Confined Aquifers

- Aquifer unit bounded above and below by low permeability confining units
- Water is pressurized, causing well water levels to rise above the top of the aquifer
- Aquifer is of infinite areal extent
- Homogenous, isotropic, constant thickness
- Piezometric surface is level prior to pumping
- Aquifer pumped at constant rate
- Well is fully penetrating and screened over entire thickness of aquifer
- Well diameter is small

Unsteady Flow

- Water is released instantaneously from storage as head declines

Variables

- Q = pumping rate
- r = distance from well
- s = water-level drawdown
- t = time since pumping began

Parameters

b = aquifer thickness

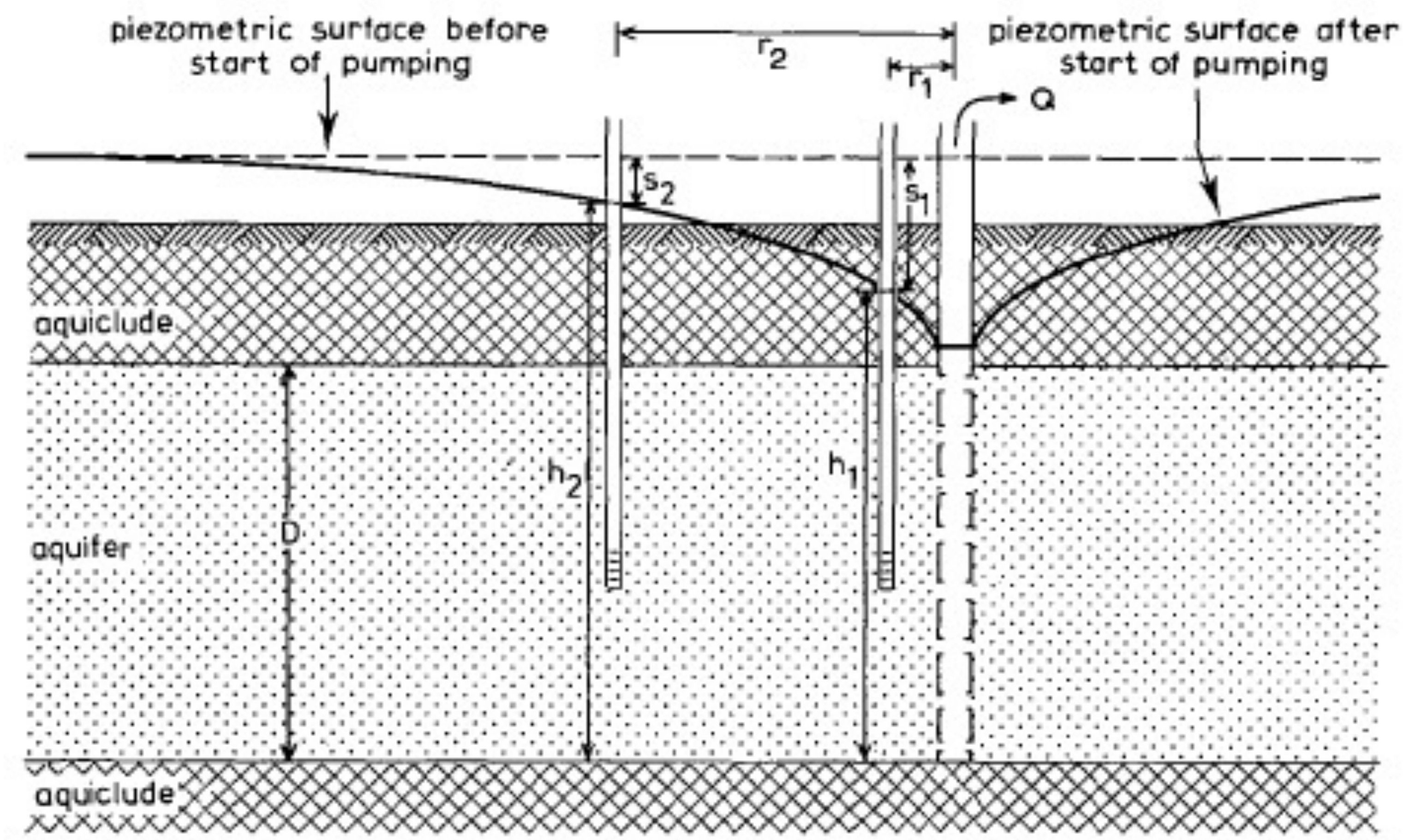
K = hydraulic conductivity (steady flow)

T = K b = transmissivity

S_s = specific storage (unsteady flow)

S = S_s b = storativity

D = T / S = K / S_s = diffusivity



Example

- Oude Korendijk polder in The Netherlands
- Aquifer is 18 to 25 m below ground surface

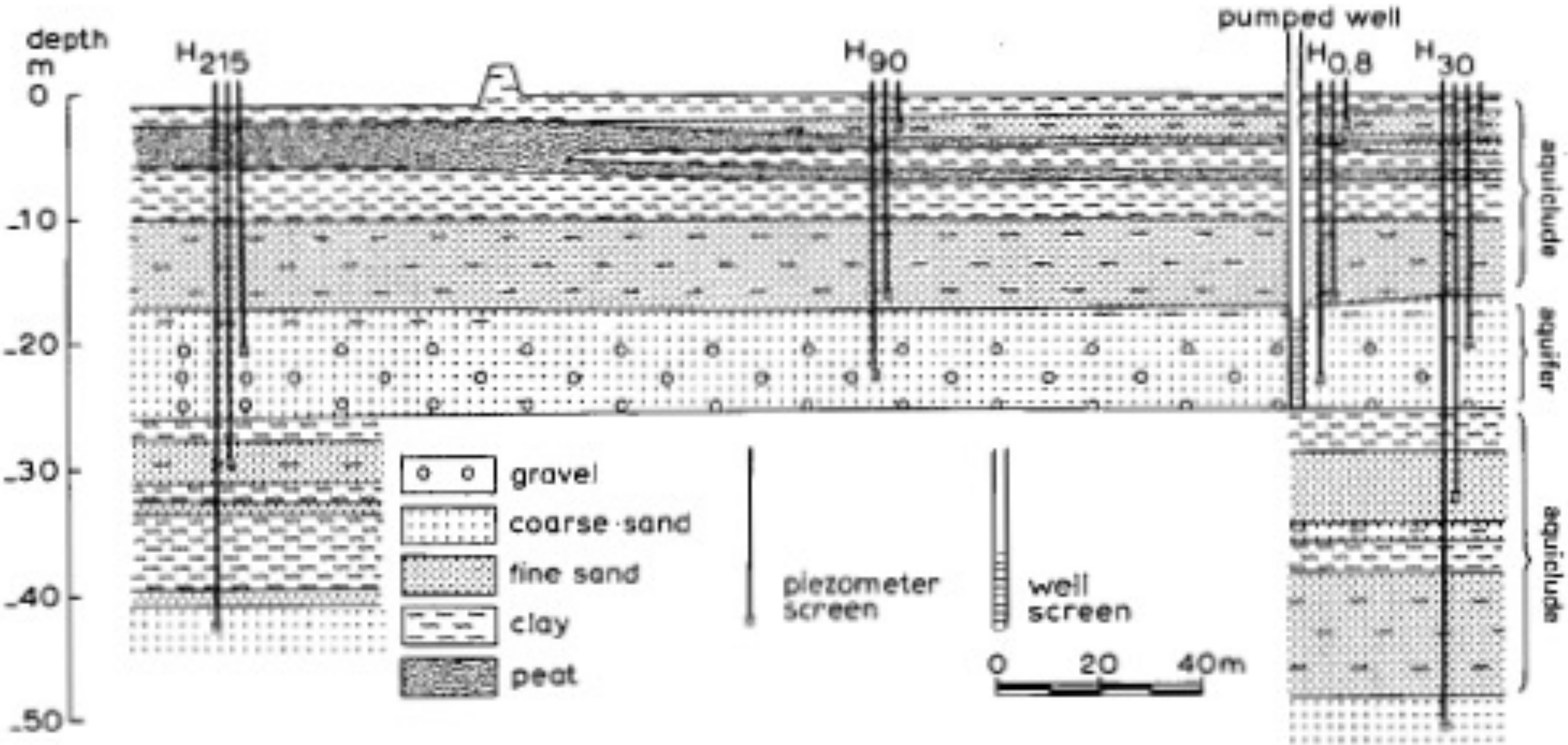
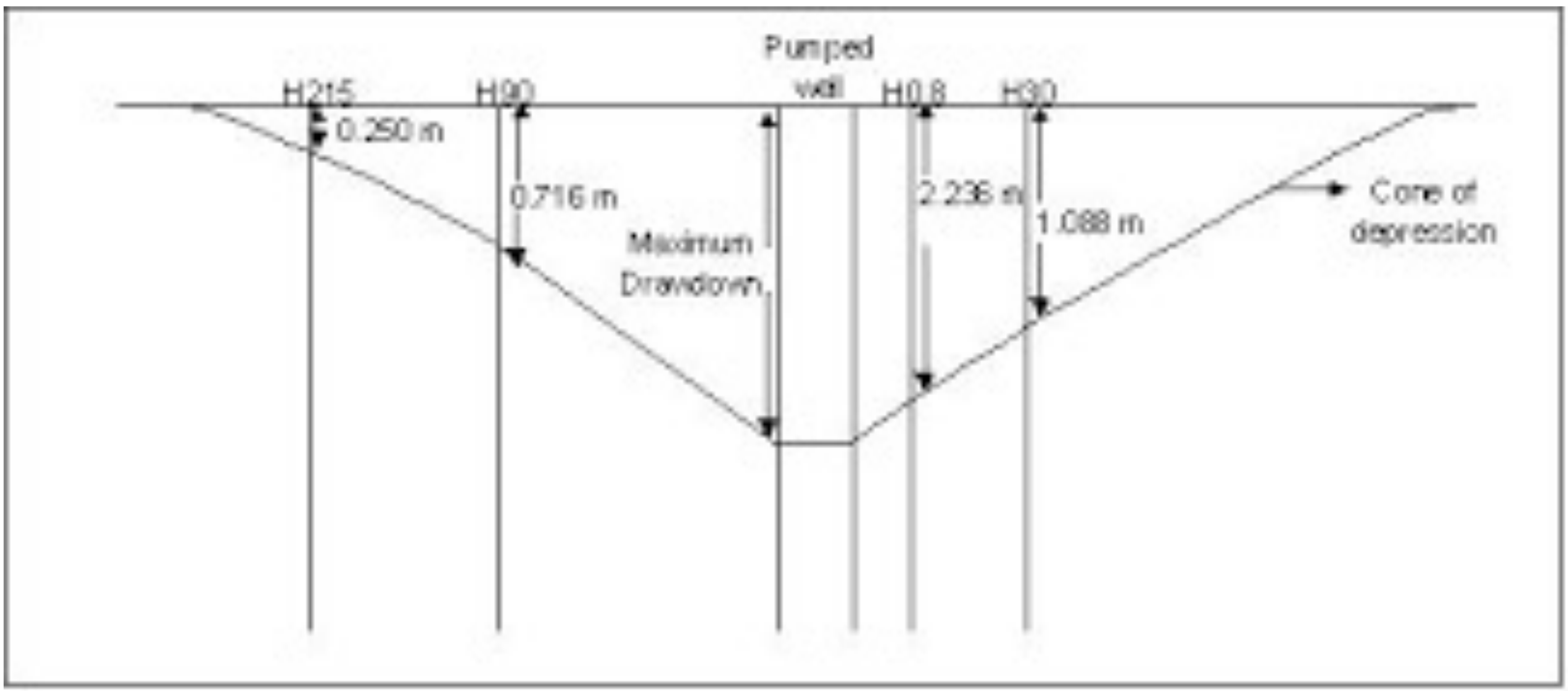


Figure 3.2 Lithological cross-section of the pumping-test site 'Oude Korendijk', The Netherlands (after Wit 1963)

Thiem Method (1906)

- Steady, radial flow (there is no "time" in "Thiem")
- $\Delta s = s_2 - s_1 = Q/2\pi T \ln (r_2/r_1)$
- s_1 and s_2 are drawdowns in piezometers located at distances r_1 and r_2 from a pumped well



Theis Method (1935)

- Radial, unsteady flow
- $s = Q/4\pi T\ W(u)$
- $W(u) = -0.5772 - \ln u + u - u^2/2\cdot 2! + u^3/3\cdot 3! - \ldots$
- $u = r^2/4Dt$

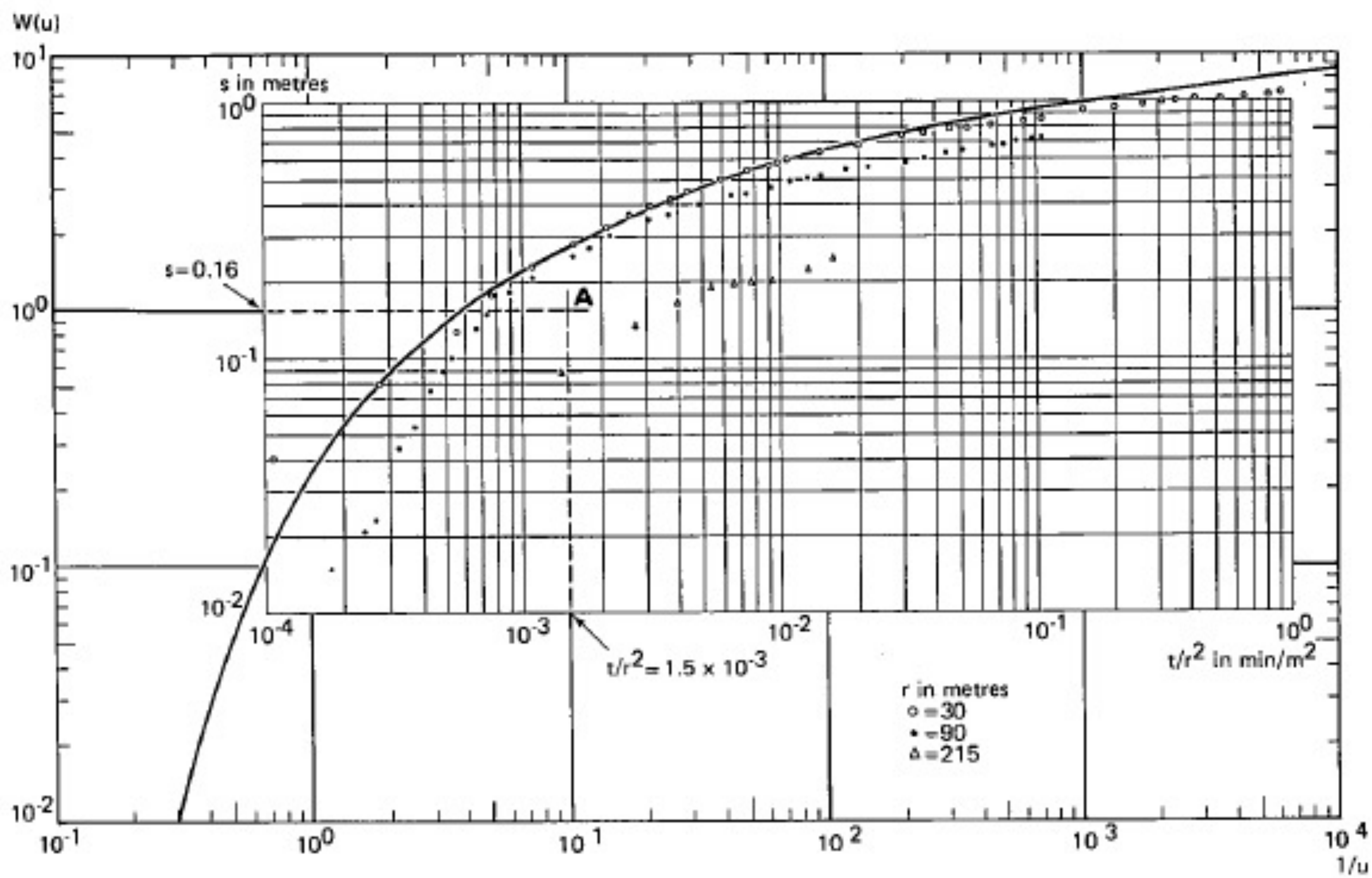
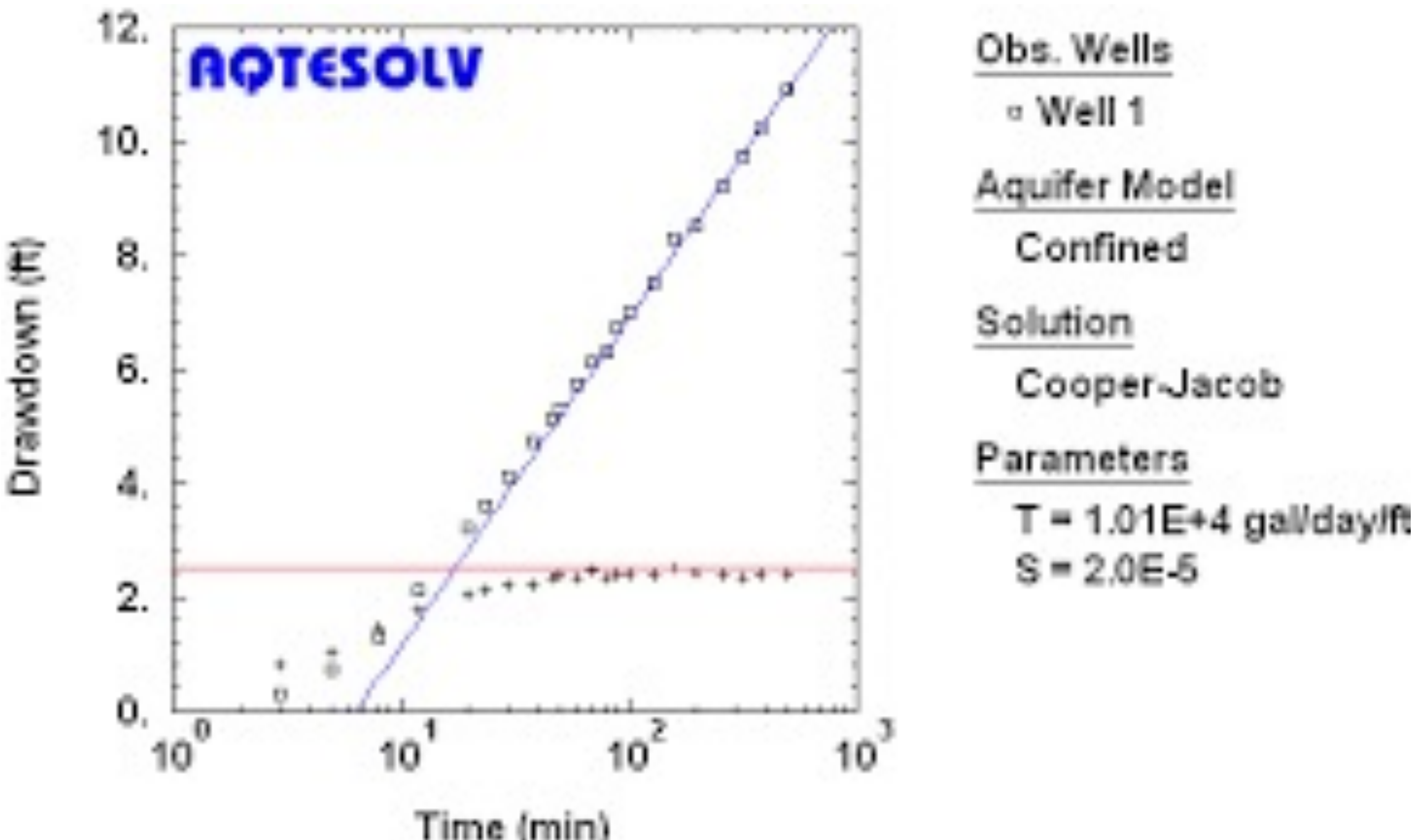


Figure 3.6 Analysis of data from pumping test 'Oude Korendijk' with the Theis method, Procedure 3.3

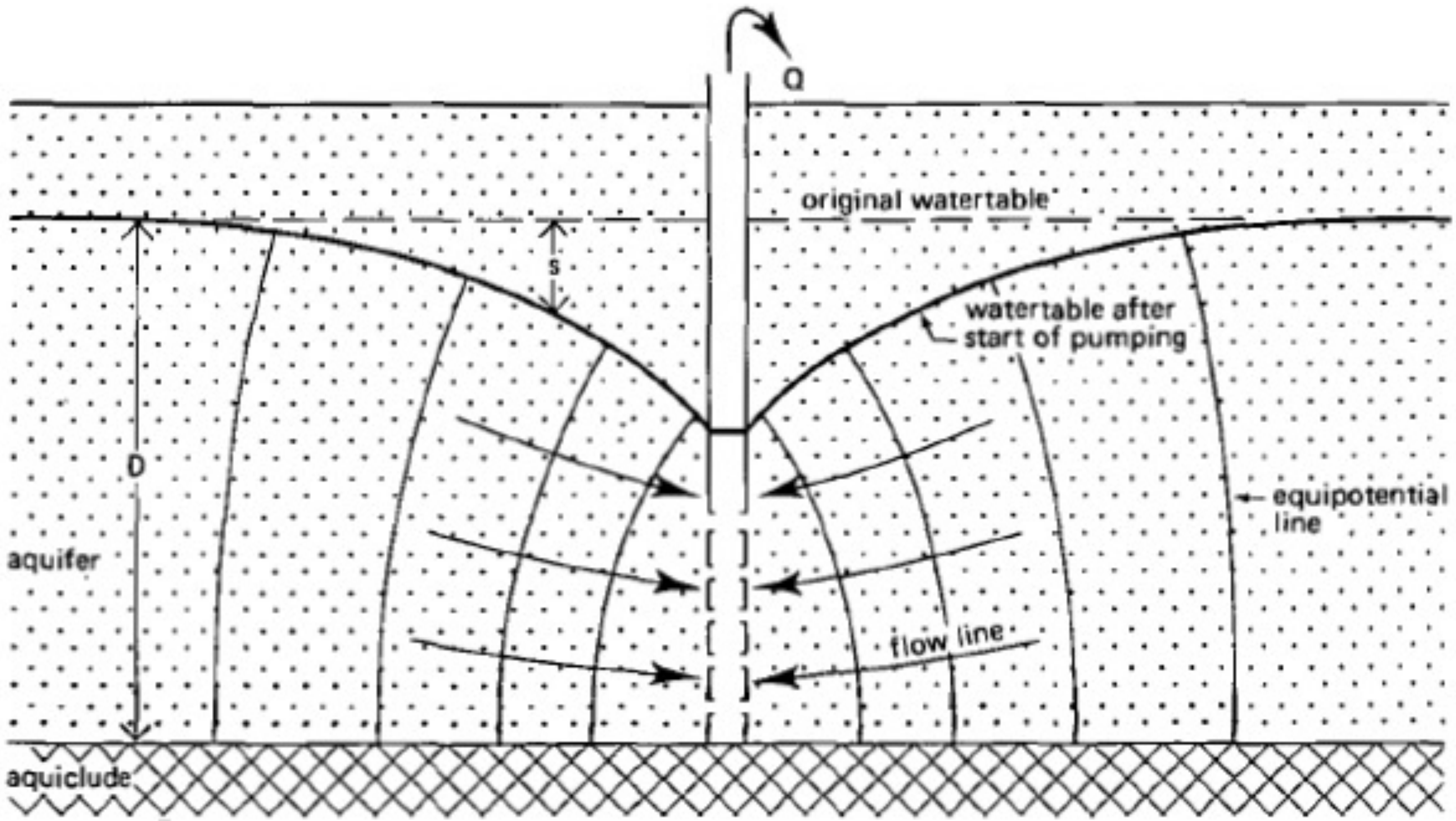
Jacob Method (1946)

- Unsteady flow for $u = r^2/4Dt < 0.01$
- Simplification of Theis method for $t > 25\ r^2/D$



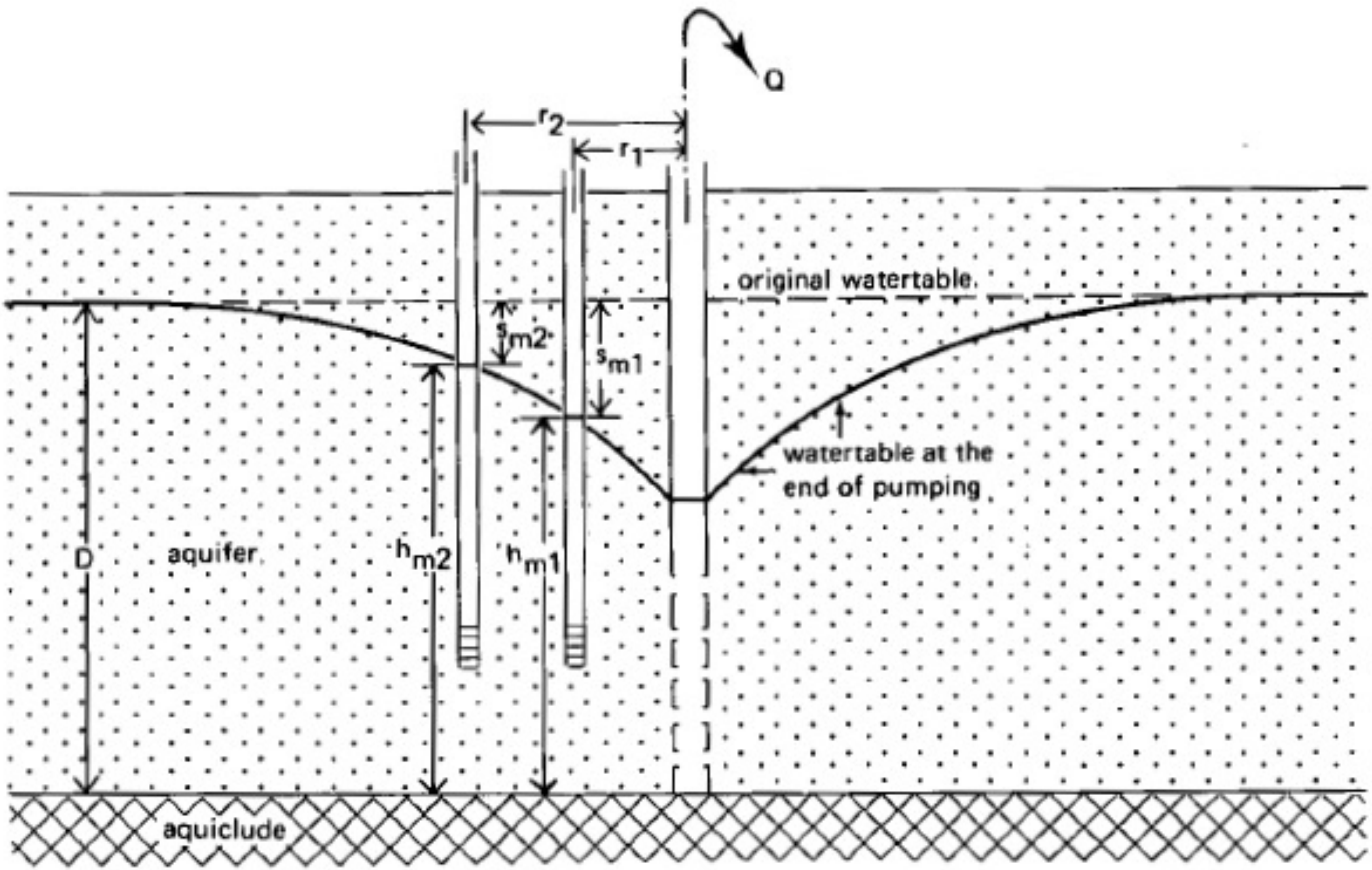
Unconfined Aquifer

- Top of aquifer is the water table
- Differences from confined aquifers:
  - Aquifer thickness is no longer constant
  - Combination of elastic storage and lowering of water table.
  - Flow is both horizonal and vertical



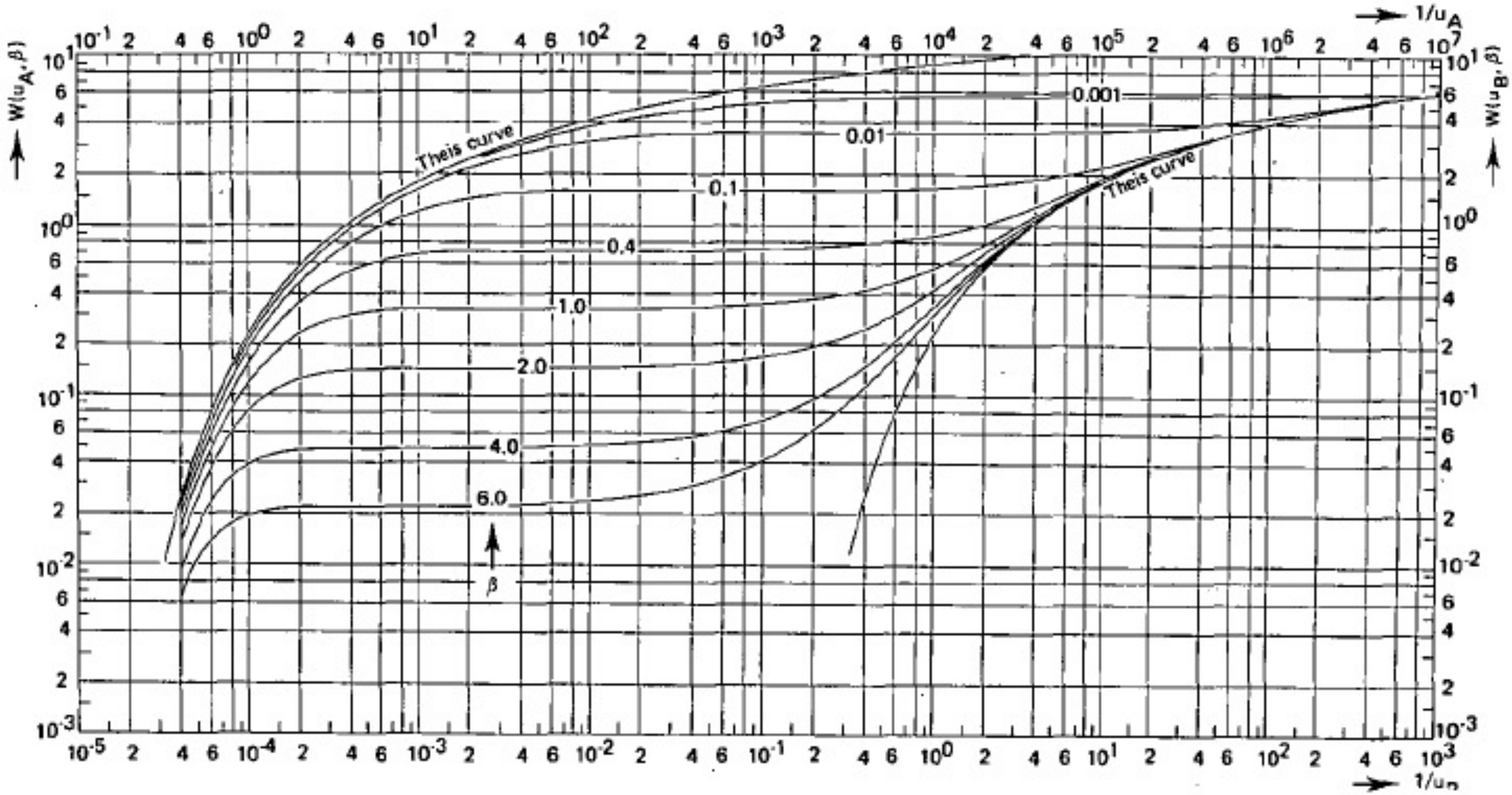
Steady horizontal flow described using

- $\Delta h^2 = h_2^2 - h_1^2 = Q/\pi K \ln r_2/r_1$



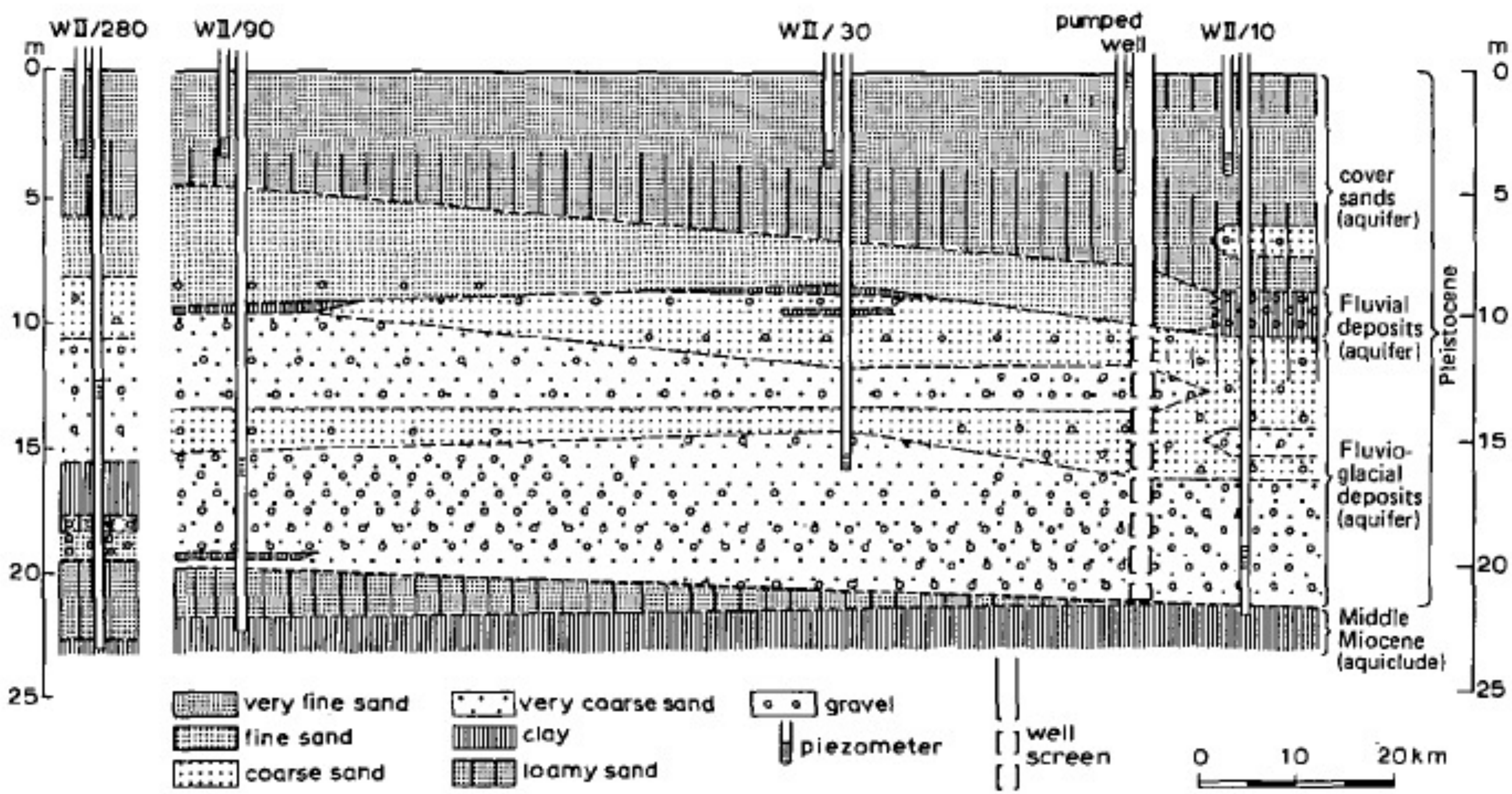
Unsteady flow

- Data shows two types of storage:
  - early-time (elastic storage, S)
  - late-time (water table drainage, S_y)

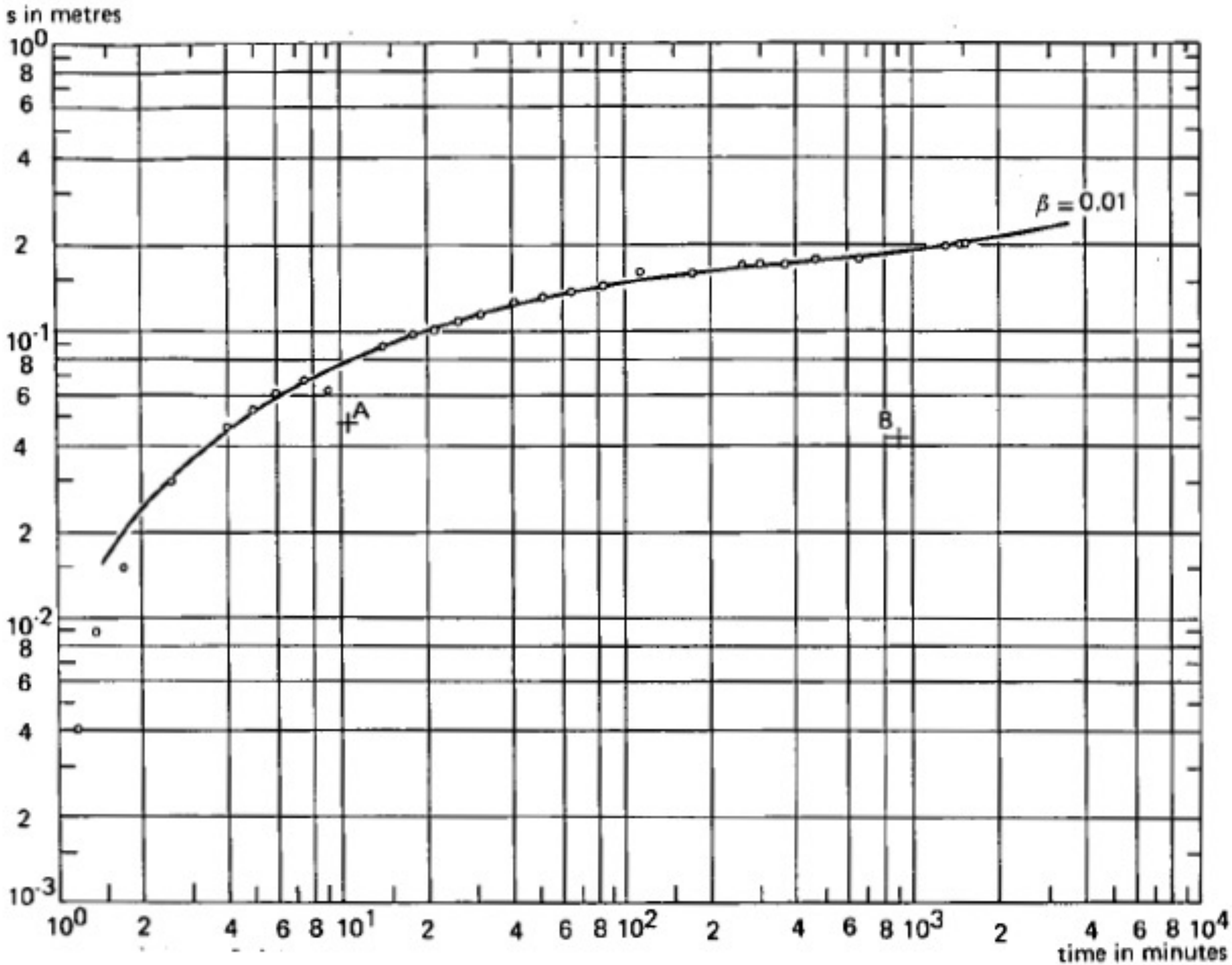


Example

- "Vennebulten" in the Netherlands
- Shallow (3 m) and deep piezometers (12-19 m)
- Pumped for 25 hours: Q = 873 m^3/d
- b = 21 m

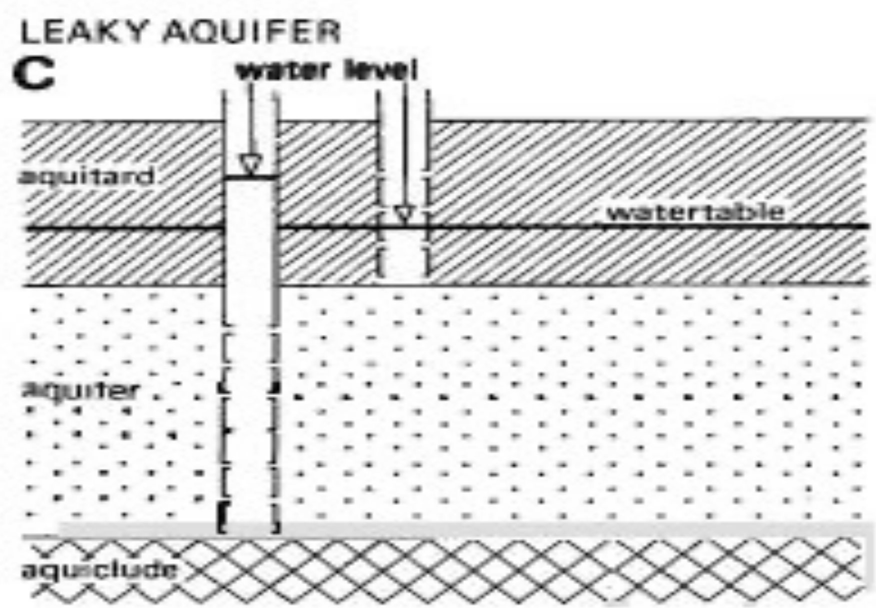


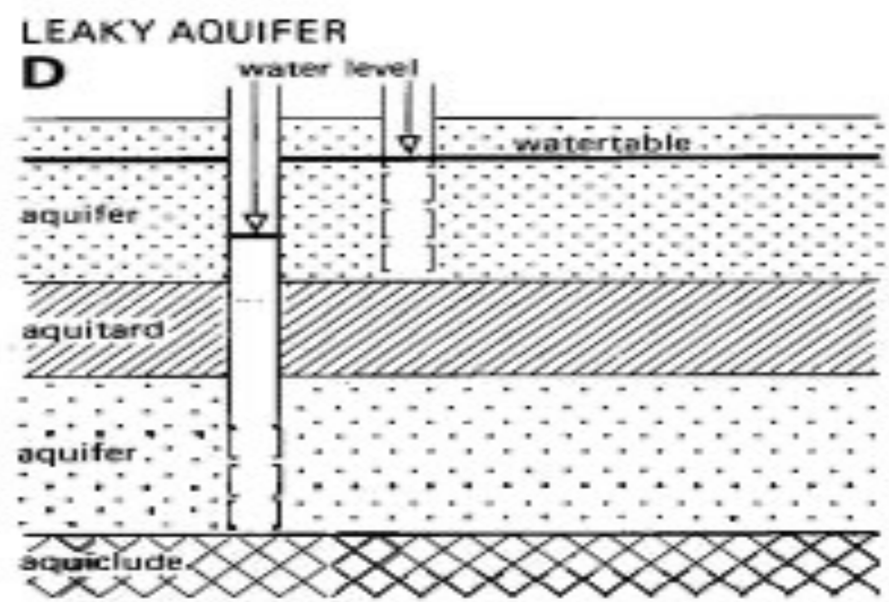
Fit two Theis curves, one for early time and second for late time



Leaky aquifers

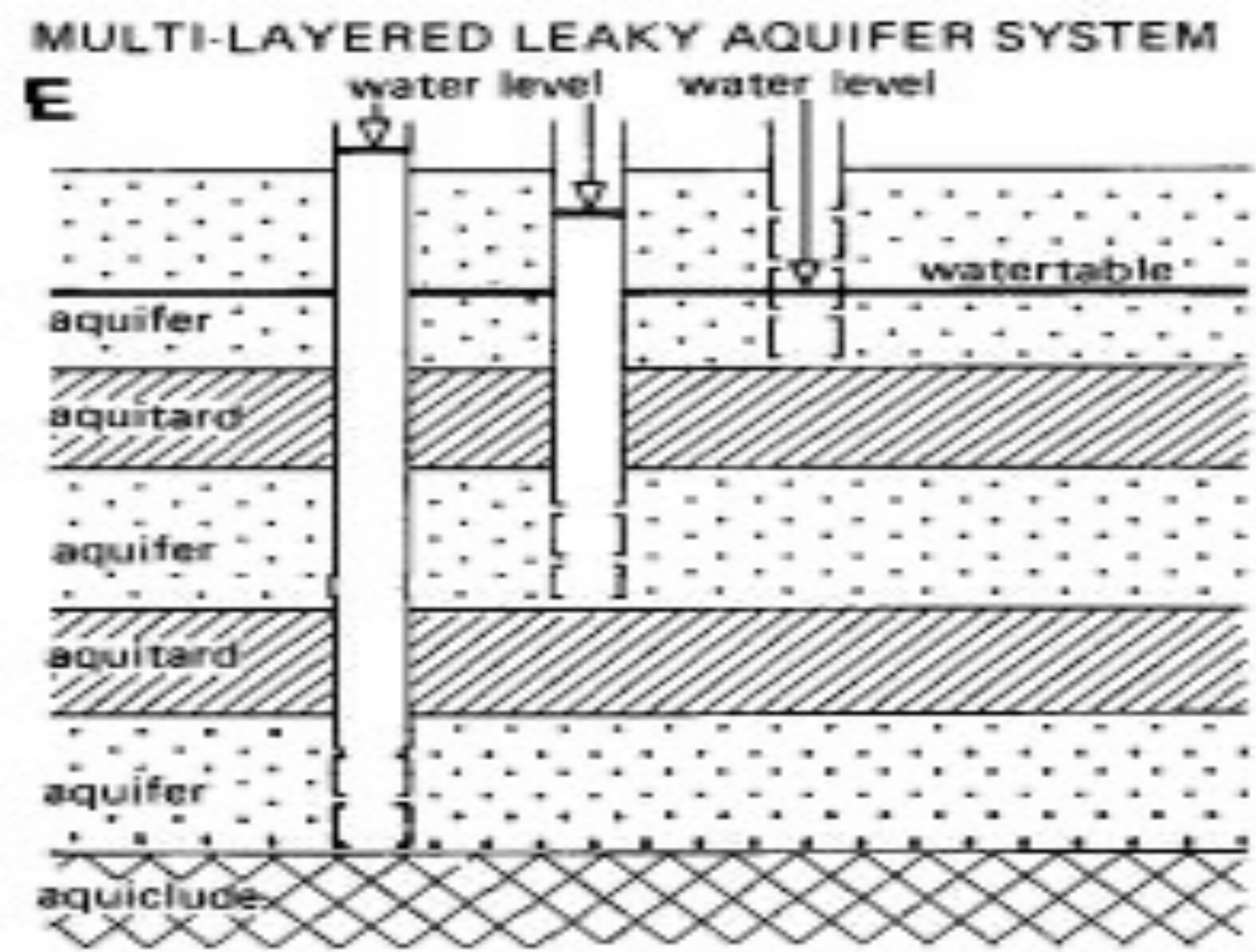
- Also known as a semi-confined aquifer
- An aquifer whose upper and lower boundaries are aquitards, or one boundary is an aquitard and the other is an aquiclude.
- An aquitard is a geological unit that is permeable enough to transmit water in significant quantities when viewed over large areas and long periods, but its permeability is not sufficient to justify production wells being placed in it. Clays, loams, and shales are typical aquitards.



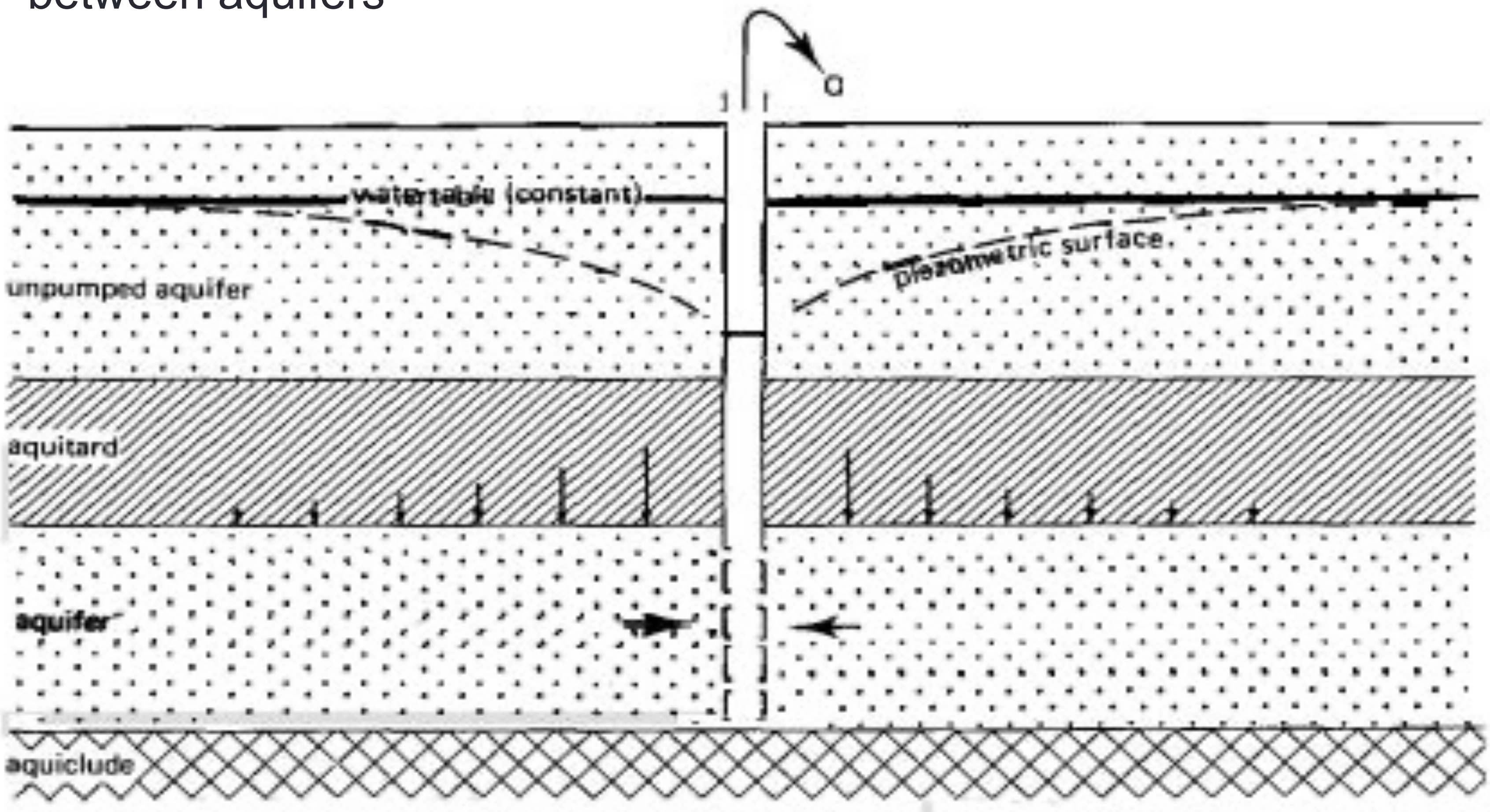


Example

- A deep sedimentary basin where an interbedded system of permeable and less permeable layers form a multi-layered aquifer system.



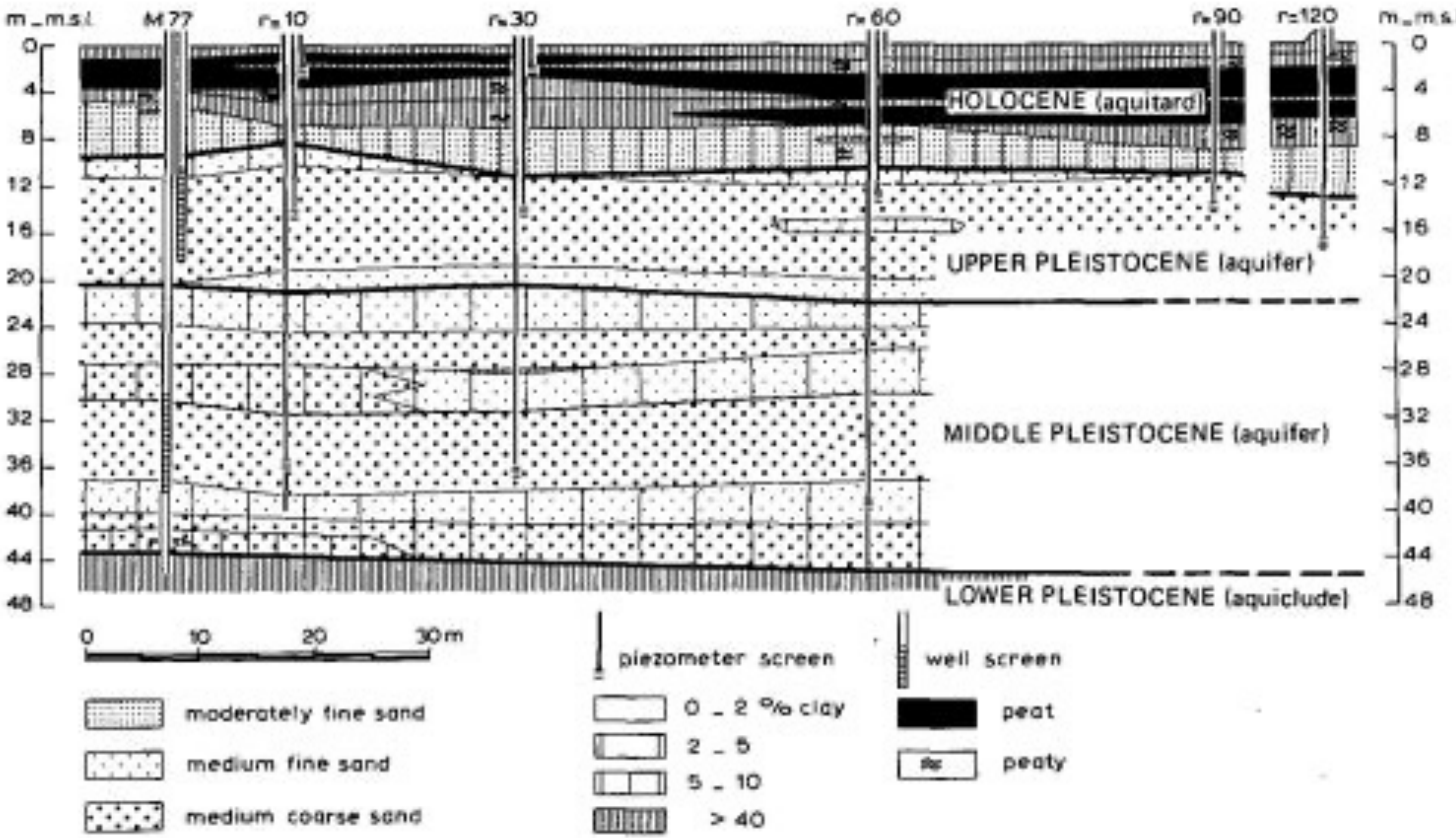
- System consists of two aquifers separated by an aquitard.
- The lower aquifer rests on an aquiclude.
- A well fully penetrates the lower aquifer and is screened over the total thickness of the aquifer.
- The well is not screened in the upper unconfined aquifer.
- Leakage (vertical arrows) is proportional to the vertical gradient between aquifers



Response to pumping

- The piezometric surface in the lower confined aquifer will drop.
- The water that the pumped aquifer contributes to the well discharge comes from storage within the confined aquifer.
- The water contributed by the aquitard comes from storage within the aquitard and leakage through it from the overlying unpumped, unconfined aquifer.
- As pumping continues, more of the water comes from leakage from the unconfined aquifer and relatively less from aquitard storage.
- The flow induced by the pumping is assumed to be vertical in the aquitard and horizontal in the pumped aquifer.
- For a proper analysis of a pumping test in a leaky aquifer, piezometers are required in the leaky confined aquifer, in the aquitard, and in the upper unconfined aquifer.

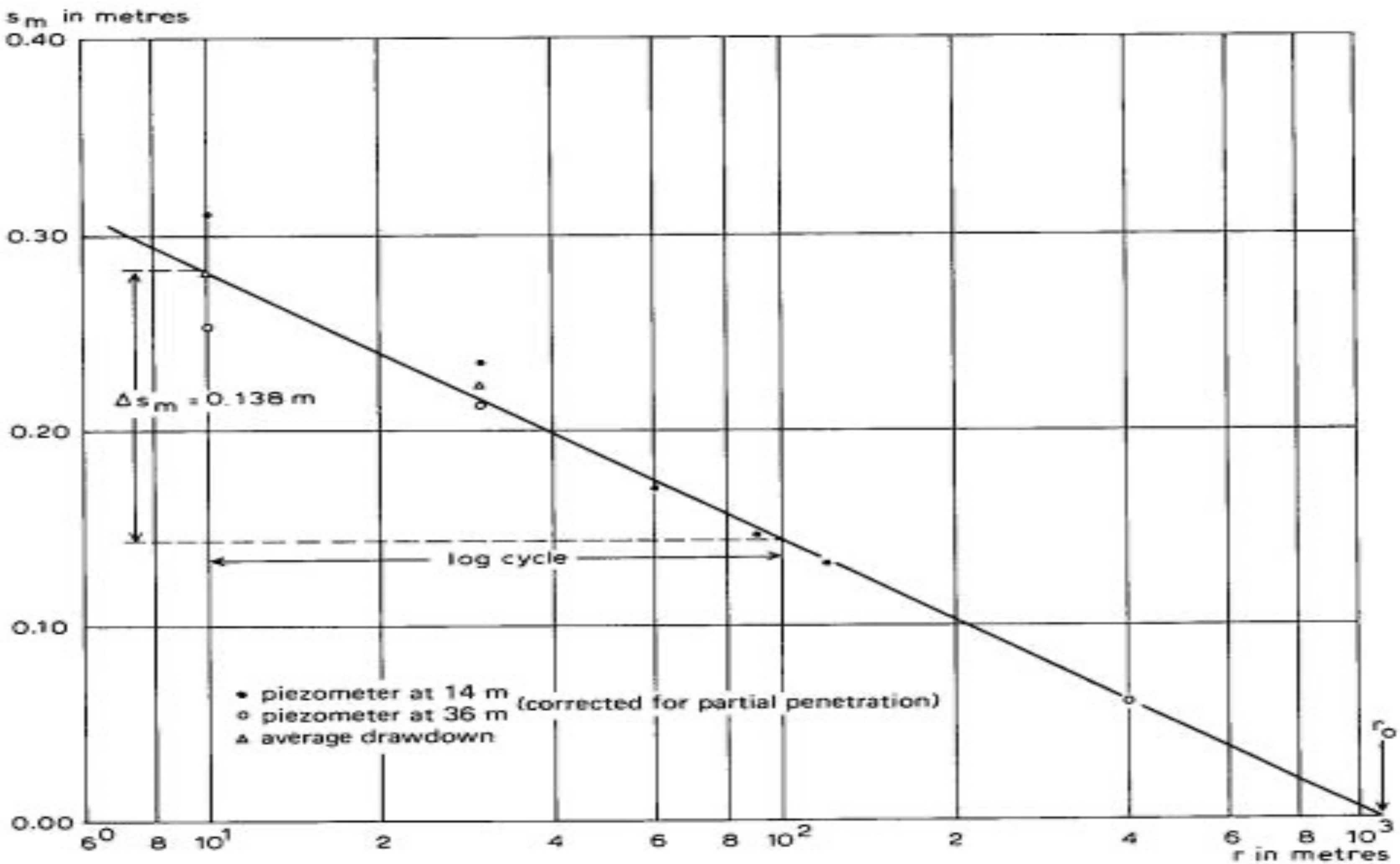
Pumping Test "Dalem"



- Well discharge eventually equilibrates with aquitard leakage
- This results in a constant (steady) drawdown
- During pumping, the water table in the upper unconfined aquifer remains constant
- The rate of leakage from the upper unconfined aquifer into the leaky aquifer is proportional to the hydraulic gradient across the aquitard.
- The assumption of a constant water table will only be satisfied if the upper unconfined aquifer is recharged by an outside source.
- Without recharge, the water table will drop due to its water leakance through the aquitard into the pumped, confined aquifer.
- We also ignore aquitard storage, which is justified for steady flow

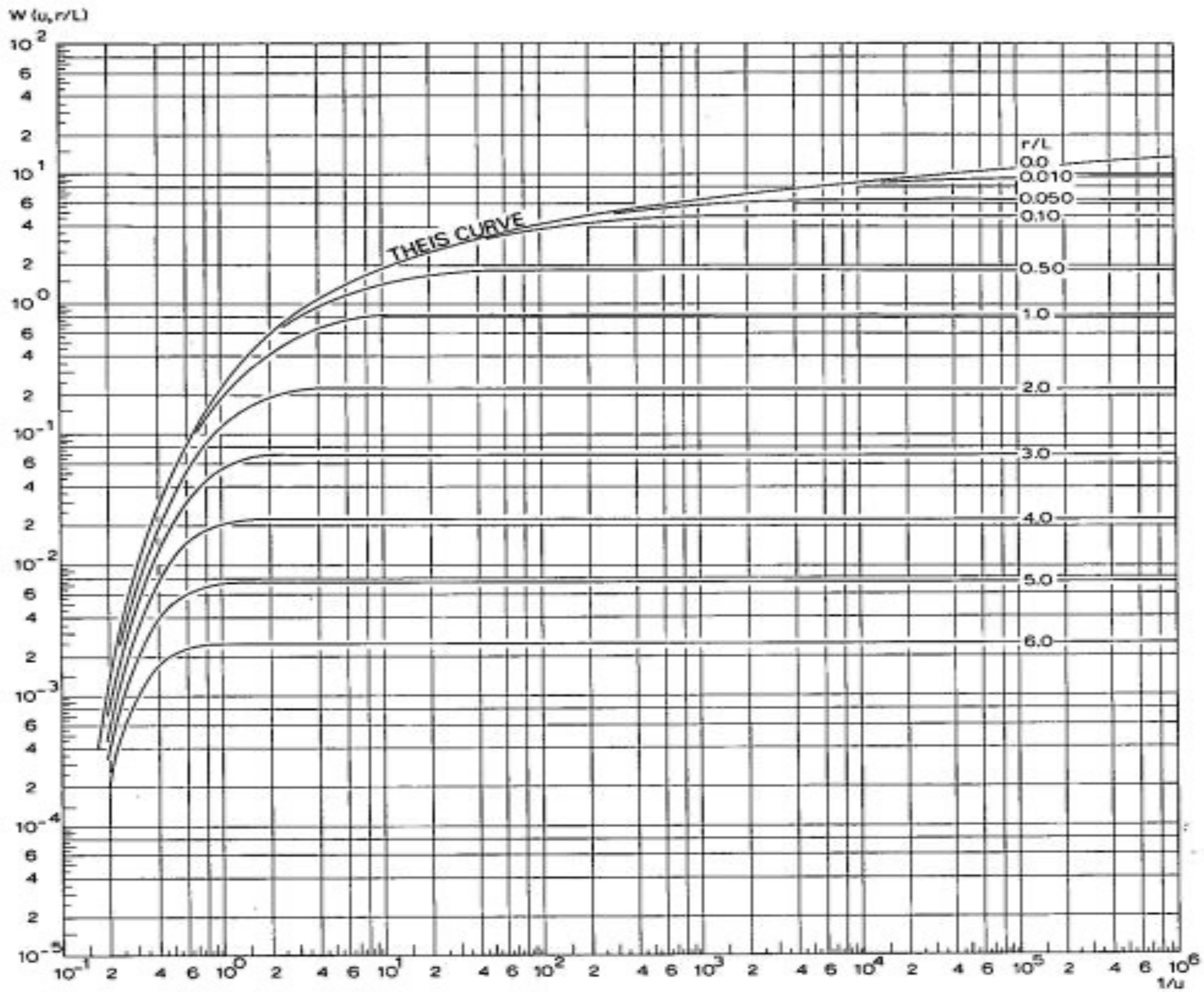
Hantush-Jacob Method

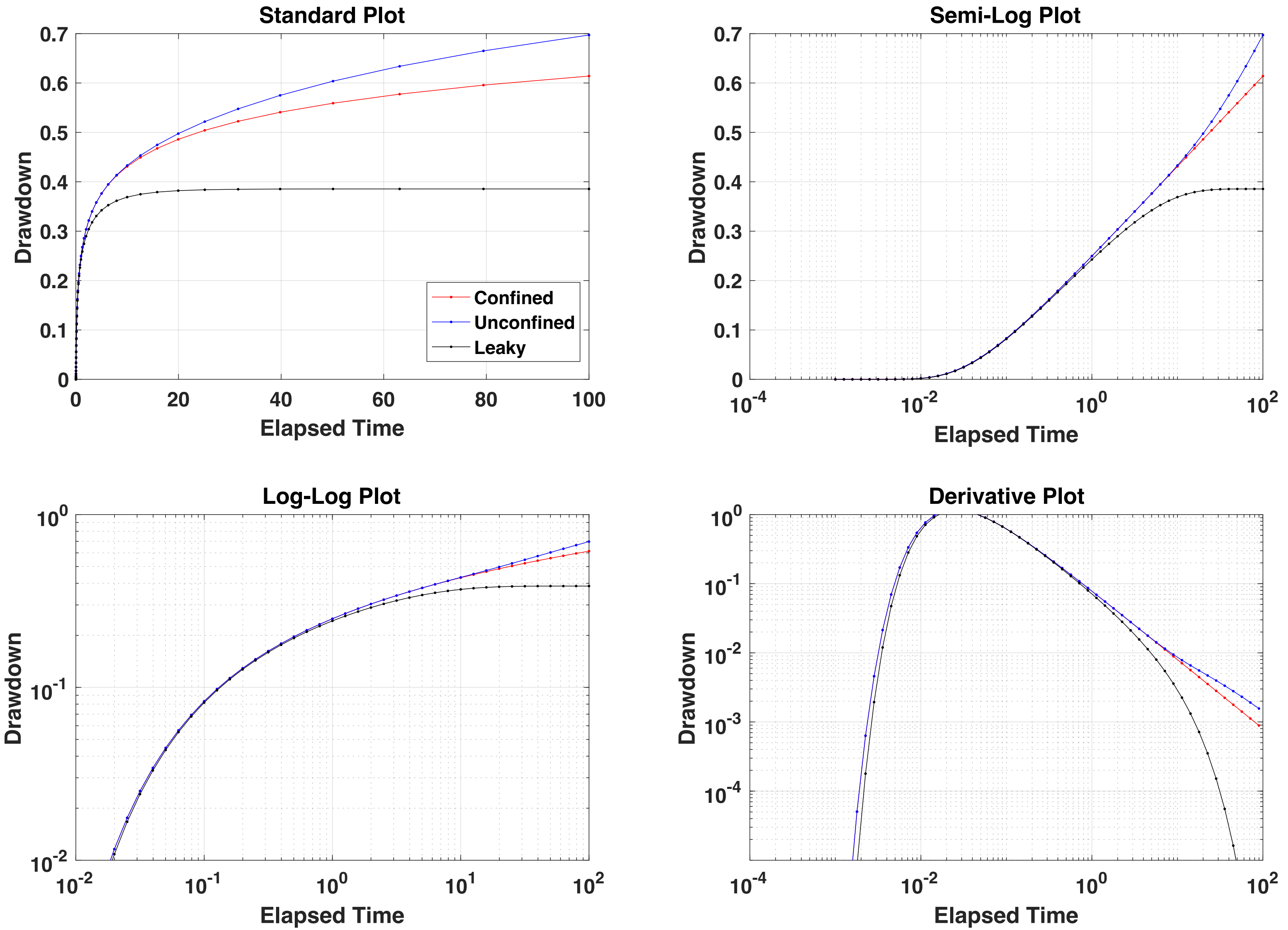
Uses steady state drawdown data and allows the characteristics of the aquifer and the aquitard to be determined.



Walton Method

- Unsteady flow
- This solution has the same form as the Theis well function, but there are two parameters in the integral: u and r/L.
- $s = Q/4\pi T \, W(u,r/L)$
- L = leakance




Standard Plot
Semi-Log Plot
Log-Log Plot
Derivative Plot
Drawdown
Elapsed Time
Confined
Unconfined
Leaky
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
20
40
60
80
100
10^-4
10^-2
10^-1
10^0
10^1
10^2
10^-3

Anisotropy

- A common feature in water-laid sedimentary deposits (fluvial, clastic lake, deltaic and glacial outwash).
- Water-lain deposits may exhibit anisotropy on the horizontal plain (X,Y if looking down from above)
- Water-laid sedimentary deposits are also “stratified” (have layers of alternating stratum, therefore alternating K’s)
- Hydraulic conductivity in the direction of flow tends to be greater than that perpendicular to flow, which causes lines of equal drawdown to form ellipses rather than circles.
- Any layer with a low K will retard vertical flow, but horizontal flow can occur easily through any layer with relatively high K.
- When K_h (parallel to the layer) is larger than K_v (perpendicular to layer), the aquifer is said to be “vertically anisotropic”.

3-D Anisotropy

- When an aquifer exhibits both vertical and horizontal anisotropy
- The principal axes are:
  - K_x: direction parallel to stream flow
  - K_y: direction perpendicular to stream flow
  - K_z: the vertical direction

Hantush Approach

- If the principal directions of anisotropy are known
  - Drawdown data from two piezometers on different rays from the pumped well will be sufficient.
- If the principal directions of anisotropy are unknown
  - Drawdown data must be available from at least three rays of piezometers.

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

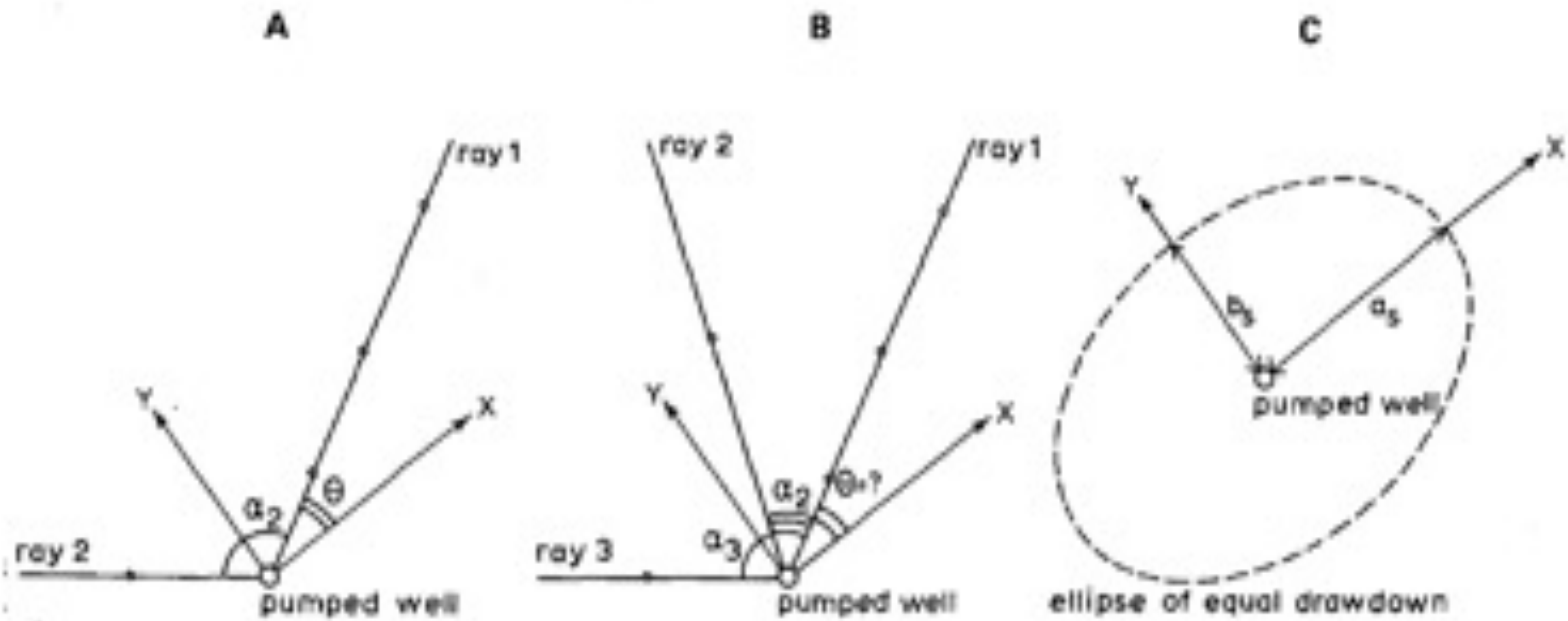


Figure 8.1 The parameters in the Hantush and the Hantush-Thomas methods for aquifers with anisotropy on the horizontal plane:

A. Principal directions of anisotropy known
B. Principal directions of anisotropy not known
C. Ellipse of equal drawdown

Bounded Aquifer

- Either confined or unconfined
- Bounded on one or more sides by either a
  - Recharging boundary (e.g., river or canal)
  - Barrier boundary (e.g., impermeable valley wall)
- Aquifer pump tests must sometimes be conducted near one or more types of boundaries
  - Invalidates the assumption that the aquifer is of “infinite areal extent”
  - The use of image wells and the “principle of superposition” are applied to transform an aquifer of finite areal extent into one of seemingly infinite extent which allows the use of methods from previous chapters

Recharging Boundary

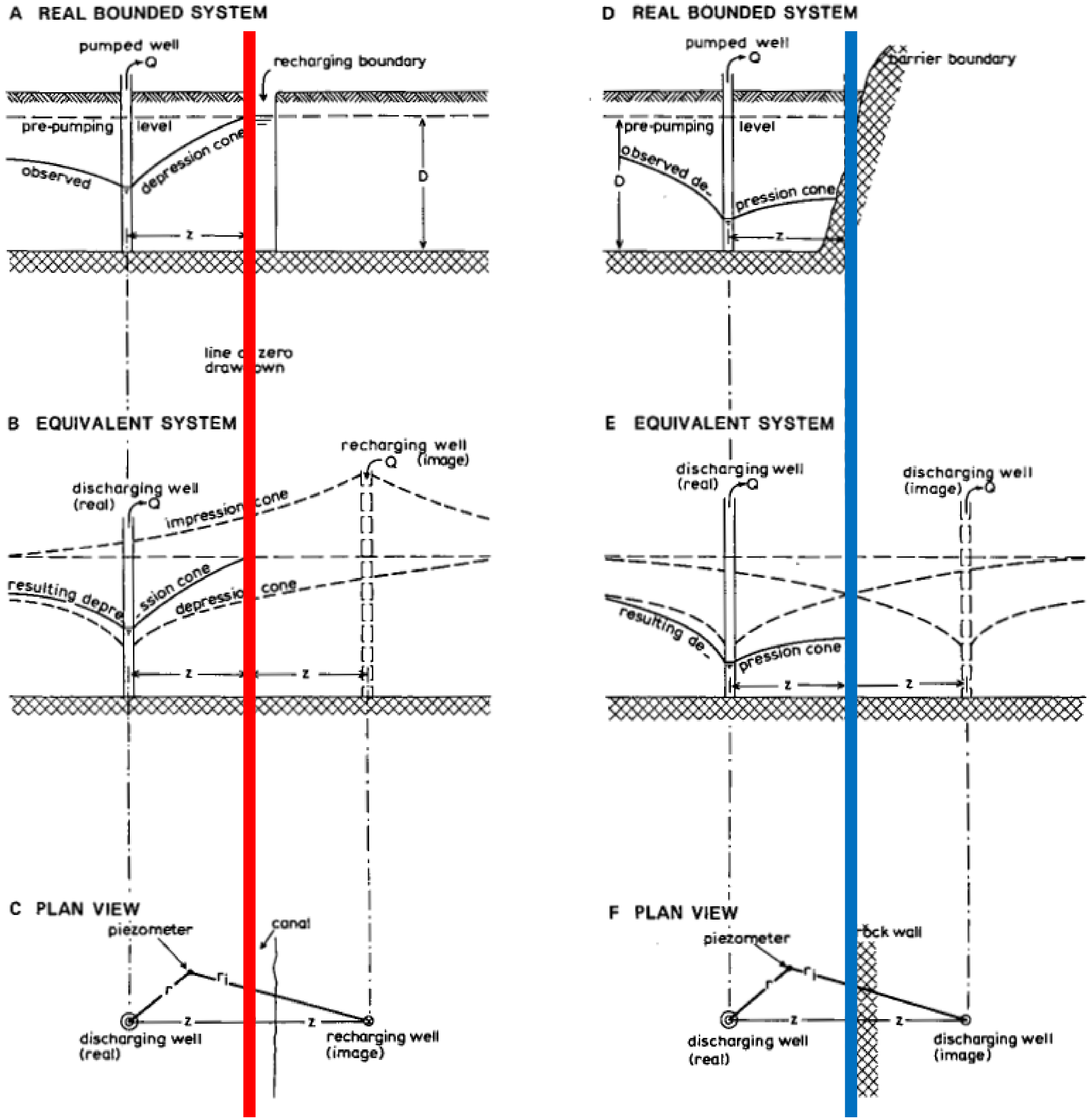


Figure 6.1 Drawdowns in the watertable of an aquifer bounded by:
A) A recharging boundary;
D) A barrier boundary.
B) and E) Equivalent systems of infinite areal extent.
C) and F) Plan views

Barrier Boundary

Image Wells

- Positioned such that that pumping well and image well form mirror images of one another:
- Located on the opposite side of boundary from the pumping well
- At the exact distance away from boundary as the pumping well
- Recharge boundary: image well is a recharge well
- Barrier boundary: image well is a discharge well
- Flow rate is always constant, and is equal to the rate of the real pumping well
- By using the **law of superposition** (i.e., the drawdown from two or more wells can be added to find the resulting overall drawdown) the drawdown from the real well and the image well will give you the actual drawdown
- More than one boundary? More than one image well will be needed

Image Well Positioning

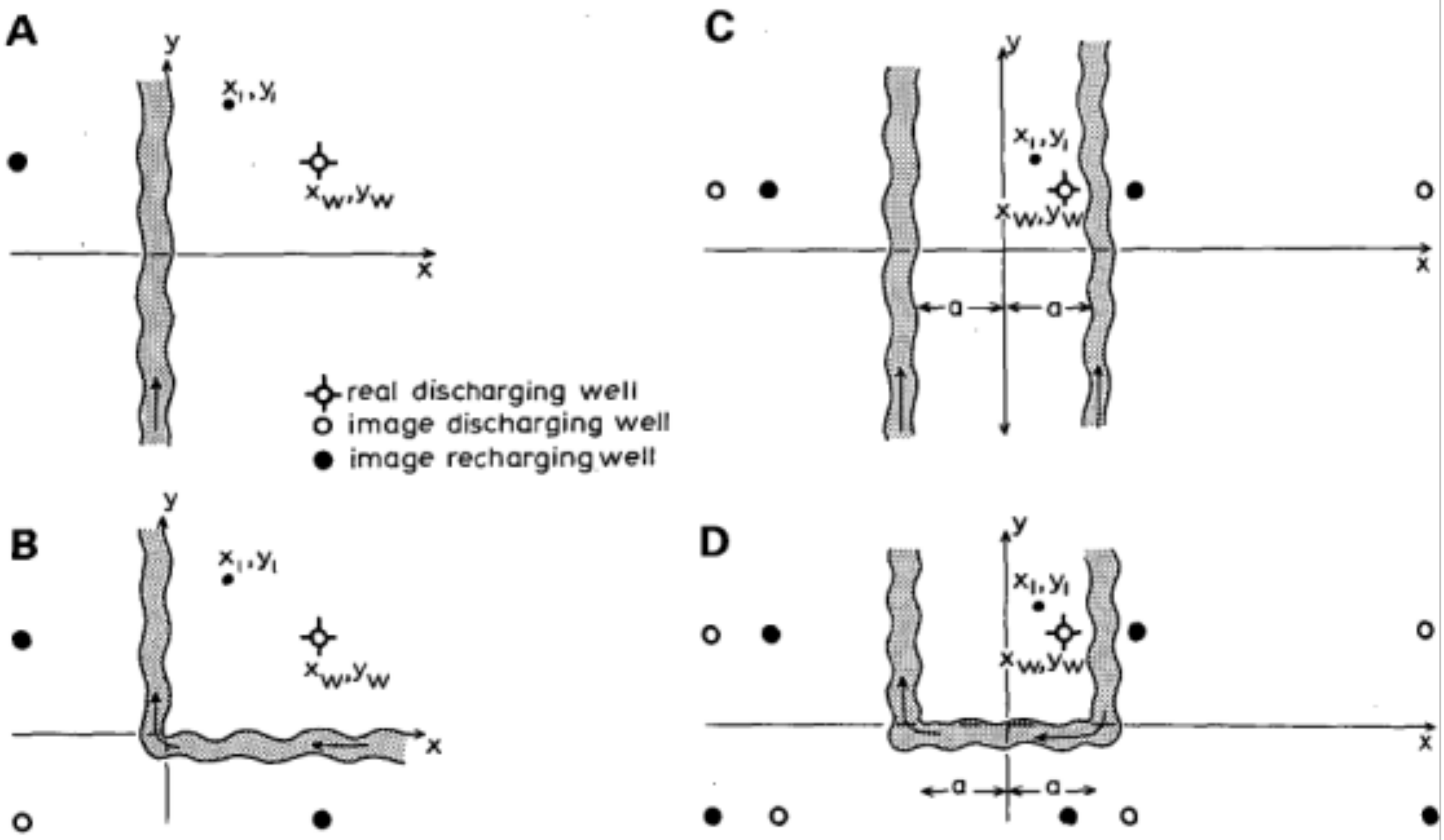
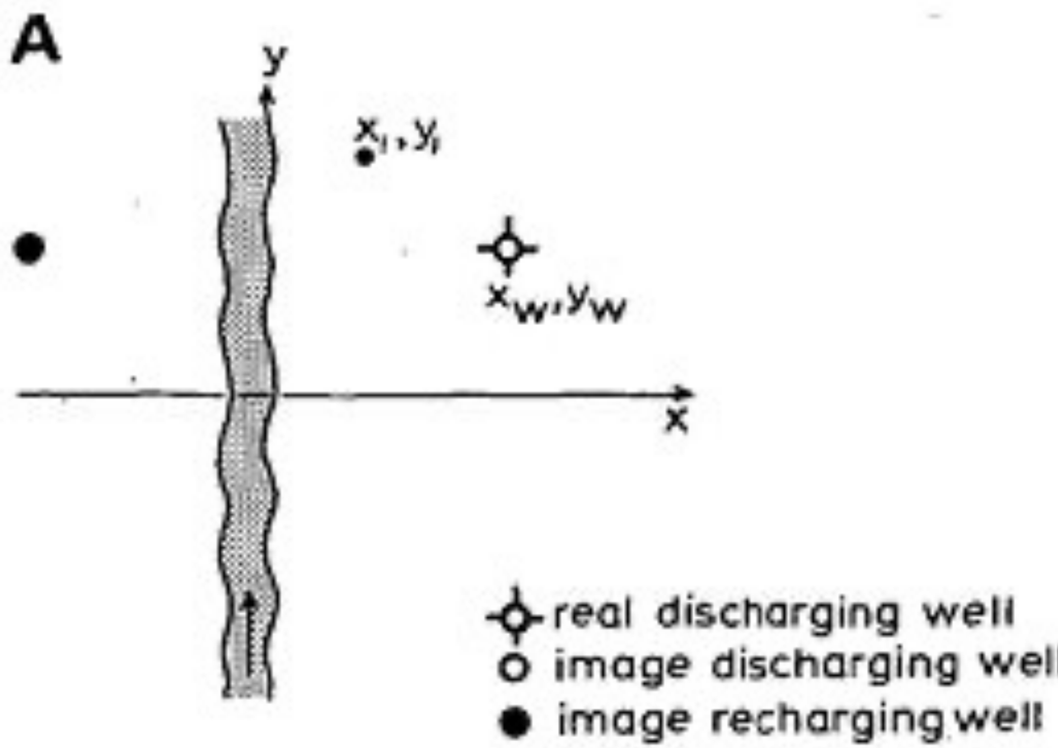


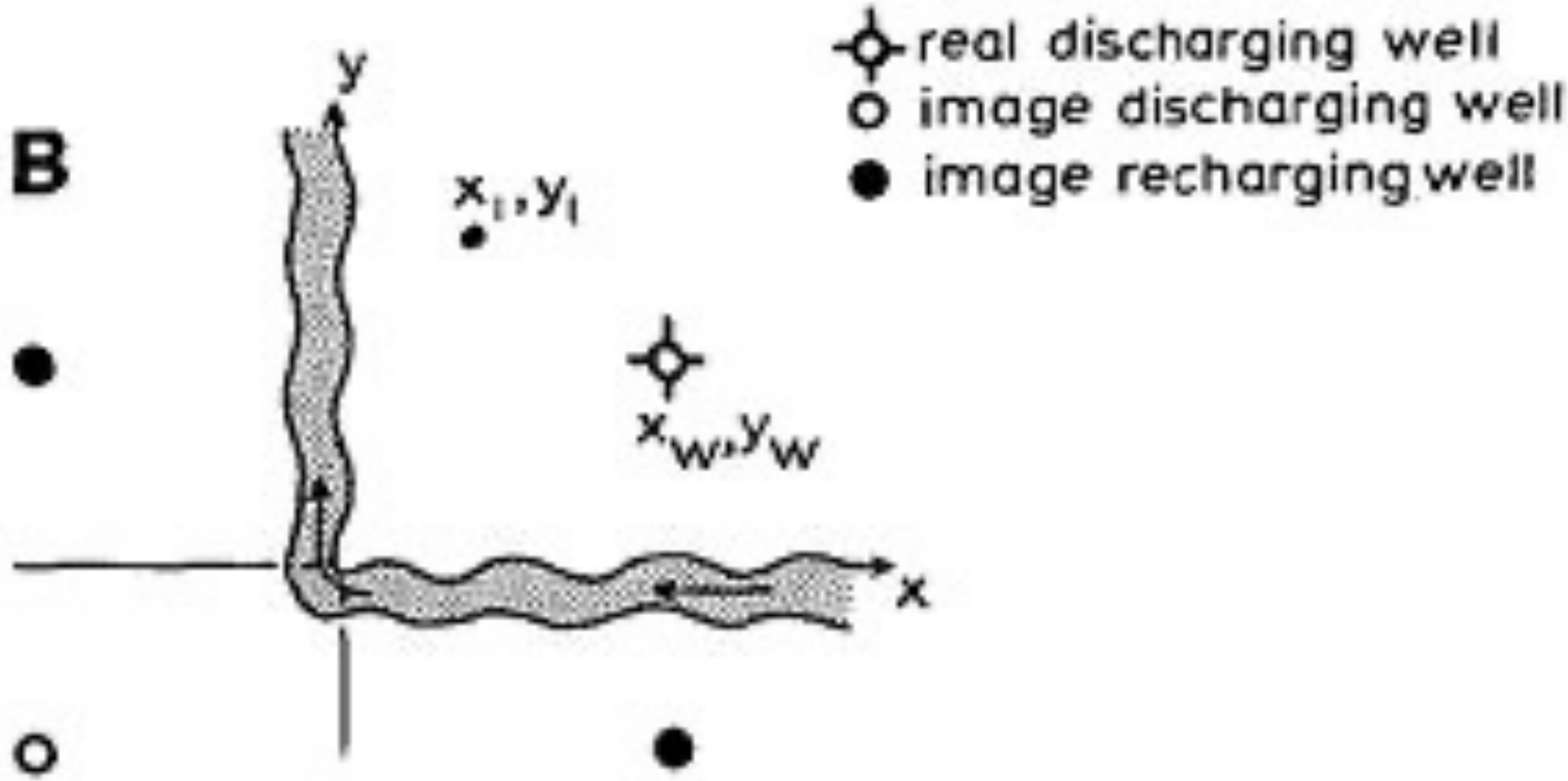
Figure 6.2 Image well systems for bounded aquifers (Dietz method)
A) One straight recharge boundary
B) Two straight recharge boundaries at right angles
C) Two straight parallel recharge boundaries
D) U-shaped recharge boundary

One straight recharge boundary:

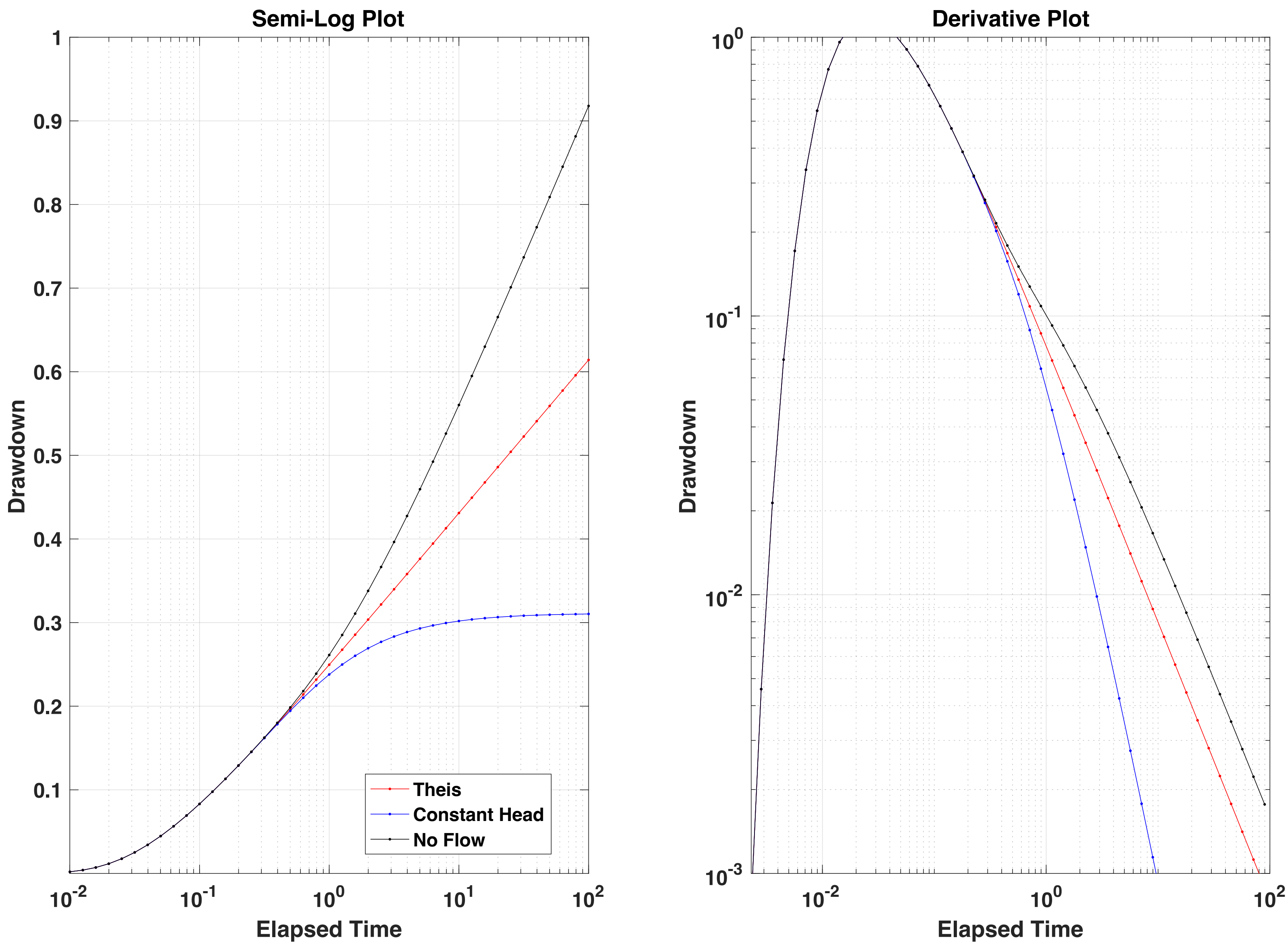


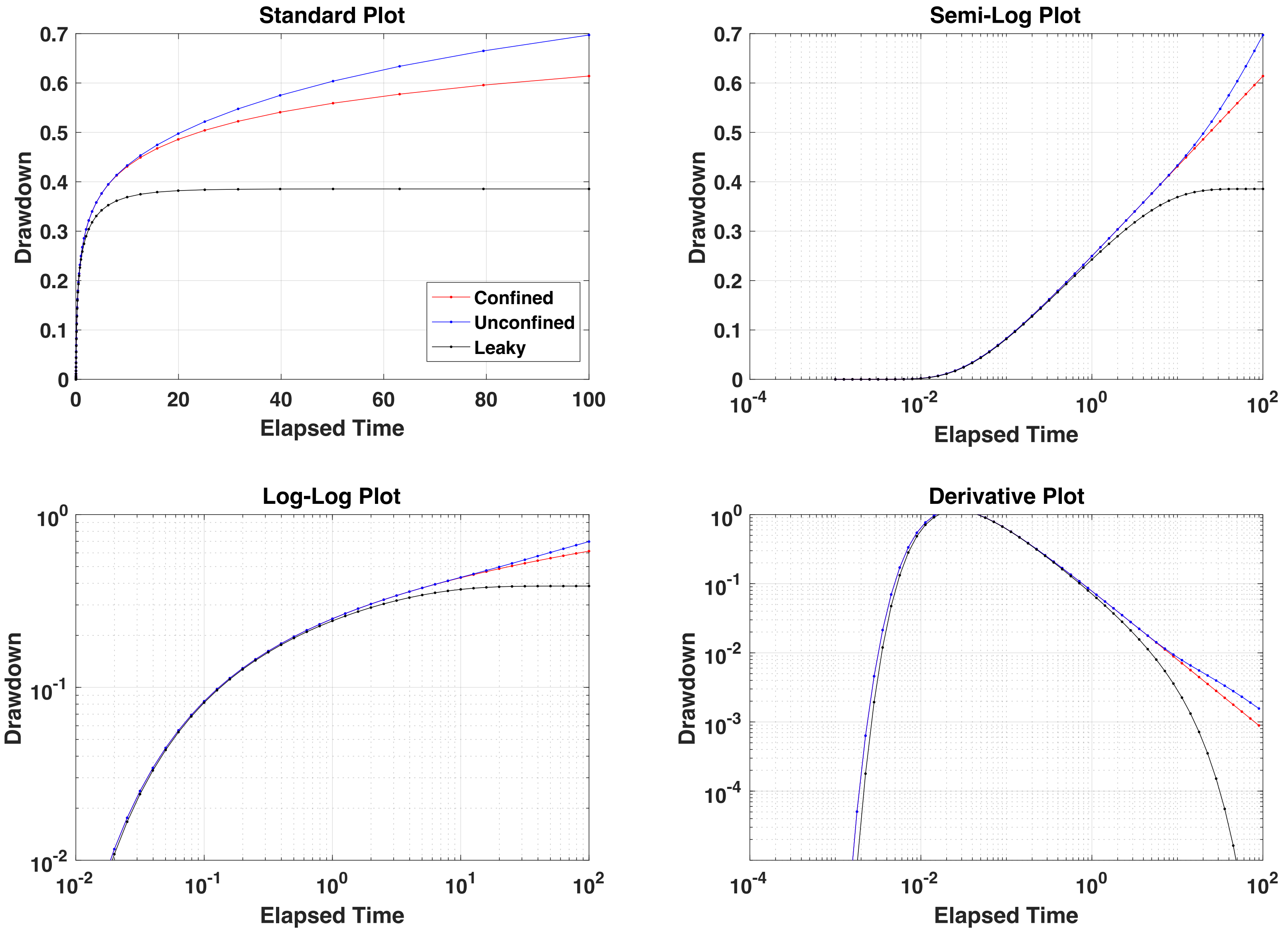
$$G(x,y) = \frac{1}{2} \ln \frac{(x_1 + x_w)^2 + (y_1 - y_w)^2}{(x_1 - x_w)^2 + (y_1 - y_w)^2}$$

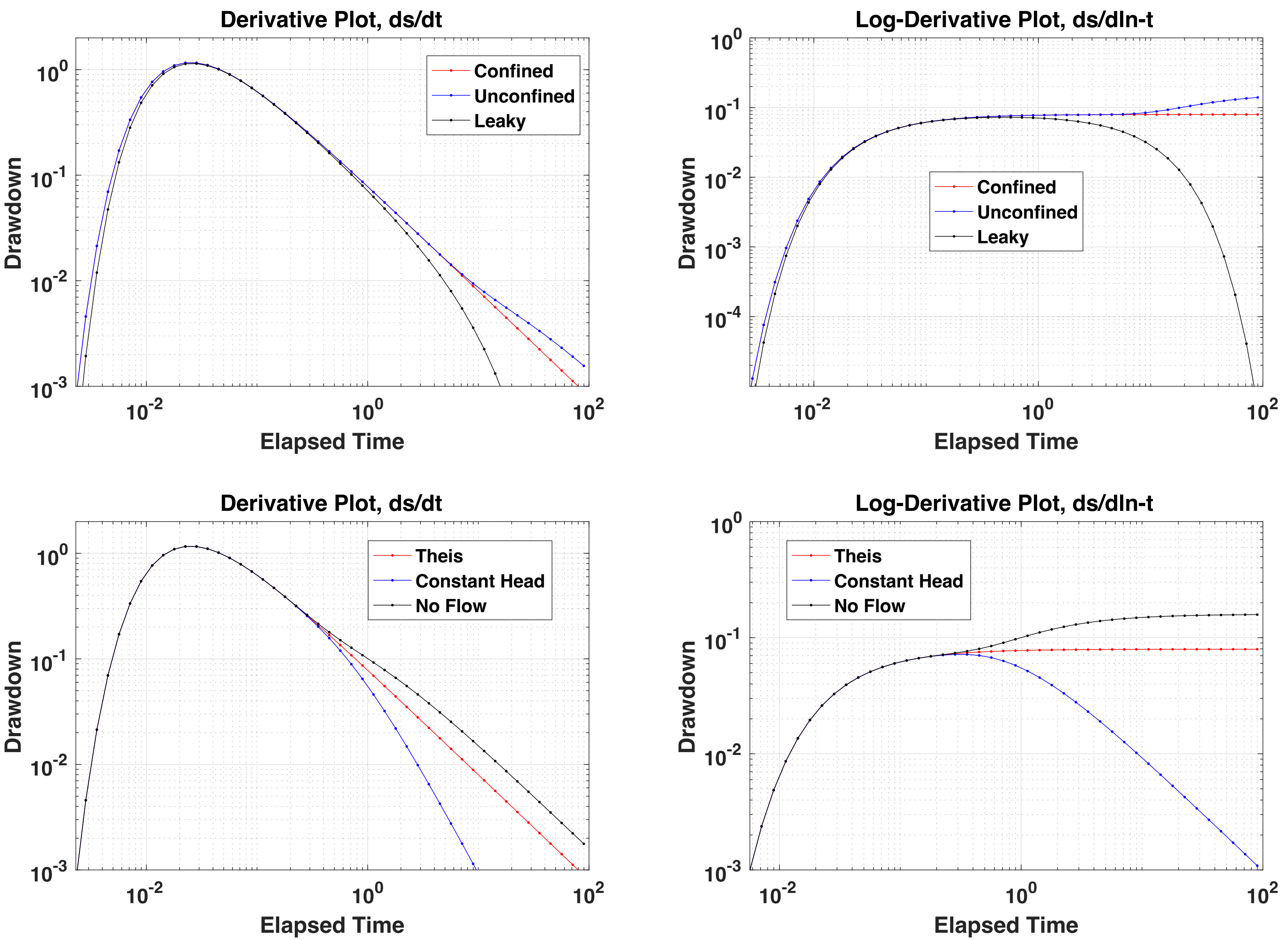
Two straight recharge boundaries at right angles to each other



$$G(x,y) = \frac{1}{2} \ln \frac{[(x_1 - x_w)^2 + (y_1 + y_w)^2]\,[(x_1 + x_w)^2 + (y_1 - y_w)^2]}{[(x_1 - x_w)^2 + (y_1 - y_w)^2]\,[(x_1 + x_w)^2 + (y_1 + y_w)^2]}$$

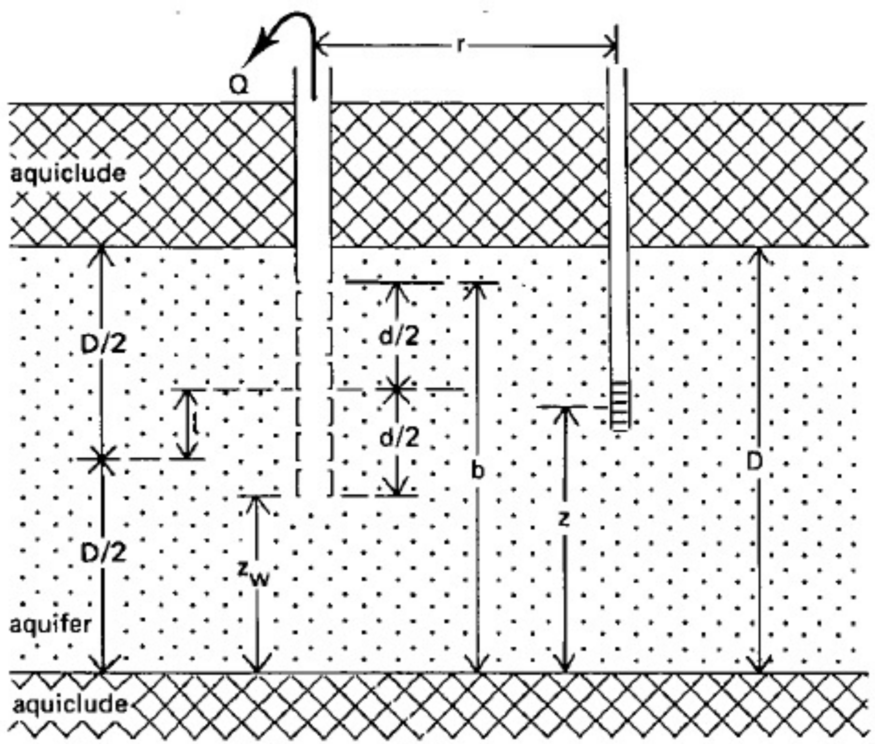

Semi-Log Plot
Drawdown
Elapsed Time
Theis
Constant Head
No Flow
Derivative Plot
Drawdown
Elapsed Time


Standard Plot
Drawdown
Elapsed Time
Confined
Unconfined
Leaky
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
20
40
60
80
100
Semi-Log Plot
Drawdown
Elapsed Time
10^{-4}
10^{-2}
10^{0}
10^{2}
Log-Log Plot
Drawdown
Elapsed Time
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Derivative Plot
Drawdown
Elapsed Time
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}


Derivative Plot, ds/dt
Confined
Unconfined
Leaky
Drawdown
Elapsed Time
Log-Derivative Plot, ds/dln-t
Confined
Unconfined
Leaky
Drawdown
Elapsed Time
Derivative Plot, ds/dt
Theis
Constant Head
No Flow
Drawdown
Elapsed Time
Log-Derivative Plot, ds/dln-t
Theis
Constant Head
No Flow
Drawdown
Elapsed Time

Partially Penetrating Wells

- Aquifer is so thick that a fully penetrating well is impractical
- Increased velocity close to well
- Extra head losses
- Effect is inversely related to distance from well
    - Negligible at distances r > 2b sqrt(Kb/Kv)
    - Standard methods cannot be used at r< 2b sqrt(Kb/Kv)



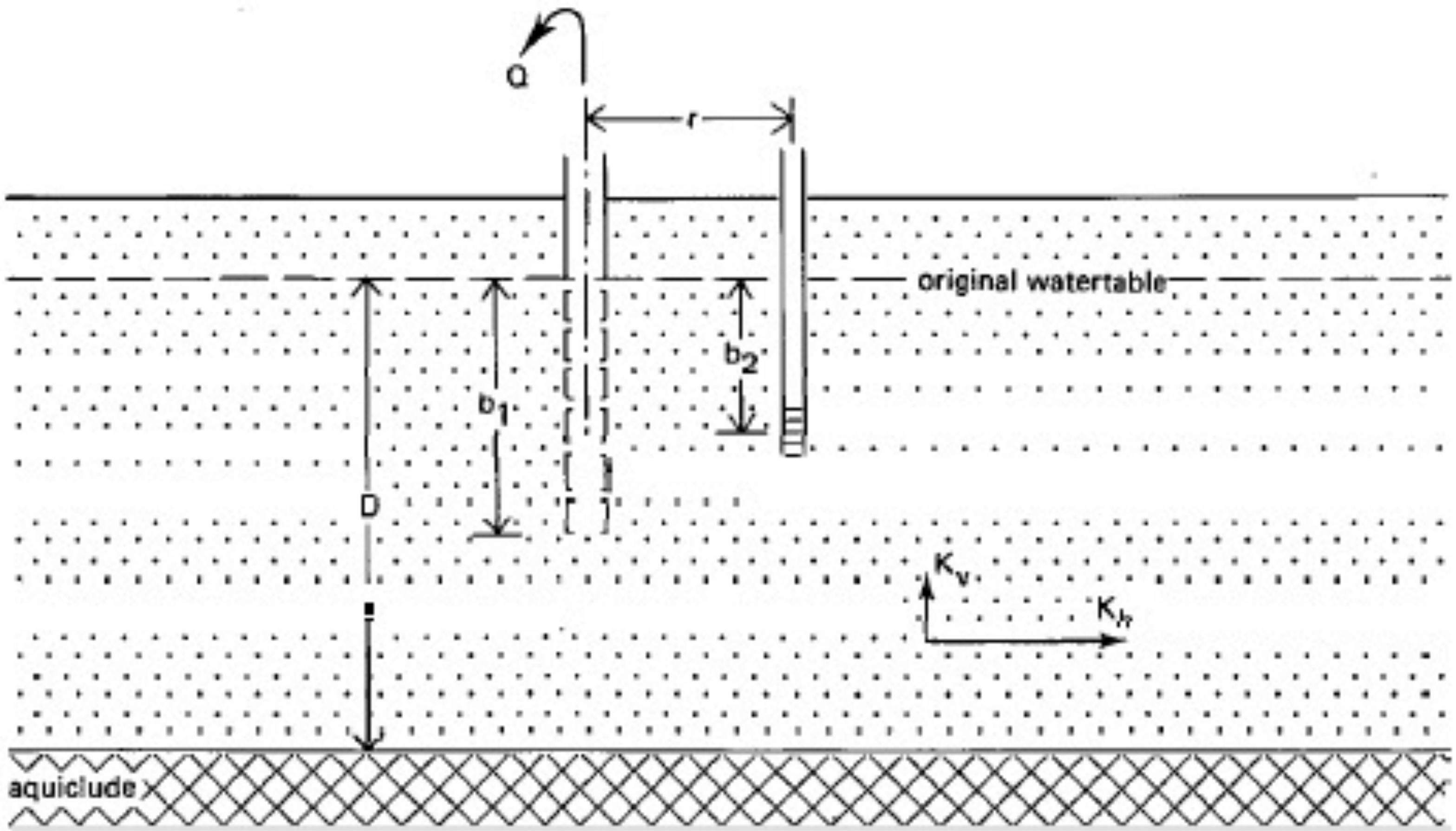


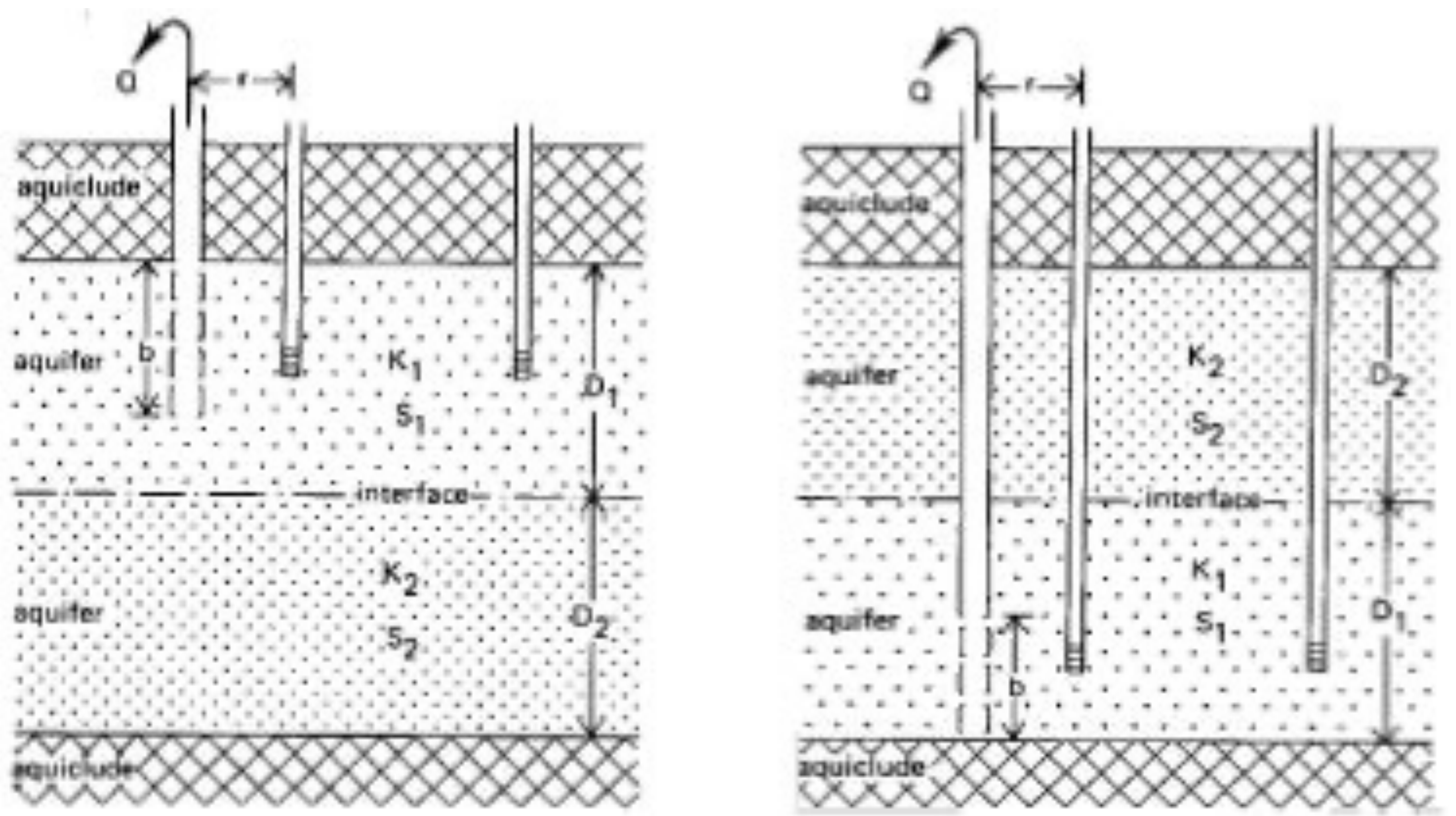
Figure 10.5 Cross-section of an unconfined anisotropic aquifer pumped by a partially penetrating well

Multilayer Aquifers: Case 1

- Consists of two or more aquifer layers separated by aquicludes
  - Two confined aquifers
  - An unconfined aquifer overlying a confined aquifer
- If data on the transmissivity and storativity of the individual layers are needed, a pumping test can be performed in each layer as long as the well does not fully penetrate the entire system
- For an aquifer system consisting of multiple confined aquifers separated by an aquiclude, use an asymptotic solution for non-steady state flow to a well that fully penetrates the system.
- For an aquifer system that consists of an unconfined aquifer overlying a confined aquifer, use a solution for non-steady state flow to a fully penetrating well.

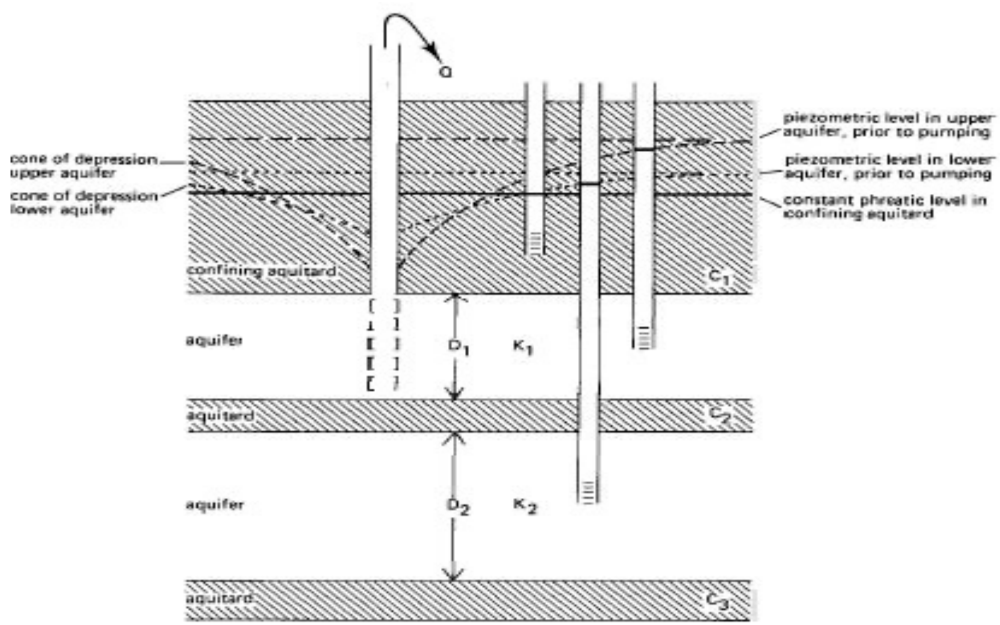
Multilayer Aquifers: Case 2

- Consists of two or more aquifers - each with its own hydraulic characteristics - that are separated by interfaces that allow for unrestricted flow between them, or crossflow.
- A response to pumping will be analogous to that of a single-layered whose transmissivity and storativity are equal to the sum of the transmissivity and storativity of the individual layers.



Multilayer Aquifers: Case 3

- Consists of multiple aquifers layers separated by aquitards.
- In this leaky system, pumping one layer has measureable effects in other layers of the aquifer system.
- The effects are dependent upon the hydraulic characteristics of the individual layers and the aquitards.
- For short pumping tests in these systems, drawdown in the unpumped layers can be considered negligible, and we would use previous methods to find aquifer properties.
- For longer pumping times, use a method for the analysis of pumping data from leaky two-layered aquifer systems in steady state.



Matrix Representation

$$\nabla^2 \vec{h} = \mathbf{D}^{-1} \frac{\partial \vec{h}}{\partial t} + \mathbf{A}\, \vec{h}$$

- h is the vector of heads in each layer
- D is the diagonal matrix of hydraulic diffusivities in each layer
- A is a matrix that represents the vertical flow between layers

$$\mathbf{A} = \begin{bmatrix} \frac{C_1}{T_1} & -\frac{C_1}{T_1} & 0 & 0 & \cdots \\ -\frac{C_1}{T_2} & \frac{C_1+C_2}{T_2} & -\frac{C_2}{T_2} & 0 & \cdots \\ 0 & -\frac{C_2}{T_3} & \frac{C_2+C_3}{T_3} & -\frac{C_3}{T_3} & \cdots \\ \vdots & & & \ddots & \vdots \\ 0 & 0 & \cdots & -\frac{C_{n-1}}{T_n} & \frac{C_{n-1}}{T_n} \end{bmatrix}$$

- $T_i = b_i K_i$ are the horizontal transmissivities in each layer
- $C_i = K_i' / b_i'$ are the vertical conductances between layers