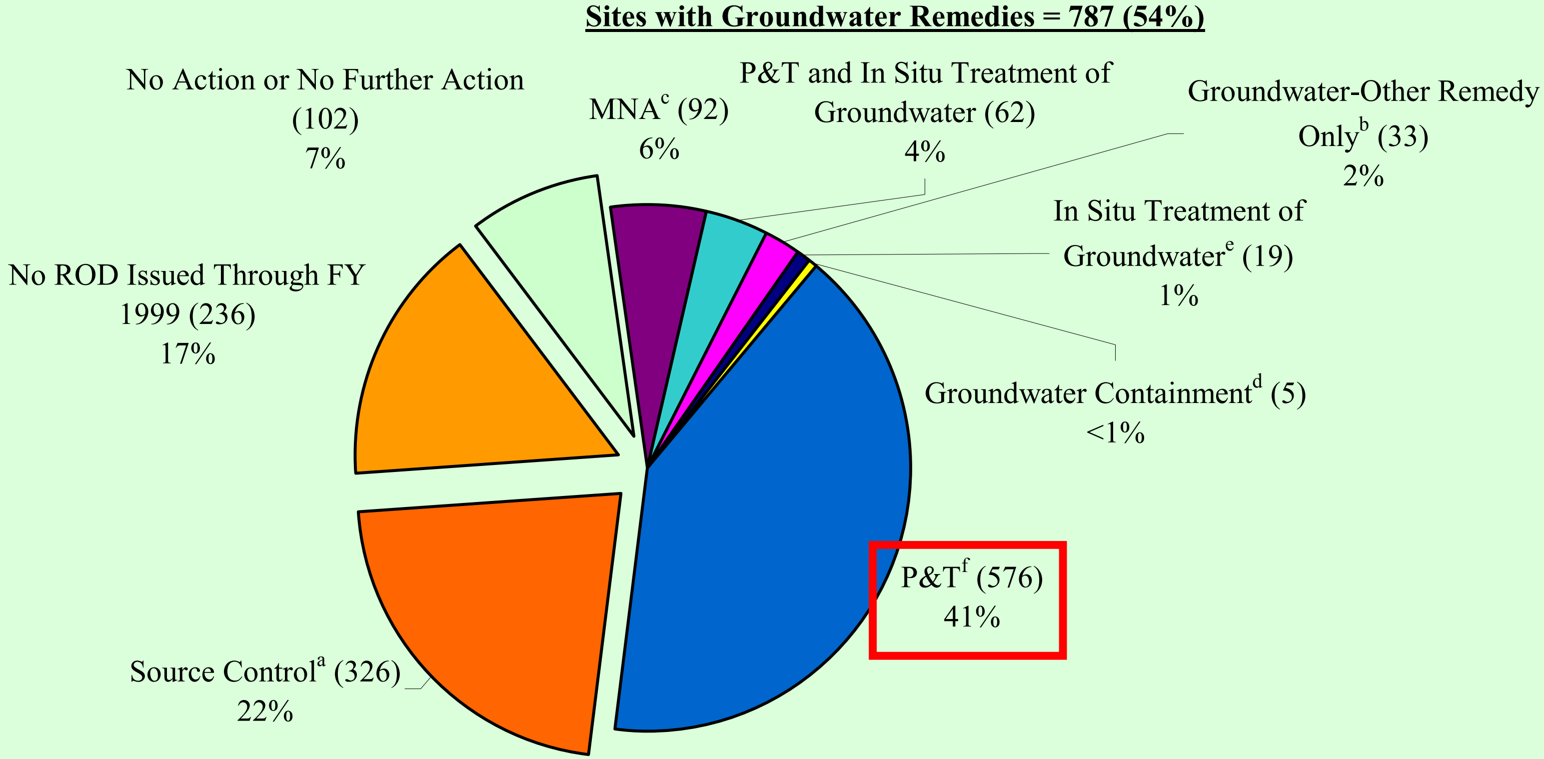
2. Treatment of contaminated ground water

   Reduce concentrations in ground water to below cleanup standards (MCLs)

Reference: U.S. EPA, 1996. Pump-and-Treat Ground-Water Remediation: A Guide for Decision Makers and Practitioners. Report Number EPA/625/R-95/005. U.S. EPA, Office of Research and Development, Washington, DC.

Figure 2. Remedy Types Selected at Sites on the National Priorities List (FY 1982 - FY 1999)

Total Number of Sites = 1,451



Sources: 1, 2, 3, 4, 5, 6, 8. Data sources are listed in the References and Data Sources Section on p. 17.
P&T = Pump and treat
MNA = Monitored natural attenuation

Source: U.S. EPA, 2002. Groundwater Remedies Selected at Superfund Sites. Report No. EPA-542-R-01-022. Office of Solid Waste and Emergency Response, U.S. EPA, Washington, D.C. January 2002.

Principles of Pump and Treat

$Q = K\,i\,A$ = flow in aquifer defined by Darcy's Law $[L^3/T]$

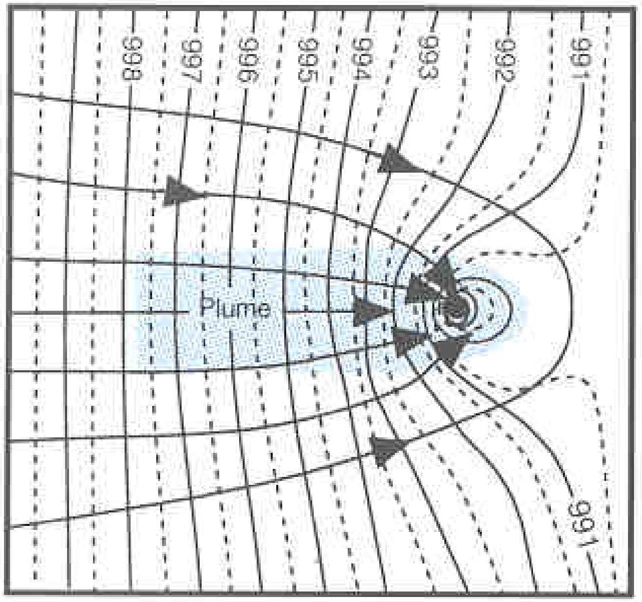
- K = hydraulic conductivity $[L/T]$
- i = hydraulic gradient $[L/L]$
- A = cross sectional area in aquifer $[L^2]$

C = concentration in the ground water $[M/L^3]$

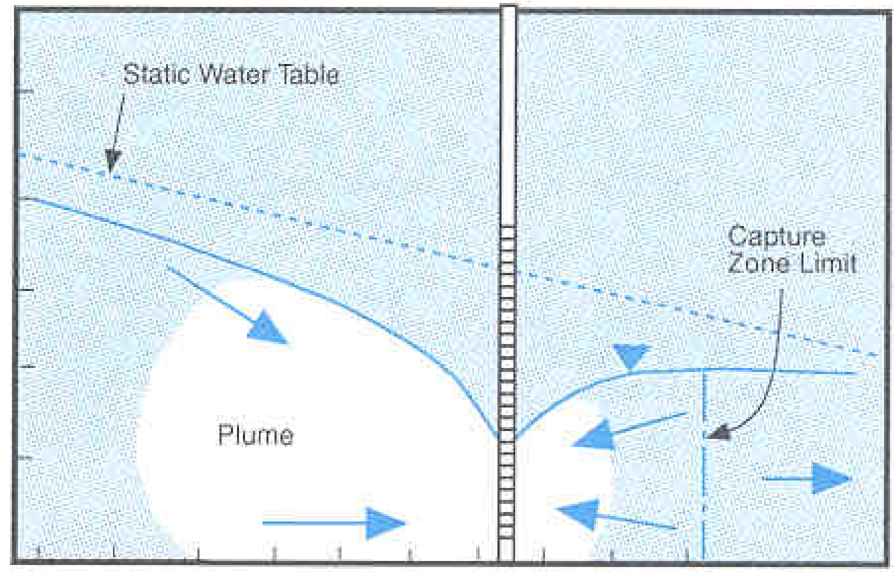
QC = mass flux $[M/T]$

$= K\,i\,A\,C$

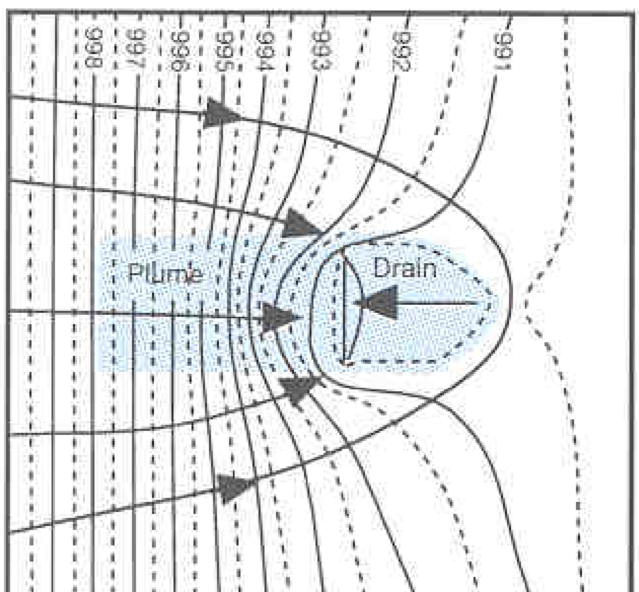
Well



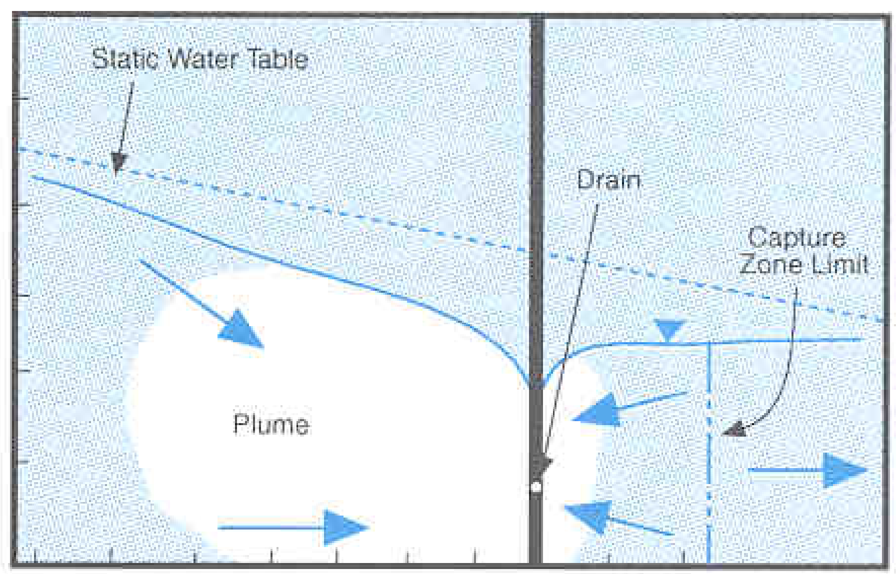
(a)



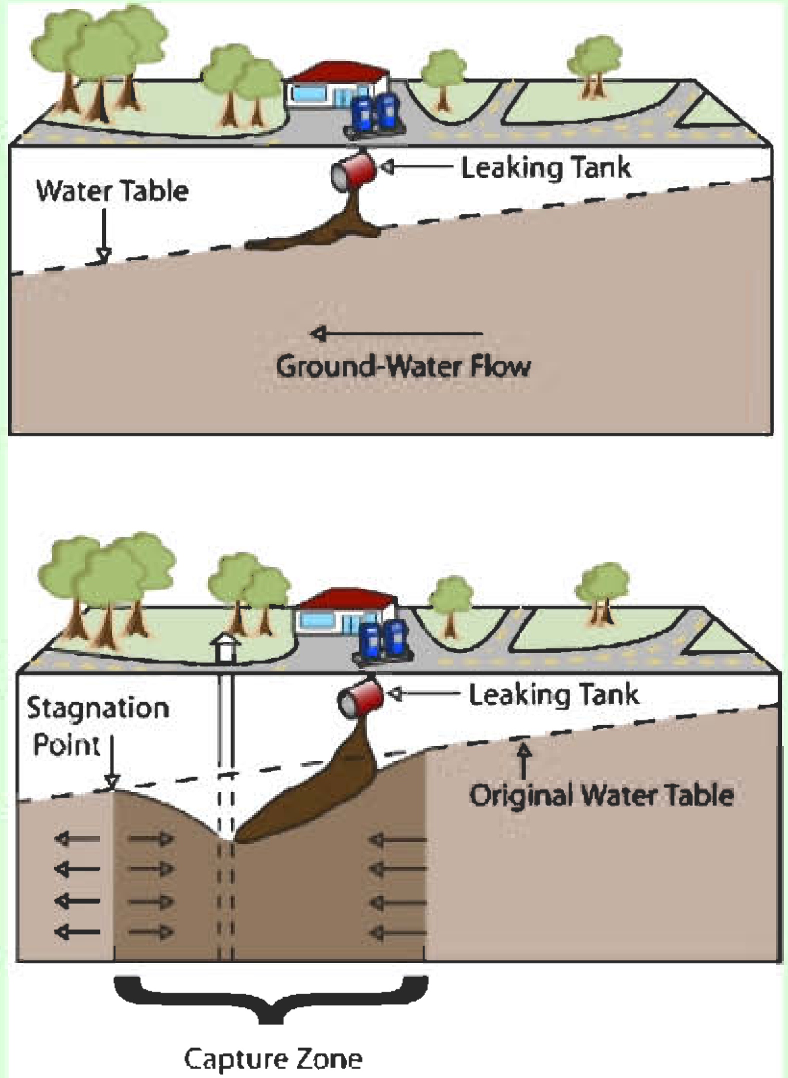
Trench



(b)



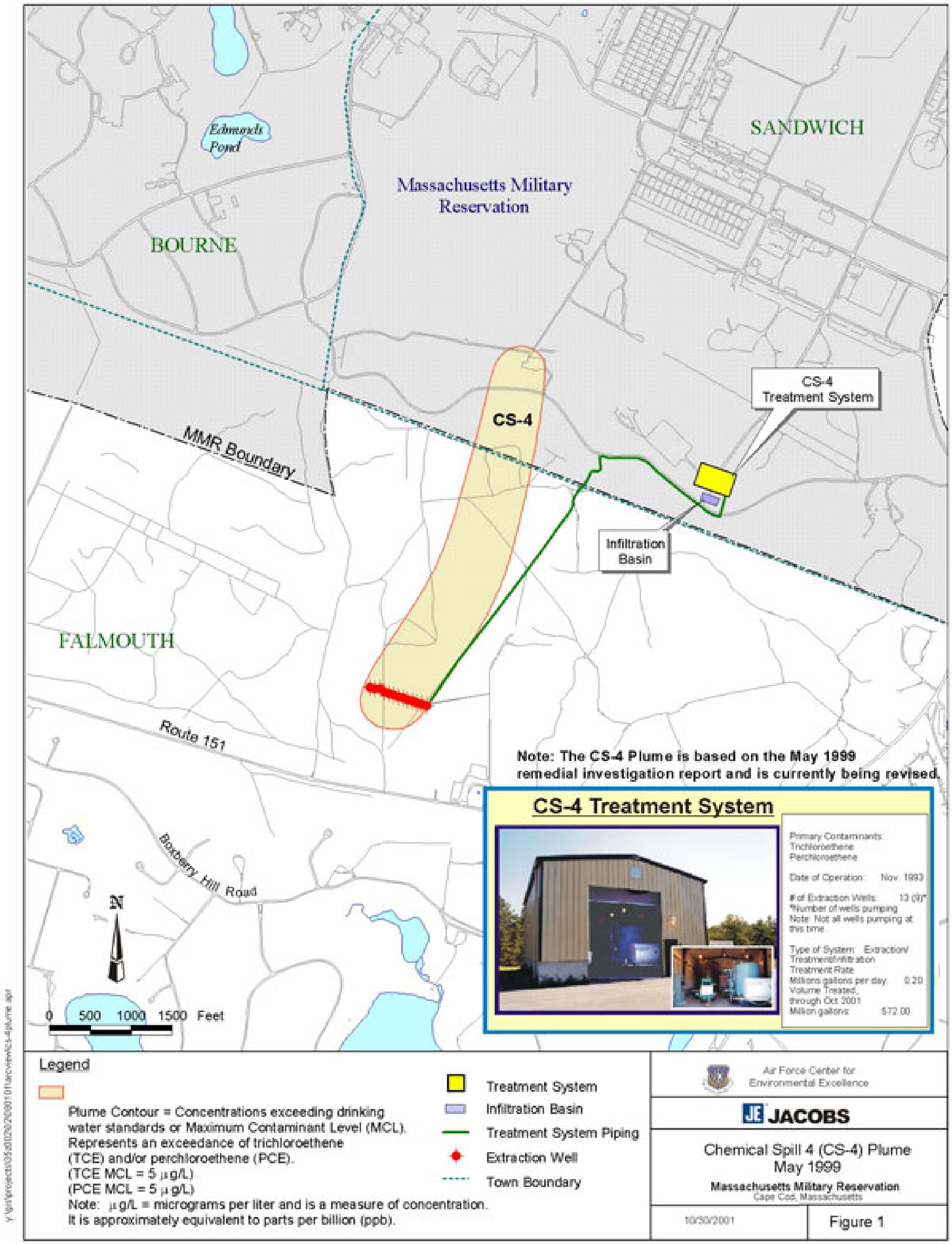
U.S. EPA, 1996. Pump-and-Treat Ground-Water Remediation: A Guide for Decision Makers and Practitioners. Report Number EPA/625/R-95/005. U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C. July 1996.



Cross section along the *x* axis showing the cone of depression for a single extraction well superimposed on the regional water table.

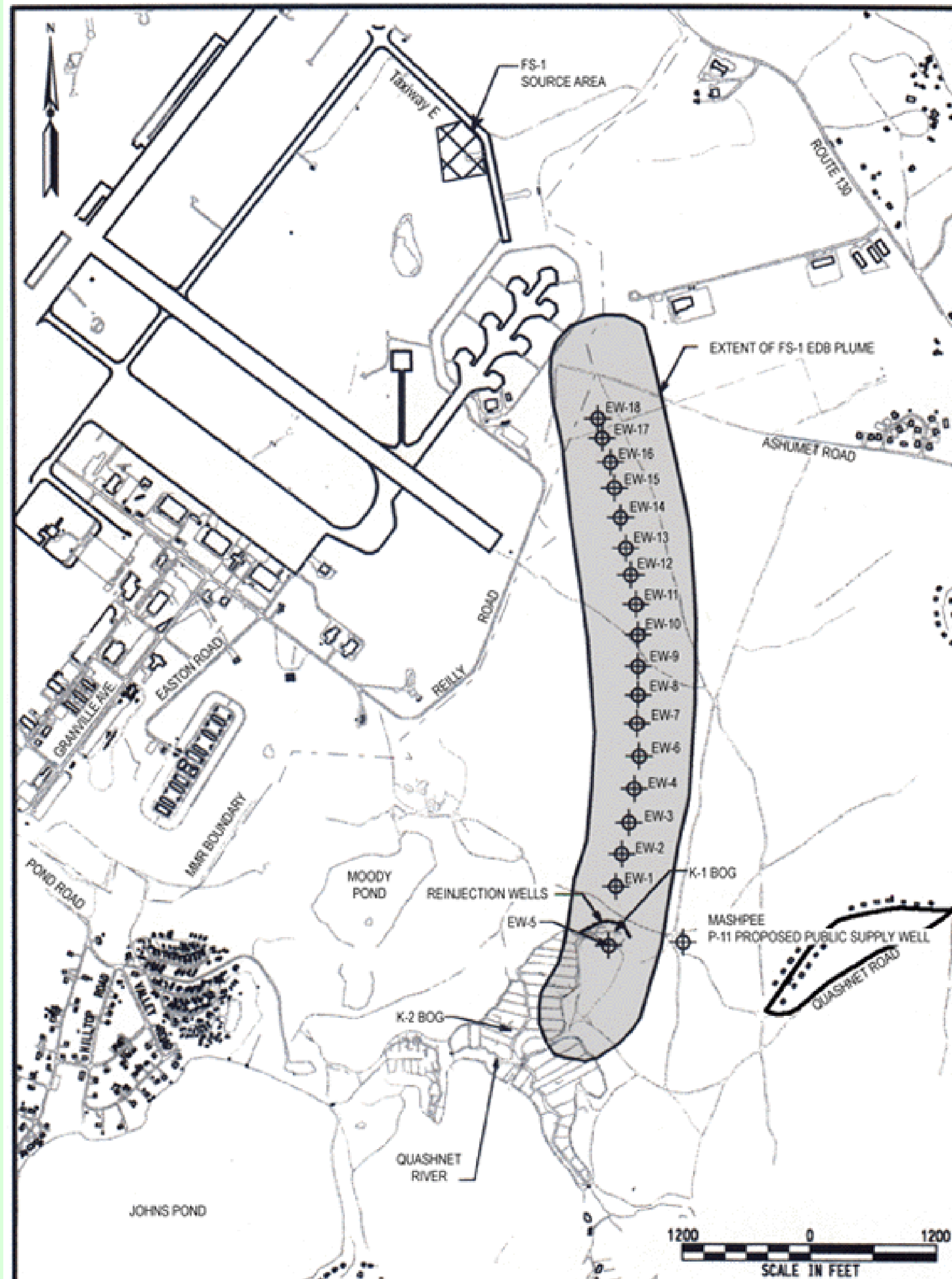
Image adapted from: Fetter, C.W., 1999. *Contaminant Hydrogeology*, Second Edition. Prentice Hall, Upper Saddle River, New Jersey.

MMR <u>Containment</u> of CS-4 Plume by Pump & Treat



Source: http://www.mmr.org/irp/plans/cip/maps/cs4_02.htm

MMR Cleanup Proposal for FS-1 Plume by Pump & Treat



Alternative 3B: Axial and Leading Edge Extraction, Treatment and Reinjection Discharge.

Source: http://www.mmr.org/cleanup/plumes/fs1/fs1699.htm

LaPlace's Equation for 2-D Flow in a Confined Aquifer

$$\mathbf{T}\left(\frac{\partial^2\phi}{\partial \mathbf{x}^2}+\frac{\partial^2\phi}{\partial \mathbf{y}^2}\right)=\mathbf{S}\frac{\partial\phi}{\partial \mathbf{t}}$$

T = transmissivity
S = storage coefficient
ϕ = potential function

$$\delta\mathbf{Q}=-\mathbf{T}\,\delta\mathbf{y}\frac{\partial\phi}{\partial \mathbf{x}}$$

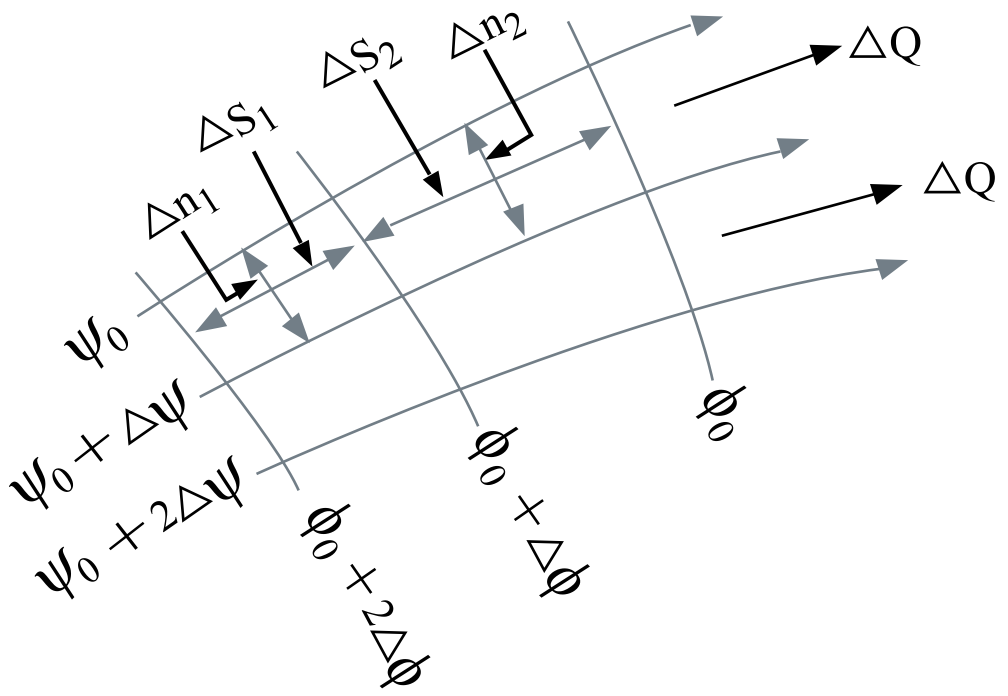
δQ = flow increment

$$\frac{\partial\phi}{\partial \mathbf{x}}=\frac{\partial\psi}{\partial \mathbf{y}} \qquad \frac{\partial\phi}{\partial \mathbf{y}}=-\frac{\partial\psi}{\partial \mathbf{x}}$$

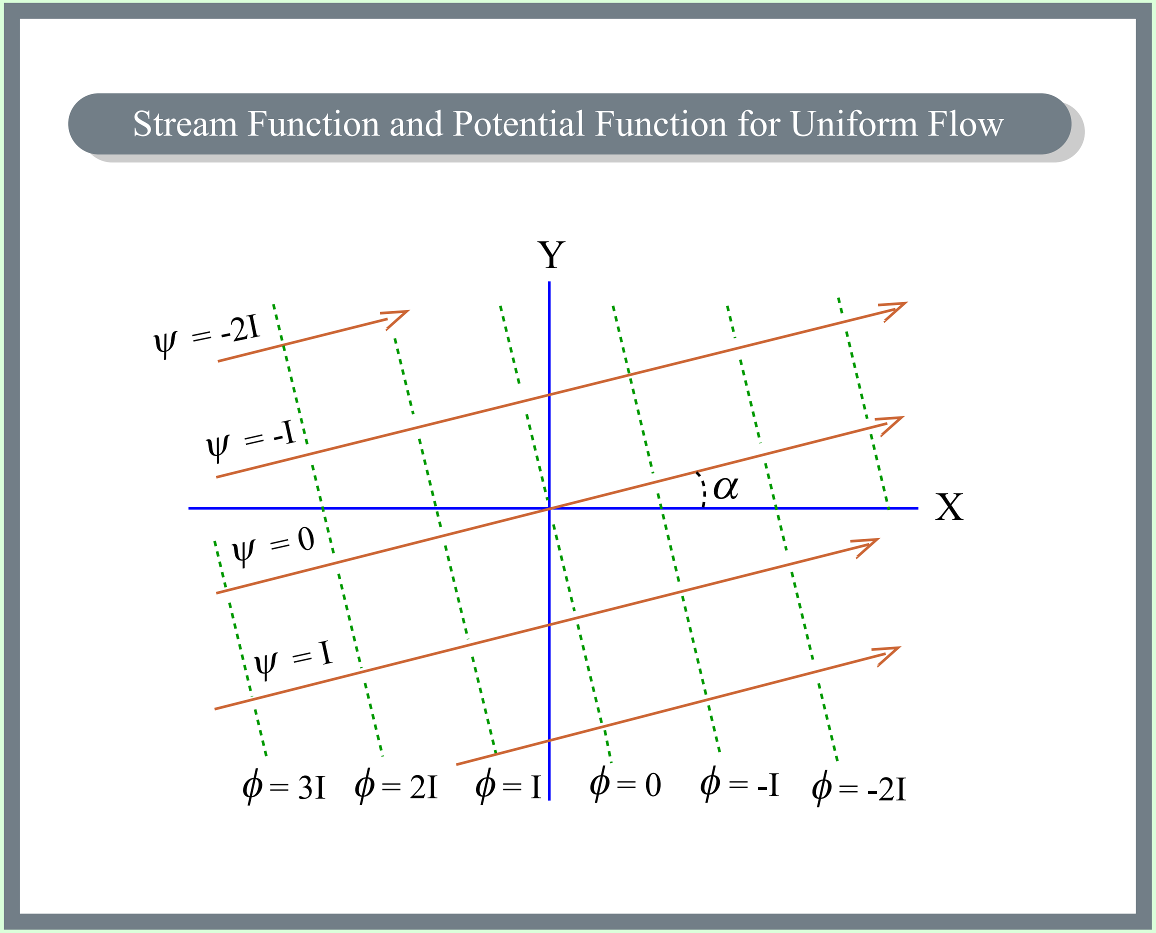
ψ = streamfunction

Flow Net Construction

A Portion of a Flow Net



Uniform Flow



Potential function

$$\phi = -I\left(x\cos\alpha + y\sin\alpha\right)$$

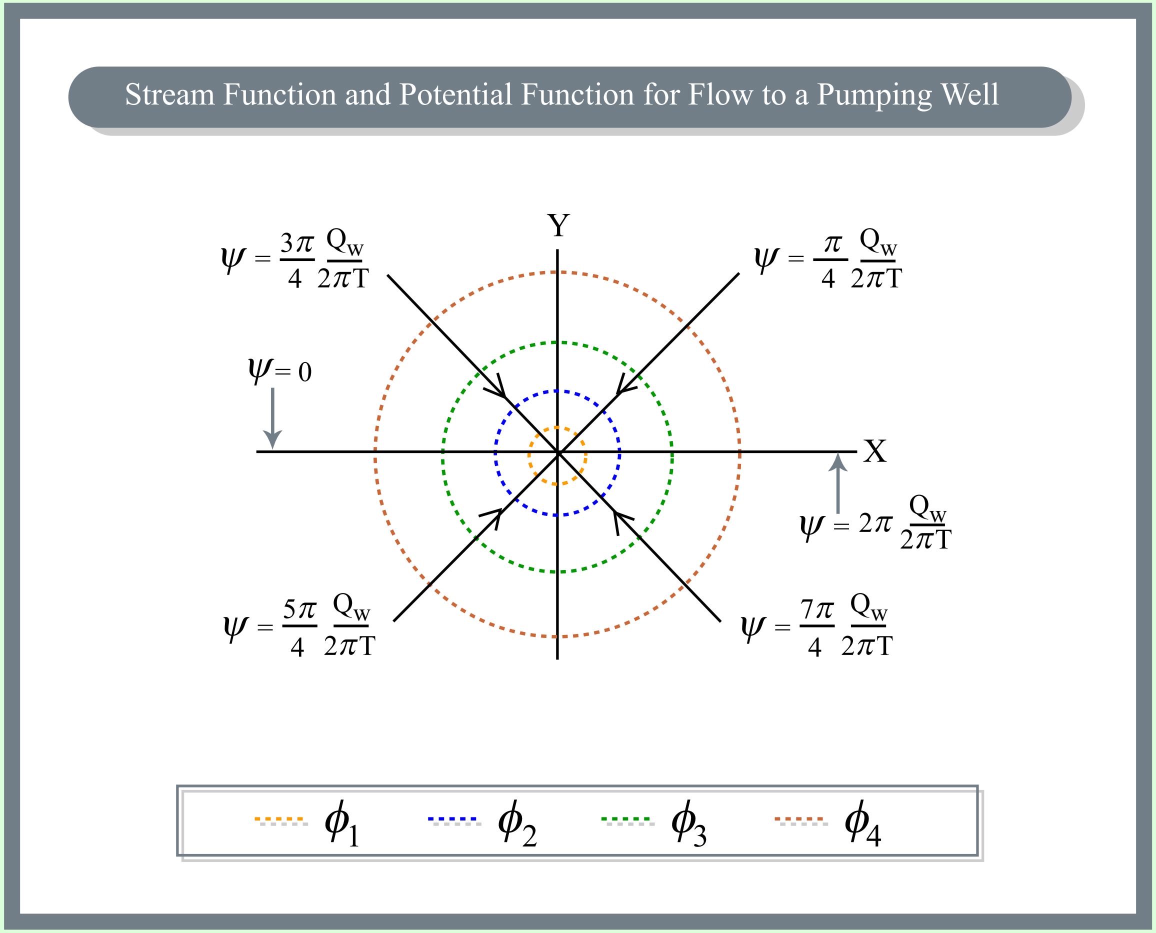
Stream function

$$\psi = -I\left(y\cos\alpha - x\sin\alpha\right)$$

$$I = \frac{q}{T}$$

q = flow per unit width
T = tranmissivity

Flow to Well



Potential function

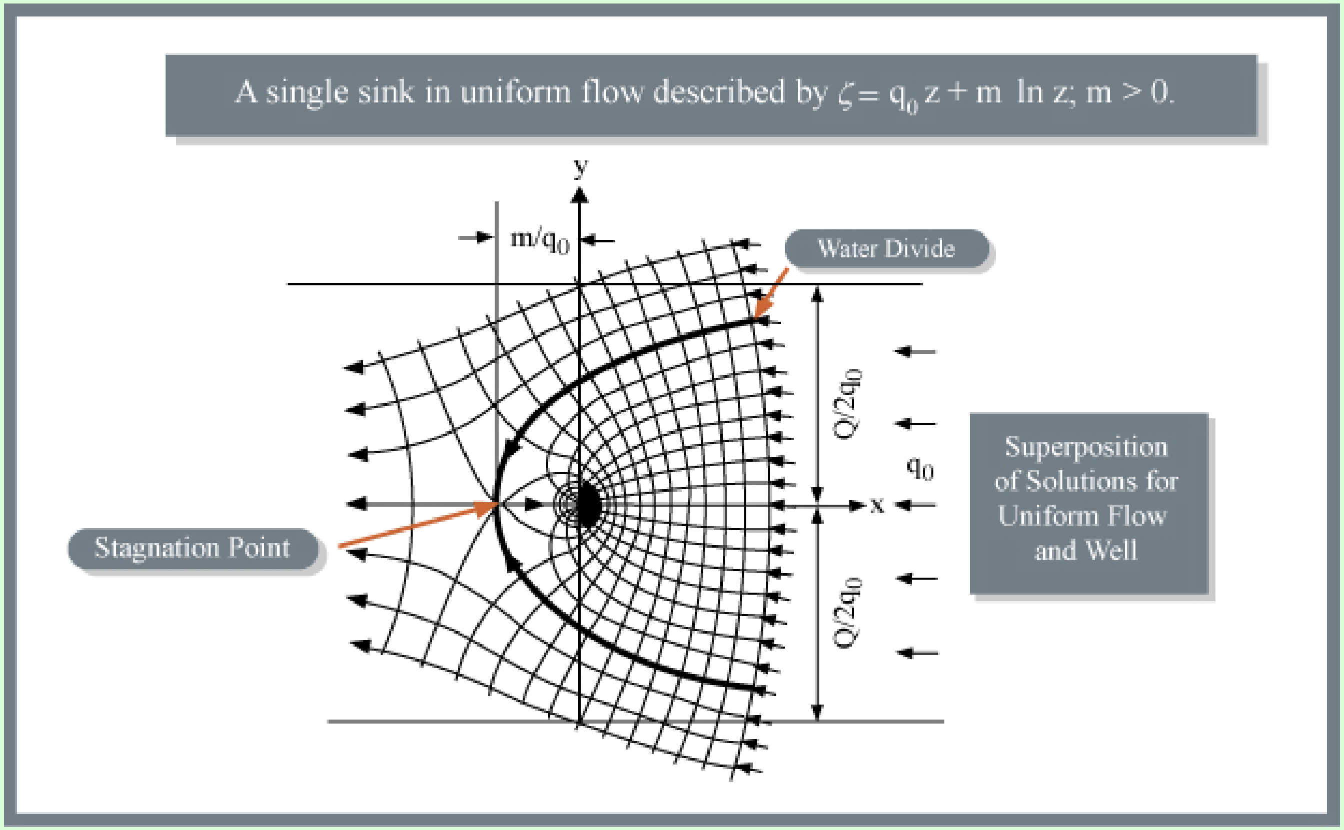
$$\phi = \frac{Q_w}{4\pi T} \ln\left[\frac{(x-x_0)^2+(y-y_0)^2}{r_w^{\,2}}\right]$$

Stream function

$$\psi = \frac{Q_w}{2\pi T} \tan^{-1}\left[\frac{y-y_0}{x-x_0}\right]$$

r_w = well radius
x_0, y_0 = well location

Flow to Well in Uniform Flow



Superposition of solutions for uniform flow and well

Image adapted from: Bear, J. *Hydraulics of Groundwater*. New York: McGraw-Hill International Book Company, 1979.

Flow to Well in Uniform Flow

$$\phi = -I(x\cos\alpha + y\sin\alpha) + \sum_{i=1}^{n}\left[\frac{Q_i}{4\pi T}\ln\frac{(x-x_i)^2+(y-y_i)^2}{r_i^2}\right]$$

$$\psi = -I(y\cos\alpha - x\sin\alpha) + \sum_{i=1}^{n}\left[\frac{Q_i}{2\pi T}\tan^{-1}\frac{y-y_i}{x-x_i}\right]$$

n = number of wells
x_i, y_i = location of well i

Note: solution is implicit in x and y

Capture zone

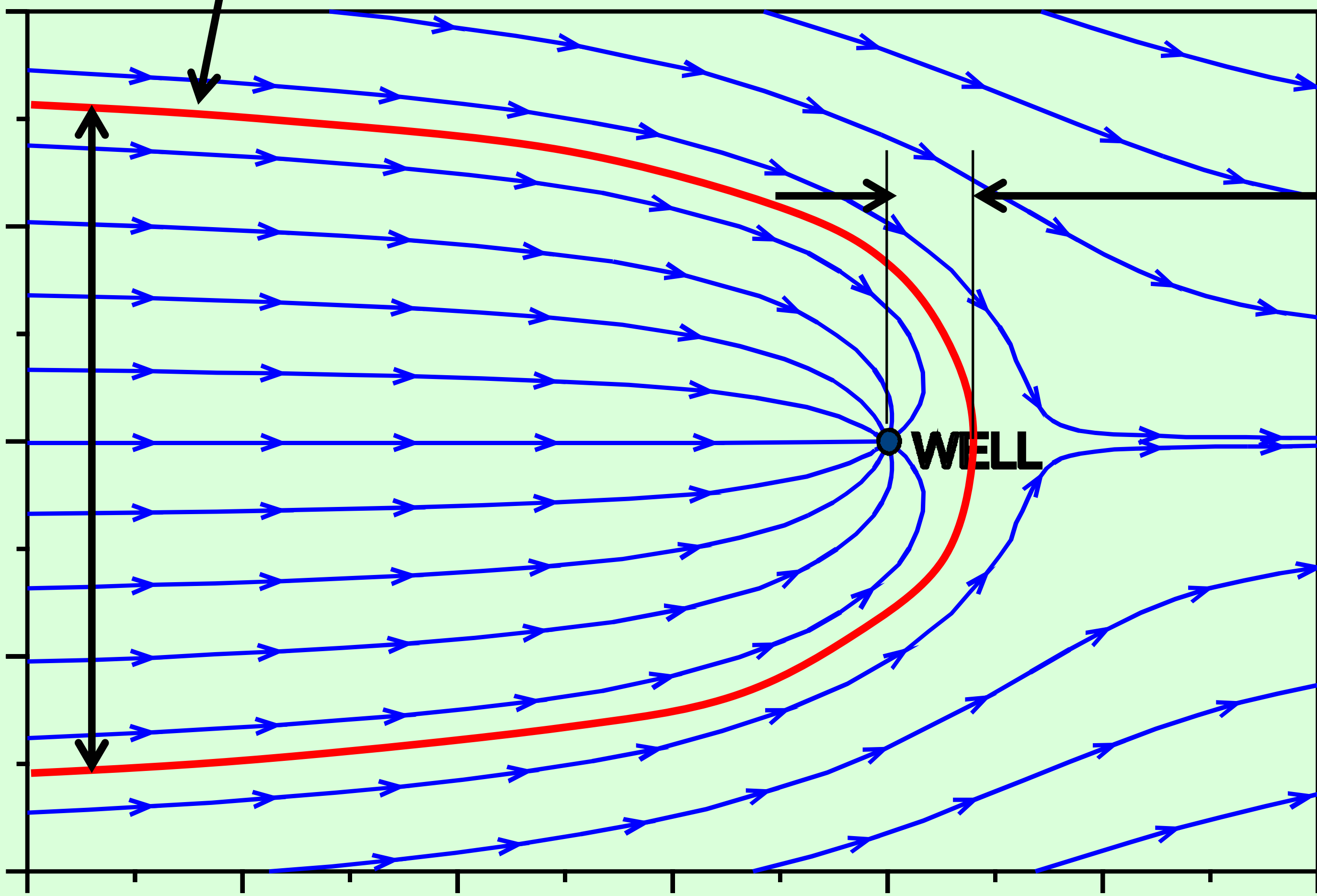
$$\frac{y}{x} = \pm \tan\left(\frac{2\pi T i y}{Q_w}\right)$$

Stagnation point

$$x_s = \frac{Q_w}{2\pi T i}$$

Capture width

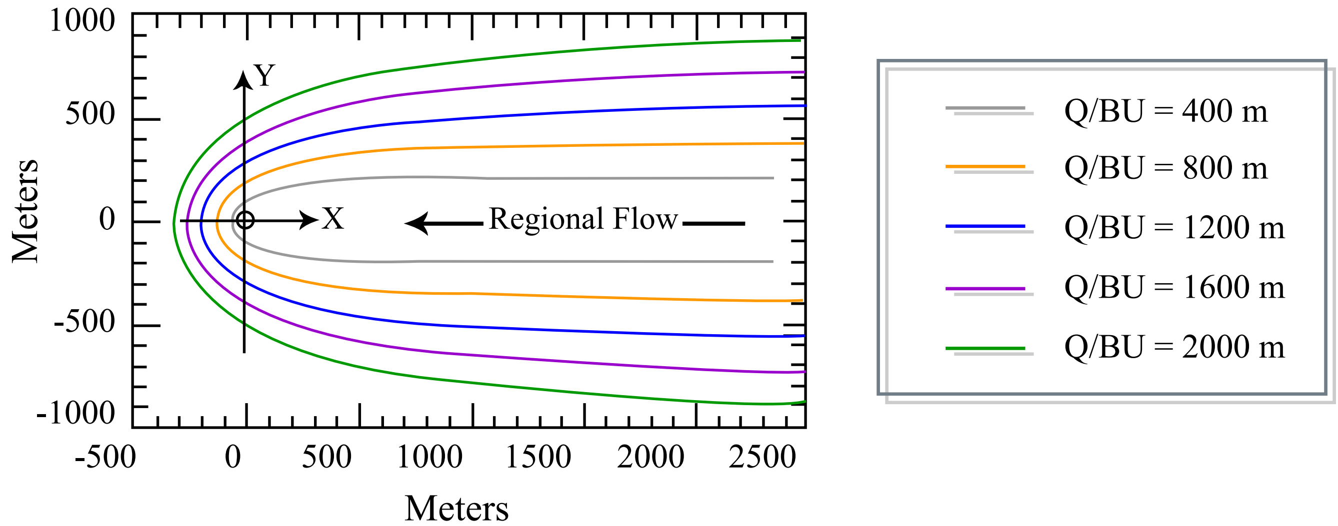
$$W = \frac{Q_w}{T i}$$



Note change in notation:

BU = Ti

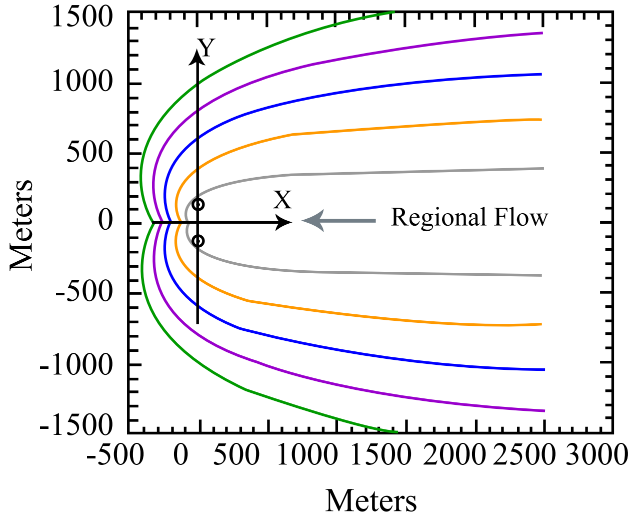
Single-Well Capture-Zone Type Curves



A set of type curves showing the capture zones of a single pumping well located at the origin for various values of (Q/BU).

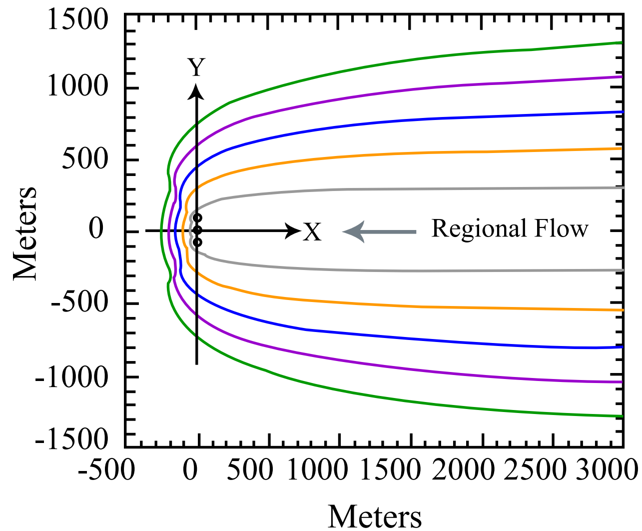
Adapted from: Javendel, I. and C.-F. Tsang. "Capture-Zone Type Curves: A Tool for Aquifer Cleanup." *Ground Water* 24, no. 5 (1986): 616-625.

Double-Well Capture-Zone Type Curves



1: A set of type curves showing the capture zones of two pumping wells located on the y-axis for various values of (Q/BU).

Three-Well Capture-Zone Type Curves



2: A set of type curves showing the capture zones of three wells located on the y-axis for various values of (Q/BU).

Adapted from: Javendel, I. and C.-F. Tsang. "Capture-Zone Type Curves: A Tool for Aquifer Cleanup." *Ground Water* 24, no. 5 (1986): 616-625.

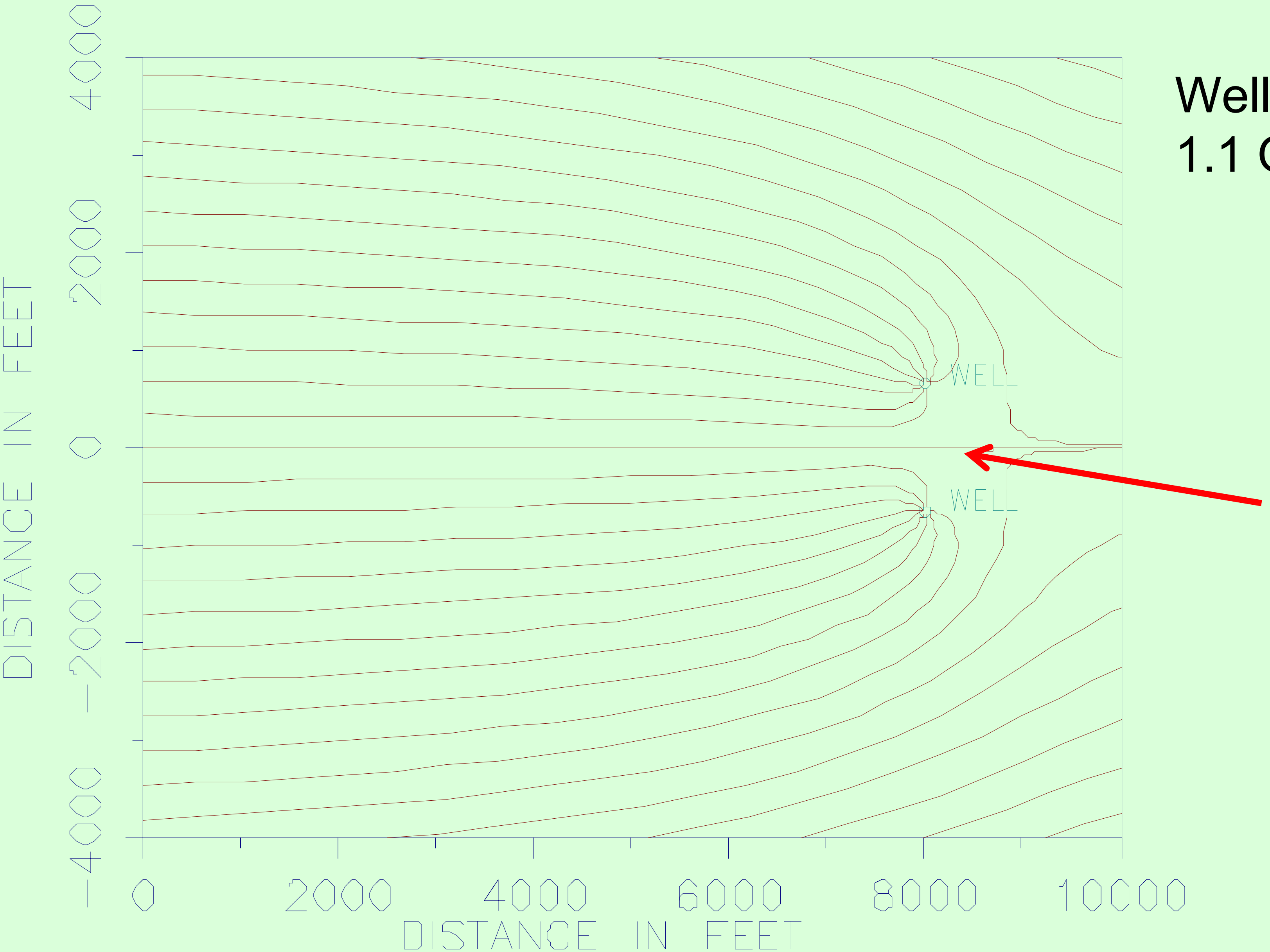
Note: <u>each</u> well has pumping rate Q

Some Characteristic Distances in Flow Regimes for One, Two, and Three Pumping Wells Under a Uniform Regional Ground-Water Flow

Number of Pumping Wells	Optimum Distance Between Each Pair of Pumping Wells	Distance Between Dividing Streamlines at the Line of Wells	Distance Between Streamlines Far Upstream from the Wells
One	—	$\frac{Q}{2BU}$	$\frac{Q}{BU}$
Two	$\frac{Q}{\pi BU}$	$\frac{Q}{BU}$	$\frac{2Q}{BU}$
Three	$\frac{\sqrt[3]{2}\,Q}{\pi BU}$	$\frac{3Q}{2BU}$	$\frac{3Q}{BU}$

Note: each well has pumping rate Q

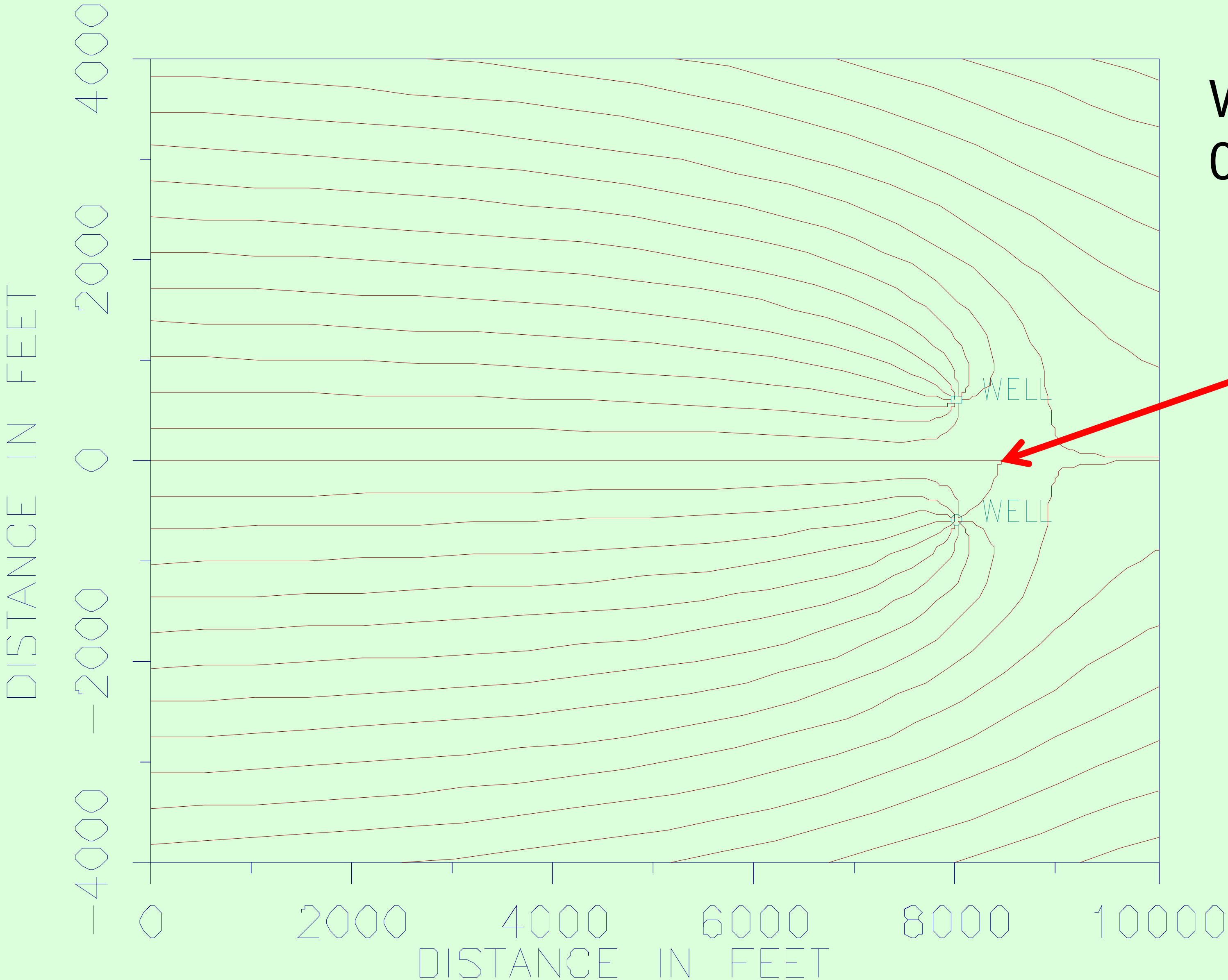
Well separation = 1.1 Q/pTi



Some flow gets through

AQUIFER FLOW STREAMLINES - INCREMENTS OF 50. GPM

Well separation = 0.94 Q/pTi



AQUIFER FLOW STREAMLINES – INCREMENTS OF 50. GPM

All flow captured (in theory)

Flow Chart for Capture Well Design

Flow Chart and Equations for Basic Containment Strategy

Equations

1) $Q = TI\,W$

2) $x_0 = -Q/(2\pi\,TI)$

3) $y = -x \tan\left(\frac{2\pi\,TI}{Q}\,y\right)$

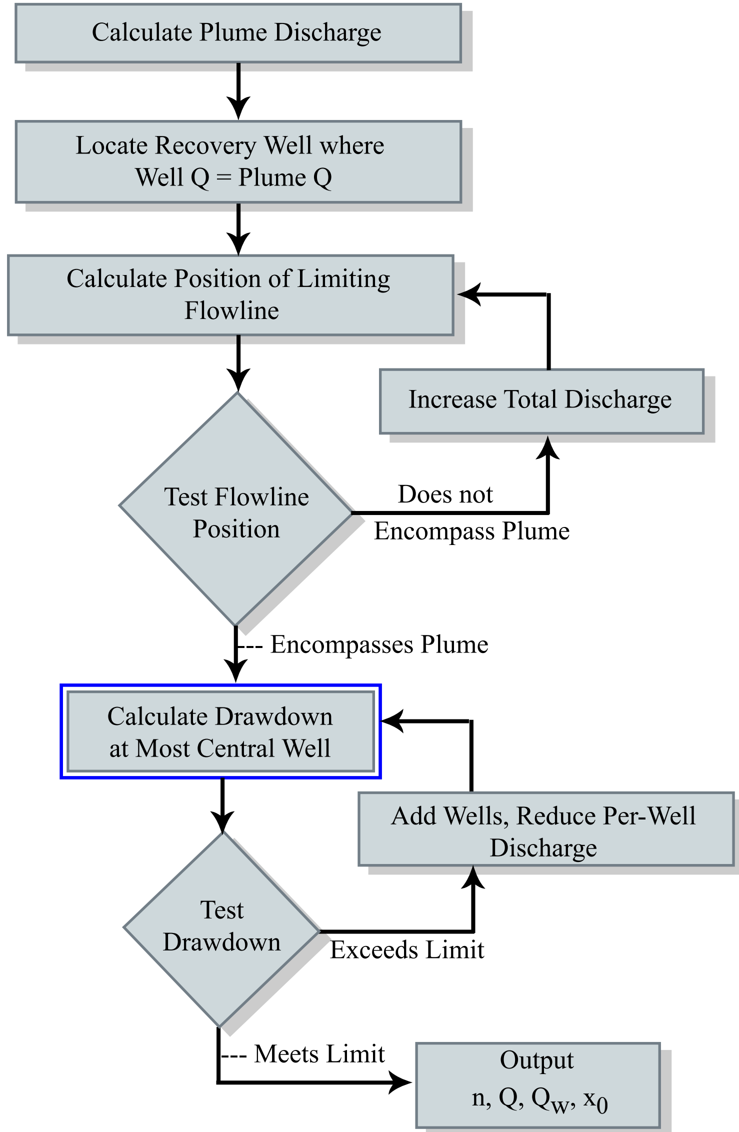
4) $Q = Q + \Delta Q$

5) $s = \frac{Q_w}{4\pi T}\,W(u)$

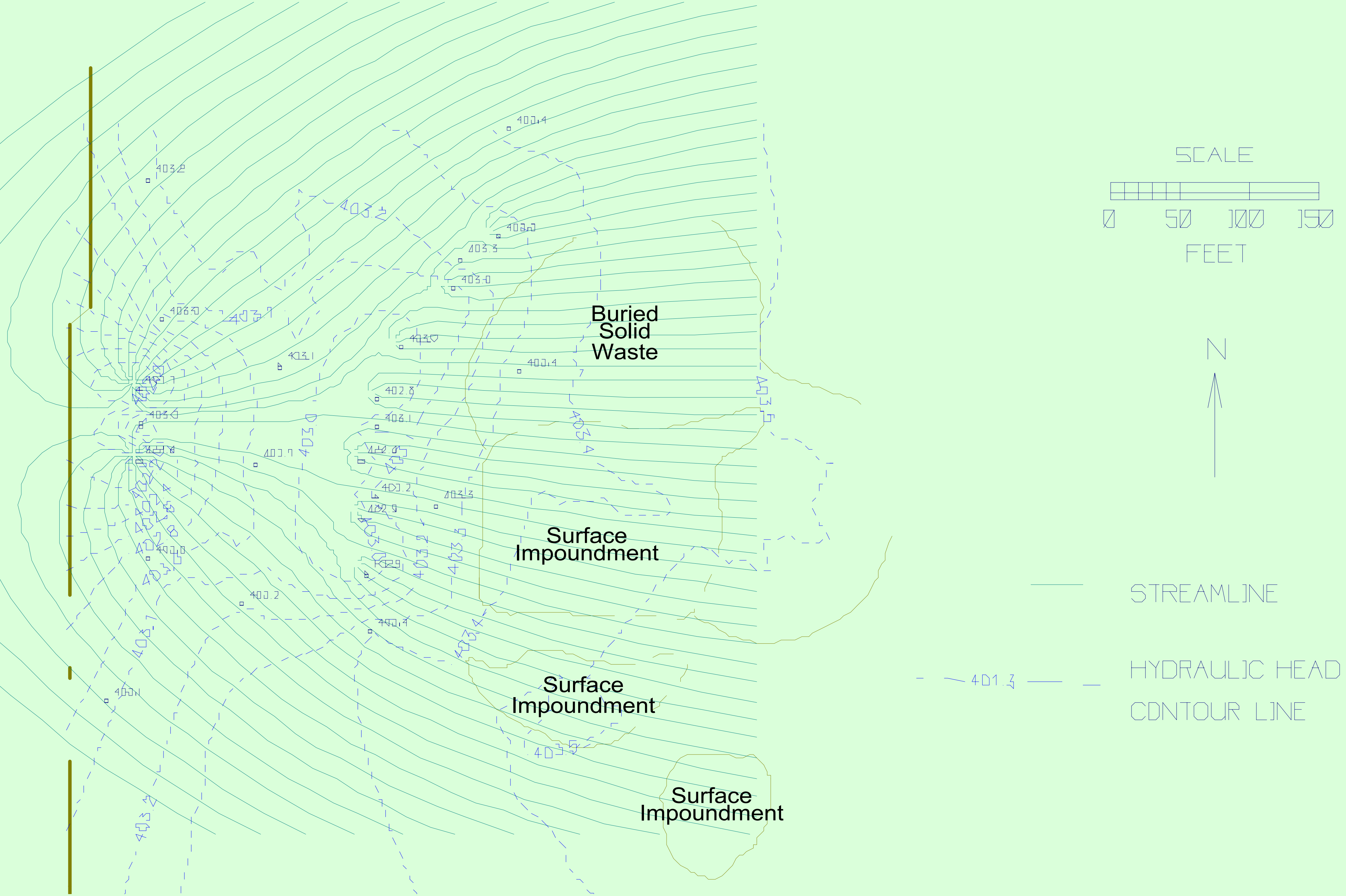
6) $Q_w = \frac{Q}{n}$

7) $n = n+1$

Flow Chart

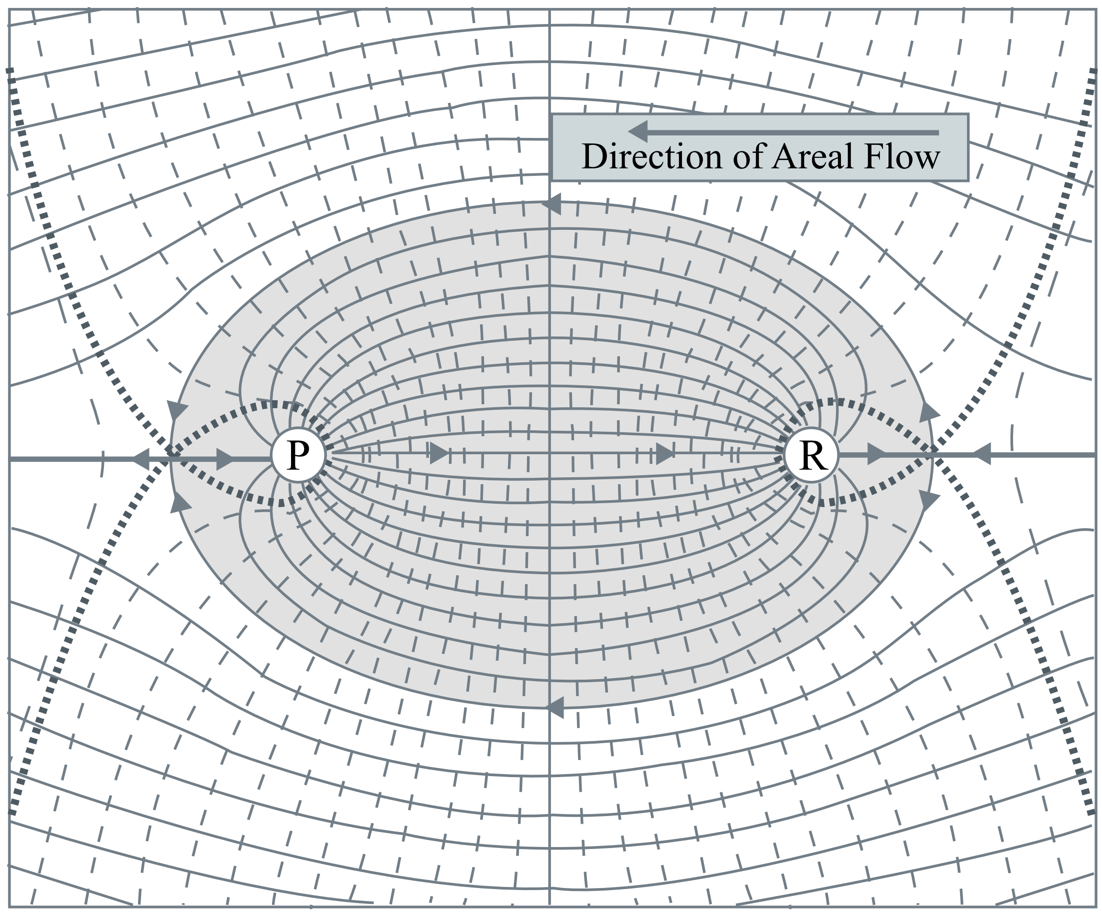


Adapted from: Lundy, D. A. and J. S. Mahan. "Conceptual Designs and Cost Sensitivities of Fluid Recovery Systems for Containment of Plumes of Contaminated Groundwater." In *National Conference on Management of Uncontrolled Hazardous Waste Sites, November 29-December 1*. Hazardous Materials Control Research Institute, Washington, DC, 1982.



Buried Solid Waste
Surface Impoundment
Surface Impoundment
Surface Impoundment
SCALE
0 50 100 150
FEET
N
STREAMLINE
HYDRAULIC HEAD CONTOUR LINE

Injection and withdrawal well pair



Adapted from: Bear, J. *Hydraulics of Groundwater*. New York: McGraw-Hill International Book Company, 1979.

Optimizing Pump-and-Treat

Optimization reduces pumping rate by 10 to 40%

(Richard Peralta, cited by Greenwald, R., 1999. Hydraulic Optimization Demonstration For Groundwater Pump-and-Treat Systems, Volume 1: Pre-optimization Screening (Method and Demonstration). Report Number EPA/542/R-99/011A. Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C. December 1999.)

Optimization requires modeling – costs $5K +

Therefore, determine potential savings before going through optimization exercise

2-minute Intro to Linear Programming

Consider an air cargo fleet with:

- X_1 large aircraft, capable of carrying 11 tons
- X_2 small aircraft, capable of carrying 4 tons

For service:

- Large aircraft require 3 hours of operating crew time and 10 hours of ground crew time
- Small aircraft require 5 and 2 hours of same

Available crew hours:

- 150 hours operating crew
- 120 hours ground crew

Linear programming formulation

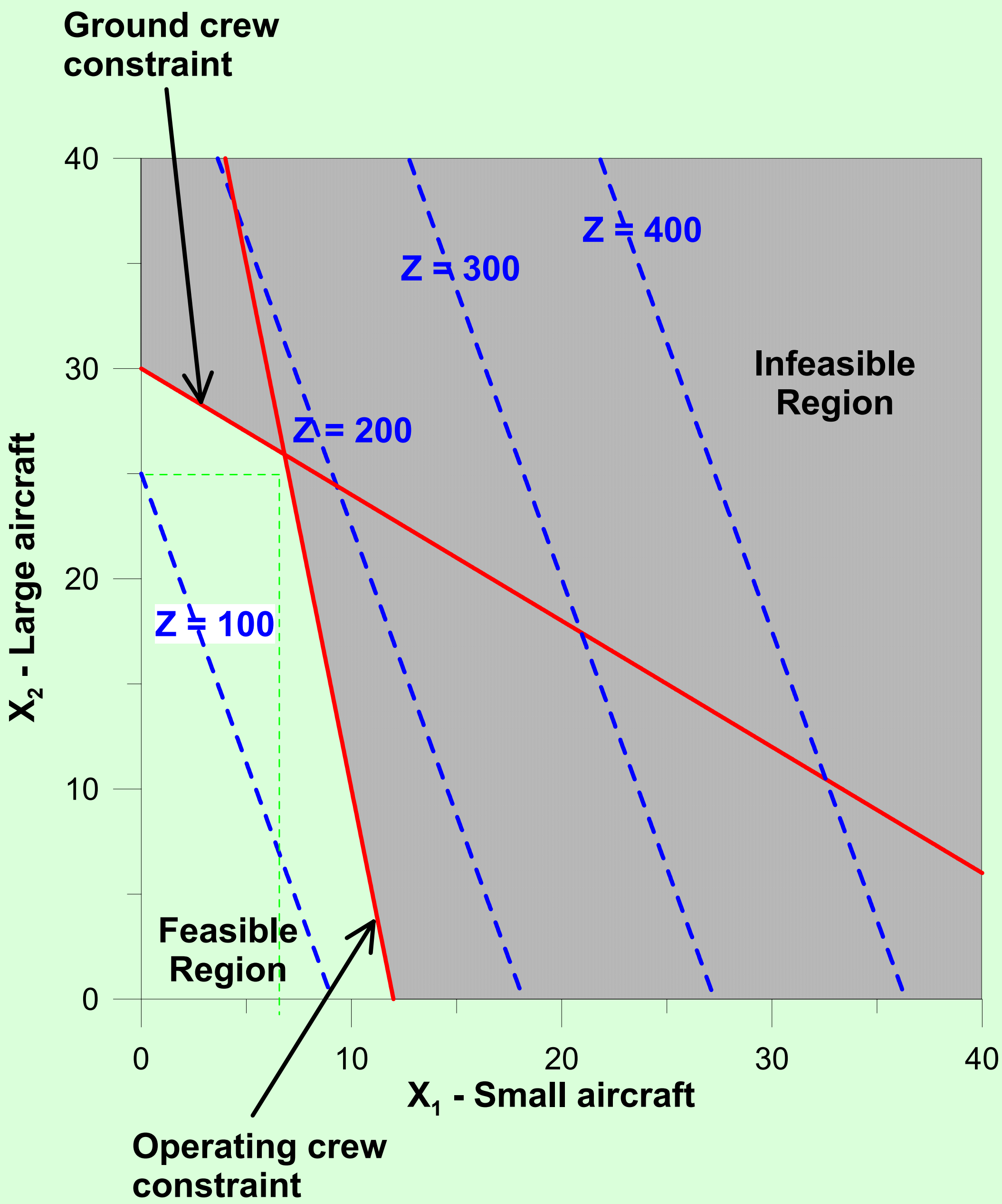
Objective function--maximize cargo moved:

$Z = 11\ X_1 + 4\ X_2$

Subject to constraints:

$3\ X_1 + 5\ X_2 \leq 150$ Operating crew availability

$10\ X_1 + 2\ X_2 \leq 120$ Ground crew availability



Ground crew
constraint
Z = 400
Z = 300
Z = 200
Z = 100
Infeasible
Region
Feasible
Region
Operating crew
constraint
X2 - Large aircraft
X1 - Small aircraft
0
10
20
30
40

Capture Well Design Optimization

Formulation of Simply Hydraulic Gradient Control Optimization Problem

Minimize Z = Total Pumping Rate
(seven pumping wells possible)

$$\sum_{i=1}^{7} Q_i$$

Subject to

1. Hydraulic gradients directed inward toward the plume around its entire boundary.

$$H_{out_j} - H_{in_j} \geq 0$$

$$j = 1\text{-}46$$

2. In-well drawdowns restricted to 30 percent of the saturated thickness, b.

$$H_i \geq \text{Bottom Elevation} + 0.7(b)$$

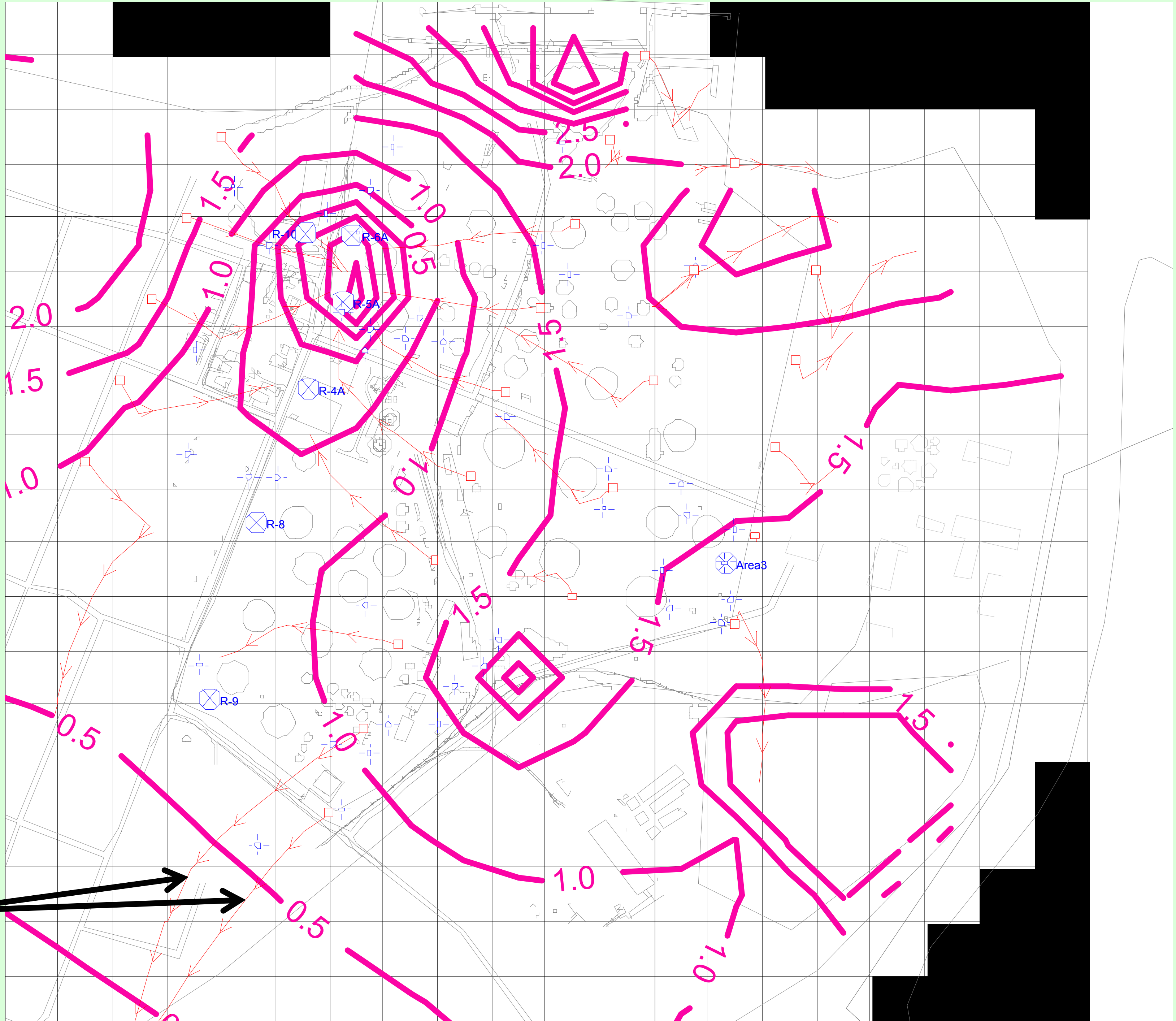
$$i = 1\text{-}7$$

Adapted from: Gorelick, S. M., R. A. Freeze, D. Donohue, and J. F. Keely. *Groundwater Contamination: Optimal Capture and Containment.* Boca Raton, Florida: Lewis Publishers, 1993.

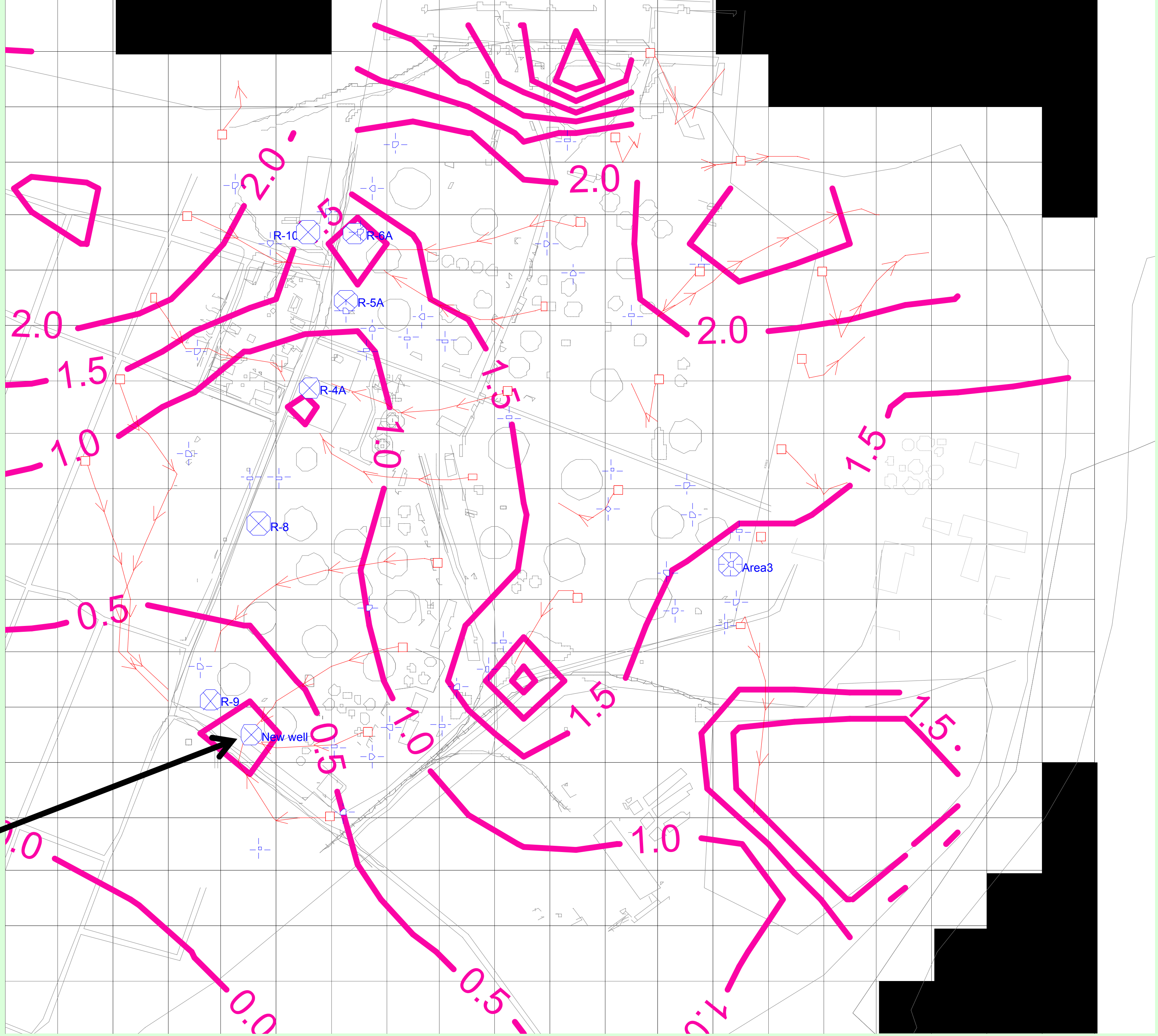
MODOFC Optimization Code

See images at the Web site of University of Massachusetts, Dept. of Civil and Environmental Engineering, Ahlfeld, D. P. and R. G. Riefler, 1998, Documentation for MODOFC: A Program for Solving Optimal Flow Control Problems Based on MODFLOW Simulation.

http://www.ecs.umass.edu/modofc/ex.html Accessed May 11, 2004.



Off-site flow



New
well

Pumping Well Construction

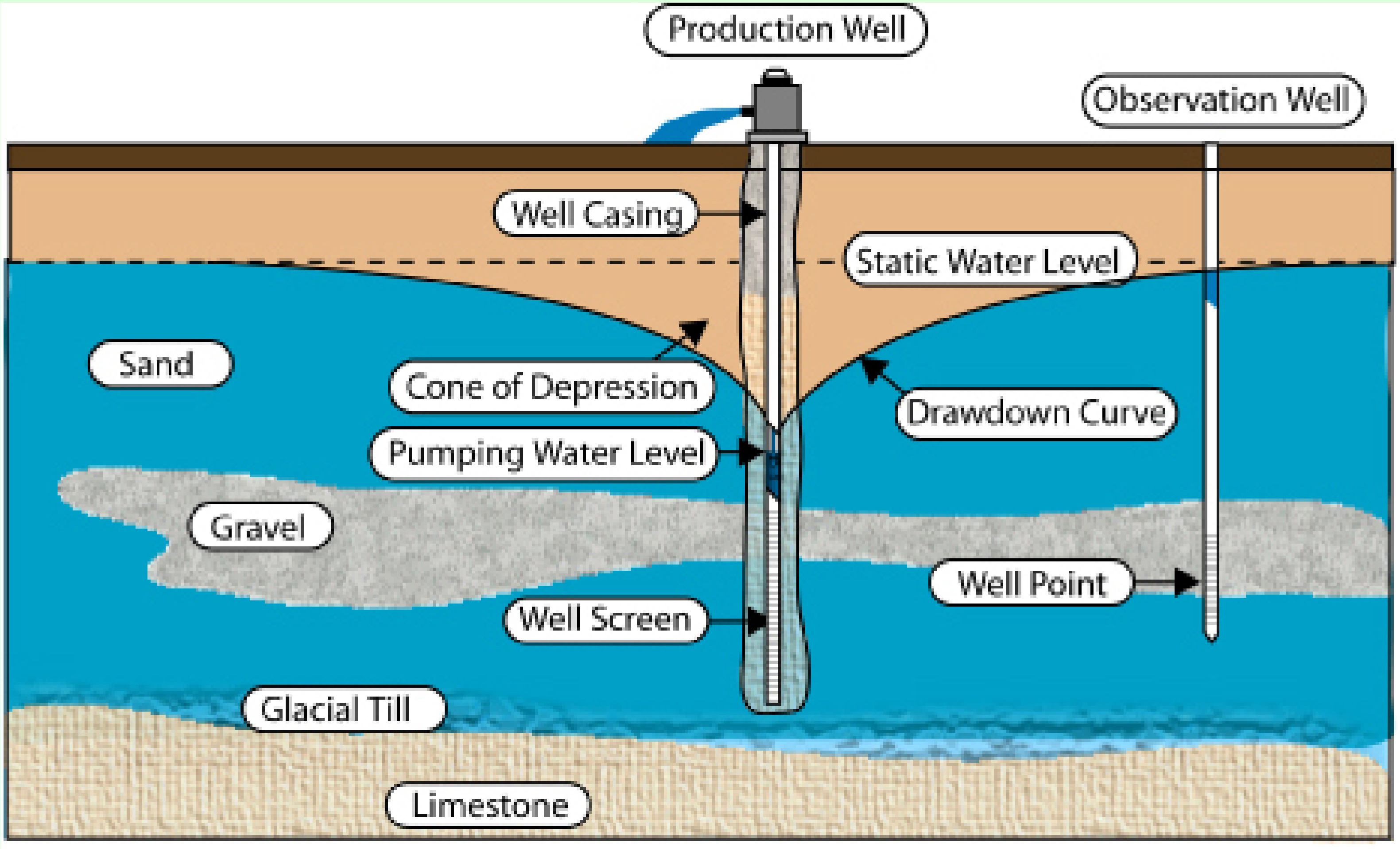
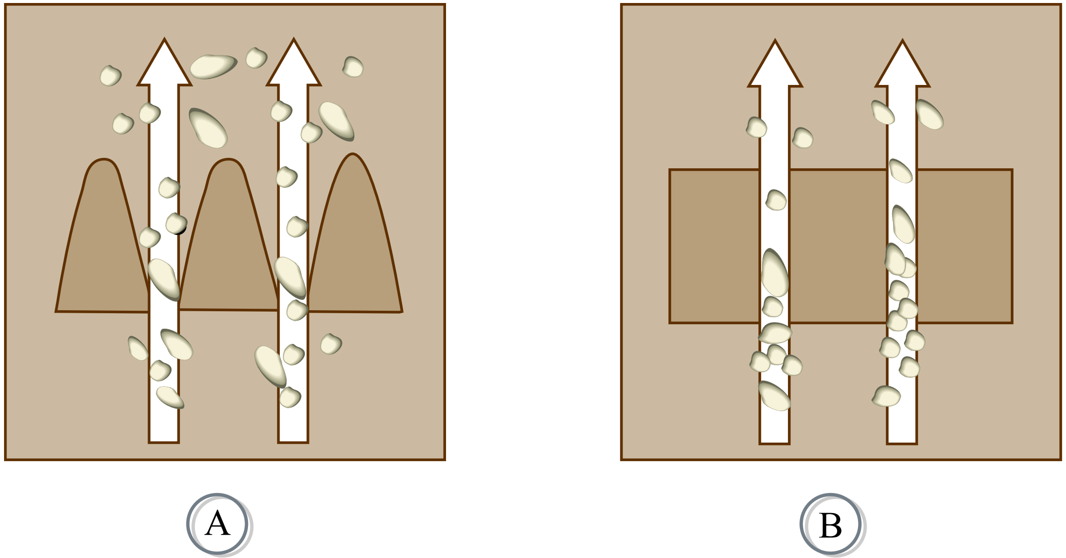


Image adapted from: Driscoll, Fletcher G. *Groundwater and Wells*, Second Edition. Johnson Screens, 1986.

Well Screen



A: Slot openings are V-shaped in continuous-slot screens. The slots are non-clogging because they widen inwardly. Particles passing through the narrow outside opening can enter the screen.

B: Elongated or slightly oversized particles can clog straight-cut, punched, or gauze-type openings.

Image adapted from: Driscoll, Fletcher G. *Groundwater and Wells*. Second Edition. Johnson Screens, 1986.

Grain Size Sieve Analysis

Recommended sieve groups suitable for sieving various classes of unconsolidated sediments.

Sand and Gravel

in	mm	Mesh No.
0.131	3.33	6
0.093	2.36	8
0.065	1.65	10
0.046	1.17	14
0.033	0.84	20
0.023	0.58	28
0.016	0.41	35
0.012	0.30	48

Bottom Pan

Coarse Sand

0.046	1.17	14
0.033	0.84	20
0.023	0.58	28
0.016	0.41	35
0.012	0.30	48
0.008	0.20	65

Bottom Pan

Fine Sand

0.023	0.58	28
0.016	0.41	35
0.012	0.30	48
0.008	0.20	65
0.006	0.15	100

Bottom Pan

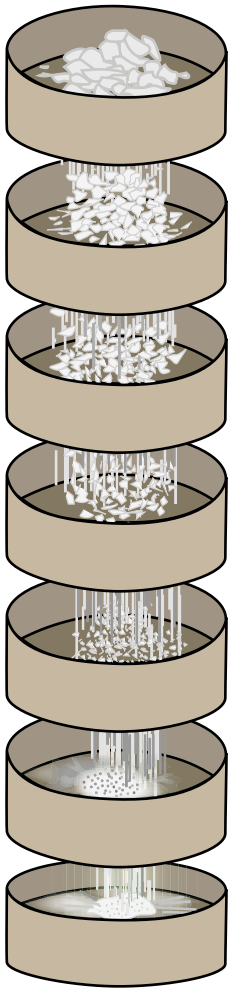
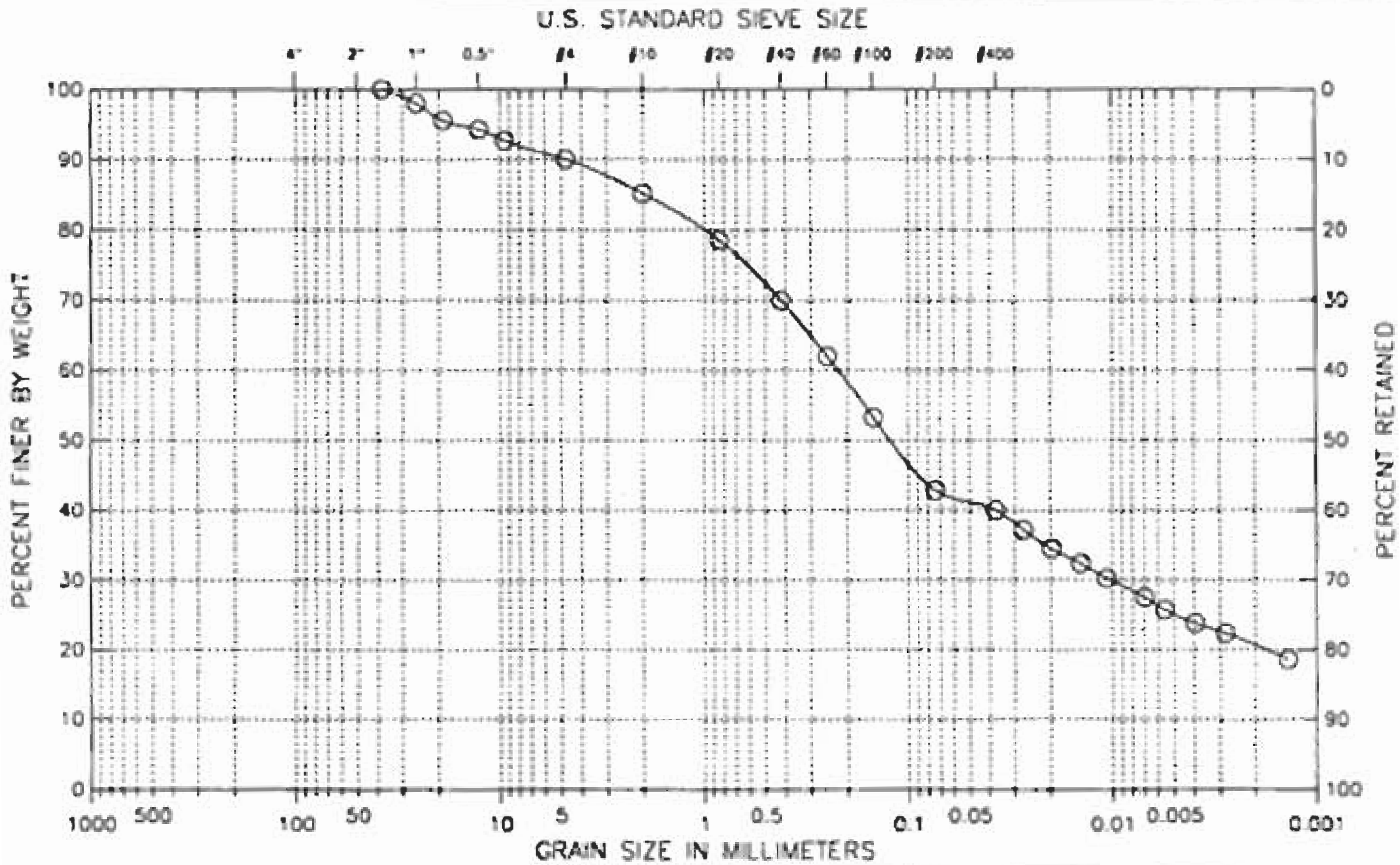


Image adapted from: Driscoll, Fletcher G. *Groundwater and Wells.* Second Edition. Johnson Screens, 1986.

Source: Paskevich, V. and L. Poppe, "U.S. Geological Survey Open-File Report 00-304, Georeferenced Sea-Floor Mapping and Bottom Photography in Long Island Sound." U.S. Geological Survey. http://pubs.usgs.gov/of/of00-304/htmldocs/chap04/. Accessed May 11, 2004.

Boring No. : Bor-1 Sample No: Sample 1 Test Method ASTM D 422 Filename : SAMPLE1	Project : ABC Project Project No.: CTX-0000 Location: DEF, GH Date : Thu Mar 25 1999



COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	

Classification :
(SC) Clayey sand

Visual Description :
Very dark brown clayey sand with gravel

Remarks :

Figure 1

Screen Size from Grain Size

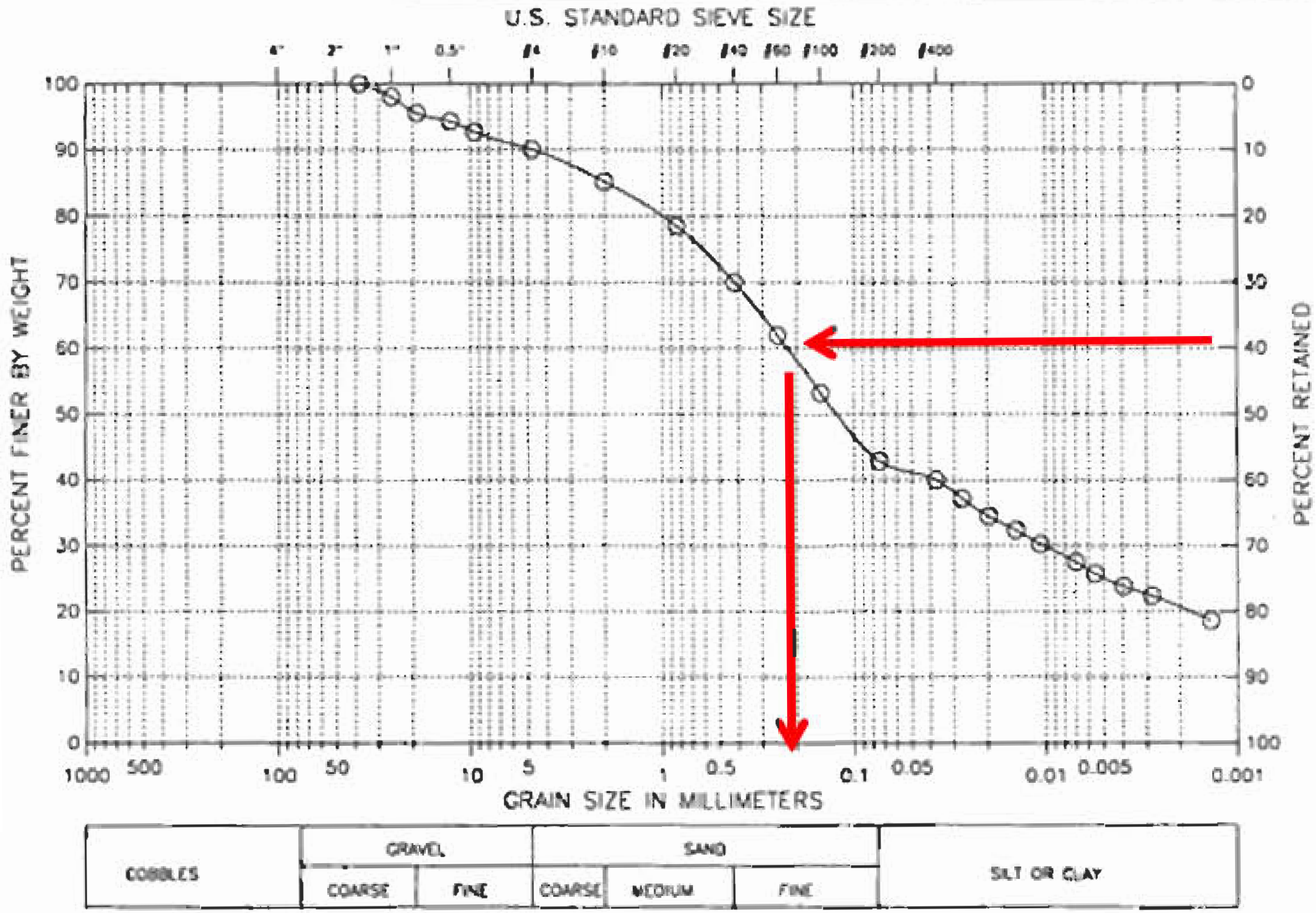
Tradeoff between maximum yield (large slot size) and sand-free water (small slot size)

Rule of thumb: slot size = 40% point on grain-size distribution

(60% passes, 40% retained)

Use smaller slot size in corrosive waters

	Boring No. : Bor-1 Sample No: Sample 1 Test Method ASTM D 422 Filename : SAMPLE1	Project : ABC Project Project No.: CTX-0000 Location: DEF, GH Date : Thu Mar 25 1999



Classification :
(SC) Clayey sand

Visual Description :
Very dark brown clayey sand with gravel

Remarks :

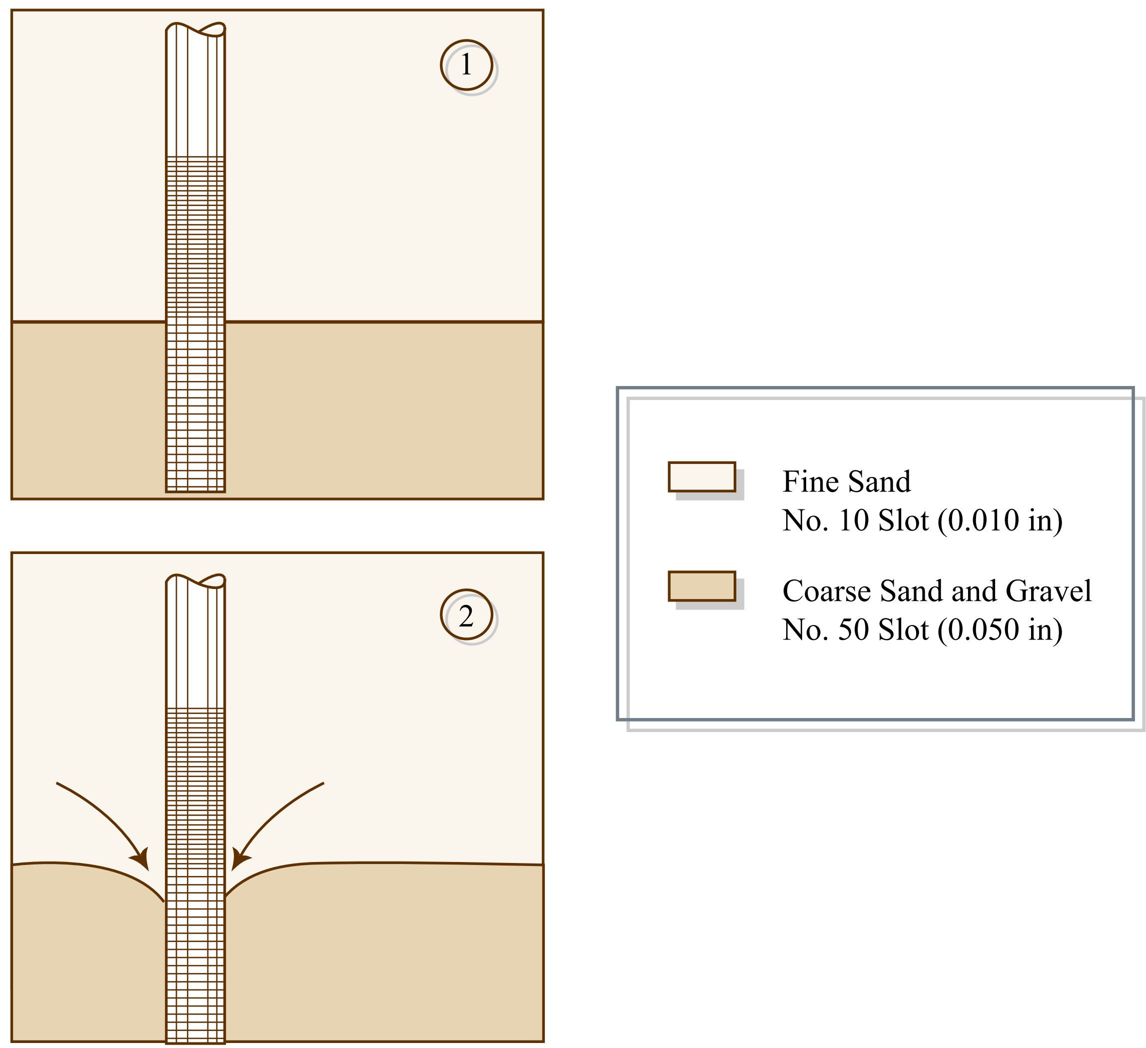
Figure 1

Screens for stratified aquifers

Different strata require different screens

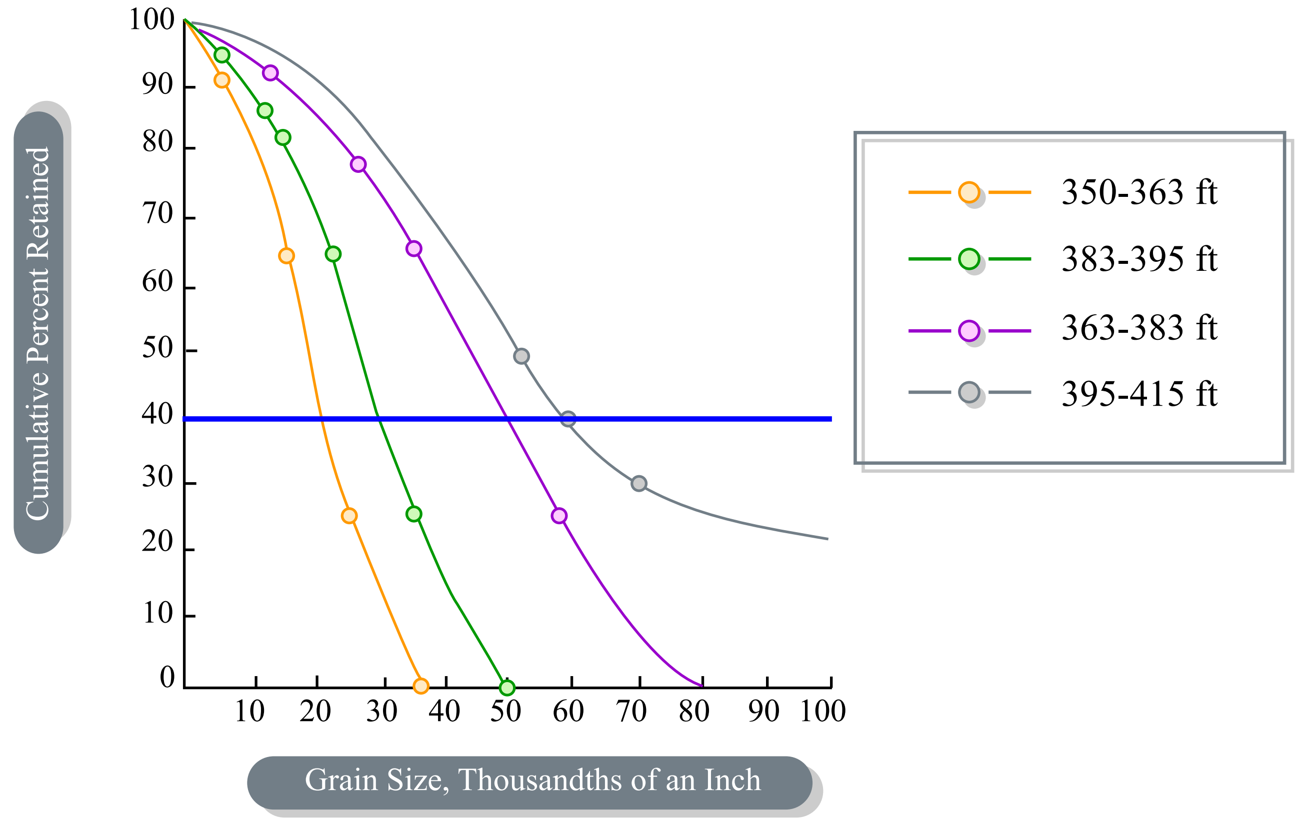
Rules of thumb:

- Fine material over coarse: extend fine screen 3 feet into coarse material
- At most double slot size when changing size
- Use 2-foot minimum sections for doubling size



Screen in lower part of stratified aquifer (1) should be shorter than the total thickness of the coarser sand, to avoid situation (2) which shows possibility of fine sand entering upper part of the screen after development.

Image adapted from: Driscoll, Fletcher G. Groundwater and Wells. Second Edition. Johnson Screens, 1986.

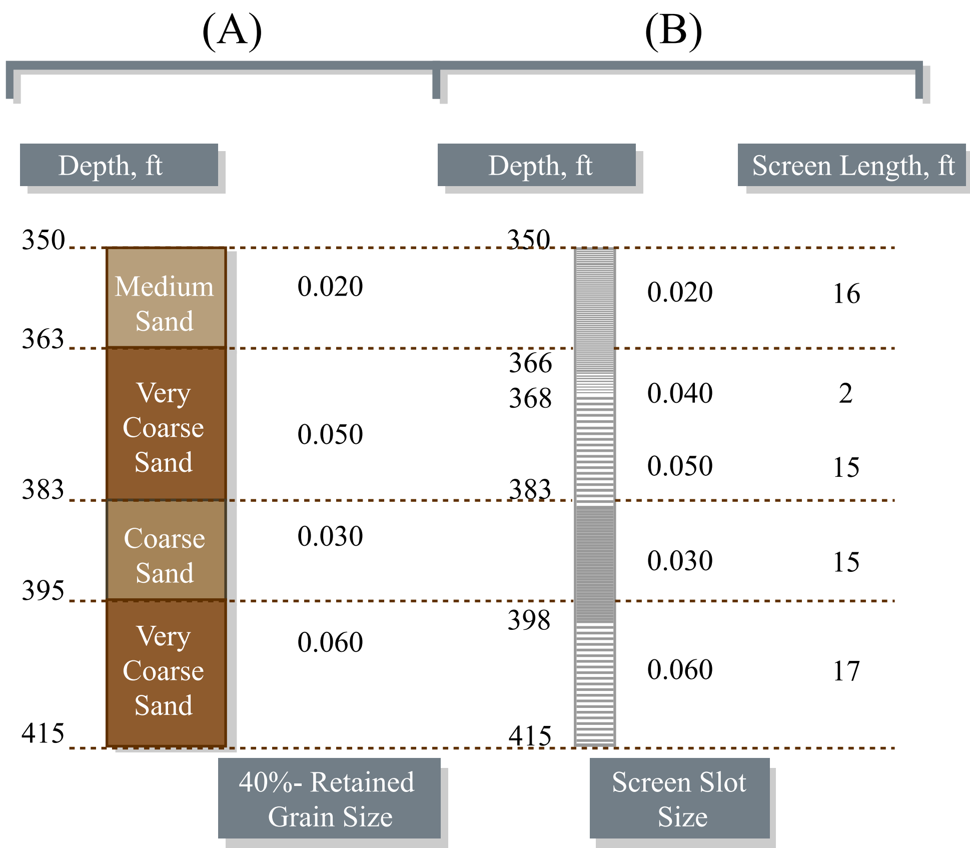


Grain-size-distribution curves respresenting the various layers in a stratified sand aquifer.

Image adapted from: Driscoll, Fletcher G. *Groundwater and Wells*. Second Edition. Johnson Screens, 1986.

Depth (ft)	Thickness (ft)	Hydraulic Conductivity (gpd/ft^2)	Transmissivity (gpd/ft)	Screen Openings (in)		
				50% Retained	40% Retained	30% Retained
350-363	13	500	6,500	0.019	0.020	0.024
363-383	20	2,000	40,000	0.045	0.050	0.056
383-395	12	1,000	12,000	0.026	0.030	0.034
395-415	20	1,500	30,000	0.052	0.060	0.070
Aquifer Transmissivity			88,500			

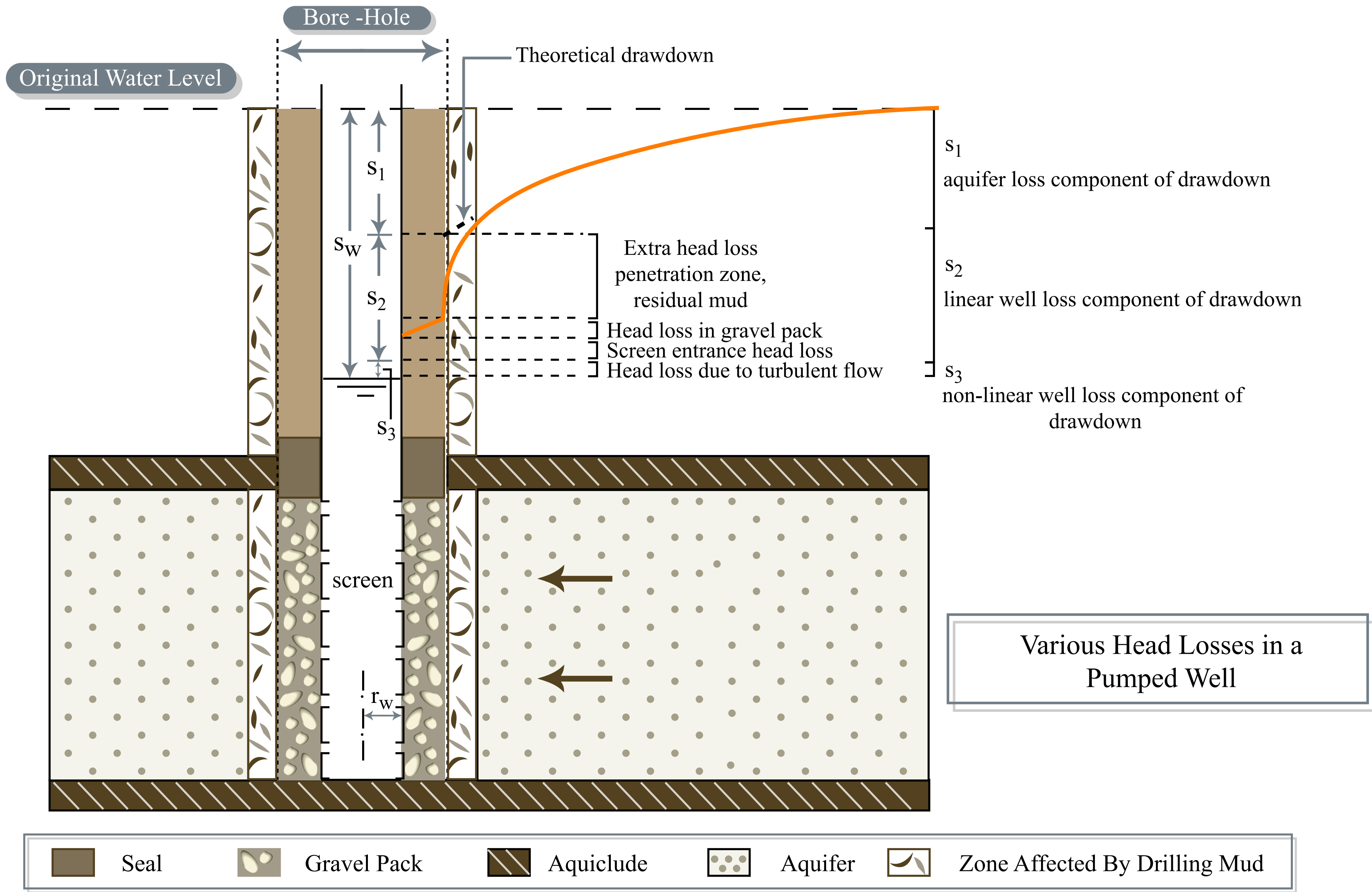
Design Table for Screen Slot Size



(a) Stratigraphic section that will be screened with slot sizes corresponding to various layers.
(b) Sketch of screen showing the slot sizes selected based on rules 1 and 2.

Images adapted from: Driscoll, Fletcher G. *Groundwater and Wells*. Second Edition. Johnson Screens, 1986.

Well efficiency



Adapted from: Kruseman, G. P. and N. A. de Ridder. *Analysis and Evaluation of Pumping Test Data.* Wageningen, The Netherlands: International Institute for Land Reclamation and Improvement, 1991.

Step-Drawdown Test

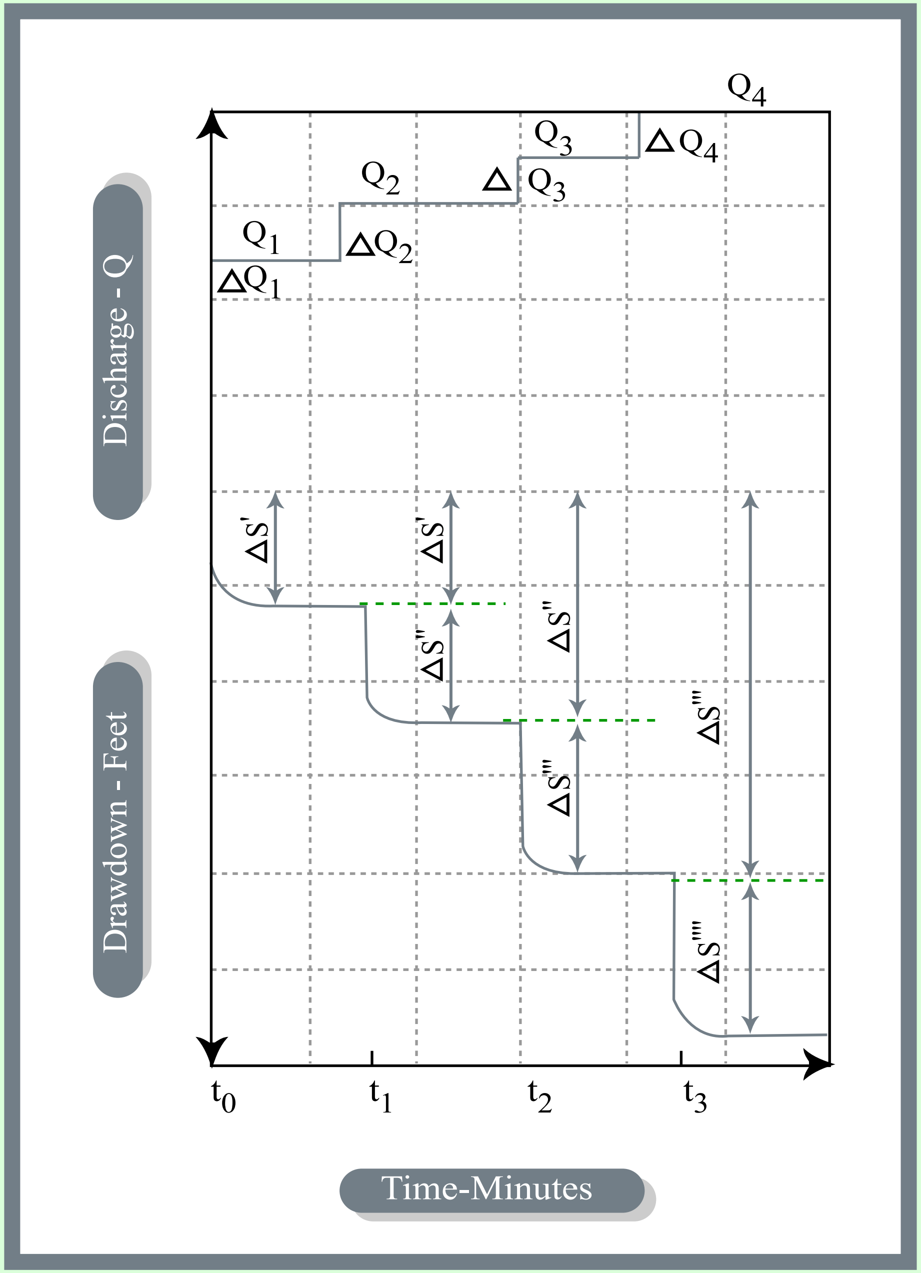


Image adapted from: Driscoll, Fletcher G. *Groundwater and Wells*. Second Edition. Johnson Screens, 1986.

Well loss theory

Drawdown, $s = BQ + CQ^2$

Q = flow rate

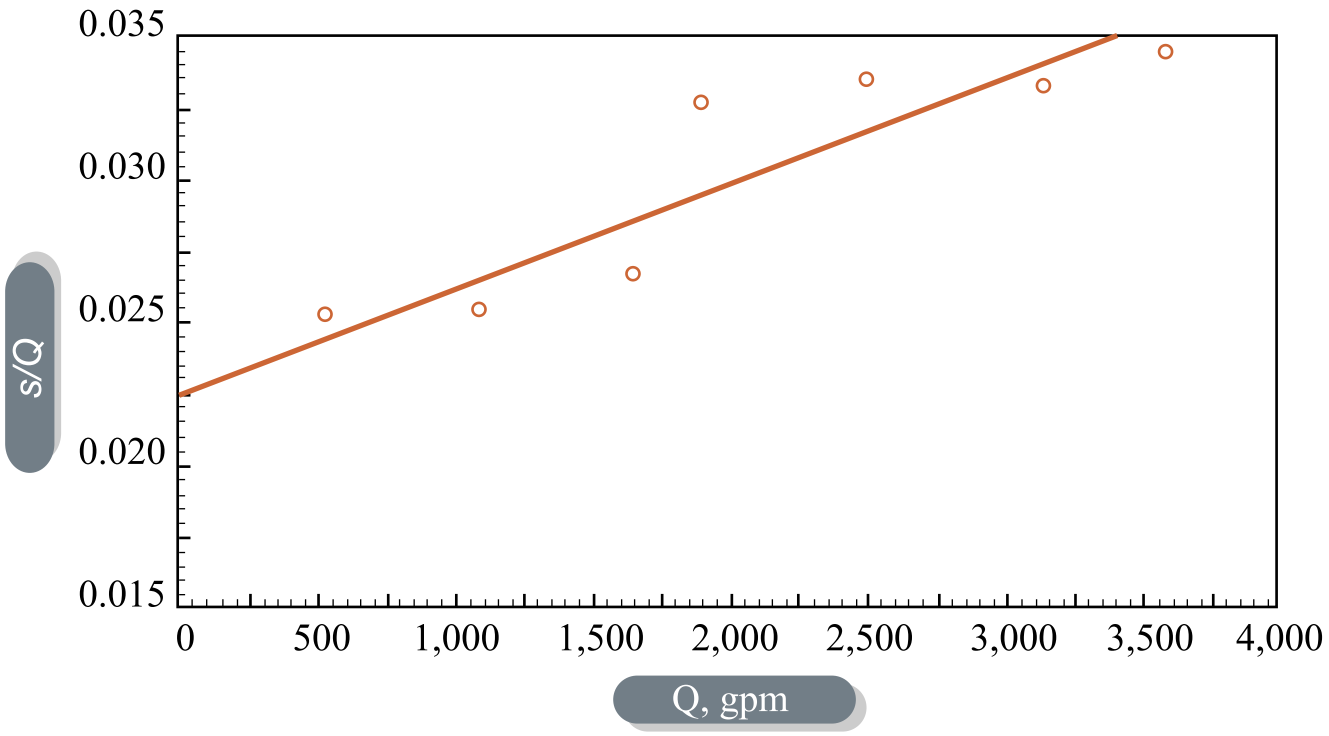
B, C parameters

BQ = aquifer (laminar) head loss

CQ^2 = well (turbulent) head loss

Efficiency, $$L_p = \frac{BQ}{BQ + CQ^2} \times 100$$

Step-Drawdown Analysis



$B = 0.0225$ $C = 3.68 \times 10^{-6}$ $L_p = \frac{BQ}{BQ + CQ^2}$ = 69% Laminar Flow

Values for *B* and *C* in the step-drawdown equation can be determined from a graph where *s/Q* is plotted against Q.

Image adapted from: Driscoll, Fletcher G. *Groundwater and Wells*. Second Edition. Johnson Screens, 1986.

Vertical Turbine Well Pumps

See images at the following Web sites:

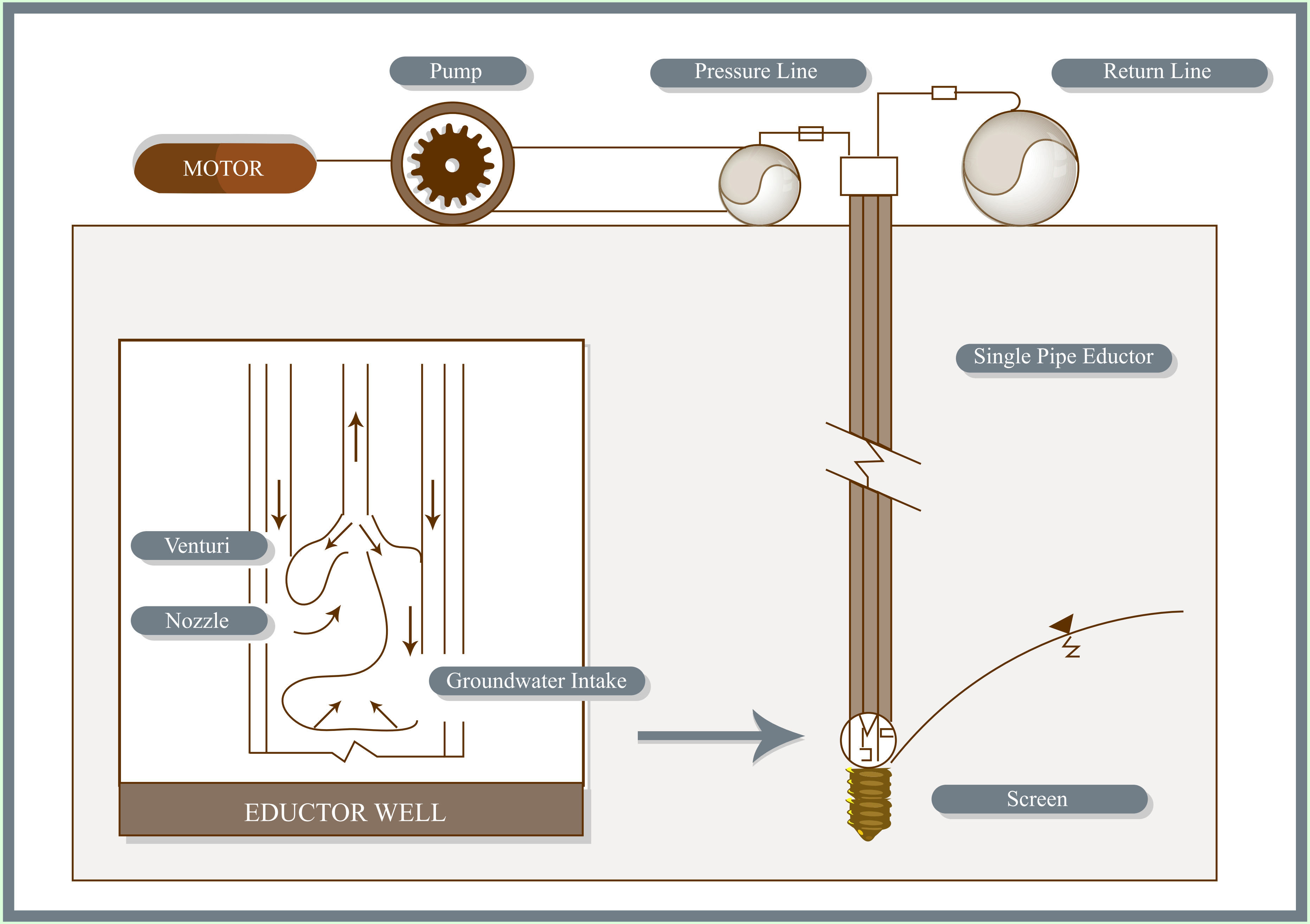
University of Georgia College of Agricultural and Environmental Sciences, “Factors to Consider in Selecting a Farm Irrigation System” (http://www.ces.uga.edu/pubcd/B882.htm)

College of Agricultural Sciences and Technology, California State University, “Agricultural Mechanics Graphics, California Vocational Agriculture --Curriculum Transparencies” (http://cast.csufresno.edu/agedweb/agmech/graphics/toc.htm).

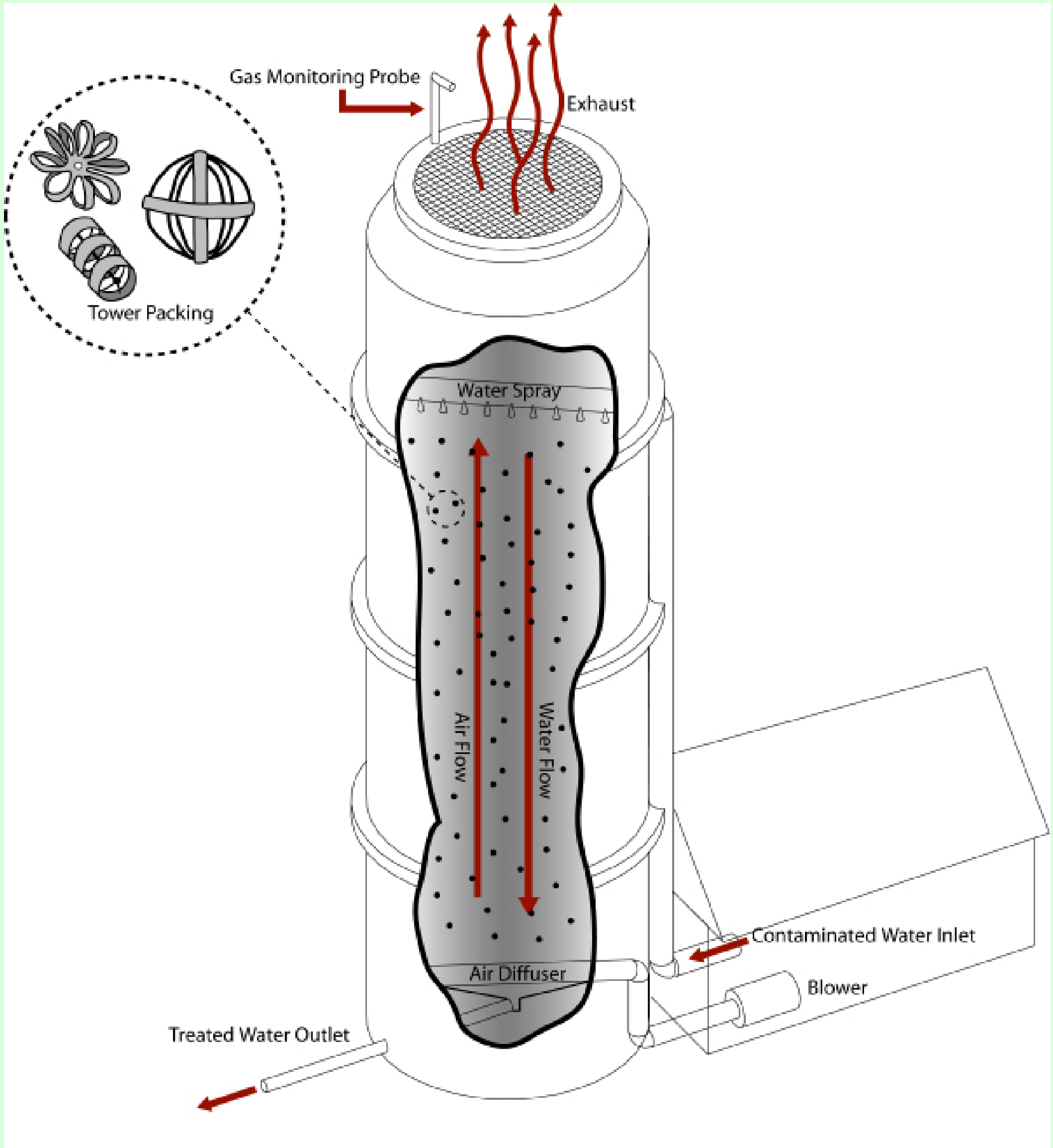
Accessed May 11, 2004.

Kulikov, S., undated. Agricultural Mechanics Graphics, California Vocational Agriculture --Curriculum Transparencies. College of Agricultural Sciences and Technology, California State University, Fresno, California. http://cast.csufresno.edu/agedweb/agmech/graphics/toc.htm. Accessed February 28, 2004.

Eductor pumps



Air Stripping Tower



Design of an Air-Stripping Tower

Image adapted from: Fetter, C. W.

Contaminant Hydrogeology, Second Edition. Upper Saddle River, NJ: Prentice Hall, 1999.

Source: Environmental Protection Agency, Region 9, San Fernando Valley, North Hollywood Treatment Plant, Air Stripping Tower, http://yosemite.epa.gov/r9/sfund/sphotos.nsf/0/7e416ed1a4259a7d88256612006c9b4c?OpenDocument/. Accessed May 11, 2004.

Catalytic Oxidizer for Vapor Exhaust

See image at the Web site of North Carolina State University, Volatile Organic Compounds, Module 6: Air Pollutants and Control Technics, http://www.epin.ncsu.edu/apti/ol_2000/module6/voc/control/control.htm.

Accessed May 11, 2004.

North Carolina State University, 2000. Volatile Organic Compounds, Module 6: Air Pollutants and Control Technics. Industrial Extension Service, Environmental Programs, North Carolina State University. Wilmington, NC. http://www.epin.ncsu.edu/apti/ol_2000/module6/voc/control/control.htm. Accessed February 27, 2003.

Thermal Oxidizer

See image at the Web site of North Carolina State University, Volatile Organic Compounds, Module 6: Air Pollutants and Control Technics, http://www.epin.ncsu.edu/apti/ol_2000/module6/voc/control/control.htm.

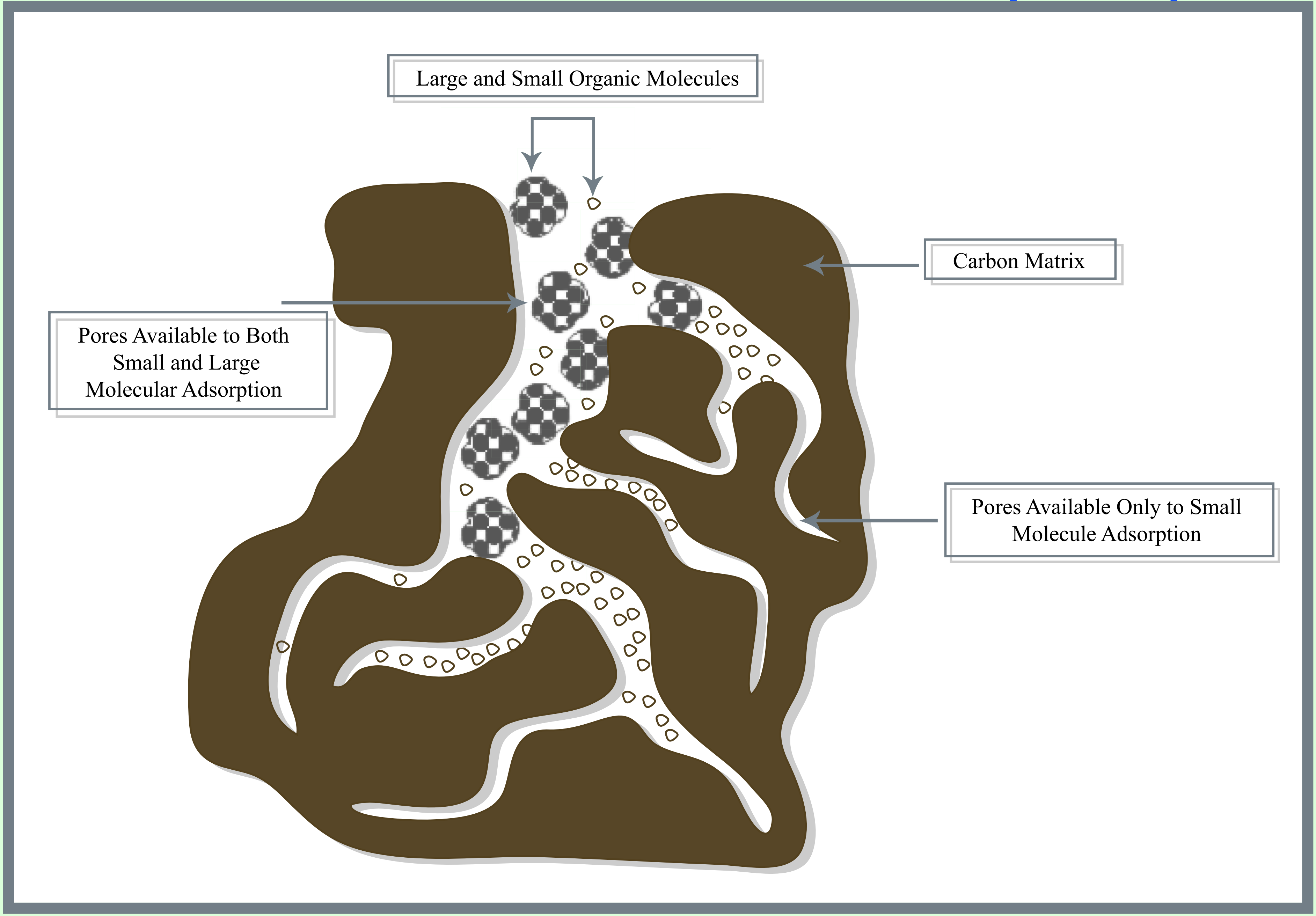
Accessed May 11, 2004.

North Carolina State University, 2000. Volatile Organic Compounds, Module 6: Air Pollutants and Control Technics. Industrial Extension Service, Environmental Programs, North Carolina State University. Wilmington, NC. http://www.epin.ncsu.edu/apti/ol_2000/module6/voc/control/control.htm. Accessed February 27, 2003.

Thermal Oxidizer

Source: Nevada Division of Environmental Protection, Nellis Air Force Base site, http://ndep.nv.gov/boff/nellis02.htm. Accessed May 11, 2004.

Granular Activated Carbon (GAC)



Activated Carbon

See images at the following Web sites:

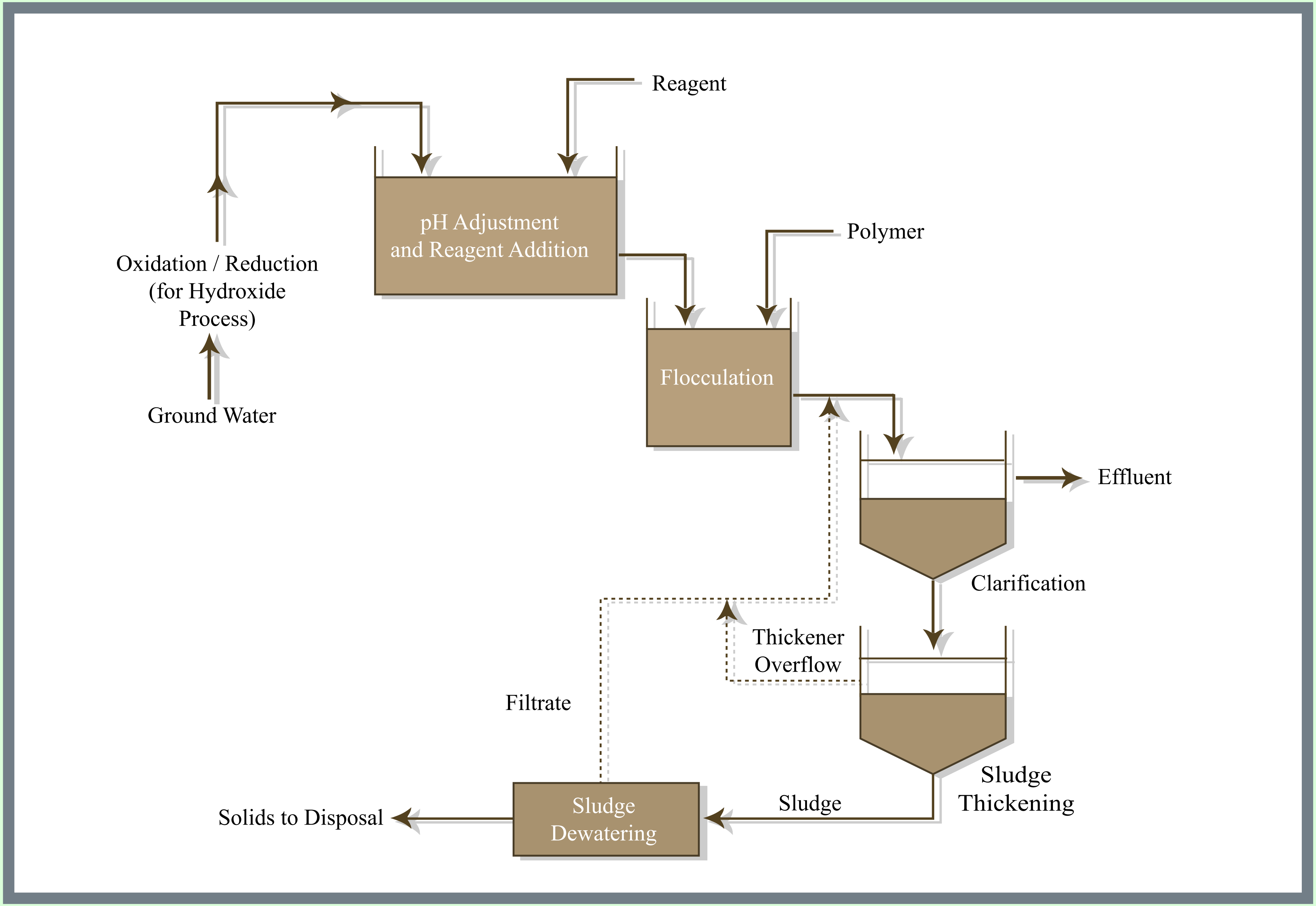
Water phase: CPL Carbon Link, Clean Flo Adsorbtion system, http://www.activated-carbon.com/swedish/4-1-sw.html.

Vapor phase: Schrader Environmental Services, Used Remediation Equipment, http://www.remediationequipment.com/usedequipment.htm

Accessed May 11, 2004.

(1/2-left):Diva Web Design, 2002. Clean Flo Adsorbtionssystem. CPL Carbon Link. Lulea, Sweden. http://www.activated-carbon.com/swedish/4-1-sw.html. Accessed February 26, 2003.
(1/2-left): Schrader Environmental Services, undated. Used Remediation Equipment. Schrader Environmental Services. Lansing, MI. http://www.remediationequipment.com/usedequipment.htm. Accessed February 27, 2003.

Metals Removal - Precipitation



Metals Removal – Iron Coprecipitation

See image at the Web site of Unipure Environmental, Unipure Process Technology, http://www.unipure.com/tech/ (select “View Process Animation”).

Accessed May 11, 2004.

Oil Water Separator