NORAD supported project in MRRD covering
Capacity Building and Institutional Cooperation in the
field of Hydrogeology for Faryab Province
Afghanistan

Hydrogeology Course 1.5
Introduction to Well Hydraulics

By Andreas de Jong
October 2013

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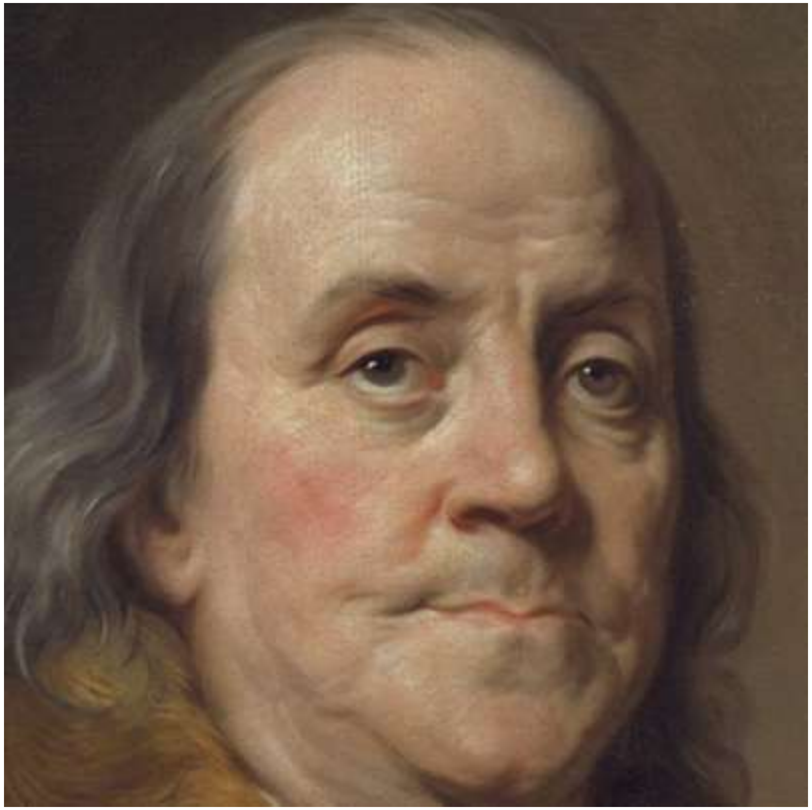

"When the well's dry,
we know the worth of water."
Benjamin Franklin (1706 - 1790)

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PURPOSE OF THIS COURSE

The purpose of this course is to provide an introduction to:

1. Key issues to consider when designing a pumping test.
2. Practical considerations for carrying out a pumping test.
3. The theory of groundwater flow to a pumping well.
4. The main techniques of pumping test interpretation, illustrated by practical examples.
5. The key issues that should be discussed in the report.

KEY REFERENCES

Kruseman & de Ridder, (1994), Analysis and Evaluation of Pumping Test Data; ILRI publication 47

Glenn M. Duffield, Aquifer Testing Reference List: http://www.aqtesolv.com/aquifer-tests/aquifer-testing-references.htm

Tentative Course Schedule

Day	Date	Activity
1	Monday 07/10/13	Opening & Introduction Lecture: Introduction to Well Hydraulics Practical: Well Performance Tests
2	Tuesday 08/10/13	Practical: Confined Aquifers Practical: Leaky - Confined Aquifers
3	Wednesday 09/10/13	Practical: Unconfined Aquifers Practical: Recovery Tests
4	Saturday 12/10/13	Practical: Pressure Transducer Data Practical: Advanced Pumping Test Programs
5	Sunday 13/10/13	Practical: Afghan examples and/or pumping test in MRRD compound
6	Monday 14/10/13	Practical: Afghan examples and/or pumping test in MRRD compound
7	Tuesday 15/10/13	Final Course Workshop & Presentation of Certificates

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TOPICS TO BE COVERED

1. Terminology
2. Purpose of pumping tests
3. How to plan and set up a pumping test
4. Analysis of pumping test data
5. Reporting

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PART 1 –Terminology

1. Pumping test terminology
2. Aquifer terminology & properties

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Pumping Test Terminology (I)

Well Yield is the quantity of water which can be pumped from a well over a period of time. It is measured in L/sec, m^3/h, m^3/d.

Specific Capacity is a measure to compare wells with different yields. It is the ration of pumping rate/drawdown (e.g. m^3/d / m)

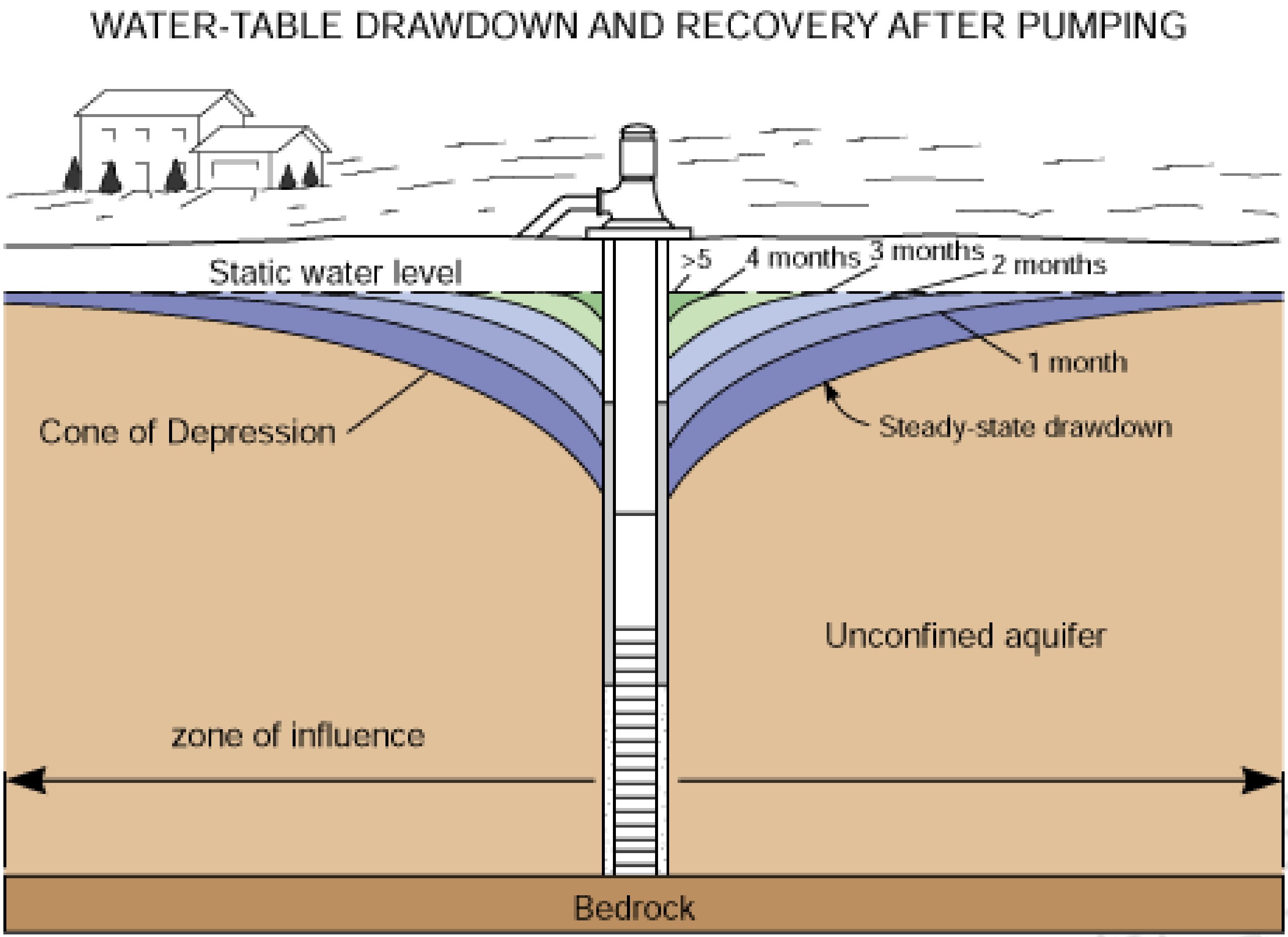
Pumping Test Terminology (II)

Static water level is the water level in a well when there is no pumping, and the water level has stabilized.

Dynamic or pumping water level is the water level in the well when it is being pumped.

Drawdown is the difference between the pumping water level and the static water level.

Drawdown



Source: http://www.kgs.ku.edu/HighPlains/atlas/drawdown.gif

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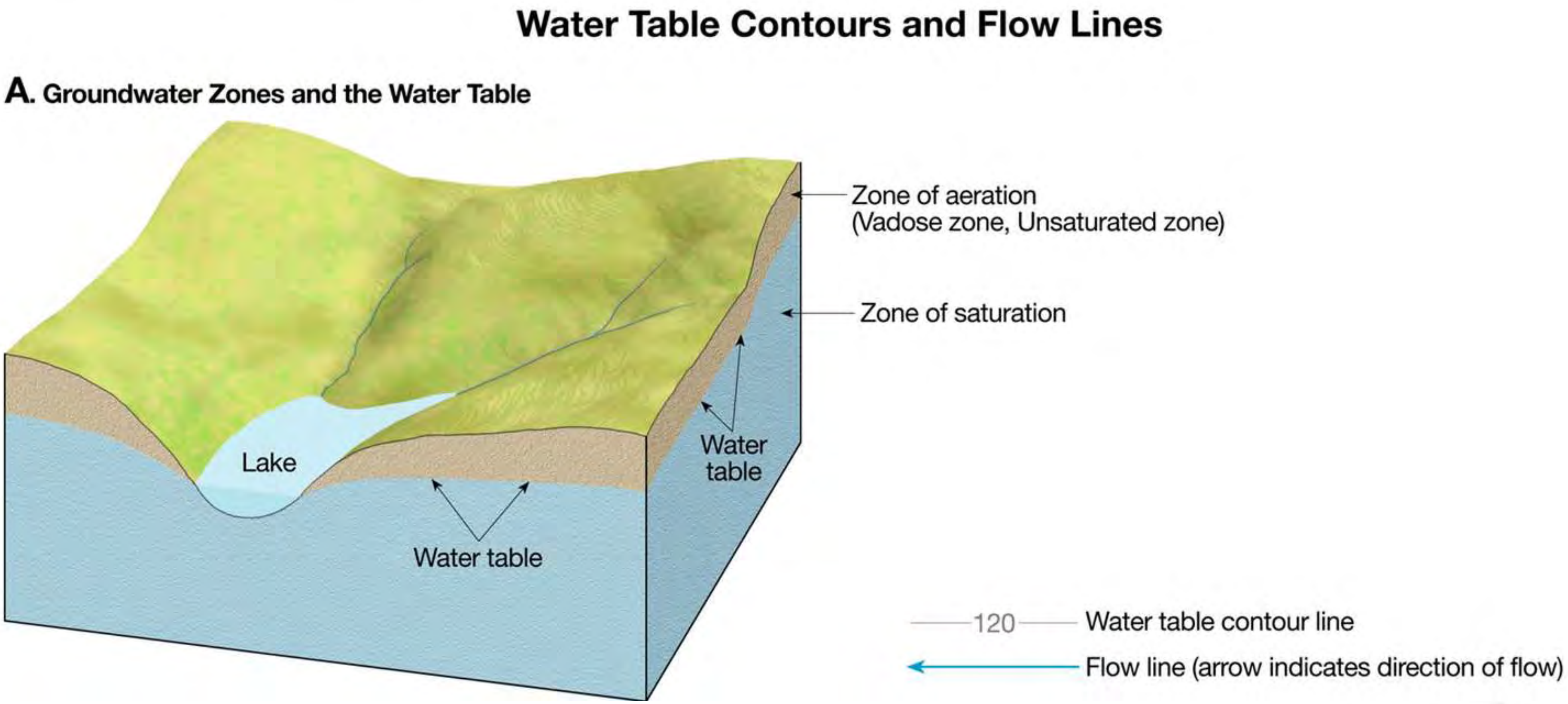
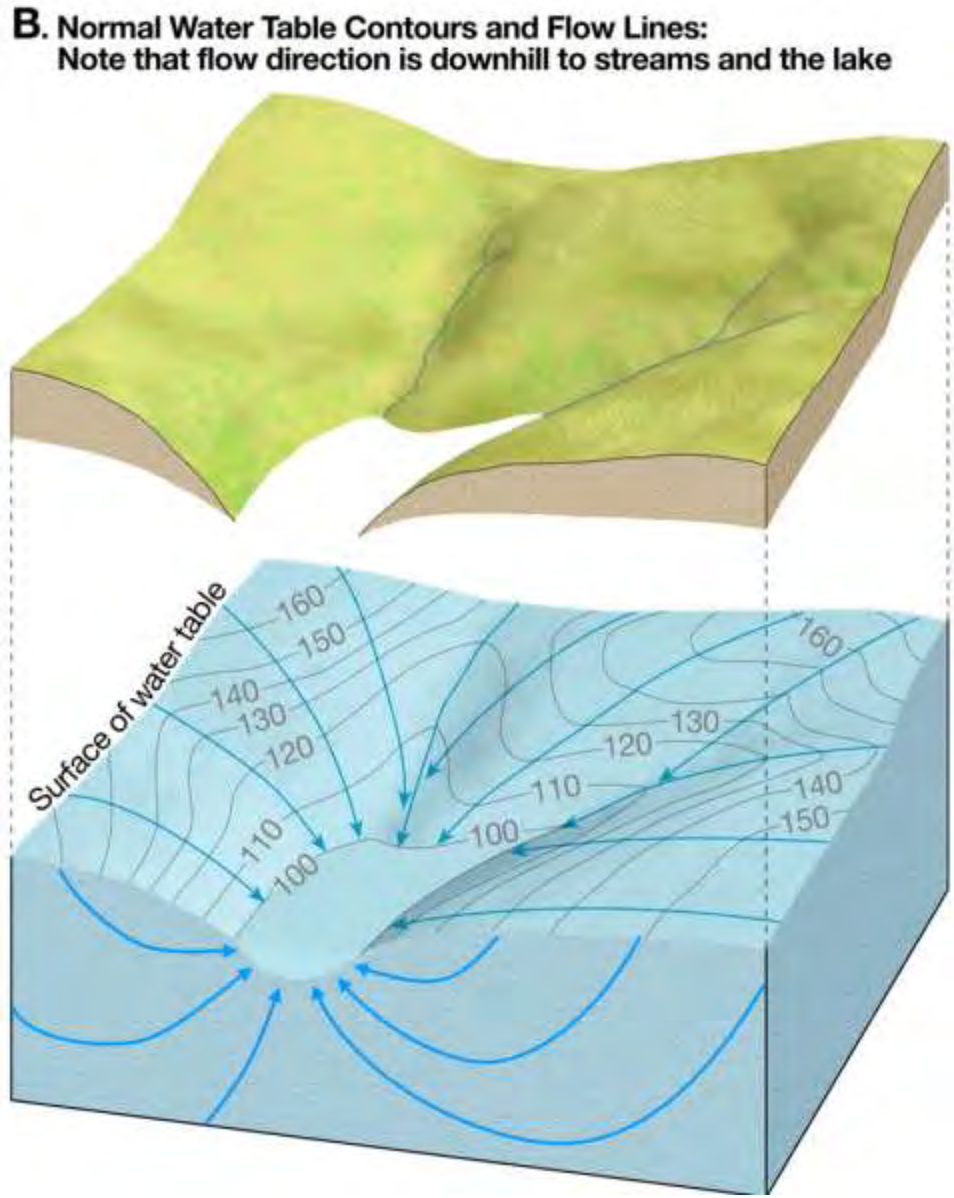
Cone of Depression



Cone of Depression



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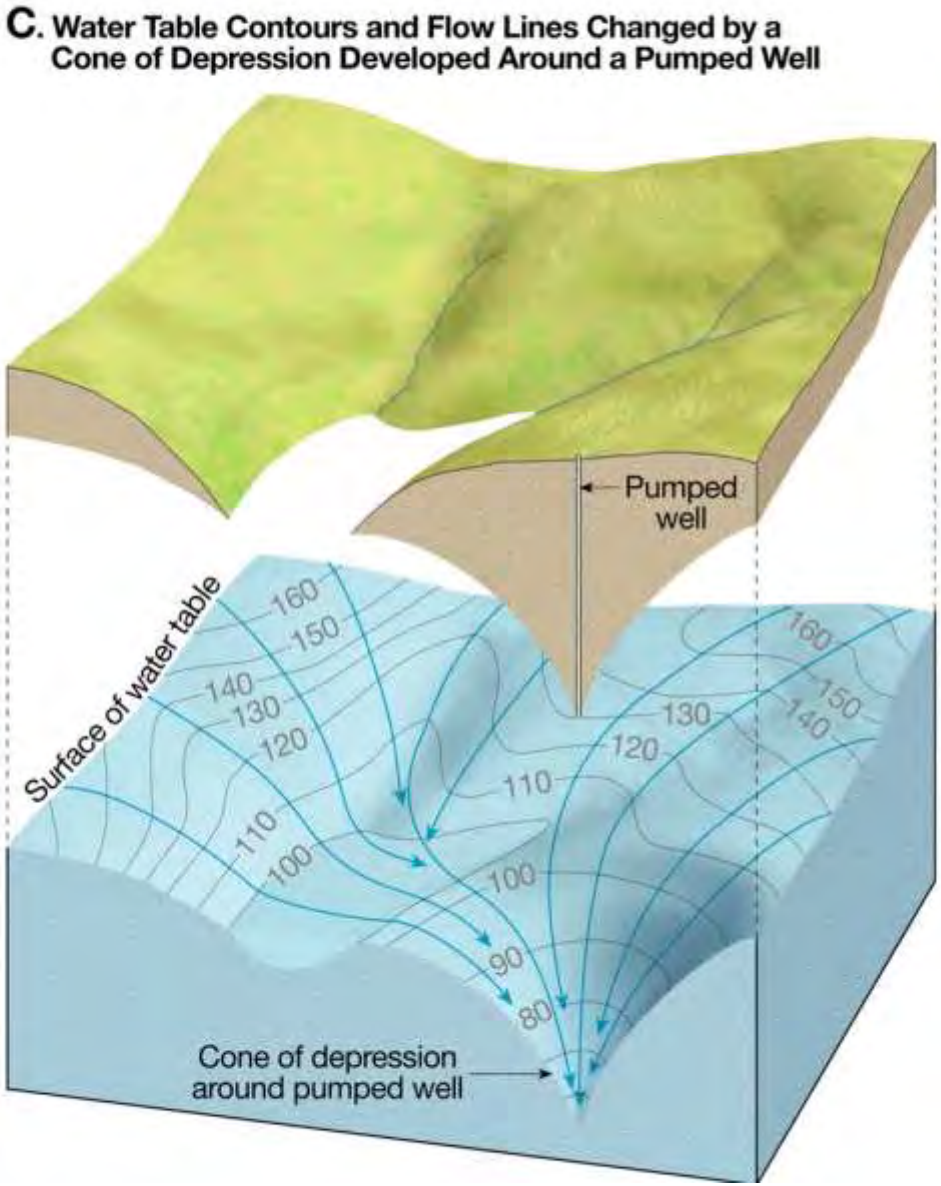
Cone of Depression



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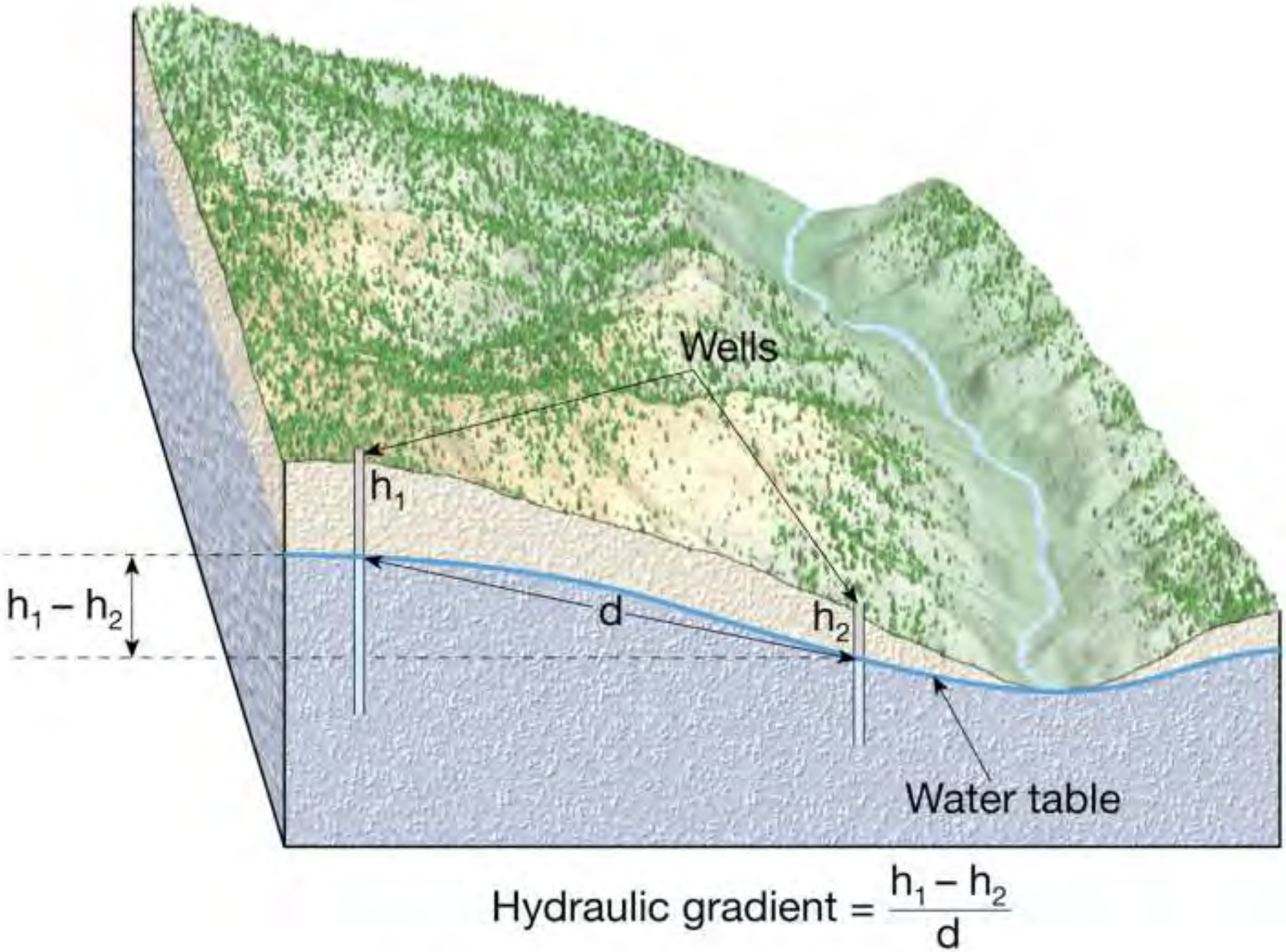
Steady & unsteady-state flow

Steady-state flow means no change in groundwater levels over time. i.e the discharge is balanced by recharge, and the system has reached equilibrium.

Unsteady-state flow occurs from when the pump is switched on until steady-state is reached.

Hydraulic Gradient



Definitions: Aquifer

An **aquifer** is a saturated permeable unit which can yield economic quantities of water to wells.
e.g. gravels, sands, fractured granites.

Definitions: Aquitard

An **aquitard** is a geological unit that is permeable enough to transmit water in significant quantities over large areas and time, but its permeability is not sufficient to justify production wells.
e.g. clays, loams and shales.

Definitions: Aquiclude

An **aquiclude** is an “impermeable” geological unit that does not transmit water at all.
e.g. dense, unfractured igneous and metamorphic rocks.

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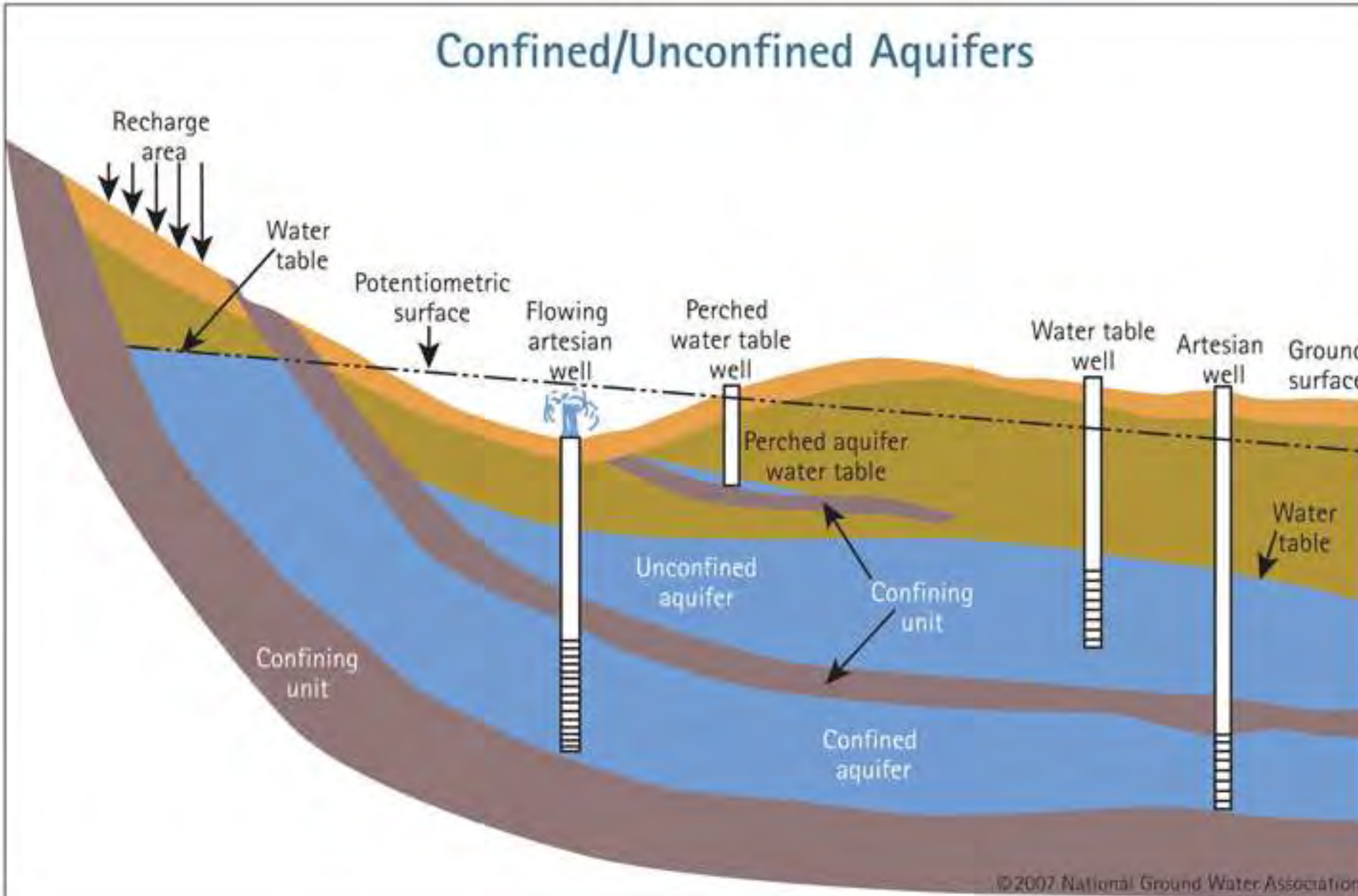
Aquifer types



Source: http://www.artinaid.com/2013/04/types-of-aquifers/

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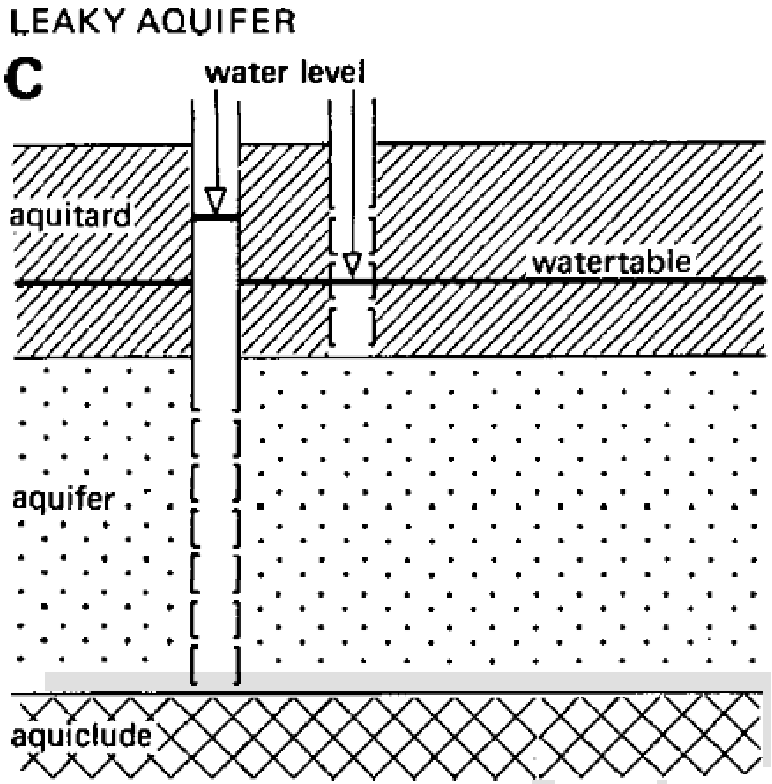
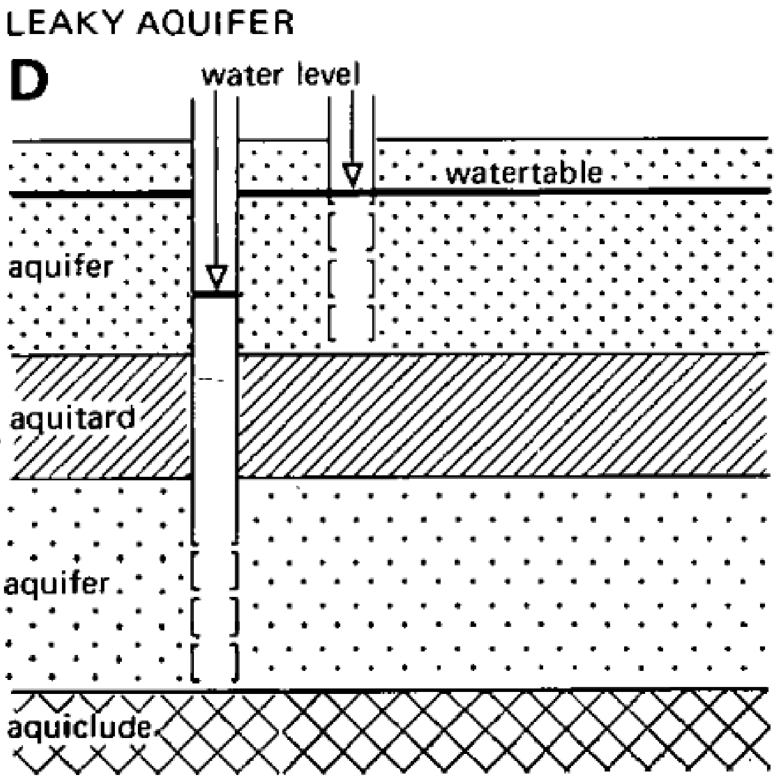
Aquifer types: leaky aquifers





Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

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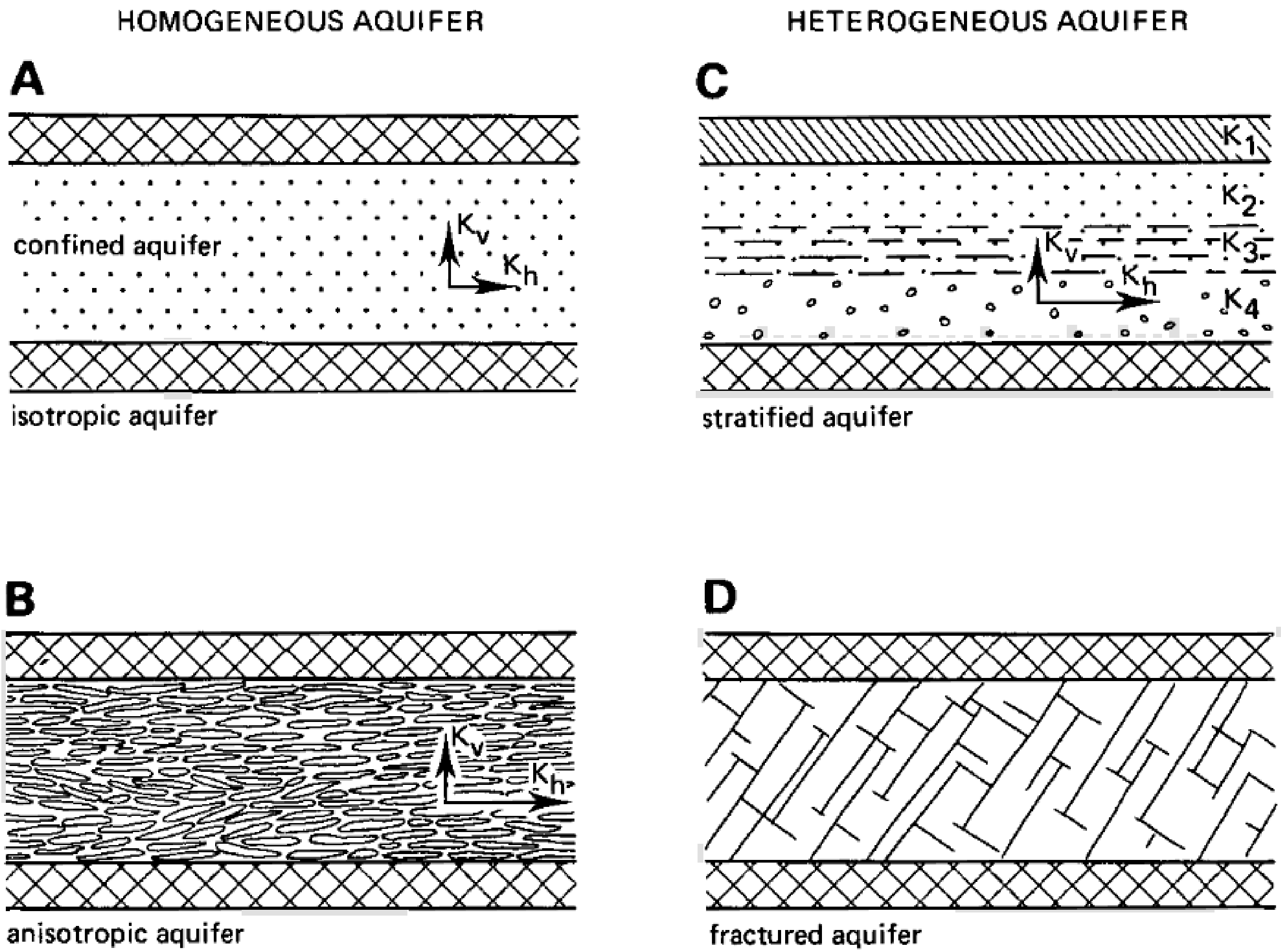
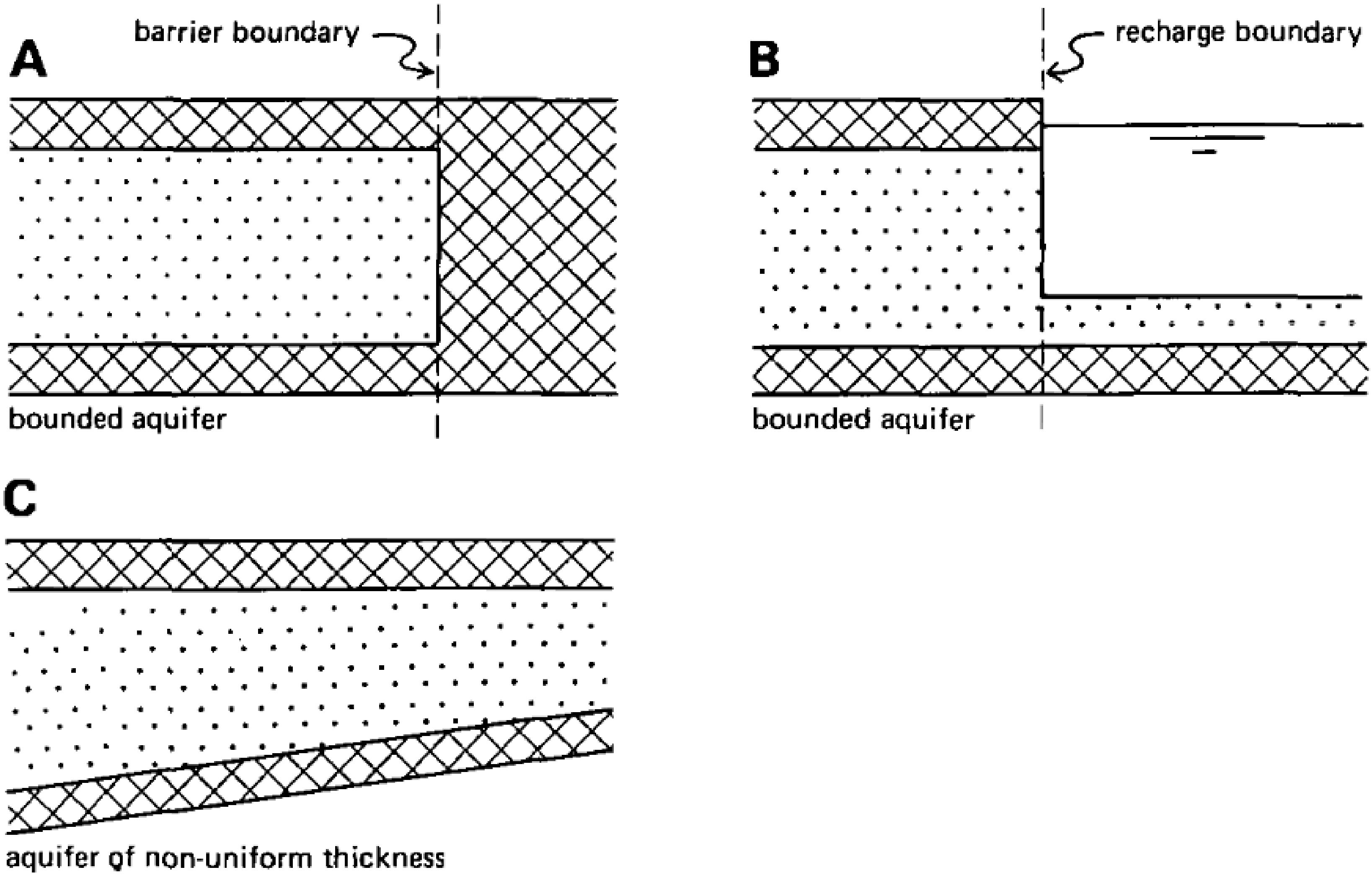
Anisotropy & heterogeneity



Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Bounded aquifers

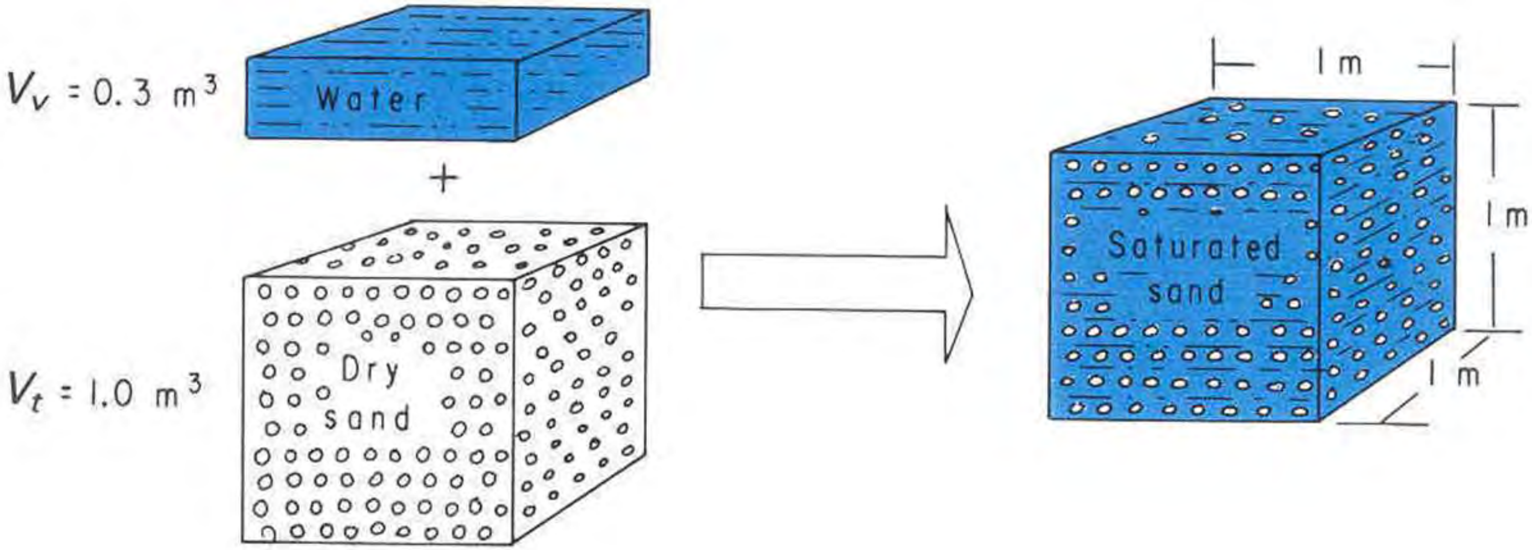


Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Physical Properties

1. Porosity (n)
2. Hydraulic conductivity (K)
3. Transmissivity (KD or T)
4. Compressibility (α & β)
5. Specific storage (S_s)
6. Storativity (S)
7. Specific yield (S_y) & specific retention (S_r)
8. Diffusivity (KD/S)
9. Hydraulic resistance (c)

Porosity



$$\text{Porosity } (n) = \frac{\text{Volume of voids } (V_v)}{\text{Total volume } (V_t)} = \frac{0.3 \text{ m}^3}{1.0 \text{ m}^3} = 0.30$$

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Porosity

Table 1.1 Range of porosity values (n) in percentages

Rocks		Unconsolidated materials	
Sandstone	5 – 30	Gravel	25 – 40
Limestone	0 – 20	Sand	25 – 50
Karstic limestone	5 – 50	Silt	35 – 50
Shale	0 – 10	Clay	40 – 70
Basalt, fractured	5 – 50		
Crystalline rock	0 – 5		
Crystalline rock, fractured	0 – 10		

Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Hydraulic conductivity (K)

The **Hydraulic conductivity** is the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Hydraulic conductivity (K)

Table 1.2 Order of magnitude of K for different kinds of rock (from Bouwer 1978)

Geological classification	K (m/d)
Unconsolidated materials:	
Clay	$10^{-8} - 10^{-2}$
Fine sand	$1 - 5$
Medium sand	$5 - 2 \times 10^{1}$
Coarse sand	$2 \times 10^{1} - 10^{2}$
Gravel	$10^{2} - 10^{3}$
Sand and gravel mixes	$5 - 10^{2}$
Clay, sand, gravel mixes (e.g. till)	$10^{-3} - 10^{-1}$
Rocks:	
Sandstone	$10^{-3} - 1$
Carbonate rock with secondary porosity	$10^{-2} - 1$
Shale	10^{-7}
Dense solid rock	$< 10^{-5}$
Fractured or weathered rock	
(Core samples)	Almost $0 - 3 \times 10^{2}$
Volcanic rock	Almost $0 - 10^{3}$

Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Transmissivity (KD or T)

Transmissivity is the rate of flow under a unit hydraulic gradient through a cross section of unit width over the whole saturated thickness of the aquifer.

Compressibility (α & β)

The **compressibility** is the change in volume, or the strain, induced in aquifer or aquitards under a given stress.

$$\alpha = \frac{-dV_T/V_T}{d\sigma_e}$$

Clay = 10^{-6} to 10^{-8}
Sand = 10^{-7} to 10^{-9}
Gravel &
fractured rocks = 10^{-8} to 10^{-10} m^2/N

$$\beta = \frac{-dV_w/V_w}{dp}$$

Water = 4.4×10^{-10} m^2/N

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Specific storage (S_s)

The **specific storage** of a saturated confined aquifer is the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head.

This is due to the compaction of the aquifer due to increasing effective stress and the expansion of the water due to decreasing pressure.

Storativity (S)

The **storativity** of a saturated confined aquifer is the volume of water released from storage per unit surface area per unit decline in piezometric surface.

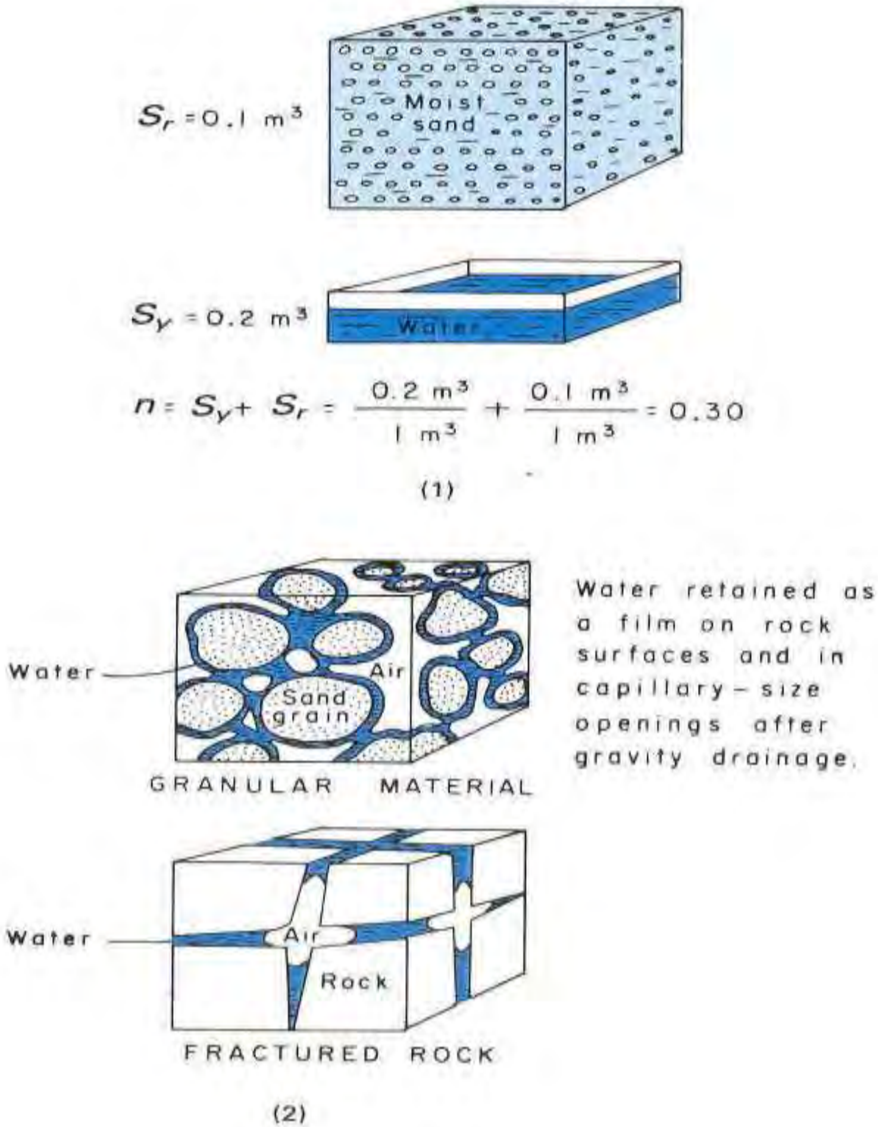
$$S = S_s D$$

S is dimensionless and ranges in confined aquifers from 5 x 10^{-5} to 5 x 10^{-3}

Specific Yield

The **specific yield** is the volume of water than an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table. The values range from 0.01 to 0.30.

Specific Yield & Specific Retention



$n = S_y + S_r$
$S_y = V_d/V_t$
$S_r = V_r/V_t$

n = porosity
S_y= specific yield
S_r= specific retention
V_d=volume of water that drains from a total volume of V_t.,
V_r is the volume of water retained in a total volume of V_t
V_t= total volume of a soil or rock sample

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Specific Yield & Specific Retention

SELECTED VALUES OF POROSITY, SPECIFIC YIELD, AND SPECIFIC RETENTION

[Values in percent by volume]

Material	Porosity	Specific yield	Specific retention
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (semiconsolidated)	11	6	5
Granite	.1	.09	.01
Basalt (young)	11	8	3

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Diffusivity (T/S)

The **hydraulic diffusivity** is the ratio of the transmissivity and storativity of a saturated aquifer. It governs the propagation in changes in hydraulic head in the aquifer.

Dimension = Length^2/Time

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Hydraulic resistance (c)

The **hydraulic resistance** is the resistance of an aquitard to vertical flow.

$$c = \frac{D'}{K'}$$

Dimension = Time

Typical values = 100s to >10 000 days

Leakage Factor (L)

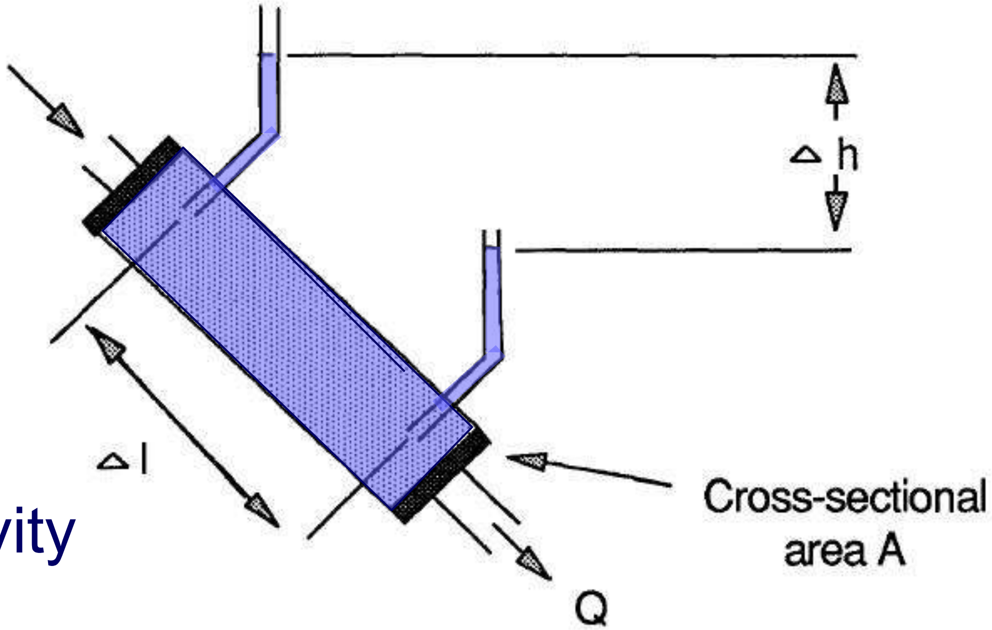
The **leakage factor** is a measure of the spatial distribution of the leakage through an aquitard into a leaky aquifer and vice versa.

$$L = \sqrt{KDc}$$

Dimension = Length (m)
Large L = low leakage rate through the aquitard.

Darcy's Law

$$Q = KiA$$



Q = discharge
K = hydraulic conductivity
i = hydraulic gradient
A = area

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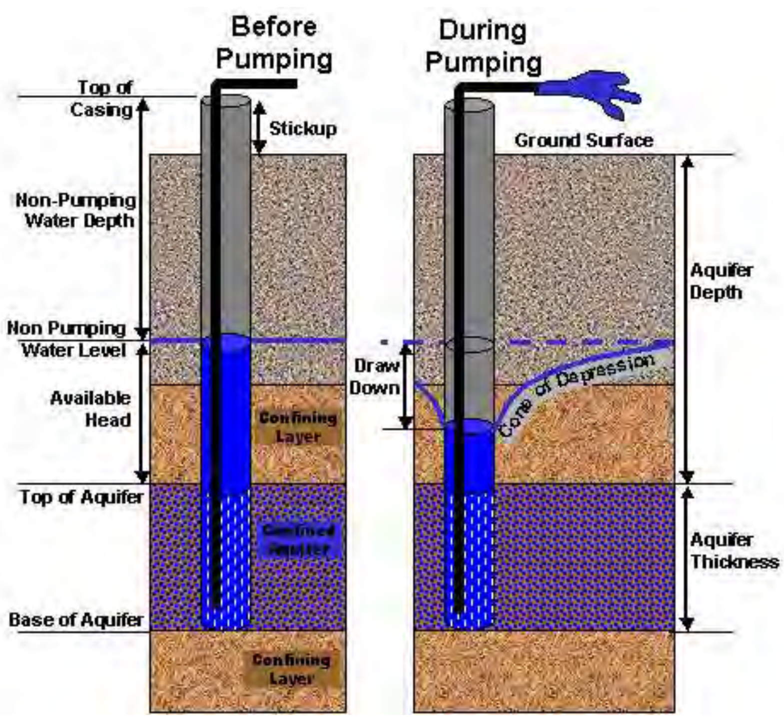
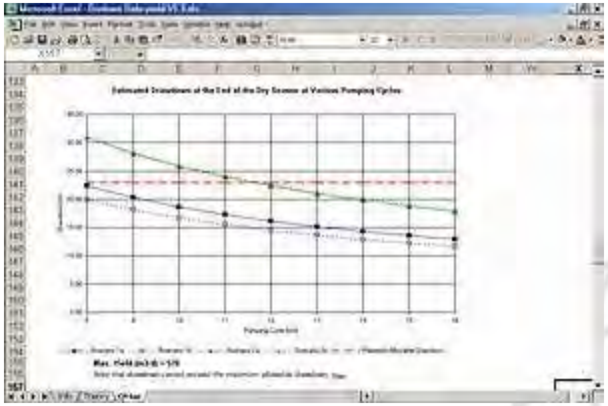
PART 2 – Purpose of Pumping Tests

Class Exercise: Why do we need to do pumping tests?



Source: http://environment.alberta.ca/images/EV3-pumptest.gif



Source: www.geosearch.co.uk

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PART 2 – Purpose of Pumping Tests (I)

1. To find reliable values of the hydraulic characteristics of the geological formations through which groundwater is moving.
2. To estimate the hydraulic efficiency of a pumping well.

PART 2 – Purpose of Pumping Tests (II)

3. To determine how much groundwater can be extracted from a production well, and estimate how this will affect other wells in the same aquifer.
4. To determine the optimum pumping rate and pump setting depth for a production well.

PART 2 – Purpose of Pumping Tests (III)

3. To obtain information on groundwater quality and it's variability over time.

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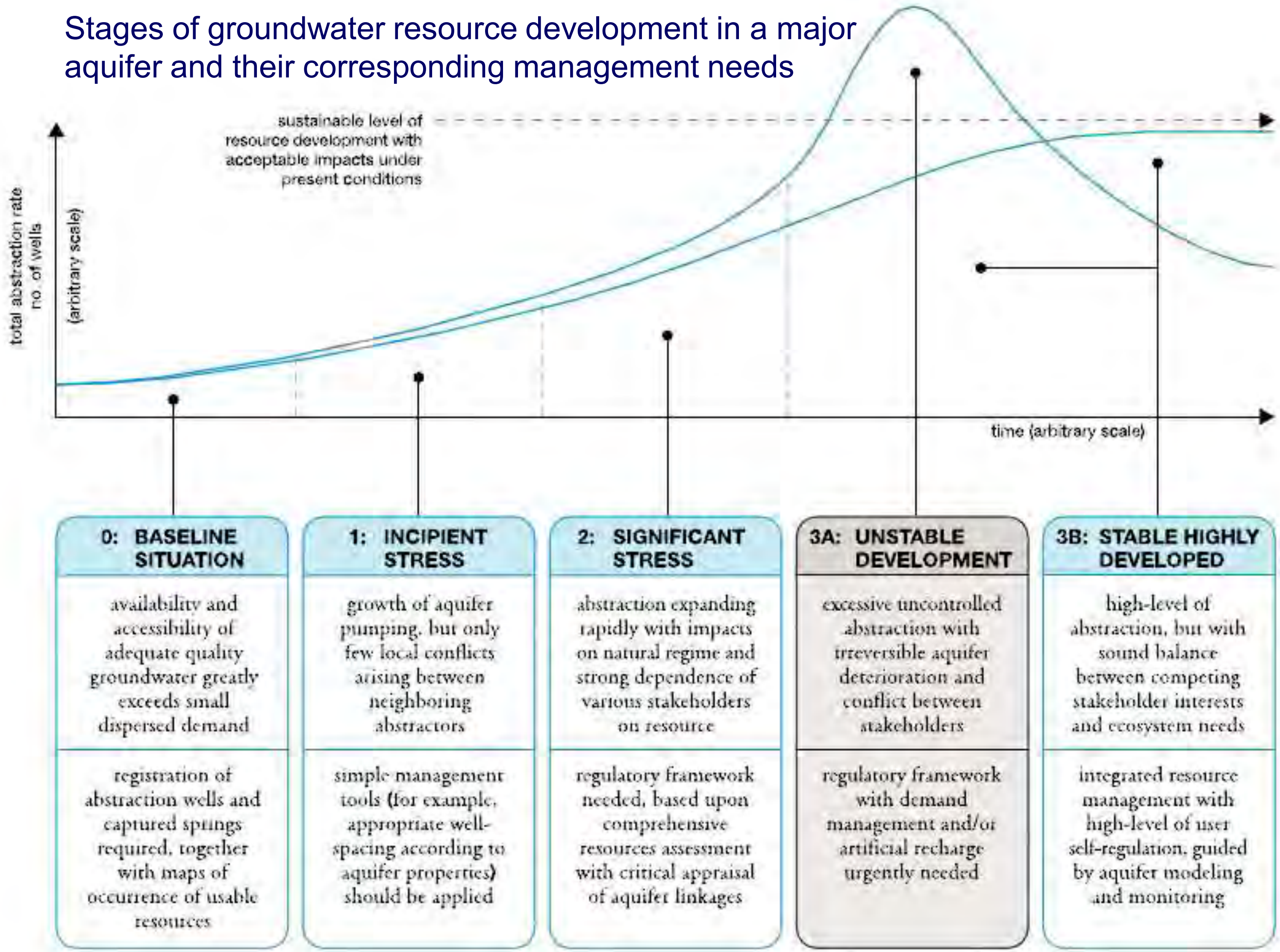
Class Exercise: At what stage is Afghanistan & why are pumping tests important?

Stages of groundwater resource development in a major aquifer and their corresponding management needs



Source: GWMATE BN_01 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

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1. Terminology
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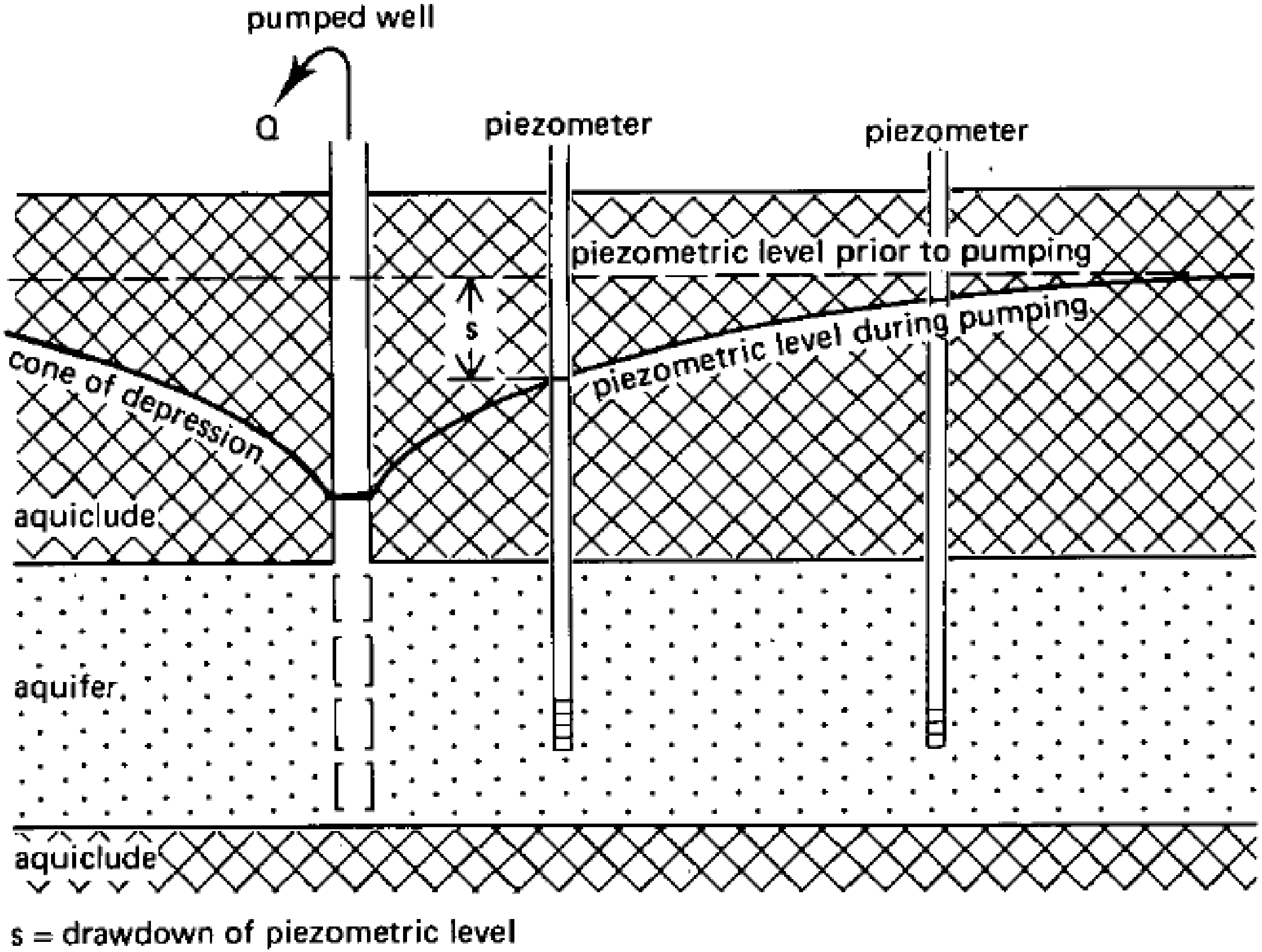
PART 3 – How to Plan and Set up a Pumping Test

1. The principle
2. Preliminary studies
3. Well site selection
4. Well characteristics
5. Piezometers
6. Measurements
7. Duration of pumping tests

The Principle



Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

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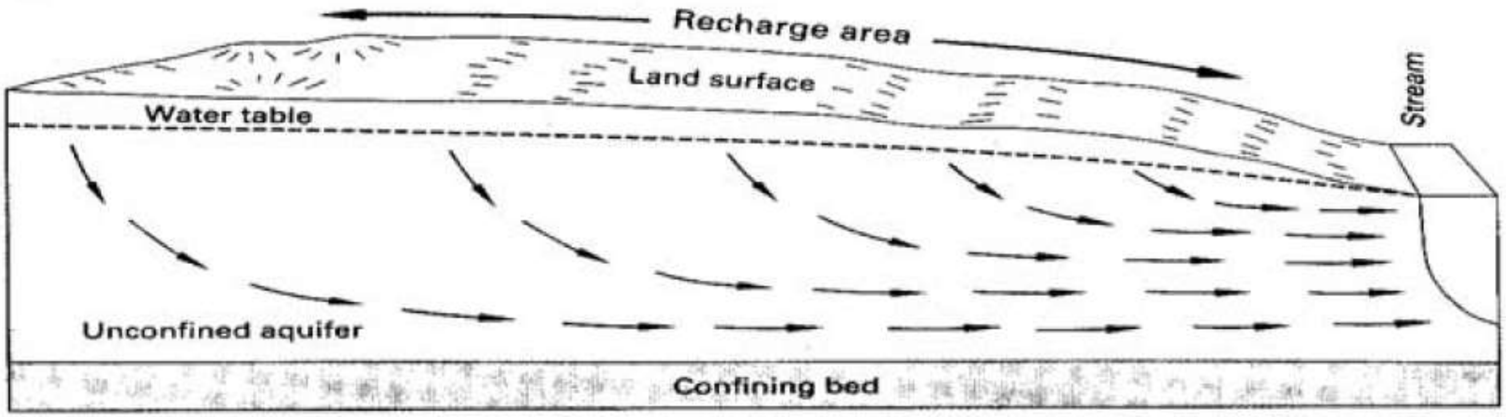
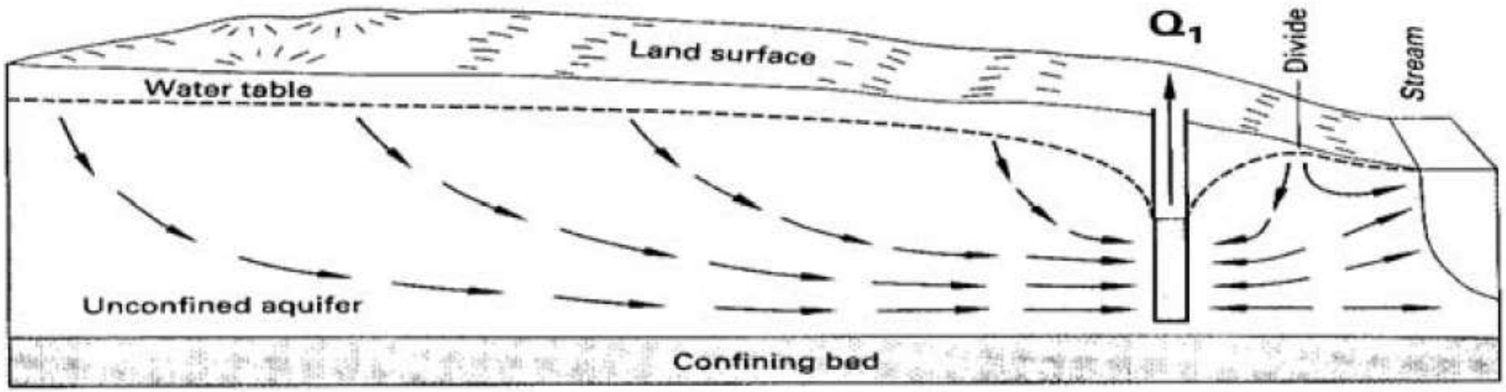
The Principle



(a)

Source: J.E. Moore Field Hydrogeology 2002

The Principle



(b)

Source: J.E. Moore Field Hydrogeology 2002

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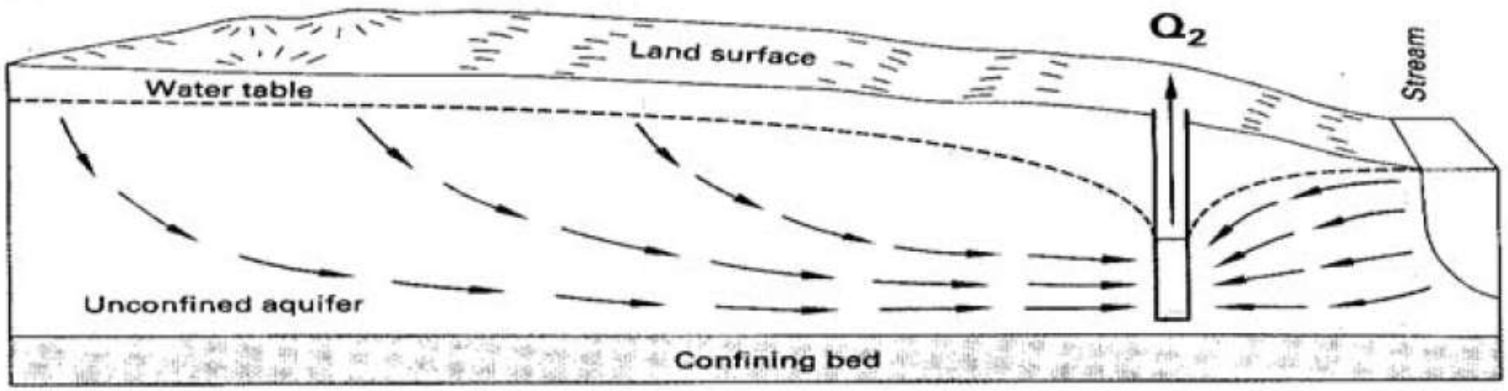
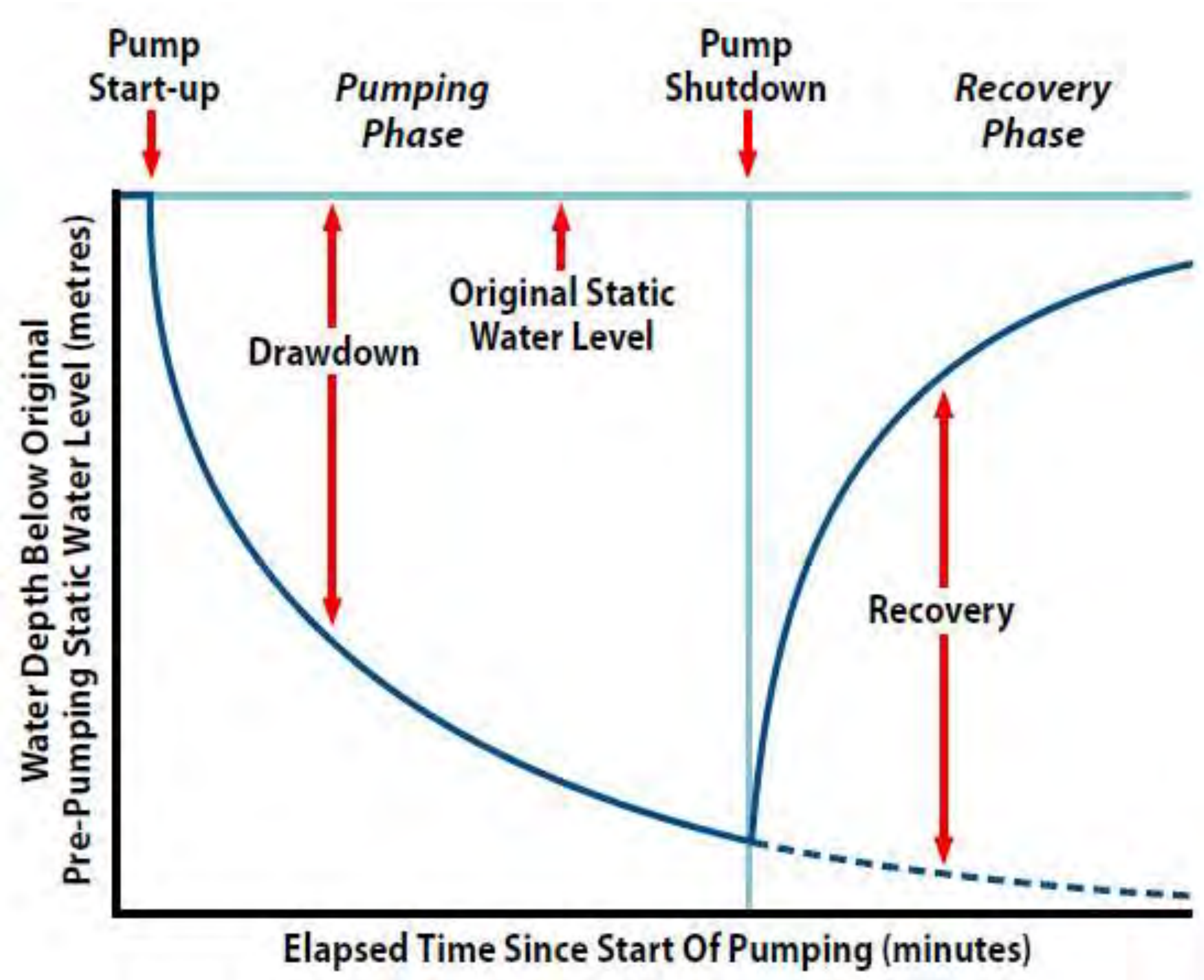
The Principle



(c)

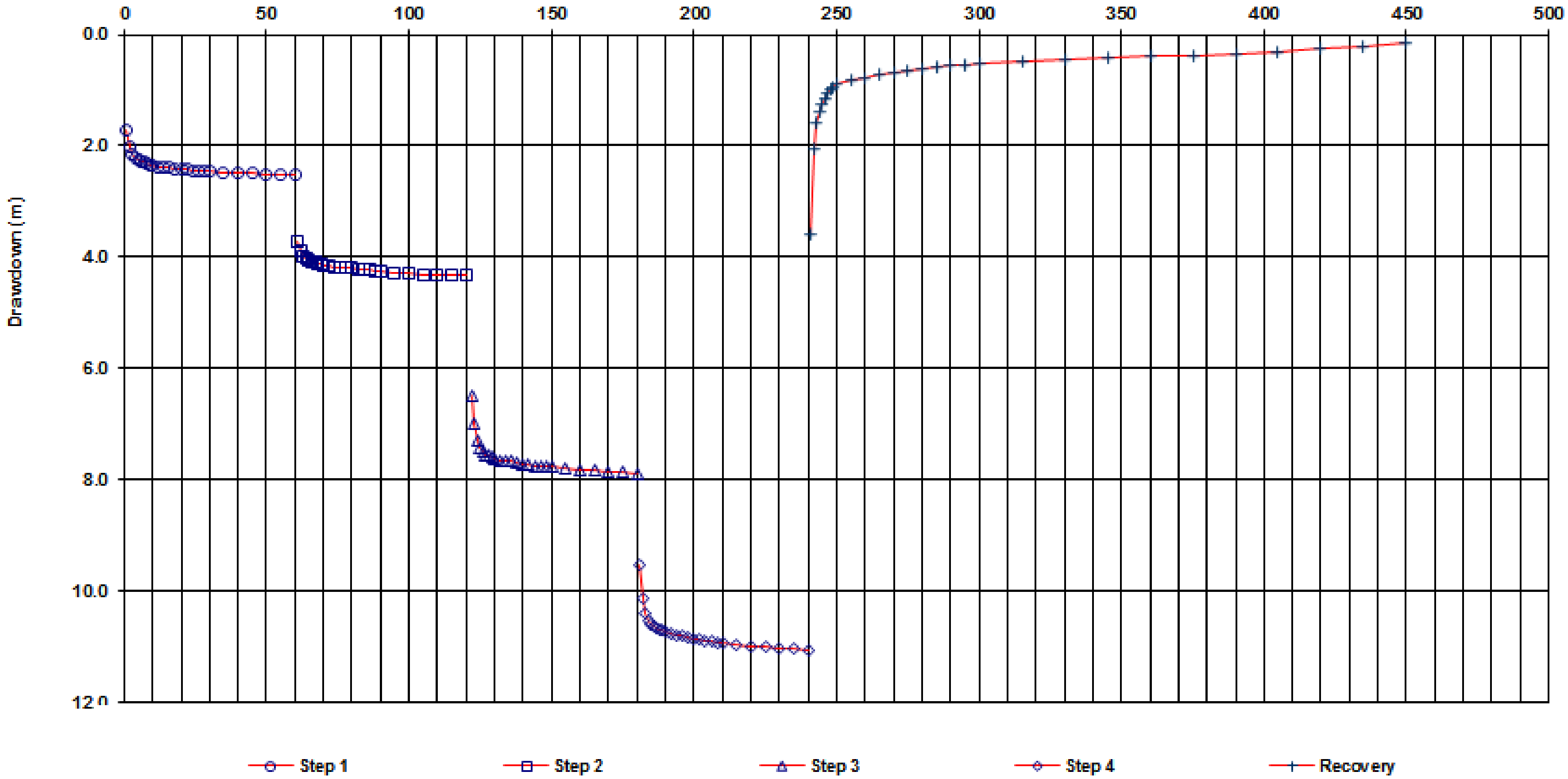
Source: J.E. Moore Field Hydrogeology 2002

Constant Rate & Recovery Pumping Tests



Source: Guide to Conducting Well Pumping Tests, British Columbia Min. of Environment, Water Stewardship Information Series ISBN 978-0-7726-7033-5.

Variable-rate Pumping Test: Step Test, Ghana



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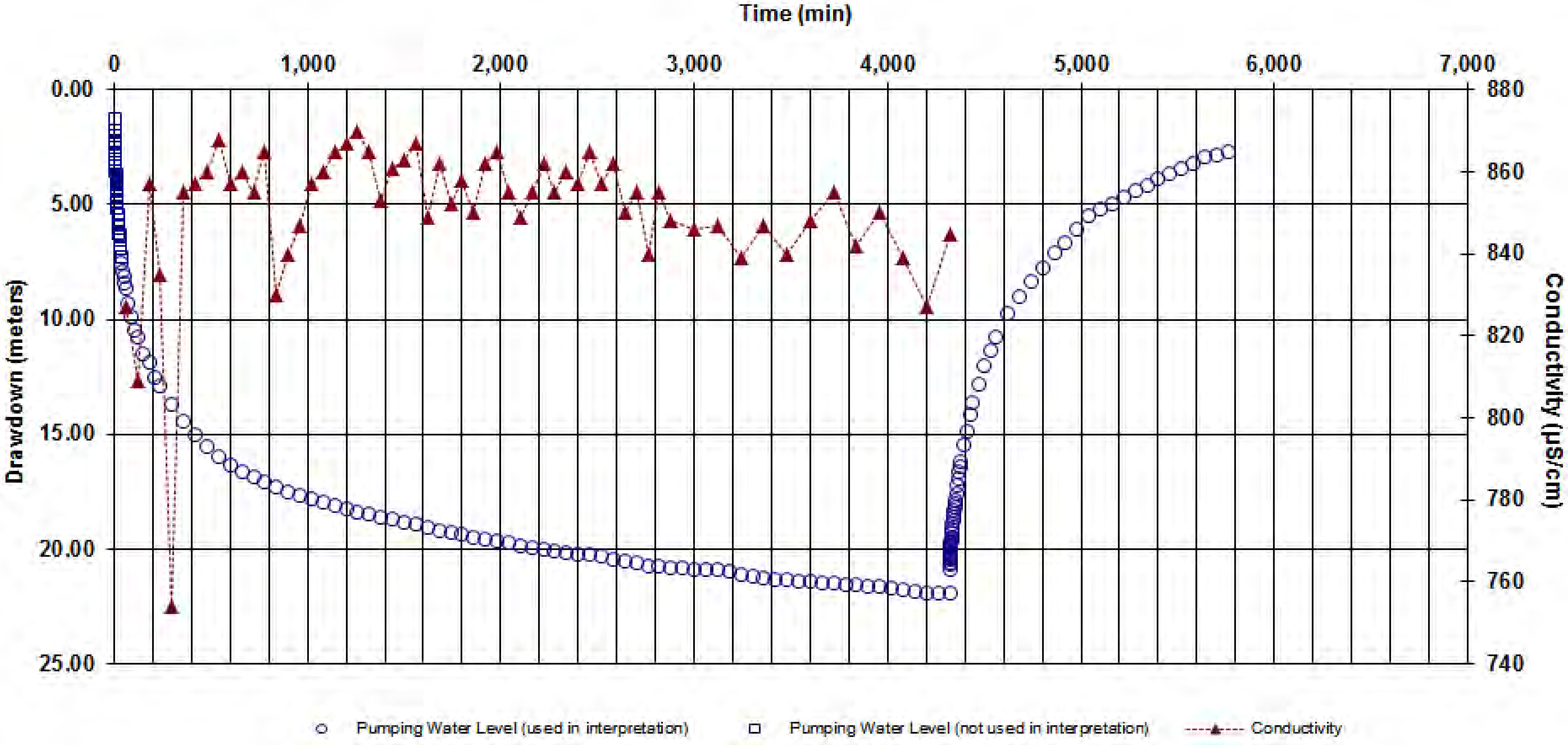
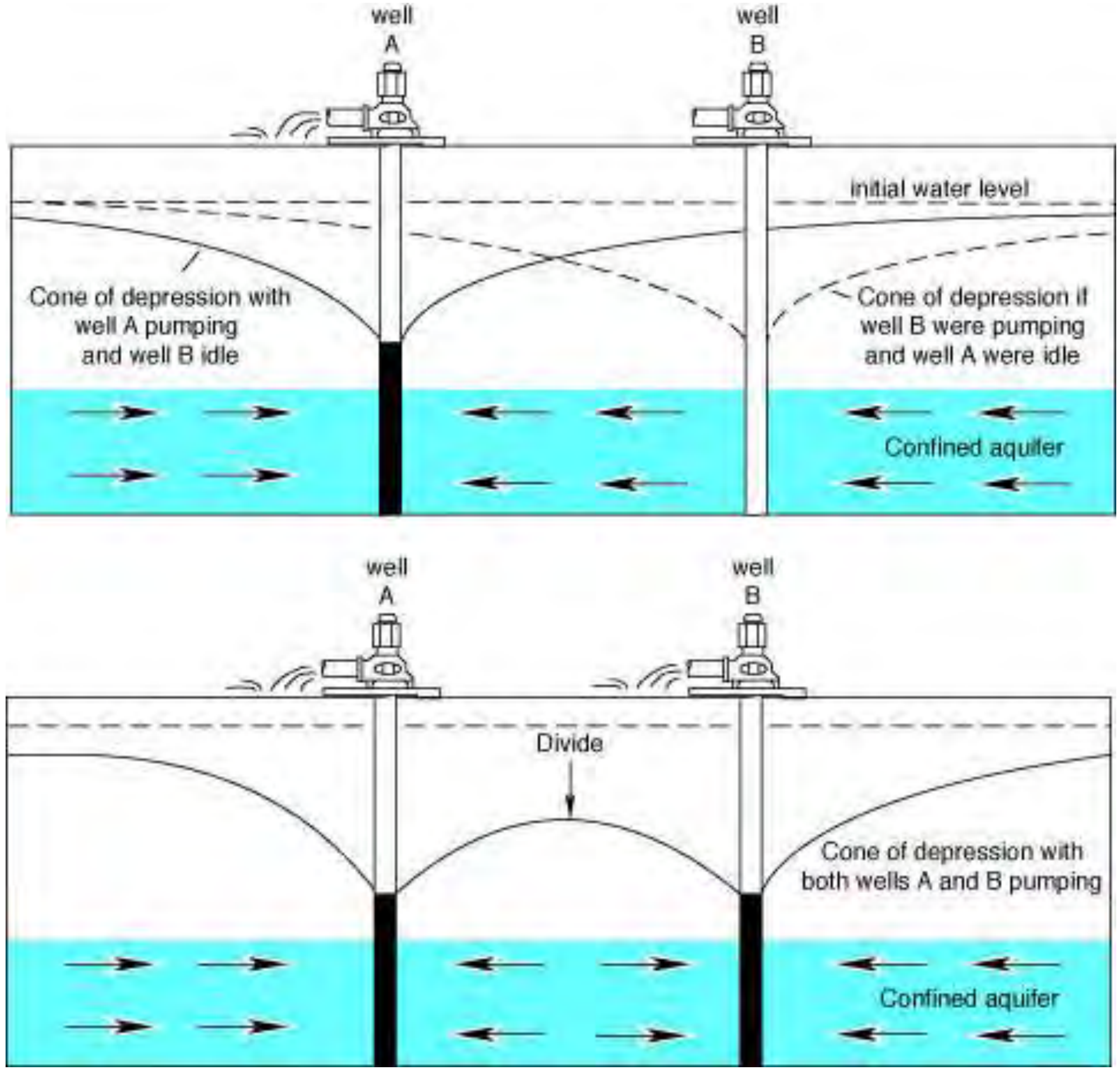
Constant Rate & Recovery Pumping Test, Ghana



The Principle



Source: http://www.kgs.ku.edu/Publications/Bulletins/ED10/06_wells.html

Preliminary studies – literature review

1. Geology of the area.
2. Type of aquifers and confining beds.
3. Thickness and extent of aquifers and confining beds.
4. Barrier and recharge boundaries.
5. Groundwater data – hydraulic gradients.
6. Data on existing wells in the area.

Preliminary studies – site visit

1. Visit existing wells in the area – GPS position, interviews with well owners, water samples etc.
2. Verify information from literature review and update as appropriate.

Well Site Selection - I

1. The site should be representative of the hydrogeological conditions of the area.
2. In confined aquifers, it should be far away from roads and railways.
3. The site should be as far away from other pumping wells as possible.

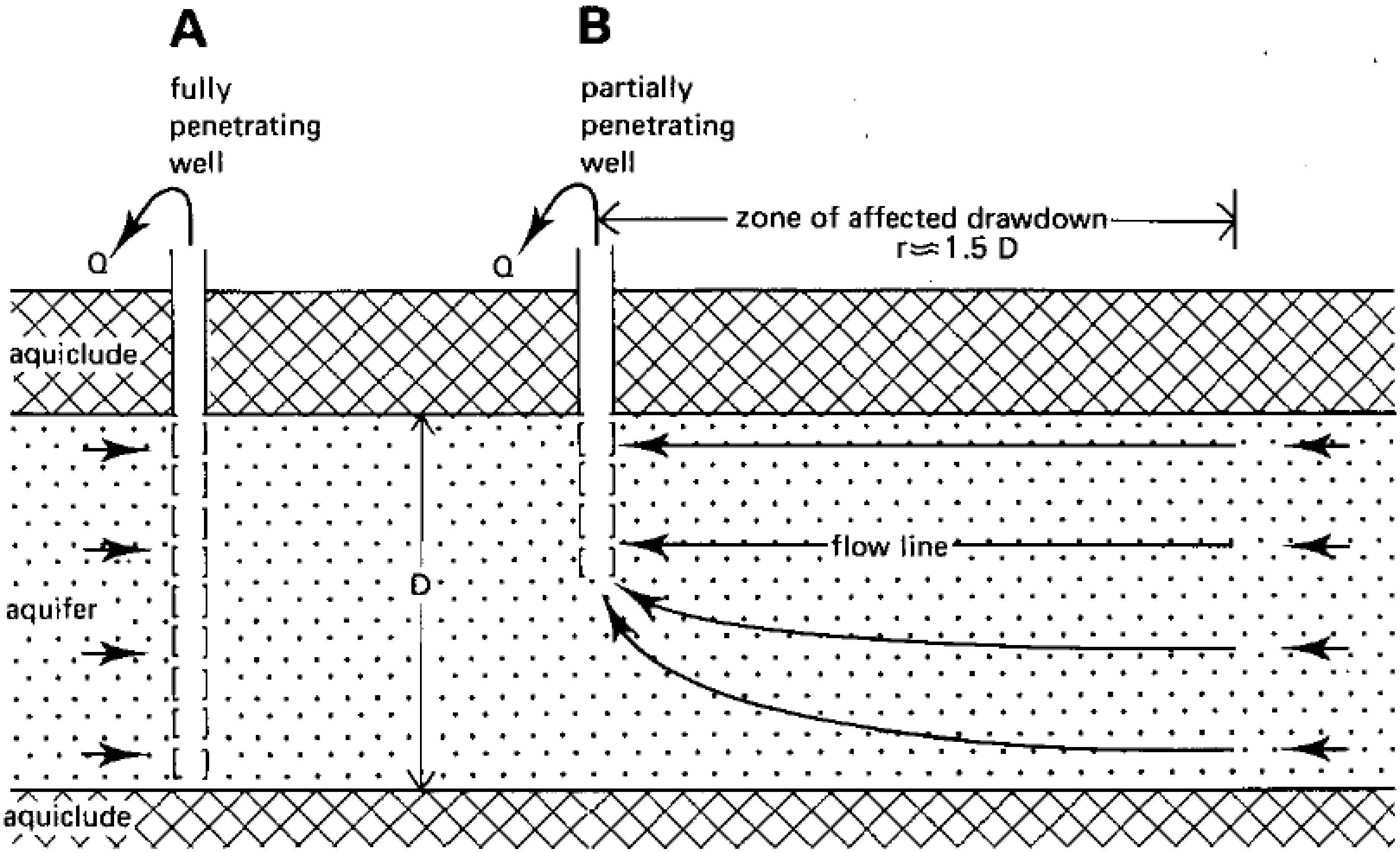
Well Site Selection - II

4. There should be a way to discharge the pumped water to prevent it from recirculating back to the aquifer.
5. The gradient of the water table or piezometric surface should be low.
6. Equipment should be able to reach the site.

Well Characteristics

1. The well diameter needs to be just big enough to accommodate the suction pipe or submersible pump. *Doubling the well diameter will only increase yields by 10%.*
2. The well depth should ideally be to the bottom of the aquifer.
3. In confined aquifers the well should be screened over 80% of the aquifer.

Well Characteristics

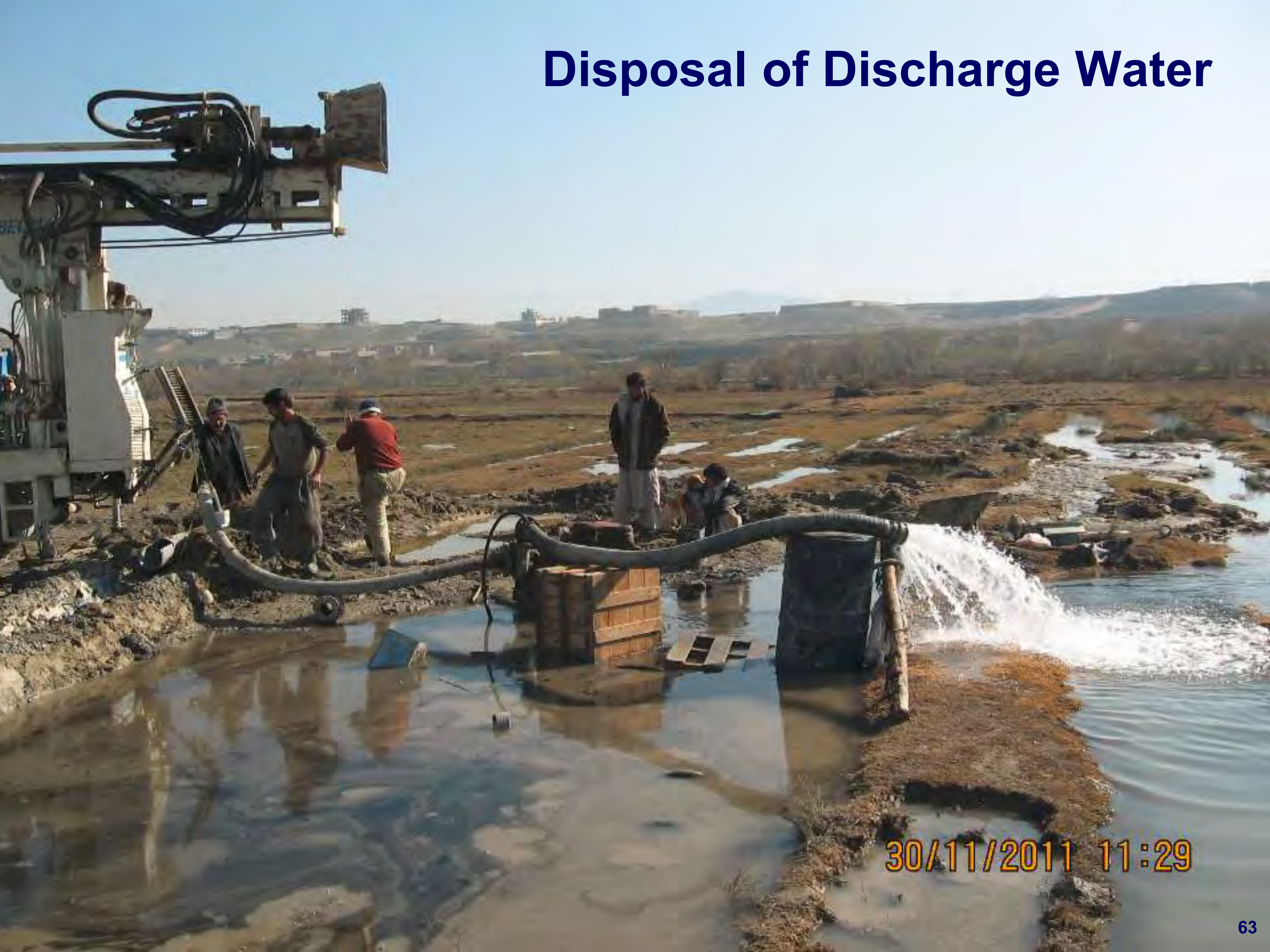


Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Pump Characteristics

1. The pump & power unit should be able to operate without breakdowns for at least a few days.
2. The discharge should be sufficient to produce drawdowns 100 – 200m from the well.
3. The discharge should be piped, say, 200m from the well & discharged into a canal or natural channel.

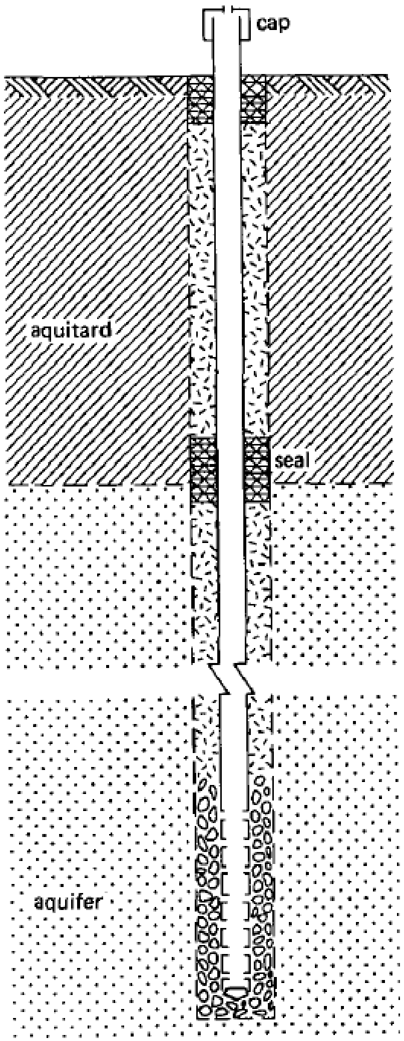
Disposal of Discharge Water

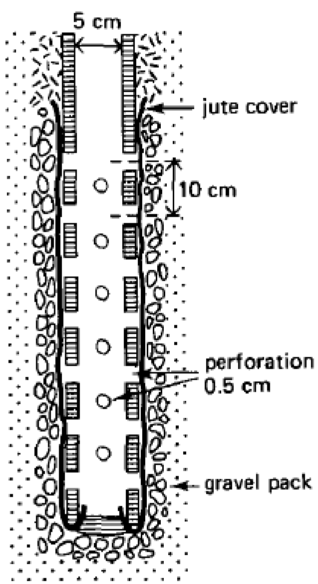


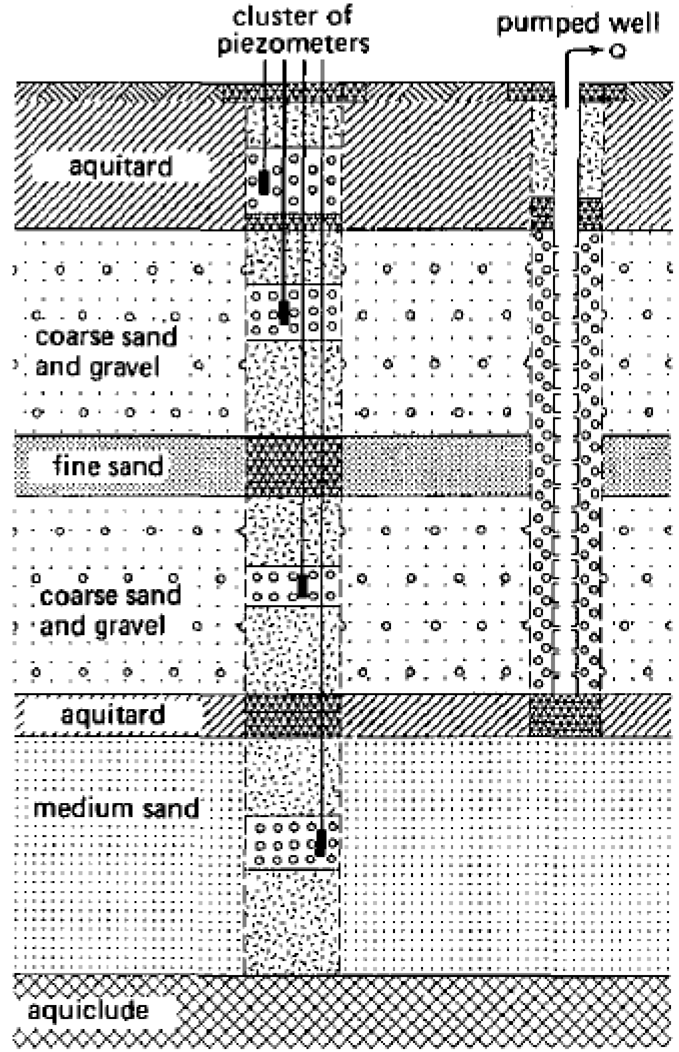
Piezometers

1. Ideally the piezometers should be small diameter, with a 0.5 to 1m screened section at their base.
2. It is recommended to have at least 3 piezometers.
3. The piezometer distance from the pumping well needs to be estimated based on aquifer characteristics, duration and rate of the pumping test.

Piezometers - design







Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Piezometers – distance from pumping well

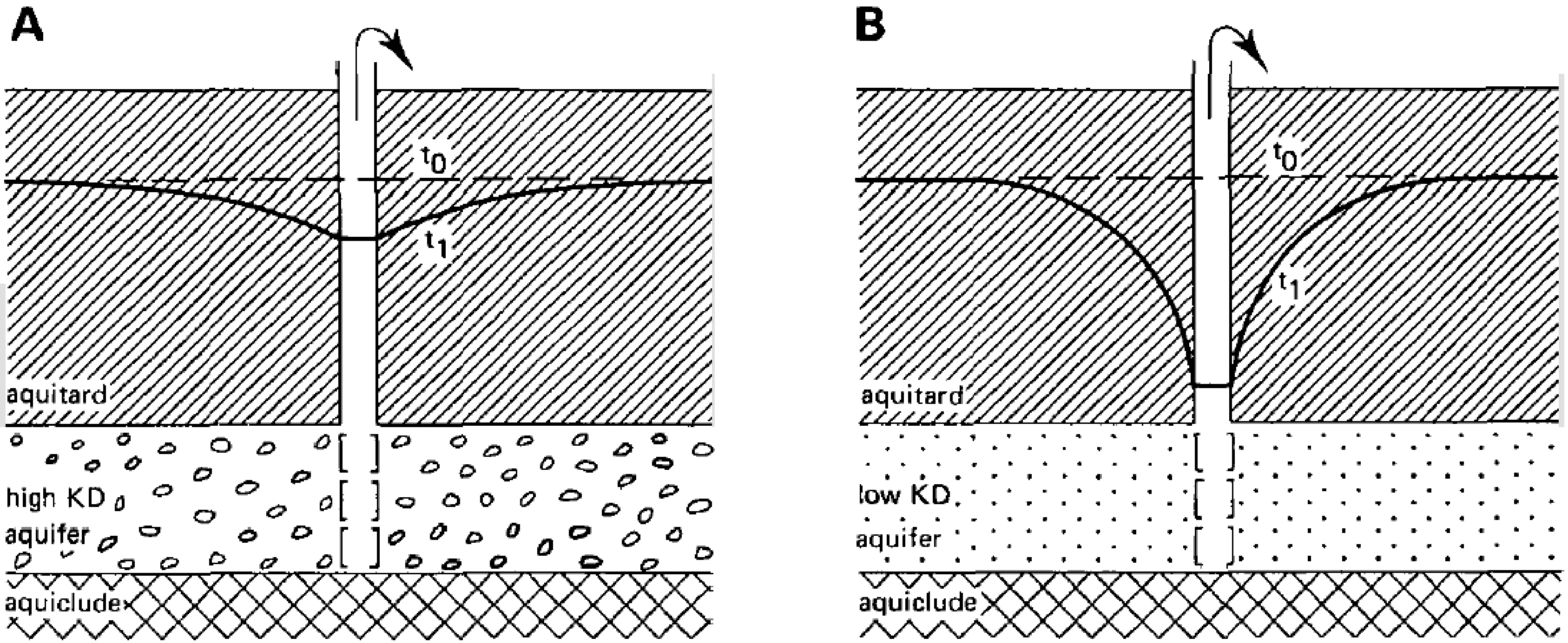
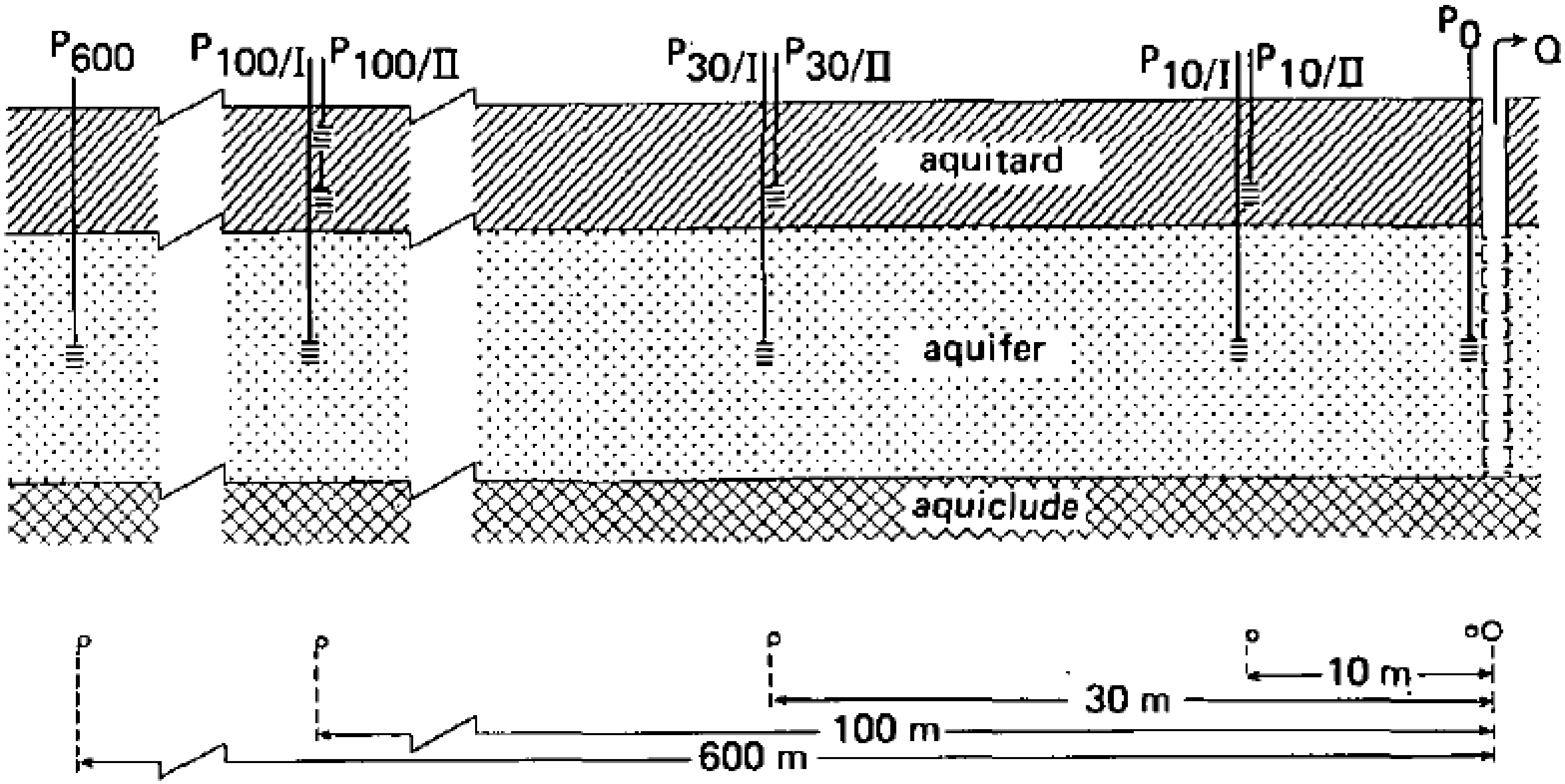


Figure 2.5 Cone of depression at a given time t in:
A) an aquifer of high transmissivity
B) an aquifer of low transmissivity

Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Piezometers – example



Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Measurements – water levels in pumping well

Table 2.1 Range of intervals between water-level measurements in well

Time since start of pumping	Time intervals
0– 5 minutes	0.5 minutes
5– 60 minutes	5 minutes
60–120 minutes	20 minutes
120–shutdown of the pump	60 minutes

Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

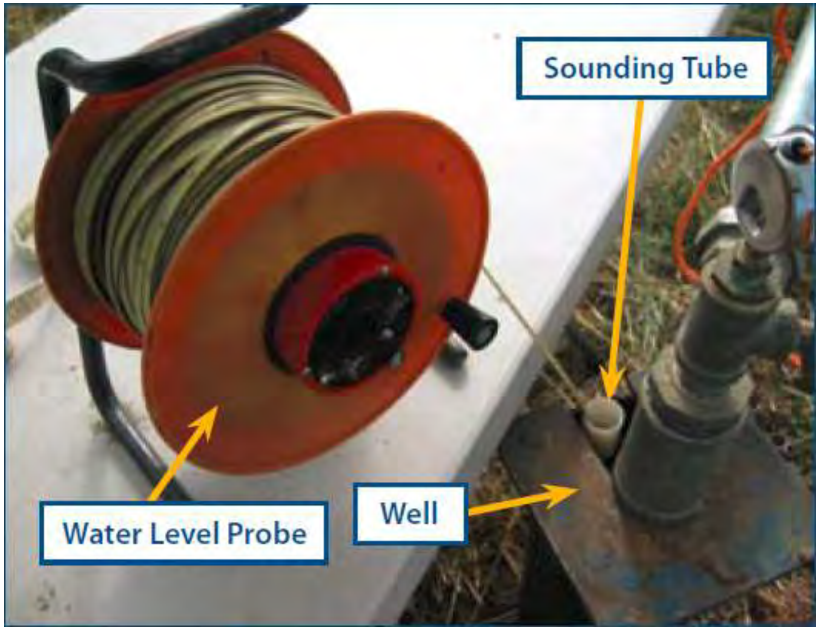
Measurements – water levels in piezometers

Table 2.2 Range of intervals between water-level measurements in piezometers

Time since start of pumping	Time intervals
0 – 2 minutes	approx. 10 seconds
2 – 5 minutes	30 seconds
5 – 15 minutes	1 minute
15 – 50 minutes	5 minutes
50 – 100 minutes	10 minutes
100 minutes – 5 hours	30 minutes
5 hours – 48 hours	60 minutes
48 hours – 6 days	3 times a day
6 days – shutdown of the pump	1 time a day

Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Water Level Measurements



Source: Guide to Conducting Well Pumping Tests, British Columbia Min. of Environment, Water Stewardship Information Series ISBN 978-0-7726-7033-5.

Measurements – discharge rates (I)

1. Container – e.g. 200L oil drum
2. Circular orifice weir
3. V-notch
4. Flow meter

Note that it is advisable to always use two independent discharge rate measurement devices.

Discharge should be measured once every hour and kept constant.

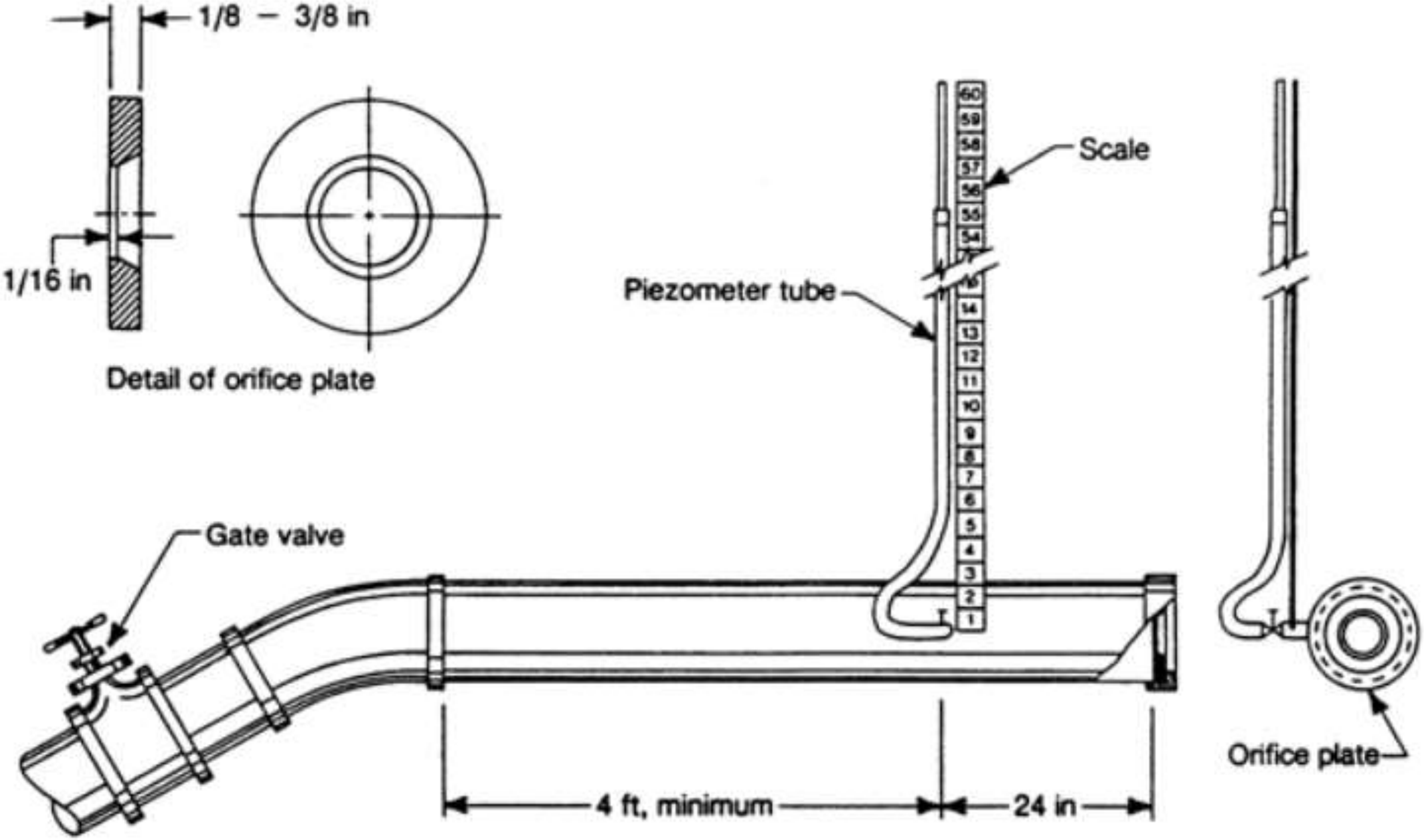
Container

Source: MEW

V-notch weir

Source: https://www.hydrogeologist.net/ipnmonitor/templates/basic_JMA/images/V-notch.png

Circular orifice weir



Source: http://www.astm.org/HTTP/IMAGES/36708.gif

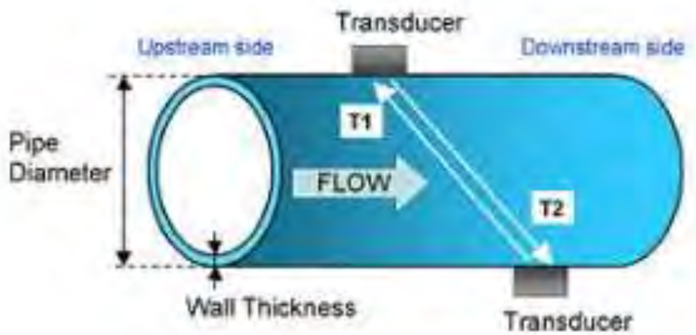
Circular orifice weir

Source: http://www.agric.wa.gov.au/objtwr/imported_assets/content/lwe/regions/nrr/rmtr_2_weaber_plain_aquifer_test_results.pdf

Standard Flow meter

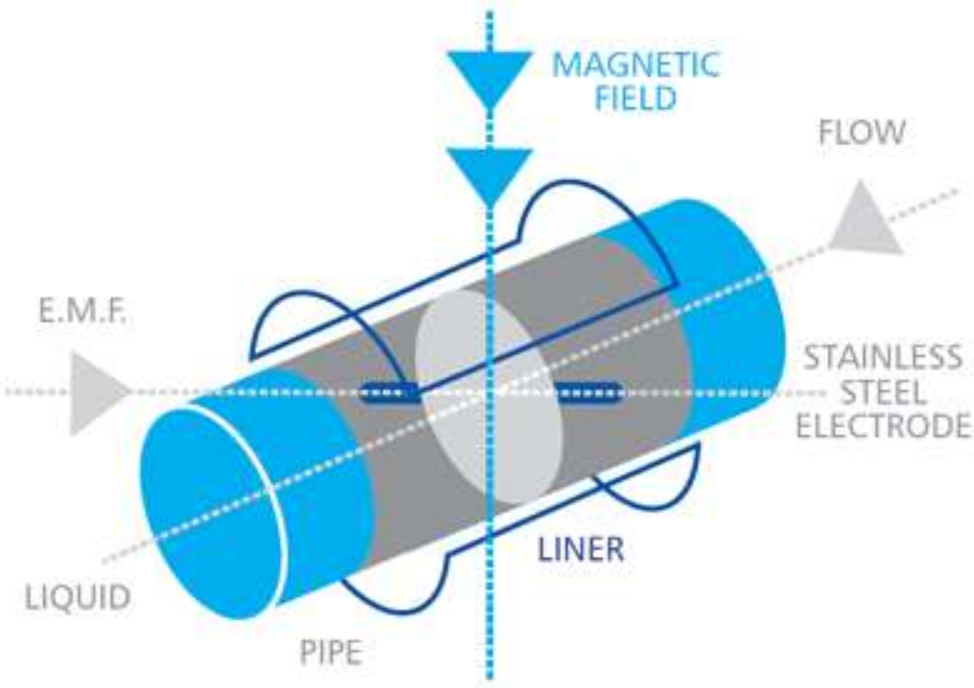
Source: http://midamericameter.com/wp-content/uploads/2011/08/T3000-e1313594892273.jpg

Ultrasonic Flow meter



Source: http://www.ultrasonic-flow.com/ultrasonic-water-meters/41-battery-powered-clamp-on-water-meter-.html

Electromagnetic Flow meter



Source: http://www.universalmetering.co.uk/bulk-meter.htm

Duration of the Pumping Test

1. Longer duration gives better data, but there are financial considerations.
2. Ideally the pumping test should reach steady state, though it is not a requirement.
3. Typical pumping test durations:
   - Confined & leaky aquifers: 24h
   - Unconfined aquifers: 3 days
   - Municipal water supply: 21 days

Equipment & personnel needs

1. Flow meter(s)
2. Water level indicators & pressure transducers.
3. Stop watches (synchronized).
4. Hydrochemical equipment (EC, pH, Eh, DO)
5. Qualified personnel (one hydrogeologist & two or more helpers depending on complexity and duration of test).

TOPICS TO BE COVERED

1. Terminology
2. Purpose of pumping tests
3. How to plan and set up a pumping test
4. Analysis of pumping test data
5. Reporting

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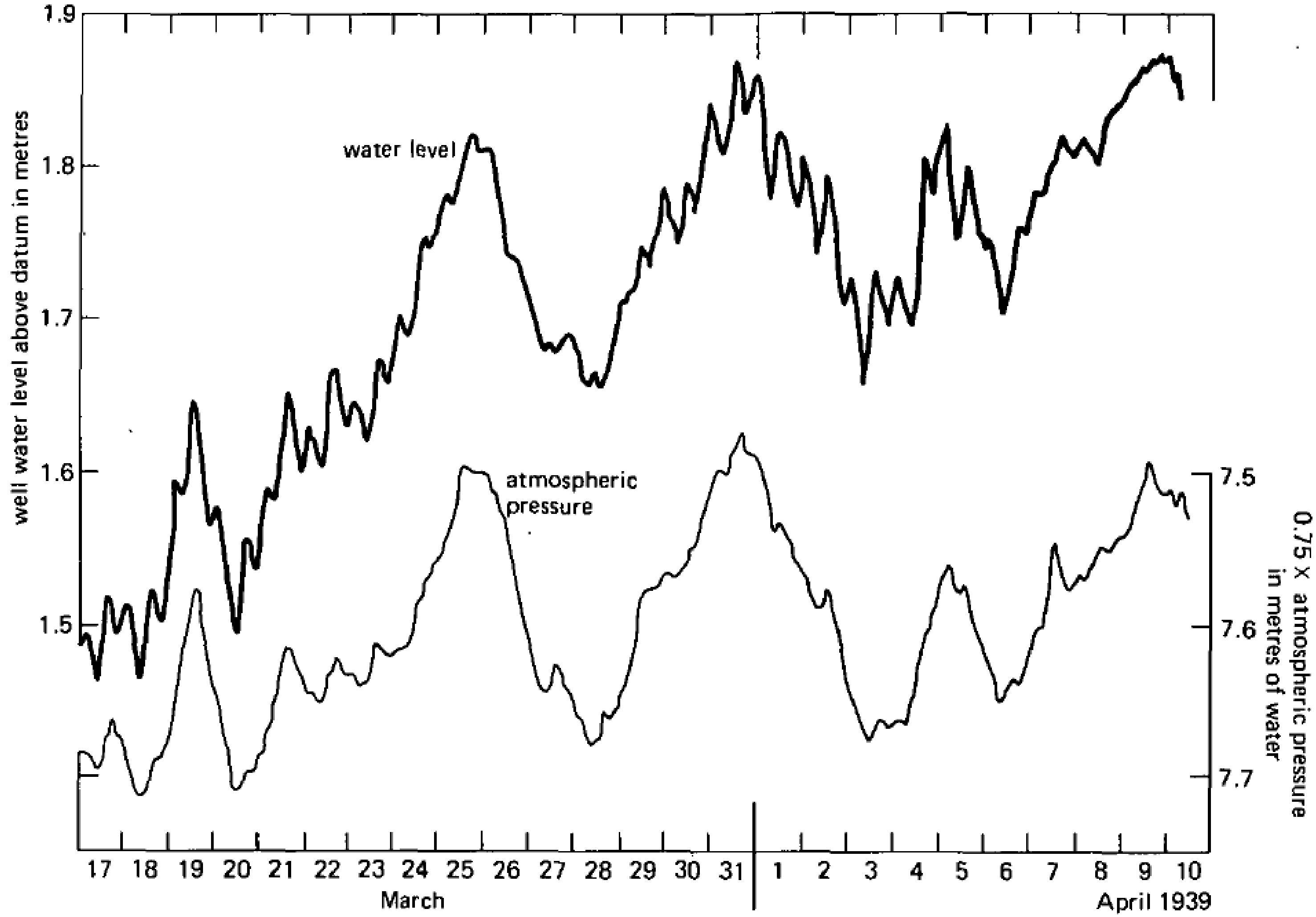
PART 4 – Analysis of Pumping Test Data

1. Data Processing
2. Data Interpretation

Data Processing

1. Convert all data into standard units.
   e.g. Time = days & Length = metres
2. Correct the data for external influences.
   e.g. water level trends before & after the test
3. Correct data for rhythmic fluctuations
   e.g. tides, barometric fluctuations, diurnal fluctuations.

Atmospheric Pressure Influences



Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

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Atmospheric Pressure & Confined Aquifers

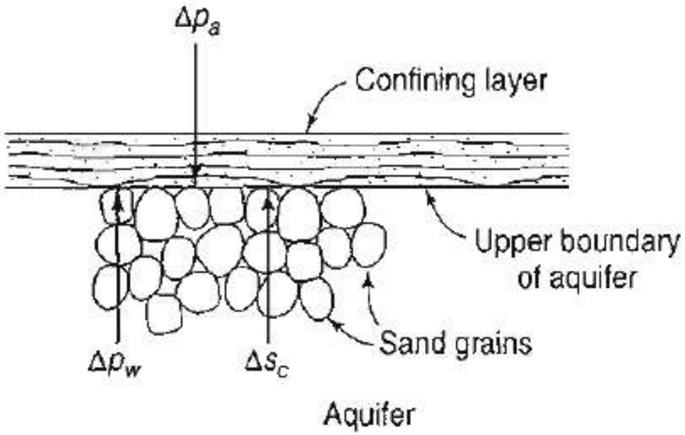

Figure 6.4.2. Idealized distribution of forces at the upper boundary of a confined aquifer resulting from a change in atmospheric pressure.

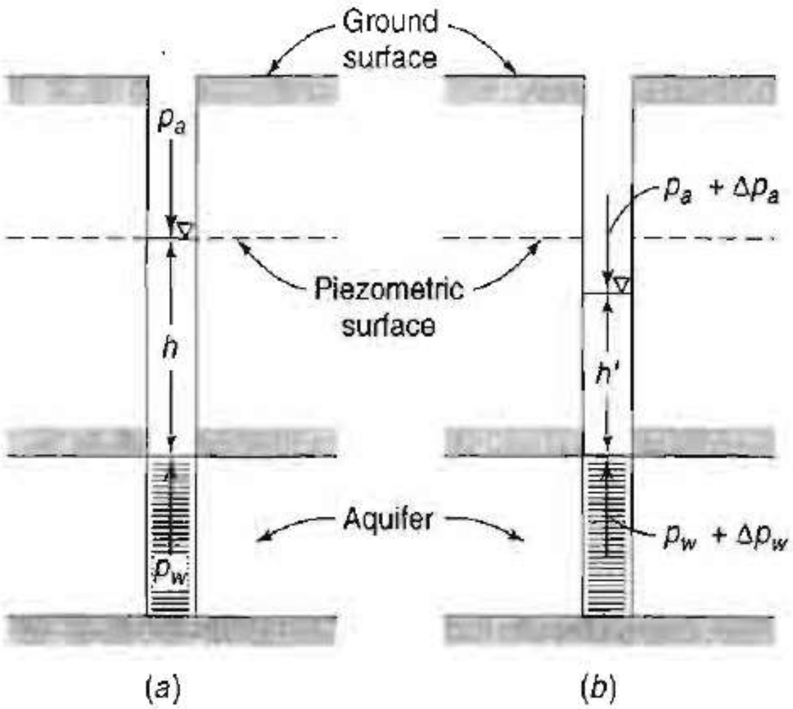

Figure 6.4.3. Effect of an increase in atmospheric pressure on the water level of a well penetrating a confined aquifer.

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

Water Table Fluctuations & Recharge

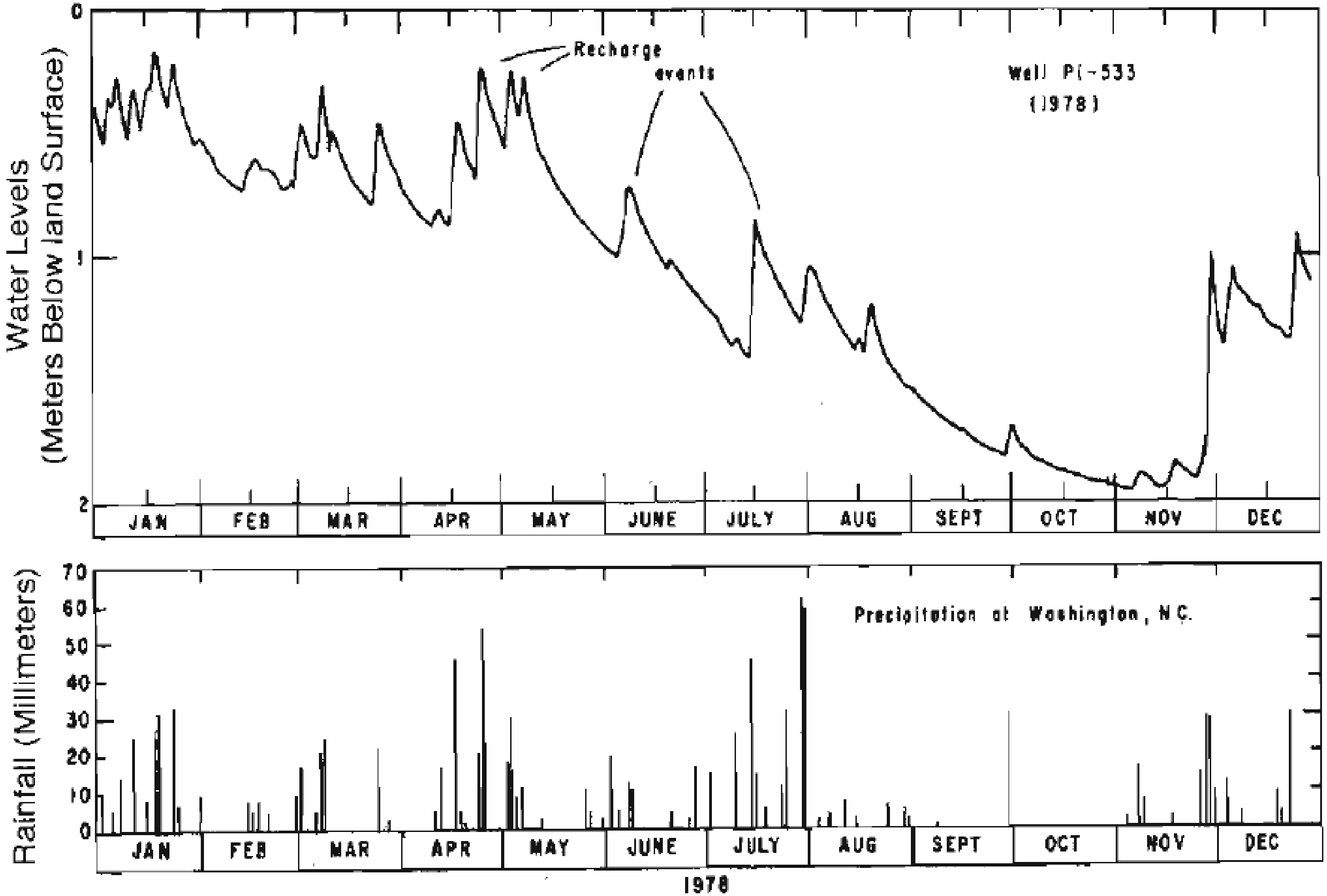

Figure 6.1.2. Fluctuation of the water table in the coastal plain of North Carolina (Heath[34]).

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

Seasonal Fluctuations

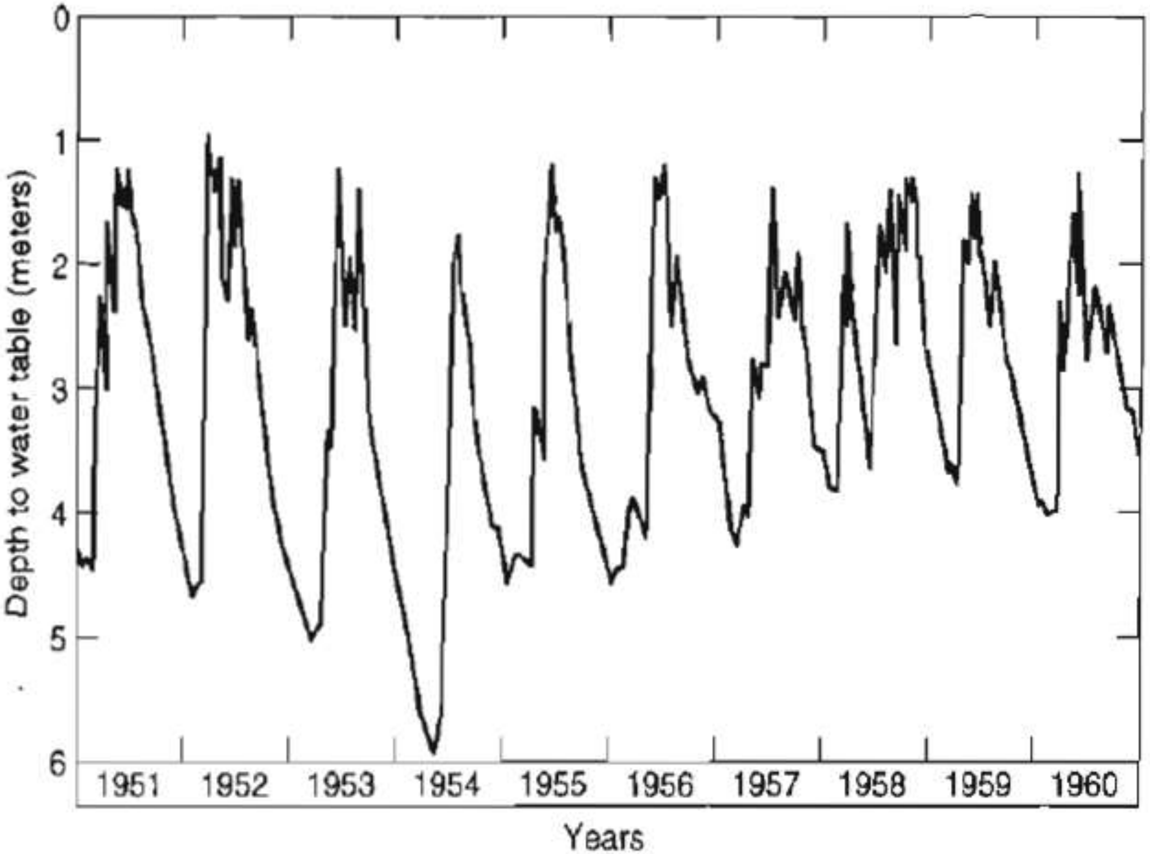

Figure 6.1.7. Seasonal fluctuations of the water table in a glacial till aquifer in Ohio. Well depth is 9 m (after Klein and Kaser[51]).

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

Evapotranspiration Effects

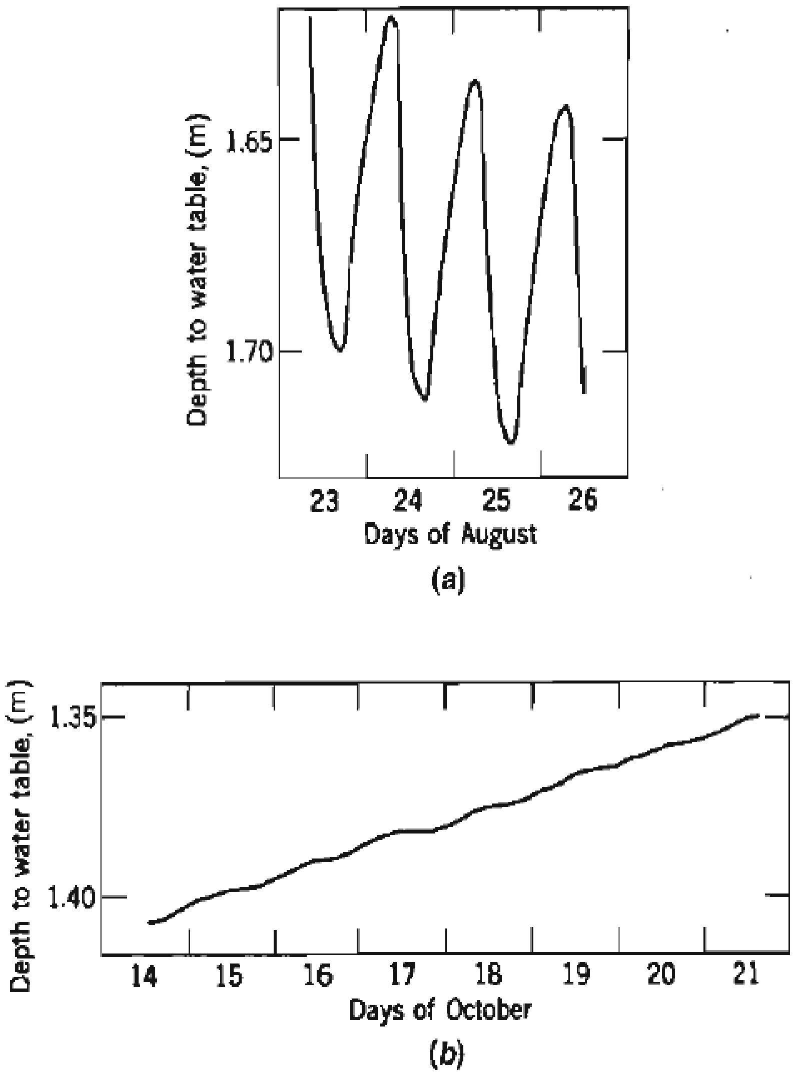

Figure 6.3.2. Effect of transpiration discharge on groundwater levels near Milford, Utah. (*a*) In summer (*b*) After frost (after White[95])

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

River Stage & Groundwater Levels

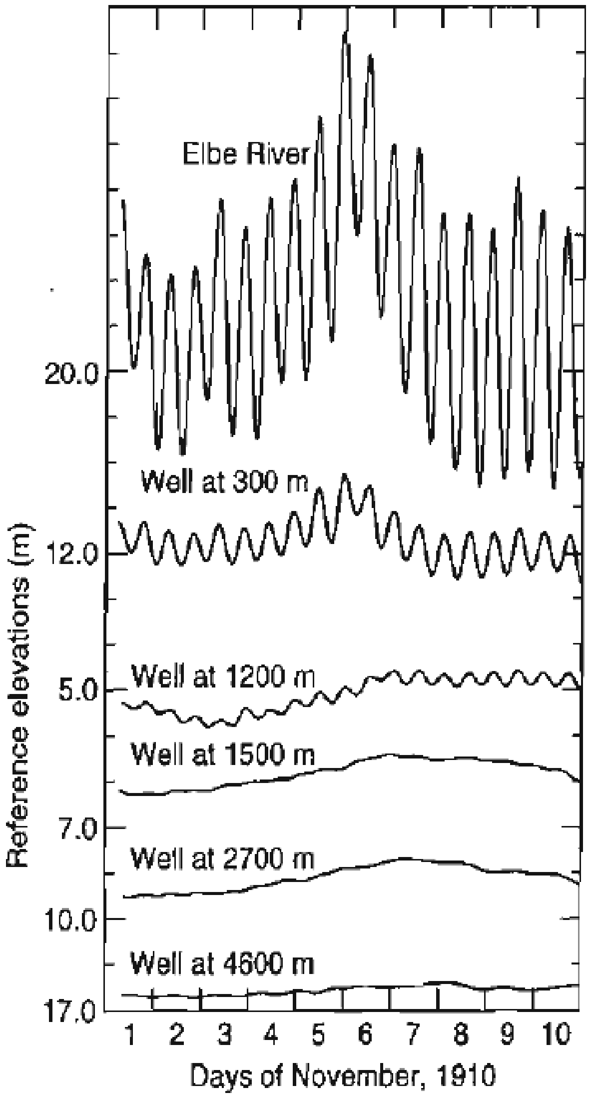

Figure 6.5.2. Fluctuations of the Elbe River and water table levels in wells at various distances from the river (after Werner and Noren[93]).

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

Tidal Influences

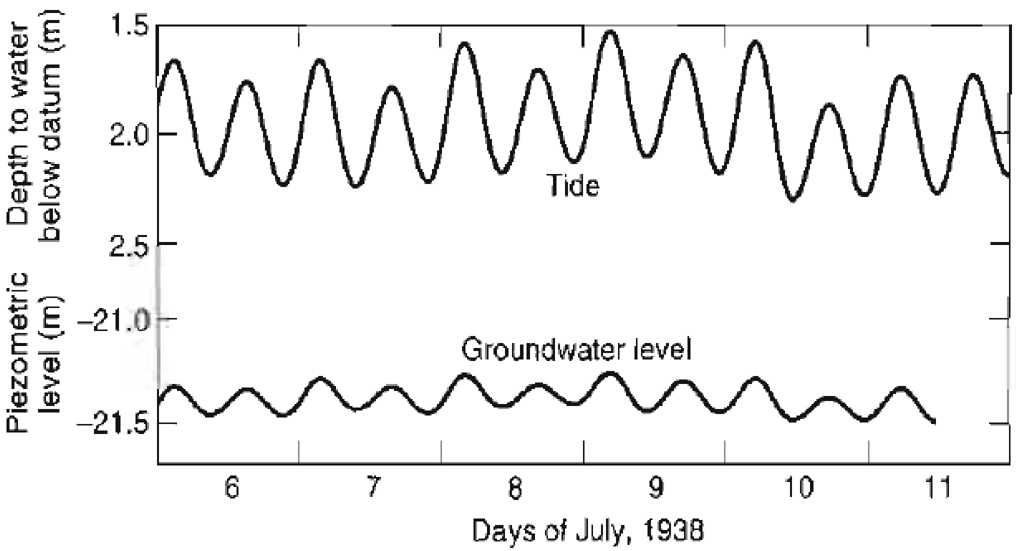

Figure 6.5.3. Tidal fluctuations and induced piezometric surface fluctuations observed in a well 30 m from shore at Mattawoman Creek, Maryland (after Meinzer[56]).

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

Earth Tides & Water Levels

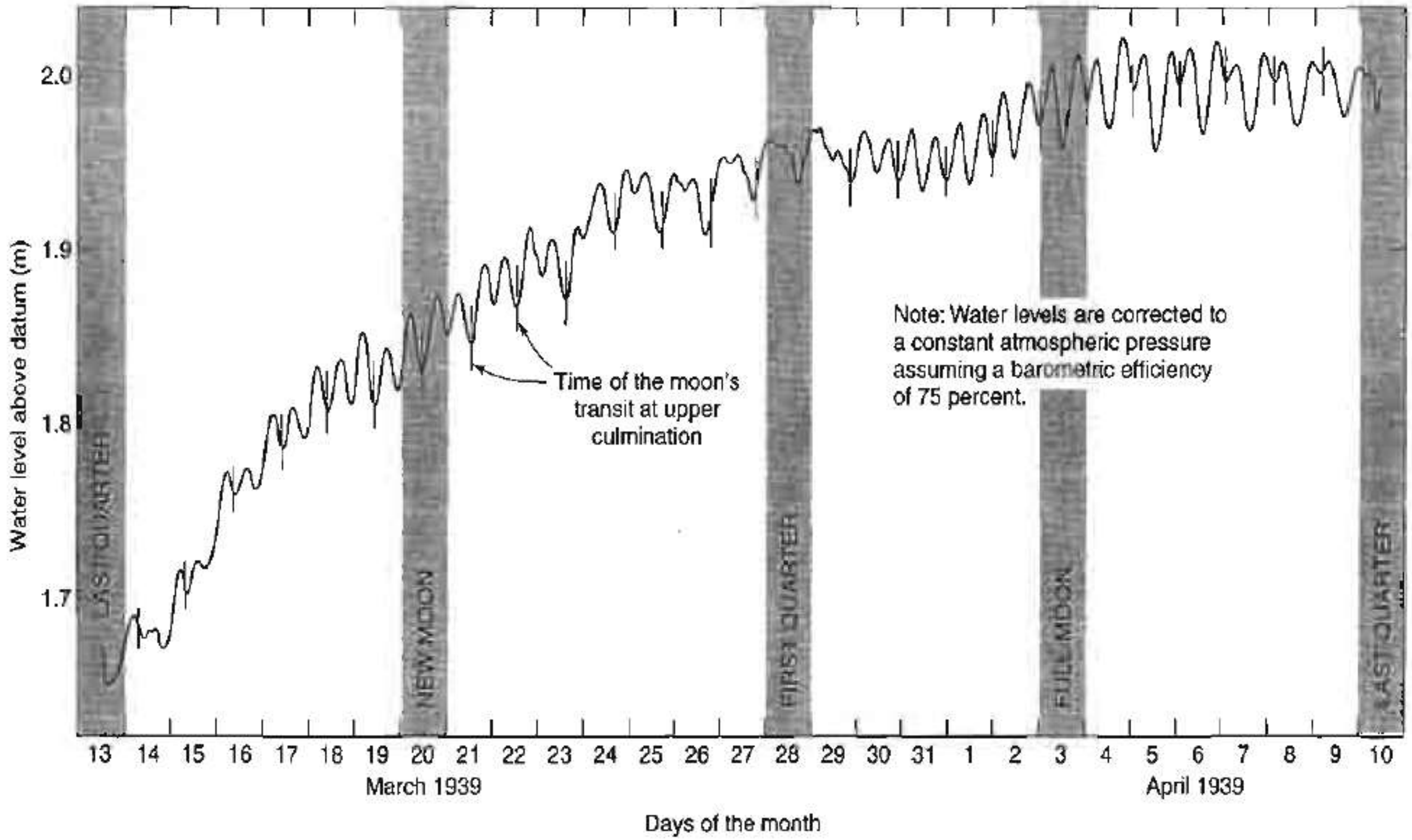

Figure 6.5.4. Water level fluctuations in a confined aquifer produced by earth tides (after Robinson[71]).

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

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Earthquakes & Water Levels

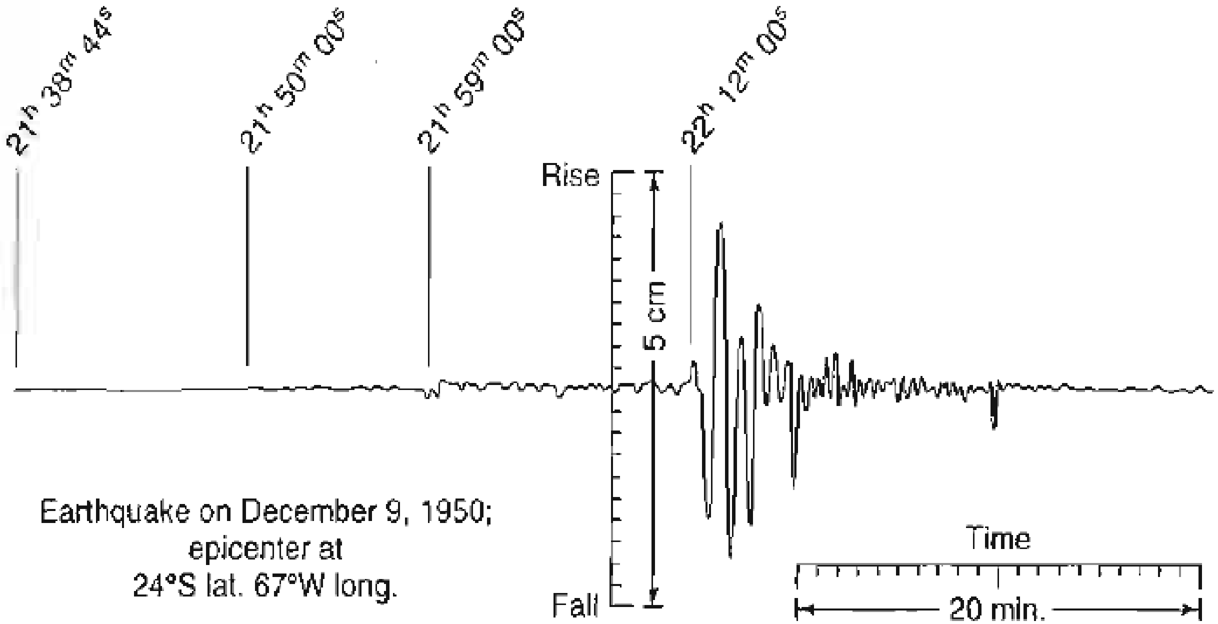


Figure 6.7.1. Water level fluctuations in a well at Milwaukee, Wisconsin, resulting from an earthquake centered on the Argentina–Chile border (after Vorhis[91])

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

Earthquakes & Water Levels

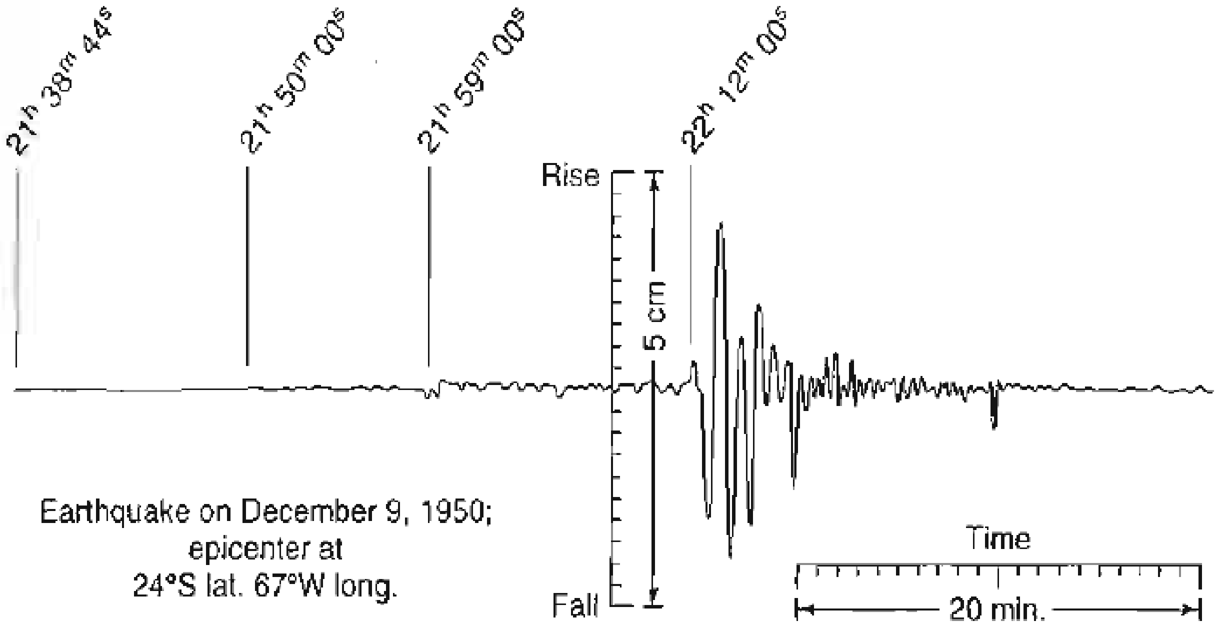
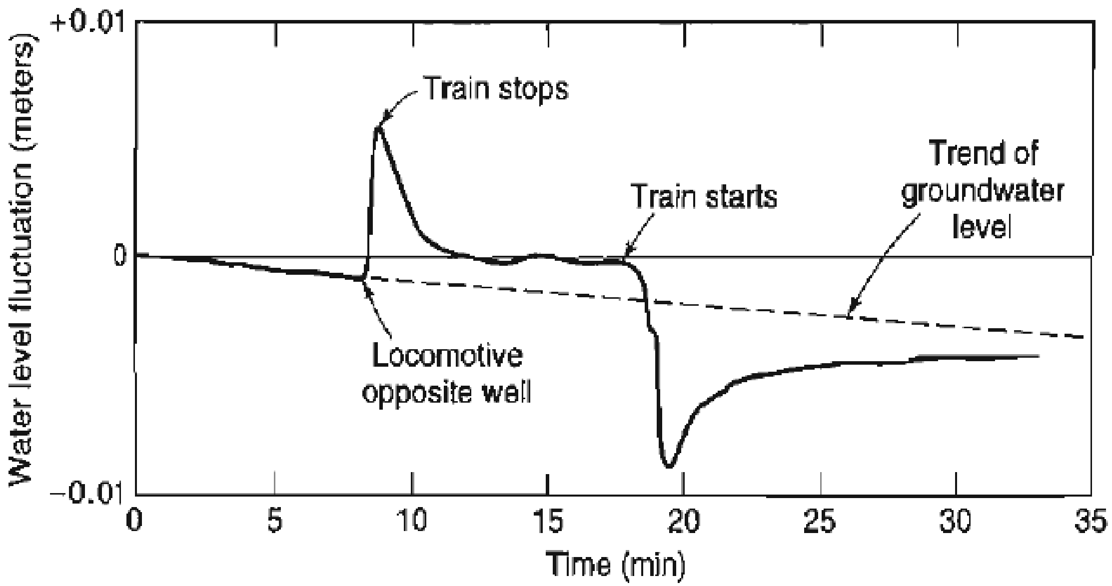


Figure 6.7.1. Water level fluctuations in a well at Milwaukee, Wisconsin, resulting from an earthquake centered on the Argentina–Chile border (after Vorhis[91])

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

External Loads & Water Levels



Source: http://www.lumixgexperience.panasonic.co.uk/wp-content/uploads/gallery/G10Col/Steam-train.jpg

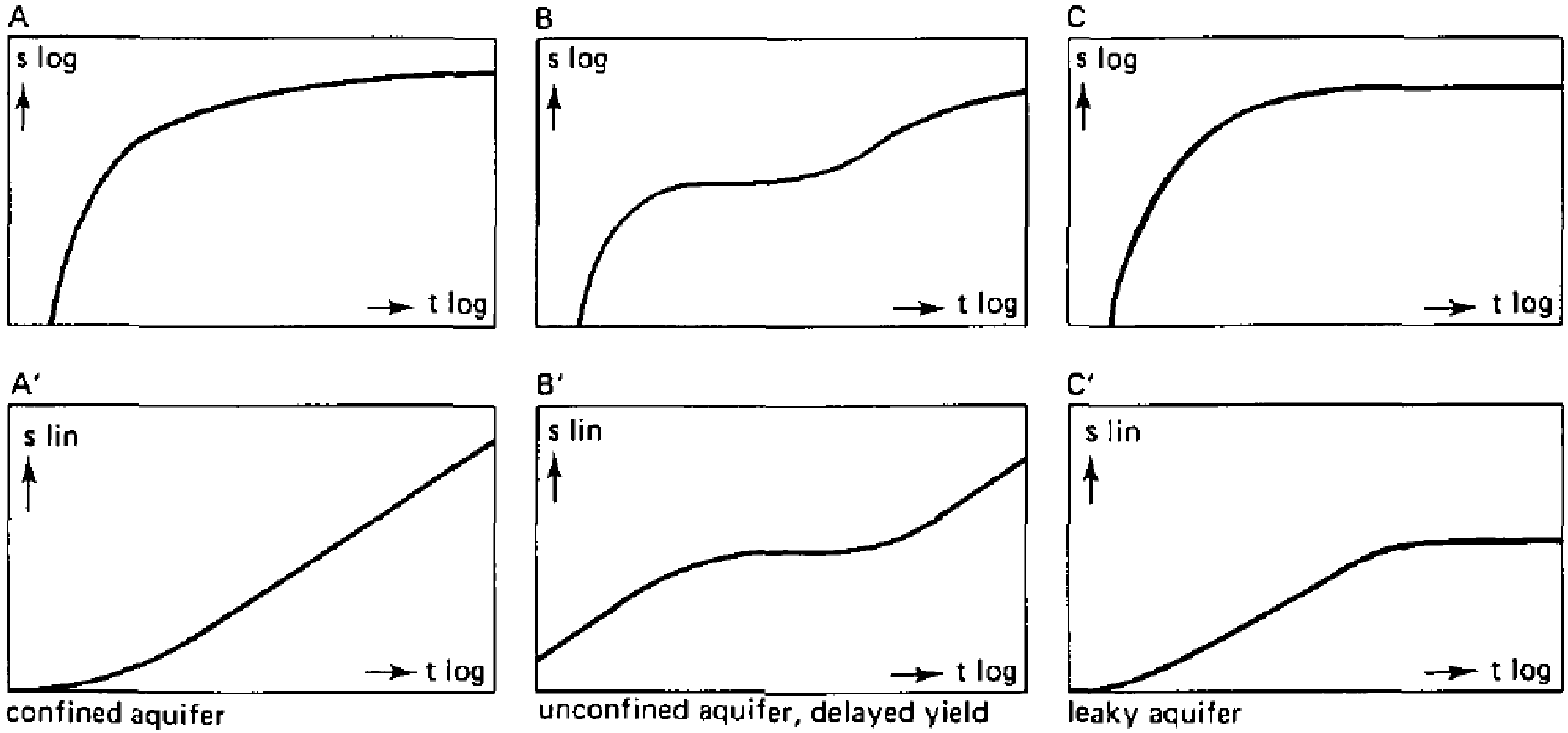
Figure 6.8.1. Water level fluctuations in a confined aquifer produced by a train stopping and starting near an observation well (after Jacob[47]).

Source: Todd, 2005; Groundwater Hydrology 3rd Ed.

Data Interpretation

1. Plot the data on log-log and semi-log plots.
2. Identify the aquifer type.
3. Chose the correct processing technique.

Data Interpretation – unconsolidated aquifers



Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

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Data Interpretation – fractured aquifers

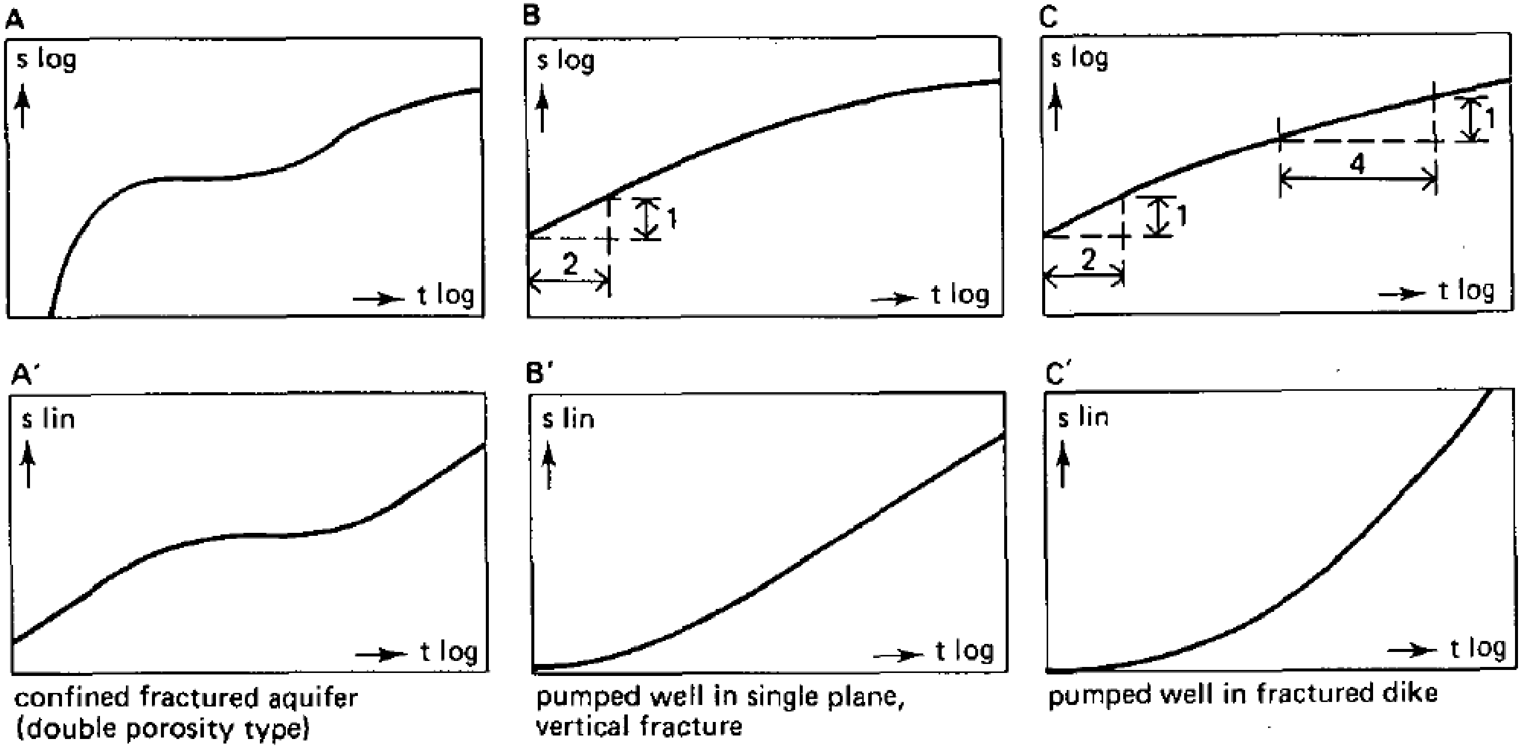
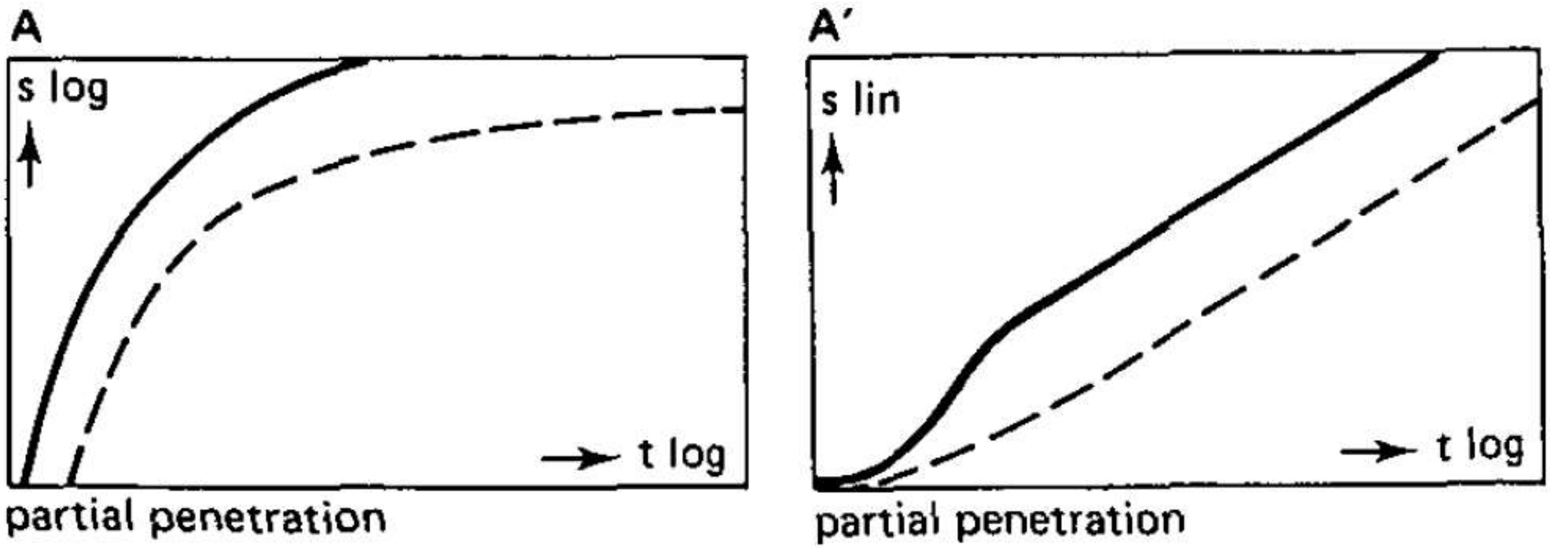


Figure 2.13 Log-log and semi-log plots of the theoretical time-drawdown relationships of consolidated, fractured aquifers:
Parts A and A′: Confined fractured aquifer, double porosity type
Parts B and B′: A single plane vertical fracture
Parts C and C′: A permeable dike in an otherwise poorly permeable aquifer

Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

Data Interpretation – partial penetration



Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

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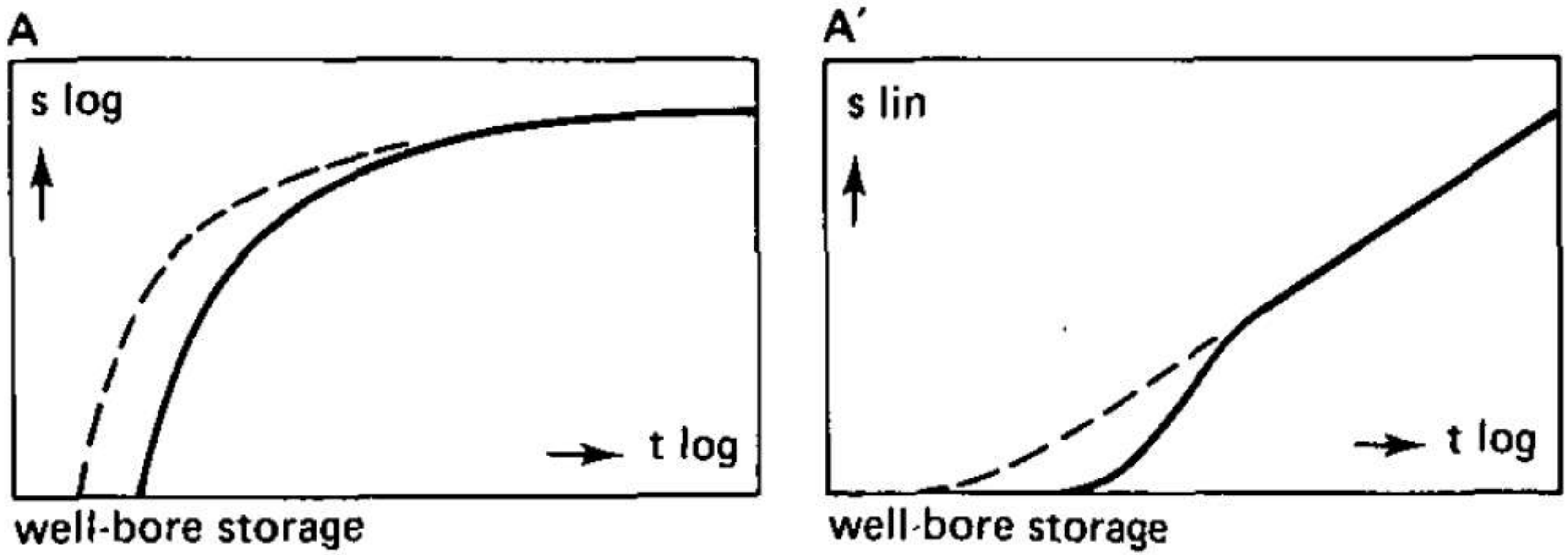
Data Interpretation – well-bore storage



Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

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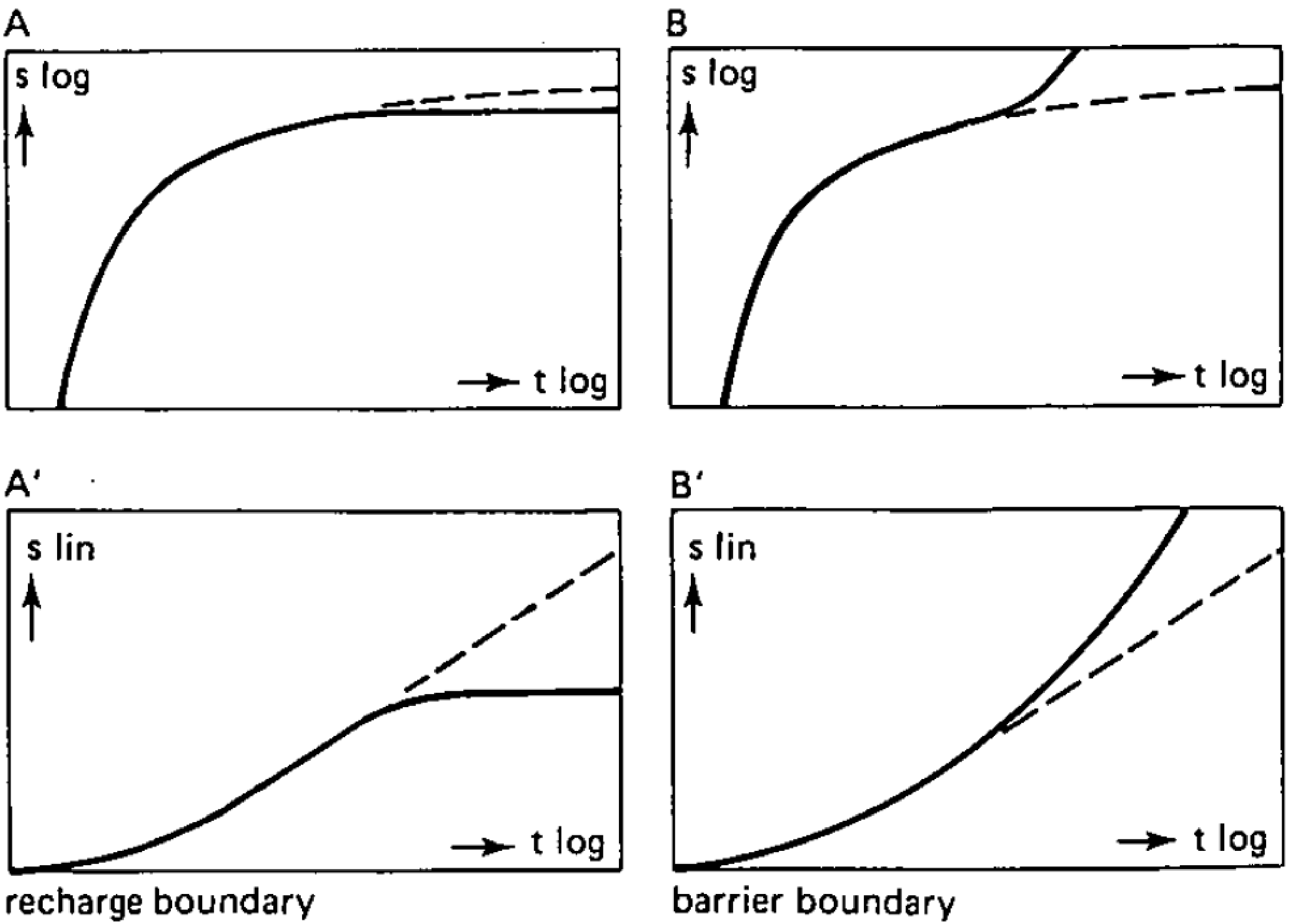
Data Interpretation – boundaries



Source: Kruseman & de Ridder, (1994), Analysis and Evalutaion of Pumping Test Data; ILRI publication 47

TOPICS TO BE COVERED

1. Terminology
2. Purpose of pumping tests
3. How to plan and set up a pumping test
4. Analysis of pumping test data
5. Reporting

PART 5 – Reporting (I)

1. Executive summary.
2. Map of the test site showing the pumping well, piezometers and any barrier or recharge boundaries.
3. Lithological cross sections.
4. Tables of field measurements

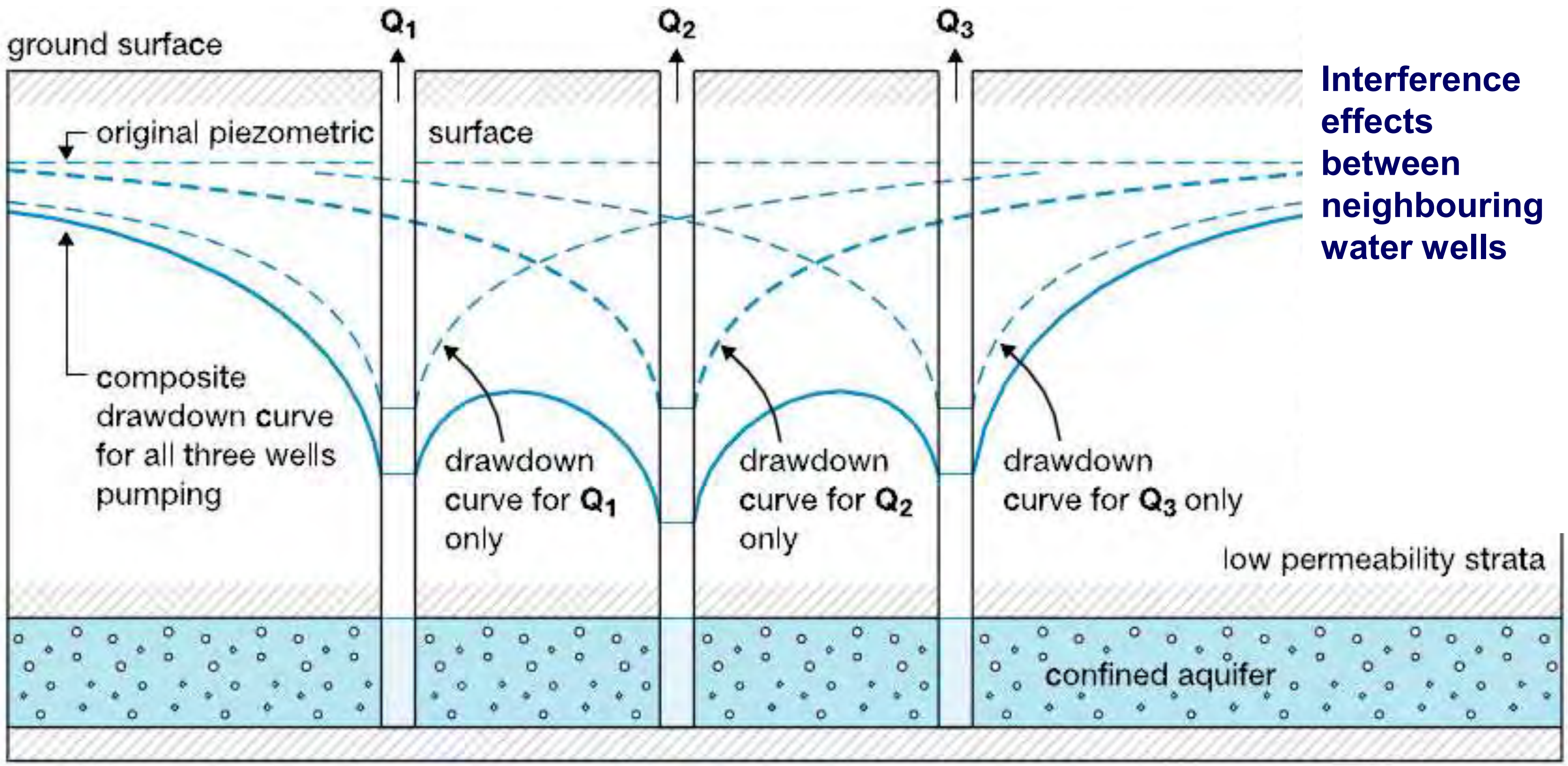
PART 5 – Reporting (II)

5. Hydrographs.
6. Time & distance drawdown curves.
7. Reasons for selecting the theoretical model.
8. Calculated values of aquifer characteristics.
9. Likely groundwater recharge areas, recharge rates & sustainability of water source.
10. Potential groundwater pollution sources.
11. Conclusions & recommendations.

Key Questions to Address in the Report

- What rate can the well be pumped at?
- What are the likely groundwater recharge rates?
- What is the likely recharge area of the well?
- How sustainable is the well at the proposed pumping rates?
- What happens when there is a drought?

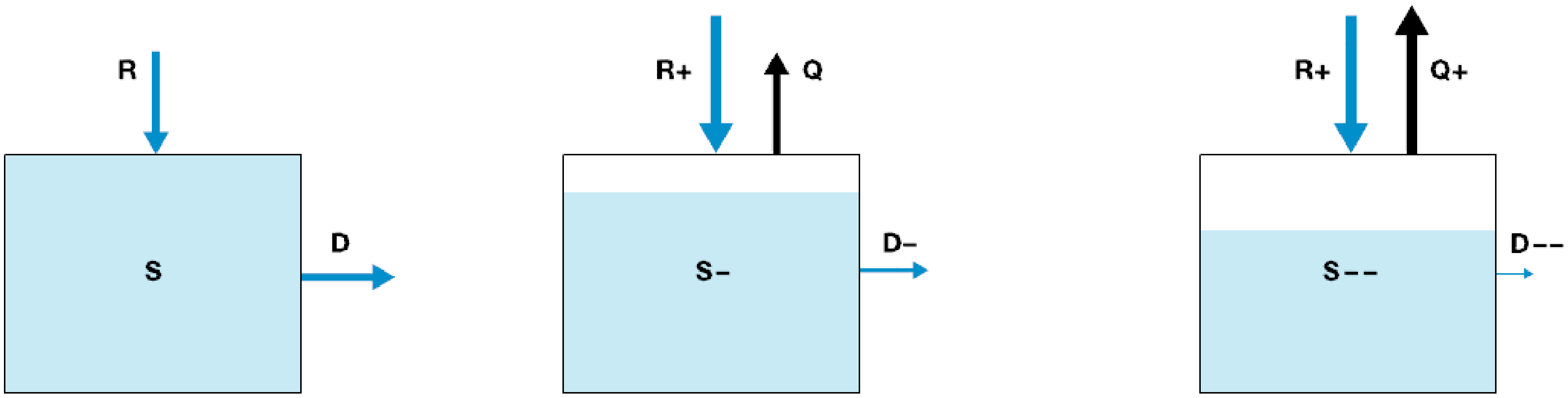
Interference Effects Between Wells



Interference effects between neighbouring water wells

Source: GWMATE BN_05 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

Groundwater Sustainability

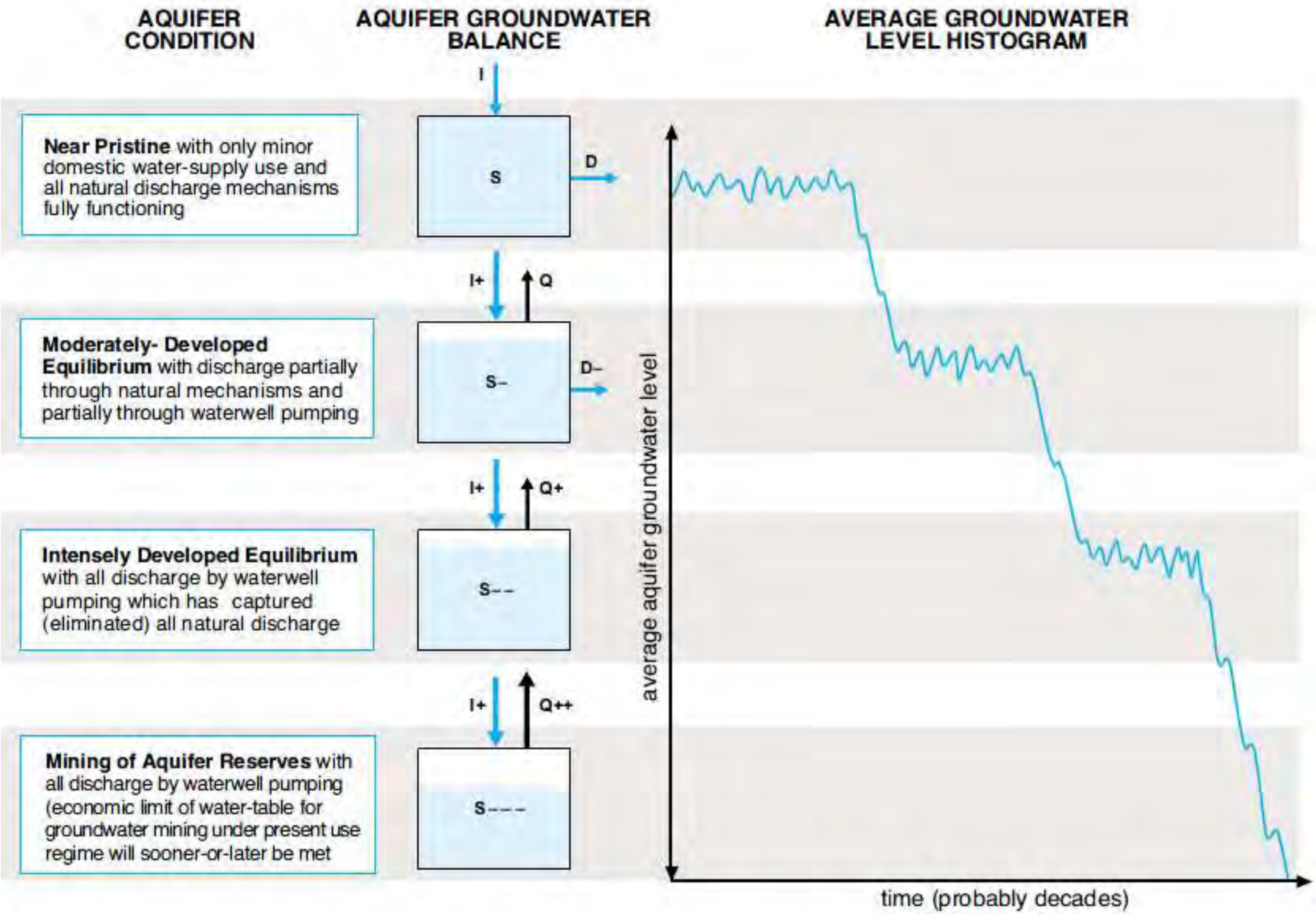


NATURAL CONDITIONS
in the long term **R** = **D**, and **S** is constant

STABLE GROUNDWATER PUMPING
Q is equivalent to reduction in **D** and **S**, plus increase in **R**

UNSUSTAINABLE GROUNDWATER PUMPING
Q+ is greater than **R+** plus **D– –** (which reduces to 0) and **S– –** decreases continuously

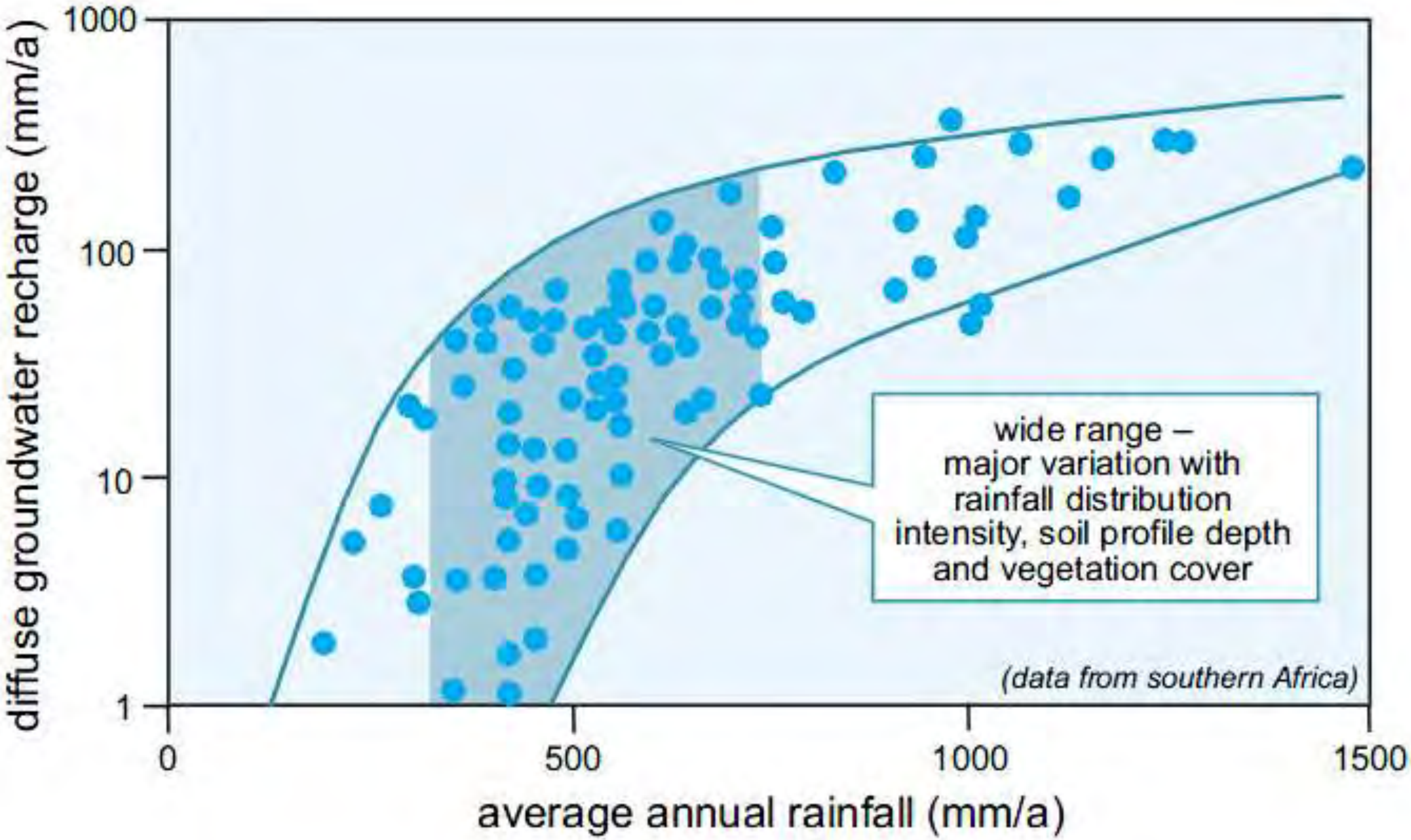
Source: GWMATE BN_02 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933



I = Infiltration
Q = waterwell pumping
D = natural discharge
S = aquifer storage
+ *and* **-** *used to indicate relative change of corresponding groundwater balance component with respect to preceding condition*

Source: GWMATE BN_016- http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

Groundwater Diffuse Recharge Rates



Source: GWMATE BN_016- http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

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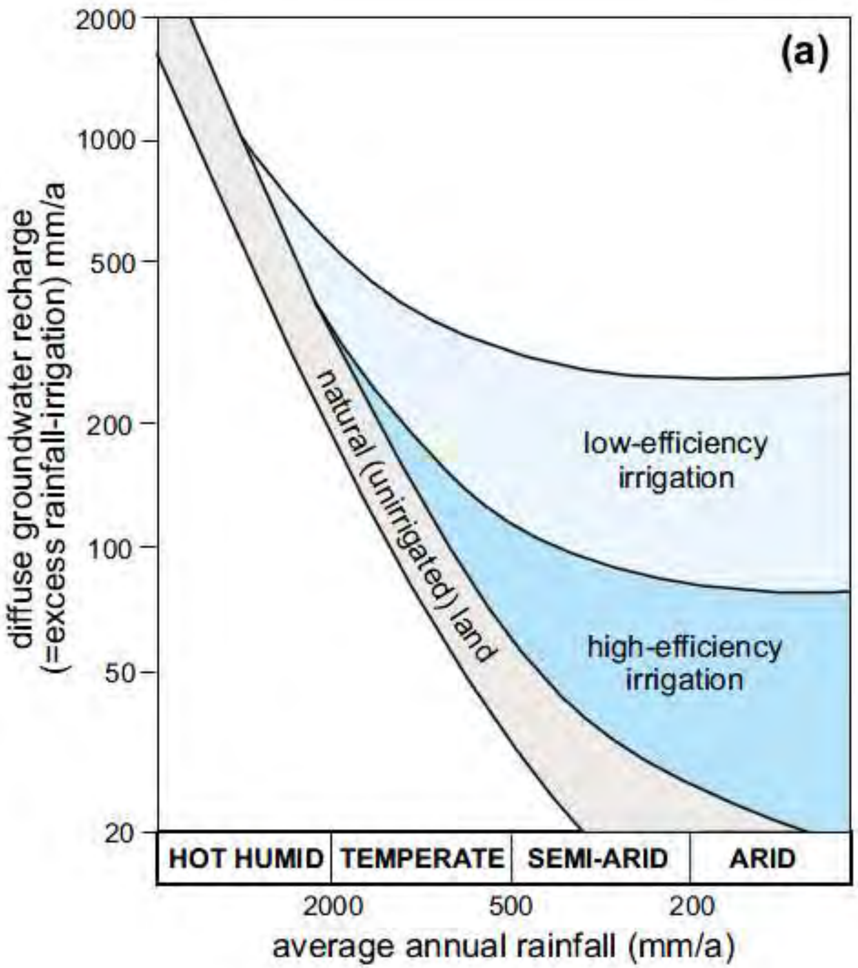
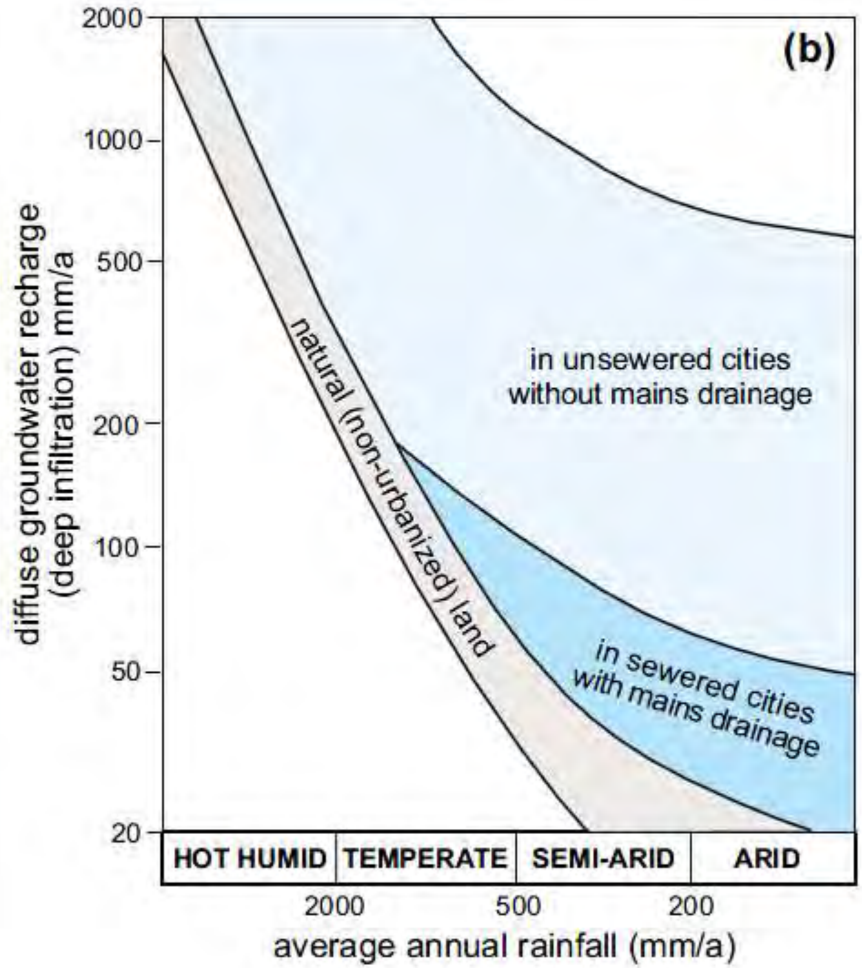
Augmented Groundwater Recharge Rates

(a) irrigated agriculture

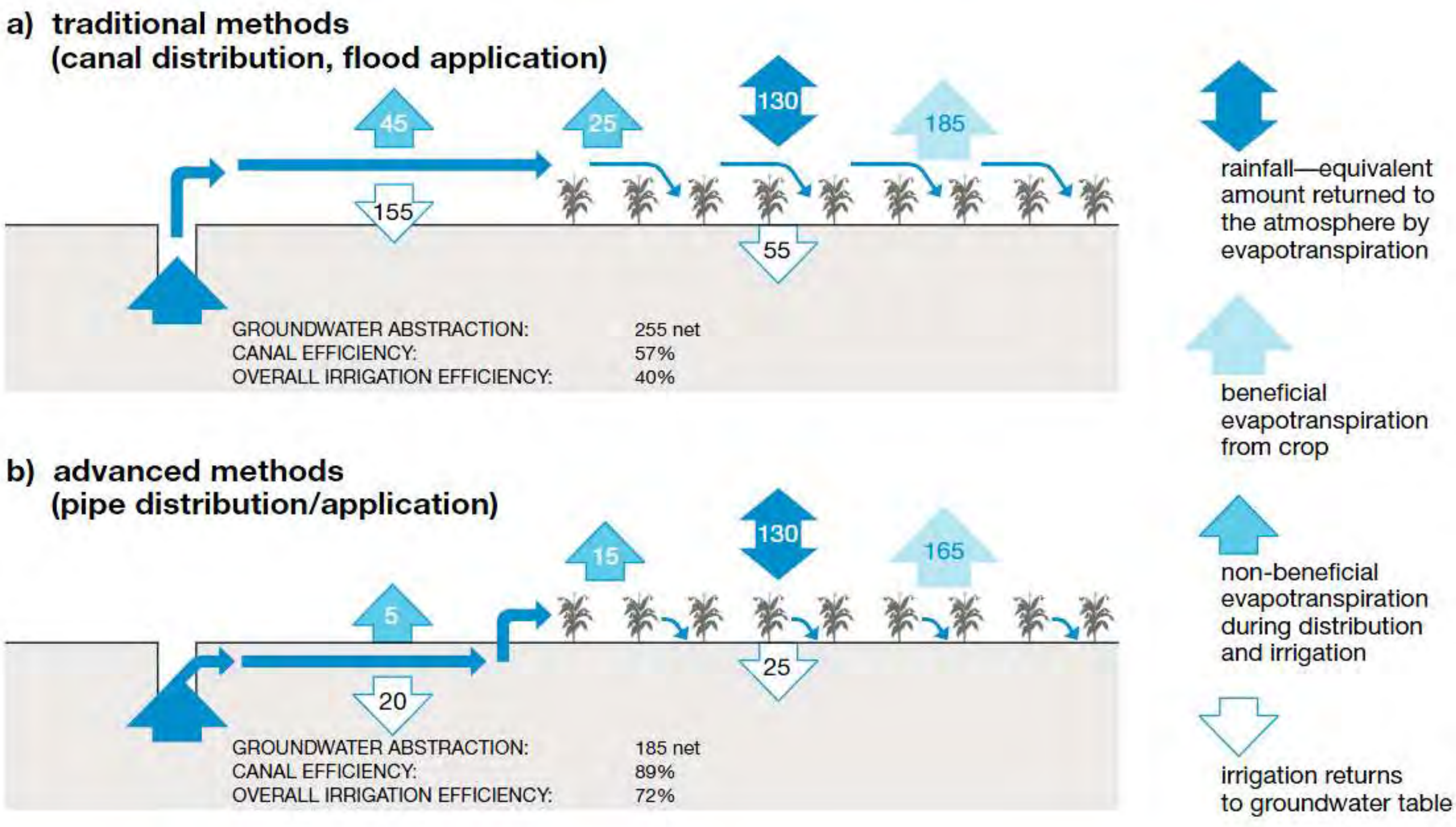


(b) urbanisation



Source: GWMATE BN_016- http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

Groundwater Recharge from Irrigation



Source: GWMATE BN_03 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

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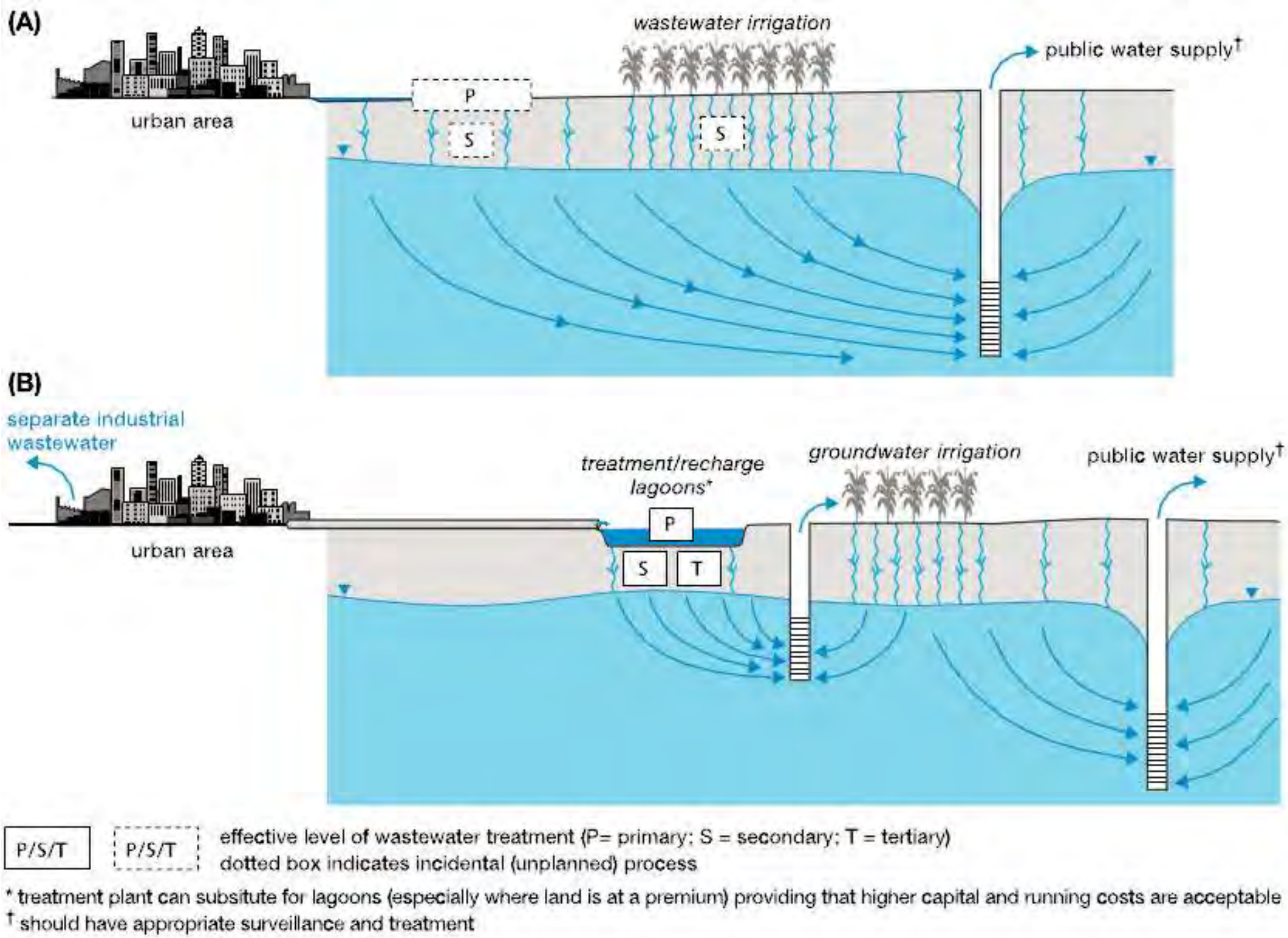
Groundwater Recharge from Urban Areas

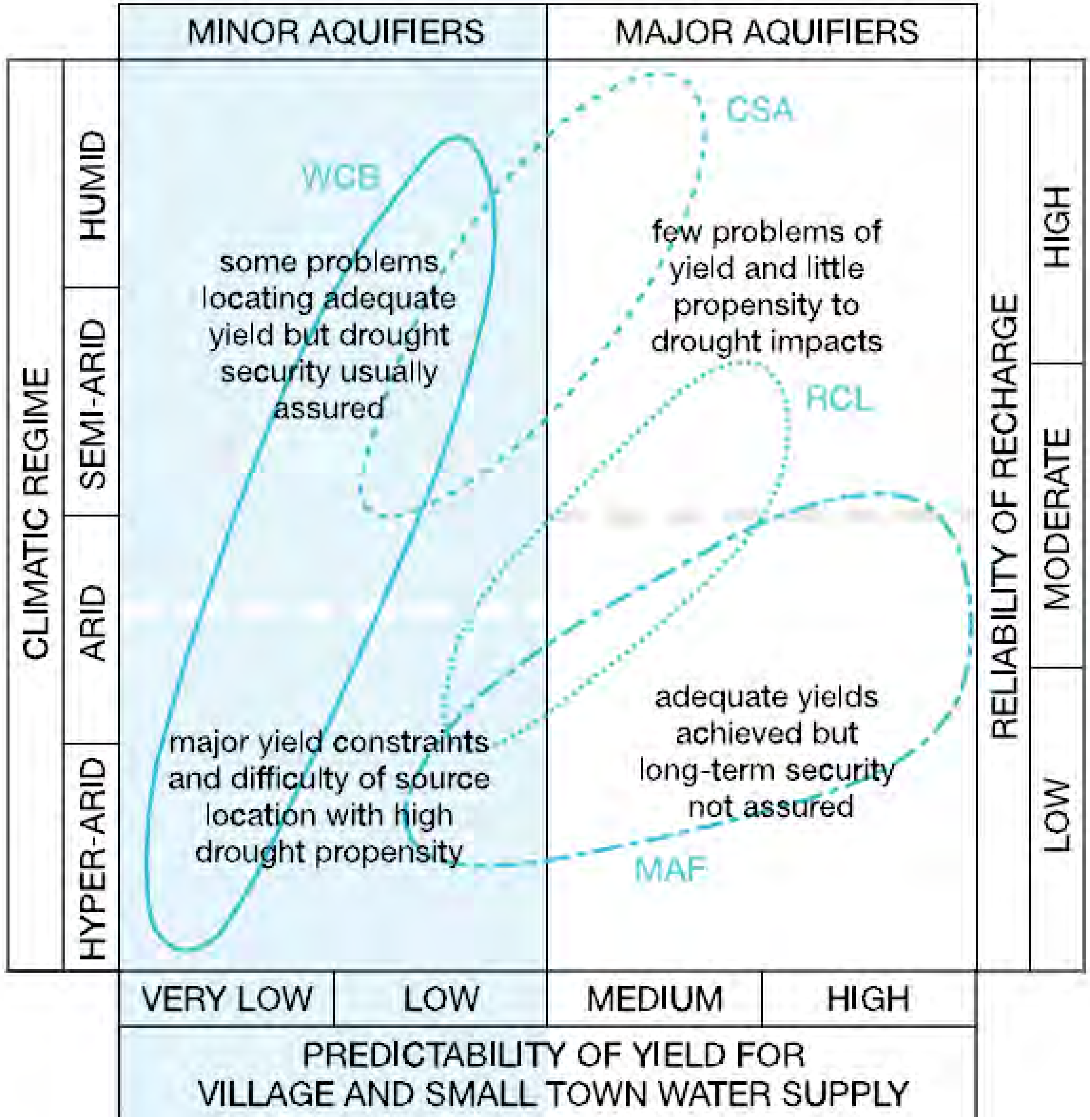


(A) commonly-occurring unplanned and uncontrolled situation

(B) economical interventions aimed at reducing groundwater source pollution risk

Source: GWMATE BN_12 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

Drought Security



Variation of water well drought security with aquifer type and climatic regime

Typical ranges for aquifer type indicated:

- WCB: Weathered Crystalline Basement
- CSA: Consolidated Sedimentary Aquifers
- RCL: Recent Coastal Limestones
- MAF: Major Alluvial Formations

Source: GWMATE BN_13 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

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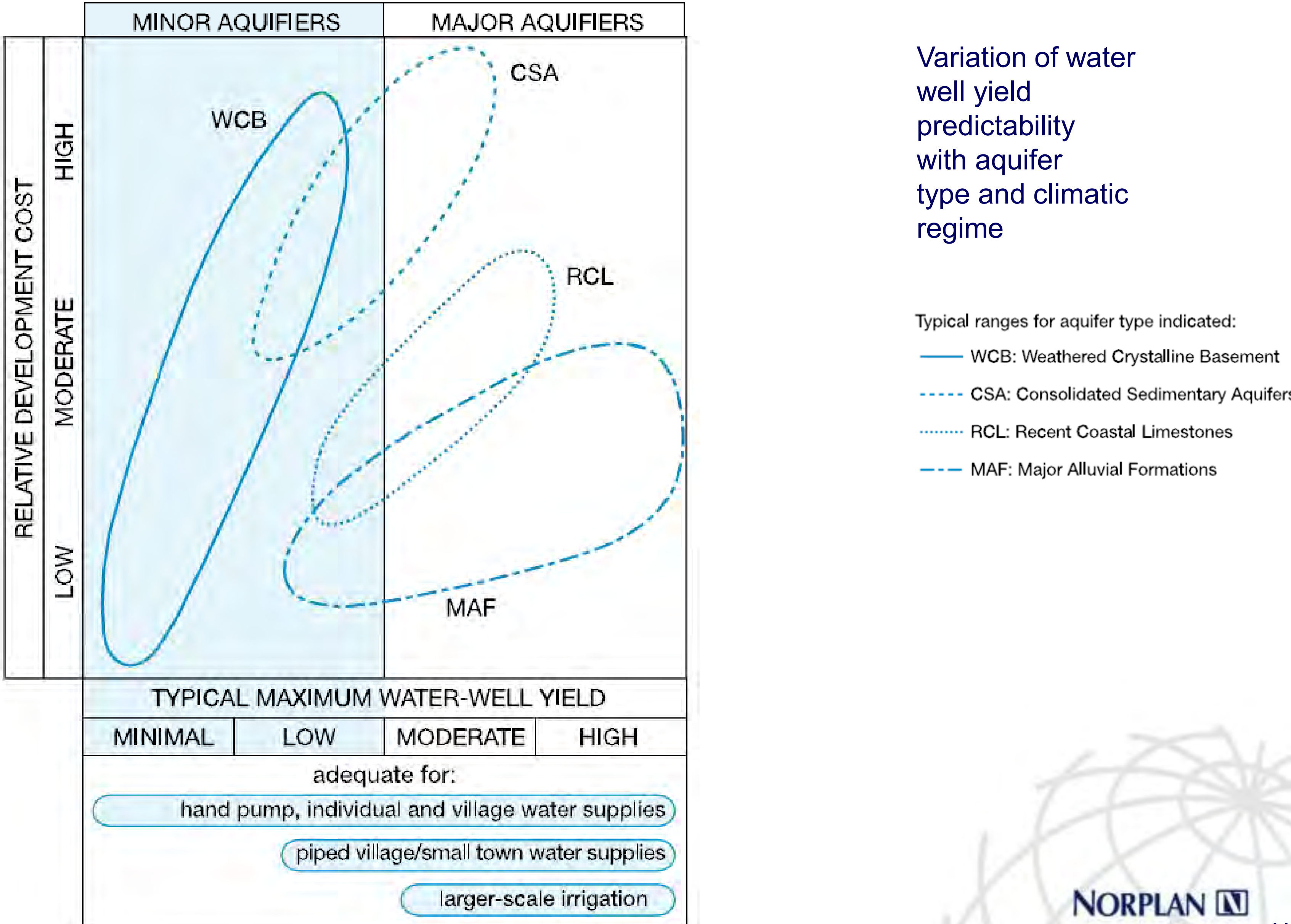
Data Interpretation – Sustainability



Variation of water well yield predictability with aquifer type and climatic regime

Source: GWMATE BN_13 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

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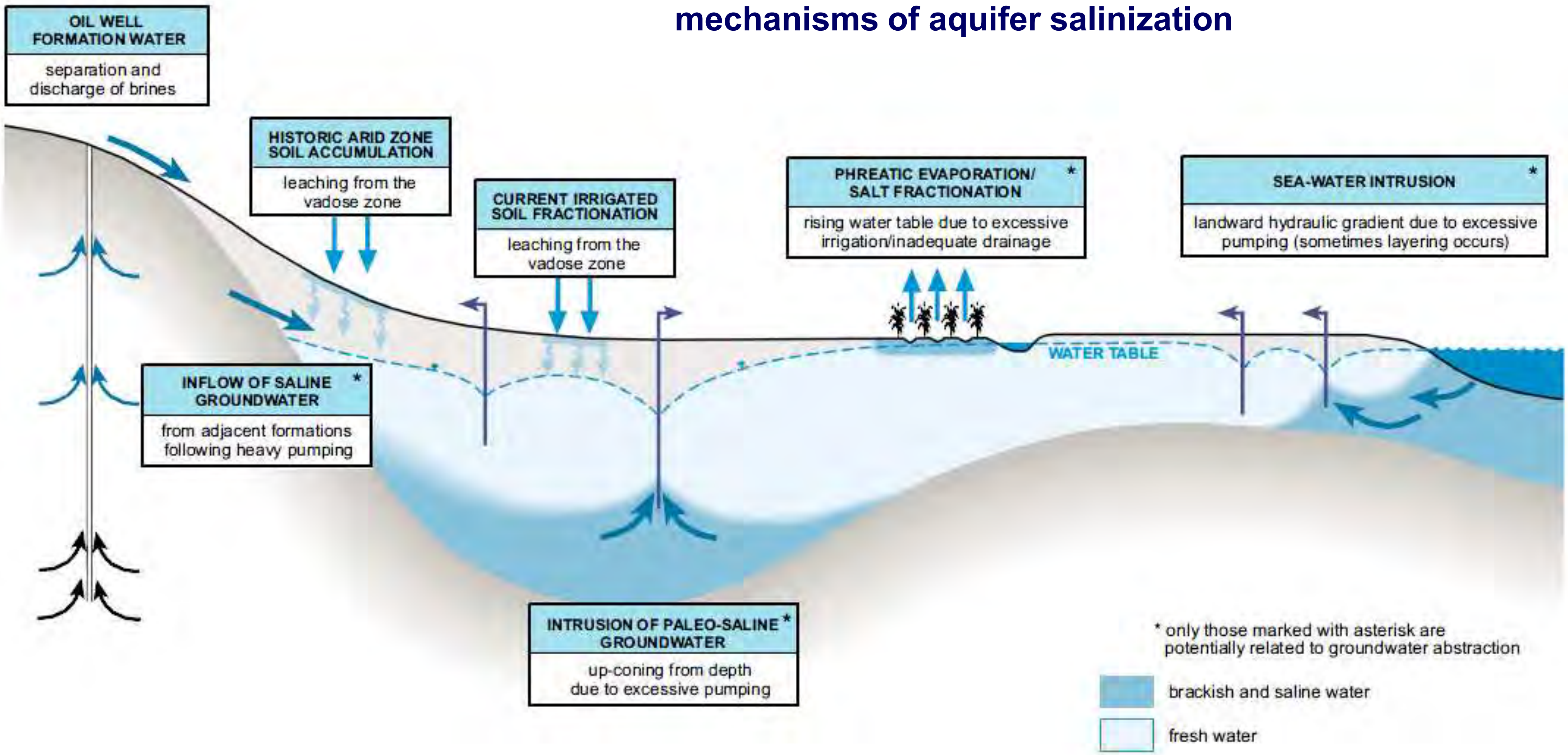
Key Questions to Address in the Report

- Are there any natural or anthropogenic (human) sources of pollution within the well's capture zone?
- Are there any lower quality groundwater zones which may end up in the well in the long term?

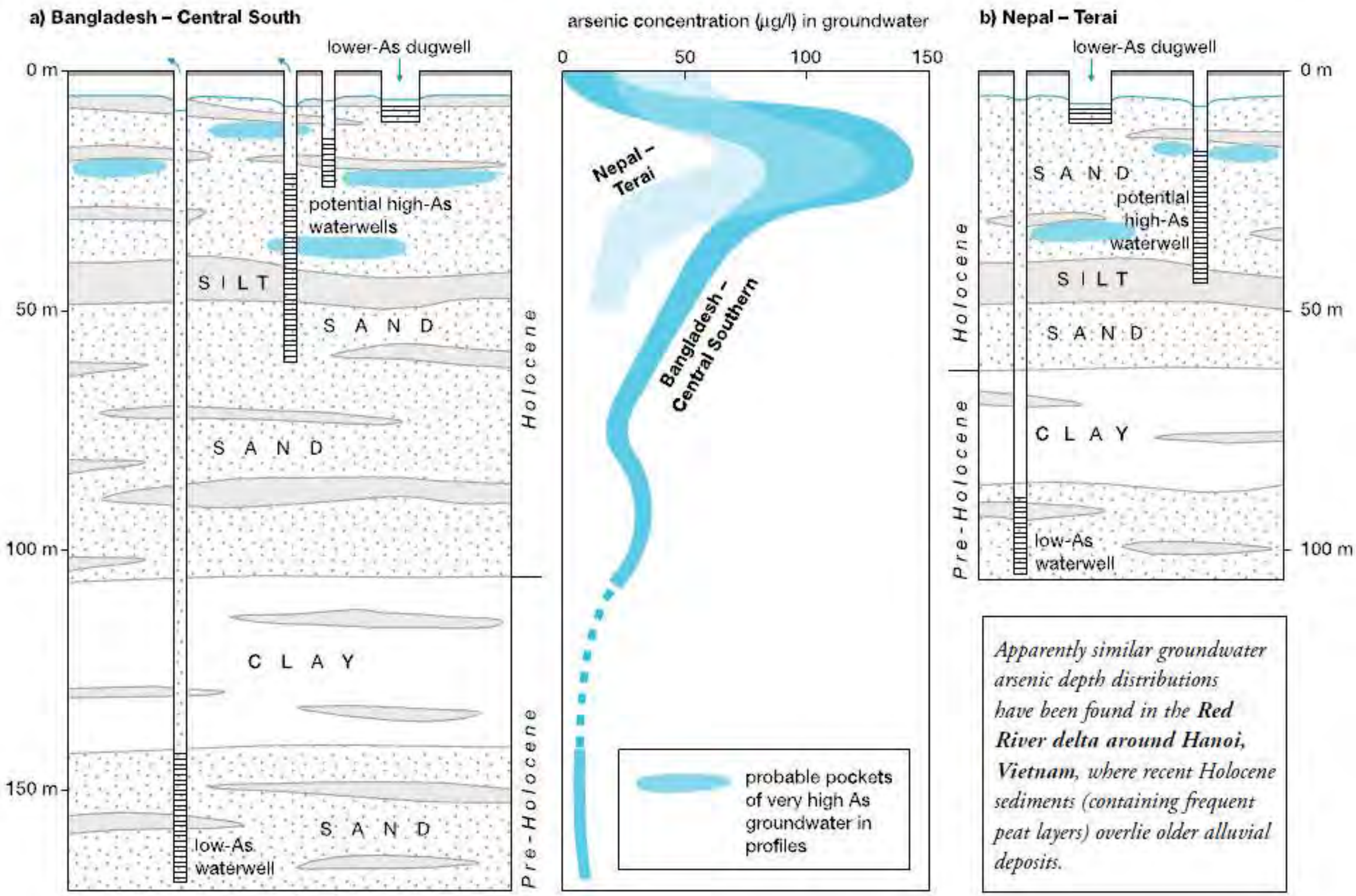
Sources of Groundwater Salinity

The possible origins of groundwater salinity and mechanisms of aquifer salinization



Source: GWMATE BN_02 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

Groundwater Quality Issues – Arsenic



Apparently similar groundwater arsenic depth distributions have been found in the ***Red River delta around Hanoi, Vietnam,*** *where recent Holocene sediments (containing frequent peat layers) overlie older alluvial deposits.*

Source: GWMATE BN_14 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

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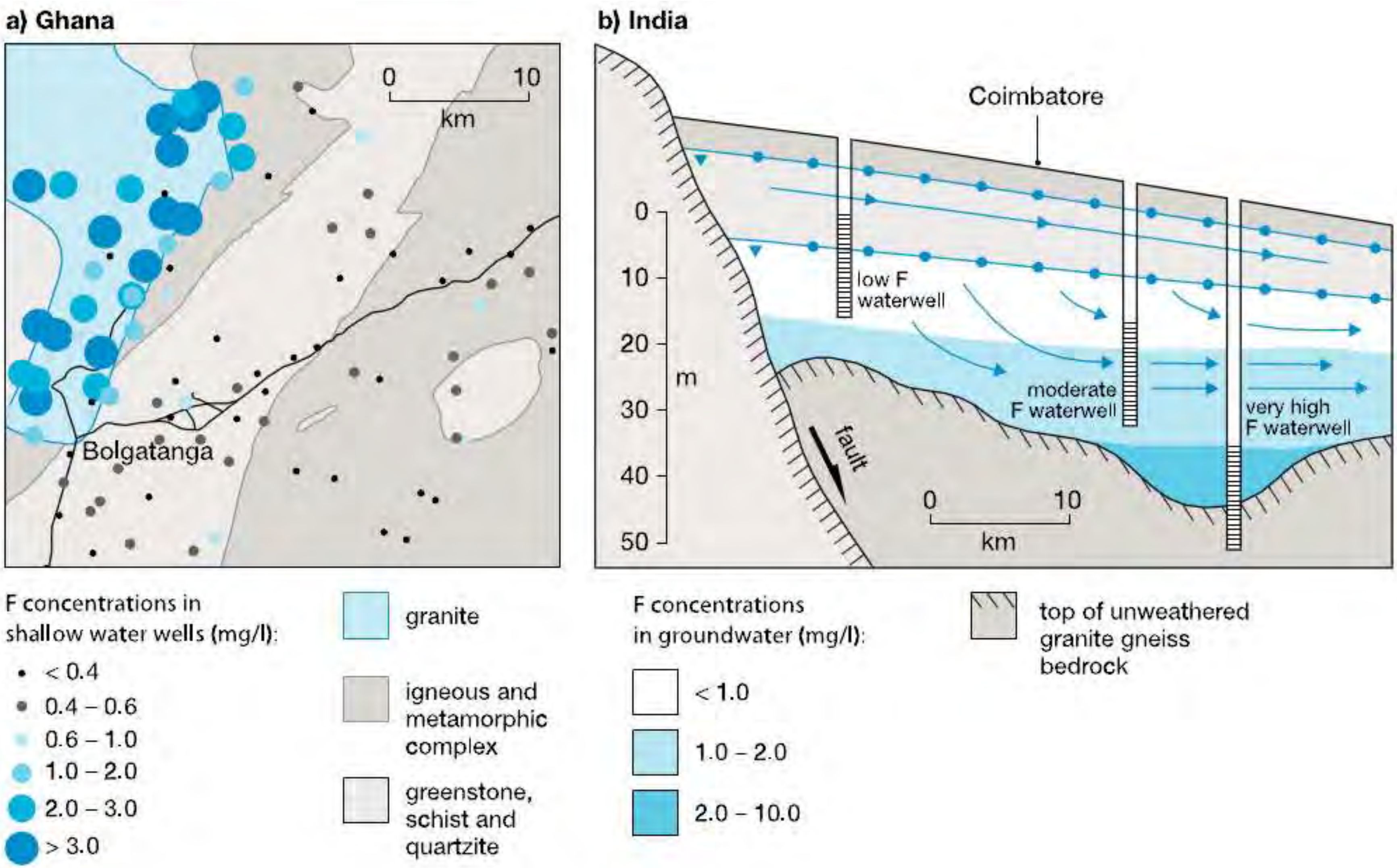
Groundwater Quality Issues – Fluoride



Source: GWMATE BN_14 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

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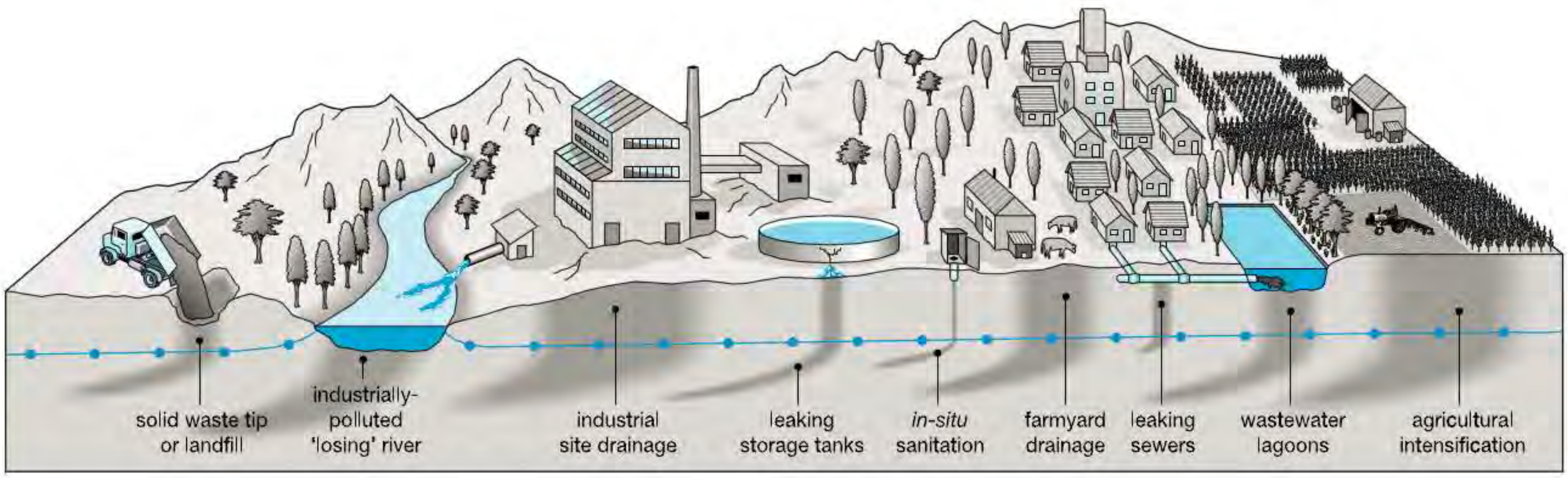
Groundwater Quality Issues – Land Use

Land-use activities commonly generating a groundwater pollution threat



Source: GWMATE BN_08 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

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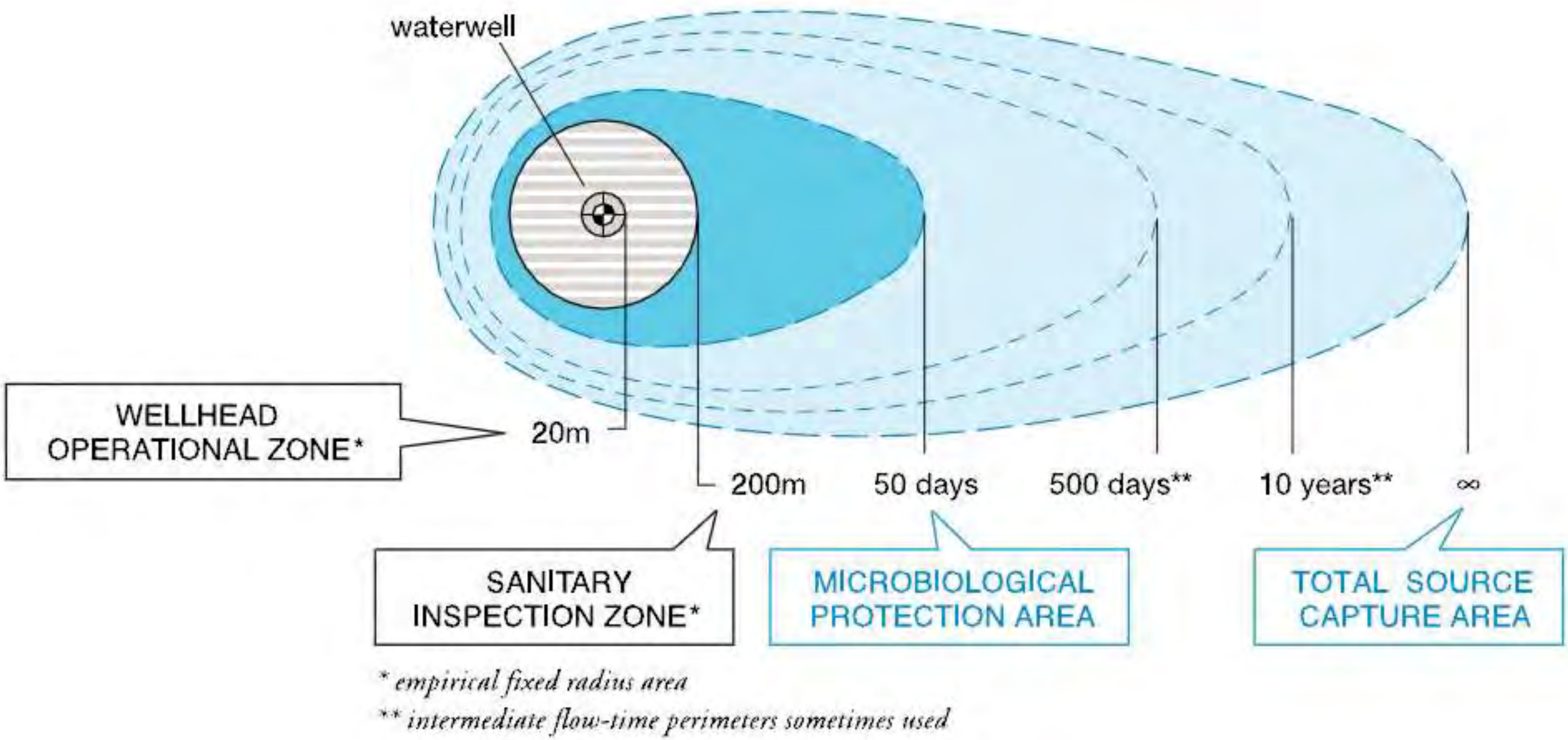
Typical Groundwater Pollution Sources

POLLUTION SOURCE	TYPE OF CONTAMINANT
Agricultural Activity	nitrates; ammonium; pesticides; fecal organisms
In-situ Sanitation	nitrates; fecal organisms; trace synthetic hydrocarbons
Gasoline Filling Stations & Garages	benzene; other aromatic hydrocarbons; phenols; some halogenated hydrocarbons
Solid Waste Disposal	ammonium; salinity; some halogenated hydrocarbons; heavy metals
Metal Industries	trichloroethylene; tetrachloroethylene; other halogenated hydrocarbons; heavy metals; phenols; cyanide
Painting and Enamel Works	alkylbenzene; tetrachloroethylene; other halogenated hydrocarbons; metals; some aromatic hydrocarbons
Timber Industry	pentachlorophenol; some aromatic hydrocarbons
Dry Cleaning	trichloroethylene; tetrachloroethylene
Pesticide Manufacture	various halogenated hydrocarbons; phenols; arsenic
Sewage Sludge Disposal	nitrates; various halogenated hydrocarbons; lead; zinc
Leather Tanneries	chromium; various halogenated hydrocarbons; phenols
Oil and Gas Exploration/Extraction	salinity (sodium chloride); aromatic hydrocarbons
Metalliferous and Coal Mining	acidity; various heavy metals; iron; sulphates

Source: GWMATE BN_08 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

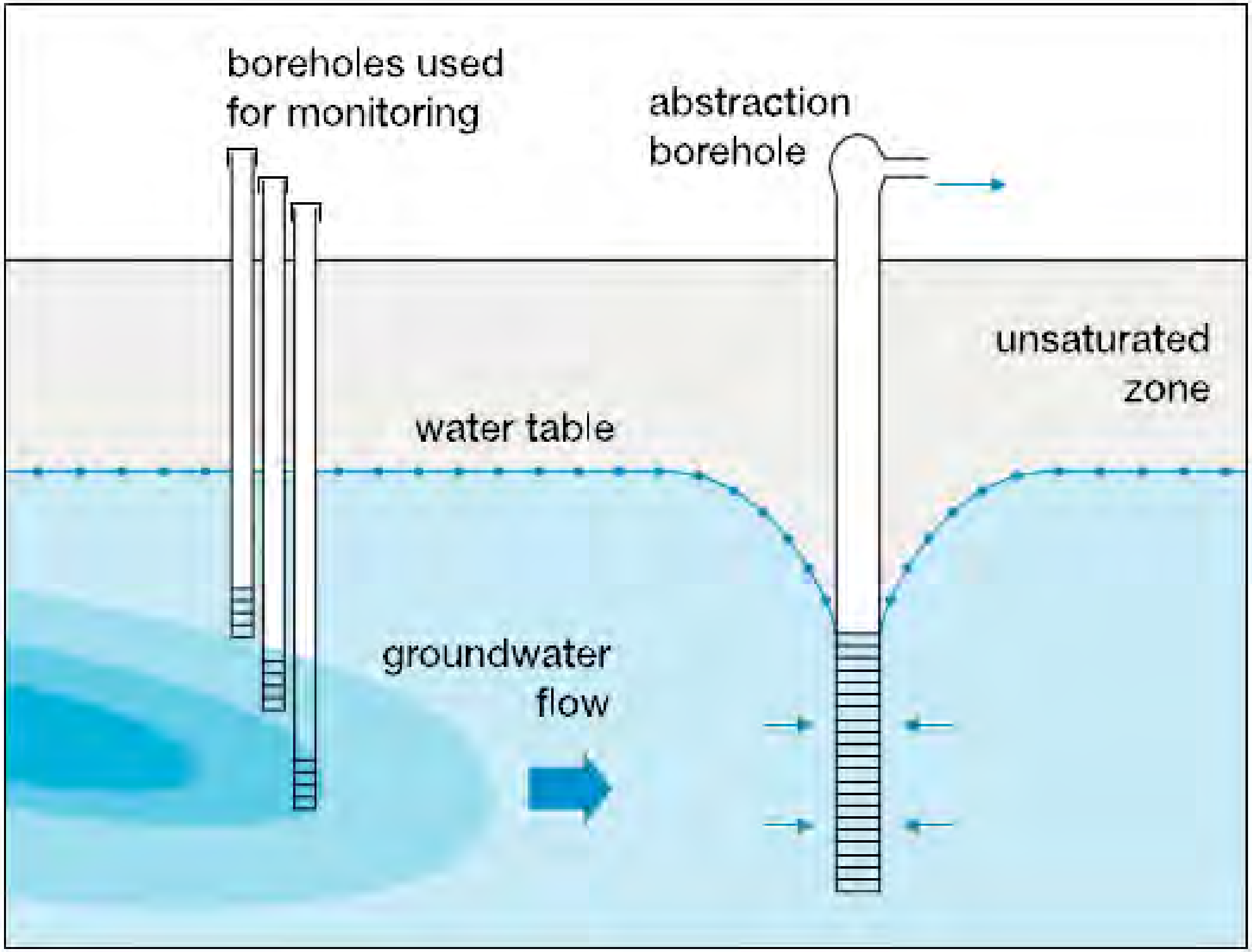
Water Well Protection Zones

Idealized scheme of surface sanitary zones and groundwater flow perimeters for the protection of a water well in an unconfined aquifer



Source: GWMATE BN_08 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

Defensive Groundwater Pollution Detection Monitoring



Source: GWMATE BN_09 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

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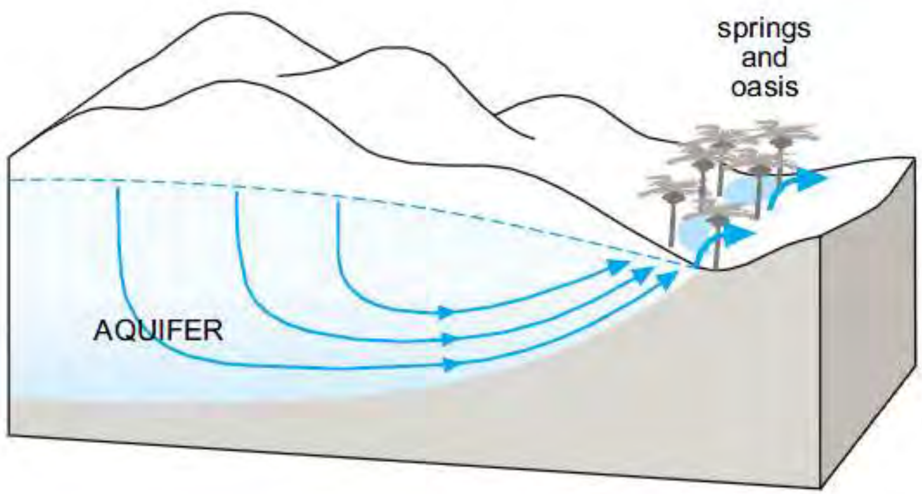
Key Questions to Address in the Report

- Does the well have any potential impact on groundwater-related ecosystems?

Groundwater-related ecosystem

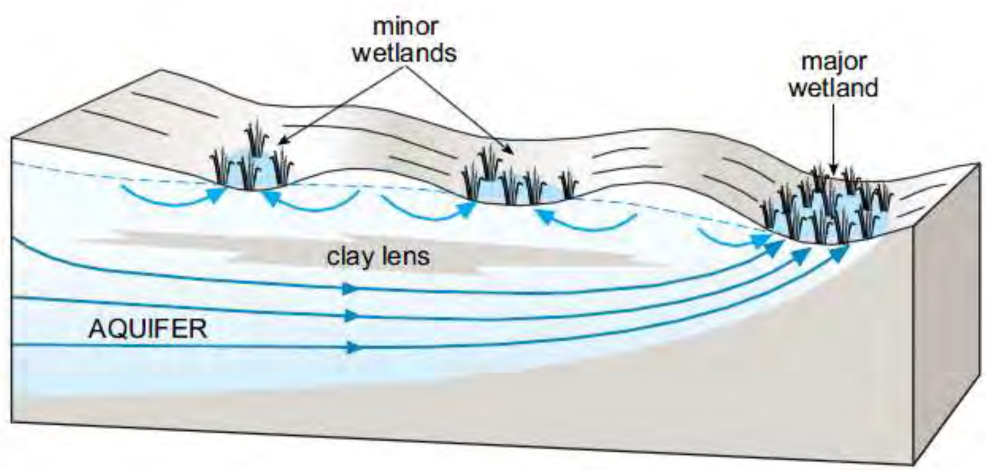


(A) WETLAND ECOSYSTEM IN ARID REGION

dependent upon deep groundwater flow system, sometimes with only limited contemporary replenishment and fossil aquifer flow

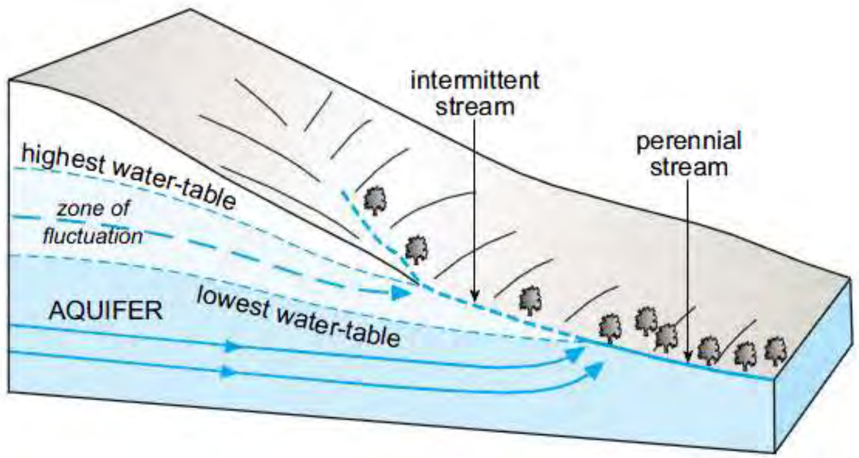
(B) WETLAND ECOSYSTEM IN HUMID REGION

individual ecosystems can be dependent upon (or using) groundwater from different depths in a multi-layered aquifer flow system



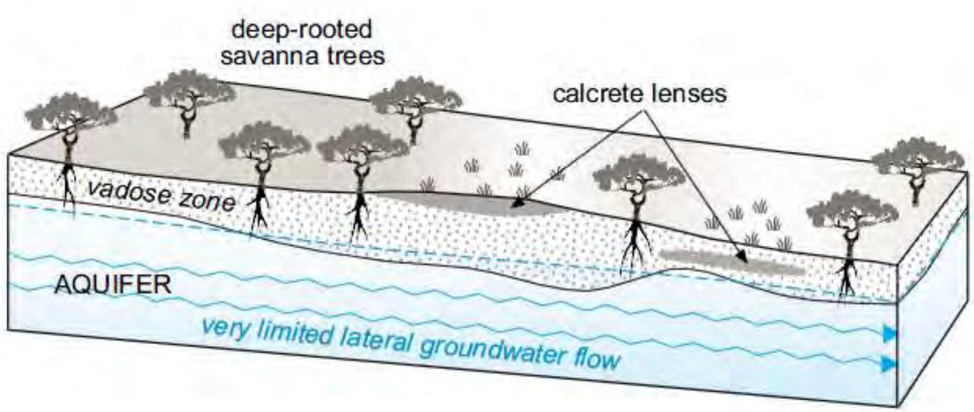
Source: GWMATE BN_15 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

Groundwater-related ecosystem



(C) AQUATIC STREAM-BED ECOSYSTEM IN HUMID REGION

variable ecosystem along upper reaches of river system in part fed by perennial groundwater discharge and in part by intermittent groundwater flow



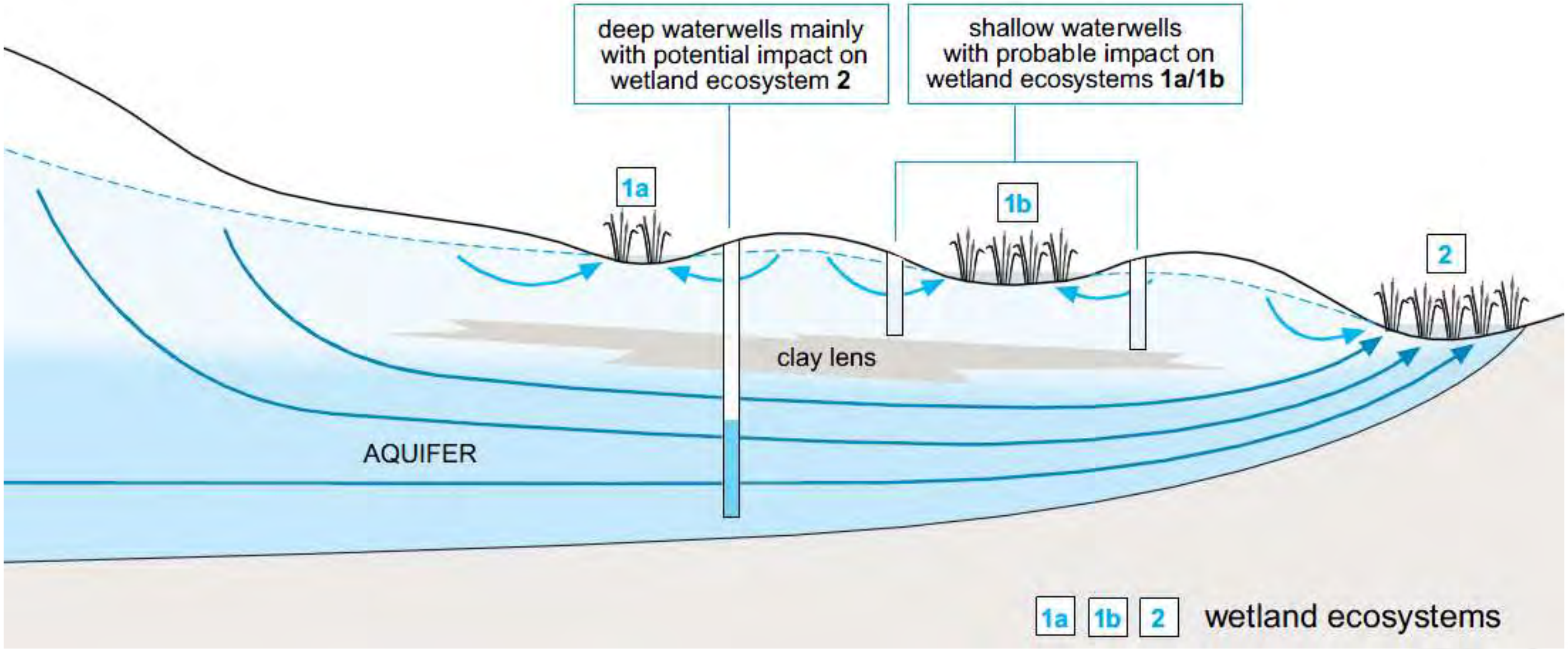
(E) TERRESTRIAL ECOSYSTEM IN ARID REGION

savanna ecosystem dependent upon exceptionally deep rooted trees and bushes which tap water table or its capillary fringe directly (distribution limited by thickness and degree of consolidation of sediments in the vadose zone)

Source: GWMATE BN_15 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

Groundwater-related ecosystem

Potential interference of groundwater pumping from a multi-layered aquifer with different types of associated wetland habitat



Source: GWMATE BN_15 - http://water.worldbank.org/node/83769?goback=.gde_703977_member_232786933

Visit the Hydrogeology Toolbox
www.geosearch.co.uk

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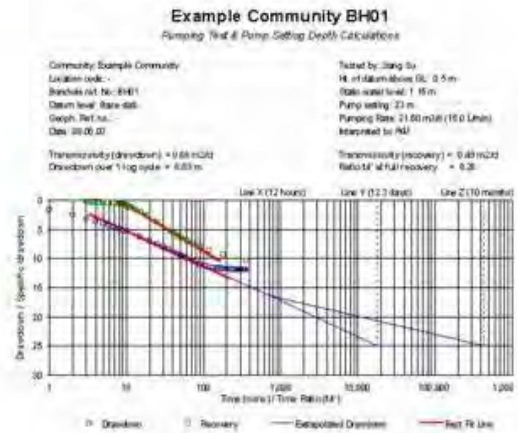
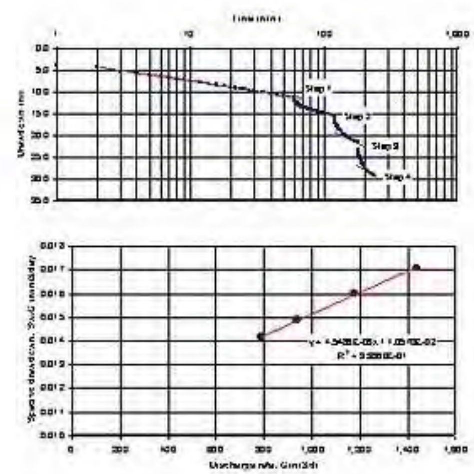
Hand Pump XL is a spreadsheet for interpreting short term pumping and recovery tests carried out in low yielding boreholes destined for the installation of hand pumps. The extrapolated drawdown is calculated at the end of the dry season, and the specific drawdown used to recommend pump installation depths. Latest update:
Hand Pump XL V1.0 (16.11.03)



Step Test XL is a spreadsheet for interpreting variable rate (step) discharge pumping tests, using the Bierschenk-Wilson approach. Latest update:
Step Test XL V1.0 (16.11.03)



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Thank you

for your attention!

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