Groundwater

United Nations
Educational, Scientific and
Cultural Organization

International Centre for
Water Security and
Sustainable Management

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Water Crisis and the Role of Groundwater

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Water Crisis and the Role of Groundwater

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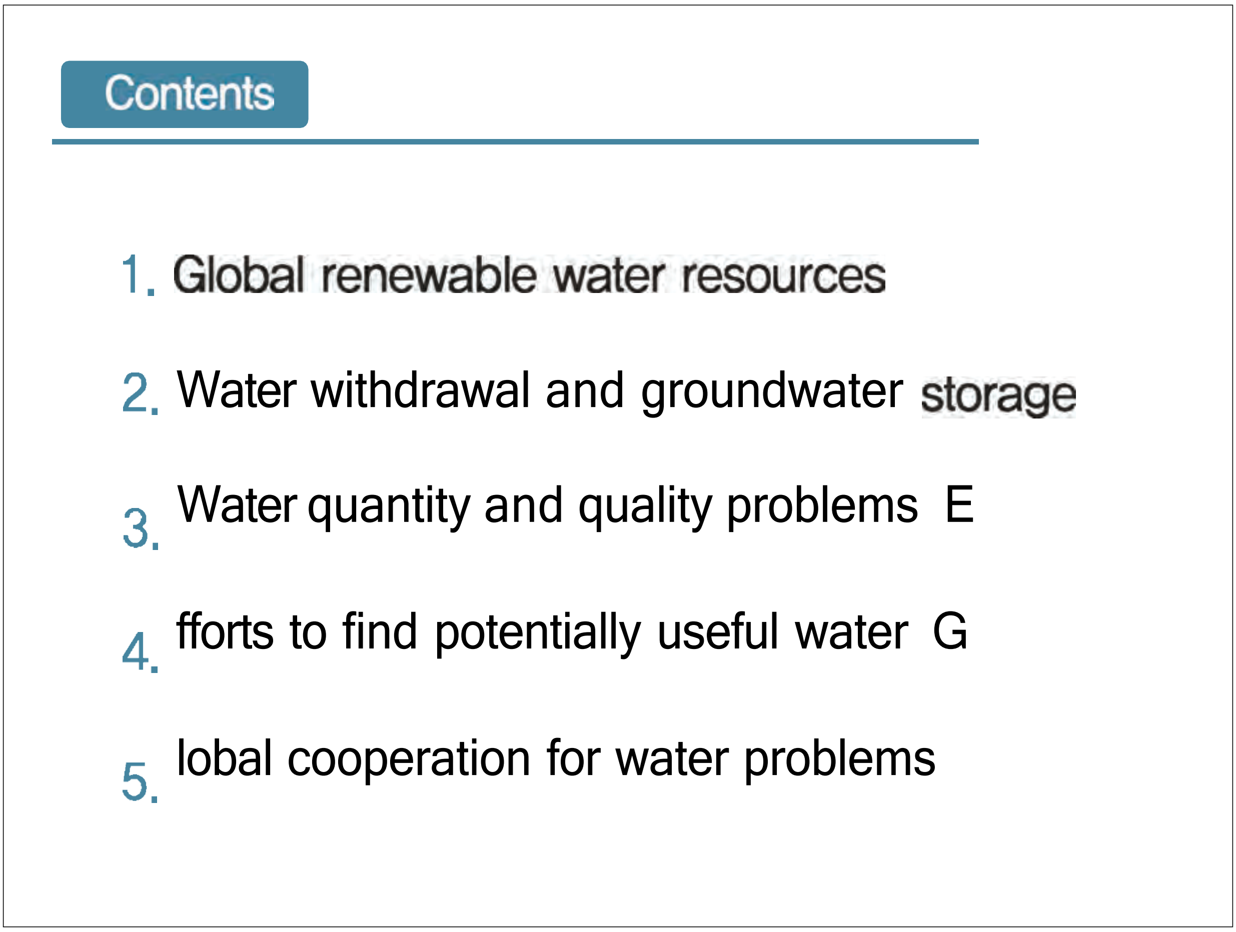
Aims & Objectives

The global water crisis is not only ongoing, but it is expected that the water crisis will intensify as climate change accelerates.

Groundwater has different flow and storage characteristics than surface water.

These characteristics could be well used to alleviate the water crisis.

In this section, we will consider such a solution.



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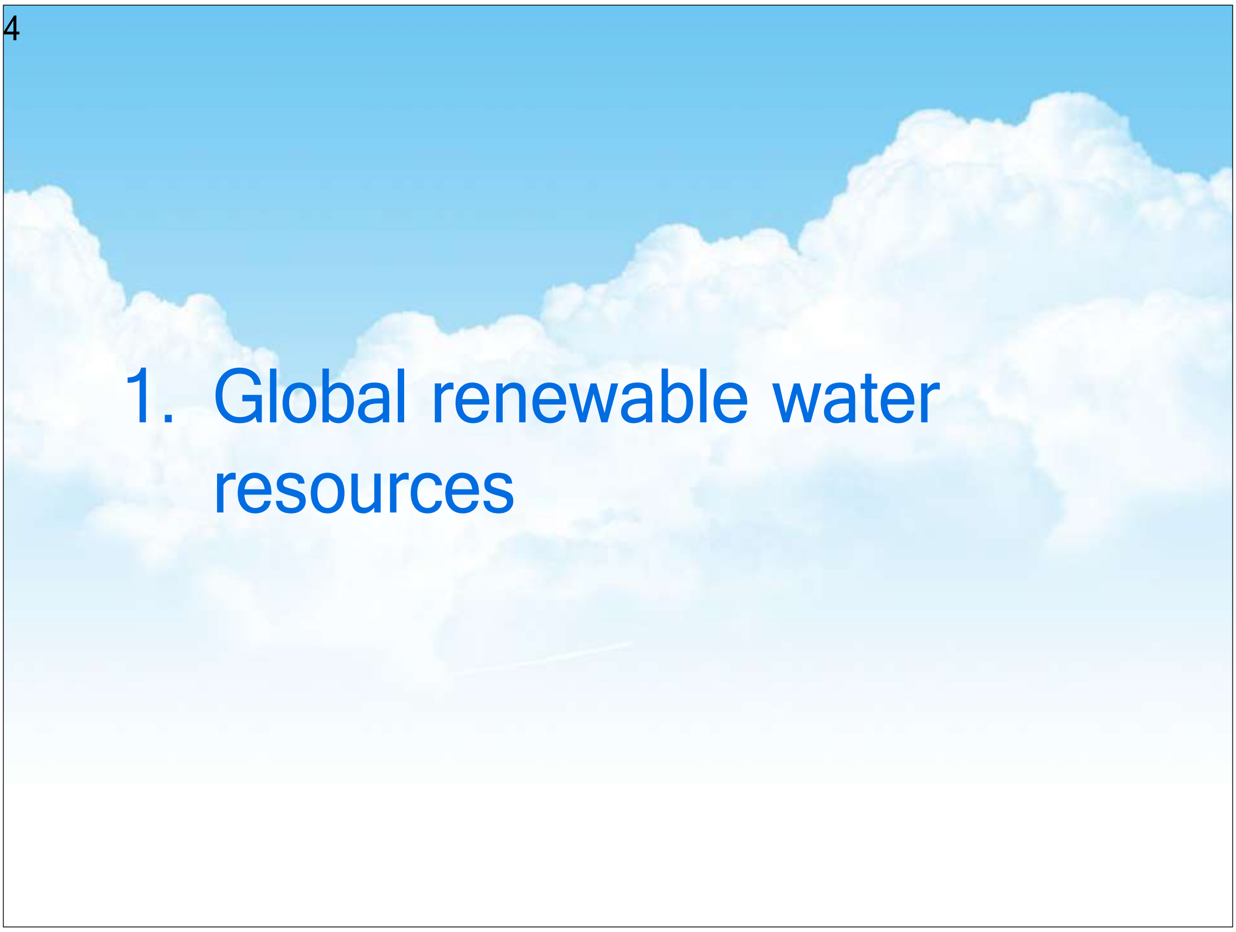

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1. Global renewable water resources

Total renewable water resources by country

SN	Country	Total renewable water resources (km³)	Date of Information
1	Brazil	8,233	2011
2	Russia	4,508	2011
3	United States	3,069	2011
4	Canada	2,902	2011
5	China	2,840	2011
6	Colombia	2,132	2011
—	European Union	2,057	2011
7	Indonesia	2,019	2011
8	Peru	1,913	2011
9	India	1,911	2011
10	Congo, Democratic Republic of the	1,283	2011
11	Venezuela	1,233	2011
12	Bangladesh	1,227	2011
13	Myanmar	1,168	2011
14	Chile	922	2011
15	Vietnam	884.1	2011

Source:
https://en.wikipedia.org/wiki/List_ of_ countries_ by_ total_ renewable_ water_ resources

71	Honduras	95.93	2011
72	Netherlands	91	2011
73	Iraq	89.86	2011
74	Cote d'Ivoire	81.14	2011
75	Austria	78	2011
76	Azerbaijan	77.7	2011
77	Korea, North	77.15	2011
78	Greece	74.25	2011
79	Portugal	69.7	2011
80	Korea, South	68.7	2011
81	Taiwan	67	2011
82	Kazakhstan	66	2011
83	Uganda	65.33	2011
84	Sudan	64.5	2011
85	Poland	63.33	2011

165	Barbados	0.08	2011
166	Qatar	0.06	2011
167	Antigua and Barbuda	0.05	2011
168	Malta	0.05	2011
169	Maldives	0.03	2011
170	Bahamas	0.02	2011
171	Kuwait	0.02	2011
172	Saint Kitts and Nevis	0.02	2011

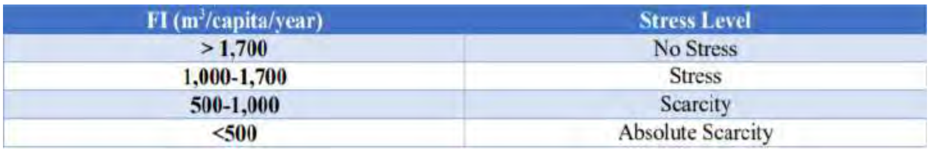
Nations with the largest estimated annual groundwater extractions (2010)

Country	Population 2010 (in thousands)	Groundwater extraction			
		Estimated groundwater extraction 2010 (km³/yr)	Breakdown by sector		
			Groundwater extraction for irrigation (%)	Groundwater extraction for domestic use (%)	Groundwater extraction for industry (%)
India	1224614	251.00	89	9	2
China	1341335	111.95	54	20	26
United States	310384	111.70	71	23	6
Pakistan	173593	64.82	94	6	0
Iran	73974	63.40	87	11	2
Bangladesh	148692	30.21	86	13	1
Mexico	113423	29.45	72	22	6
Saudi Arabia	27448	24.24	92	5	3
Indonesia	239871	14.93	2	93	5
Turkey	72752	13.22	60	32	8
Russia	142985	11.62	3	79	18
Syria	20411	11.29	90	5	5
Japan	126536	10.94	23	29	48
Thailand	69122	10.74	14	60	26
Italy	60551	10.40	67	23	10

From NGWA “**Facts About Global Groundwater Usage**”

Falkenmark Indicator (FI) and Water Stress Indicator (WSI)

Falkenmark Indicator (FI) = Surface Runoff / Population



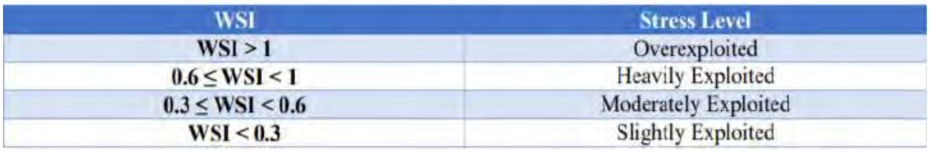
FI (m^3/capita/year)	Stress Level
> 1,700	No Stress
1,000-1,700	Stress
500-1,000	Scarcity
<500	Absolute Scarcity

Vladimir Smakhitn's Water Stress Indicator (WSI)

$$WSI = \frac{Withdrawals}{MAR - EWR}$$

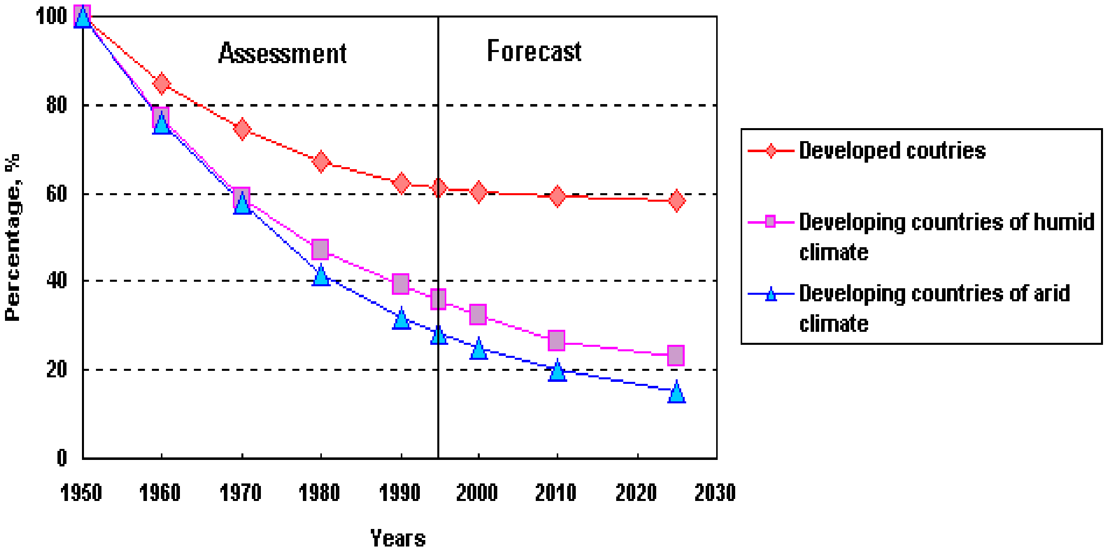
MAR: Mean Annual Runoff
EWR: Environmental Water Requirements
(The environment requires a certain water volume for upkeep, and therefore not all water (measured as MAR) can be considered available for human consumption.)

Table 2. Water stress indicator proposed by Smakhtin, 2005.

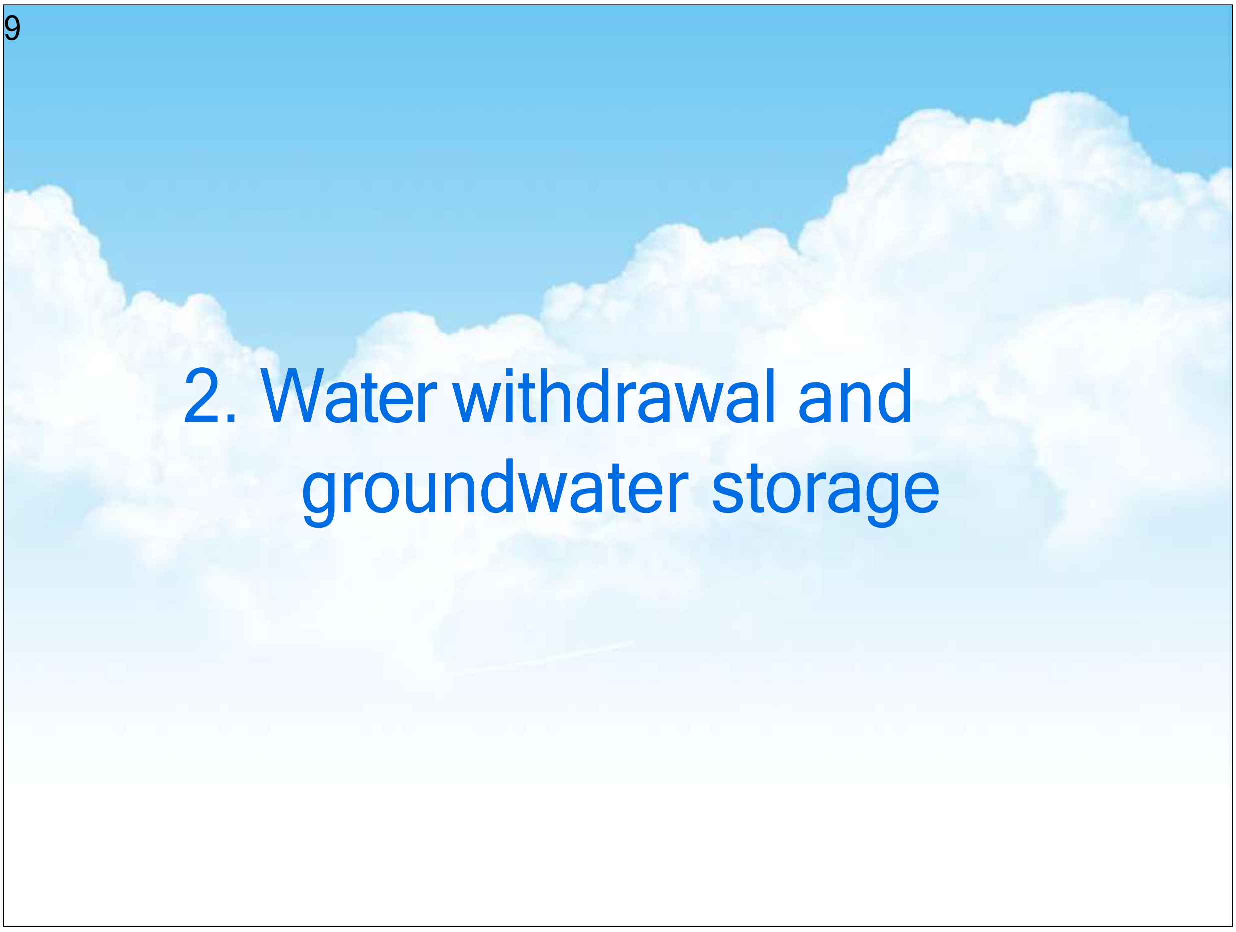


WSI	Stress Level
WSI > 1	Overexploited
$0.6 \leq$ WSI < 1	Heavily Exploited
$0.3 \leq$ WSI < 0.6	Moderately Exploited
WSI < 0.3	Slightly Exploited

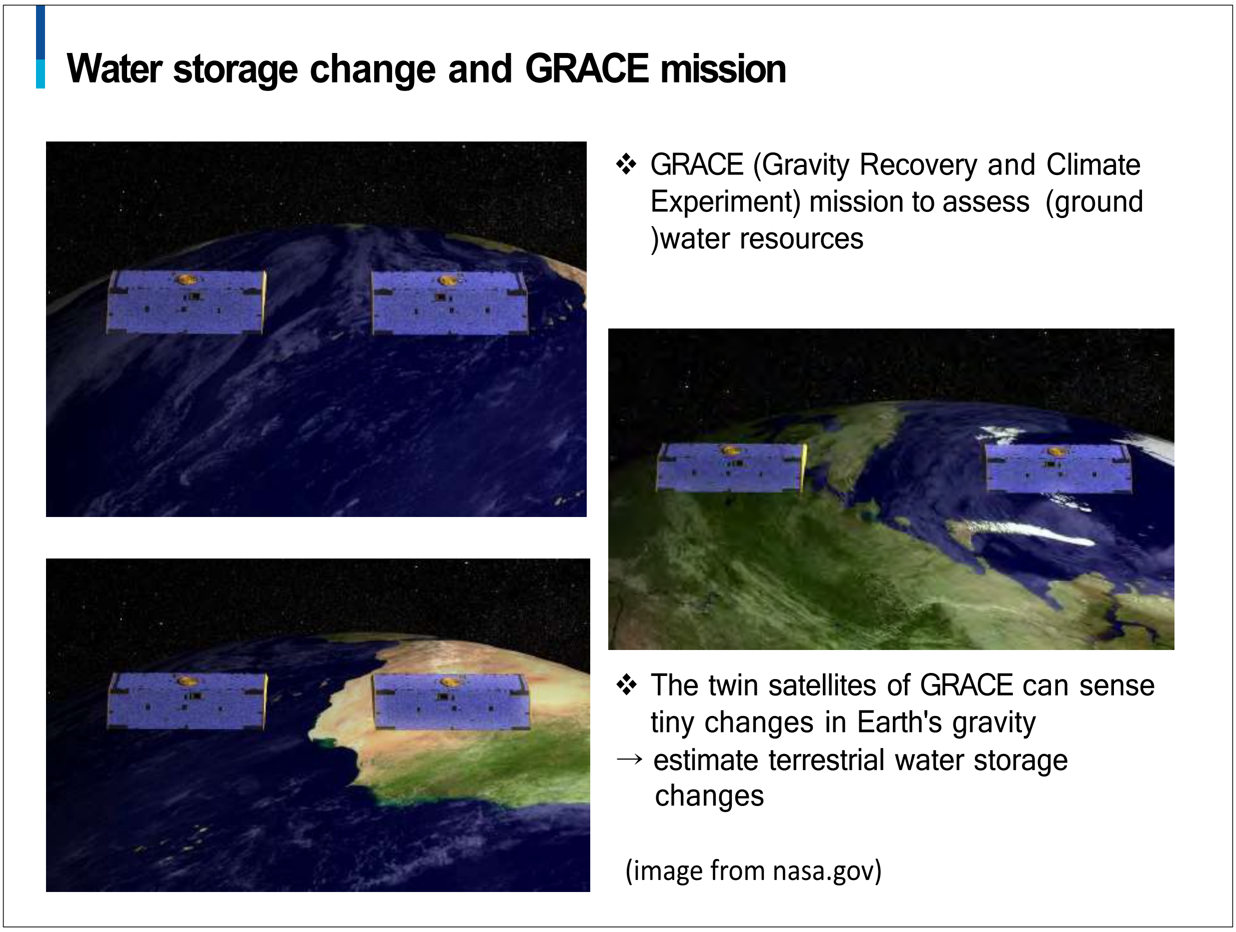
Trends and prospects of available water resources



Trends and prospects of available water resources (UNESCO)



2. Water withdrawal and groundwater storage



Water storage change and GRACE mission

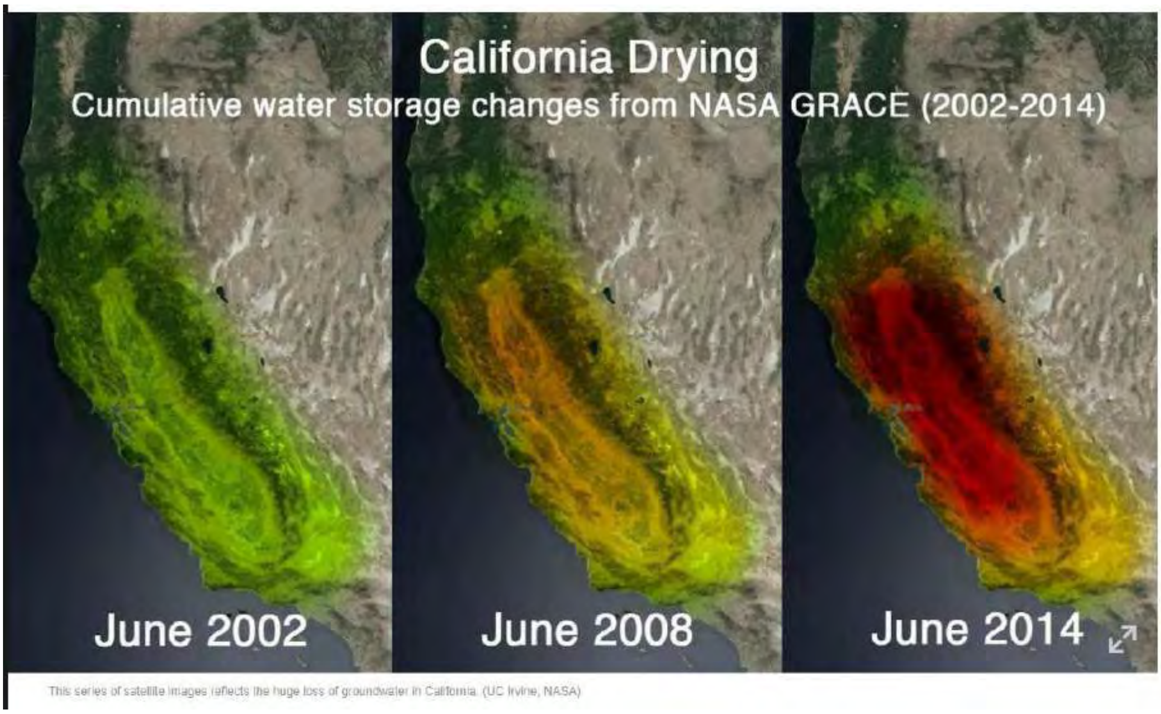
- ❖ GRACE (Gravity Recovery and Climate Experiment) mission to assess (ground)water resources

- ❖ The twin satellites of GRACE can sense tiny changes in Earth's gravity

→ estimate terrestrial water storage changes

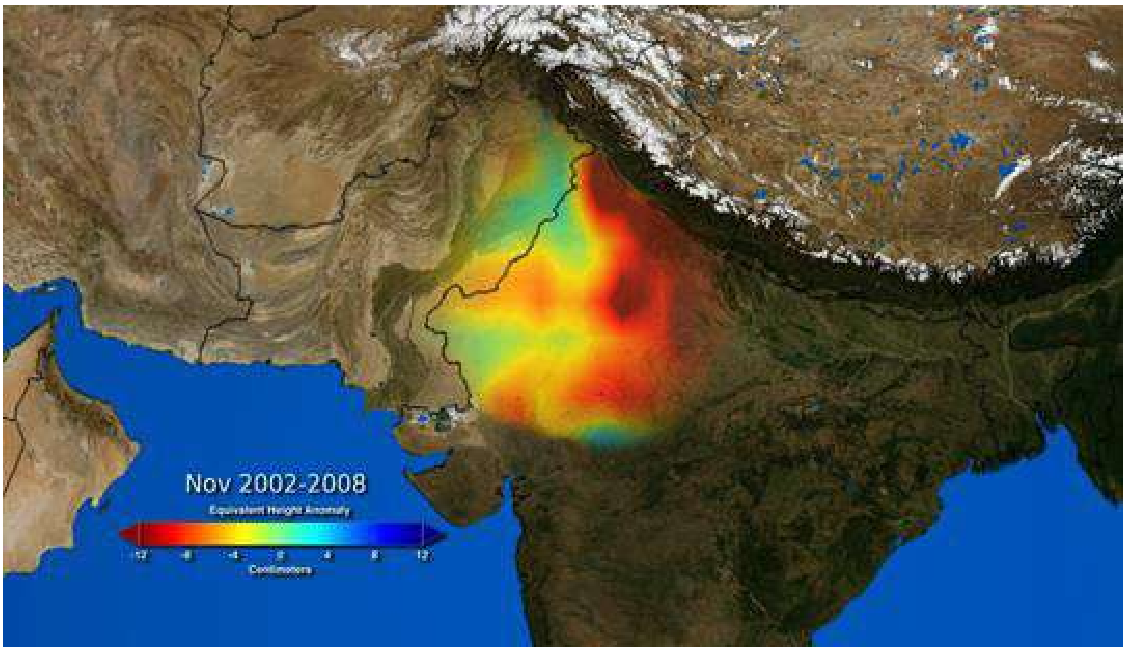
(image from nasa.gov)

Water storage change estimated by GRACE data (1)



This series of satellite images reflects the huge loss of groundwater in California. (UC Irvine, NASA)

Water storage change estimated by GRACE data (2)



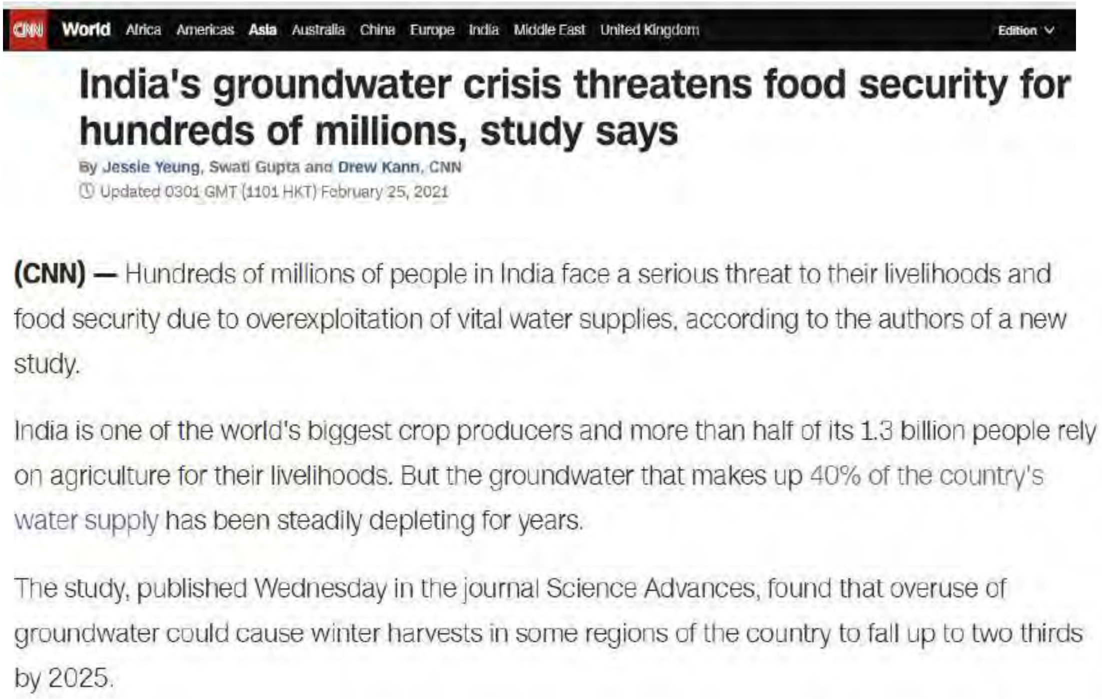
India's groundwater losses (red) and gains (blue) between 2002 and 2008 from NASA's Scientific Visualization Studio (svs.gsfc.nasa.gov)

Indian population and water availability

Year	Population in Million	Per capita water availability in CM
1951	361	5177
1965	395	4732
1991	846	2209
2001	1027	1820
2025	1394 (projective)	1341
2050	1640 (projective)	1140

From Prasad (2007)

India's groundwater problem



India's groundwater crisis threatens food security for hundreds of millions, study says

By Jessie Yeung, Swati Gupta and Drew Kann, CNN
Updated 0301 GMT (1101 HKT) February 25, 2021

(CNN) — Hundreds of millions of people in India face a serious threat to their livelihoods and food security due to overexploitation of vital water supplies, according to the authors of a new study.

India is one of the world's biggest crop producers and more than half of its 1.3 billion people rely on agriculture for their livelihoods. But the groundwater that makes up 40% of the country's water supply has been steadily depleting for years.

The study, published Wednesday in the journal Science Advances, found that overuse of groundwater could cause winter harvests in some regions of the country to fall up to two thirds by 2025.

Scientific prediction on China's water problem

NATURE NEWS

China faces up to groundwater crisis

Researchers call for effective monitoring and management of water resources.

A crisis is developing beneath China's thirsty farms and cities, but no one knows its full extent. With about 20% of the world's population but only about 5-7% of global freshwater resources, China draws heavily on ground water.

Groundwater is an essential source of Irrigation for much of China's arid land.

Global water shortage

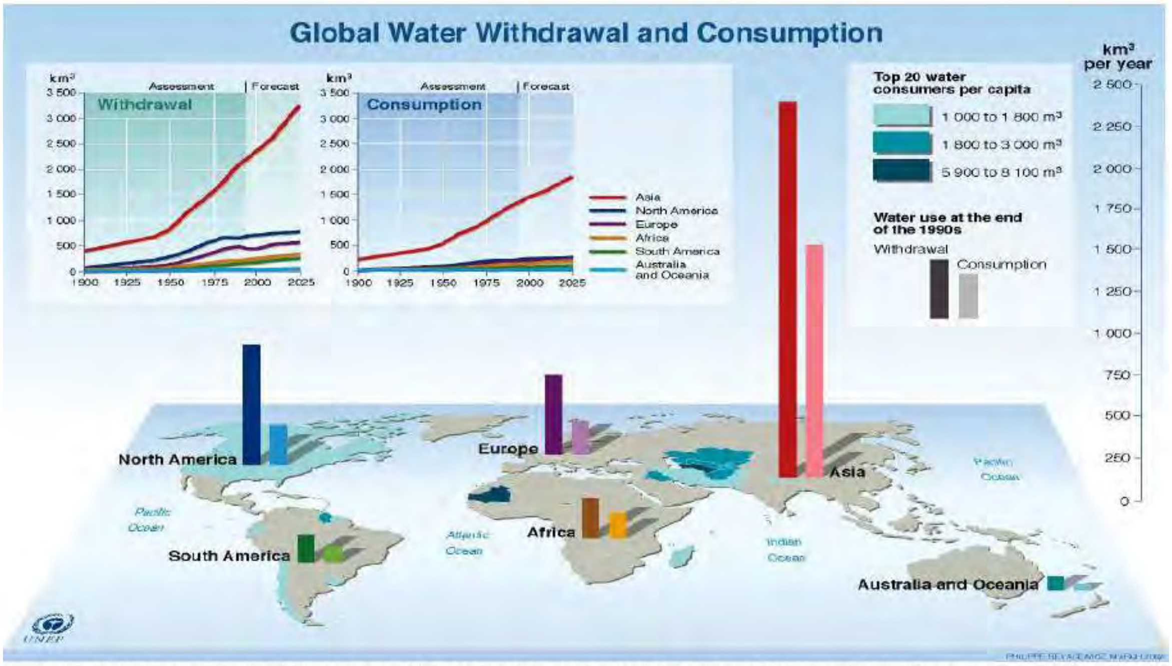
SCIENCE ADVANCES

Four billion people facing severe water scarcity

Abstract

Freshwater scarcity is increasingly perceived as a global systemic risk. Previous global water scarcity assessments, measuring water scarcity annually, Have underestimated experienced water scarcity by failing to capture the seasonal Fluctuations in water consumption and availability. We assess blue water scarcity Globally at a high spatial resolution and availability. We find that two-thirds of The global population(4.0 billion people) live under conditions of svere water Scarcity at least 1 month of the year. Nearly half of those people live in India and China. Half a billion people in the world face severe water scarcity all year round. Putting caps to water consumption by river basin, increasing water-use efficiencies, And better sharing of the limited freshwater resources will be key in reducing the Threat posed by water scarcity on biodiversity and human welfare.

Increasing water demands in ASIA



Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational,Scientific and Cultural Organisation (UNESCO, Paris), 1999; *World Resources 2000-2001, People and Ecosystems: The Fraying Web of Life*, World Resources Institute (WRI), Washington DC, 2000; Paul Harrison and Fred Pearce, *AAAS Atlas of Population 2001*, American Association for the Advancement of Science, University of California Press, Berkeley.

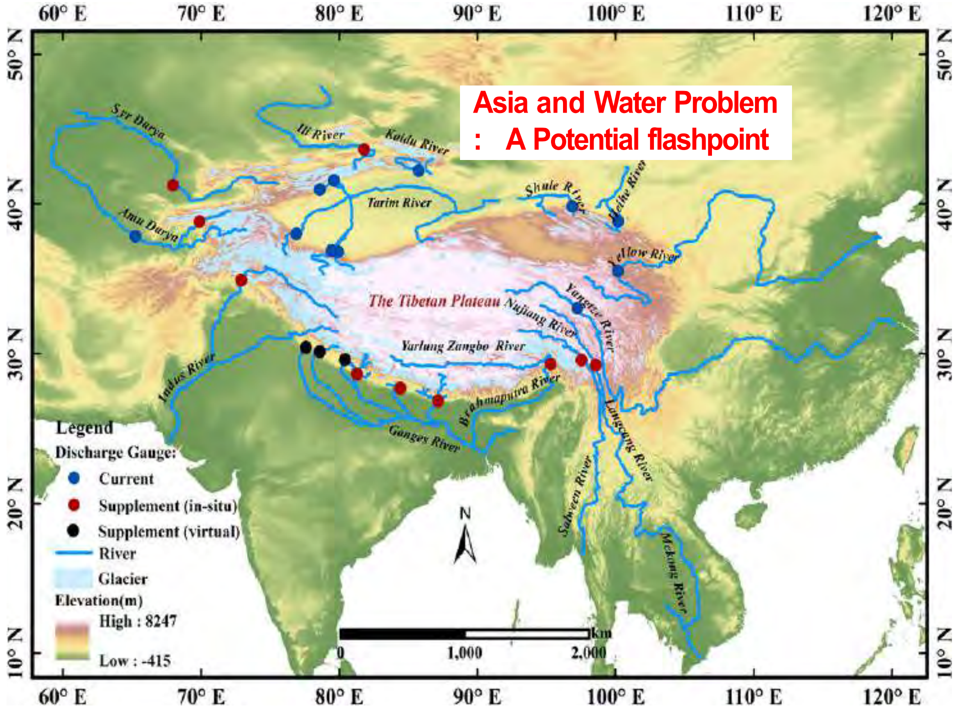
Water problem threats Asia's economic growth

❖The water problem in Asia

→ a threat to economic growth:

- water based industry (steel, computer chip, paper factories, and others, need large amounts of water)
- intensive farming for foods needs large amounts of fresh water resources (+ polluting water resources)
- people living in the Asian region grow richer (more household machines - dishwashers, clothes-washing machines)

Global warming effect on Tibetian snowpack?



Asia and Water Problem
: A Potential flashpoint

Map from Bulletin of the American Meteorological Society 102, 5; 10.1175/BAMS-D-20-0207.1

Global warming effect on Tibetian snowpack?

❖ Global warming → Melt the glaciers and snow of the Tibetan Plateau that feed Asia's largest rivers (Ganges, Indus, Mekong, Yangtze, Yellow)

❖ Glaciers:
- natural storage system.
- Shrinking ice sheets and snowpack could aggravate water imbalances. (causing flooding as the melting accelerates, followed by a reduction in river flows)

3. Water quantity and quality problems

Global problems of water quantity and quality

❖ **Global water quantity:**

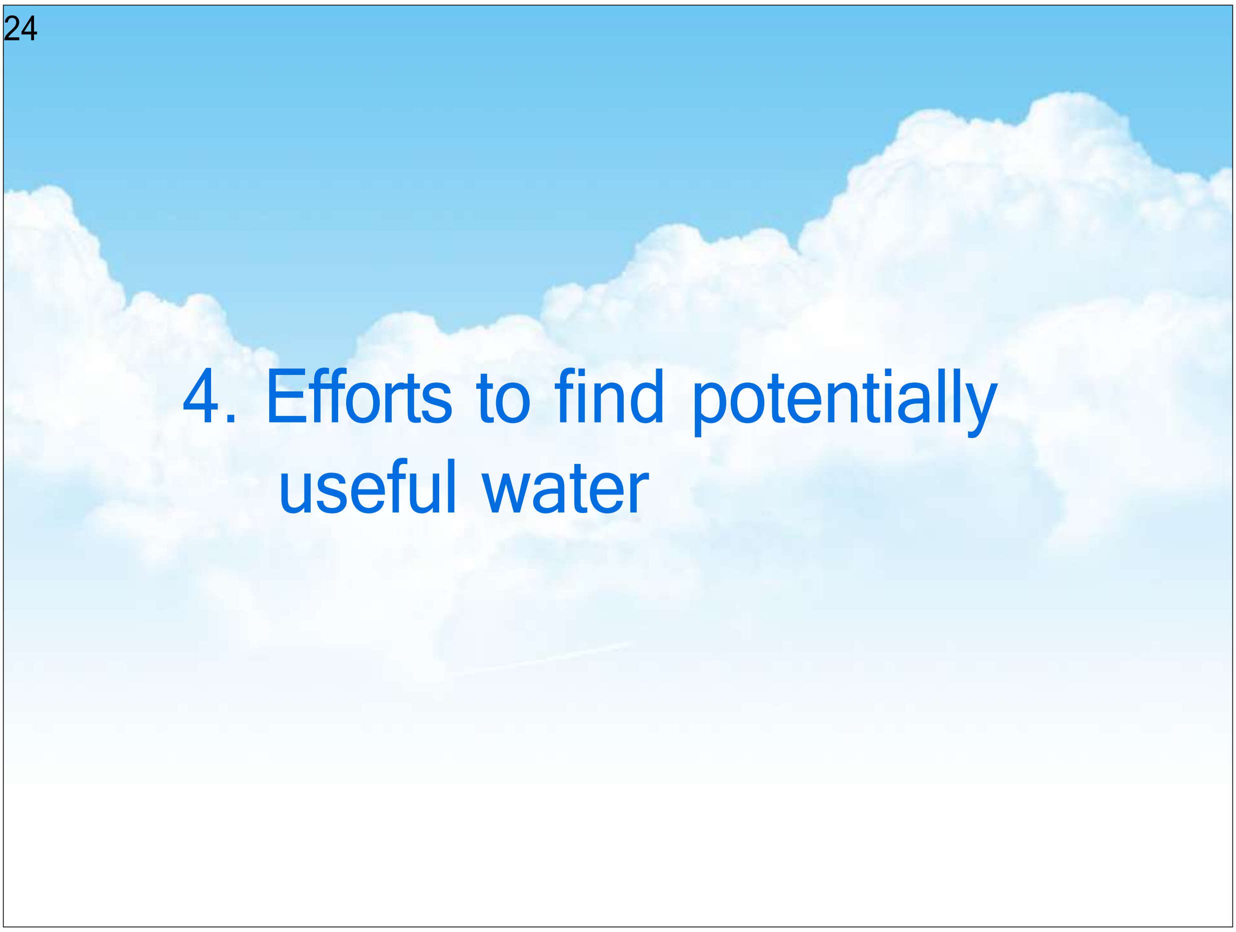
- As of 2015, 748 million people did not have access to clean water for daily living
- World population estimated at 9 billion in 2050, water demand in 2050 will increase by 55% compared to present (2015)
- By 2030, water supply will only account for 60% of human needs (unless we innovate current water use trends)

❖ **Global water quality:**

- More than 2 billion people suffer from water-related diseases each year. Of these, several million die from unsanitary water use
- In July 2010, the UN General Assembly adopted a resolution declaring clean and sanitary water a basic human right of mankind

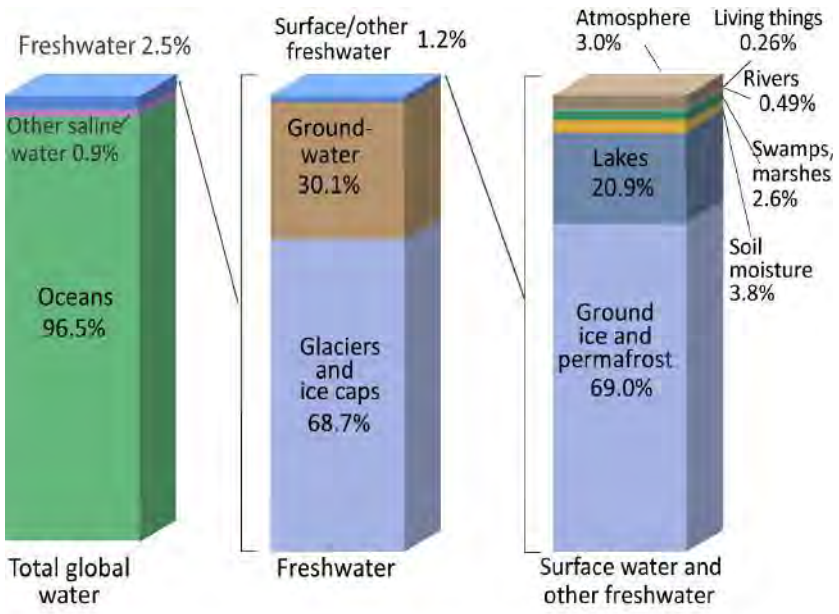
'Blue gold' and Global water problem

Blue Gold	**Blue Gold**	***"Anyone who can solve the problems of water, "will be worthy of two Nobel prizes- one for peace and one for science."*** **John F. Kennedy**
World Water Wars	**The global water crisis and the commodification of the world's water Supply**	
A documentary film by Sam Bozzo 2008	**A Special Report by the International Forum on Globalization (IFG) by Maude Barlow 2001**	***"The wars of the next century will be about water"*** **Ismail Serageldin, Vice President of the World Bank**



4. Efforts to find potentially useful water

Water distribution and potentially useful water



Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. (Numbers are rounded).

Responding to global water shortage

❖Find Potentially useful waters and apply developed technology
- Saline water → Desalination plant
- Frozen water → Lasso iceberg
- Groundwater → Mining groundwater
- Groundwater → Increase recharge/storage/restore quality (*)
- Recycling → Water treatment
- Rain → Rainwater harvesting

➔Opportunity of industrial growth for technologically developed countries

➔Crisis of technologically or economically poor countries

❖ Countries suffering from water shortage or water quality problem do not have the necessary technology or economy

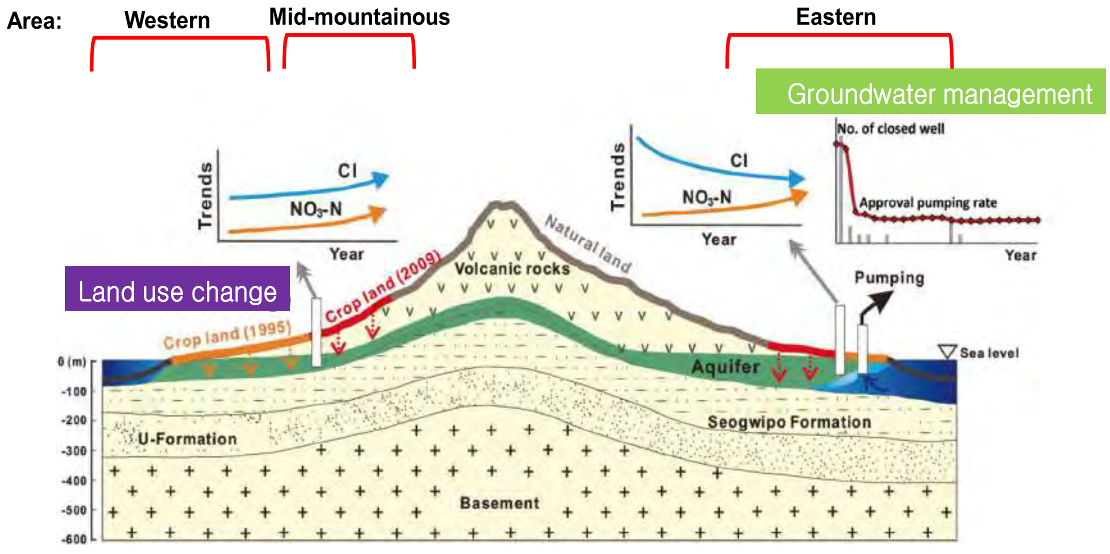
Make groundwater more useful

❖ We can increase the quantity and improve the quality of groundwater

- Optimized management of quantity and quality of groundwater
- Artificial recharge
- Subsurface dam
- Smart well grid system
- Groundwater quality enhancement

Long-term Trend of contamination and water quality management

❖ **Schematic diagram of long-term changes in NO_3-N and Cl**



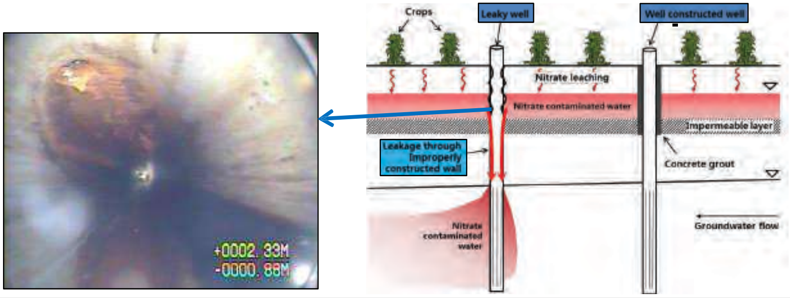
(Image from E. Koh)

NO_3-N Contamination in Groundwater

❖ How to conserve groundwater in terms of water quality?

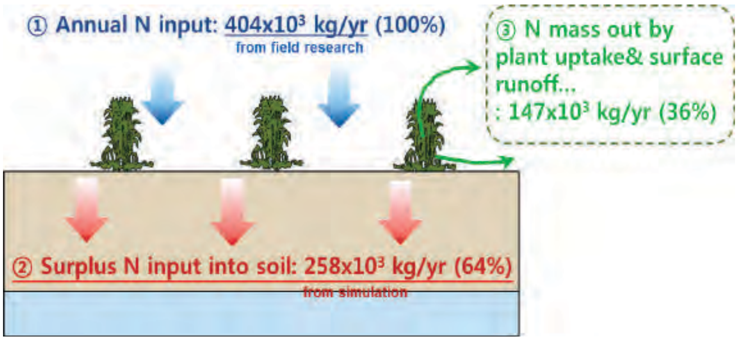
1. Manage land use or manage fertilizer usage.

2. Detect and treat short circuits of contamination and allow more time of natural attenuation.



Numerical Modeling to estimate allowable loading

Estimation of maximum allowable loading for the fertilizer use



Based on the prediction results

For lowering NO_3-N Conc. at the regional GW well,
Amount of ② is required to be reduced as 45%

Fertilizer a pplication rate

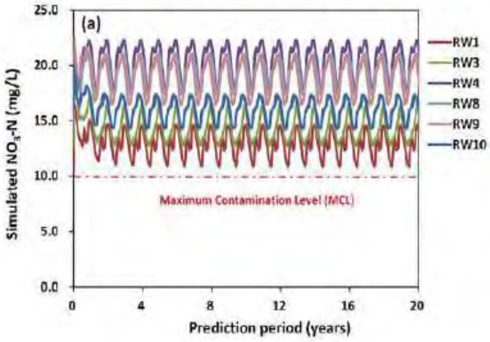
<MIN>
0.45*(②+③) = 281.6 kg-N/ha/yr (45% of present fertilizer use)

<MAX>
(0.45* ②) + ③ = 407.8 kg-N/ha/yr (65% of present fertilizer use)

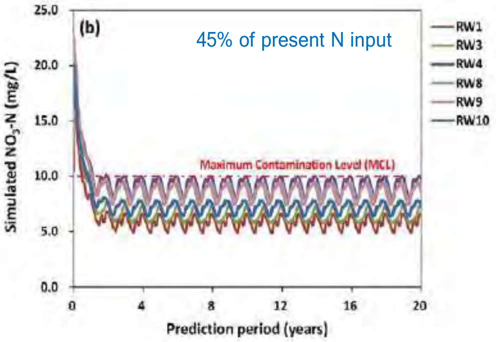
Sealing of the leaky wells rapidly decrease the NO_3-N concentration below the MCL without reducing fertilizer usage

Long-term prediction by numerical Modeling

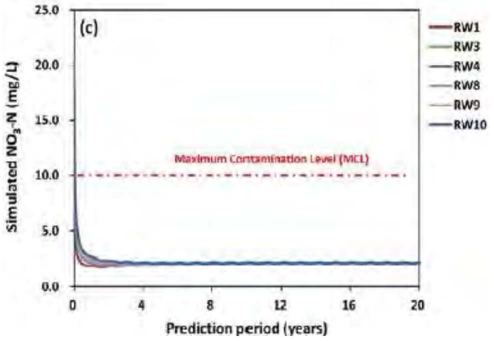
<Leaky well + Present N input>



<Leaky well + N input reduction>



<Sealing well+ Present N input>



(from E. Koh)

5. Global corporation for water problems

Blue Covenant – by Maude Barlow

"The world is running out of available, clean freshwater at an exponentially dangerous rate just as the population of the world is set to increase again. It is like a comet poised to hit the Earth"

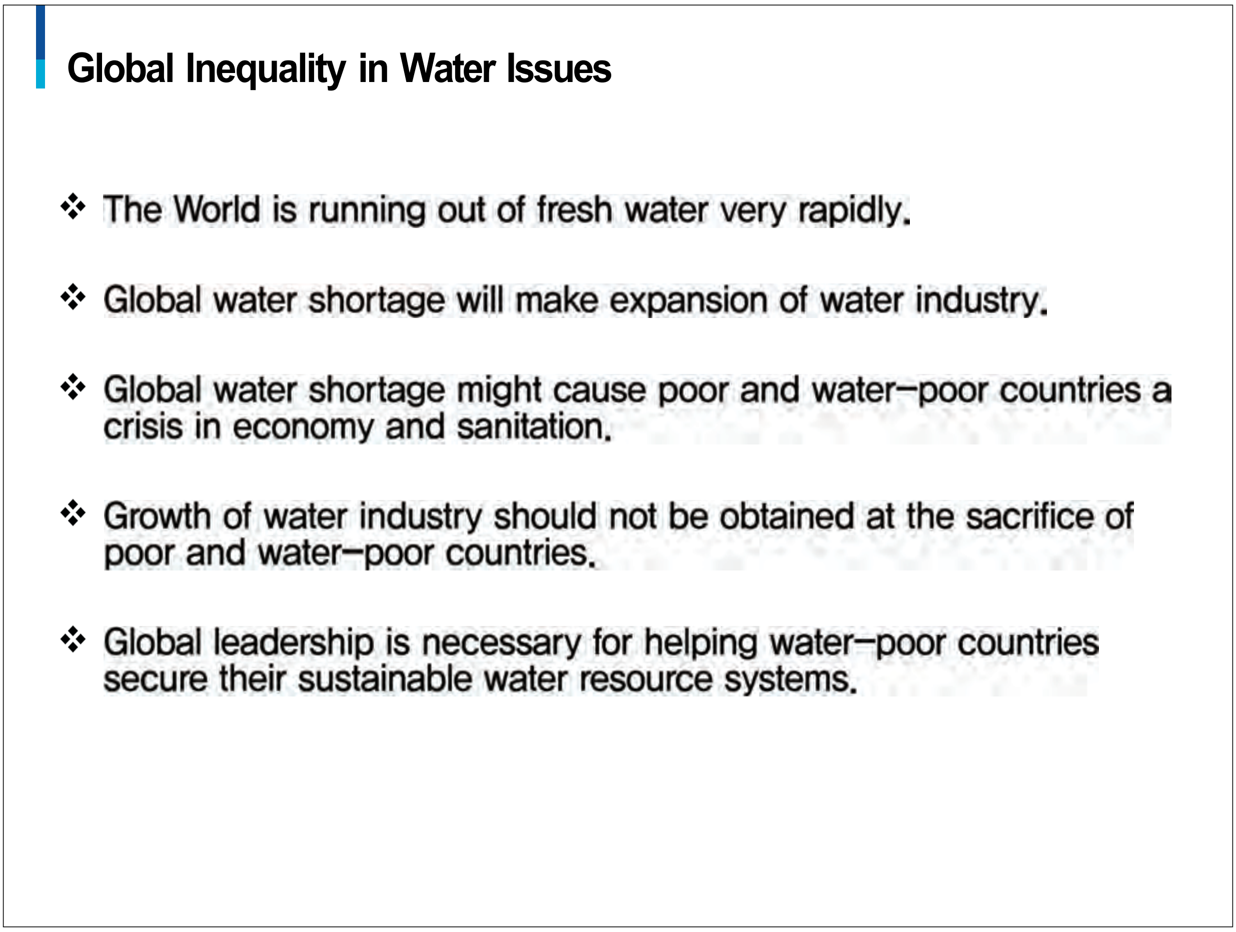
"The fresh-water crisis is easily as great a threat to the Earth and humans as climate change (to which it is deeply linked) but has had very little attention paid to it in comparison"

International leadership for water problems

❖Global Imbalance of Water Resources and Water Trade

Poor and water-poor countries export huge amounts of water just for economic survival

(destroy their aquifers or reservoirs for exporting foods, flowers, growing "biofuels" – sugarcane, corn, palm oil, soy)



Global Inequality in Water Issues

- The World is running out of fresh water very rapidly.
- Global water shortage will make expansion of water industry.
- Global water shortage might cause poor and water-poor countries a crisis in economy and sanitation.
- Growth of water industry should not be obtained at the sacrifice of poor and water-poor countries.
- Global leadership is necessary for helping water-poor countries secure their sustainable water resource systems.

Thank you very much

Introduction to Groundwater: Origin, Distribution, and Flow Principles

Groundwater

Introduction to Groundwater:
Origin, Distribution, and Flow Principles

UNESCO
United Nations
Educational, Scientific and
Cultural Organization

i-WSSM
International Centre for
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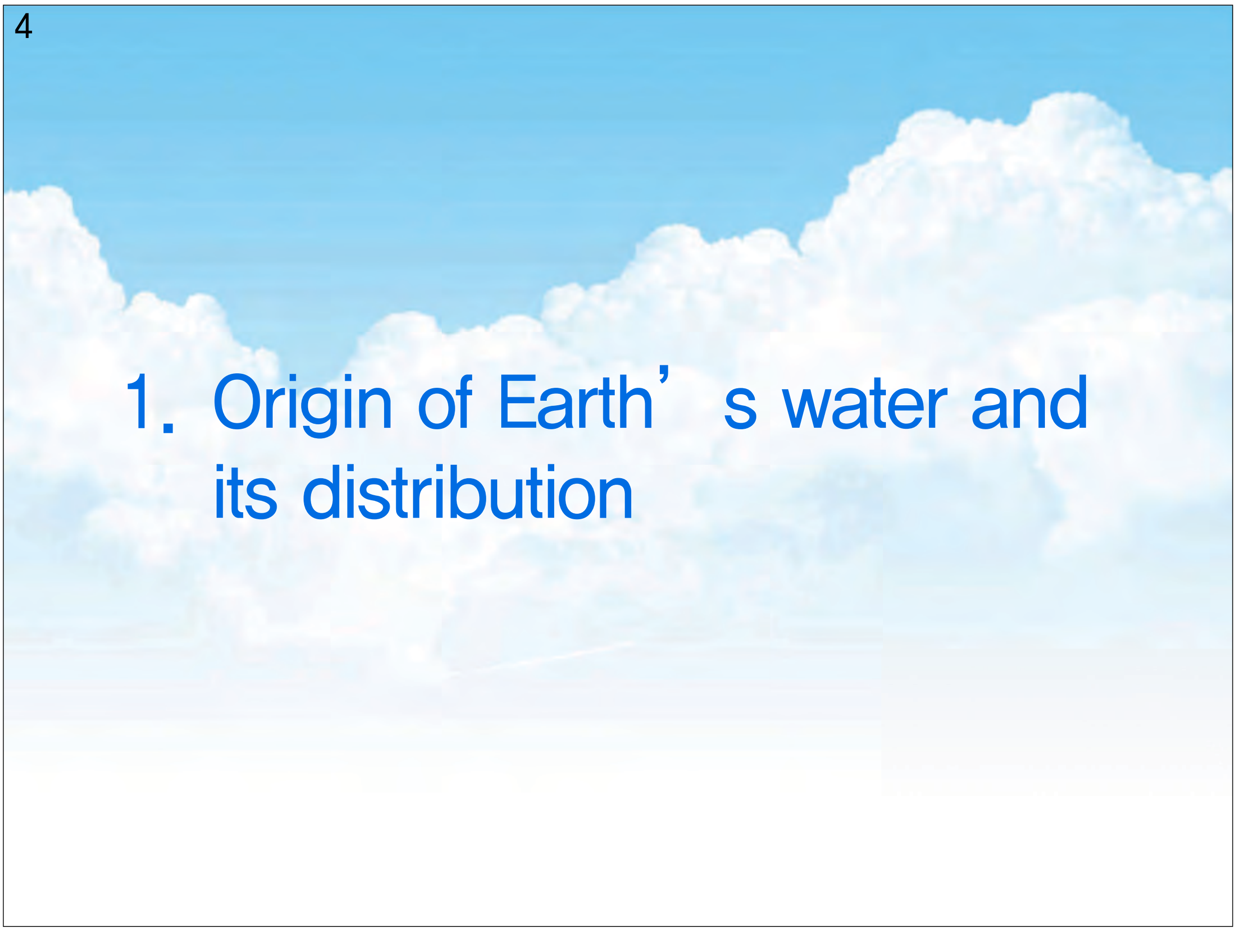
Aims & Objectives

Starting from the origin of water on Earth, this chapter deals with the global distribution of water, the definition of groundwater, the subsurface space of groundwater, the basic principle of groundwater flow, the potential of groundwater, and the residence time of groundwater.

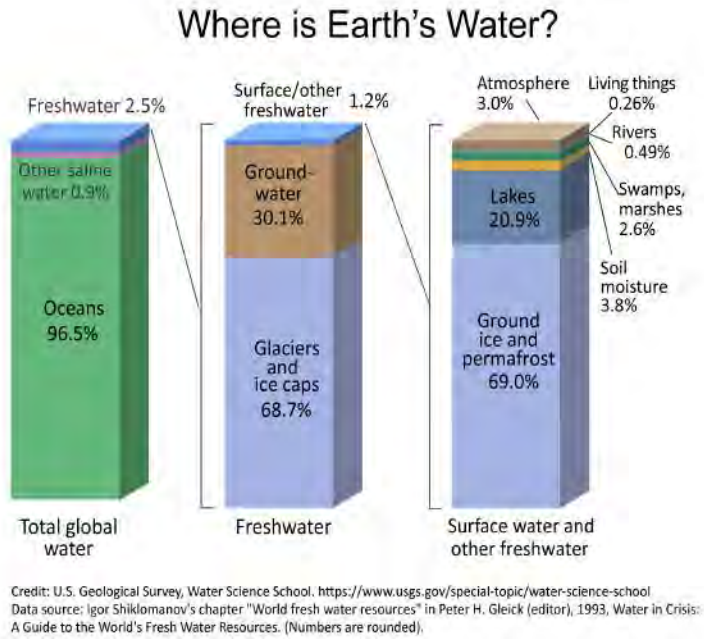
The purpose of this chapter is to establish the basic conceptual understanding on groundwater and its flow system.

Contents



1. Origin of Earth’s water and its distribution

Earth’s Water Distribution

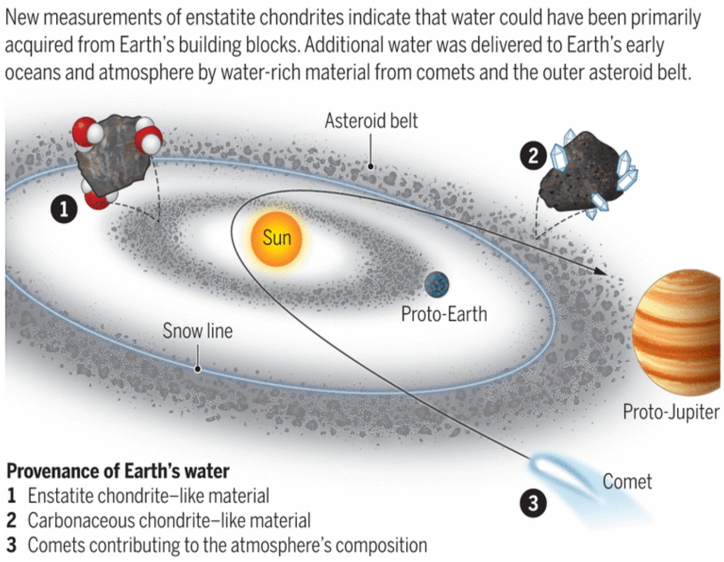


Credit: U.S. Geological Survey, Water Science School. https://www.usgs.gov/special-topic/water-science-school
Data source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. (Numbers are rounded).

Though the amount of water locked up in groundwater is a small percentage of all of Earth's water,

it represents a large percentage of total freshwater on Earth

The Origin of Water in the Earth


New measurements of enstatite chondrites indicate that water could have been primarily acquired from Earth’s building blocks. Additional water was delivered to Earth’s early oceans and atmosphere by water-rich material from comets and the outer asteroid belt.

Provenance of Earth’s water
1 Enstatite chondrite–like material
2 Carbonaceous chondrite–like material
3 Comets contributing to the atmosphere’s composition

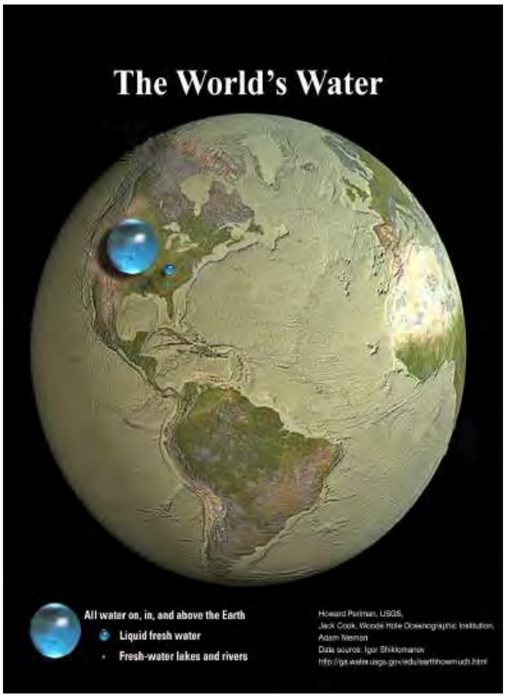
Image from *SCIENCE* •28 Aug 2020•Vol 369, Issue 6507•p. 1058

Groundwater exclusively below the groundwater table? How much water below the Earth’ s surface?

About 1/2 of groundwater is distributed to a depth of 800 meters, and about 1/2 is distributed to more than a few kilometers underground, but as the depth increases, the porosity decreases and there is almost no groundwater.

Recent researches indicate that Earth’ s mantle might hold more water than all the oceans. Exist as atoms of hydrogen and oxygen embedded in the crystal structure of the mineral This hydrous mineral when it melts, spills out water.

Relative Amounts of Earth's Water



This image (from USGS) shows blue spheres representing relative amounts of Earth's water in comparison to the size of the Earth.

About 71 percent of the Earth's surface is water-covered, and the oceans hold about 96.5 percent of all Earth's water. Water also exists in the air as water vapor, in rivers and lakes, in icecaps and glaciers, in the ground as soil moisture and in aquifers.

2. Definition of Groundwater and Aquifer

Groundwater and Aquifer

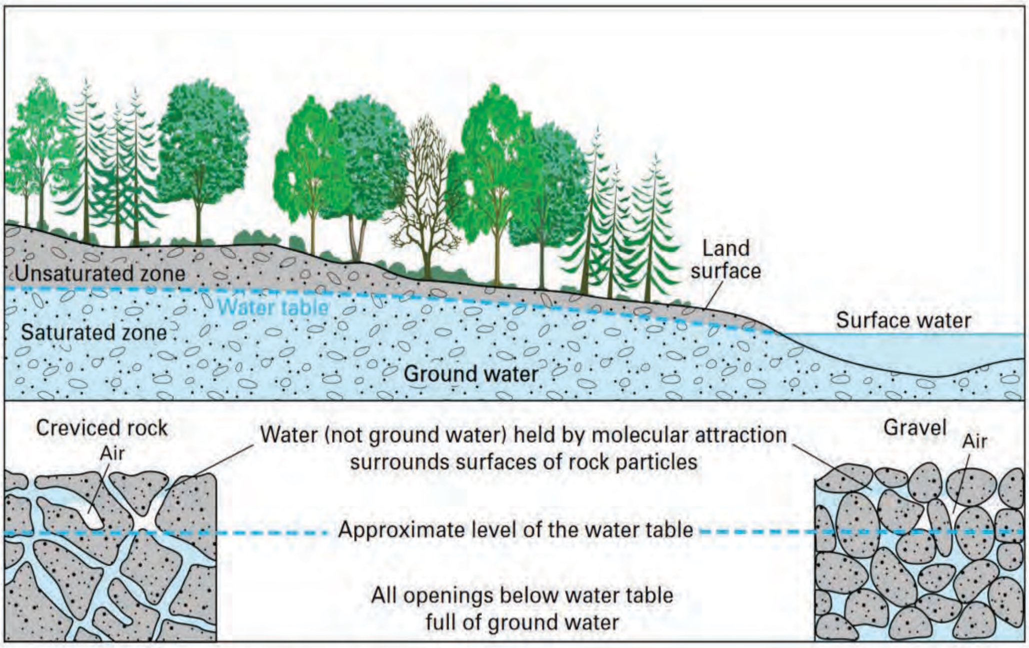
What is groundwater?

Groundwater is the subsurface water that occurs beneath the water table in soils and geologic formations that are fully saturated (classical definition).

Unsaturated soil–moisture regime directly interact with the groundwater and the study of groundwater must rest on an understanding of the subsurface water regime in a broader sense.

Aquifer is best defined as a saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients (Freeze and Cherry, 1919) That is a body of saturated rock or geological formation through which water can easily move so that it contains and releases water in appreciable amounts.

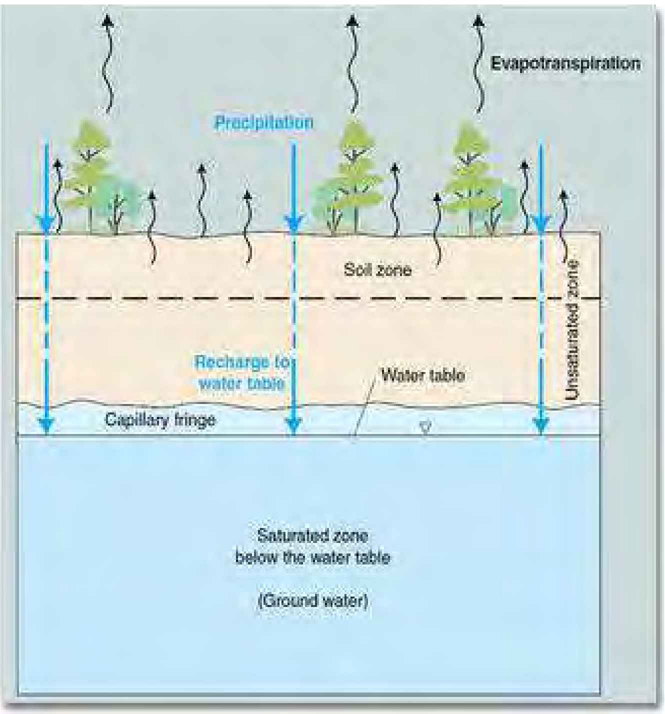
Visualization of water in subsurface soil and rocks



How ground water occurs in rocks.

(image from USGS)

Groundwater System and Recharge



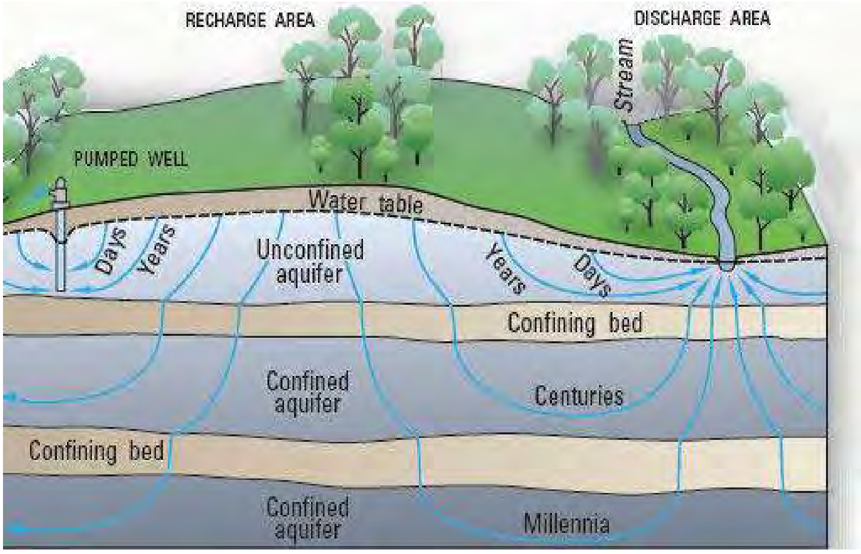
Groundwater system (USGS; Winter and others, 1998; Cohen and others, 1968)

Groundwater that is easily obtainable by wells occurs in aquifers, which are water–bearing formations capable of yielding enough water to supply peoples' uses.

The upper layer is the unsaturated zone, where water is present in varying amounts that change over time.

Groundwater Flow Rates

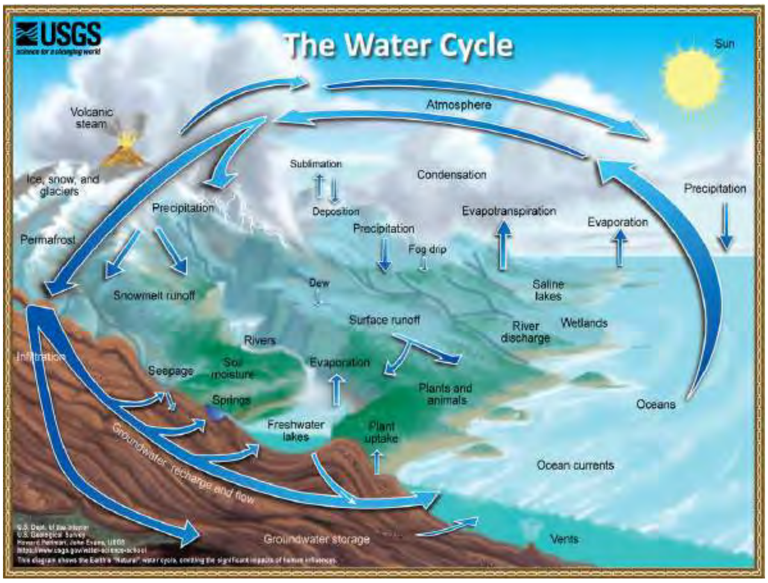
Groundwater flows underground...at different rates (from USGS)



The direction and speed of groundwater movement is determined by the various characteristics of aquifers and fluid potential of groundwater

3. Hydrologic Cycle and Groundwater

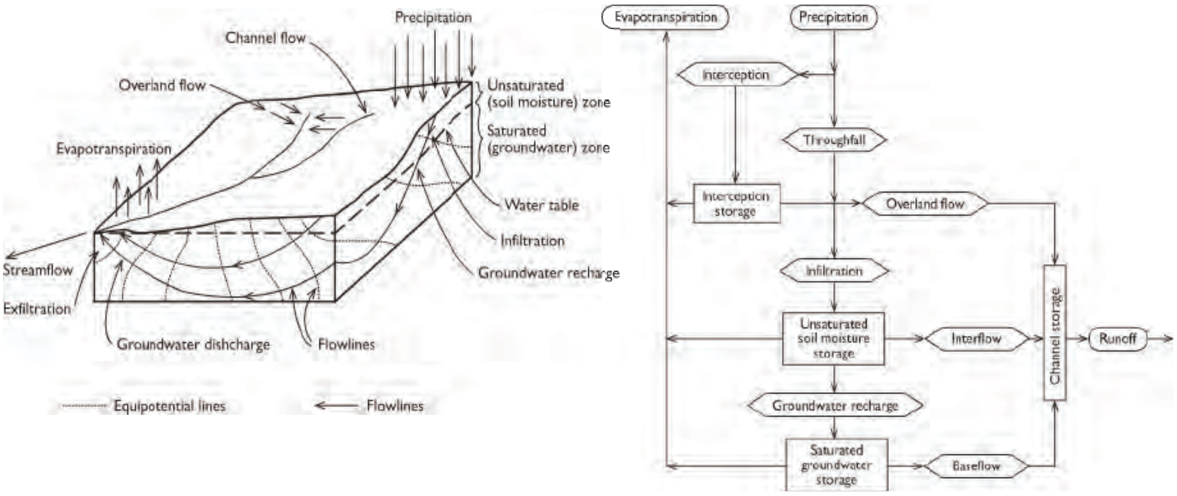
The Natural Water Cycle and Components



The Natural Water Cycle

Earth's water is always in movement, and the natural water cycle, also known as the hydrologic cycle, describes the continuous movement of water on, above, and below the surface of the Earth. Water is always changing states between liquid, vapor, and ice, with these processes happening in the blink of an eye and over millions of years.

Groundwater and the Hydrologic Cycle



From Freeze and Cherry (1979)

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4. Hydraulic Head and Groundwater Flow

Fluid Potential and Flow

For Water to Move
a driving force is needed

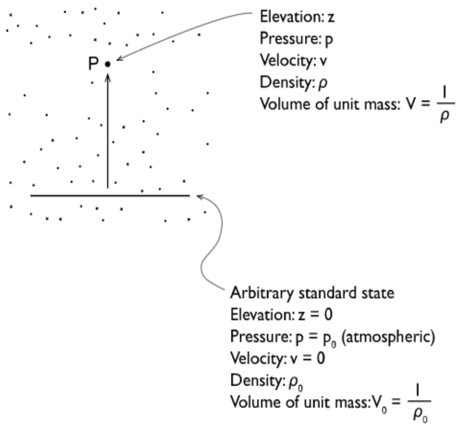
But it doesn’t necessarily flow downhill

Nor from high p to low p

Consider a siphon

Hydraulic Head and Fluid Potential (1)

Hubbert’s Analysis of the Fluid Potential



W1: the work required to lift the mass from elevation z = 0 to elevation z = mgz

W2: the work required to accelerate the fluid from velocity v = 0 to velocity v = ½ mv2

W3: the work done on the fluid in raising the fluid pressure from $\mathrm{P} = P_0\ to\ P = m\int_{P_0}^{P}\frac{V}{m}dp = m\int_{P_0}^{P}\frac{dp}{\rho}$

W = W1 + W2 + W3

Hydraulic Head and Fluid Potential (2)

Total work done or total mechanical energy difference W = W1 + W2 + W3

Total fluid potential Φ = W/m

$$\Phi = gz + \frac{v^2}{2} + \int_{P_0}^{P} \frac{dp}{\rho}$$

Total head h = W/mg = Φ/m

For porous-media flow, velocities are extremely low, so the second term can almost always be neglected.

For incompressible fluids (fluids with a constant density, so that ρ is not a function of p), hydraulic head can be simplified to

h = z + v2/2g = elevation head (z) + pressure head (v2/2g)

Hydraulic Head and Fluid Potential (3)

Flow Proceeds from High to Low Head

Recall the Bernoulli Equation from Fluid Mechanics :

$$h_2 - h_1 = \left(\frac{P_2}{\gamma} + z_2 + \frac{v_2^2}{2g}\right) - \left(\frac{P_1}{\gamma} + z_1 + \frac{v_1^2}{2g}\right)$$

When flow is laminar, the velocity component can be neglected

Reynolds number reflects flow regime

$$R = \frac{Velocity * diameter\ particle}{kinematic\ viscosity} = \frac{Vd}{\upsilon} \qquad \upsilon = \frac{dynamic\ viscosity}{fluid\ density} = \frac{\mu}{\rho}$$

R 〈 100 laminar
R 〉 1000 turbulent
Between – transitional

Hydraulic Conductivity and Permeability (1)

PROPERTIES AND PARAMETERS THAT INFLUENCE GROUNDWATER FLOW - continued

PERMEABILITY

The capacity of a porous medium to transmit fluid

HYDRAULIC CONUCTIVITY

When the fluid is water

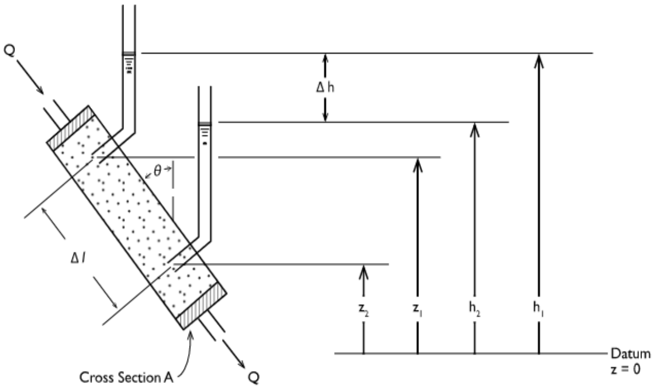
The range of value spans many orders of magnitude:

Gravel ~ $1 \times 10^{2} \mathrm{cm/sec}$

Unfractured Crystalline Rock ~ $1 \times 10^{-11} \mathrm{cm/sec}$

Darcy’ s Law and Groundwater Flow (1)

Darcy’s law obtained from experiments



We will define q, the specific discharge through the cylinder, as

q = Q/A

If the dimensions of the Q are [L3/T] and those of A are [L2], q has the dimensions of velocity [L/T].

The experiments carried out by Darcy showed that q is directly proportional to h1 – h2 when Δl is held constant, and inversely proportional to Δl when h1 – h2 is held constant. If we define Δh = h2 – h1,
Darcy’ s law can be written as

q = – K (Δh/Δl) or in differential form
Q = –K (dh/dl)

where h is the hydraulic head, K is the hydraulic conductivity

Darcy’s Law and Groundwater Flow (2)

Calculate K
Using data from
Darcy Apparatus

What measurements will you need?

What equation will you solve?

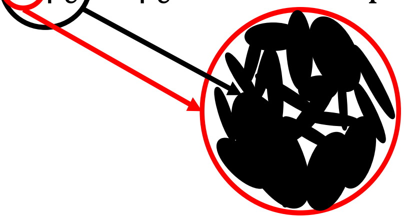
Darcy Velocity vs Interstitial Velocity

Darcy velocity is a DISCHARGE per unit AREA

$$V_{Darcy} = \frac{Q}{A}$$

Interstitial Velocity
Velocity through the pores
This governs rate of pollutant movement

$$V_{Interstitial} = \frac{Q}{A\phi_e} = \frac{V_D}{\phi_e} = \frac{V_D}{\text{effective porosity}}$$



Hydraulic Conductivity (K)

K VALUES VARY WITHIN
SPACE AND WITH DIRECTION

HETEROGENEITY - describes spatial variation

ANISOTROPY - describes direction variation

HOMOGENEOUS - uniform throughout
(K independent of position)

ISOTROPIC - properties do not vary with direction

Hydraulic Conductivity (K)

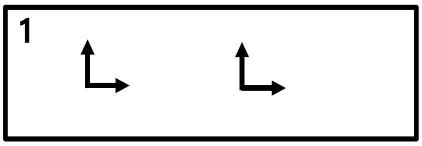
ANISOTROPY

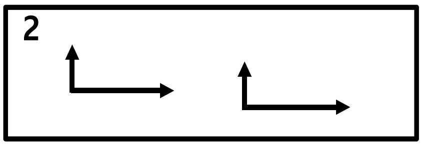
CONSIDER K IN THE PRINCIPLE DIRECTIONS X,Y,Z

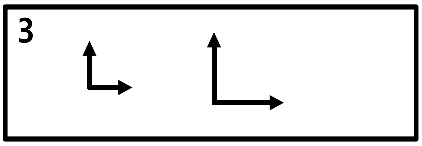
ISOTROPIC - $K_X = K_Y = K_Z$

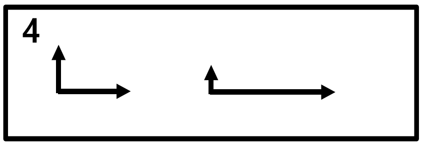
TRANSVERSELY ISOTROPIC - $K_X = K_Y \text{ not} = K_Z$

CONSIDER THE RELATIONS OF K IN A VERTICAL CROSS SECTION



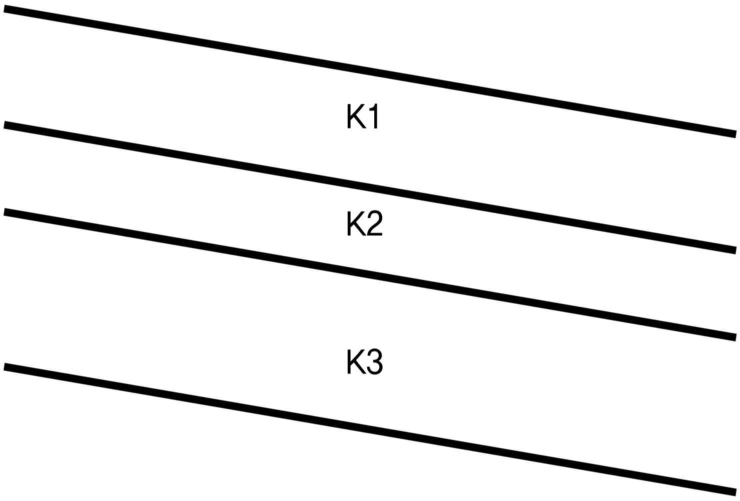






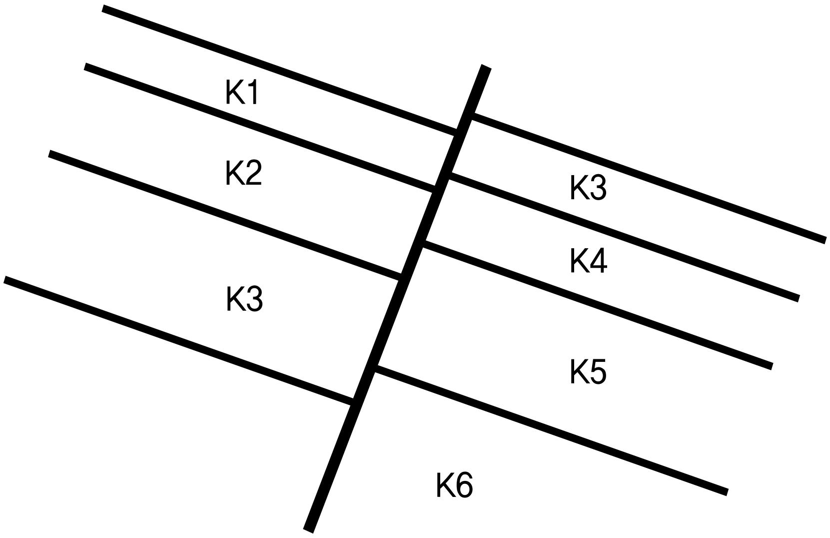
Hydraulic Conductivity (K)

LAYERED HETEROGENEITY
Individual layers are homogeneous



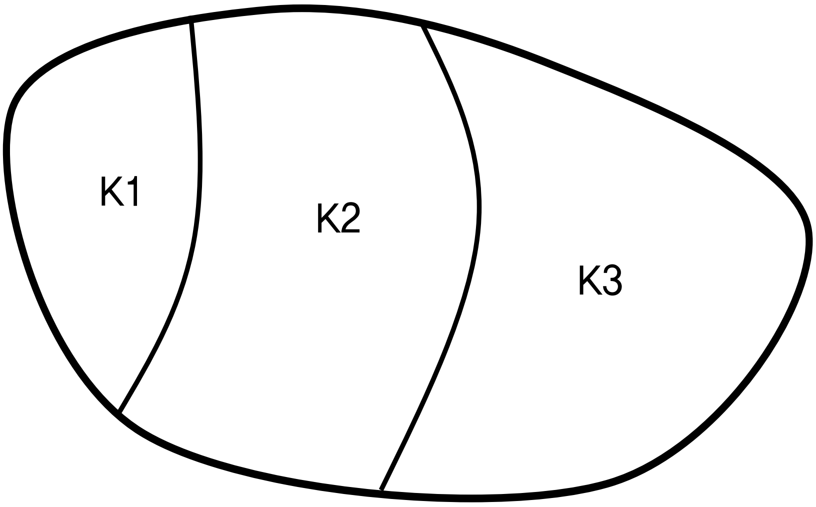
Hydraulic Conductivity (K)

DISCONTINUOUS HETEROGENEITY
e.g. across a fault



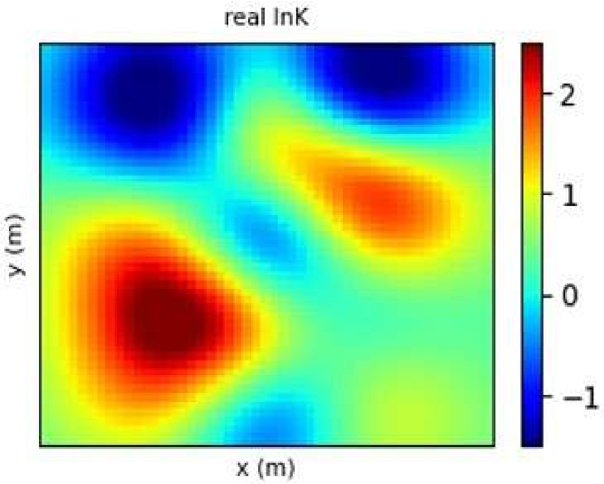
Hydraulic Conductivity (K)

TRENDING HETEROGENEITY
Variation in sedimentation patterns



Hydraulic Conductivity (K)

RANDOM HETEROGENEITY
Small scale variation with a structure that isn’ t easily tied to geologic process, although we know it is its basis we can describe with geostatistics (spatial statistics)



Hydraulic Conductivity (K)

AVERAGING OPTIONS

Arithmetic

$$\frac{K_1 + K_2 + K_3 + \cdots + K_N}{N}$$

Geometric

$$\sqrt[N]{K_1 K_2 K_3 \ldots K_N} \text{ or } 10^{\left(\frac{1}{N}(\log K_1 + \log K_2 + \cdots + \log K_N)\right)} \text{ or } 10^{\left(\frac{1}{N}\log(K_1 K_2 \ldots K_N)\right)}$$

Harmonic

$$\frac{\sum d_i}{\sum \frac{d_i}{K_i}}$$

Porosity and Storage Coefficients

PROPERTIES AND PARAMETERS THAT INFLUENCE GROUNDWATER FLOW

PORE SPACE -

WHERE GW IS STORED AND MOVES THROUGH MATERIALS

POROSITY (TOTAL) - % OF MATERIAL THAT IS VOIDS

$$\phi = V_v / V_T$$

V_v - VOL OF VOIDS

V_T - TOTAL VOLUME

Porosity and Storage Coefficients

METHODS OF MEASURING POROSITY (φ ,n)
DUDUCE from
PD - PARTICLE DENSITY
FD - FLUID DENSITY
BD - BULK DENSITY
BD = (1-) PD + ϕ(FD)

OR
SW - SATURATED WEIGHT
V_T - TOTAL VOL
DW - DRY WEIGHT

$$\phi = \frac{SW - DW}{V_T}$$

OR
DW - DRY WEIGHT
V_T - TOTAL VOLUME

$$\frac{DW}{V_T} = PD(1 - \phi)$$

$$\phi = 1 - \frac{DW}{DP * V_T}$$

Porosity and Storage Coefficients

EFFECTIVE POROSITY - % OF ROCK THAT IS INTERCONNECTED PORE SPACE

$$\phi_e = \frac{V_{\mathrm{IV}}}{V_T}$$

V_{IV} - VOL OF INTERCONNECTED VOIDS

MEASUREMENT OF EFFECTIVE POROSITY

GRAVITY DRAINAGE @ 100% RELATIVE HUMID

TRACER TEST - MONITOR RATE OF MOVEMENT OF A TAG ON THE WATER

Porosity and Storage Coefficients

PRIMARY POROSITY
- FORMED CONTEMPORANEOUSLY WITH ROCK
SECONDARY POROSITY
- FORMED AFTER ROCK IS FORMED

POROSITY DEPENDS ON:

SHAPE AND ARRANGEMENT OF PARTICLES

DEGREE OF SORTING (MIX OF PARTICLE SIZES)

CEMENTATION OR COMPACTION

REMOVAL OF MATERIAL BY SOLUTION

FRACTURING AND JOINTING

Porosity and Storage Coefficients

SHAPE AND ARRANGEMENT OF PARTICLES

Magnitude of p depends on packing as well as shape

Packing
- The spacing and mutual arrangement of particles within the mass
- Will influence not only porosity but also density, bearing capacity, strength, amt of setting, permeability
- Difficult to study with real particles because shapes are so varied, so consider spheres

Porosity and Storage Coefficients

WE CAN'T RECOVER ALL THE WATER FROM THE PORES,
SO CONSIDER HOW MUCH A MATERIAL WILL YIELD

SPECIFIC YIELD - % OF TOTAL VOLUME THAT CAN BE DRAINED BY GRAVITY

sound familiar?
what else was defined this way?
they can be used interchangeably

SPECIFIC RETENTION - % OF TOTAL VOLUME HELD AGAINST GRAVITY

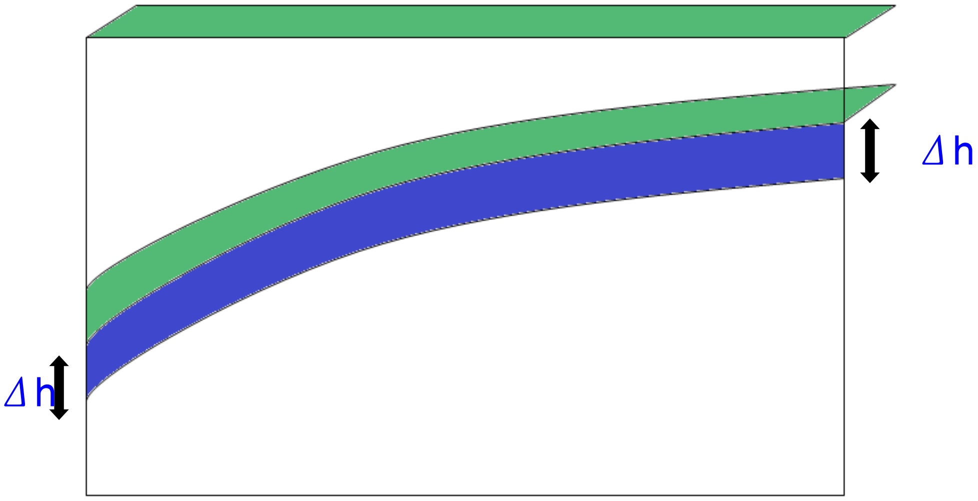
BY DEFINITION - $\phi = SY + SR$

Storage Coefficients and Groundwater Yield

Water level decline in an Unconfined Aquifer water drains from pores which fill with air

Volume Yielded = $\Delta h * SY * Area$ (see later qualification)

(plan area of surface extending "into" the drawing)



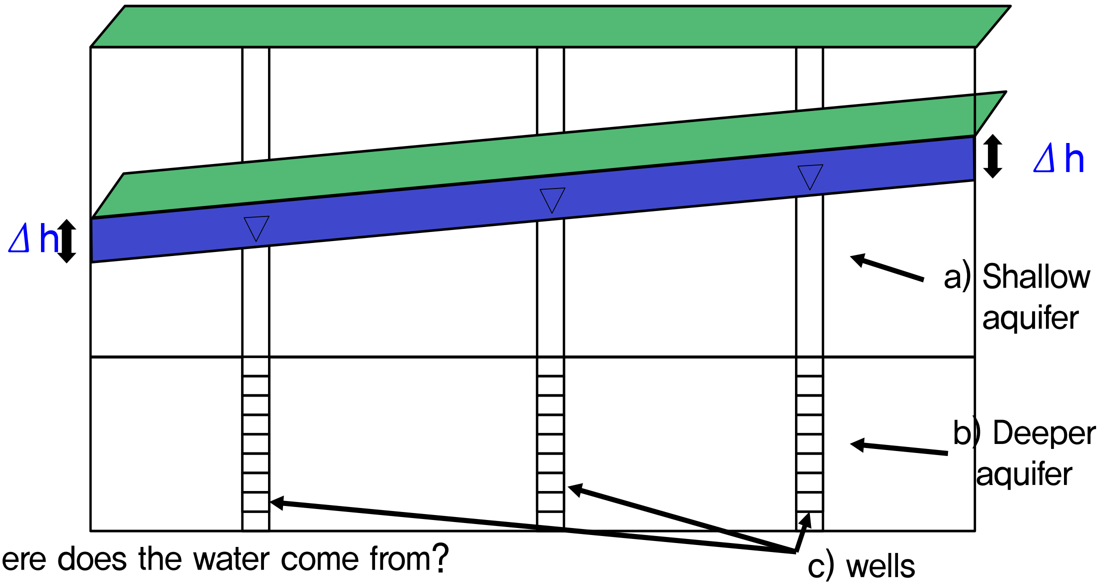
Storage Coefficients and Groundwater Yield

Water level decline in a Confined Aquifer

water pressure decreases in pores which stay full of water

Volume Yielded = $\Delta h * S * Area$

(plan area of surface extending “into” the drawing)



Where does the water come from?

Storage Coefficients and Groundwater Yield

STORATIVITY - S : unitless

Also called Storage Coefficient

VOLUME OF WATER AQUIFER RELEASES

PER UNIT SURFACE AREA

PER UNIT CHANGE IN HEAD

NORMAL TO THE SURFACE

SPECIFIC STORAGE - s or S_S : L^{-1}

VOLUME OF WATER AQUIFER RELEASES

PER UNIT VOLUME

PER UNIT CHANGE IN HEAD

NORMAL TO THE SURFACE

For aquifer thickness = b

$S = S_S b \qquad s = S_S / b$

Storage Coefficients and Groundwater Yield1

Define :

Φ - POROSITY

α - VERTICAL COMPRESSIBILITY OF AQUIFER SKELETON

β - COMPRESSIBILITY OF WATER

b - THICKNESS

IF WE

IGNORE LATERAL COMPRESSIBILITY

IGNORE COMPRESSIBILITY OF SOLID

And EXPLORE PARTS OF STORAGE TERM :

Storage Coefficients and Groundwater Yield

IF AQUIFER IS RIGID - water given up from a unit volume for a unit drop in head would be entirely due to expansion of water

$$\phi\, b\, \beta\, \gamma$$

IF WATER IS RIGID - water given up from a unit volume for a unit drop in head would be entirely due to compression of aquifer

$$b\, \alpha\, \gamma$$

STORAGE COEFFICIENT

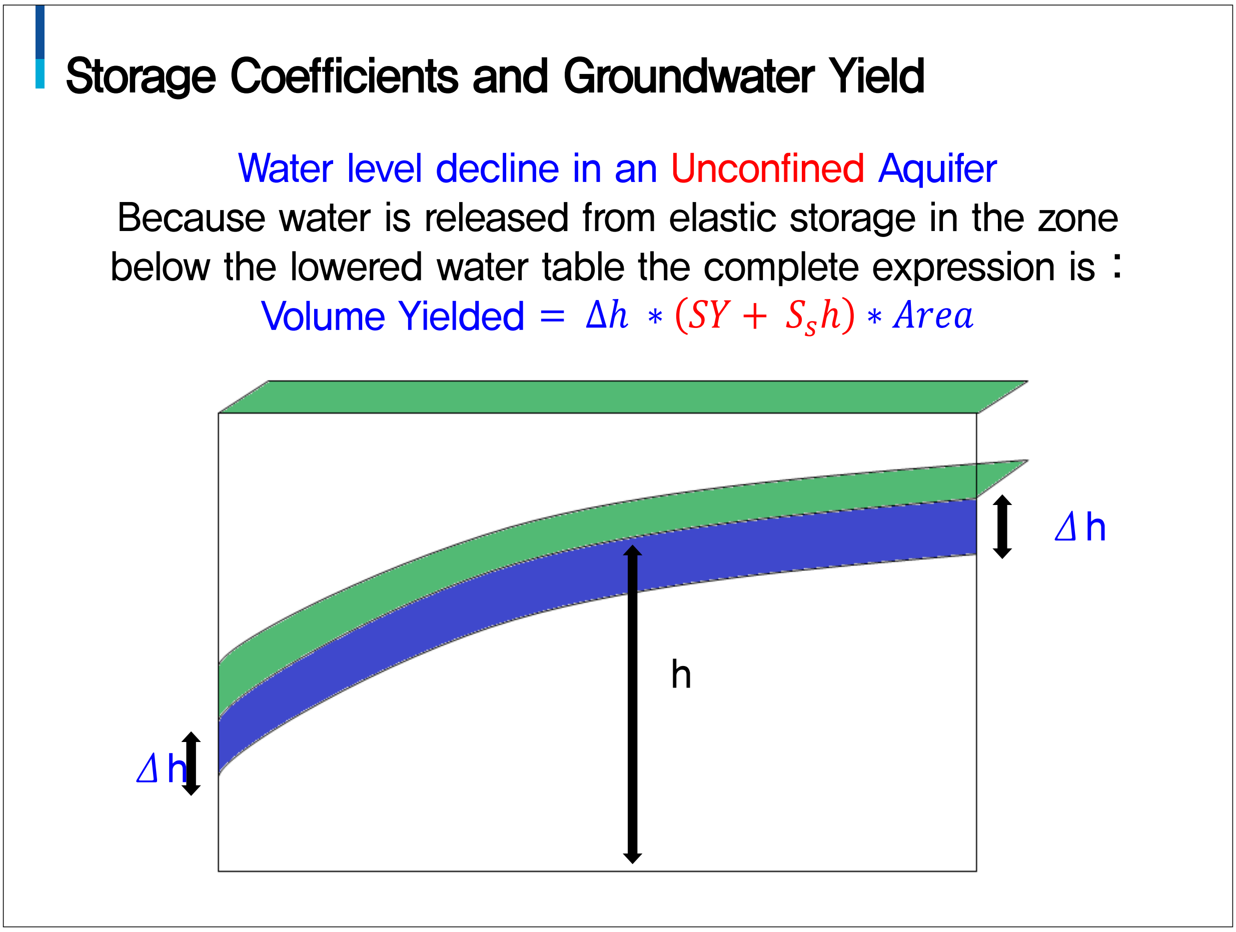
$$S = \gamma\, b\, (\phi\, \beta + \alpha)$$

SPECIFIC STORAGE

$$S_s = S/b$$

VOLUME :

$$S\, \Delta h\, A$$

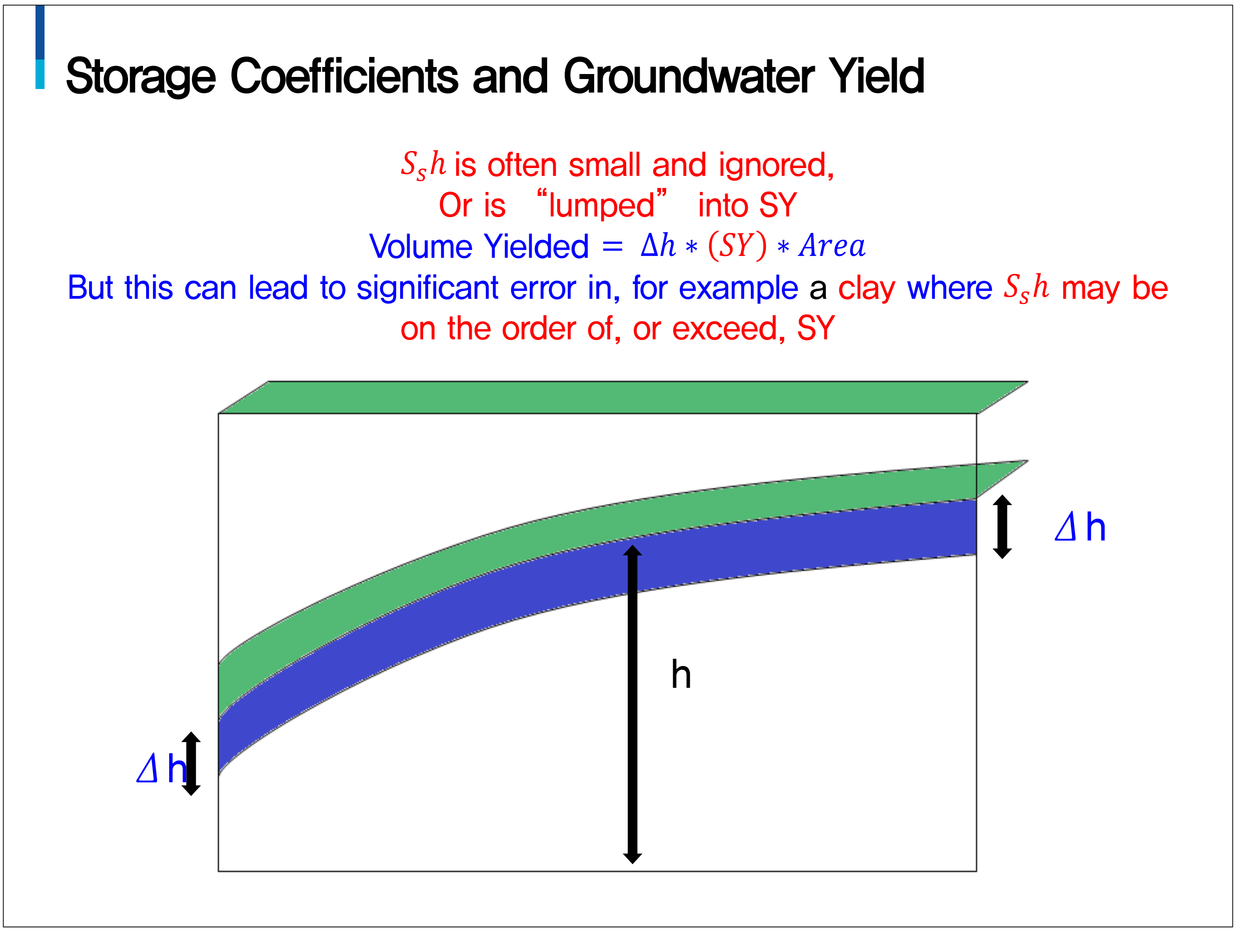


Storage Coefficients and Groundwater Yield

Water level decline in an Unconfined Aquifer

Because water is released from elastic storage in the zone below the lowered water table the complete expression is :

Volume Yielded = $\Delta h * (SY + S_s h) * Area$



Storage Coefficients and Groundwater Yield

$S_s h$ is often small and ignored,
Or is "lumped" into SY

Volume Yielded = $\Delta h * (SY) * Area$

But this can lead to significant error in, for example a clay where $S_s h$ may be on the order of, or exceed, SY

5. Groundwater Basin and Residence Time

Drainage Basin and Groundwater Basin (1)

BALANCE APPLIES NOT ONLY TO THE ENTIRE EARTH, BUT ALSO TO ANY SUB - DOMAIN OF THE HYDROLOGIC SYSTEM

e.g. Atmosphere
Ocean
Continent
Watershed
Stream Segment
Lake
Even anthropogenic objects: processing tank or a pool
Or Political entities: counties, states, nations

COMPONENTS OF A BASIN WATER BUDGET

INFLOW = OUTFLOW +/− CHANGE IN STORAGE

IN' S
PRECIPITATION + SW INFLOW + SW INFLOW + IMPORTED WATER =

OUT' S
ET + EVAPORATION + SW OUT + GW OUT + EXPORT + CONSUMPTION

STORAGE
+ INCREASE IN SW STORAGE + INCREASE IN GW STORAGE

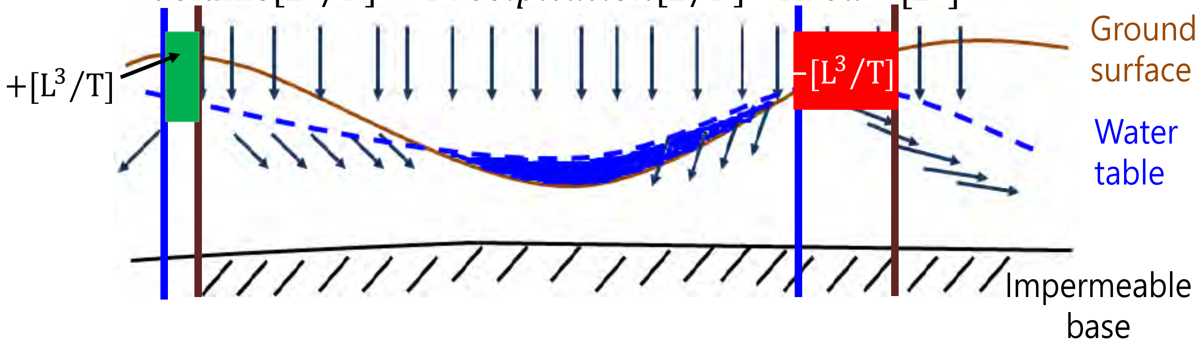
Drainage Basin and Groundwater Basin (2)

DRAINAGE BASIN - Area Surrounded by a Topographic Divide may Differ from GroundWater Basin

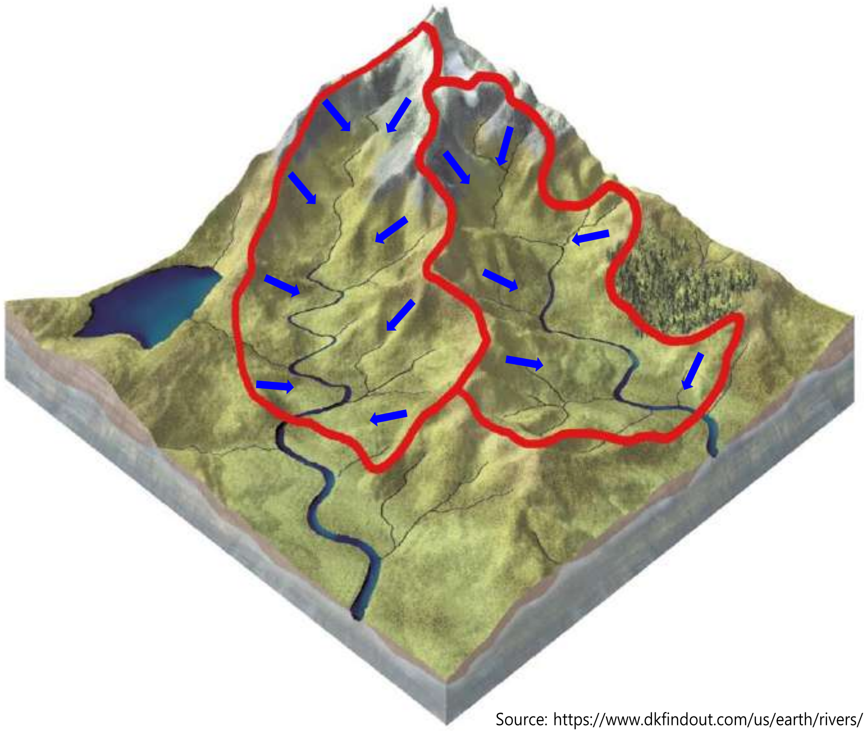
GROUNDWATER BASIN - Surrounded by Phreatic (Water Table) Divide
Water Table - Surface below which all cracks and pores in the subsurface are full of water
Phreatic - All Water in Saturated Zone

WHEN DIVIDES DO NOT CORRESPOND - INTERBASIN FLOW

$$\mathrm{Volume}[L^3/T] = Precipitation[L/T] * Area * [L^2]$$

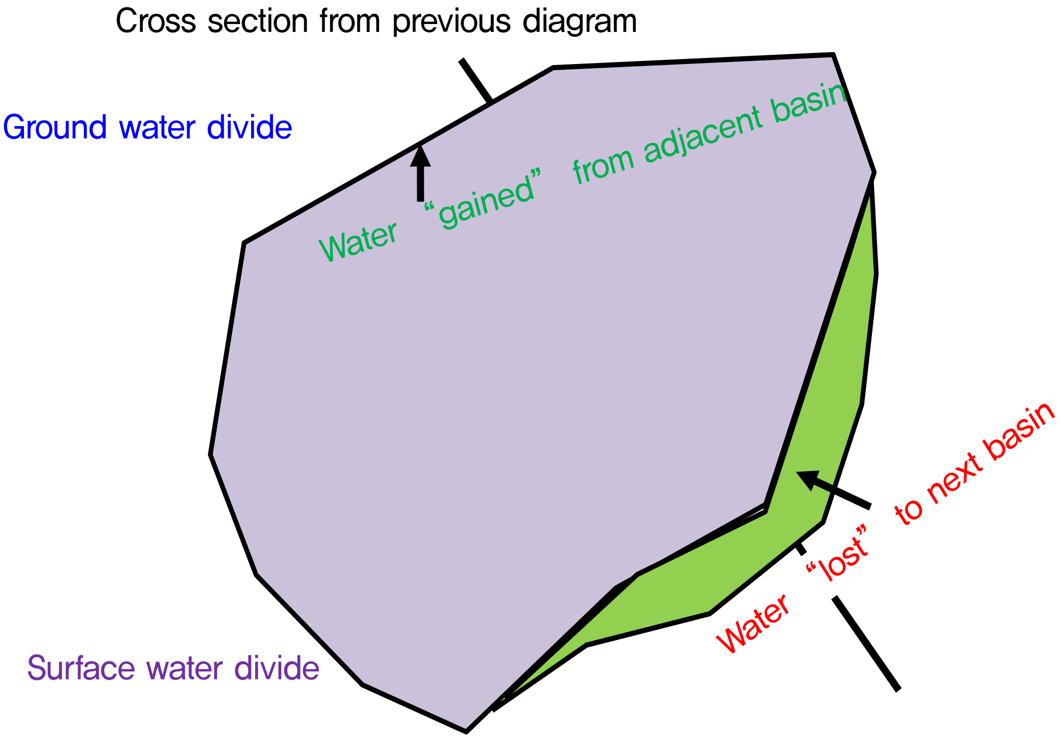


Drainage Basin and Groundwater Basin (3)



Source: https://www.dkfindout.com/us/earth/rivers/how-do-rivers-form/

Drainage Basin and Groundwater Basin (4)

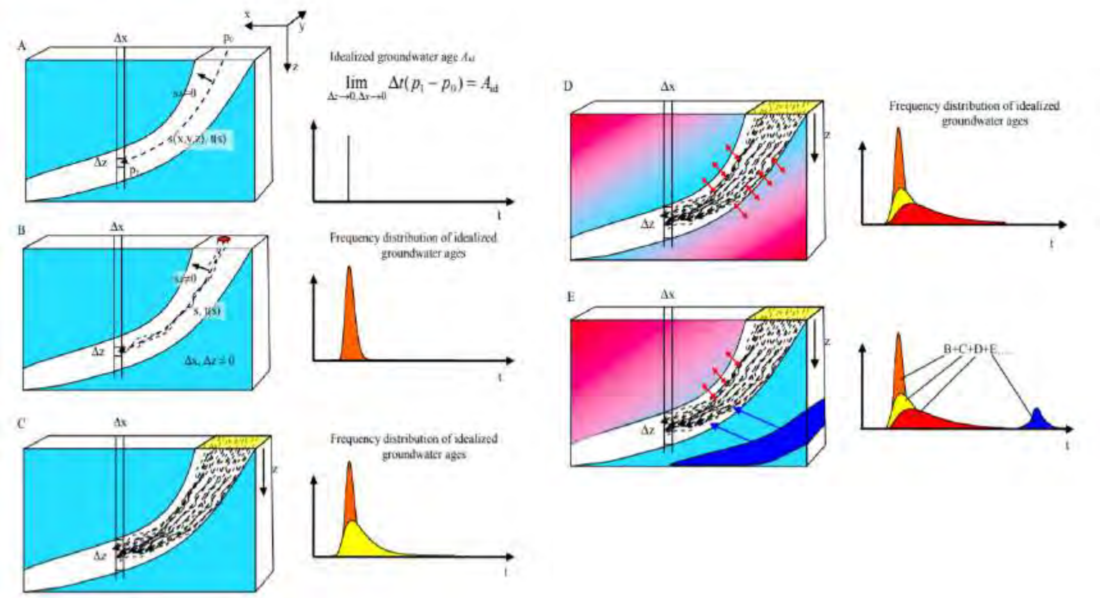


Groundwater Flow, Aquifer Residence and Age (1)

Groundwater Age (⊿t) :

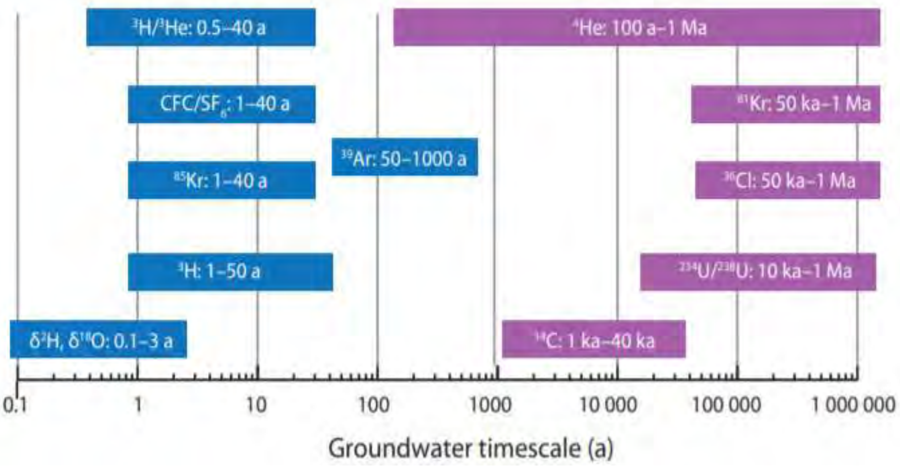
the time interval between the time when water entered the saturated zone (the time water entered into groundwater) and the time when the water was sampled at a specific location (x, y, z)

Groundwater Flow, Aquifer Residence and Age (2)



The concept of groundwater dating represents levels of complexity (IAEA, 2013)

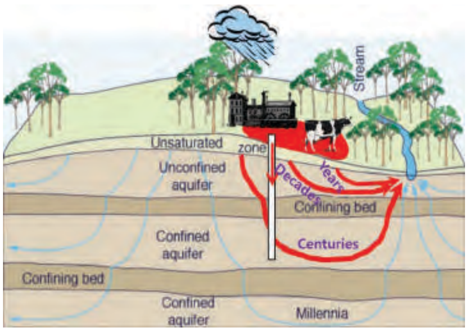
Groundwater Flow, Aquifer Residence and Age (3)

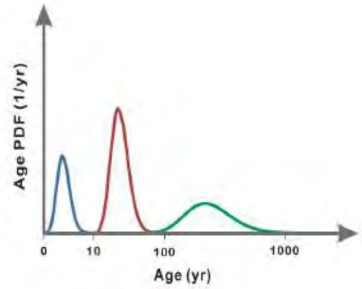


Isotope and chemical tracers use for estimating groundwater age (IAEA, 2013)

Groundwater Flow, Aquifer Residence and Age (4)

Groundwater age mixing





Modified from Winter et al., 1998

- Groundwater age is composed of water particles with various ages depending on aquifer structure, heterogeneity of the physical parameters and recharge patterns (Cook & Böhlke, 2000; Cornaton, 2004; Bethke and Johnson, 2008).
- Groundwater age mixing process → Aquifer vulnerability by various sources

---

Groundwater Flow, Aquifer Residence and Age (5)

Comparison of age estimation models

1) Lumped parameter model (LPM)

(Maloszewski and Zuber, 1982; 1993)

: Applying mixing of tracers using simplified aquifer geometry and flow characteristics

Decay of radioactive tracer

$$\underset{\text{Conc. of age tracer}}{C_{out}(t)} = \int_0^\infty \underbrace{C_{in}(t-t')}_{\text{Input conc.}} \exp(-\lambda t')\, \underbrace{g(t')}_{\text{Age distribution functions}} dt'$$

2) Numerical model

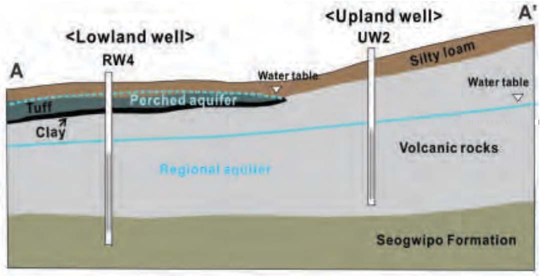
(Therrien et al., 2010)

: Advection–dispersion equation for age CDF (cumulative density function, G_A)

$$\frac{\partial G_A}{\partial t}\theta = \nabla \cdot \theta D \nabla G_A - \nabla q G_A - q_O G_A$$

$$g_A(a) = \frac{dG_A(a)}{da}$$

← Age PDF (probability density function)

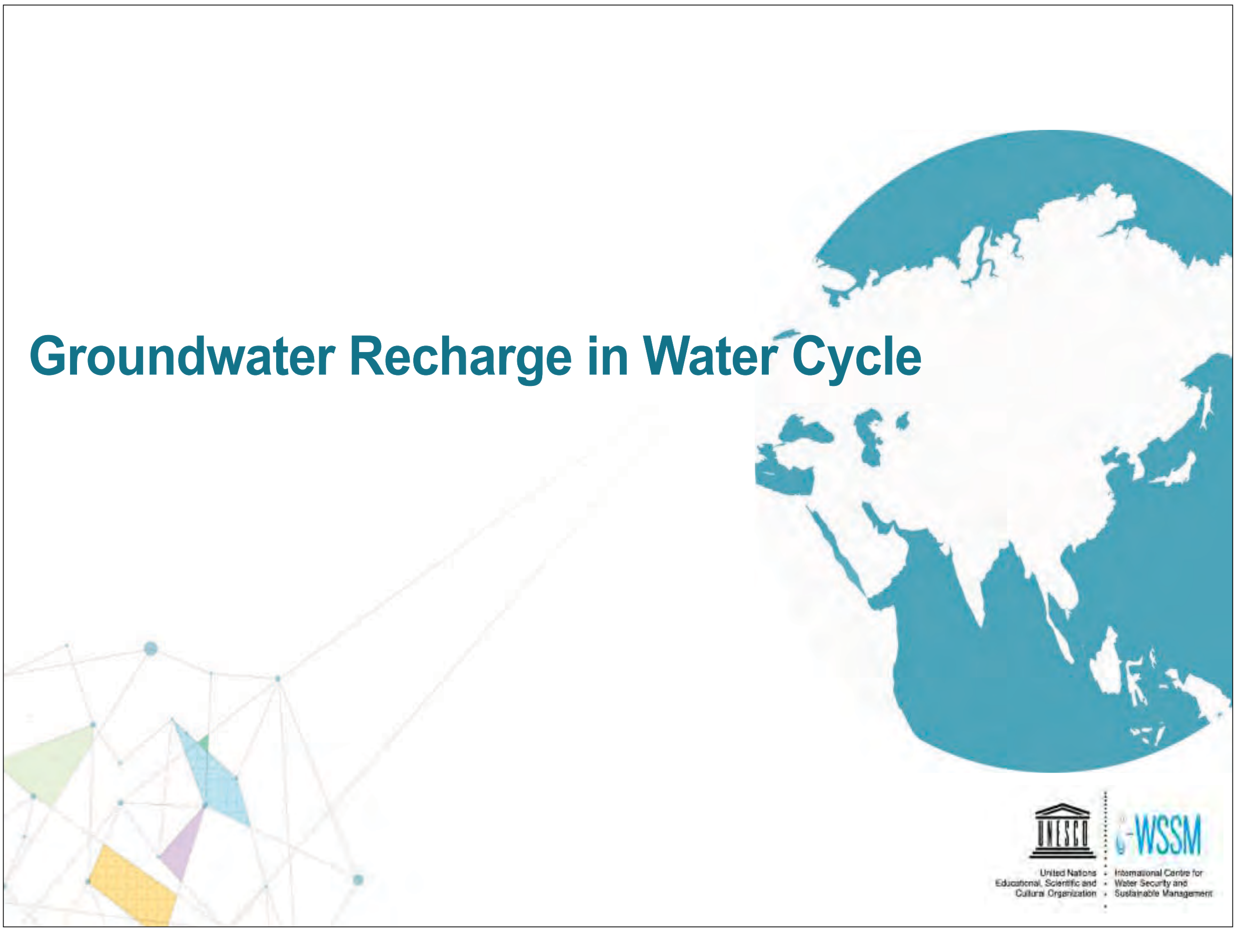


- Aquifer complexity
→ Age distribution?
→ Nitrate timescale?

Thank you very much

Groundwater Recharge in Water Cycle

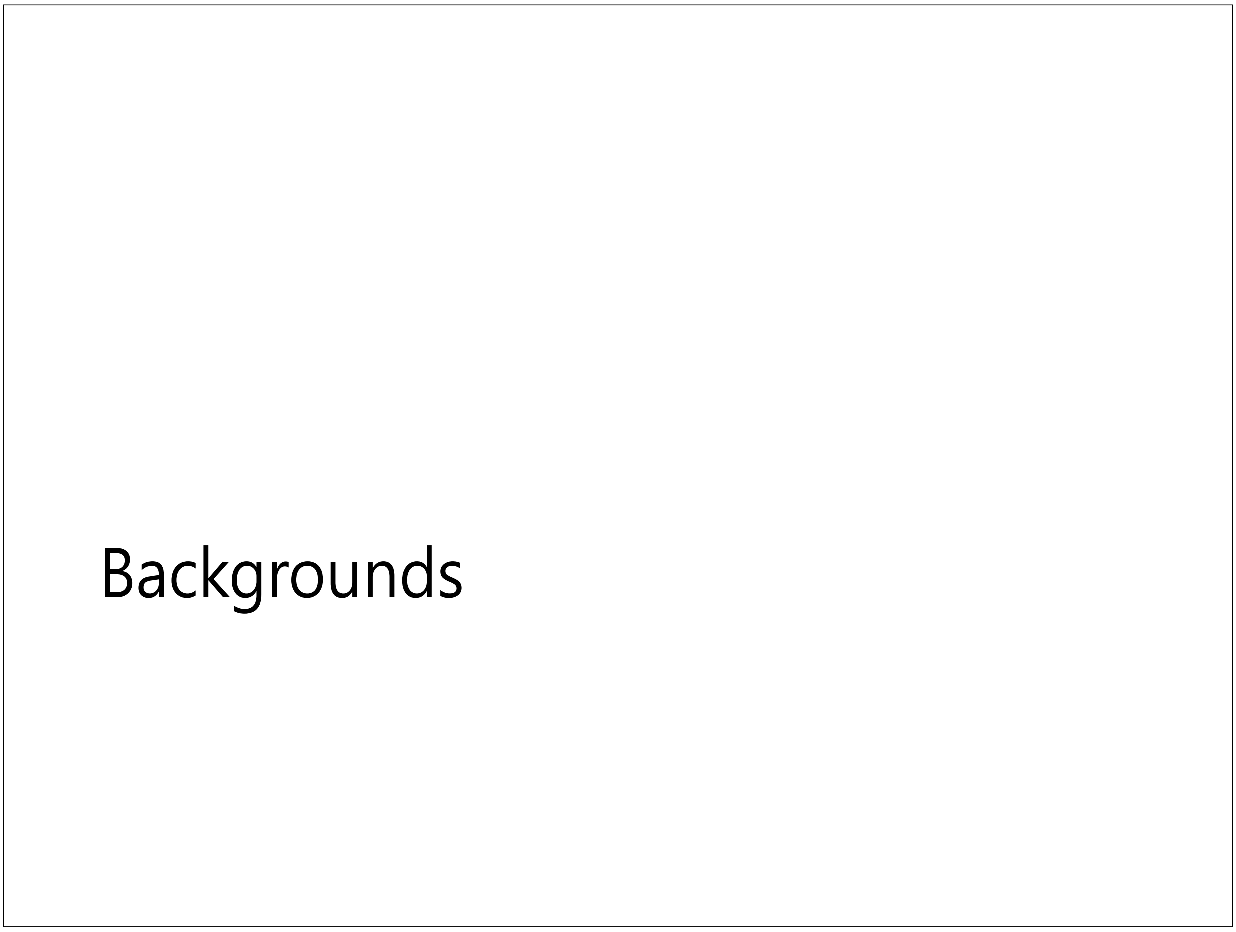
Groundwater



Groundwater Recharge in Water Cycle

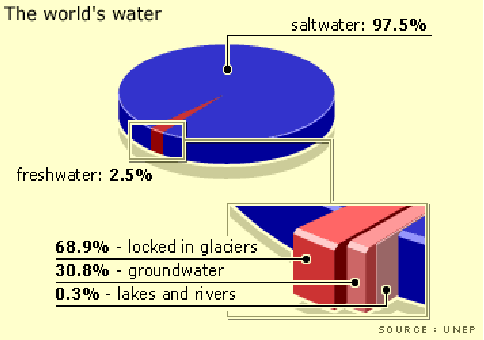
United Nations
Educational, Scientific and
Cultural Organization

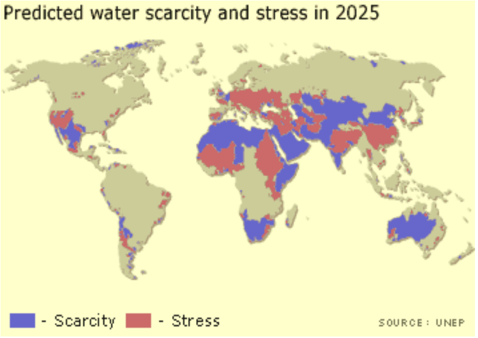
i-WSSM
International Centre for
Water Security and
Sustainable Management



Backgrounds

The world's water





- The amount of water on Earth is fixed. Less than 0.01% of the planet's 1.4 billion cubic kilometres is easily accessible freshwater in lakes and rivers.
- Africa and Asia are already hard-hit by water stress. Increasing populations will create more pressure in the coming decades.

Water Distribution on Earth

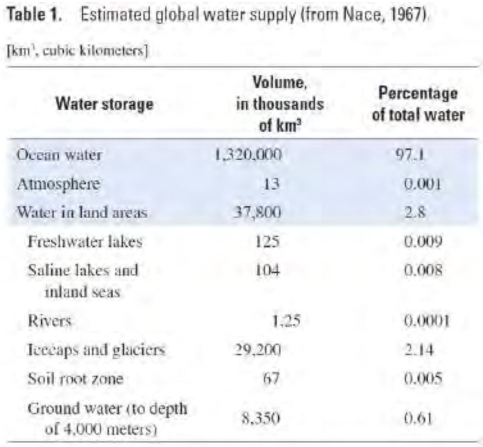


Table 1. Estimated global water supply (from Nace, 1967)

[km^3, cubic kilometers]

Water storage	Volume, in thousands of km^3	Percentage of total water
Ocean water	1,320,000	97.1
Atmosphere	13	0.001
Water in land areas	37,800	2.8
Freshwater lakes	125	0.009
Saline lakes and inland seas	104	0.008
Rivers	1.25	0.0001
Icecaps and glaciers	29,200	2.14
Soil root zone	67	0.005
Ground water (to depth of 4,000 meters)	8,350	0.61

Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, Water budgets: Foundations for effective water-resources and environmental management: U.S. Geological Survey Circular 1308, 90 p.

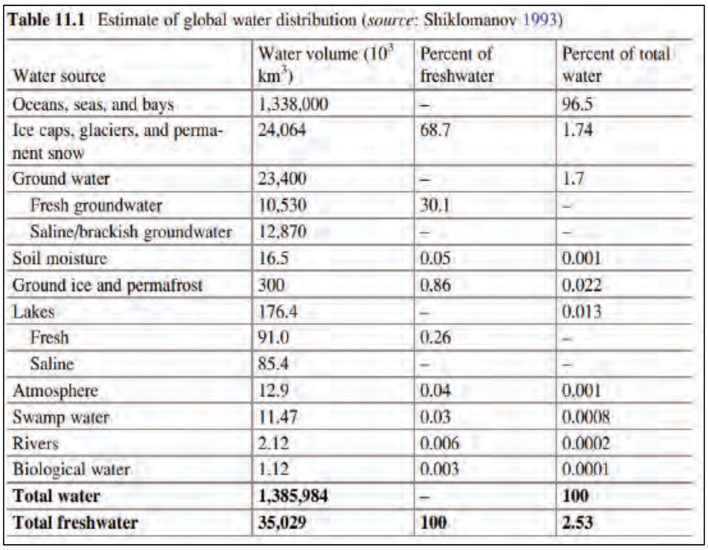


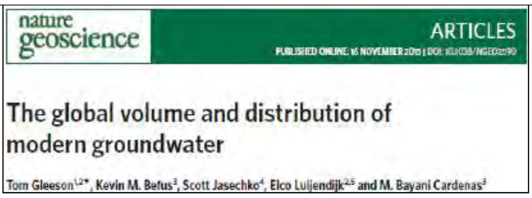
Table 11.1 Estimate of global water distribution (*source*: Shiklomanov 1993)

Water source	Water volume (10^3 km^3)	Percent of freshwater	Percent of total water
Oceans, seas, and bays	1,338,000	–	96.5
Ice caps, glaciers, and permanent snow	24,064	68.7	1.74
Ground water	23,400	–	1.7
Fresh groundwater	10,530	30.1	–
Saline/brackish groundwater	12,870	–	–
Soil moisture	16.5	0.05	0.001
Ground ice and permafrost	300	0.86	0.022
Lakes	176.4	–	0.013
Fresh	91.0	0.26	–
Saline	85.4	–	–
Atmosphere	12.9	0.04	0.001
Swamp water	11.47	0.03	0.0008
Rivers	2.12	0.006	0.0002
Biological water	1.12	0.003	0.0001
Total water	**1,385,984**	–	**100**
Total freshwater	**35,029**	**100**	**2.53**

A. Fares (ed.), Emerging Issues in Groundwater Resources, Advances in Water Security, DOI 10.1007/978-3-319-32008-3_11

Modern groundwater

(<50yrs old)



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ARTICLES

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The global volume and distribution of modern groundwater

Tom Gleeson[1,2*], Kevin M. Befus[3], Scott Jasechko[4], Elco Luijendijk[2,5] and M. Bayani Cardenas[3]

- Less than 6% of the groundwater in the uppermost portion of earth's landmass is modern(<50 yrs)

- The total gw volume in the upper 2 km of continental curst is aprox. 22.6 M km3
- 0.1-5.0 M km3 is less than 50 yrs old

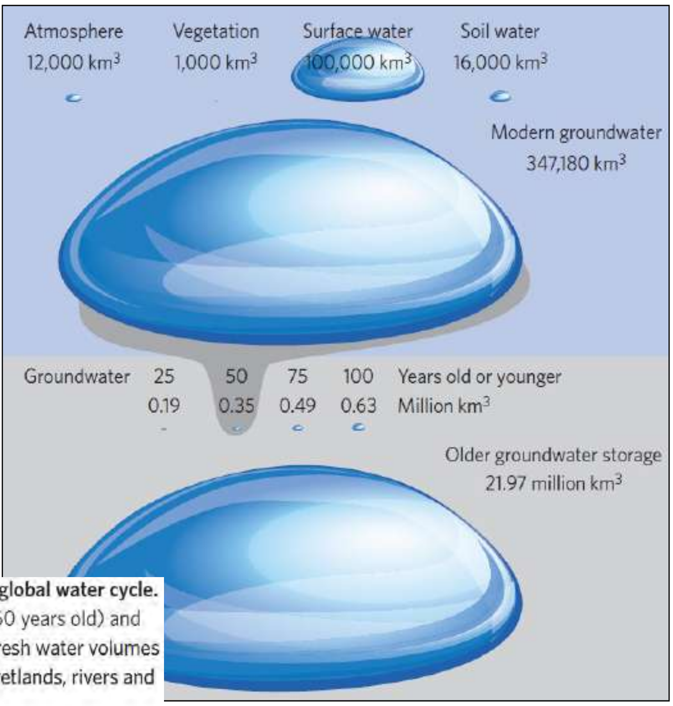
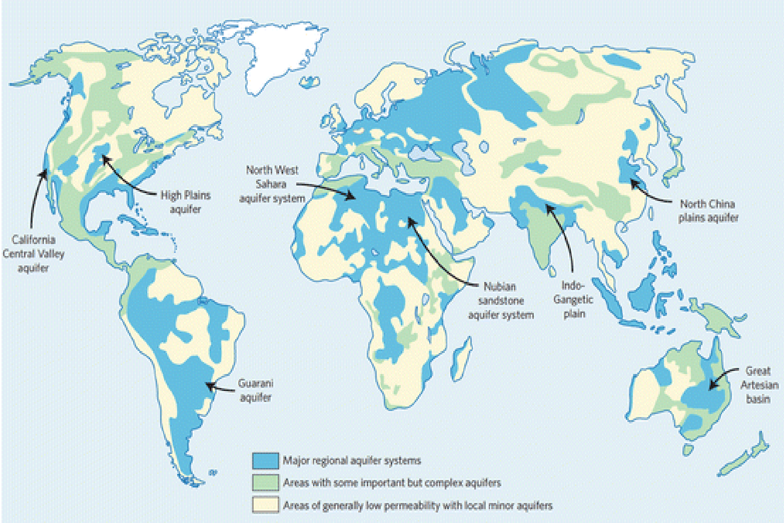


Figure 5 | The different volumes of water stored in the global water cycle. Global volumes of young (<100 years old), modern (<50 years old) and total groundwater to 2 km depth compared with other fresh water volumes stored in the atmosphere[33], in surface waters (that is, wetlands, rivers and lakes)[33], within plants or in soils[33].

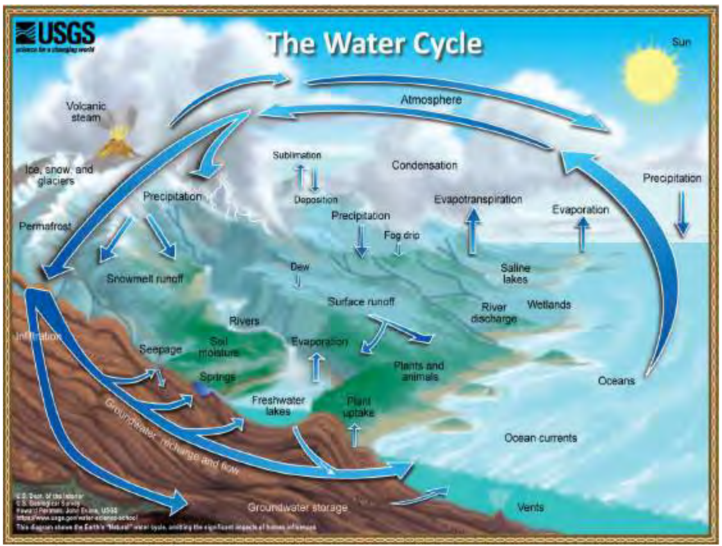
Global Aquifer System



A. Fares (ed.), Emerging Issues in Groundwater Resources, Advances in Water Security, DOI 10.1007/978-3-319-32008-3_11

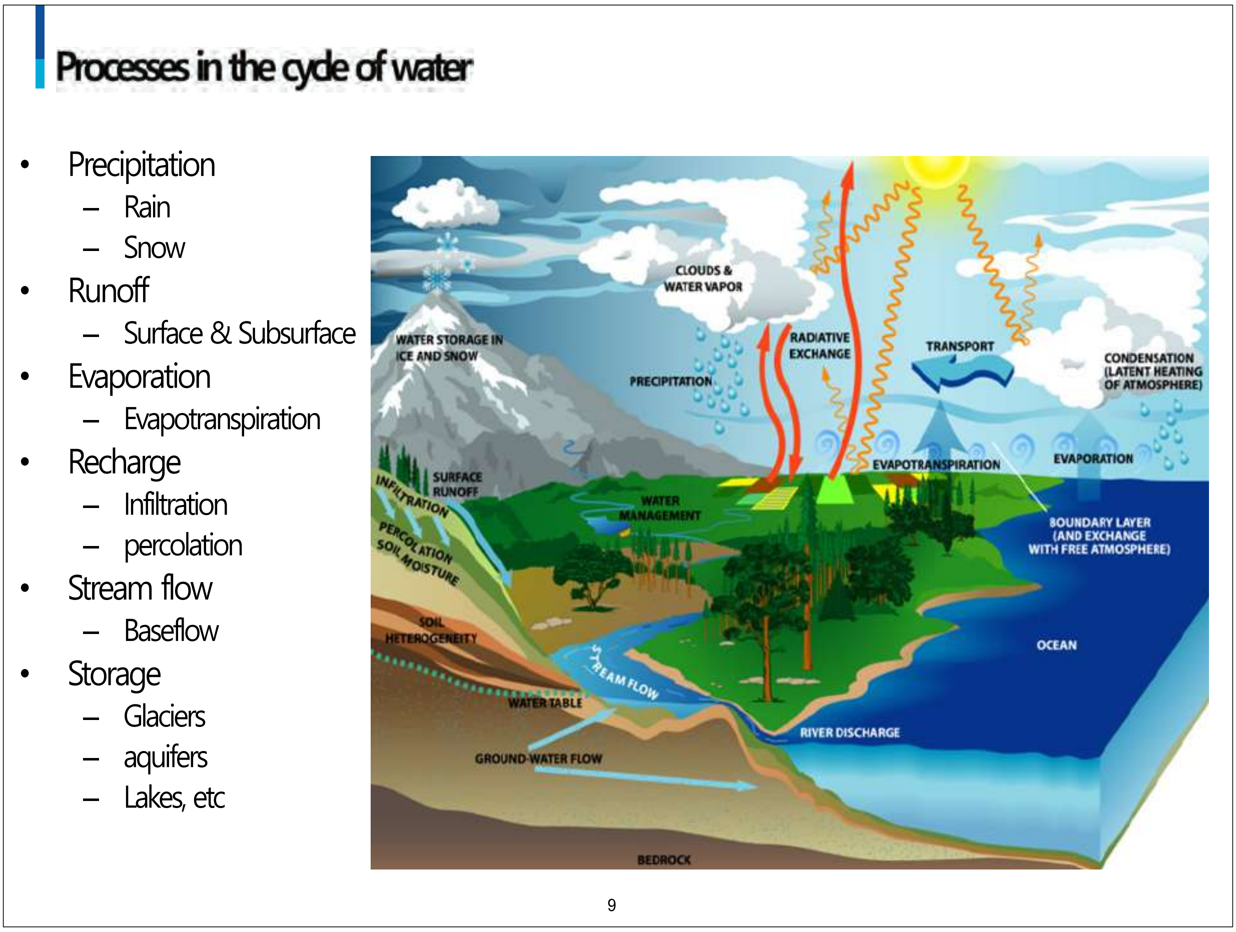
Water Cycle (hydrologic Cycle)

- (Definition) cycle that involves the continuous circulation of water in the Earth-atmosphere system
- Endless, global scale, process linking water in atmosphere, on continents, and in oceans



Source : USGS

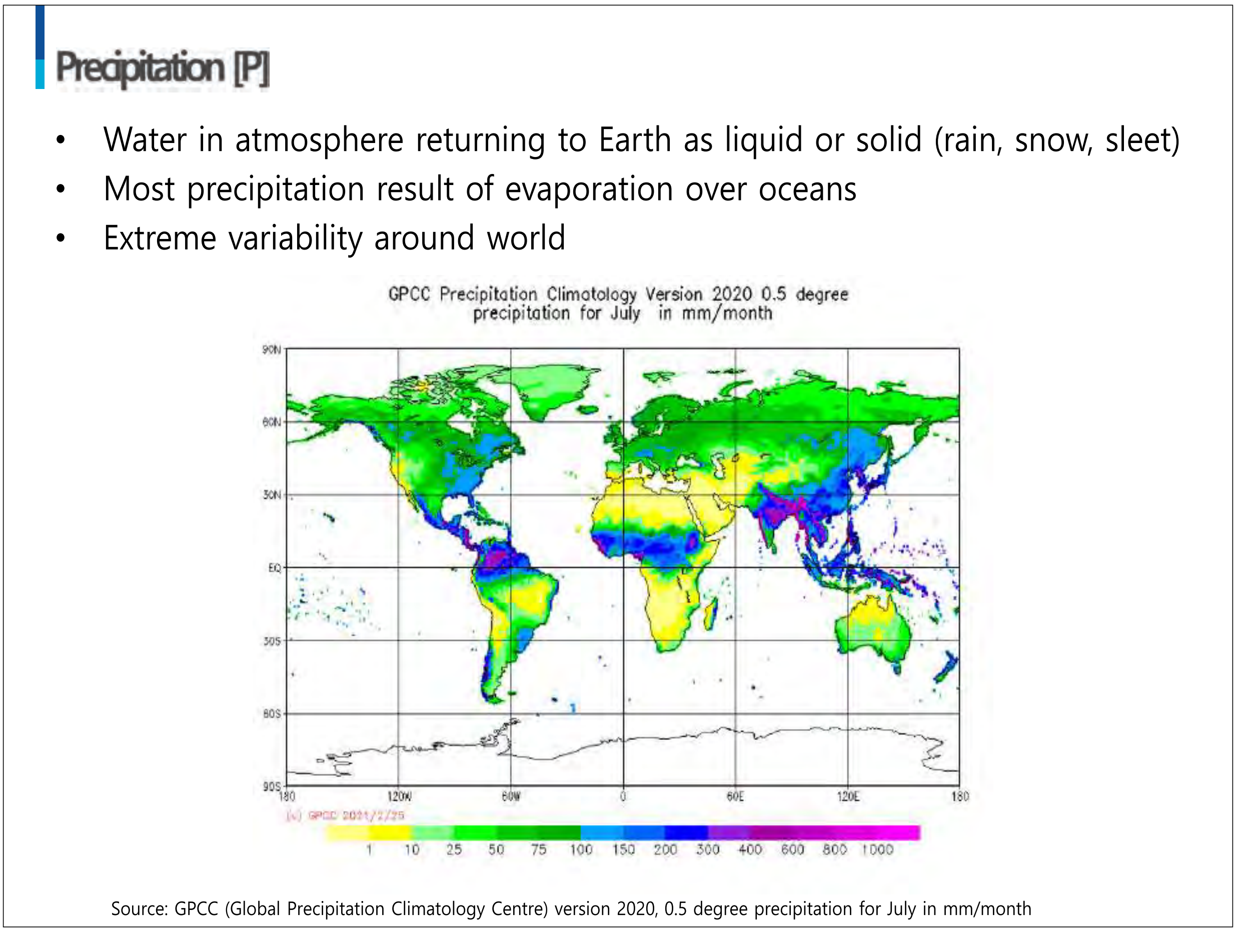
Processes in Hydrologic Cycle



Processes in the cycle of water

- Precipitation
  - Rain
  - Snow
- Runoff
  - Surface & Subsurface
- Evaporation
  - Evapotranspiration
- Recharge
  - Infiltration
  - percolation
- Stream flow
  - Baseflow
- Storage
  - Glaciers
  - aquifers
  - Lakes, etc

9



Precipitation [P]

- Water in atmosphere returning to Earth as liquid or solid (rain, snow, sleet)
- Most precipitation result of evaporation over oceans
- Extreme variability around world

GPCC Precipitation Climatology Version 2020 0.5 degree precipitation for July in mm/month

Source: GPCC (Global Precipitation Climatology Centre) version 2020, 0.5 degree precipitation for July in mm/month

Runoff / Evaporation / Evapotranspiration / Water storage (ΔS) / Water budget

- Surface Runoff:
  - Water flowing across land surface as streams, rivers, and drains after rain storm or melting snow
- Subsurface (Groundwater) Runoff [Q_{gw}]:
  - Water flowing beneath land surface through sediments and rock
- Evaporation
  - Process converting water to water vapor
- Evapotranspiration [ET]
  - Evaporation from soil surface and transpiration from plants
- Water Storage (ΔS)
  - Water collected in naturally occurring or manmade bodies along hydrologic cycle
  - Storage bodies include: lakes, reservoirs, wetlands, aquifer, ice caps
- Water Budget
  - Volume of water transferred in hydrologic cycle
  - Water budget developed for a hydrologic system e.g., watershed or where water stored e.g., surface or groundwater
  - Calculation involves a direct accounting for the inflows and outflows of water

Estimating Evapotranspiration

- Lysimeter – Container holding soil and plants

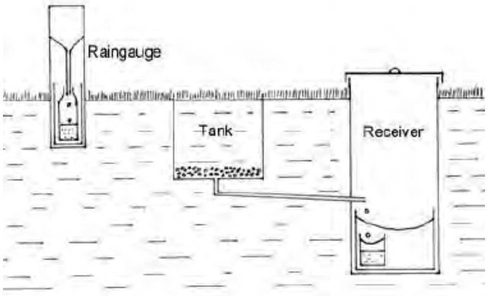


Fig 2. Lysimeter apparatus for measuring evapotranspiration

From http://www.llansadwrn-wx.co.uk

$$E_T = S_i + P + I - S_f - D$$

S_i = Volume of initial soil moisture

S_f = Volume of final soil moisture

P = Precipitation

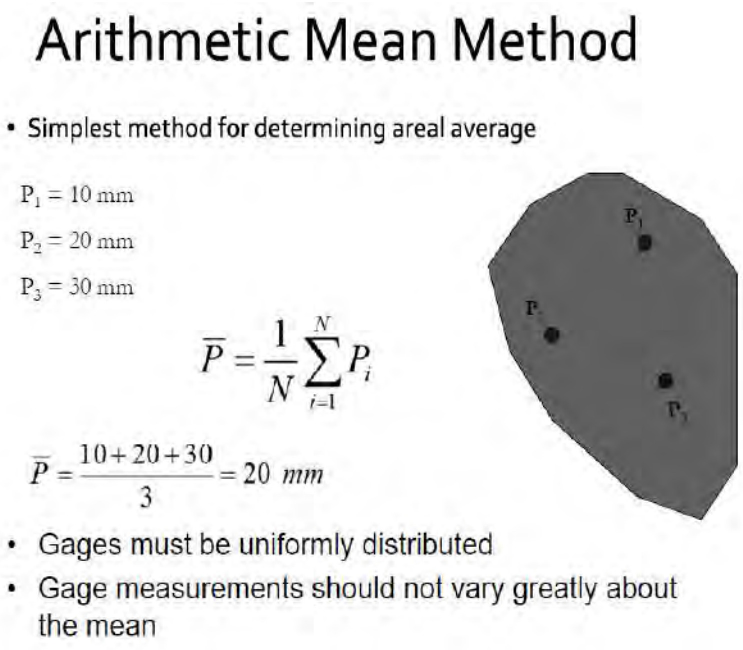
I = Irrigation water added

D = Excess moisture drained from the soil

Estimating precipitation

- Precipitation
  - Water in atmosphere returning to Earth as liquid or solid (rain, snow, sleet)
  - Most precipitation result of evaporation over oceans
  - Extreme variability around world
- Effective depth of precipitation = Effective Uniform Depth(EUD)
- "average" rainfall value over watershed
- Estimating EUD
  - Generally uniform rain density = arithmetic average
  - Non uniform rain density
    - 1. Thiessen polygon method: based on a weighting factor for each rain gage
    - 2. Isohyetal method (lines of equal rainfall): based on relative size of each isohyets area

Estimating precipitation



Arithmetic Mean Method

- Simplest method for determining areal average

$P_1 = 10$ mm

$P_2 = 20$ mm

$P_3 = 30$ mm

$$\overline{P} = \frac{1}{N}\sum_{i=1}^{N} P_i$$

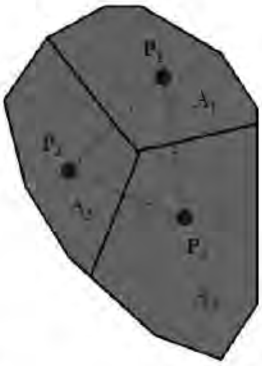
$$\overline{P} = \frac{10+20+30}{3} = 20\ mm$$

- Gages must be uniformly distributed
- Gage measurements should not vary greatly about the mean

Estimating precipitation

Thiessen polygon method

- Steps
  1. Draw lines joining adjacent gages
  2. Draw perpendicular bisectors to the lines created in step 1
  3. Extend the lines created in step 2 in both directions to form representative areas for gages
  4. Compute representative area for each gage
  5. Compute the areal average using the following formula



$P_1 = 10$ mm, $A_1 = 12$ Km^2

$P_2 = 20$ mm, $A_2 = 15$ Km^2

$P_3 = 30$ mm, $A_3 = 20$ km^2

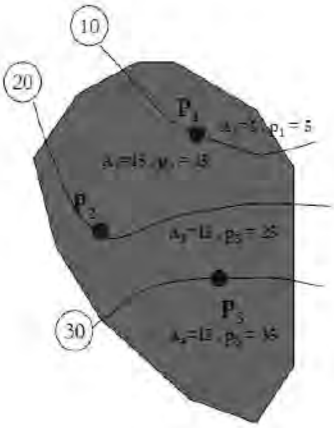
$$\overline{P} = \frac{1}{A}\sum_{i=1}^{N} A_i P_i$$

$$\overline{P} = \frac{12\times10+15\times20+20\times30}{47} = 20.7\ mm$$

Estimating precipitation

Isohyetal method

- Steps
  - Construct isohyets (rainfall contours)
  - Compute area between each pair of adjacent isohyets (A_i)
  - Compute average precipitation for each pair of adjacent isohyets (p_i)
  - Compute areal average using the following formula

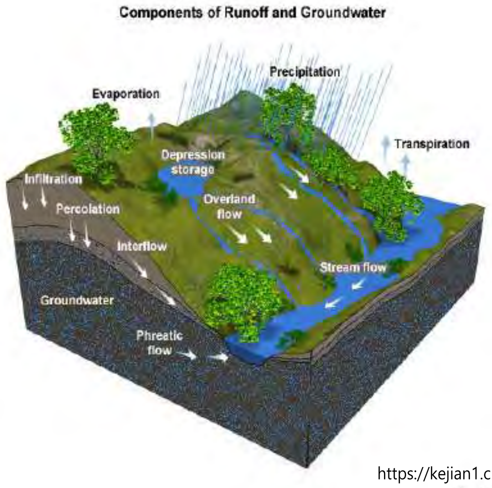


$$\overline{P} = \frac{1}{A}\sum_{i=1}^{N} A_i P_i$$

$$\overline{P} = \frac{5\times5+18\times15+12\times25+12\times35}{47} = 21.6\ mm$$

Estimating Stream flow
(= overland flow + base flow)

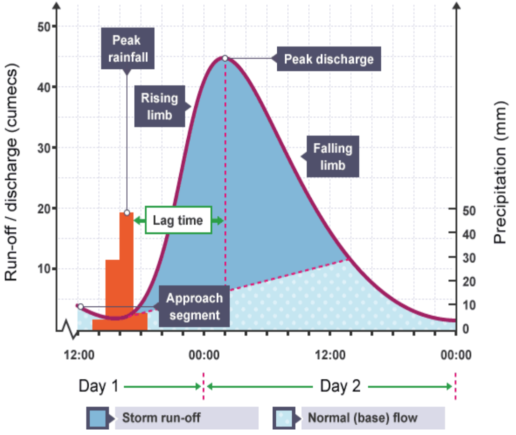
- Events during precipitation
- 1. Interception: 8-35%
- 2. Stem flow
- 3. Infiltration (-> recharge)
- 4. Depression storage (puddle)
- 5. Overland flow (Runoff)



https://kejian1.cmatc.cn

©The COMET Program

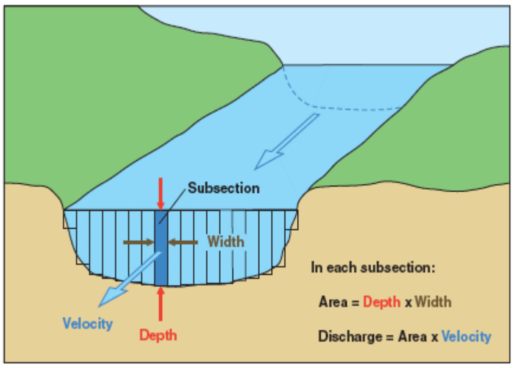
Hydrograph



https://geographyaslevelaqa.wordpress.com

Measurement of Stream flow
(= overland flow + base flow)

- Stream flow (Q) = avg. velocity (V) x cross sectional area (A)



Current-meter discharge measurements are made by determining the discharge in each subsection of a channel cross section and summing the subsection discharges to obtain a total discharge.

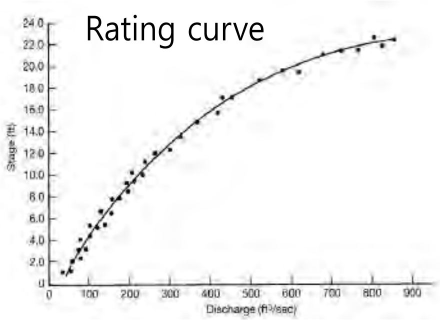
https://water.usgs.gov

Propeller current meter

Measurement of Stream flow

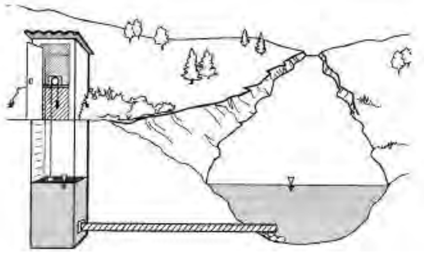
How to measure this in real time

- Rating curve is a graph of discharge versus stream water level (stage) for a given point on a stream
- Rating curve enables us to convert the water level to discharge rate in real time

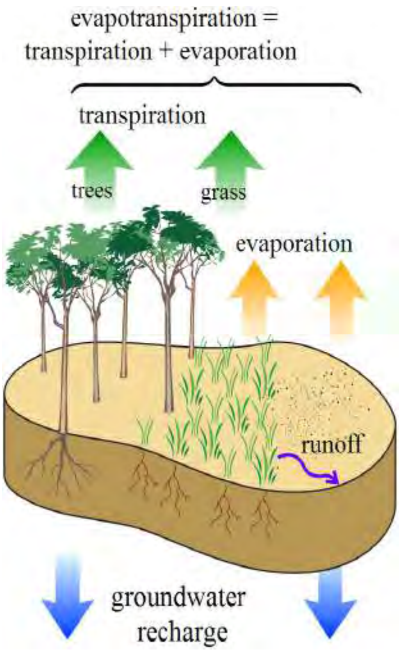


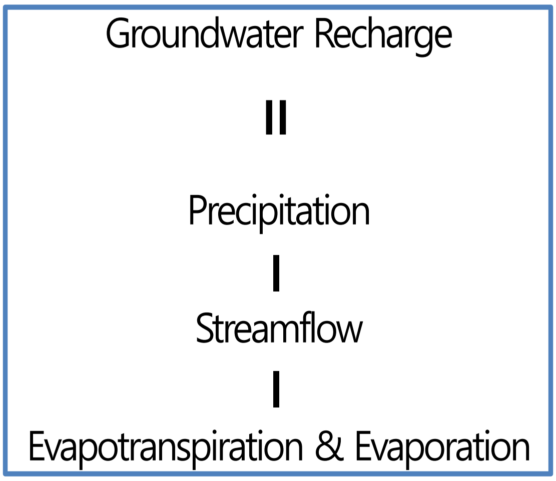
https://www.utdallas.edu

Stream water level monitoring station



Estimating Groundwater Recharge





Groundwater Recharge

II

Precipitation

I

Streamflow

I

Evapotranspiration & Evaporation

*Stream flow = runoff + base flow

Water Budget Equation (Hydrologic Eqn.)

For a given control volume (e.g., watershed) in a time interval Δt

Input – Output = Δstorage (Continuity equation)

IN (Precipitation, Surface water inflow, Groundwater inflow, Imported water)

OUT (Evapotranspiration, Reservoir evaporation, Surface water outflow, Groundwater outflow, Exported water)

Δ [Storage change in a watershed (groundwater, surface water)]

$$P + Q_{in} = ET + Q_{out} + \Delta S$$

Written for a control volume
such as watershed or catchment

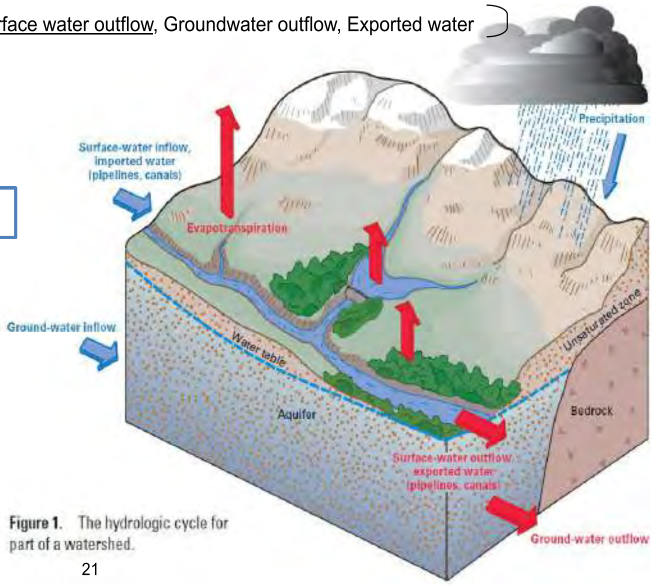


Figure 1. The hydrologic cycle for part of a watershed.

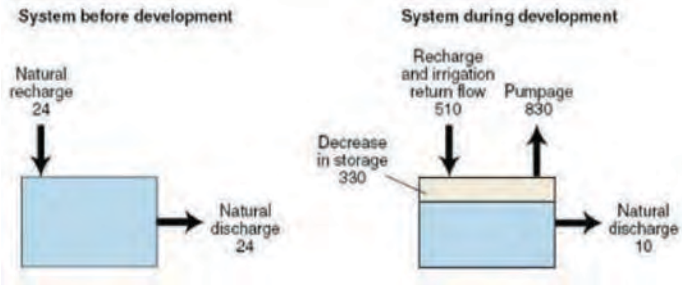
Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, Water budgets: Foundations for effective water-resources and environmental management: U.S. Geological Survey Circular 1308, 90 p.

Examples: Water budget analysis

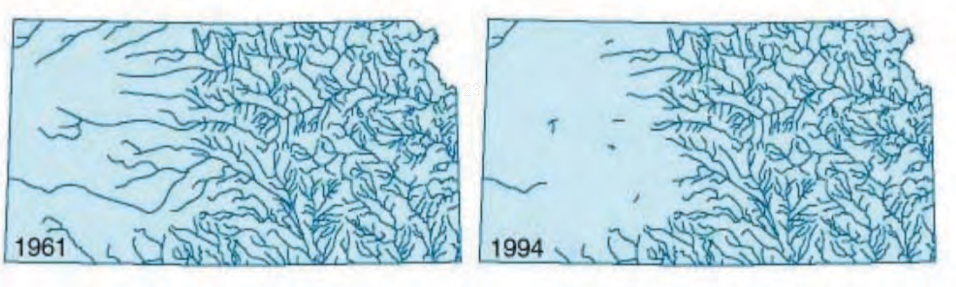
Write a hydrologic budget equation for the scenarios below.
Calculate the change in storage.
Write whether the hydrologic budget is at a loss, a gain, or at steady state.

- a. Groundwater pumping [Q_{pump}] = 10 mm/yr.
- b. Surface water Runoff [Q_{runoff}]= 96 mm/yr.
- c. Evapotranspiration [ET]= 550 mm/yr.
- d. Precipitation [P]= 600 mm/yr.
- e. Groundwater inflow [Q_{in_gw}]= 80 mm/yr.

Examples: Water budget analysis (Southern High Plain Aquifer, USA)

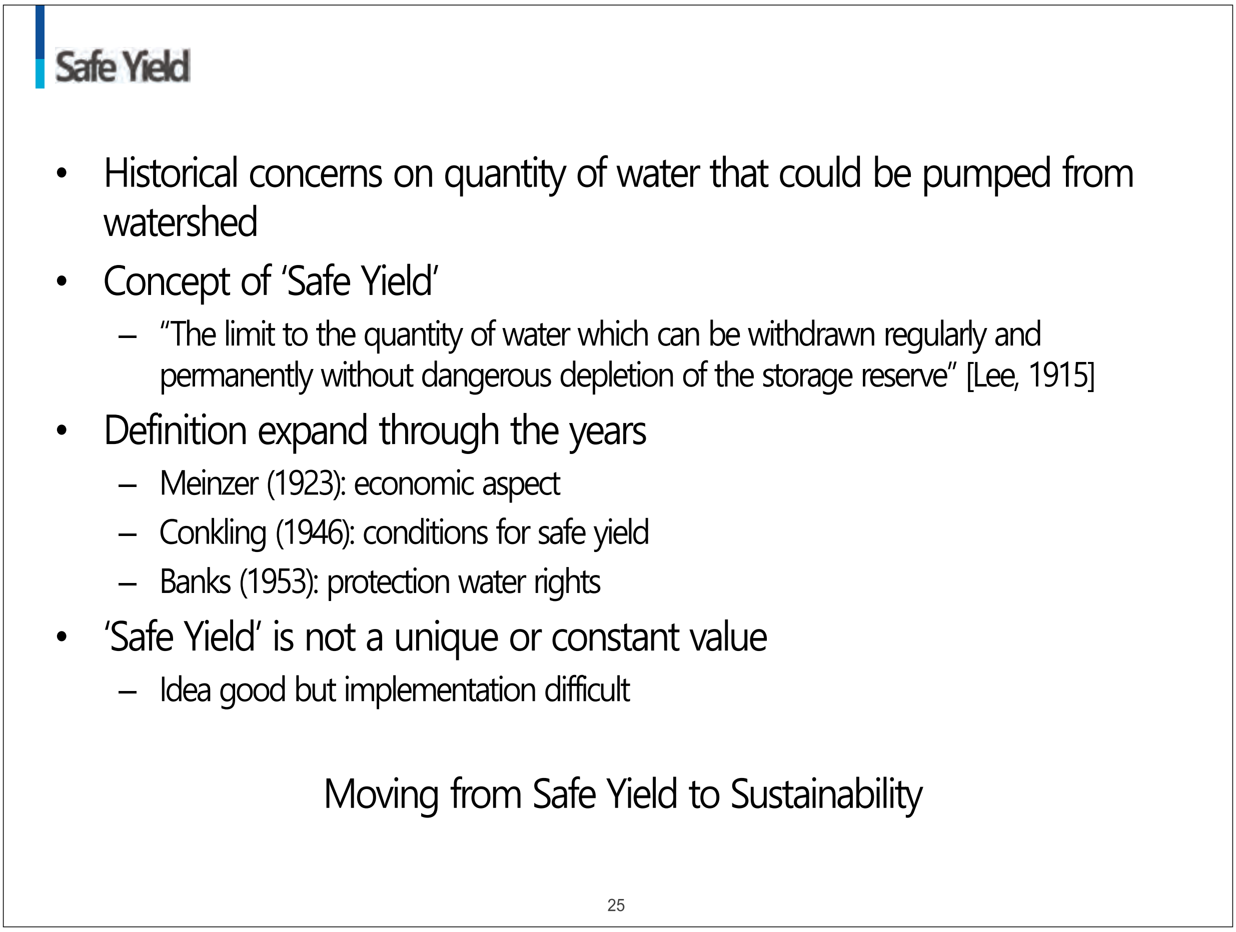


Write hydrologic budget equations for the aquifer system before/after development.



Source: V.M. Ponce, 2007; USGS; Alley et al., 1999

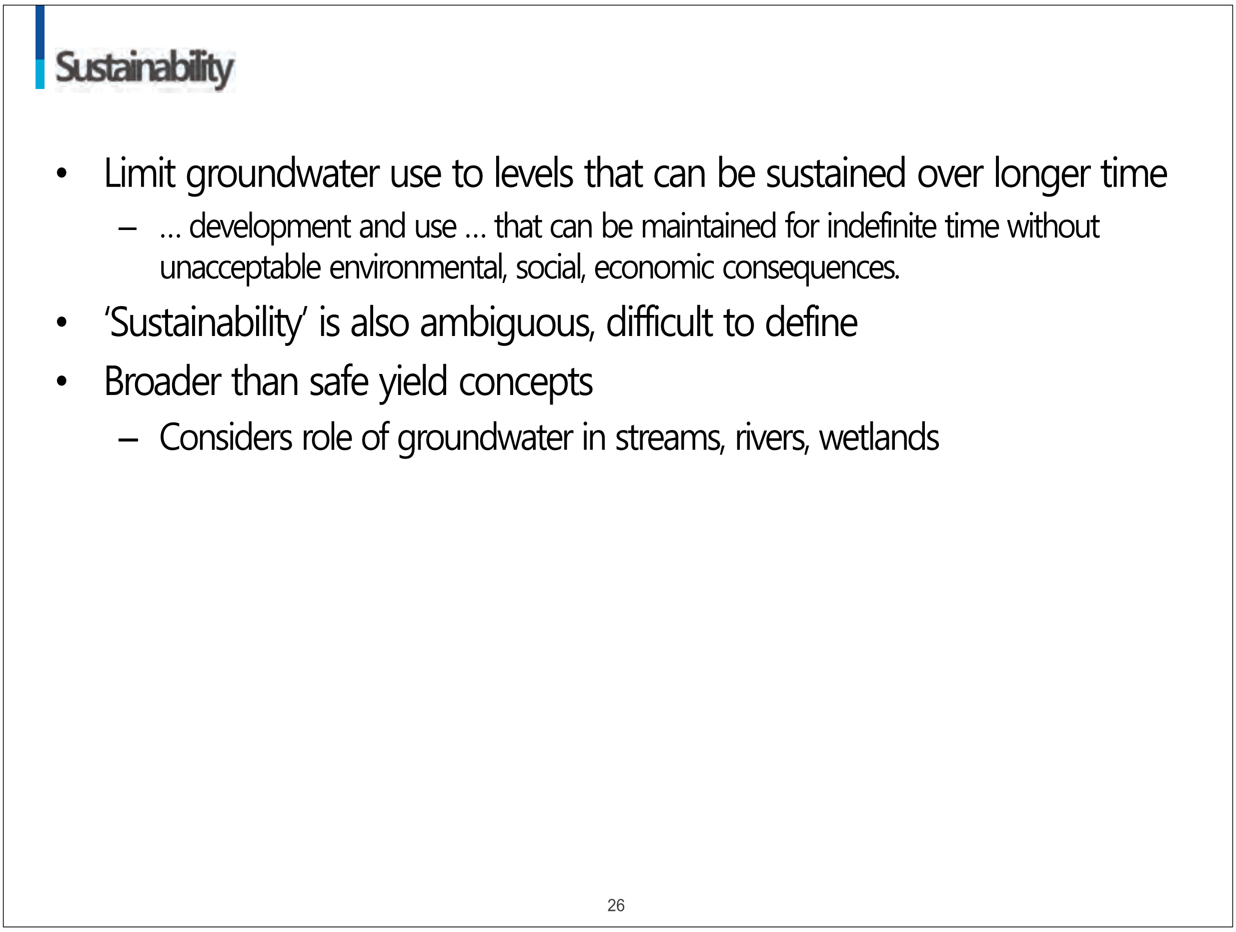
Sustainability
in the context of water cycle



Safe Yield

- Historical concerns on quantity of water that could be pumped from watershed
- Concept of 'Safe Yield'
  - "The limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve" [Lee, 1915]
- Definition expand through the years
  - Meinzer (1923): economic aspect
  - Conkling (1946): conditions for safe yield
  - Banks (1953): protection water rights
- 'Safe Yield' is not a unique or constant value
  - Idea good but implementation difficult

Moving from Safe Yield to Sustainability



Sustainability

- Limit groundwater use to levels that can be sustained over longer time
  - … development and use … that can be maintained for indefinite time without unacceptable environmental, social, economic consequences.
- 'Sustainability' is also ambiguous, difficult to define
- Broader than safe yield concepts
  - Considers role of groundwater in streams, rivers, wetlands

Groundwater-surface water connections

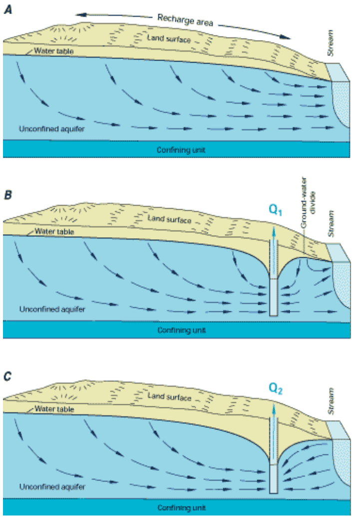
- Concept of safe yield obsolete because groundwater and surface water connected

- groundwater depletion causes depletion of surface water

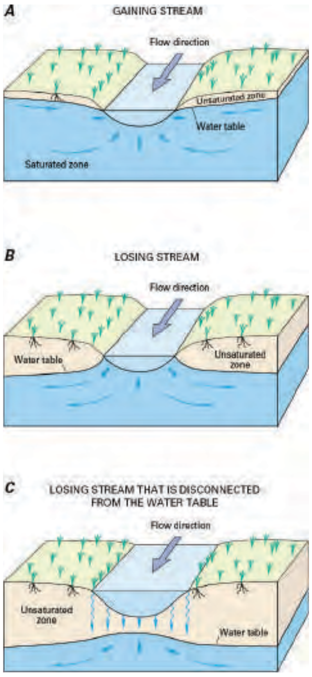
A. Natural system with groundwater discharge to stream (Natural recharge = natural discharge)

B. Moderate pumping causes reduced inflow to stream (pumping=captured recharge + captured discharge)

C. Heavy pumping induces flow from stream (pumping = CR+CD + captured storage)



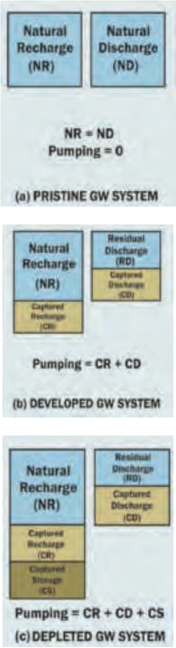
Source: USGS

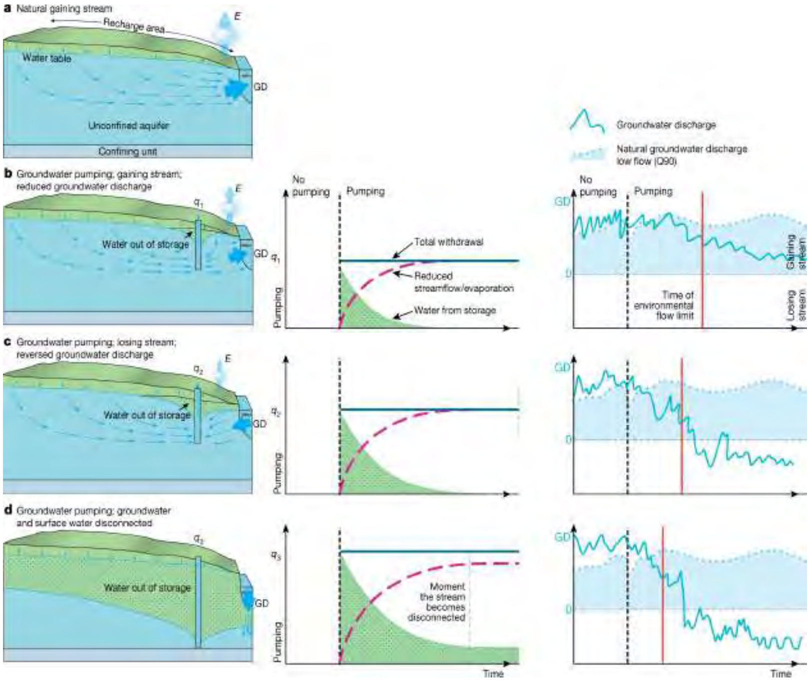


Source : Winter TC, Harvey JW, Franke OL, Alley WM (1998) Ground water and surface water: a single resource. U.S. Geological Survey Circular 1139:79

Environmental flow limits to groundwater pumping

- Declines in groundwater level resulting from pumping decrease streamflow, affecting aquatic ecosystems.
- Pumping when environmentally critical streamflows will no longer be sustained.

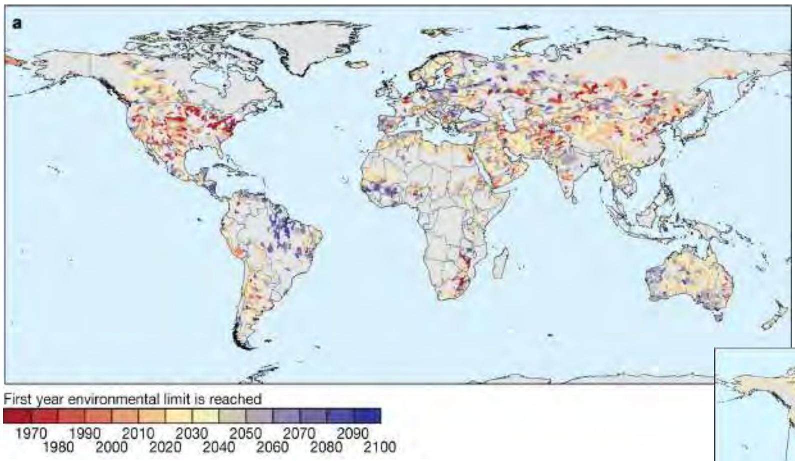




Source: de Graaf, I.E.M., Gleeson, T., (Rens) van Beek, L.P.H. et al. Environmental flow limits to global groundwater pumping. Nature 574, 90–94 (2019). https://doi.org/10.1038/s41586-019-1594-4

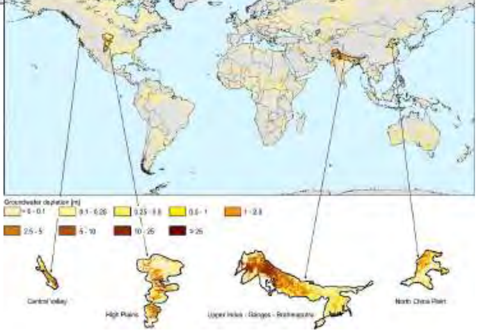
Groundwater crisis caused by unsustainable pumping

The first time at which environmental flow limits have been, or will be, reached



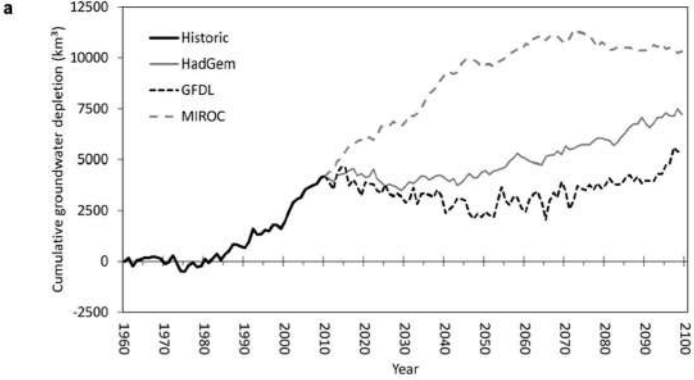
Source: de Graaf, I.E.M., Gleeson, T., (Rens) van Beek, L.P.H. et al. Environmental flow limits to global groundwater pumping. Nature 574, 90–94 (2019). https://doi.org/10.1038/s41586-019-1594-4

Gridded estimates of cumulative groundwater water depletion (in m3 per m2) for 1960–2099



Groundwater crisis caused by unsustainable pumping

Cumulative groundwater depletion (km^3) in historic and model simulation



Source: de Graaf, I.E.M., Gleeson, T., (Rens) van Beek, L.P.H. et al. Environmental flow limits to global groundwater pumping. Nature 574, 90–94 (2019). https://doi.org/10.1038/s41586-019-1594-4

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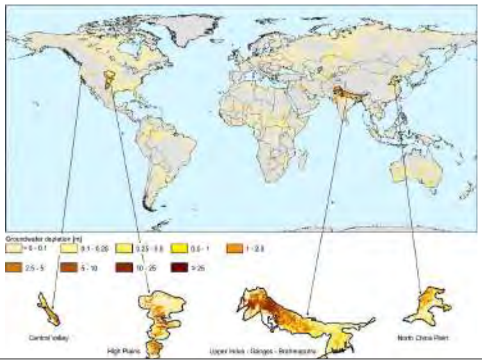
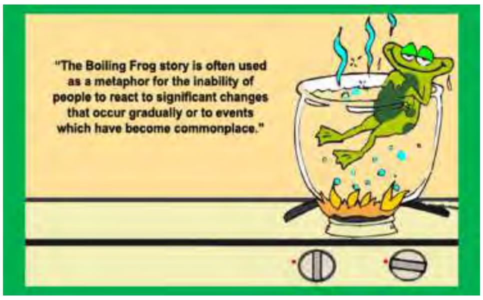


"the frog in the pot"



"The Boiling Frog story is often used as a metaphor for the inability of people to react to significant changes that occur gradually or to events which have become commonplace."

Source: https://www.linkedin.com/pulse/frog-pot-how-correlates-stress-management-stefan-trappitsch

Thank you very much

Managed Aquifer Recharge (MAR)

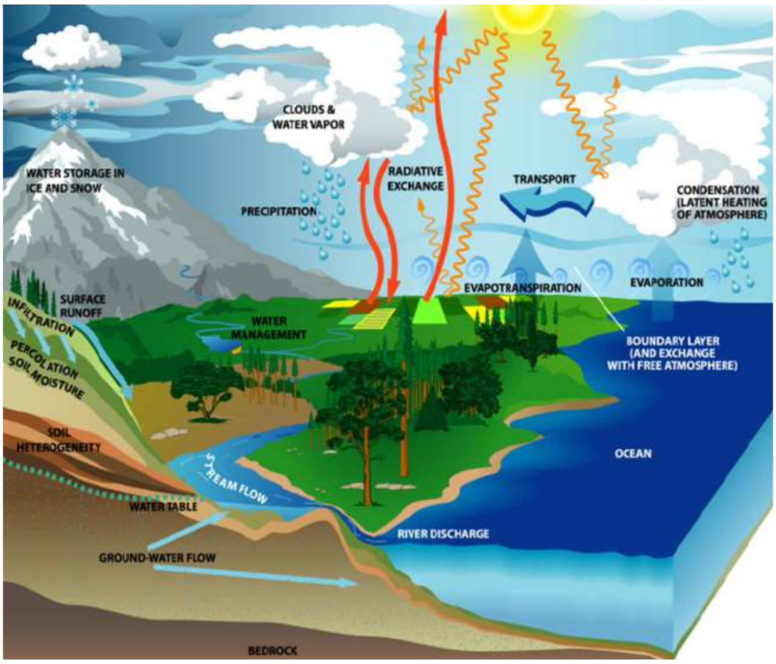
Groundwater

Managed Aquifer Recharge (MAR)

United Nations
Educational, Scientific and
Cultural Organization

i-WSSM
International Centre for
Water Security and
Sustainable Management

Groundwater in the cycle of water



Modern groundwater

(<50yrs old)

nature geoscience ARTICLES

PUBLISHED ONLINE: 16 NOVEMBER 2015 | DOI: 10.1038/NGEO2590

The global volume and distribution of modern groundwater

Tom Gleeson[1,2*], Kevin M. Befus[3], Scott Jasechko[4], Elco Luijendijk[2,5] and M. Bayani Cardenas[3]

- The total GW volume in the upper 2 km of continental curst is approx. 22.6 M km^3
- Modern GW (younger than 50 yrs old) volume is 0.35 M km^3 (1.6%)
- Volume of Modern GW is much larger than those of surface water, soil water, water in atmosphere and vegetation.

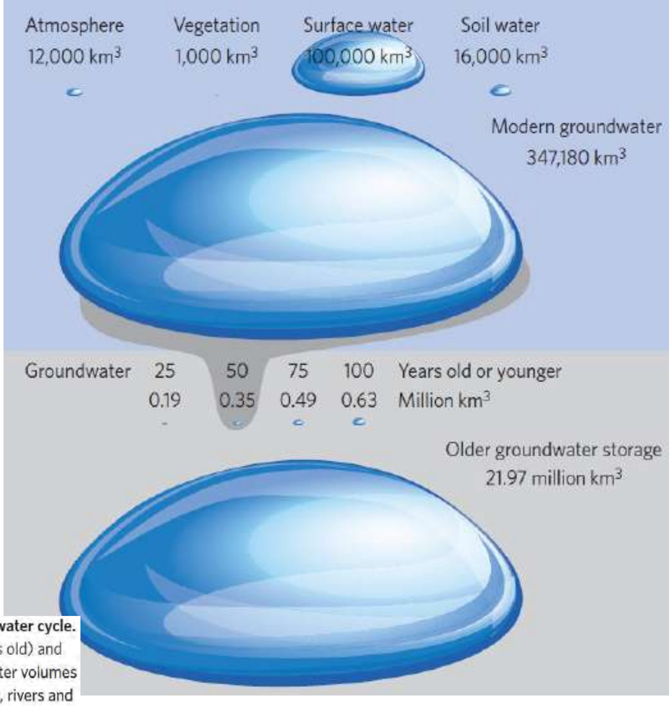
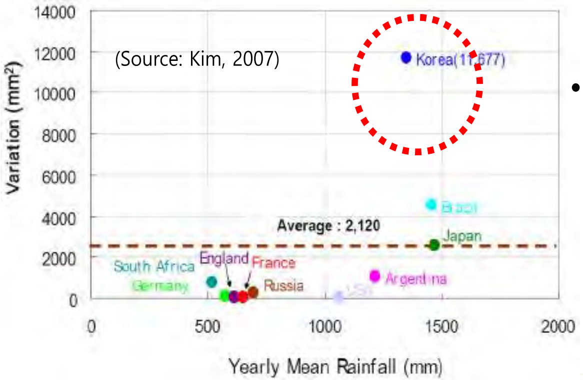


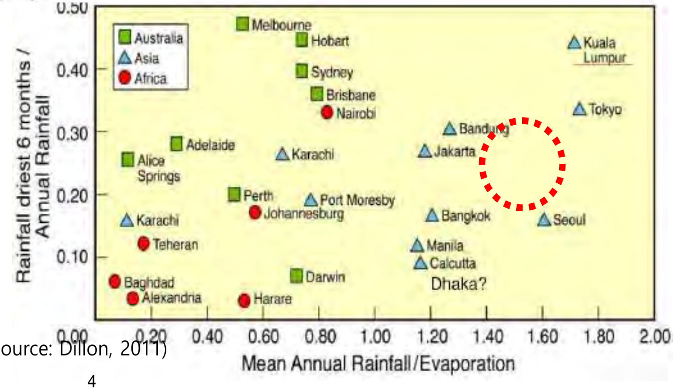
Figure 5 | The different volumes of water stored in the global water cycle. Global volumes of young (<100 years old), modern (<50 years old) and total groundwater to 2 km depth compared with other fresh water volumes stored in the atmosphere[33], in surface waters (that is, wetlands, rivers and lakes)[33], within plants or in soils[33].

Opportunity of MAR in Korea



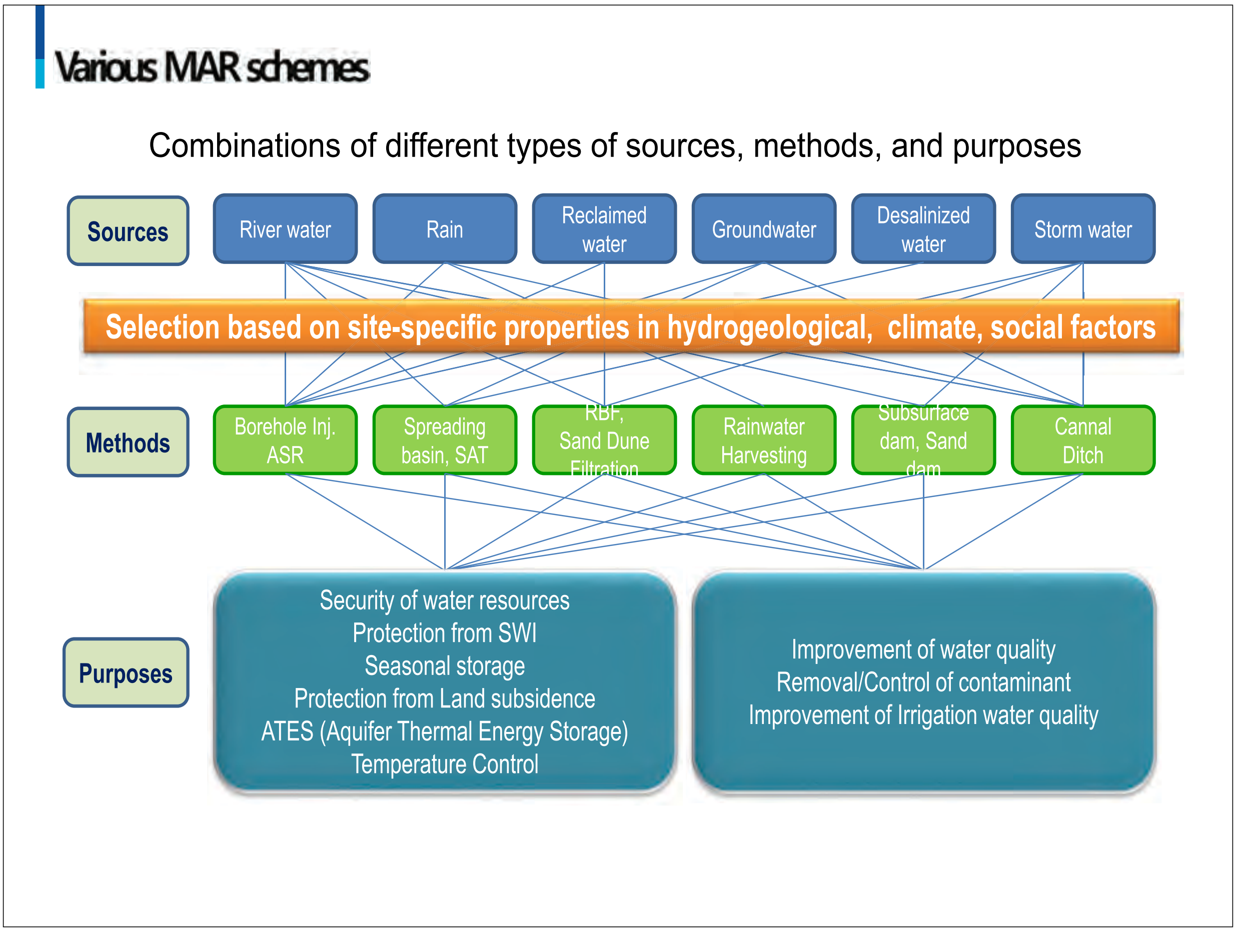
(Source: Kim, 2007)

- High variation in annual mean rainfall compared to other countries



- Necessity of seasonal storage due to high seasonal variation in PPT

(Source: Dillon, 2011)



Various MAR schemes

Combinations of different types of sources, methods, and purposes

Sources
River water
Rain
Reclaimed water
Groundwater
Desalinized water
Storm water

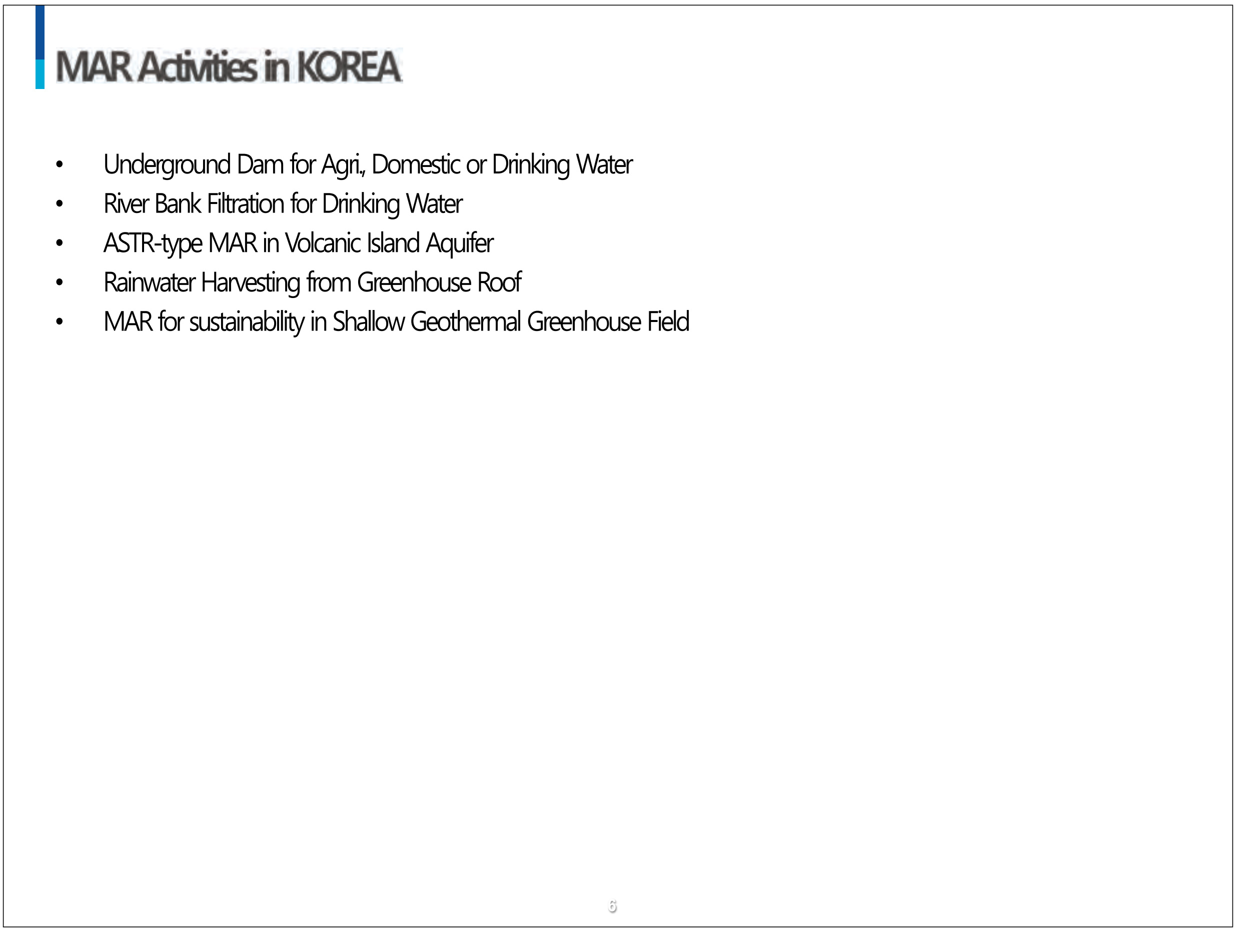
Selection based on site-specific properties in hydrogeological, climate, social factors

Methods
Borehole Inj. ASR
Spreading basin, SAT
RBF, Sand Dune Filtration
Rainwater Harvesting
Subsurface dam, Sand dam
Cannal Ditch

Purposes

Security of water resources
Protection from SWI
Seasonal storage
Protection from Land subsidence
ATES (Aquifer Thermal Energy Storage)
Temperature Control

Improvement of water quality
Removal/Control of contaminant
Improvement of Irrigation water quality

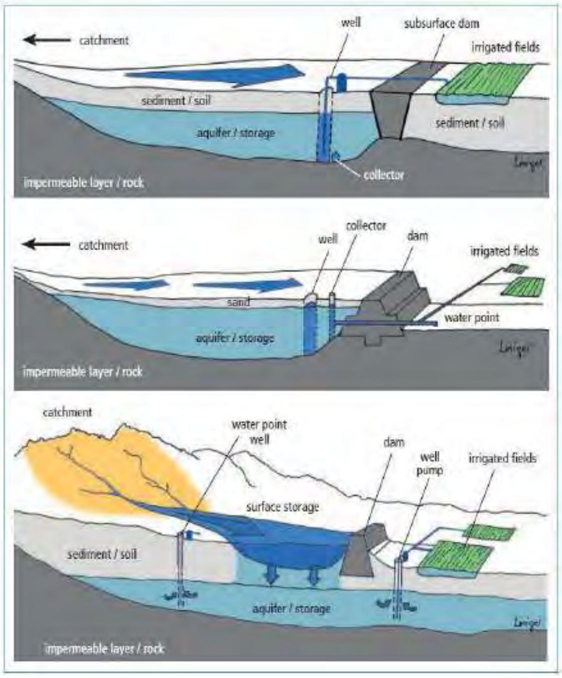


MAR Activities in KOREA

- Underground Dam for Agri., Domestic or Drinking Water
- River Bank Filtration for Drinking Water
- ASTR-type MAR in Volcanic Island Aquifer
- Rainwater Harvesting from Greenhouse Roof
- MAR for sustainability in Shallow Geothermal Greenhouse Field

Groundwater dams (Retention weirs)

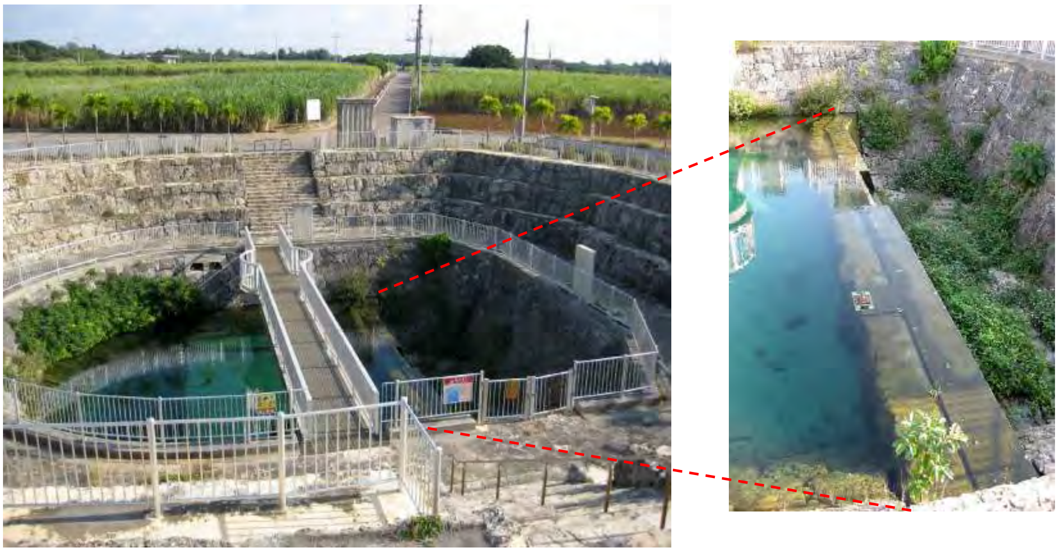
- Subsurface (underground) dam
  - built entirely underground into sandy riverbeds of seasonal water cours
- Sand dam
  - larger than subsurface dams and weirs as they can be raised to several
- Percolation dam
  - do not block ground water flow as the previous systems.
  - They serve three purposes: (a) to reduce the speed of surface flow, (b) i nents.



Source: https://www.geo.fu-berlin.de
Image credit: Mekdaschi & Liniger (2013)

Fukuzato underground dam, Japan

underground dam constructed in Miyakojima, Okinawa Prefecture



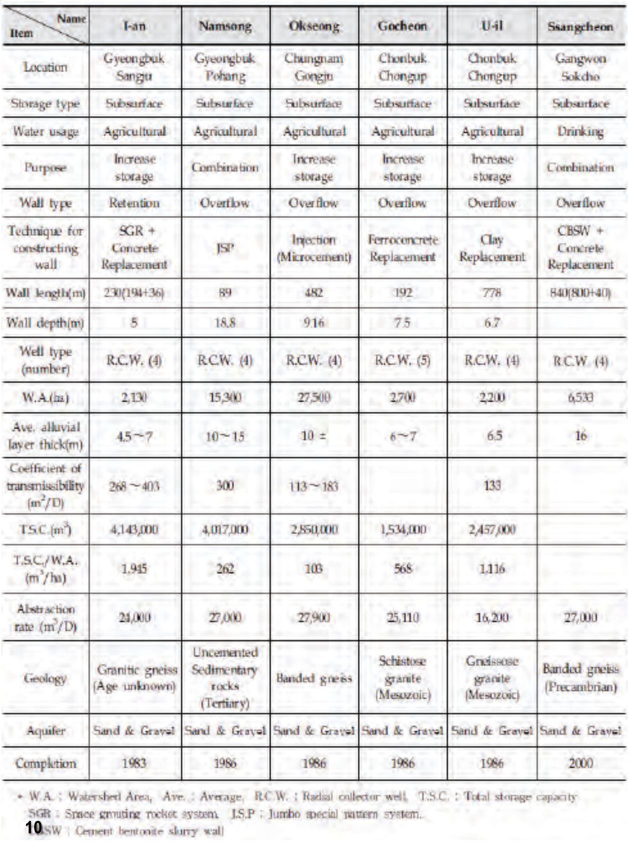
Source: Wikipedia.org

1. Agricultural use at Inland Area (KRC)

Location	Purposes	Watershed area(km^2)	Capacity (m^3/d)	Cut-off wall length (m)	Administration	Year
I-an (Sangju, KB)	Agricultural	21.3	24,000	230	KRC	1983
Namsong(Yungil, KB)	Agricultural	153.0	27,000	89	KRC	1986
Okseong (Kongju, CN)	Agricultural	275.0	27,900	482	KRC	1986
Gocheon (Jeongeup, JB)	Agricultural	27.0	25,110	192	KRC	1986
U-il (Jeongeup, JB)	Agricultural	22.0	16,200	778	KRC	1986
Ssangcheon (Sokcho, GW)	Domestic	65.3	43,000	800	KRC	2000

- Provinces (KB: Kyungbuk; CN: Chungnam; JB: Jeonbuk; GW: Gangwon)
- KRC: Korea Rural Community Corporation

1. Agricultural use at Inland Area (KRC)



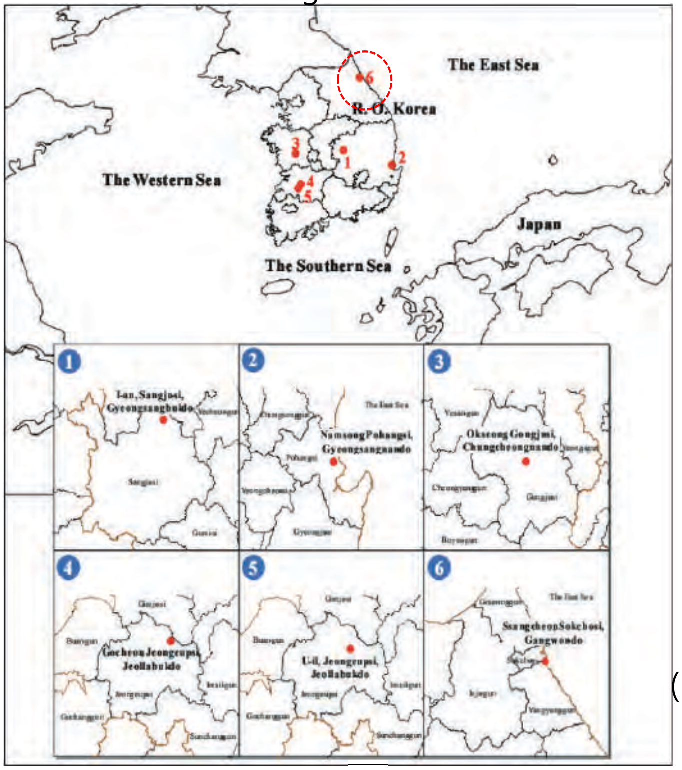
Item \ Name	I-an	Namsong	Okseong	Gocheon	U-il	Ssangcheon
Location	Gyeongbuk Sangju	Gyeongbuk Pohang	Chungnam Gongju	Chonbuk Chongup	Chonbuk Chongup	Gangwon Sokcho
Storage type	Subsurface	Subsurface	Subsurface	Subsurface	Subsurface	Subsurface
Water usage	Agricultural	Agricultural	Agricultural	Agricultural	Agricultural	Drinking
Purpose	Increase storage	Combination	Increase storage	Increase storage	Increase storage	Combination
Wall type	Retention	Overflow	Overflow	Overflow	Overflow	Overflow
Technique for constructing wall	SGR + Concrete Replacement	JSP	Injection (Microcement)	Ferroconcrete Replacement	Clay Replacement	CBSW + Concrete Replacement
Wall length(m)	230(194+36)	89	482	192	778	840(800+40)
Wall depth(m)	5	18.8	9.16	7.5	6.7	
Well type (number)	R.C.W. (4)	R.C.W. (4)	R.C.W. (4)	R.C.W. (5)	R.C.W. (4)	R.C.W. (4)
W.A.(ha)	2,130	15,300	27,500	2,700	2,200	6,533
Ave. alluvial layer thick(m)	4.5~7	10~15	10 ±	6~7	6.5	16
Coefficient of transmissibility (m^2/D)	268 ~ 403	300	113 ~ 183		133	
T.S.C.(m^3)	4,143,000	4,017,000	2,850,000	1,534,000	2,457,000	
T.S.C./W.A. (m^3/ha)	1,945	262	103	568	1,116	
Abstraction rate (m^3/D)	24,000	27,000	27,900	25,110	16,200	27,000
Geology	Granitic gneiss (Age unknown)	Uncemented Sedimentary rocks (Tertiary)	Banded gneiss	Schistose granite (Mesozoic)	Gneissose granite (Mesozoic)	Banded gneiss (Precambrian)
Aquifer	Sand & Gravel	Sand & Gravel	Sand & Gravel	Sand & Gravel	Sand & Gravel	Sand & Gravel
Completion	1983	1986	1986	1986	1986	2000

* W.A. : Watershed Area, Ave. : Average, R.C.W. : Radial collector well, T.S.C. : Total storage capacity
SGR : Space grouting rocket system, J.S.P : Jumbo special pattern system,
SW : Cement bentonite slurry wall

(Source: KRC, 2006)

1. Agricultural use at Inland Area (KRC)

Location of Underground Dams in Korea

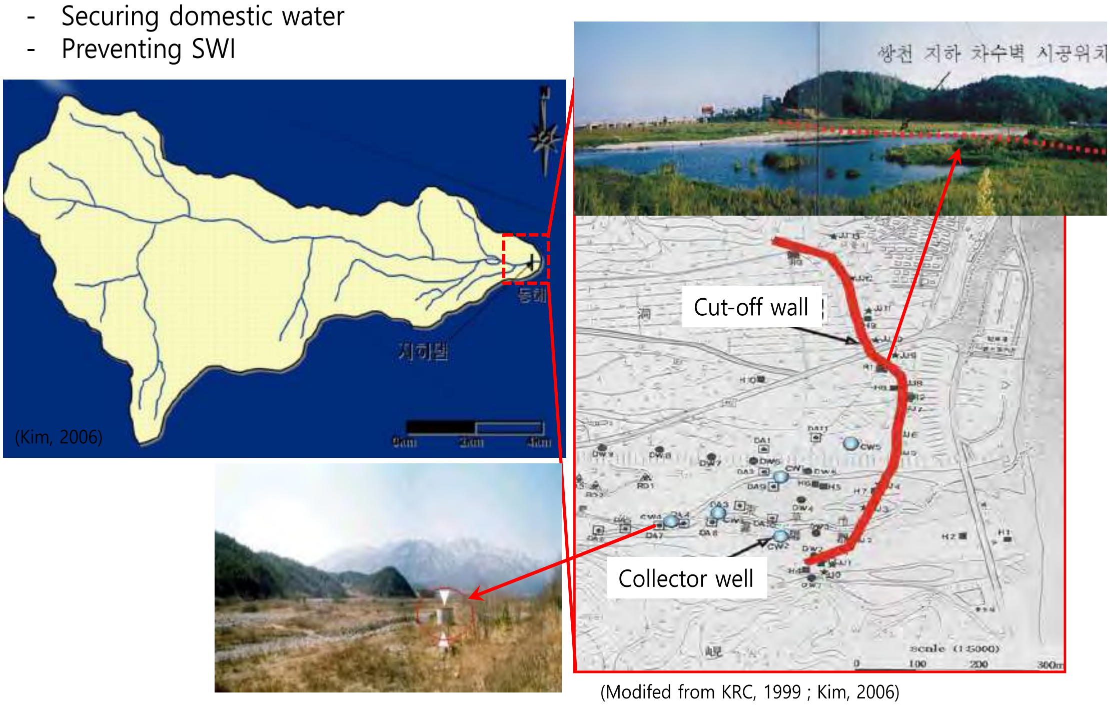


(MIST,2004)

1. Agricultural use at Inland Area (KRC)

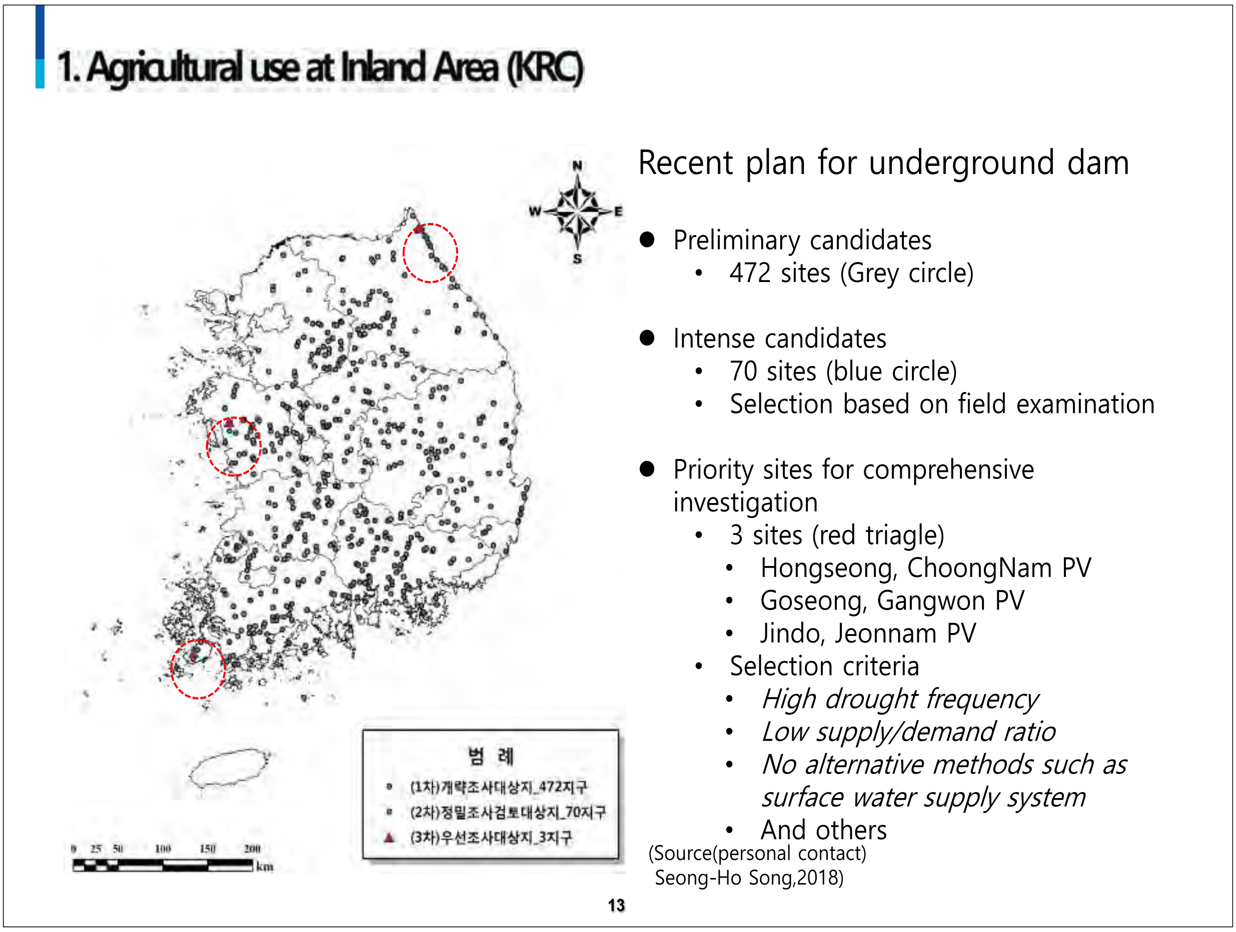
Ssangcheon Underground Dam

- Securing domestic water
- Preventing SWI



(Kim, 2006)

(Modifed from KRC, 1999 ; Kim, 2006)



1. Agricultural use at Inland Area (KRC)

Recent plan for underground dam

- Preliminary candidates
  - 472 sites (Grey circle)
- Intense candidates
  - 70 sites (blue circle)
  - Selection based on field examination
- Priority sites for comprehensive investigation
  - 3 sites (red triagle)
    - Hongseong, ChoongNam PV
    - Goseong, Gangwon PV
    - Jindo, Jeonnam PV
  - Selection criteria
    - *High drought frequency*
    - *Low supply/demand ratio*
    - *No alternative methods such as surface water supply system*
    - And others

(Source(personal contact)
Seong-Ho Song,2018)

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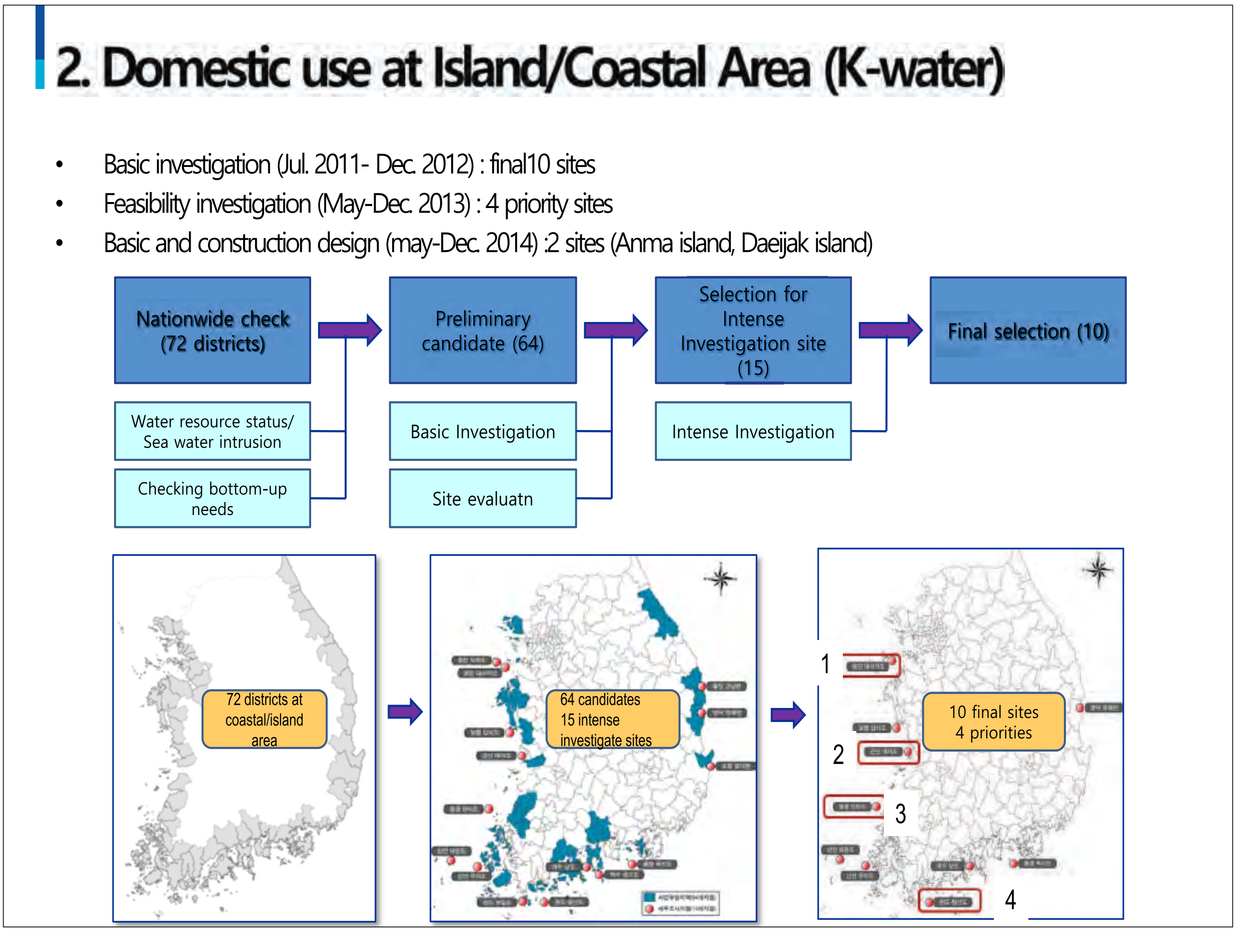


2. Domestic use at Island/Coastal Area (K-water)

- Basic investigation (Jul. 2011- Dec. 2012) : final10 sites
- Feasibility investigation (May-Dec. 2013) : 4 priority sites
- Basic and construction design (may-Dec. 2014) :2 sites (Anma island, Daeijak island)

Nationwide check (72 districts) → Preliminary candidate (64) → Selection for Intense Investigation site (15) → Final selection (10)

Water resource status/ Sea water intrusion

Checking bottom-up needs

Basic Investigation

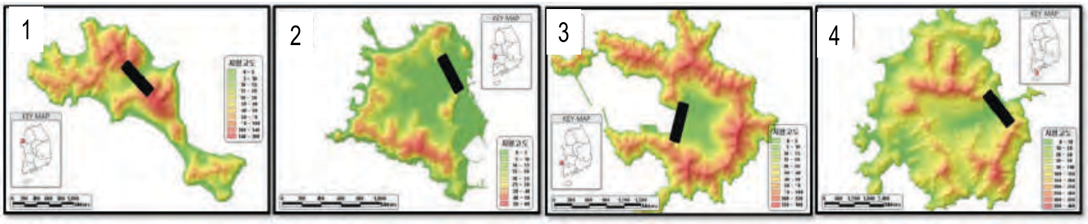
Site evaluatn

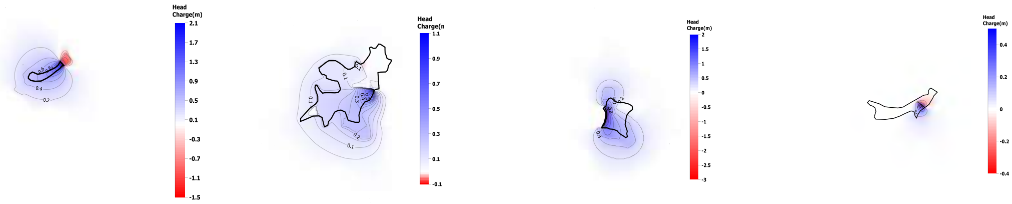
Intense Investigation

2. Domestic use at Island/Coastal Area (K-water)

- 4 Priority sites (Group A)

Location	Demands by 2025 (m³/d)	Watershed area (km²)	Supply/ Capacity (m³/d)	Cut-off method	wall length/ depth (m)	No. of Intake Wells
1. Daeijak-do	**-109**	**0.35**	**110 / 180**	**Open cut**	**80 / 11.3**	**3**
2. Gaeya-do	-129		130	Inj. Well (3-line)	271 / 23	5
3. Anma-do	**-93**	**1.17**	**100**	**Inj. Well (3-line)**	**480 / 31**	**6**
4. Cheongsan-do	-323		330	Inj. Well (3-line)	400 / 25	10





2. Domestic use at Island/Coastal Area (K-water)

1. Daeijak-do


3 Intake wells
Q=60m³/d/well

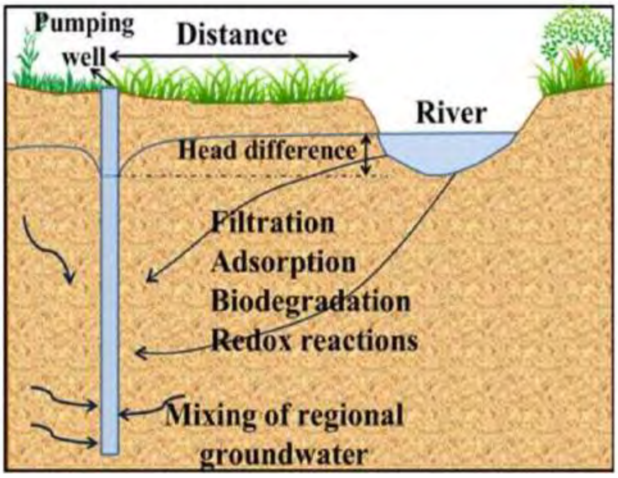
Cut-off wall
L=60m

2. Domestic use at Island/Coastal Area (K-water)

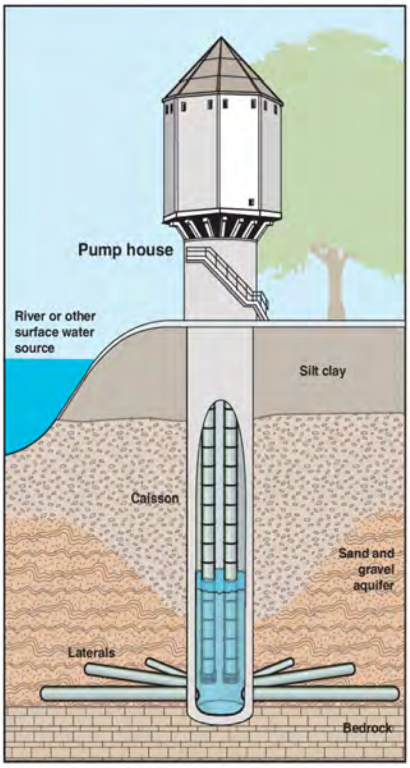
3. Anma-do

River bank filtration

A technology that operates
by pumping out water from boreholes
drilled along the banks of a river or lake



Mauro & Utari, 2011 (Water Practice and Technology (2011) 6 (4): wpt20110073.)



Schematic courtesy of Reynolds Inc., Orleans, Ind.

PARTINOUDI, VASILIKI & Collins, Michael. (2007)

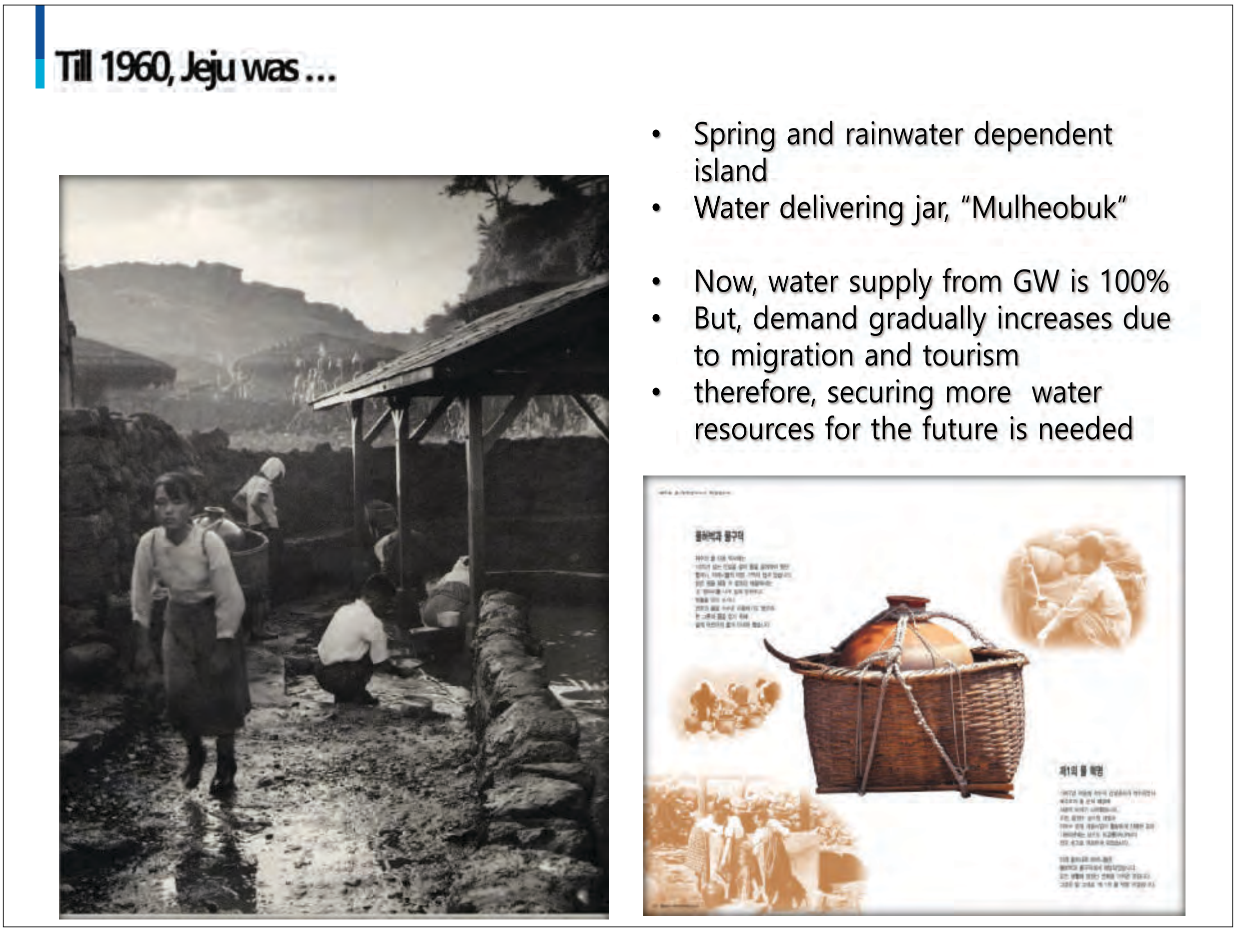
River bank filtration in Korea

- 18 sites (as of 2016)
  - Radial : vertical : others = 12 (67%) : 4 (22%) : 2
- Total facility capacity: 1,106,210 m^3/d
  - Radial : vertical : others = 926 (84%) : 110 (10%) : 70
- Pumping capacity per well (m^3/d)
  - Radial (16,500), vertical (1,400)
- Purposes
  - Water works(7), agriculture(5), stream discharge(3), others (2)
- Watershed
  - Han-river (5 sites, 188,000m^3/d)
  - Nakdong-river (6 sites, 709,000 m^3/d)

River bank filtration in Korea

- First RBF : domestic water supply for a military base from Han-river bank at Seoul in 1970's
  - 20 Vertical wells / 10,000 m^3/d
- Largest facility:
  - 351,000 (Changneung-Jeungsan phase 1)
- Most active MAR method in Korea

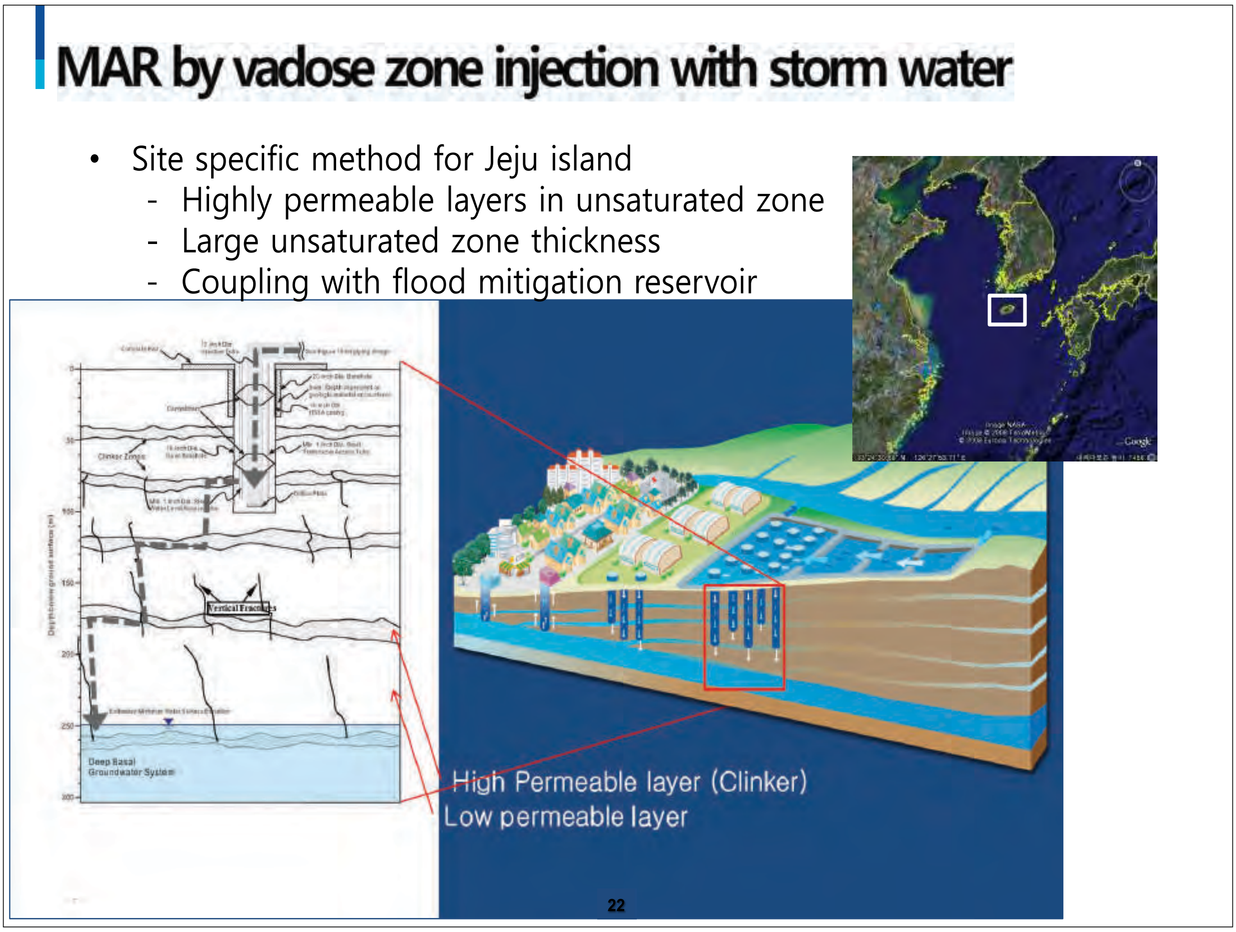
Source: https://cnews.co.kr/uhtml/read.jsp?idxno=201112271107425210440&section=S1N10



Till 1960, Jeju was ...

- Spring and rainwater dependent island
- Water delivering jar, "Mulheobuk"

- Now, water supply from GW is 100%
- But, demand gradually increases due to migration and tourism
- therefore, securing more water resources for the future is needed



MAR by vadose zone injection with storm water

- Site specific method for Jeju island
  - Highly permeable layers in unsaturated zone
  - Large unsaturated zone thickness
  - Coupling with flood mitigation reservoir

High Permeable layer (Clinker)
Low permeable layer

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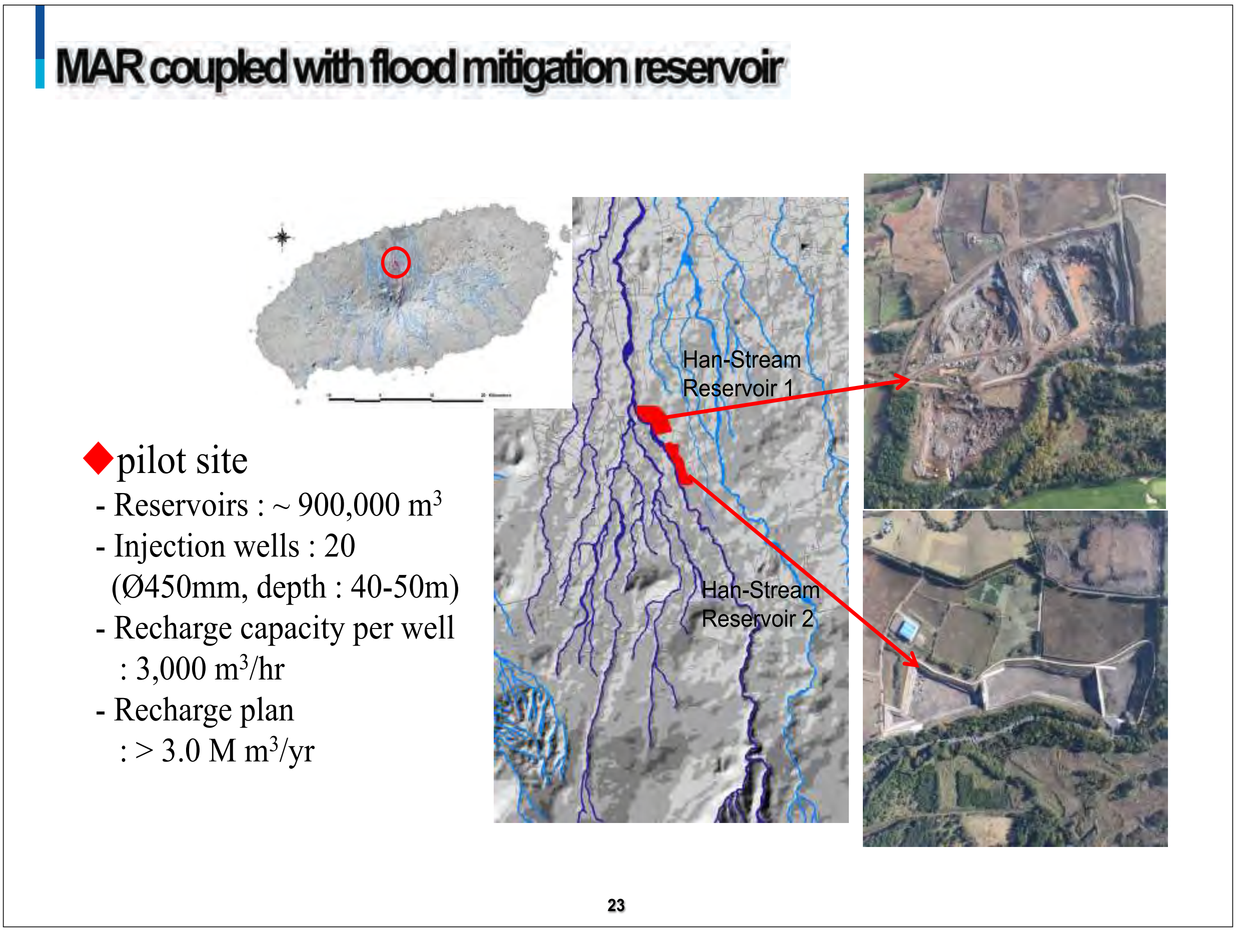
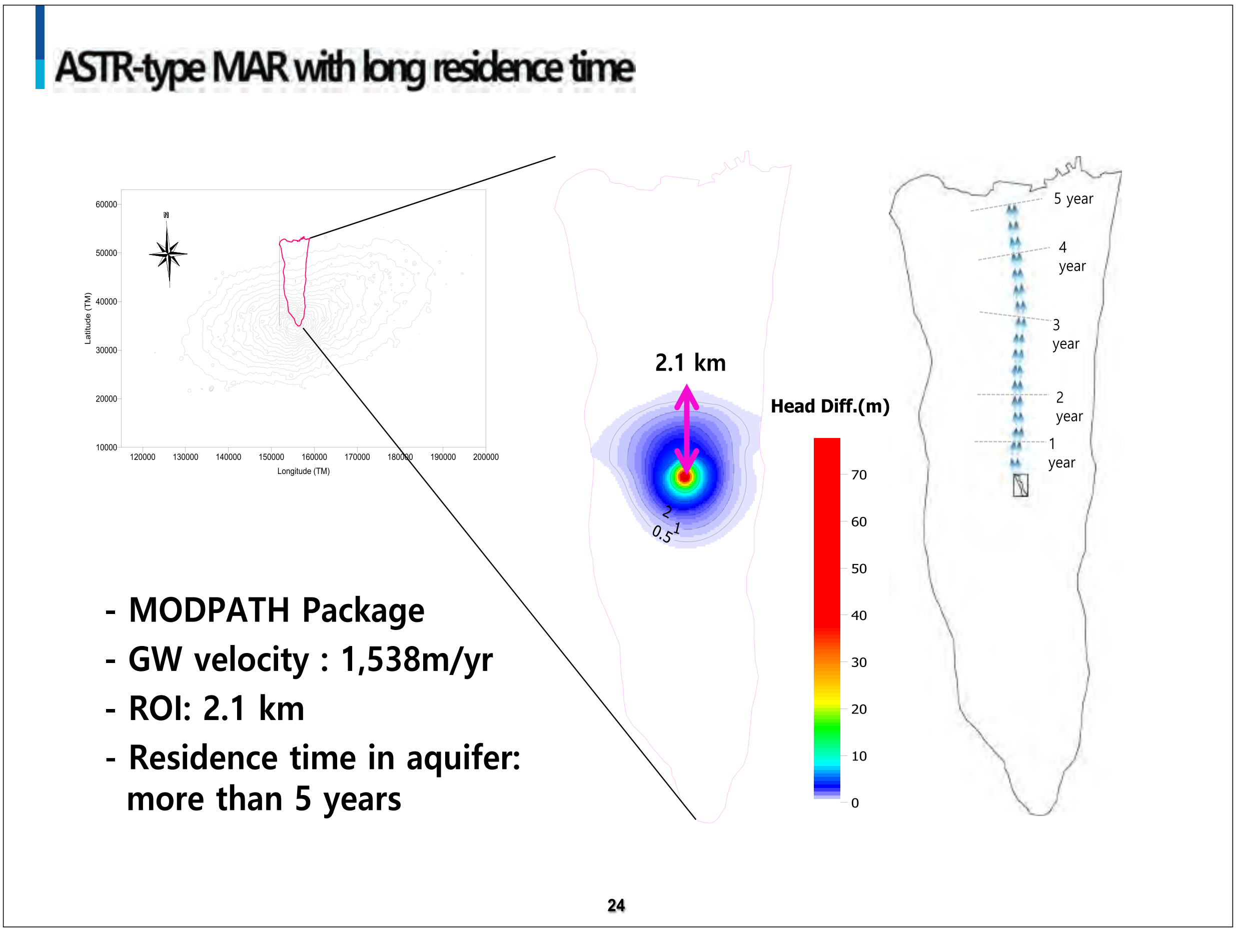


MAR coupled with flood mitigation reservoir

◆pilot site
- Reservoirs : ~ 900,000 m^3
- Injection wells : 20
  (Ø450mm, depth : 40-50m)
- Recharge capacity per well
  : 3,000 m^3/hr
- Recharge plan
  : > 3.0 M m^3/yr



ASTR-type MAR with long residence time

- **MODPATH Package**
- **GW velocity : 1,538m/yr**
- **ROI: 2.1 km**
- **Residence time in aquifer: more than 5 years**

MAR for GW security and flood control

- In 2010, total 2,500,000 m^3 of water had been injected through bottom infiltration.
- Through reservoir bottom infiltration, the flood mitigation reservoir can be increased its capacity up to 300,000 m^3/day (33% of reservoir capacity increase) without further construction.

Rainwater harvesting in Jeju Island

- Since 2004
- Facilities: 176
- Recharge amount : 1,276,000 m^3 in 2011

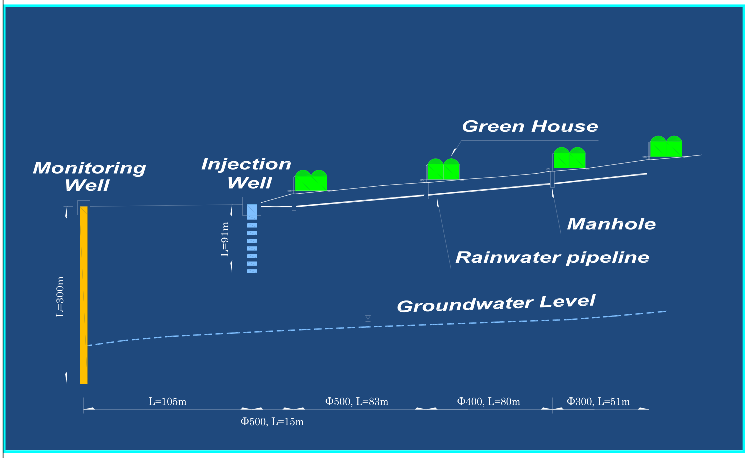
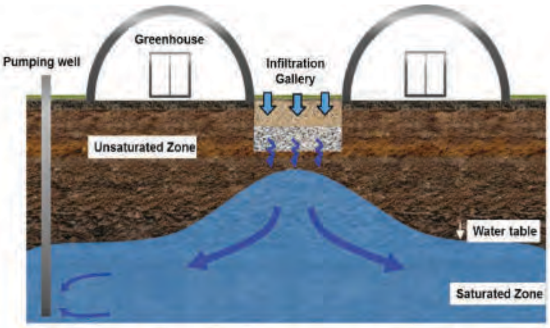
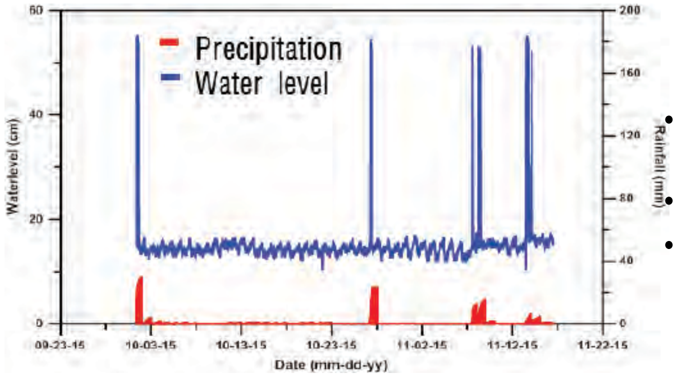


Photo by Kiwon Koh

Rainwater harvesting at a separated greenhouses



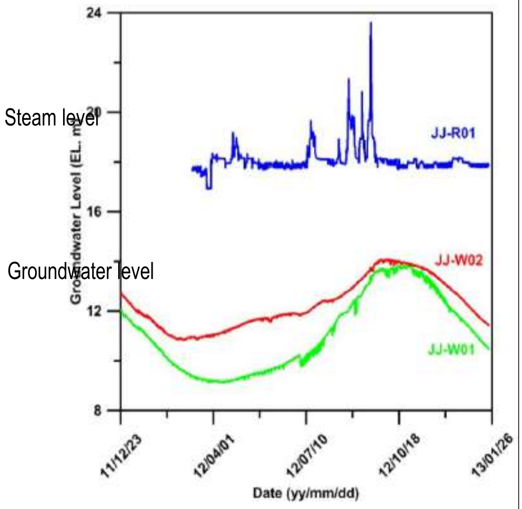


- Recharge through infiltration gallery btw greenhouses
- Pilot research
- Recharge amount : 28% of rainfall

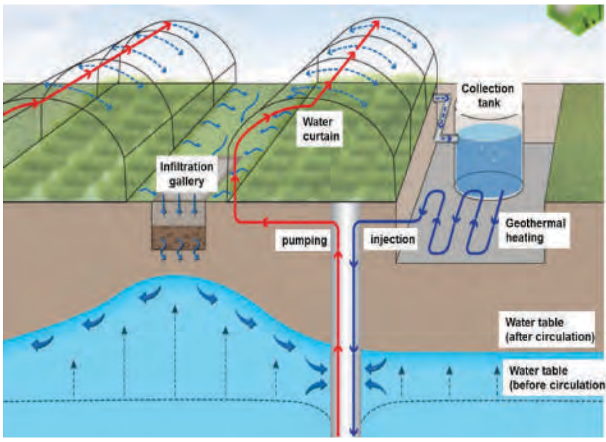
MAR for Sustainability in greenhouse complex

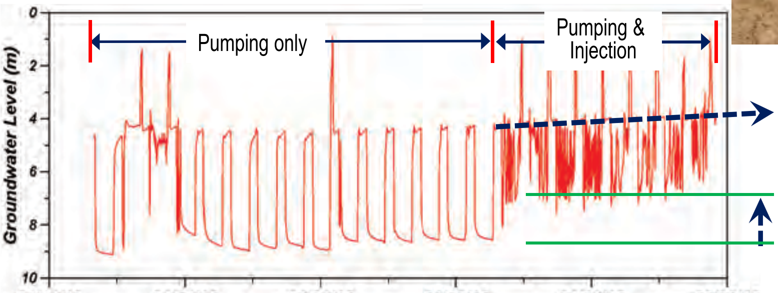
- Water curtain insulated greenhouse complex

- Losing stream by groundwater level decline



MAR for Sustainability in greenhouse complex



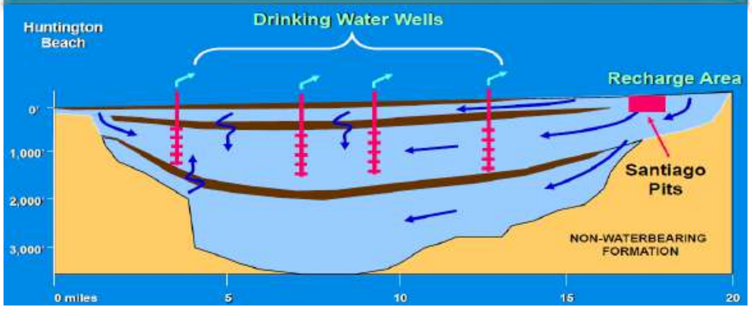


Rising water level
: 4.2 -> 3.6 m BGL

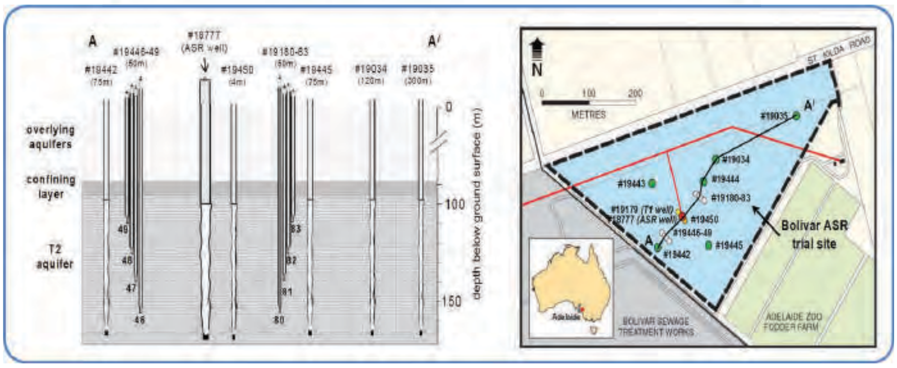
Increase in min. level
: 8.5 -> 6.3 m BGL

MAR using reclaimed water

Groundwater Replenishment System, California, USA

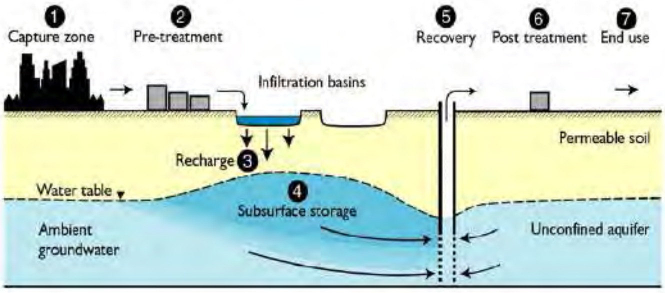


Bolivar ASR systems, Australia



MAR using reclaimed water

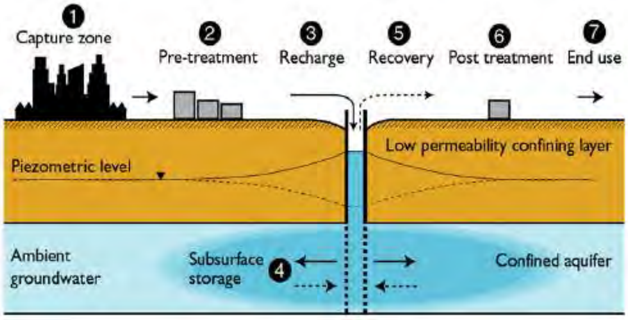
Unconfined aquifer (SAT; soil aquifer treatment)



As the effluent moves through the soil and the aquifer, it can undergo significant quality improvements through physical, chemical and biological processes - Attenuation

The water is stored in the underlying unconfined aquifer generally for subsequent reuse, such as irrigation. This is a valuable water resources management method in areas with high evaporation rates.

Confined aquifer



In confined conditions, artificial recharge has in general to be achieved using infiltration wells as the potentiometric groundwater surface is above the confining layer

Australian guidelines for Water recycling, 24: Managed Aquifer Recharge (2009)

SAT

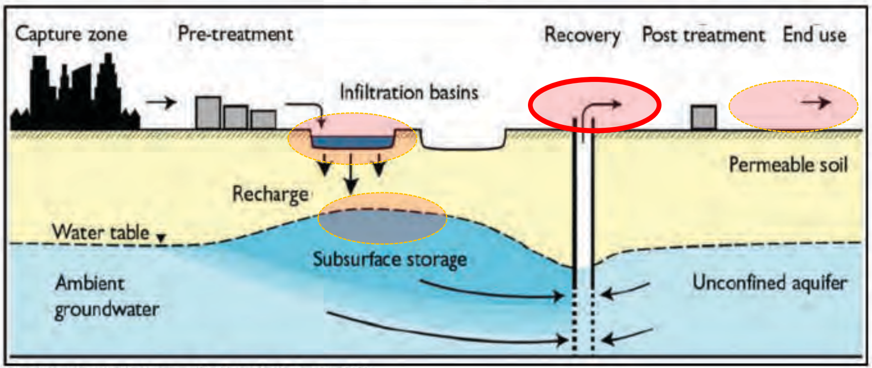
- **If Point of Compliance is at the extraction point**

Pessimistic

Neglecting the main advantage of MAR = degradation processes in subsurface
‚worst case scenario‘: infiltrated water conc = extracted water conc < legal limit for use

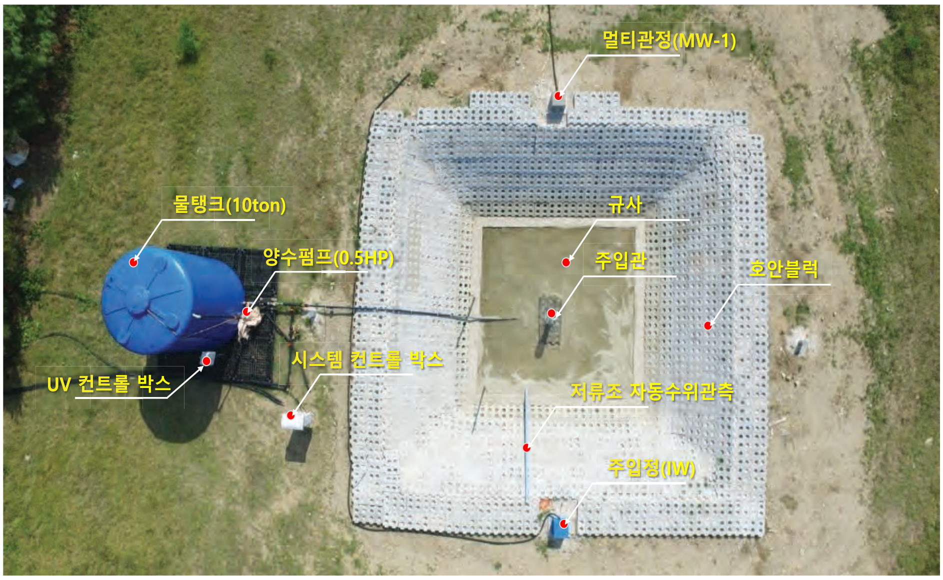
Optimistic

Defined minimum degradation in the subsurface to meet regulations at recovery
‚maximum faith scenario‘: infiltrated water conc > extracted water conc < legal limit for use

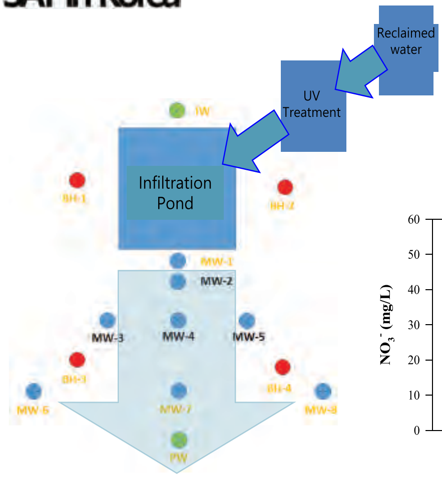


Australian guidelines for Water recycling, 24: Managed Aquifer Recharge (2009)

SAT in Korea

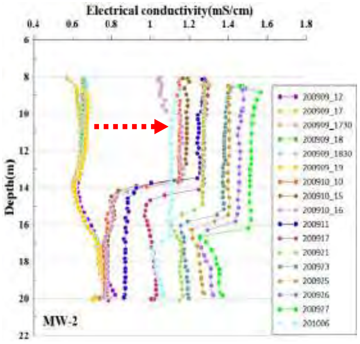


SAT in Korea

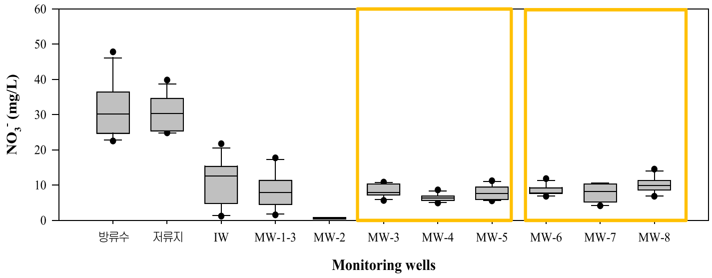

Reclaimed water

UV Treatment

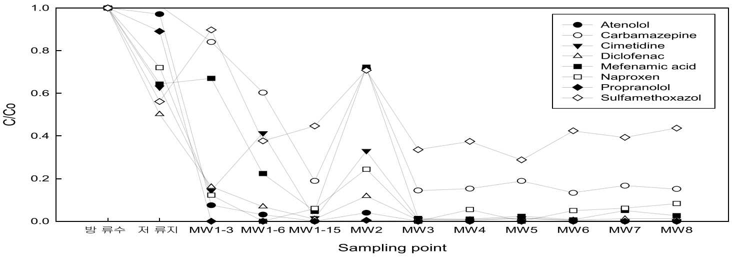
Infiltration Pond

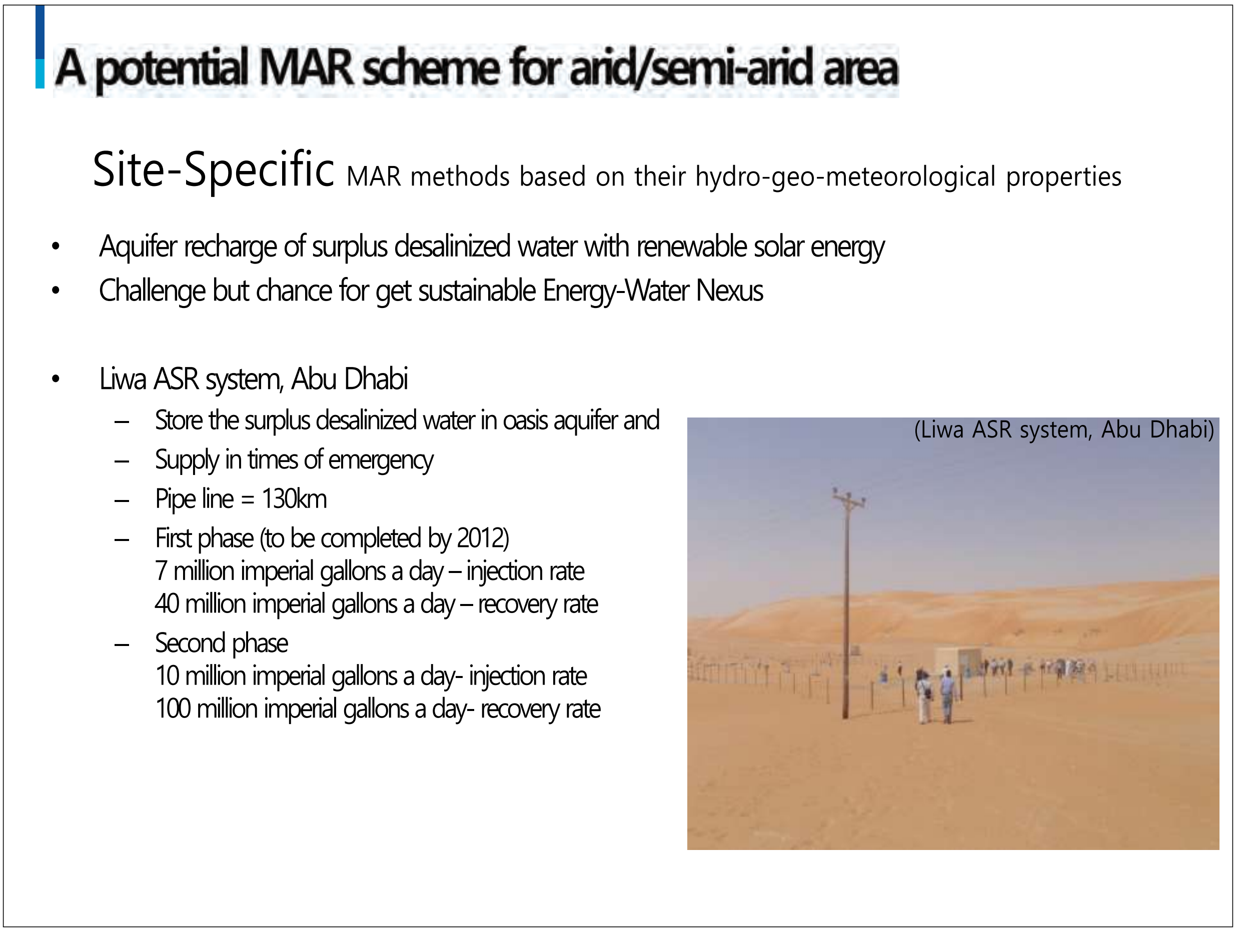


Nitrate reduction



Emerging contaminants





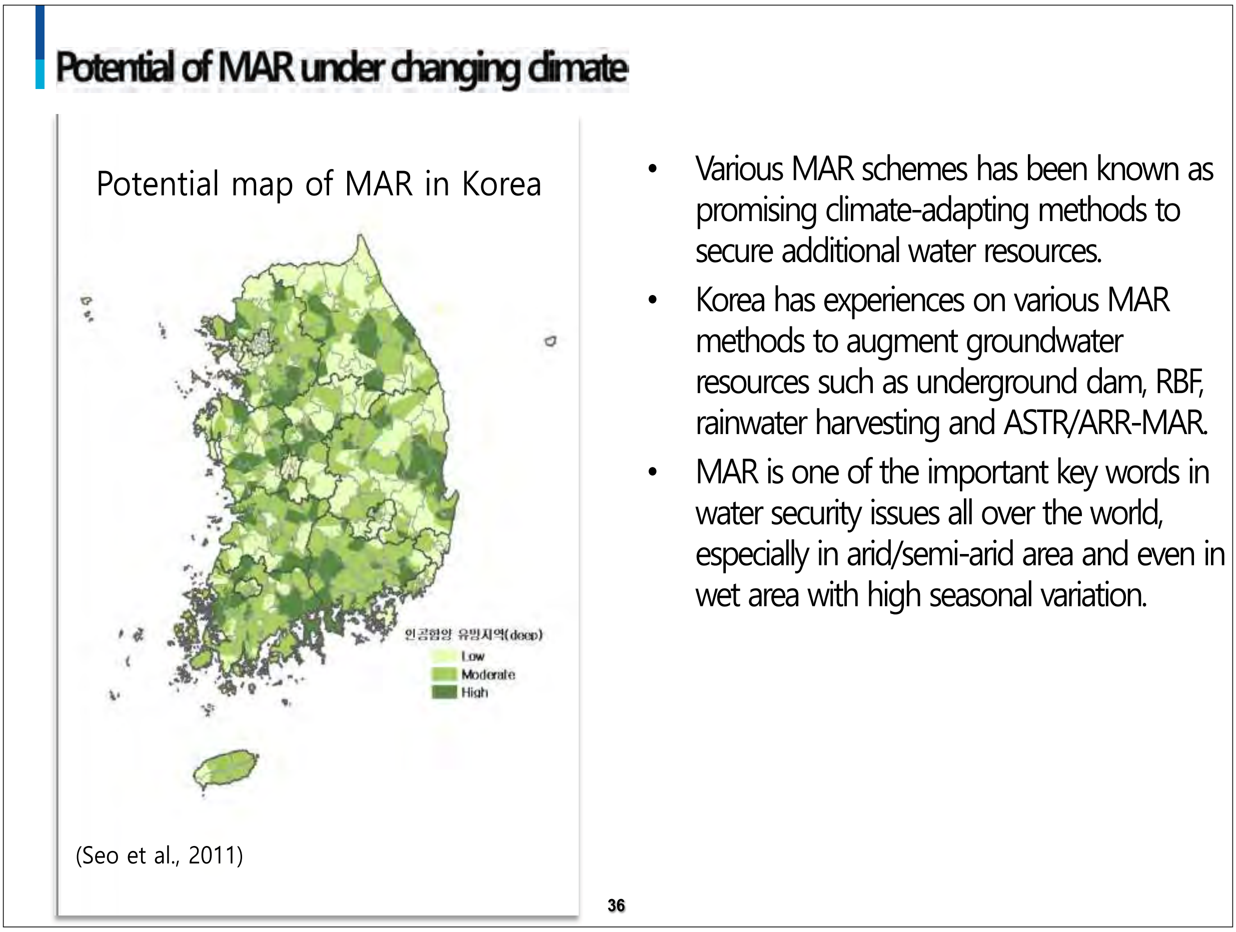
A potential MAR scheme for arid/semi-arid area

Site-Specific MAR methods based on their hydro-geo-meteorological properties

- Aquifer recharge of surplus desalinized water with renewable solar energy
- Challenge but chance for get sustainable Energy-Water Nexus

- Liwa ASR system, Abu Dhabi
  - Store the surplus desalinized water in oasis aquifer and
  - Supply in times of emergency
  - Pipe line = 130km
  - First phase (to be completed by 2012)
    7 million imperial gallons a day – injection rate
    40 million imperial gallons a day – recovery rate
  - Second phase
    10 million imperial gallons a day- injection rate
    100 million imperial gallons a day- recovery rate

(Liwa ASR system, Abu Dhabi)



Potential of MAR under changing climate

Potential map of MAR in Korea

(Seo et al., 2011)

- Various MAR schemes has been known as promising climate-adapting methods to secure additional water resources.
- Korea has experiences on various MAR methods to augment groundwater resources such as underground dam, RBF, rainwater harvesting and ASTR/ARR-MAR.
- MAR is one of the important key words in water security issues all over the world, especially in arid/semi-arid area and even in wet area with high seasonal variation.

Thank you very much

Hydraulic Properties and Parameters of Aquifer

Groundwater

Hydraulic Properties and Parameters of Aquifer

Aquifer terminology and aquifer types

- **Aquiclude (confining unit, confining bed)**

a water-bearing layer of rock or sediment that is incapable of transmitting water

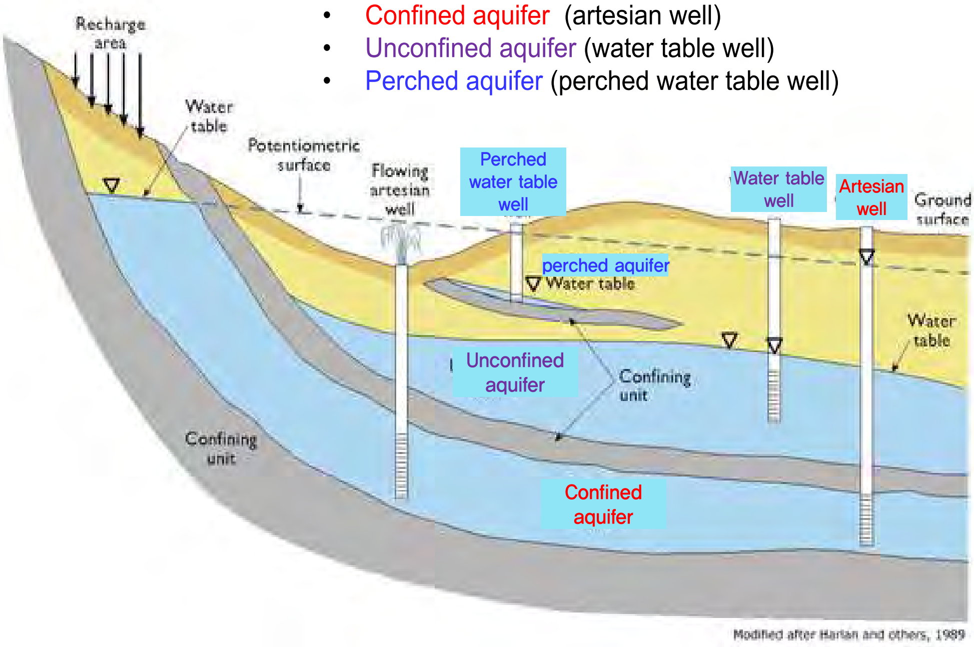
- **Aquifer**

a water-bearing layer of rock or sediment that is capable of transmitting significant quantities of water

- **Aquitard (confining unit, confining bed)**

a water-bearing layer of rock or sediment that transmits small quantities of water in relation to aquifer

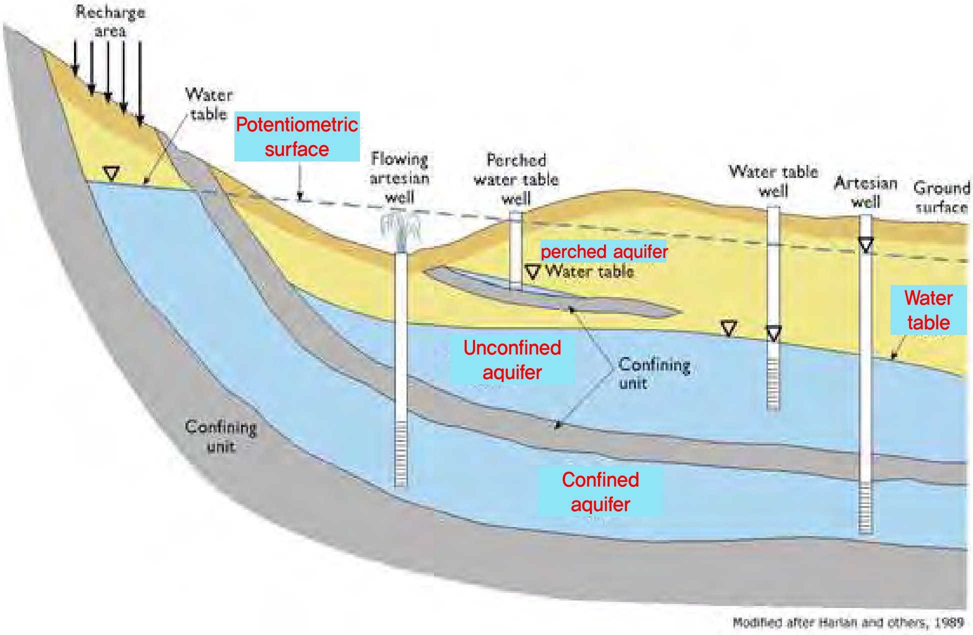
- Confined aquifer (artesian well)
- Unconfined aquifer (water table well)
- Perched aquifer (perched water table well)



Modified after Harlan and others, 1989

aquifer and groundwater surface

- **Confined aquifer:** an aquifer whose upper and lower boundaries are defined by aquicludes.
- **Drawdown:** the amount of water level decline in a well due to pumping. Usually measured relative to static level
- **Unconfined aquifer:** an aquifer in which the water table forms the upper boundary
- **Potentiometric surface:** an imaginary surface to which water would rise in wells from a given point in confined aquifer. The water table is a particular potentiometric surface for unconfined aquifers.

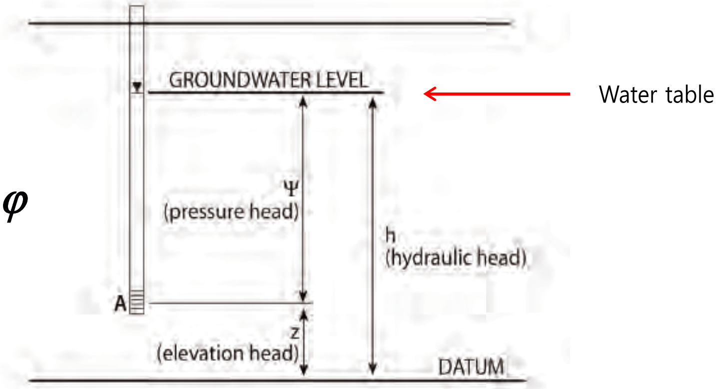


Modified after Harlan and others, 1989

Hydraulic Head

- Potential energy driving groundwater movement normalized by specific gravity

$$h = z + \varphi$$



Source: Maureen Feineman, Pennsylvania State University

Water table : where pore water pressure is equal to atmospheric pressure

- above water table : unsaturated or partially saturated zone (negative pressure)
- below water table : saturated zone (positive pressure)
- capillary fringe : area immediately above water table

Hydraulic Conductivity (K)

- A measure of the ability of a substance (usually soil) to transmit water
- **Hydraulic conductivity is a function of fluid and media**

$$K = \frac{Nd^2 \rho_f g}{\eta}$$

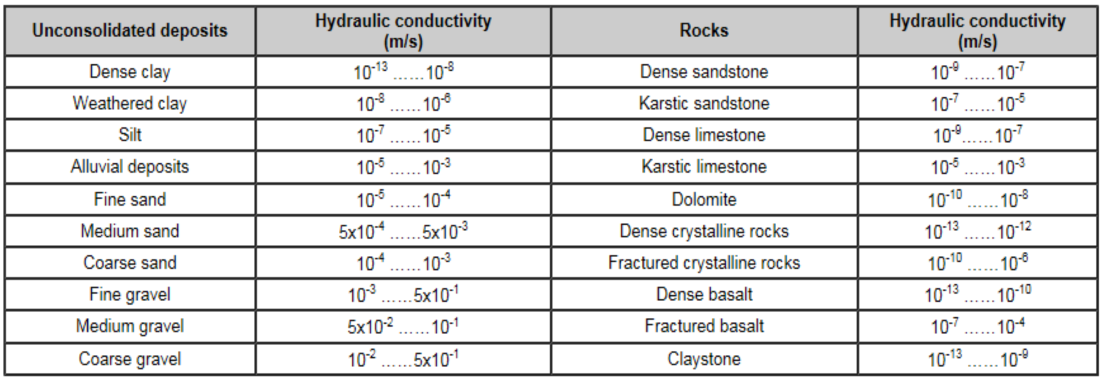
K : hydraulic conductivity (L/T)
ρ_f: fluid density
g : gravitational acceleration
η : dynamic viscosity (M/LT)
d : mean grain diameter (L)
N : dimensionless factor depending on the shape of pore spac

- Permeability
- Q ~ d^2 (grain diameter)
- Q~ γ (fluid specific weight)
- Q ~ 1/μ (fluid viscosity)
- Q = (Cd^2 γ A / μ) (dh/dl)
- k = Cd^2 (intrinsic permeability, C=shape factor of grain)
- **Intrinsic permeability is a function of only media**

Hydraulic Conductivity

- Conventional Values of Hydraulic Conductivity

Table 5.1. Ranges of hydraulic conductivities



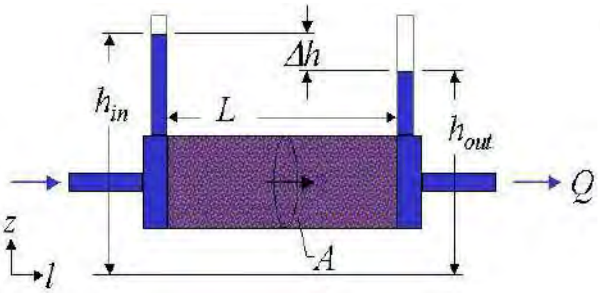
Unconsolidated deposits	Hydraulic conductivity (m/s)	Rocks	Hydraulic conductivity (m/s)
Dense clay	10^{-13} ......10^{-8}	Dense sandstone	10^{-9} ......10^{-7}
Weathered clay	10^{-8} ......10^{-6}	Karstic sandstone	10^{-7} ......10^{-5}
Silt	10^{-7} ......10^{-5}	Dense limestone	10^{-9}......10^{-7}
Alluvial deposits	10^{-5} ......10^{-3}	Karstic limestone	10^{-5} ......10^{-3}
Fine sand	10^{-5} ......10^{-4}	Dolomite	10^{-10} ......10^{-8}
Medium sand	$5x10^{-4}$ ......$5x10^{-3}$	Dense crystalline rocks	10^{-13} ......10^{-12}
Coarse sand	10^{-4} ......10^{-3}	Fractured crystalline rocks	10^{-10} ......10^{-6}
Fine gravel	10^{-3} ......$5x10^{-1}$	Dense basalt	10^{-13} ......10^{-10}
Medium gravel	$5x10^{-2}$ ......10^{-1}	Fractured basalt	10^{-7} ......10^{-4}
Coarse gravel	10^{-2} ......$5x10^{-1}$	Claystone	10^{-13} ......10^{-9}

http://echo2.epfl.ch/VICAIRE/mod_3/chapt_5/main.htm

Darcy's Law

- Basic Theorem in Groundwater Physics :

Volumetric flow rate is proportional to the difference of hydraulic heads, cross-sectional area and reciprocal of length



Q : Volumetric Flow Rate (L^3/T)
A : Cross-sectional Area (L^2)
K : Hydraulic Conductivity (L/T)
L : Length of Column (L)
h : Hydraulic Head (L)

$$Q = KA\frac{h_{out} - h_{in}}{L}$$

Henry Darcy (1856)

Laboratory measurement of K

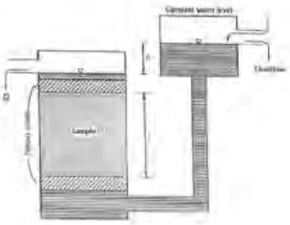
Constant-head permeameter

$$Q = -\frac{KAh}{L}$$

$$V = -\frac{KAh}{L}t$$

$$K = \frac{VL}{Ath}$$

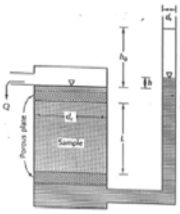
V = volume collected in time t



Falling-head Permeameter

$$K = \frac{d_t^2 L}{d_c^2 t}\ln\frac{h_o}{h}$$

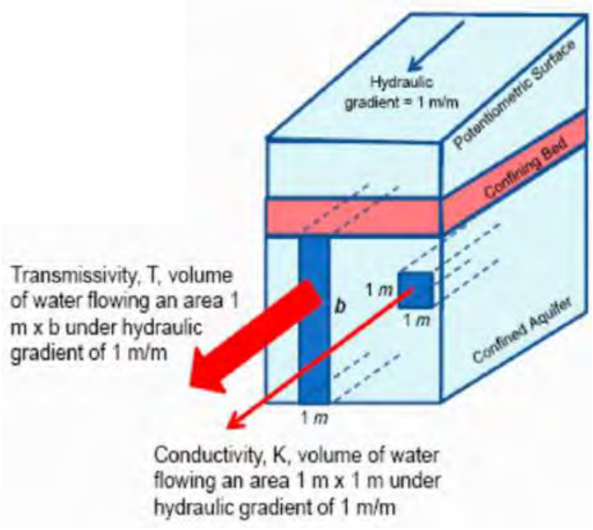
h_o = initial head
h = final head
t = time for head to fall
d_t = diameter of tube
d_c = inside diameter of sample chamber



Transmissivity (T)

- T = b K $[L^2/T]$
  - b = saturated aquifer thickness

- Transmissivity can be defined as the amount of v
hydraulic gradient



Transmissivity, T, volume of water flowing an area 1 m x b under hydraulic gradient of 1 m/m

Conductivity, K, volume of water flowing an area 1 m x 1 m under hydraulic gradient of 1 m/m

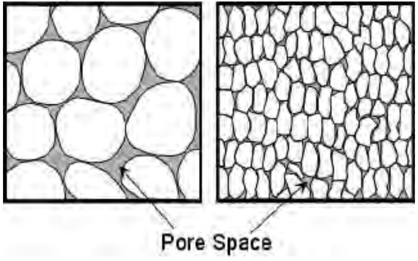
Porosity

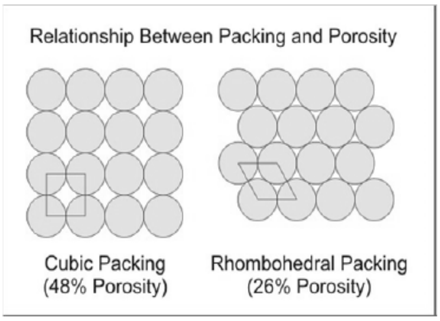
- Aquifer : ability to "conduct" water and ability to hold water
- Porosity :

  - The ratio of void space to the total volume of medium(soil and/or rock mass)

  $N= V_V/V_T \times 100$
- Effective Porosity :
  - Fraction of interconnected pore space
  - Much more important to the fluid flow

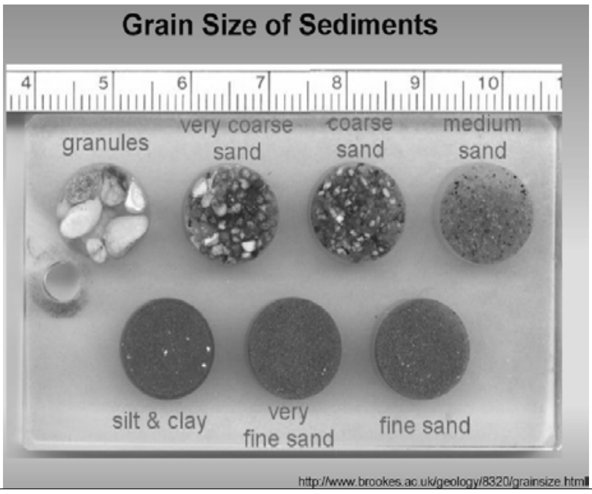
Porosity of well rounded material = 26-



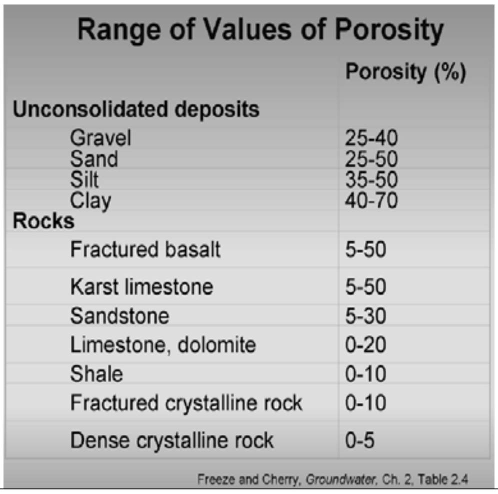


Porosity

- Dependent on sorting : well-sorted, smaller porosity
- Can use grain size distribution to classify sediments, which can be used to estimate porosity



http://www.brookes.ac.uk/geology/8320/grainsize.html



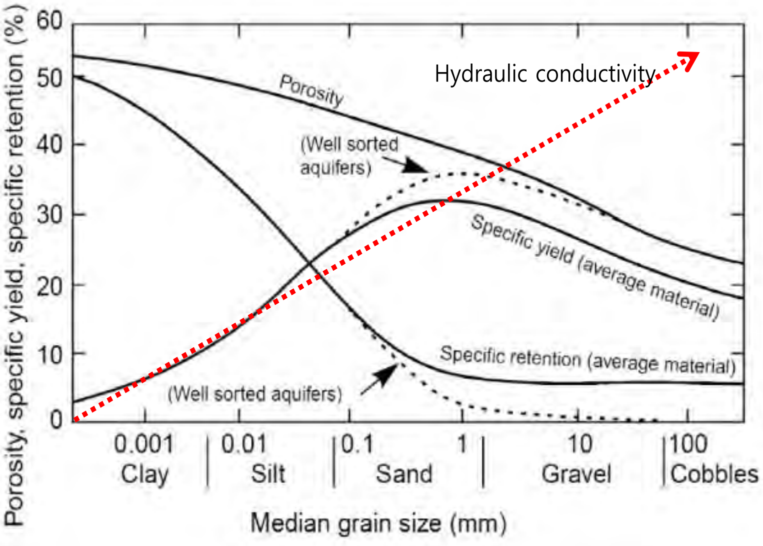
Range of Values of Porosity

	Porosity (%)
Unconsolidated deposits	
Gravel	25-40
Sand	25-50
Silt	35-50
Clay	40-70
Rocks	
Fractured basalt	5-50
Karst limestone	5-50
Sandstone	5-30
Limestone, dolomite	0-20
Shale	0-10
Fractured crystalline rock	0-10
Dense crystalline rock	0-5

Freeze and Cherry, *Groundwater*, Ch. 2, Table 2.4

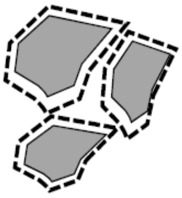
Grain size-porosity-specific yield- specific retention

The relation between grain size, porosity, specific yield and specific retention (Davis & Dewiest, 1966)



Specific Yield

- The volume of water which will drain under gravity from a unit volume of aquifer
- Sy = volume of water drained by gravity / total volume of rock
- Cannot release water when gravity force = surface tension (called pendular water)
- Porosity can be the same, Sy is smaller for finer material (large
- n(porosity) = Sy + Sr (Specific retention)

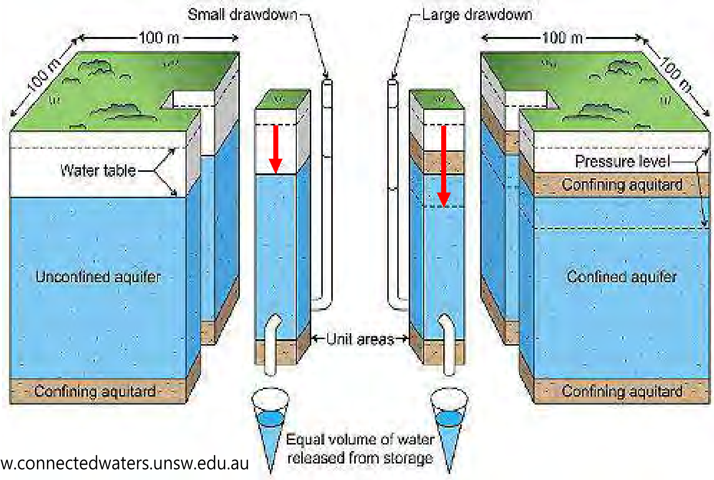


- Conventional values of specific yield

Rock	Specific Yield (%)
Clay	1 - 10
Sand	10 - 30
Gravel	15 - 30
Sand and Gravel	15 - 25
Sandstone	5 - 15
Shale	0.5 - 5

Storativity, Specific Storage, Specific yield

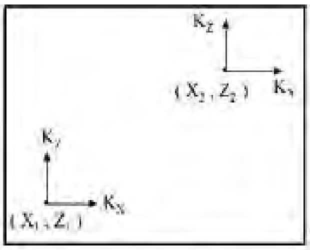
- Storage coefficient (or storativity) (S) : volume of water absorbed or expelled per unit surface area per unit change in head [dimensionless]
- Specific storage (S_S) : The volume of absorbed or expelled per unit volume per unit change in head [1/L]
  - ✓ function of compressibility of fluid and medium
- $S = b S_S$ for confined aquifer
- S =



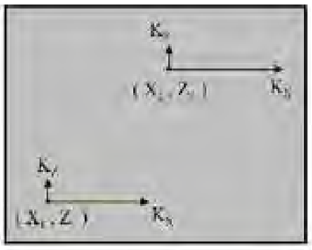
Source: http://www.connectedwaters.unsw.edu.au

Homogeneity and isotropy

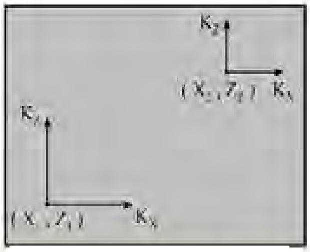
- Homogeneous = same properties at all locations
  - heterogeneous
- Isotropic = same conductivity in all directions
  - anisotropic



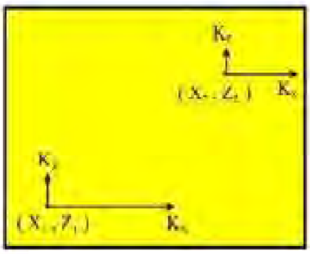
Homogeneous, Isotropic



Homogeneous, Anisotropic

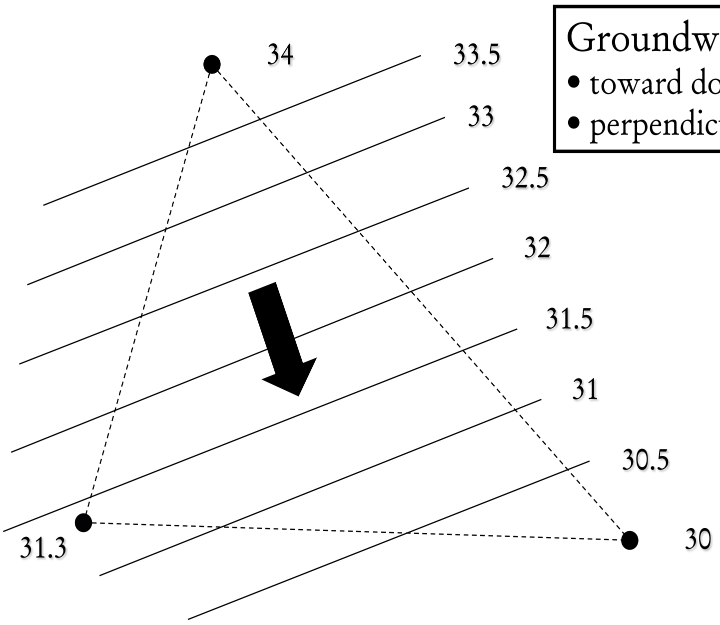


Heterogeneous, Isotropic



Heterogeneous, Anisotropic

Gradient and Groundwater Flow



Groundwater flow occur

- toward down-gradient direction
- perpendicular to equipotential line

Transport processes

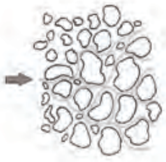
- Fluxes are controlled by advection and hydrodynamic dispersion
- Loss or gain by chemical/biological reaction or radioactive decay

- **Advection (convection):**

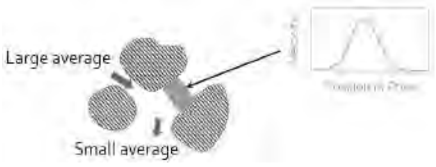
- Mass transport due to the flow of water in which the mass is carried
- The direction and rate of transport coincide with that of the groundwater flow

- **Hydrodynamic dispersion (spreading) : mechanical dispersion+molecular diffusion**

1. Mechanical dispersion (mechanical mixing during advection)
   - apparent diffusion by the complexity of flow path through the porous or fractured media
2. Molecular diffusion due to thermal-kinetic energy of solute particles

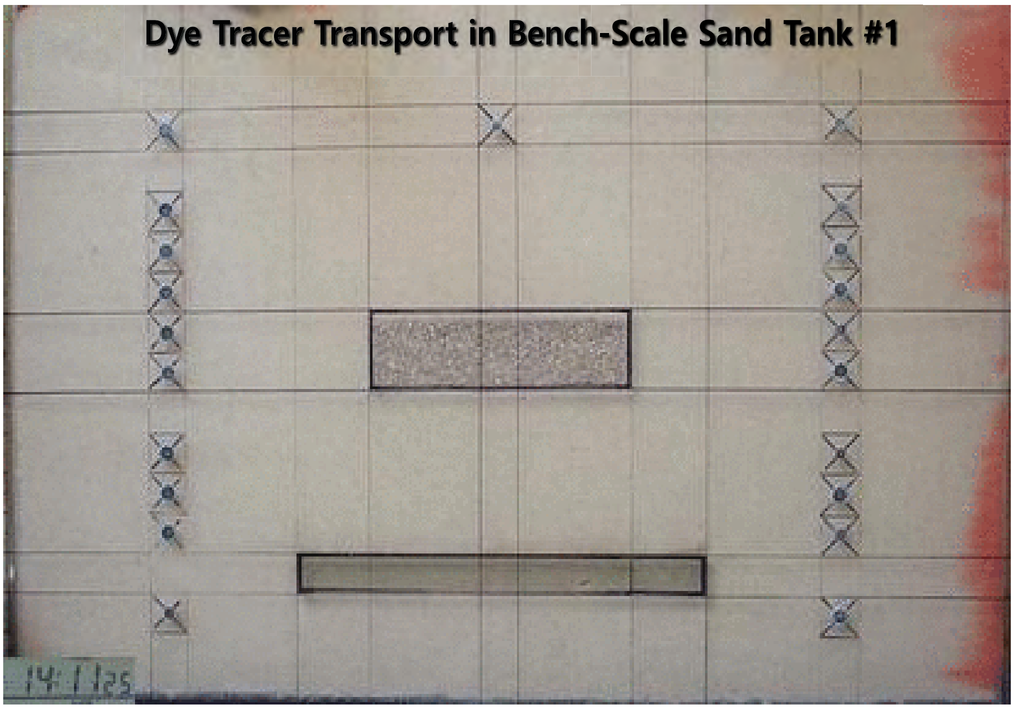


Path difference



Velocity difference within same channel

Solute Transport through Porous Media

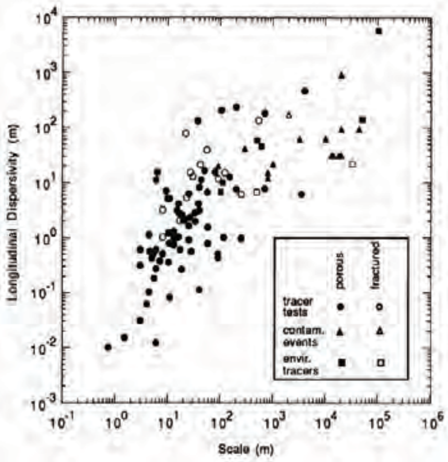


Dispersion coefficient, Dispersivity

- Hydrodynamic dispersion coefficient (D) : is a combination of mechanical dispersion (D_L) and molecular diffusion(D_d) [L2/T]
  - ✓ The advective flow velocity (v) and mean grain diameter (d_m) is the main factors
  - ✓ Longitudinal /Transverse dispersion

- Dispersivity(α_L) : a scale dependent property of an aquier that determines the degree to which a dissolved constituent will spread in flowing groundwater [L]
  - ✓ $D_L = \alpha_L \cdot v$ for longitudinal dispersion

- Scale dependency in the dispersion
  - ✓ Microscopic scale dispersivities as a result of velocity changes on the pore scale are about two orders of magnitude smaller than macroscopic dispersivities arising from heterogeneity in hydraulic conductivity.



Thank you very much

Groundwater Flow and Solute Transport Equations

Groundwater

Groundwater Flow and Solute Transport Equations

United Nations
Educational, Scientific and
Cultural Organization

International Centre for
Water Security and
Sustainable Management

Aims & Objectives

In this chapter, steady-state and transient differential equations of groundwater flow are derived using Darcy's equation, which expresses the flow rate of groundwater flow.

Using the velocity of groundwater, transport equations representing how contaminants or solutes in groundwater move.

A simple modification of the basic transport equation is to be discussed when there is a sorption reaction.

Contents

1. Groundwater flow equations

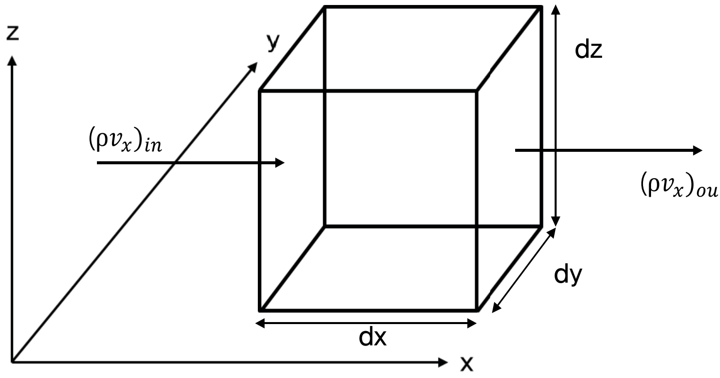
Assumptions

- Soil is saturated
    - We could derive the equations to describe unsaturated flow but we will stick to saturated flow in the class.
- Darcy’s law is valid
- Mass is conserved
    - i.e. , What goes in must come out or be stored based on conservation of mass.

Steady State Saturated Flow

Inflow - outflow = 0

Mass flow rate = ρv



$$(\rho v_x)_{out} = (\rho v_x)_{in} + \frac{\partial(\rho v_x)}{\partial x} dx$$

Steady State Saturated Flow

$$(inflow-outflow)_x=\left[(\rho v_x)_{in}-(\rho v_x)_{in}-\frac{\partial(\rho v_x)}{\partial x}dx\right]dydz\ =-\frac{\partial(\rho v_x)}{\partial x}dxdydz$$

$$(inflow-outflow)_y=\left[(\rho v_y)_{in}-(\rho v_y)_{in}-\frac{\partial(\rho v_y)}{\partial y}dy\right]dxdz\ =-\frac{\partial(\rho v_y)}{\partial y}dxdydz$$

$$(inflow-outflow)_z=\left[(\rho v_z)_{in}-(\rho v_z)_{in}-\frac{\partial(\rho v_z)}{\partial z}dz\right]dxdy\ =-\frac{\partial(\rho v_z)}{\partial z}dxdydz$$

Steady State Saturated Flow

$$(inflow-outflow)_{total}$$
$$=(inflow-outflow)_x+(inflow-outflow)_y+(inflow-outflow)_z=0$$

$$-\frac{\partial(\rho v_x)}{\partial x}dxdydz-\frac{\partial(\rho v_y)}{\partial y}dxdydz-\frac{\partial(\rho v_z)}{\partial z}dxdydz=0$$

$$\left[-\frac{\partial(\rho v_x)}{\partial x}-\frac{\partial(\rho v_y)}{\partial y}-\frac{\partial(\rho v_y)}{\partial y}\right]dxdydz=0$$

$$\frac{\partial(\rho v_x)}{\partial x}+\frac{\partial(\rho v_y)}{\partial y}+\frac{\partial(\rho v_z)}{\partial z}=0$$

Concentration Units

Assume that the fluid density is constant

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0$$

Use Darcy’s law to express velocity

$$\begin{bmatrix} v_x \\ v_y \\ v_y \end{bmatrix} = -\begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix}\begin{bmatrix} \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial y} \\ \frac{\partial h}{\partial z} \end{bmatrix}$$

$$\frac{\partial v_x}{\partial x}=\frac{\partial}{\partial x}\left[-k_{xx}\frac{\partial h}{\partial x}-k_{xy}\frac{\partial h}{\partial y}-k_{xz}\frac{\partial h}{\partial z}\right]=-k_{xx}\frac{\partial^2 h}{\partial x^2}-k_{xy}\frac{\partial^2 h}{\partial x\partial y}-k_{xz}\frac{\partial^2 h}{\partial x\partial z}$$

Concentration Units

Substituting $v_x , v_y , and\ v_z$:

$$k_{xx}\frac{\partial^2 h}{\partial x^2}+k_{xy}\frac{\partial^2 h}{\partial x\partial y}+k_{xz}\frac{\partial^2 h}{\partial x\partial z}$$

$$+k_{yx}\frac{\partial^2 h}{\partial y\partial x}+k_{yy}\frac{\partial^2 h}{\partial y^2}+k_{yz}\frac{\partial^2 h}{\partial y\partial z}$$

$$+k_{zx}\frac{\partial^2 h}{\partial z\partial x}+k_{zy}\frac{\partial^2 h}{\partial z\partial y}+k_{zz}\frac{\partial^2 h}{\partial z^2}=0$$

Concentration Units

Combining terms:

$$k_{xx}\frac{\partial^2 h}{\partial x^2}+k_{yy}\frac{\partial^2 h}{\partial y^2}+k_{zz}\frac{\partial^2 h}{\partial z^2}$$

$$+2k_{xy}\frac{\partial^2 h}{\partial x \partial y}+2k_{xz}\frac{\partial^2 h}{\partial x \partial z}+2k_{yz}\frac{\partial^2 h}{\partial y \partial z}=0$$

If x, y, and z correspond to principle axes of permeability:

$$k_{xy}=k_{xz}=k_{yz}=0$$

$$k_{xx}\frac{\partial^2 h}{\partial x^2}+k_{yy}\frac{\partial^2 h}{\partial y^2}+k_{zz}\frac{\partial^2 h}{\partial z^2}=0$$

Concentration Units

More commonly written as:

$$k_x\frac{\partial^2 h}{\partial x^2}+k_y\frac{\partial^2 h}{\partial y^2}+k_z\frac{\partial^2 h}{\partial z^2}=0$$

If $k_x=k_y=k_z$:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=0$$

“Laplace Equation”

Note:

1) The solution is independent of K
2) The solution is a function describing h in terms of x, y, and z → h(x, y, z)

Transient Saturated Flow

$$inflow\ - out\ flow = \frac{\Delta storage}{\Delta t} + source, sink$$

Assume that we have no sources and sinks.

The term:

$$\frac{\Delta storage}{\Delta t}$$

Represents the change in mass stored in the system

Transient Saturated Flow

The mass per unit volume can be expressed as the density times the volume of the voids:

$$m = \rho V_v = \rho(n\, V_{total}) = \ \rho\, n\, dx\, dy\, dz$$

The change in storage with respect to time can then be represented as:

$$\frac{\partial(\rho n)}{\partial t} dxdydz$$

Transient Saturated Flow

The law of conservation of mass for transient flow requires that the net rate at which fluid enters a control volume is equal to the time rate of change of fluid mass storage within the control volume.

$$net\ rate\ of\ inflow = inflow\ - outflow = rate\ of\ change\ in\ storage \quad \text{------[A.1]}$$

From equation mentioned previously we can write

$$net\ rate\ of\ inflow = -\frac{\partial(\rho v_x)}{\partial x} - \frac{\partial(\rho v_y)}{\partial y} - \frac{\partial(\rho v_z)}{\partial z} \quad \text{------[A.2]}$$

In steady-state flow, the change in storage within the control volume is zero.
In transient flow, the change in storage is not zero and equation.
So [A.2] becomes:

$$\underbrace{-\frac{\partial(\rho v_x)}{\partial x} - \frac{\partial(\rho v_y)}{\partial y} - \frac{\partial(\rho v_z)}{\partial z}}_{\text{Net rate of inflow}} = \underbrace{\frac{\partial(\rho n)}{\partial t}}_{\text{Rate of change in storage}} \quad \text{------[A.3]}$$

Transient Saturated Flow

Where n is the porosity of the porous mediA. The dimensions of the term $\frac{\partial(\rho n)}{\partial t}$ are M/L^3T or the time rate of change of fluid mass per unit volume of the control volume. Now assume that the porous media is saturated. Then using the chain-rule we can expand the right-hand side of equation [A.3] .

$$\frac{\partial}{\partial t}(\rho n) = \frac{\partial}{\partial h}(\rho n)\frac{\partial h}{\partial t} \quad \text{------[A.4]}$$

Where we can see that, in transient, saturated flow, the rate of change in fluid storage in the control volume is related to the rate of change in hydraulic head. Using the product rule we can expand the first term on the right-hand side of equation [A.4] .

$$\frac{\partial}{\partial h}(\rho n) = \rho\frac{\partial n}{\partial h} + n\frac{\partial \rho}{\partial h} \quad \text{------[A.5]}$$

The first term on the right-hand side of equation [A.5] is the mass of water produced by the expansion or compression of the porous media and the second term is the mass of water produce by expansion or compression of the fluid. In the case of saturated flow, water can only enter the control volume if the porosity increases $\left(\frac{\partial n}{\partial h} > 0\right)$ or the fluid density

Transient Saturated Flow

Increase $\left(\frac{\partial \rho}{\partial h} > 0\right)$.

To continue we must define two new terms: the porous media compressibility α and the fluid compressibility β . Compression or expansion of the porous media is caused by a change in effective stress σ_e. If the porous media is saturated

$$d\sigma_e = -\rho g d\psi$$ ------ [A.6]

Where ψ is the pressure head. But since $d\psi = d(h - z^*) = dh - \cancelto{0}{dz^*}$ we can write

$$d\sigma_e = -\rho g dh$$ ------ [A.7]

Now define the porous media compressibility α

$$\alpha = -\frac{dV_f}{V}\frac{1}{d\sigma_e} = \frac{dn}{d\sigma_e}$$ ------ [A.8]

Where V_f is the volume of fluid and V is control volume. Combining equation [A.7] and [A.8] we have

$$\frac{dn}{dh} = \alpha\rho g$$ ------ [A.9]

Transient Saturated Flow

The fluid compressibility β is defined as

$$\beta = \frac{dV_f}{V_f}\frac{1}{dp}$$ ------ [A.10]

Where p is the fluid pressure. The change in pressure is given by

$$dp = \rho g d\psi = \rho g dh$$ ------ [A.11]

And with $dV_f/V_f = d\rho/\rho$ equation [A.10] becomes

$$\beta = \frac{d\rho}{\rho}\frac{1}{\rho g dh} \quad or \quad \frac{d\rho}{dh} = \rho^2 g\beta$$ ------ [A.12] , [A.13]

Substituting equation [A.9] and [A.13] in to equation [A.4] gives

$$\frac{\partial}{\partial t}(\rho n) = \left(\rho\frac{\partial n}{\partial h} + n\frac{\partial \rho}{\partial h}\right)\frac{\partial h}{\partial t} = (\rho^2 g\alpha + n\rho^2 g\beta)\frac{\partial h}{\partial t}$$ ------ [A.14]

Now define the specific storage S_s as

$$S_s = \rho g(\alpha + n\beta)$$ ------ [A.15]

Transient Saturated Flow

The dimensions of S_s are L^{-1} representing the volume of water that a unit volume of aquifer releases from storage for a unit decline in hydraulic head. Substituting equation [A.15] into equation [A.14] gives

$$\frac{\partial}{\partial t}(\rho n) = \rho S_s \frac{\partial h}{\partial t} \qquad \text{------ [A.16]}$$

And substituting equation [A.16] into equation [A.3] we have

$$-\frac{\partial}{\partial x}(\rho v_x) - \frac{\partial}{\partial y}(\rho v_y) - \frac{\partial}{\partial z}(\rho v_z) = \rho S_s \frac{\partial h}{\partial t} \qquad \text{------ [A.17]}$$

If we assume that density is constant in the three coordinate directions equation [A.17] becomes

$$\rho\left(-\frac{\partial v_x}{\partial x} - \frac{\partial v_y}{\partial y} - \frac{\partial v_z}{\partial z}\right) = \rho S_s \frac{\partial h}{\partial t} \qquad \text{------ [A.18]}$$

Canceling ρ from both sides of equation [A.18] and using Darcy's Law we arrive at the transient, saturated-flow equation.

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} \qquad \text{------ [A.19]}$$

Transient Saturated Flow

If the porous media is homogeneous, k_x, k_y, and k_z are constant and equation [A.19] reduces to

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_z \frac{\partial^2 h}{\partial z^2} = S_s \frac{\partial h}{\partial t} \qquad \text{------ [A.20]}$$

If the porous media is also isotropic, $k_x = k_y = k_z = k$, equation [A.20] is written

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{k}\frac{\partial h}{\partial t} \qquad \text{------ [A.21]}$$

Which is known to mathematicians as the diffusion equation. For the special case of horizontal, two-dimensional groundwater flow in a confined aquifer of constant thickness b equation [A.21] simplifies to

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad \text{------ [A.22]}$$

Where $S = S_s b$ and $T = kb$.

S is storativity and T is transmissivity

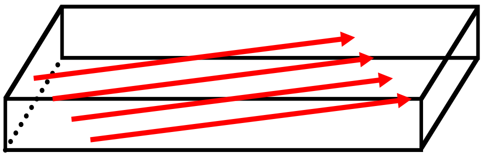
Transient Saturated Flow

For 2D flow parallel to the formation:

$$K\left[\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}\right]=s\frac{\partial h}{\partial t}$$

$$Kb\left[\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}\right]=sb\frac{\partial h}{\partial t}$$

$$T\left[\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}\right]=S\frac{\partial h}{\partial t}$$



For steady flow:

$$\left[\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}\right]=0$$

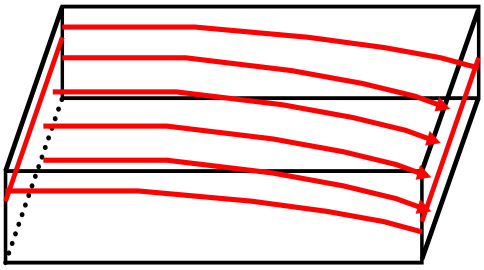
Transient Saturated Flow

For unconfined flow (nonlinear)

Boussinesq equation simplifies by taking the head drop over horizontal distance rather than the path length, and average thickness, h:

$$K\left[\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}\right]=s\frac{\partial h}{\partial t}$$

$$\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(h\frac{\partial h}{\partial z}\right)=\frac{S_y}{K}\frac{\partial h}{\partial t}$$



Transient Saturated Flow

For unconfined flow (nonlinear)

head drop over x rather than the path length, L (also know as Dupuit Assumptions):

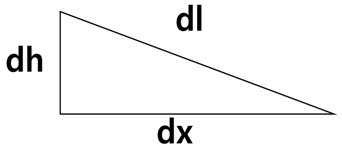
$$q = -Kh\frac{dh}{dx}$$

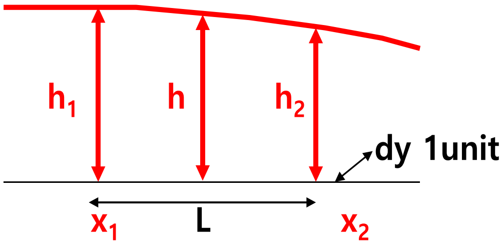
$$qdx = -Khdh$$

$$\int_0^L qdx = -K\int_{h_1}^{h_2} hdh$$

$$q\,x\Big|_0^L = -K\frac{h^2}{2}\Big|_{h_1}^{h_2}$$

$$qL = -K\left(\frac{{h_2}^2}{2} - \frac{{h_1}^2}{2}\right)$$





Transient Saturated Flow

If we do the same for confined flow(linear)

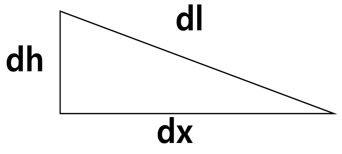
$$q = -Kb\frac{dh}{dx}$$

$$\int_0^L qdx = -Kb\int_{h_1}^{h_2} dh$$

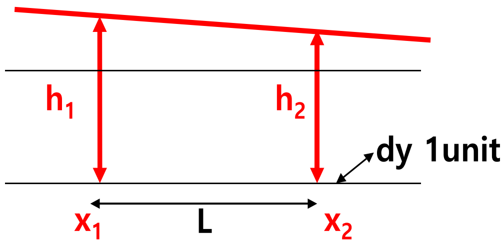
$$q\,x\Big|_0^L = -Kb\,h\Big|_{h_1}^{h_2}$$

$$qL = -Kb(h_2 - h_1)$$

$$q = -Kb\frac{h_2 - h_1}{L}$$



$$Q = KiA$$



Source and Sinks

If we have sources or sinks we can simply add one more term, R, which is intrinsically positive and represents inflow to the system.

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_z \frac{\partial^2 h}{\partial z^2} + R = S_s \frac{\partial h}{\partial t}$$

or

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_z \frac{\partial^2 h}{\partial z^2} = S_s \frac{\partial h}{\partial t} - R$$

For outflow, R = -W where W is the withdrawal rate. R can represent:

1. Injection wells
2. Extraction wells
3. Rainfall
4. Evaporation

2. Contaminant/solute transport equations

Contaminant / Solute Transport

Process of solute movement complex

Diffusion
moving from higher
to lower concentrations

Advection
solute moves
with groundwater

Dispersion
Dilution and spreading

Advection

Contaminants traveling at same velocity as the groundwater
(Dissolved in the groundwater)

$$V_x = -\frac{K}{n_e}\frac{dh}{dl}$$

V_x = average linear velocity
K = hydraulic conductivity
n_e = effective porosity
dh/dl = hydraulic gradient

Diffusion

A solute in water will move from an area of greater concentration toward an area where it is less

Fick's Law (diffusion of solute through water)

$$F = -D_d \frac{dC}{dx}$$

F = mass flux of solute per unit area per unit time
D_d = diffusion coefficient
C = concentration
dC/dx= concentration gradient

Negative sign – movement from higher to lower concentration

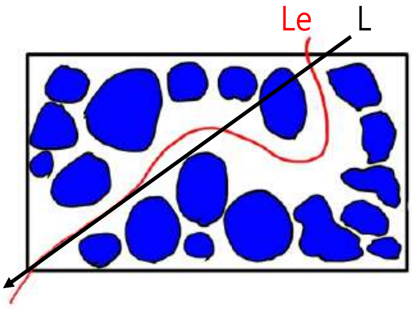
Diffusion

In porous medium, diffusion not as effective as in open water

Tortuosity: actual length of flow path (Le) divided by straight line distance (L)

$$Tortuosity = {}^{Le}/_{L}$$

Solute only moves through pores



D* = effective diffusion coefficient

$$D^* = \omega D_d$$

ω = empirical coefficient
Function of the tortuosity, always <1
For non sorbed species, ω = 0.01 ~ 0.5

Diffusion

A solute in water will move from an area of greater concentration toward an area where it is less

Fick's Law (diffusion of solute through water)

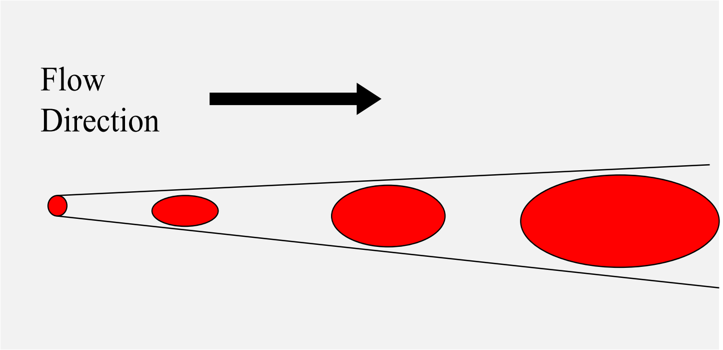
$$F = -D_d \frac{dC}{dx}$$

F = mass flux of solute per unit area per unit time
D_d = diffusion coefficient
C = concentration
dC/dx= concentration gradient

Negative sign – movement from higher to lower concentration

Dispersion

Mechanical dispersion – caused by motion of the fluid



Longitudinal dispersion – along the streamline

Transverse dispersion – perpendicular to flow path

Dispersion , Hydrodynamic Dispersion

Dispersion

Coeff. Of Longitudinal Mechanical Dispersion = $\alpha_L v_x$

α_L = longitudinal dispersivity

Coeff. Of Transverse Mechanical Dispersion = $\alpha_T v_x$

α_T = transverse dispersivity

Hydrodynamic Dispersion

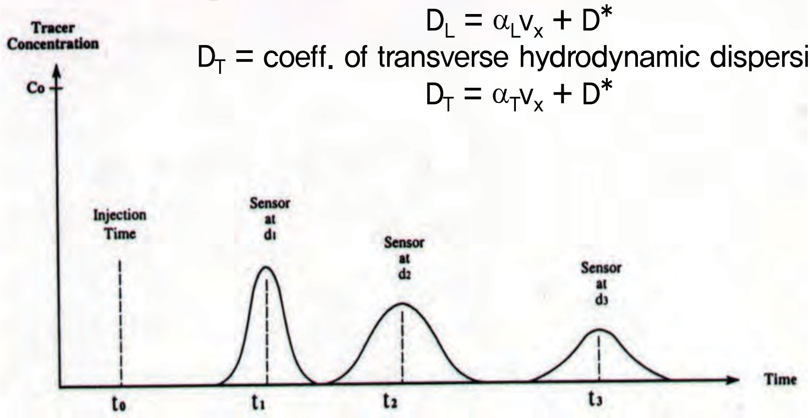
Processes of diffusion and dispersion can’t be separated out

D_L = coeff. of longitudinal hydrodynamic dispersion

$$D_L = \alpha_L v_x + D^*$$

D_T = coeff. of transverse hydrodynamic dispersion

$$D_T = \alpha_T v_x + D^*$$



Derivation of Advection Dispersion Equation

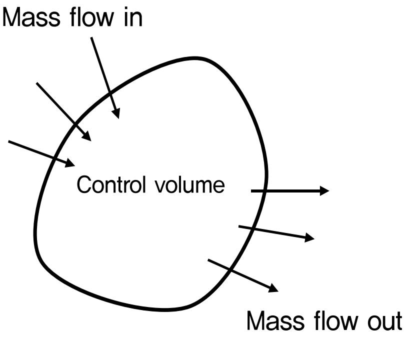
Solute transport is governed by laws of physics

Consider an Representative Elementary Volume

Homogeneous, isotropic saturated porous medium

Darcy’s Law applies

Law of Mass Conservation

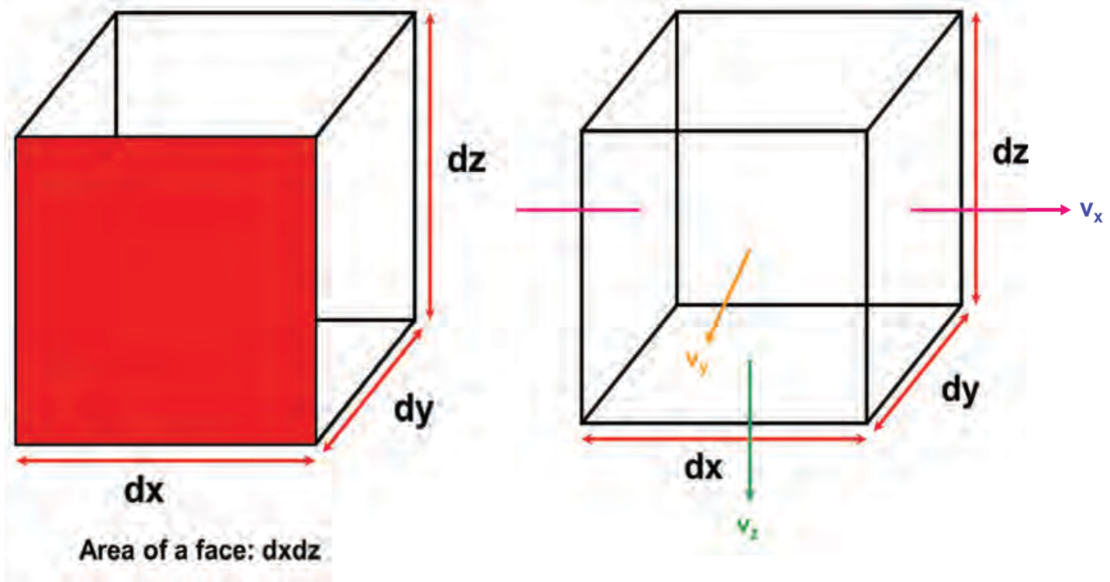


Mass is neither created or destroyed

Any change in mass flowing into the small volume of the aquifer must be balanced by the corresponding change in mass flux out of the volume or a change in the mass stored in the volume or both

Derivation of Advection Dispersion Equation

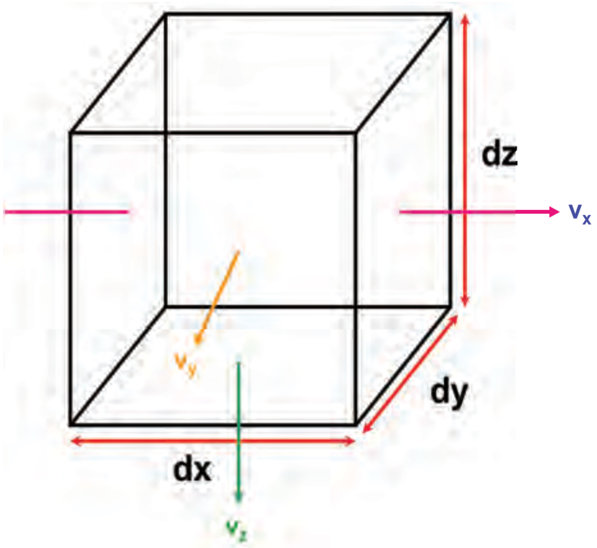
Let’ s consider an REV …



Solute will be transported by two processes:

1) Advection   2) hydrodynamic dispersion

Derivation of Advection Dispersion Equation



v = velocity
n_e= effective porosity
C = concentration
D = hydrodynamic dispersion coeff.

Advective transport in x direction = $v_x n_e C\ (dydz)$

Dispersive transport in x direction = $n_e D_x\ (dC/dx)\,(dydz)$

Derivation of Advection Dispersion Equation

Total mass of solute in the x direction

$$\text{Total mass} = v_x n_e C(dydz) - n_e D_x(dC/dx)(dydz)$$

$$F_x = v_x n_e C - n_e D_x(dC/dx)$$

F_x=mass flux per unit area per unit time

Total amount of solute entering REV is:

$$F_x dydz + F_y dxdz + F_z dxdy$$

Total amount of solute leaving REV is:

$$\left(F_x + \frac{\partial F_x}{\partial x}dx\right)dydz + \left(F_y + \frac{\partial F_y}{\partial y}dy\right)dxdz + \left(F_z + \frac{\partial F_z}{\partial z}dz\right)dxdz$$

Conservation of mass

The conservation of mass requires that the change in mass stored in a control volume over time (t) equal the difference between the mass that enters the control volume and that which exits the control volume over this same time increment.

$$change\ in\ mass\ in\ control\ volume = mass\ flux\ in\ - mass\ flux\ out$$

$$\boldsymbol{mass\ flux\ in}$$

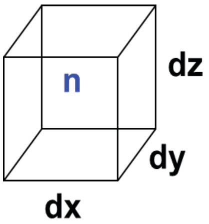
$$= F_x dzdy + F_y dxdz + F_z dxdy$$

$$\boldsymbol{mass\ flux\ out}$$

$$= \left(F_x + \frac{\partial F_x}{\partial x}dx\right)dydz + \left(F_y + \frac{\partial F_y}{\partial y}dy\right)dxdz + \left(F_z + \frac{\partial F_z}{\partial z}dz\right)dxdz$$
$$- \left(\frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z}\right)dxdydz$$

Conservation of mass

$$change\ in\ mass\ in\ control\ volume = mass\ flux\ in\ - mass\ flux\ out$$



Volume of control volume = $dxdydz$

Volume of water in control volume = $(n_e)dxdydz$

Mass of contaminant in control volume = $(\mathrm{C})(\mathrm{n})dxdydz$

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial t}(C)(n)dxdydz$$

Conservation of mass

$$change\ in\ mass\ in\ control\ volume = mass\ flux\ in\ - mass\ flux\ out$$

$$\frac{\partial}{\partial t}[(C)(n_e)dxdydz] = -\left(\frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z}\right)dxdydz$$

Divide both sides by the volume

$$\frac{\partial}{\partial t}[(C)(n_e)] = -\left(\frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z}\right)$$

Substitute in expression for F

$$F_x = v_x n_e C - n_e D_x (dC/dx)$$

Conservation of mass

$$-\frac{\partial}{\partial t}[(C)(n_e)] = \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z}$$

$$F_x = v_x n_e C - n_e D_x (dC/dx)$$

$$F_y = v_y n_e C - n_e D_y (dC/dy)$$

$$F_z = v_z n_e C - n_e D_z (dC/dz)$$

$$\frac{\partial C}{\partial t} = \left[\frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right)\right] - \left[\frac{\partial}{\partial x}(v_x C) + \frac{\partial}{\partial y}\left(v_y C\right) + \frac{\partial}{\partial z}(v_z C)\right]$$

Equation for Mass Transport for a Conservative Solute

3 Dimensional

$$\frac{\partial C}{\partial t} = \left[\frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right)\right] - \left[\frac{\partial}{\partial x}(v_x C) + \frac{\partial}{\partial y}\left(v_y C\right) + \frac{\partial}{\partial z}(v_z C)\right]$$

2 Dimensional

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - v_x \frac{\partial C}{\partial x}$$

1 Dimensional

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x}$$

Hydrodynamic Dispersion

$$D_{xx} = \alpha_L \frac{v_x^2}{|v|} + \alpha_{TH} \frac{v_y^2}{|v|} + \alpha_{TV} \frac{v_z^2}{|v|} + D^*$$

$$D_{yy} = \alpha_L \frac{v_y^2}{|v|} + \alpha_{TH} \frac{v_x^2}{|v|} + \alpha_{TV} \frac{v_z^2}{|v|} + D^*$$

$$D_{zz} = \alpha_L \frac{v_z^2}{|v|} + \alpha_{TH} \frac{v_x^2}{|v|} + \alpha_{TV} \frac{v_y^2}{|v|} + D^*$$

$$D_{xy} = D_{yx} = (\alpha_L - \alpha_{TH}) \frac{v_x v_y}{|v|}$$

$$D_{xz} = D_{zx} = (\alpha_L - \alpha_{TH}) \frac{v_x v_z}{|v|}$$

$$D_{yz} = D_{zy} = (\alpha_L - \alpha_{TH}) \frac{v_y v_z}{|v|}$$

α_L	longitudinal dispersivity
α_{TH}, α_{TV}	transverse dispersivity
D^*	effective molecular diffusion coefficient
v_x, v_y, v_z	components of the velocity vector
$|v| = \left(v_x^2 + v_y^2 + v_z^2\right)^{\frac{1}{2}}$	magnitude of the velocity vector

Solute Transport

Conservative and Reactive Solute

Conservative

Do not react with soil / groundwater

Reactive

Sorbed on to mineral grains
As well as organic matter

If solute is reactive,
it will travel slower than groundwater rate due to adsorption

Solute Transport

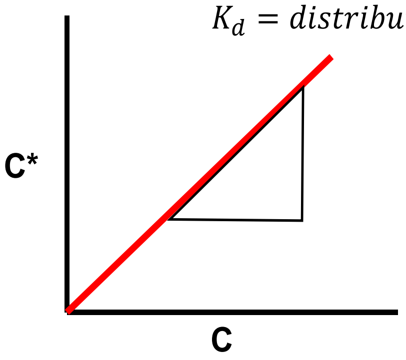
Direct linear relationship between amount of solute
Sorbed onto solid (C^*) and the concentration of the solute (C)

$$C^* = K_d C$$

$$C^* = mass\ of\ solute\ sorbed\ per\ dry\ unit\ weight\ of\ solid\ (mg/kg)$$

$$C = concentration\ of\ solute\ in\ solution\ in\ equilibrium\ with\ the\ mass\ of\ solute\ sorbed\ onto\ the\ solid\ (mg/L)$$

$$K_d = distribution\ coefficient\ (L/kg)$$



Slope of linear isotherm = K_d

Solute Transport

One dimension advection – dispersion with sorption

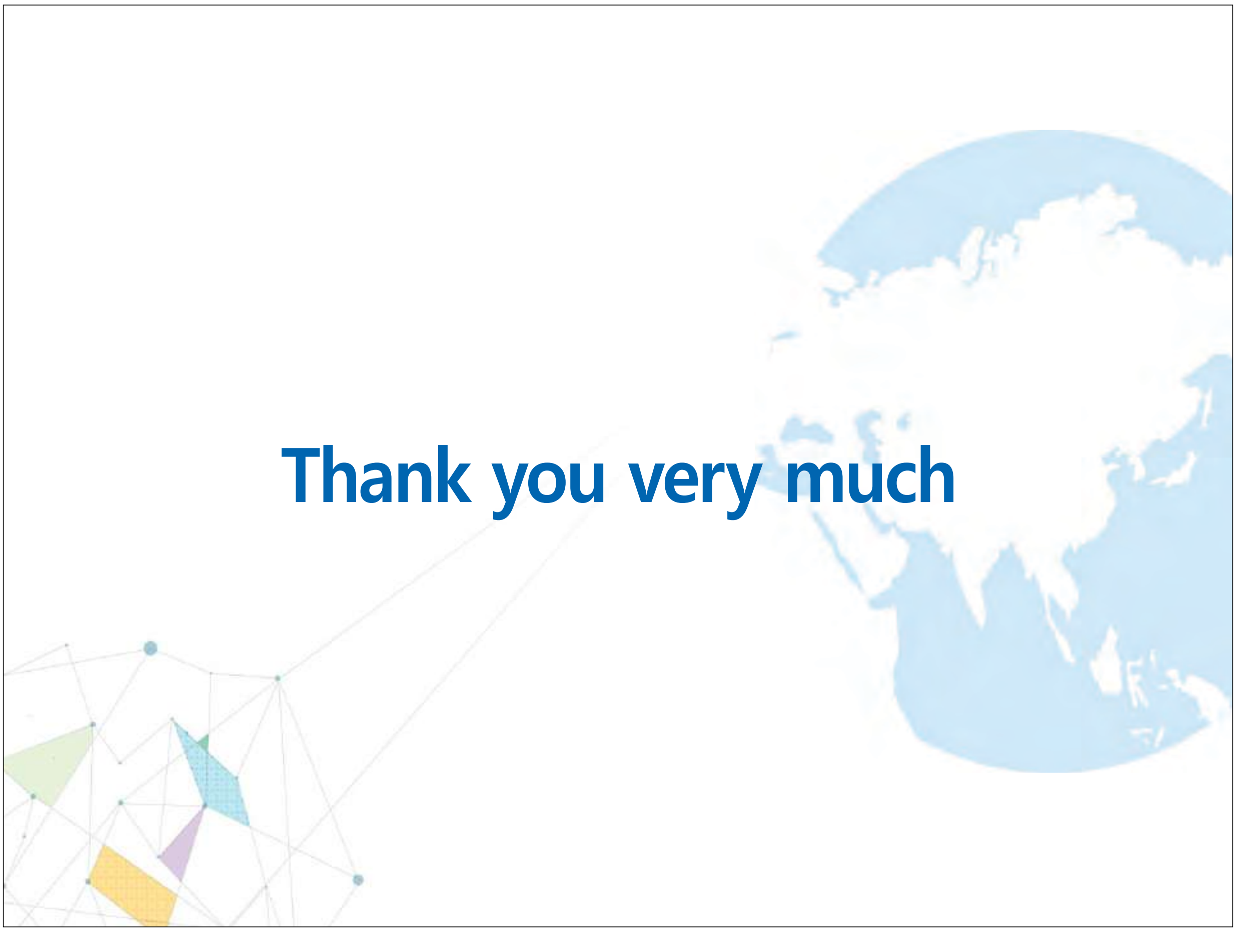
$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} - \frac{B_d}{\theta}\frac{\partial C^*}{\partial t}$$

Substitute into advection – dispersion equation

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} - \frac{B_d}{\theta}\frac{\partial C^*}{\partial t}$$

$$\frac{\partial C}{\partial t}(1 + \frac{B_d}{\theta}K_d) = D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x}$$

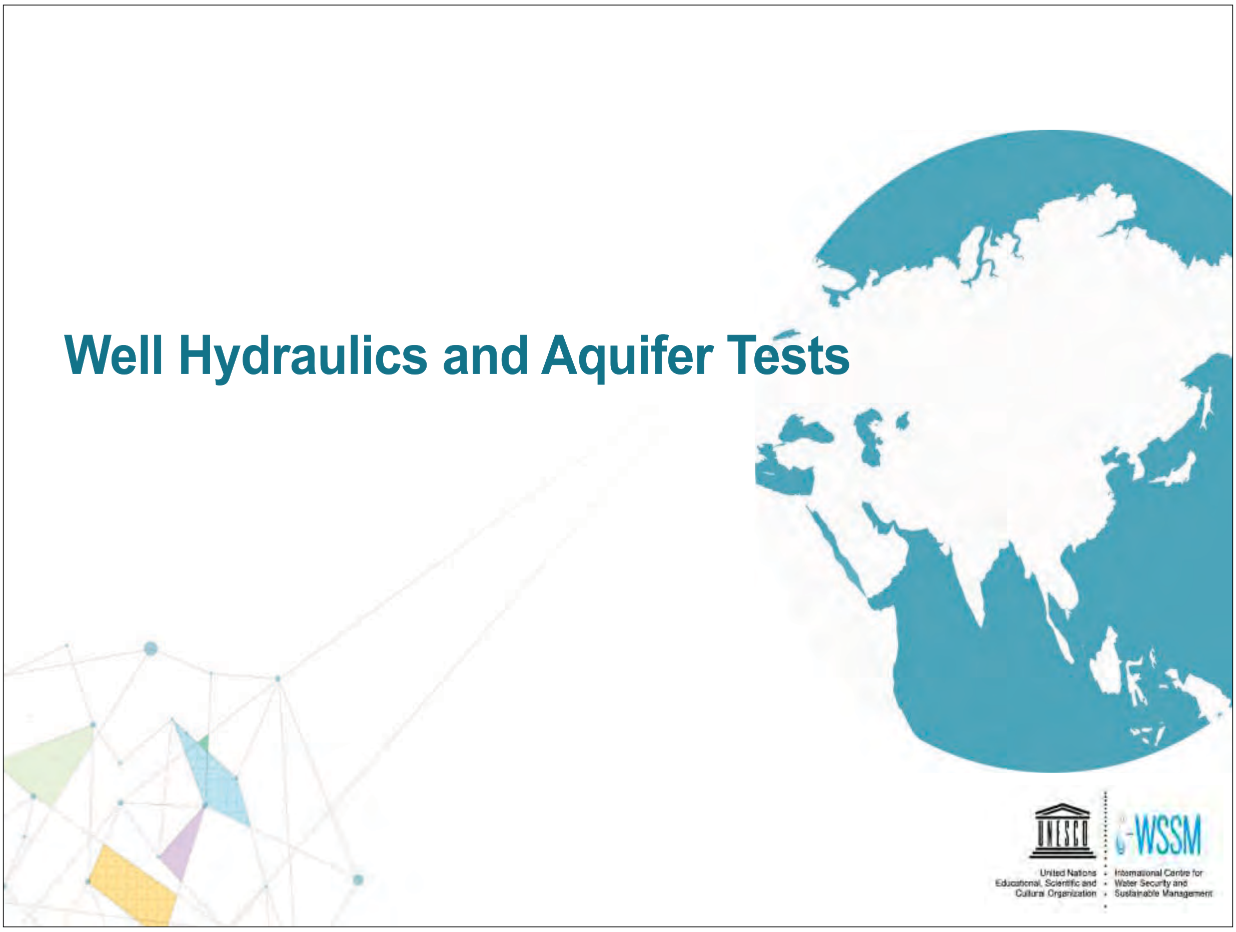
$$\left(1 + \frac{B_d}{\theta}K_d\right) = r_f = retardation\ factor$$



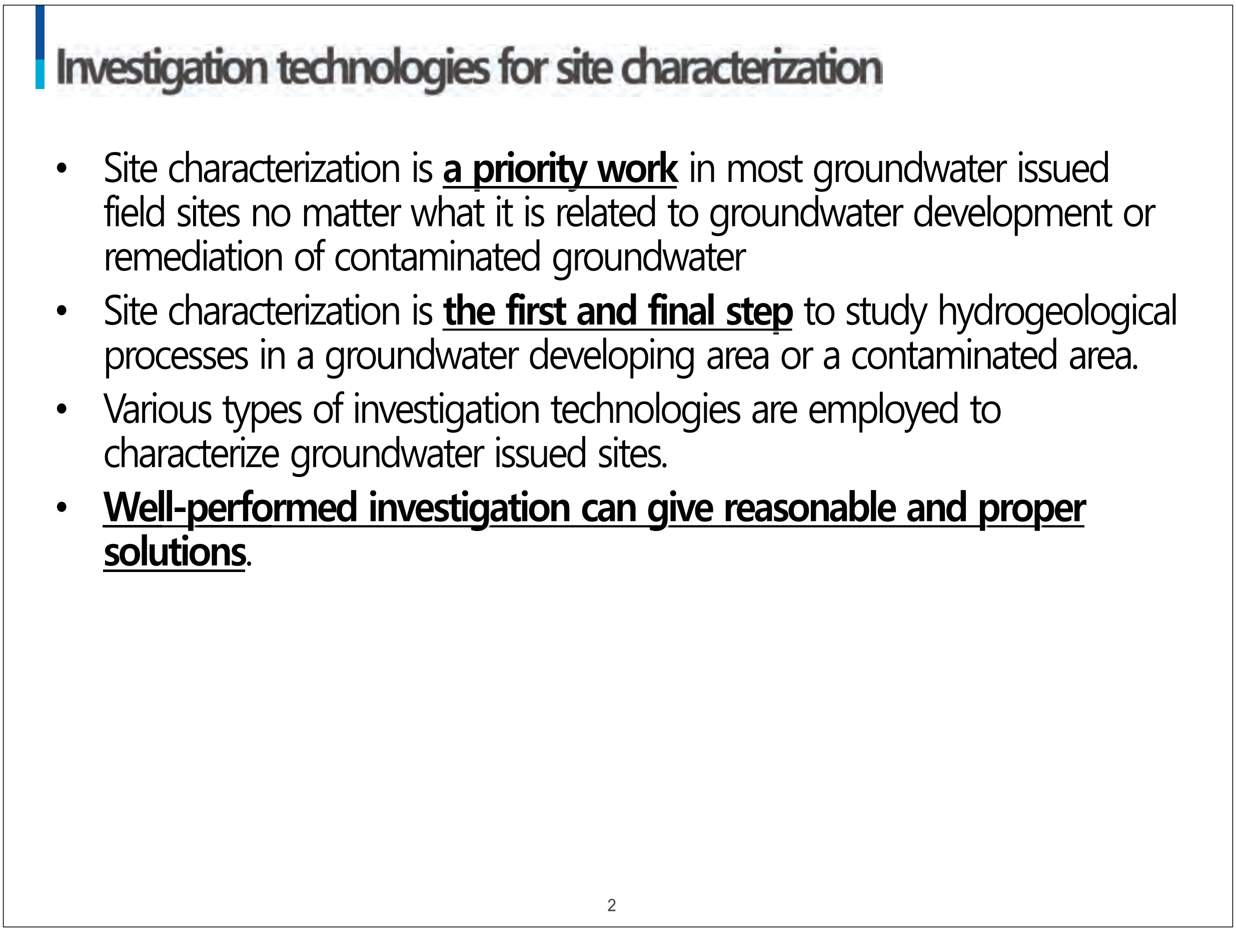
Thank you very much

Well Hydraulics and Aquifer Tests

Groundwater

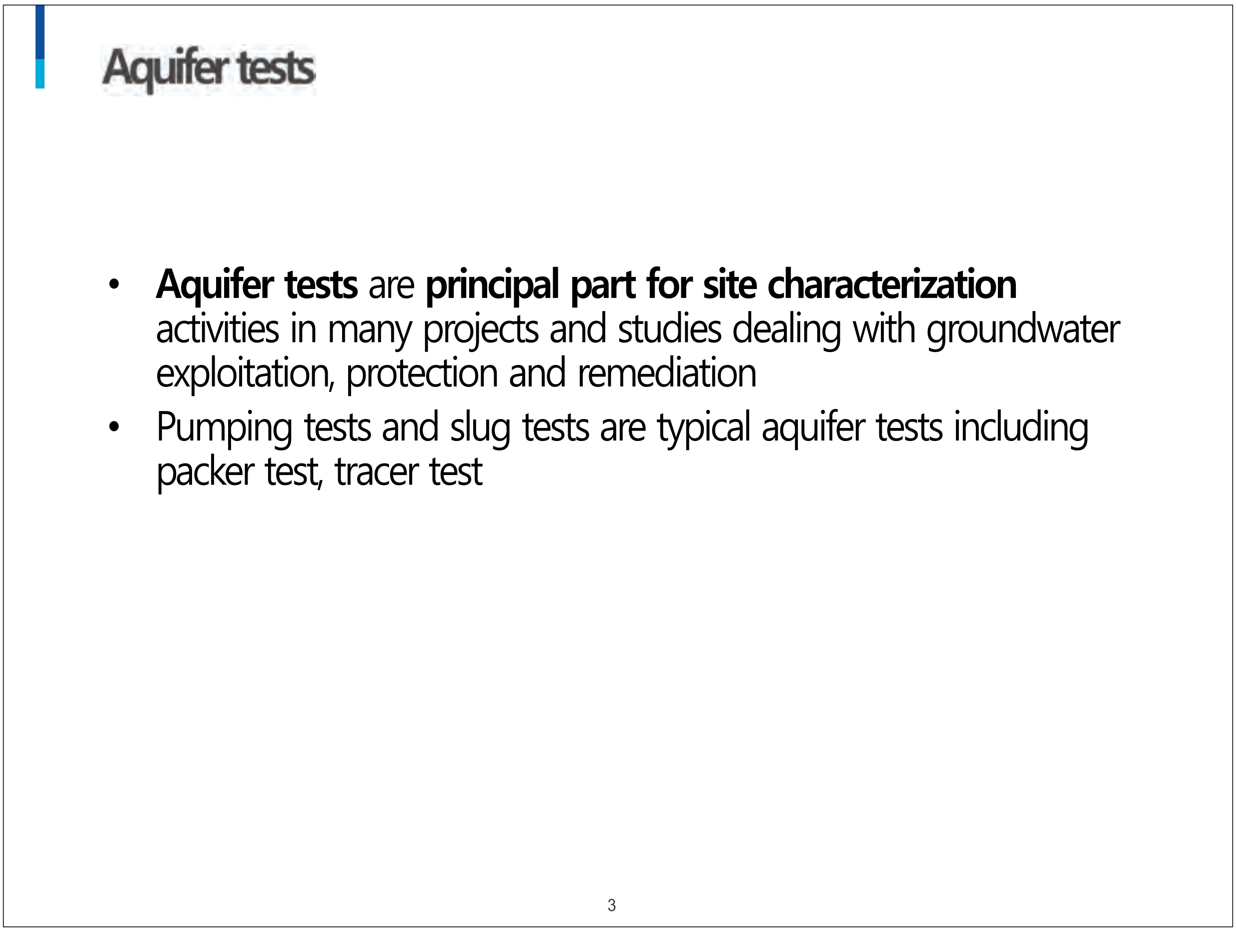


Well Hydraulics and Aquifer Tests



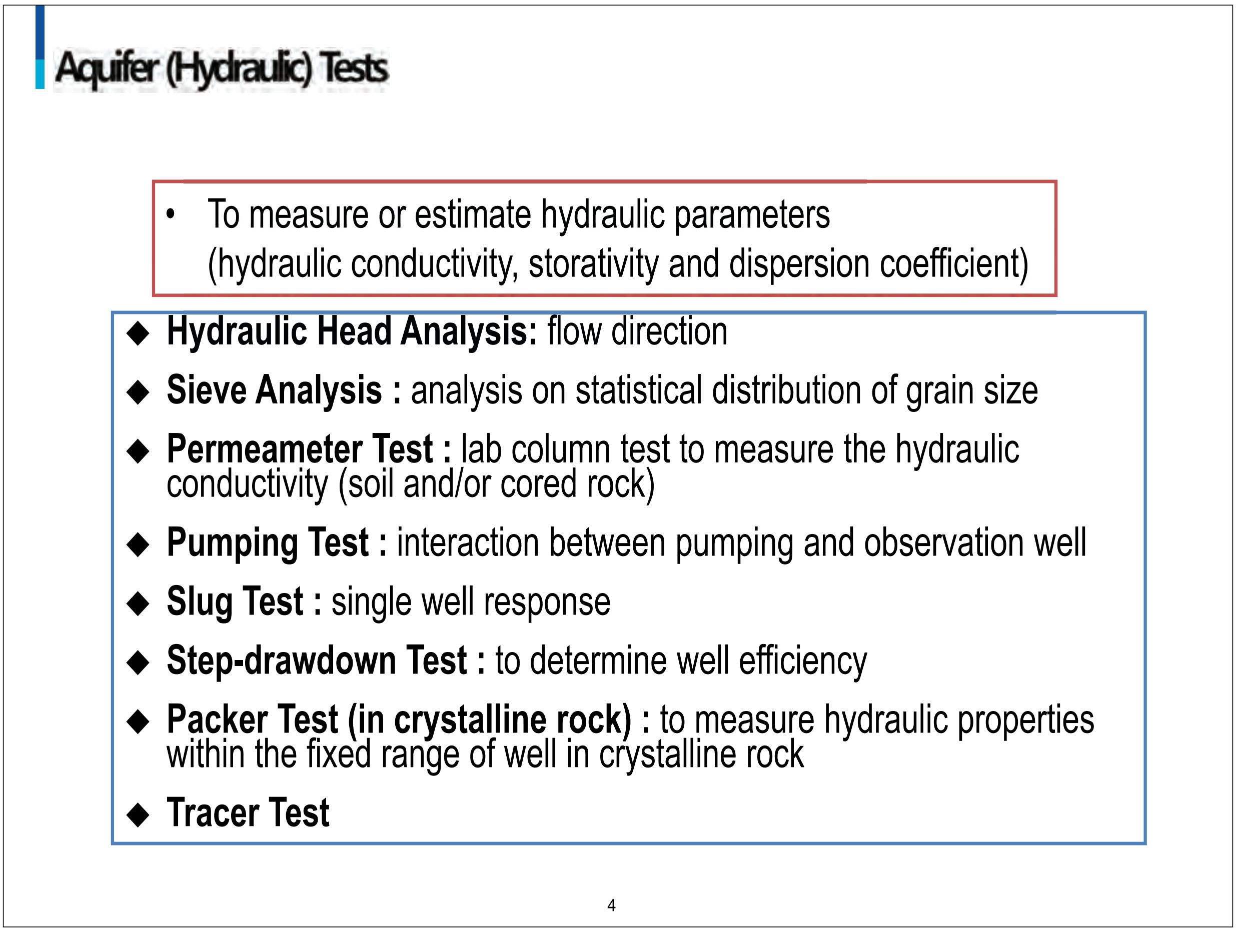
Investigation technologies for site characterization

- Site characterization is **a priority work** in most groundwater issued field sites no matter what it is related to groundwater development or remediation of contaminated groundwater
- Site characterization is **the first and final step** to study hydrogeological processes in a groundwater developing area or a contaminated area.
- Various types of investigation technologies are employed to characterize groundwater issued sites.
- **Well-performed investigation can give reasonable and proper solutions**.



Aquifer tests

- **Aquifer tests** are **principal part for site characterization** activities in many projects and studies dealing with groundwater exploitation, protection and remediation
- Pumping tests and slug tests are typical aquifer tests including packer test, tracer test



Aquifer (Hydraulic) Tests

- To measure or estimate hydraulic parameters (hydraulic conductivity, storativity and dispersion coefficient)

◆ **Hydraulic Head Analysis:** flow direction

◆ **Sieve Analysis :** analysis on statistical distribution of grain size

◆ **Permeameter Test :** lab column test to measure the hydraulic conductivity (soil and/or cored rock)

◆ **Pumping Test :** interaction between pumping and observation well

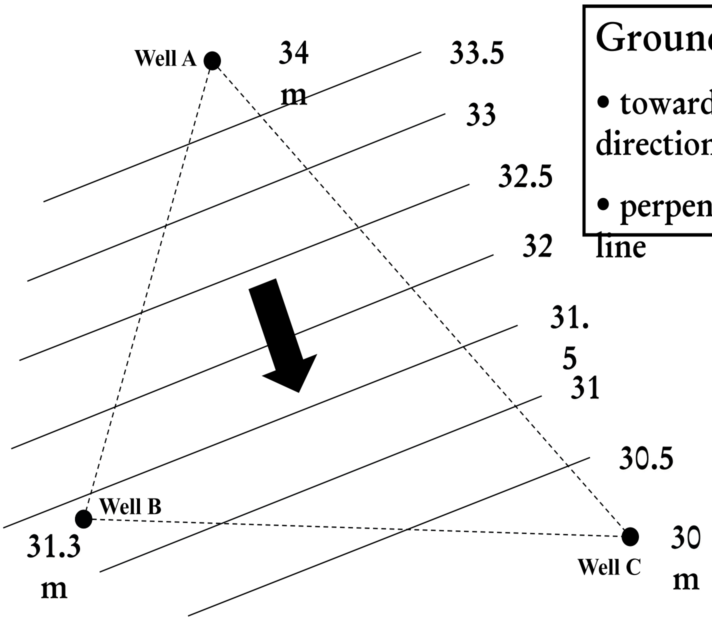
◆ **Slug Test :** single well response

◆ **Step-drawdown Test :** to determine well efficiency

◆ **Packer Test (in crystalline rock) :** to measure hydraulic properties within the fixed range of well in crystalline rock

◆ **Tracer Test**

Hydraulic Head analysis:
Flow Direction



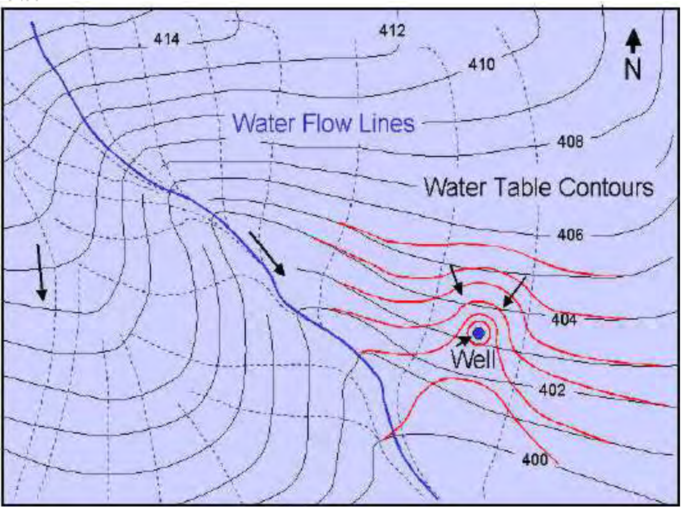
Groundwater flow occur

- toward down-gradient direction
- perpendicular to equipotential line

Hydraulic Head analysis:
Flow Net

- Definition of flow net:

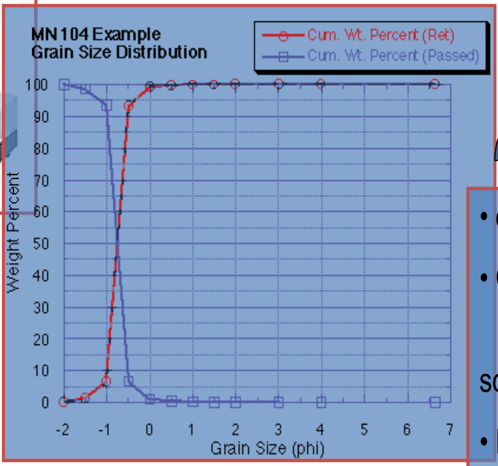
A net combined with equipotential line and flow line in groundwater syst



from http://wapi.isu.edu/envgeo/aquifer_gw_review/flownets.htm

Red lines indicate positions of water table contours when well is pumping

Sieve Analysis



- d_{10} = 10% finer by weight(mm)
- C_u = Uniformity coeff. (=d_{60}/d_{10})

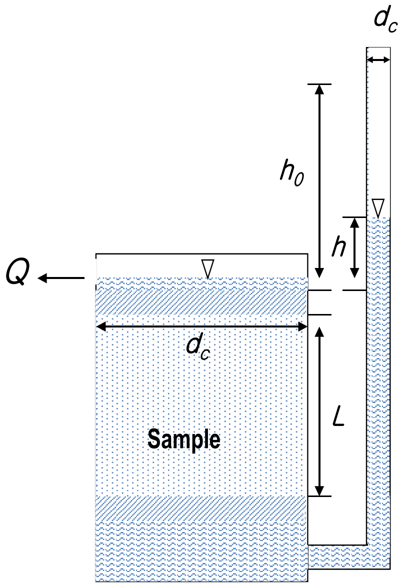
  <4, well sorted; >6, poorly sorted
- Hazen Method

  $K = C\,(d_{10})^2$

  C=coeff. depending on size & sorting

Permeameter Tests

- Const. Head Permeameter Test
  - Moderate to high K
  - K=VL/Ath
- Falling Head Permeameter Test
  - Low K
  - $K=[d_t^2L/(d_c^2t)][\ln(h_0/h)]$



PUMPING TESTS

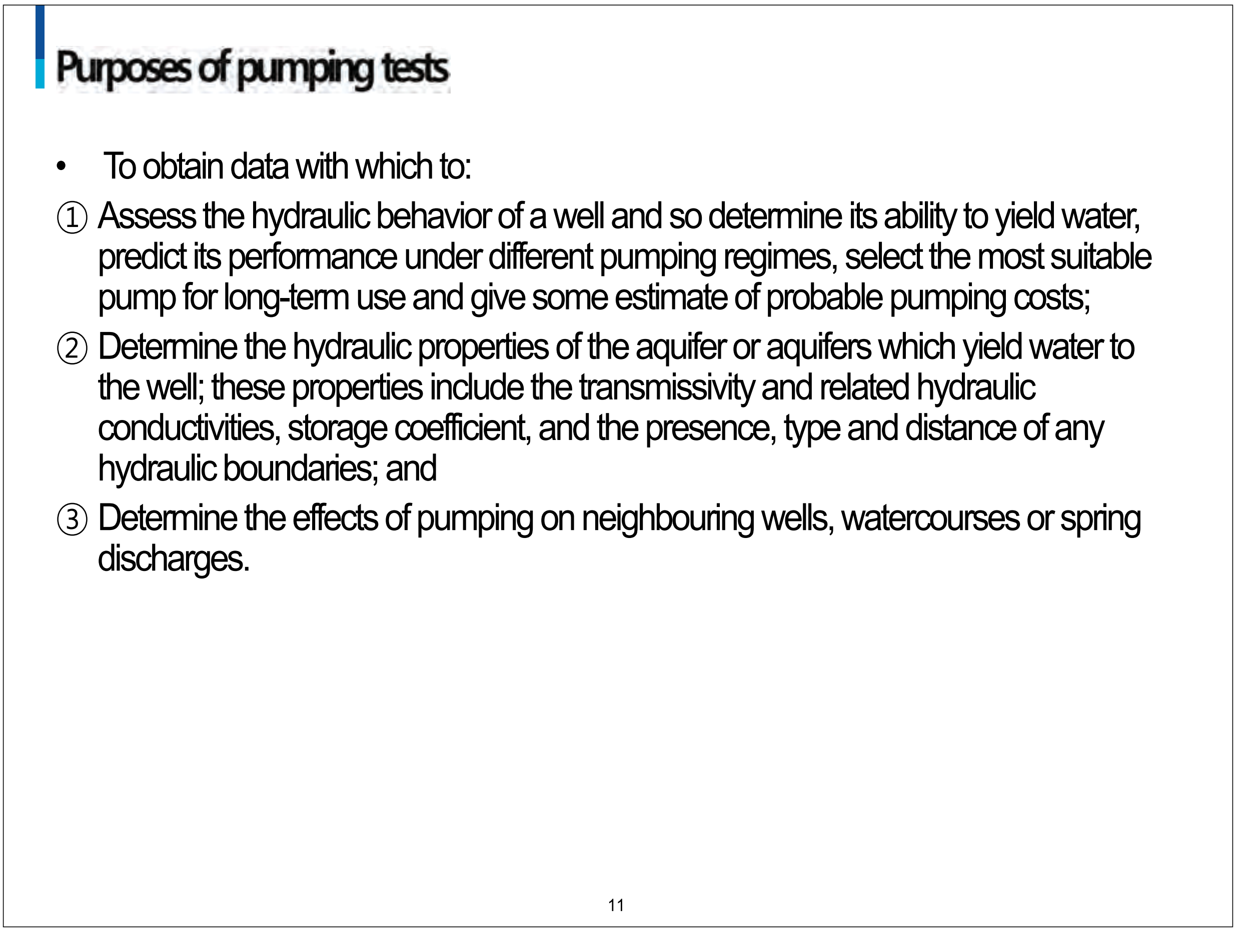
Principle of pumping test

- The principle of a pumping test involves

 - applying a stress to an aquifer by extracting groundwater from a pumping well
 - measuring the aquifer response to that stress by monitoring drawdown as a function of time.

These measurements are then incorporated into an appropriate well-flow equation to calculate the hydraulic parameters of the aquifer.

It can be applied to single-well or multi-wells (observations)



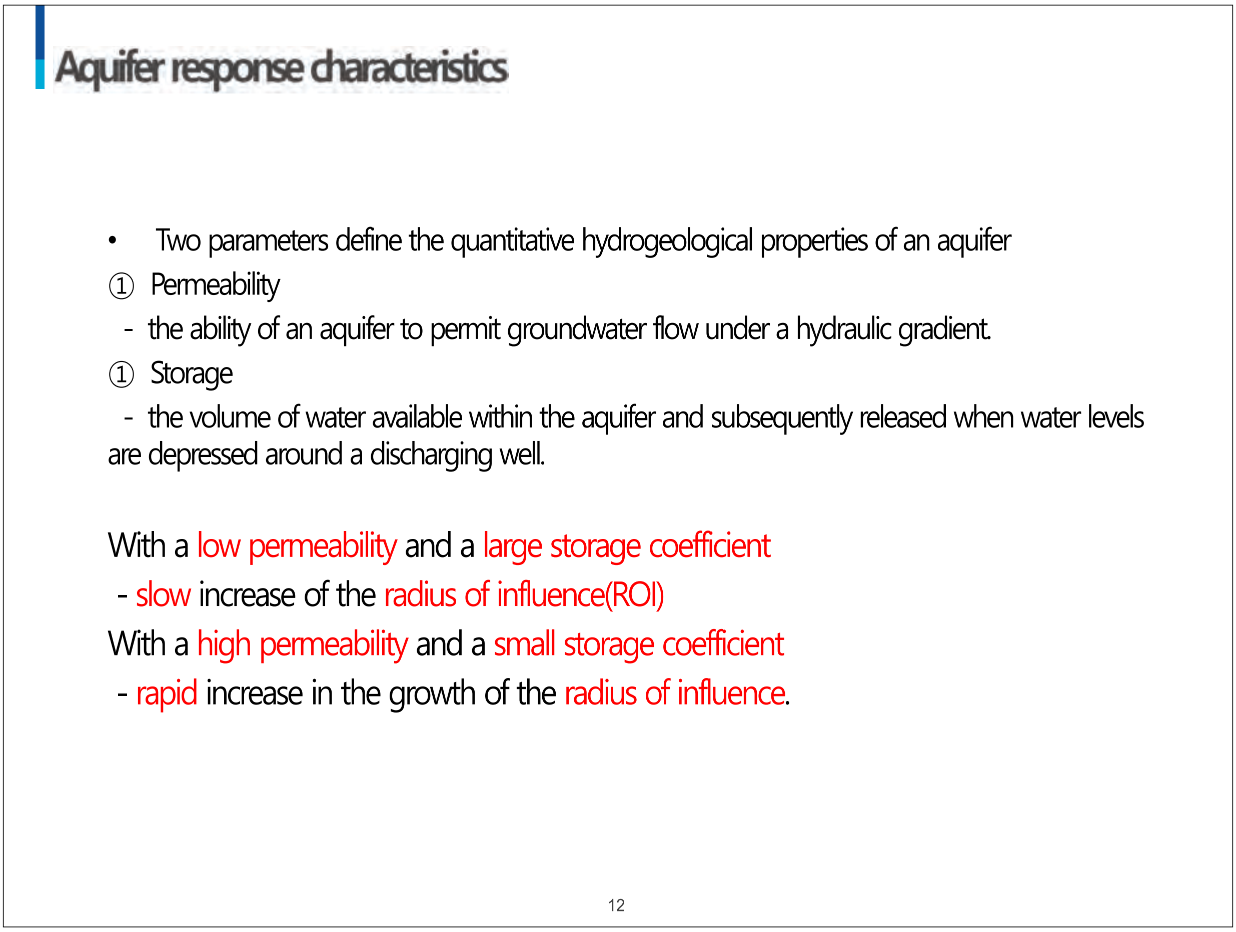
Purposes of pumping tests

- To obtain data with which to:

① Assess the hydraulic behavior of a well and so determine its ability to yield water, predict its performance under different pumping regimes, select the most suitable pump for long-term use and give some estimate of probable pumping costs;

② Determine the hydraulic properties of the aquifer or aquifers which yield water to the well; these properties include the transmissivity and related hydraulic conductivities, storage coefficient, and the presence, type and distance of any hydraulic boundaries; and

③ Determine the effects of pumping on neighbouring wells, watercourses or spring discharges.



Aquifer response characteristics

- Two parameters define the quantitative hydrogeological properties of an aquifer

① Permeability

- the ability of an aquifer to permit groundwater flow under a hydraulic gradient.

① Storage

- the volume of water available within the aquifer and subsequently released when water levels are depressed around a discharging well.

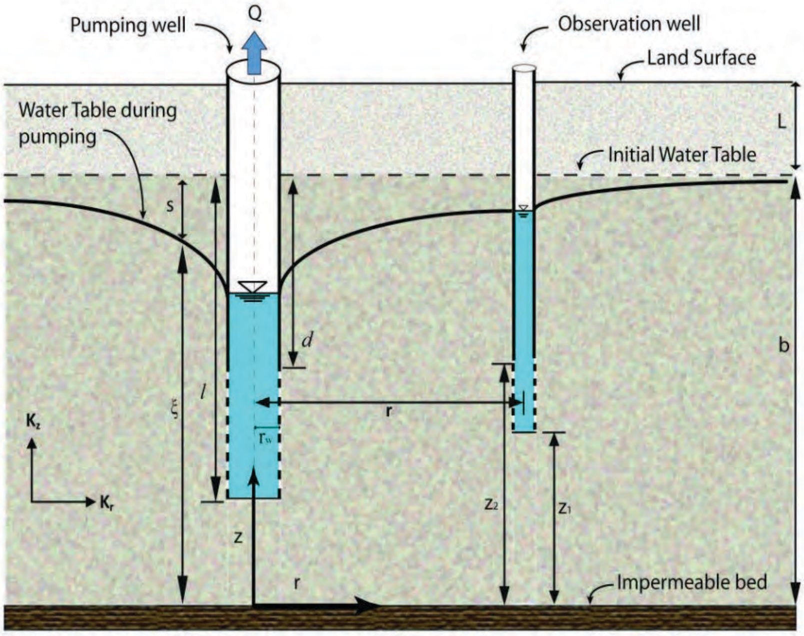
With a low permeability and a large storage coefficient

- slow increase of the radius of influence(ROI)

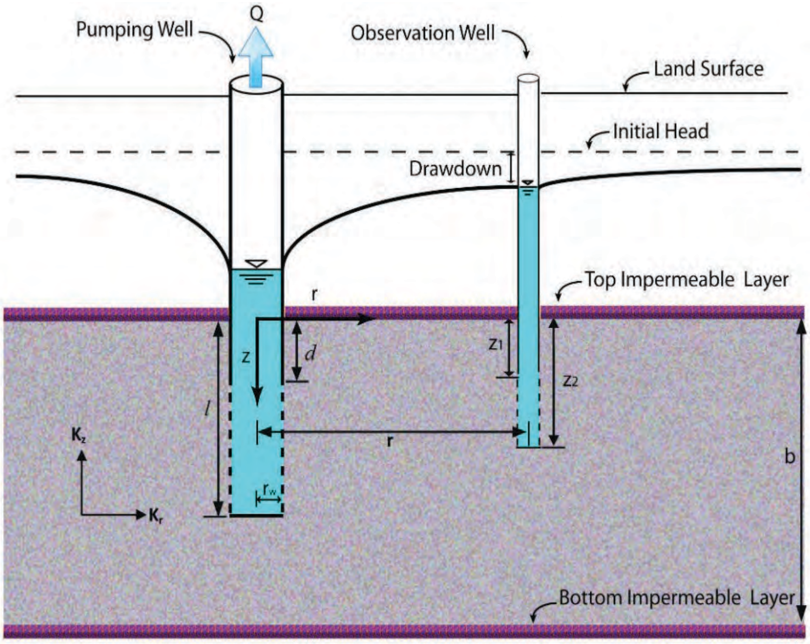
With a high permeability and a small storage coefficient

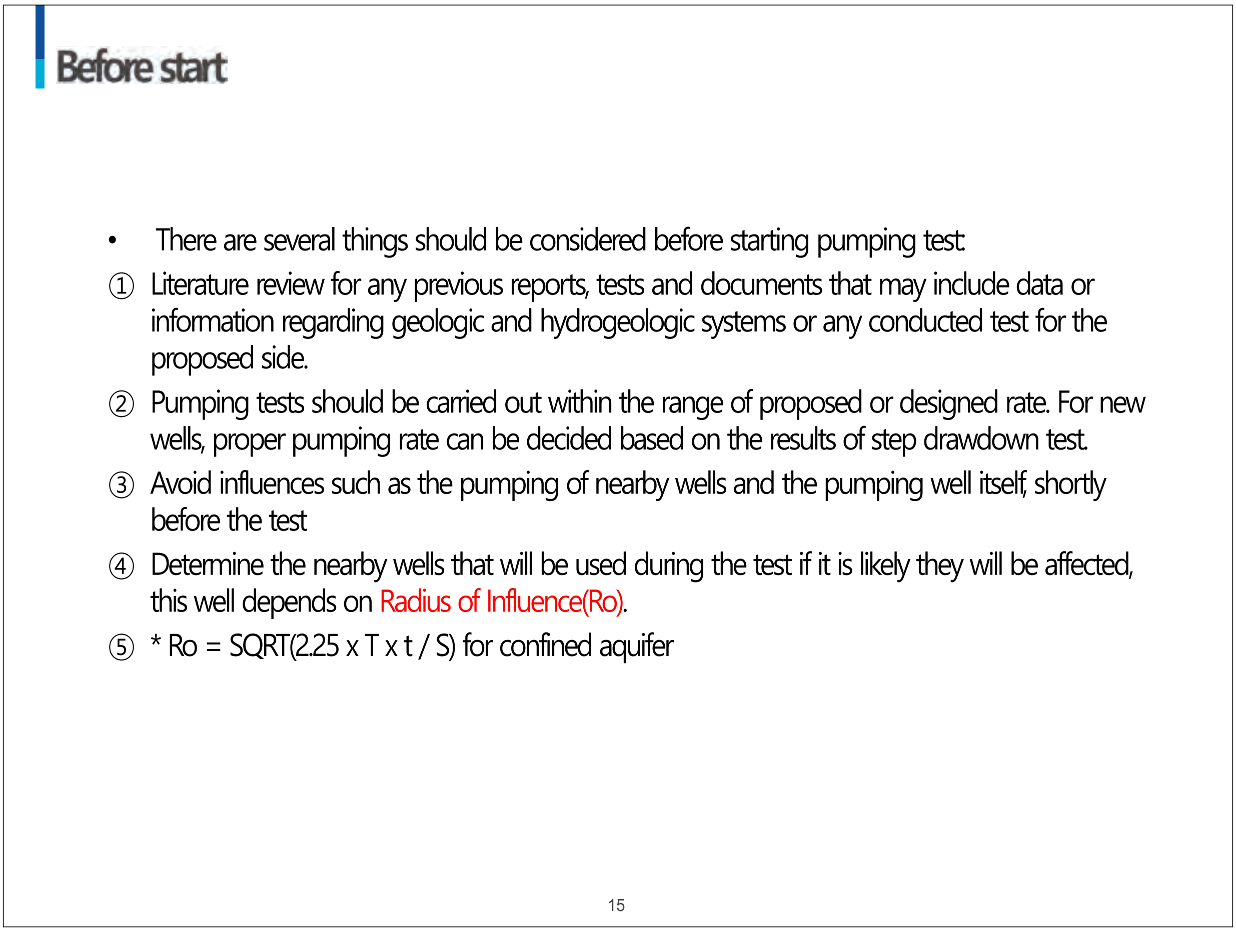
- rapid increase in the growth of the radius of influence.

Pumping well with observation well in unconfined aquifer



Pumping well with observation well in confined aquifer





Before start

- There are several things should be considered before starting pumping test:

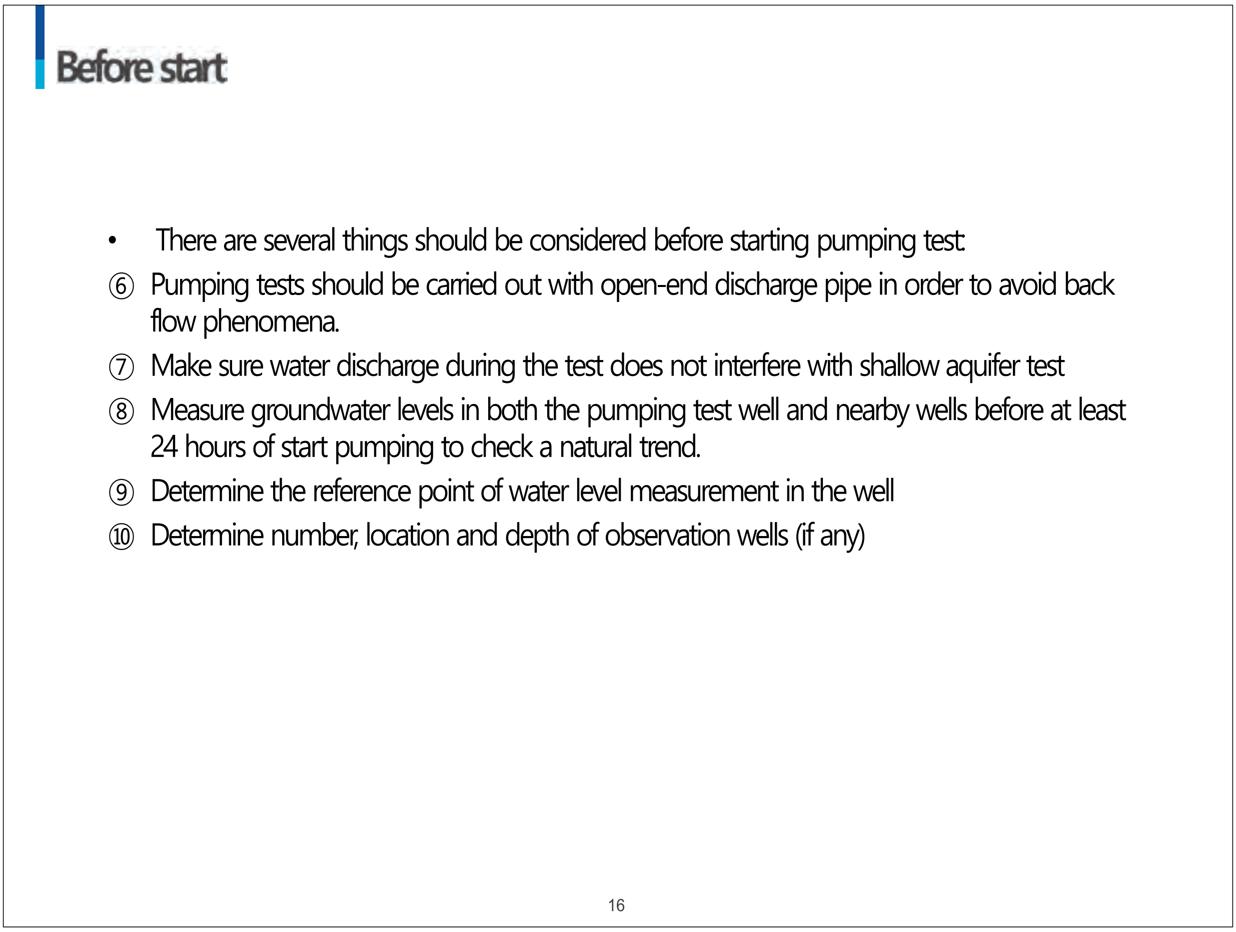
① Literature review for any previous reports, tests and documents that may include data or information regarding geologic and hydrogeologic systems or any conducted test for the proposed side.

② Pumping tests should be carried out within the range of proposed or designed rate. For new wells, proper pumping rate can be decided based on the results of step drawdown test.

③ Avoid influences such as the pumping of nearby wells and the pumping well itself, shortly before the test

④ Determine the nearby wells that will be used during the test if it is likely they will be affected, this well depends on Radius of Influence(Ro).

⑤ * Ro = SQRT(2.25 x T x t / S) for confined aquifer



Before start

- There are several things should be considered before starting pumping test:

⑥ Pumping tests should be carried out with open-end discharge pipe in order to avoid back flow phenomena.

⑦ Make sure water discharge during the test does not interfere with shallow aquifer test

⑧ Measure groundwater levels in both the pumping test well and nearby wells before at least 24 hours of start pumping to check a natural trend.

⑨ Determine the reference point of water level measurement in the well

⑩ Determine number, location and depth of observation wells (if any)

Equipment

- Pumping well and one or more observation wells
- Equipment preparation
  - (Submersible) pump, discharge pipe(hose) and check valve for pumping
  - Flowmeter (or bucket) and stopwatch for measuring flow rate
  - Electrical tape and/or ata logger for measuring drawdown
  - Data collection sheet

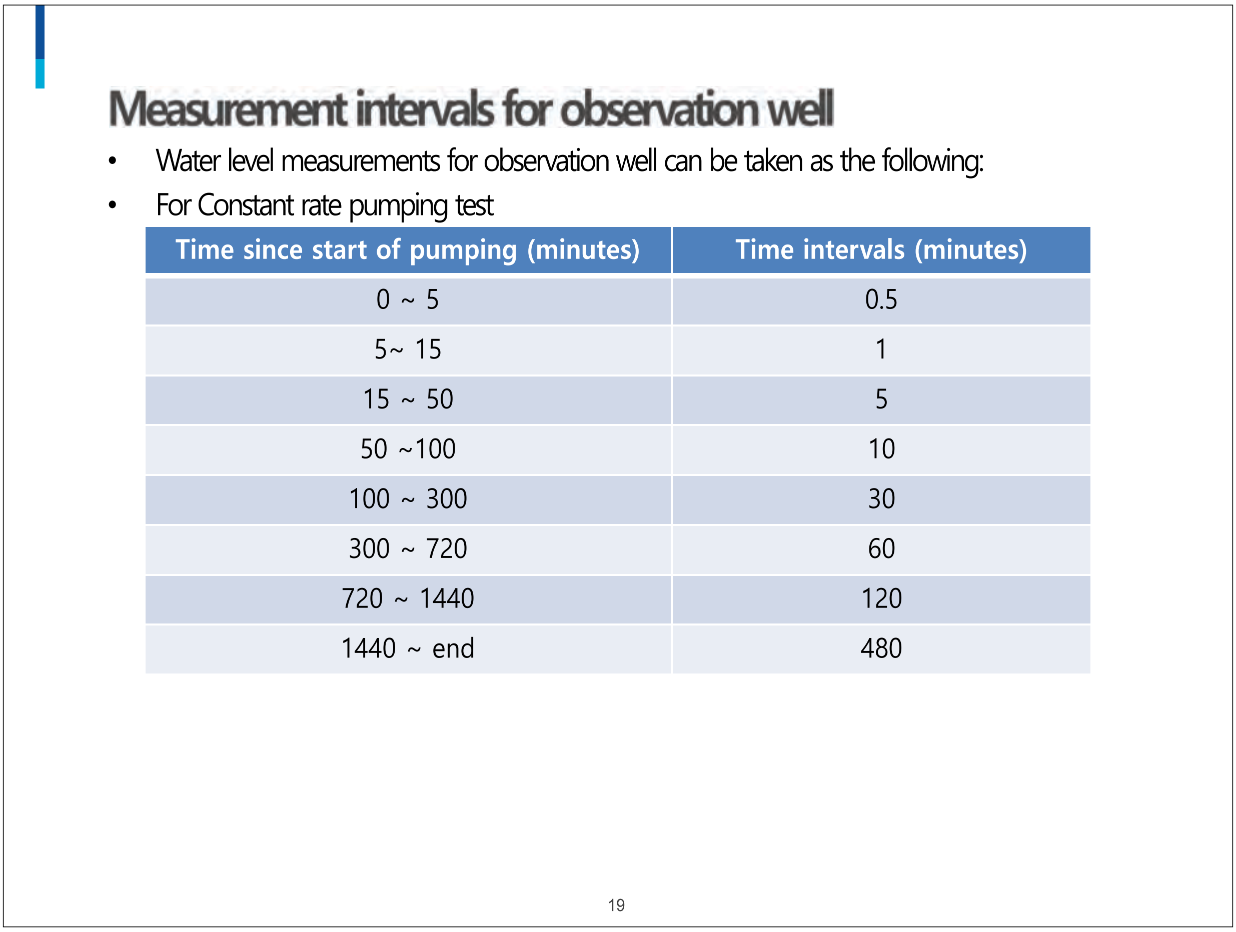
Measurement intervals for pumping well

- Water level measurements for pumping well could be taken as the following:
- For Constant rate pumping test

Time since start of pumping (minutes)	Time intervals (minutes)
0 ~ 5	0.5
5~ 60	5
60 ~ 120	20
120 ~ 720	60
720 ~1440	120

- For each step of step drawdown pumping test

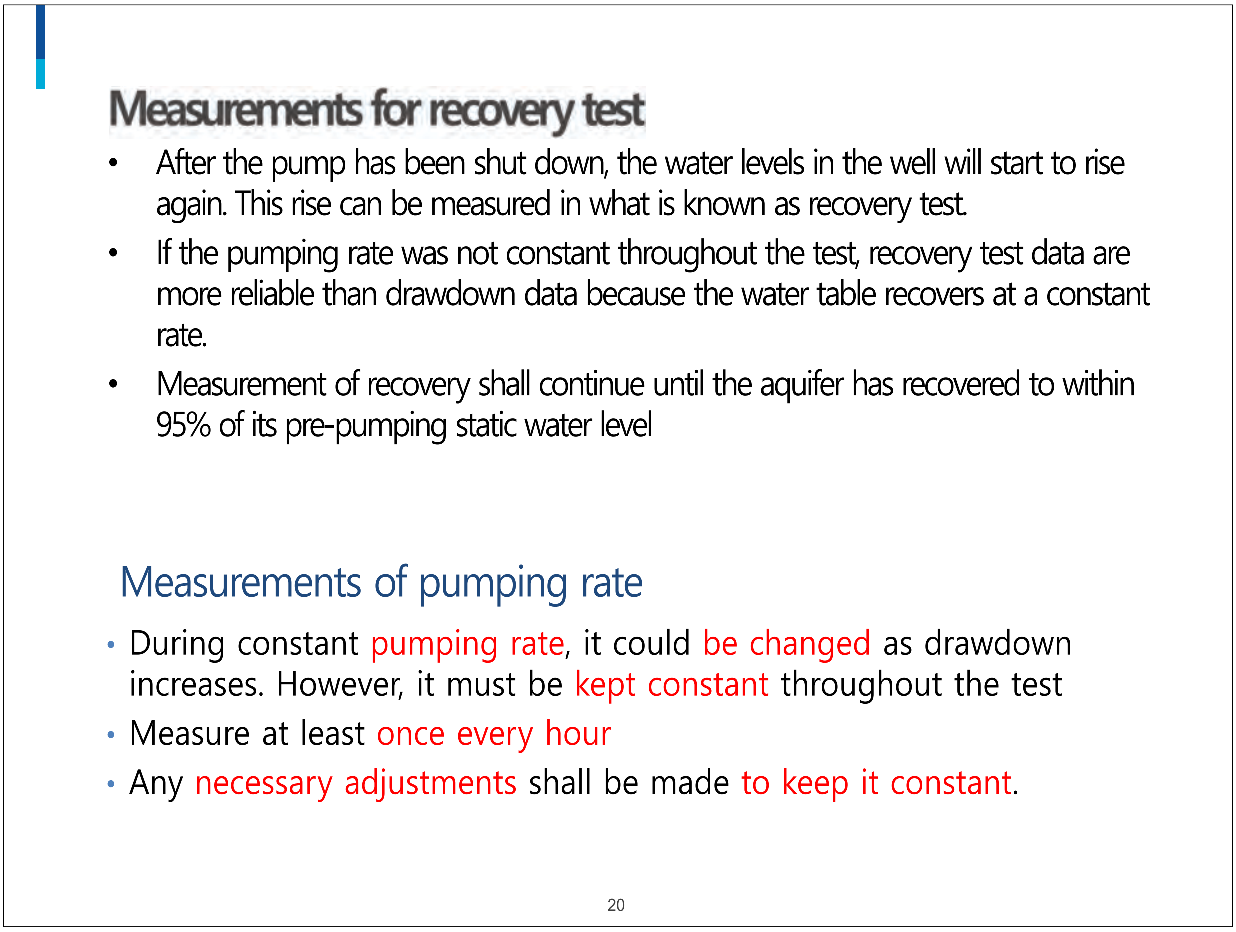
Time since start of pumping (minutes)	Time intervals (minutes)
0 ~ 10	1
10~ 20	2
20 ~ 60	5



Measurement intervals for observation well

- Water level measurements for observation well can be taken as the following:
- For Constant rate pumping test

Time since start of pumping (minutes)	Time intervals (minutes)
0 ~ 5	0.5
5~ 15	1
15 ~ 50	5
50 ~100	10
100 ~ 300	30
300 ~ 720	60
720 ~ 1440	120
1440 ~ end	480



Measurements for recovery test

- After the pump has been shut down, the water levels in the well will start to rise again. This rise can be measured in what is known as recovery test.
- If the pumping rate was not constant throughout the test, recovery test data are more reliable than drawdown data because the water table recovers at a constant rate.
- Measurement of recovery shall continue until the aquifer has recovered to within 95% of its pre-pumping static water level

Measurements of pumping rate

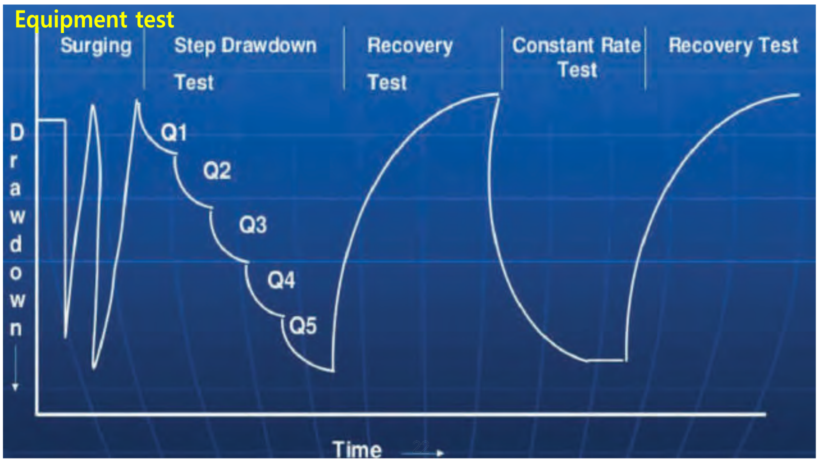
- During constant pumping rate, it could be changed as drawdown increases. However, it must be kept constant throughout the test
- Measure at least once every hour
- Any necessary adjustments shall be made to keep it constant.

Duration of pumping test

- It is difficult to determine the pumping duration because the pumping period depends on the type and natural materials of the aquifer. In general pumping test is going on until pseudo-steady state flow is attained or dynamic water level fluctuate slightly.
- In some tests, steady state occurs a few hours after pumping, in others, they never occur. However, 24-72 hours test duration is enough to produce diagnostic data.

General pumping test procedures

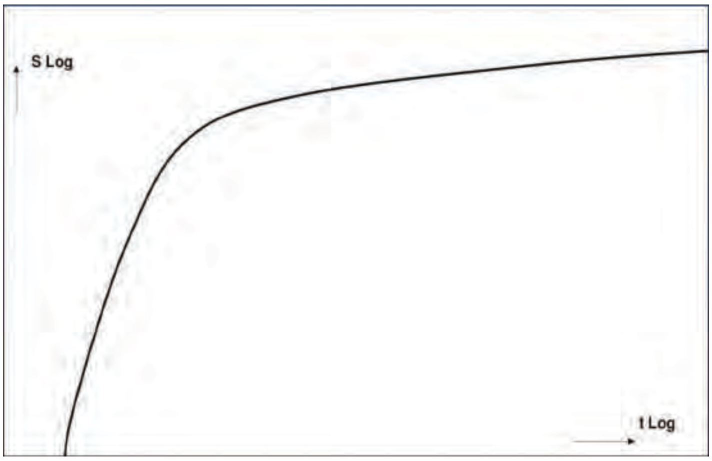
- For a new well, through a equipment test for well development (surging), well productivity can be preliminary estimated.
- Through step drawdown test following recovery test, optimal pumping rate can be determined for the long-term pumping test.
- Constant rate pumping test can be carried out at the pumping rate which determined by step drawdown test



Specific boundary conditions

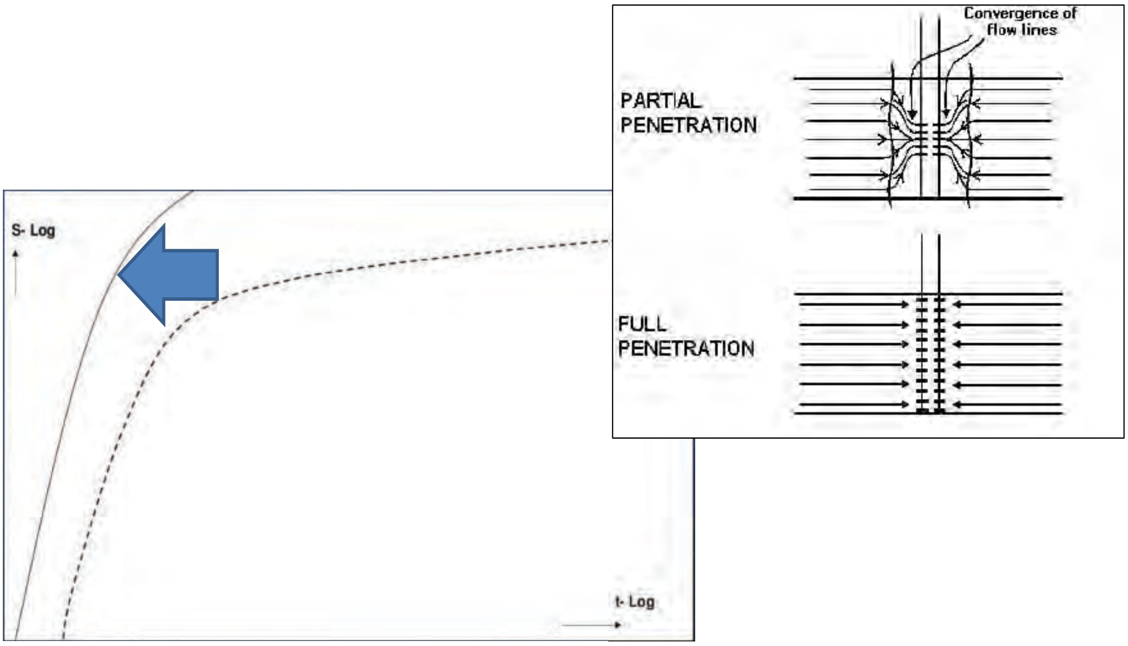
- When field data curves of drawdown versus time deviated from theoretical curves of the main types of aquifer, the deviation is usually due to specific boundary conditions such as partial penetration well, wellbore storage, recharge boundary, or impermeable boundary.

Theoretical curve for confined aquifer



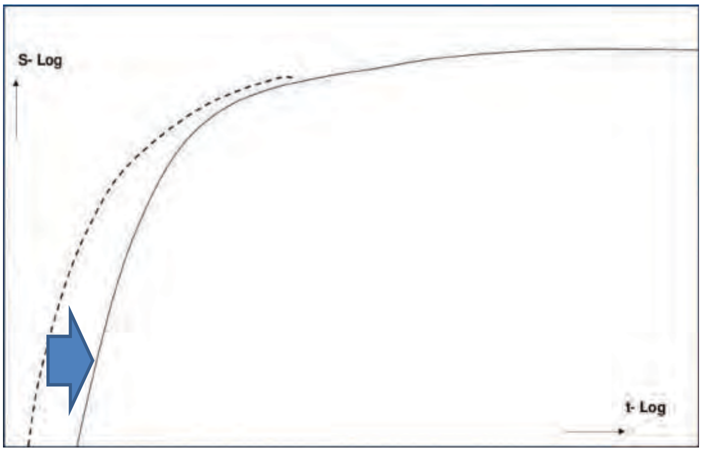
Partial penetration effect

- With partial penetration well, the condition of horizontal flow is not satisfied, at least not in the vicinity of the well. Vertical flow components are inducing extra head losses in the well.



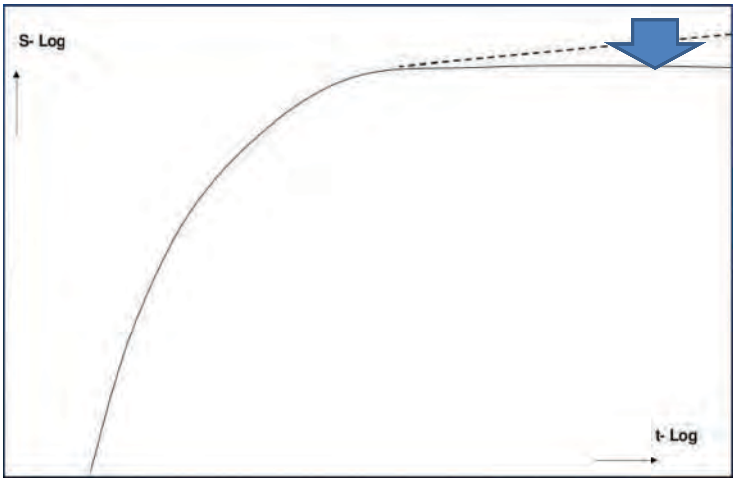
Wellbore storage effect

- If a pumping test is conducted in a large-diameter well, the data will be affected by the wellbore storage in the pumped well. At early pumping time, data will deviate from the theoretical curve.
- Delayed drawdown compared to the theoretical curve
- Disappears as pumping continues



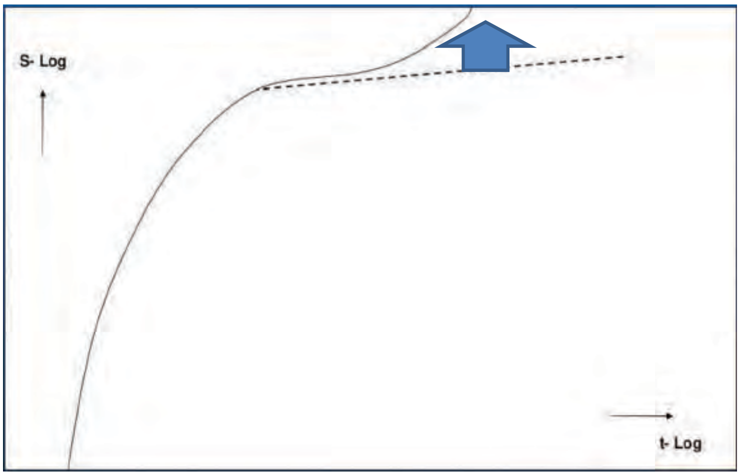
Effect of recharge boundary

- Recharge or impermeable boundaries can also affect the theorectical curves of all aquifer types.
- The field data curve then begins to deviate from the theoretical curve up to stabilization in recharge case



Effect of impermeable boundary

- Impermeable boundaries have the opposite effect on the drawdown.
- If the cone of depression reaches such a boundary, the drawdown will double.



Data analysis methods

- Pumping test solution methods: to estimate aquifer properties

- Theis (confined)
- Cooper-Jacob (Time-drawdown) (confined)
- Hantush and Jacob (leaky-confined)
- Neuman (unconfined)
- Moench (unconfined/ partial penetrations well)
- Moench (fracture flow)

- Step test solution methods: to determine well performance and efficiency

- Theis (confined)
- Cooper-Jacob (confined)
- recovery test

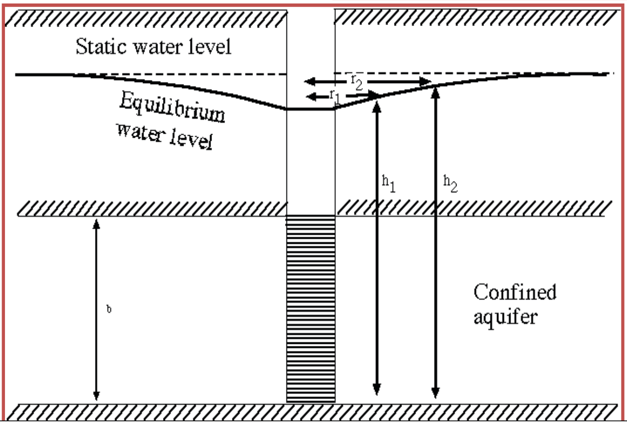
Analytical Models for pumping Tests:
Confined Aquifer

- Steady state
  - Theim's method
- Transient
  - Theis's method
  - Jacob's straight line method

$$\boxed{T=\frac{Q}{2\pi(h_2-h_1)}\ln(\frac{r_2}{r_1})}$$

$$\boxed{T=\frac{Q}{4\pi(h_0-h)}W(u)\ \ \text{and}\ \ S=\frac{4Ttu}{r^2}}$$

$$\boxed{T=\frac{2.3Q}{4\pi(h_0-h)}\log(\frac{2.25Tt}{r^2S})}$$



Analytical Models for pumping Tests:
Unconfined Aquifer

- Neuman graphical method

1. Drawdown vs time on log-log paper
2. Overlay type curves
3. Pick match points

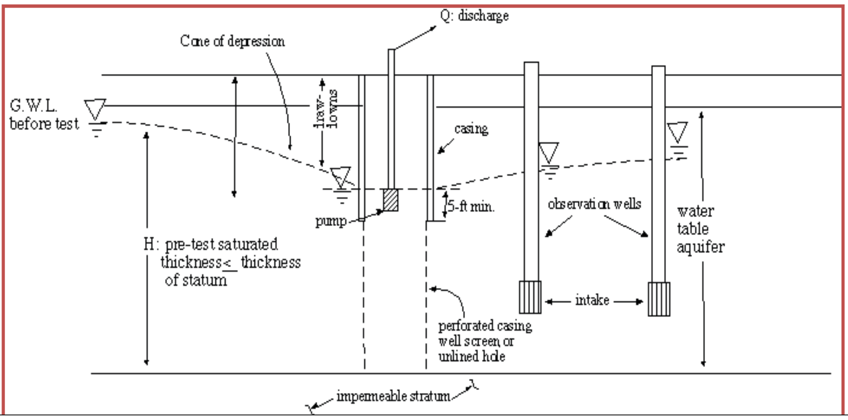
   w(u_A,u_B,Γ), u_A(early time drawdown), u_B(late time drawdown), **Γ** from type curve

   t, s from field data
4. Calculate

$$\boxed{T=\frac{Q}{4\pi s}W(u_A,u_B,\Gamma)}$$

$$\boxed{S=\frac{4Tu_At}{r^2}}\quad\boxed{S_y=\frac{4Tu_Bt}{r^2}}$$

$$\boxed{\Gamma=\frac{(r^2K_v)}{b^2K_h}}$$



Analytical Models for step drawdown test

- Step drawdown test developed to assess the well performance (well losses due to turbulent flow)
- At lest 5 pumping steps are needed, each step lasting from 1 to 2 hours
- step drawdown test is used to determine the optimum pumping rate
- Step drawdown test can be used to determine T and S from each step

---

Analytical Models for step drawdown test

- Total drawdown in a well (Jacob)

$s_T = s_a + s_W = BQ + CQ^2$ (1)

where

s_T is the total drawdown,

s_a(=BQ) : part of drawdown due to aquifer losses (as laminar term)

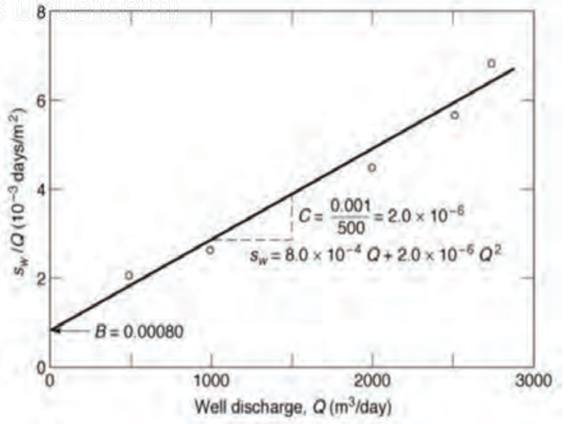
s_W(=CQ^2) : drawdown due to well losses (as turbulent term)

Q : Pumping rate

$s/Q = B + CQ$ (2)

$Lp = BQ/(BQ+CQ^2)x100$ (3)

-> Well efficiency



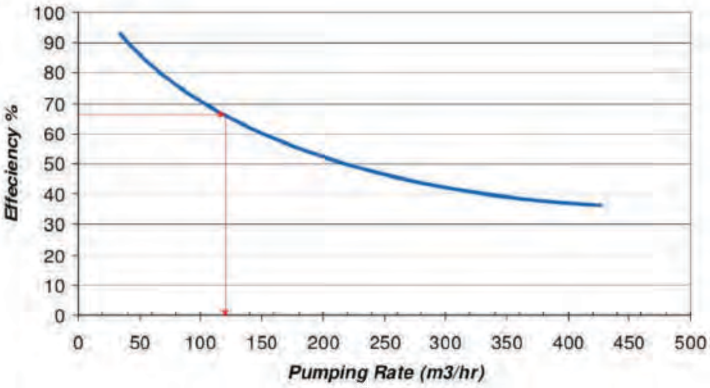
Well efficiency:

- Well efficiency is the ratio between theoretical drawdown and the actual drawdown measured in the well
- A well efficiency of 70% or more is usually acceptable
- If a newly developed well has less than 65% well efficiency, it should not be accepted. It need a well development process such as surging.

Optimum pumping rate

- Determining the optimum pumping rate is based on the well loss and well efficiency

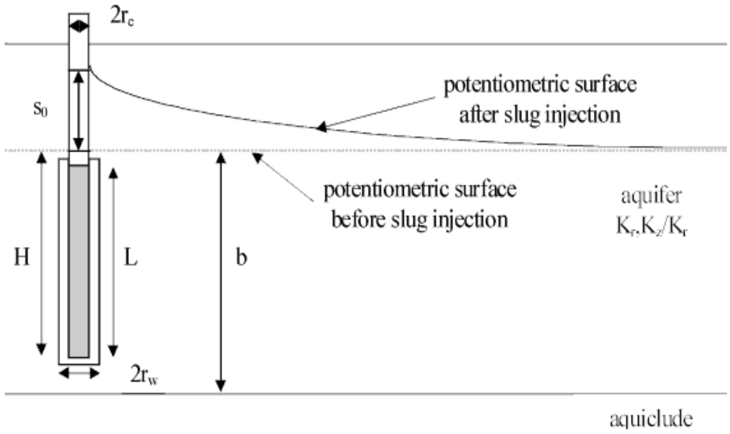
1. for up to ten different Q, find s_T based on the equation $s_T = BQ + CQ^2$
2. for the same pumping rate, find theoretical drawdown(s) through the equation, s= $(Q/2\pi T)\ln(R/r_w)$
3. calculate well efficiency for all pumping rates
4. demonstrate graph between efficiencies and pumping rates, and choose the Q value that correspond more than 65% efficiency or more.



SLUG TESTS

Slug Test

- Advantages of Slug Test
    - Simpler and quicker than pumping test
    - Useful for small scale study
    - Good in low K layer



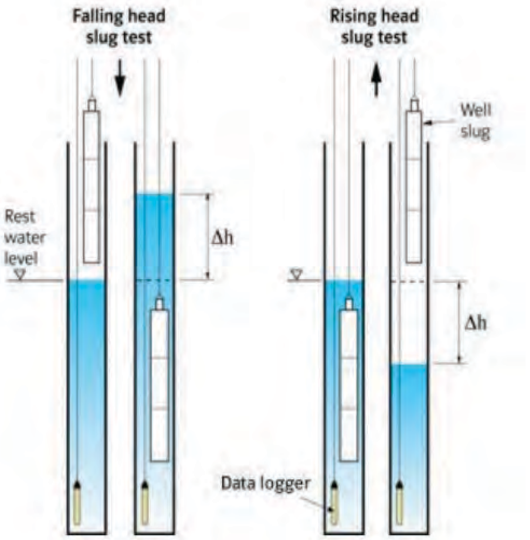
Falling head or rising head slug test

Falling head slug test:

- place transducer sufficiently below to avoid interference with slug
- place slug just above top of water column
- drop slug
- record water level as it returns to static position

Rising head slug test:

- place slug just below water table
- withdraw slug as quick as possible
- monitor water level



Data analysis methods

- Slug test solution methods:

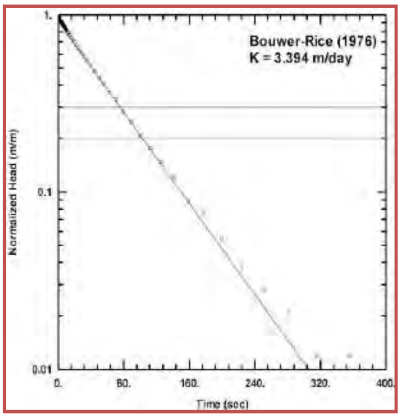
- Hvorslev
- Bouwer-Rice
- Hantush-Bierschenk

Analytical Methods for Slug Test

- Hvorslev straight line method (confined aq.)
  - Plot of h/ho vs. time on semi-log plot
  - Draw straight line through data
  - Draw straight line through data at H/H_0=0.37
  - Calculate K using T_o, r, L, R

$$\boxed{K = \frac{r^2 \ln(L/R)}{2LT_0}}$$

- Bouwer-Rice method (unconfined aq.)
  - Similar with the procedure of Hvorslev method



- Recommended normalized head range for straight line match
  - Hvorslev = 0.15~0.25
  - Bouwer-Rice = 0.2~0.3

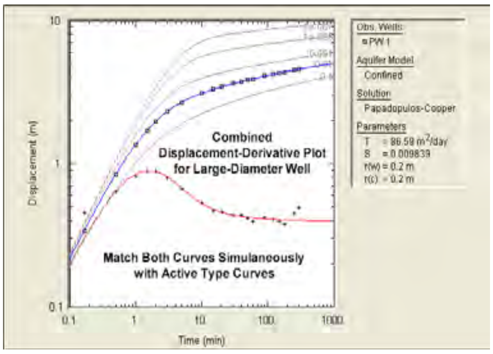
Pumping Test reports

Pumping test reports should include the following:

- ✓ A map, showing the location of the investigated site, pumping and observation wells.
- ✓ Details on the existed wells (main data).
- ✓ Well logs and construction details for all wells.
- ✓ Geological cross--section of the study area.
- ✓ Tables of field measurements: Drawdown measurements, time of measurement and flow rate (including soft copy)
- ✓ The calculations in an abbreviated form, including the values obtained for the aquifer parameters and discussion of their accuracy.
- ✓ Recommendations.
- ✓ Summary.

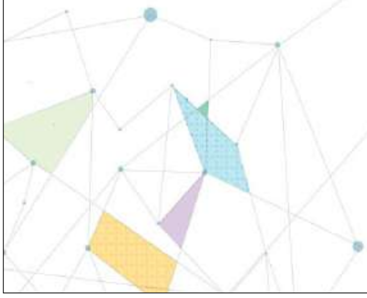
Training by using Pumping Test Analysis Software

- Analytical Software
  - AQTESOLV or Aquifer Test …



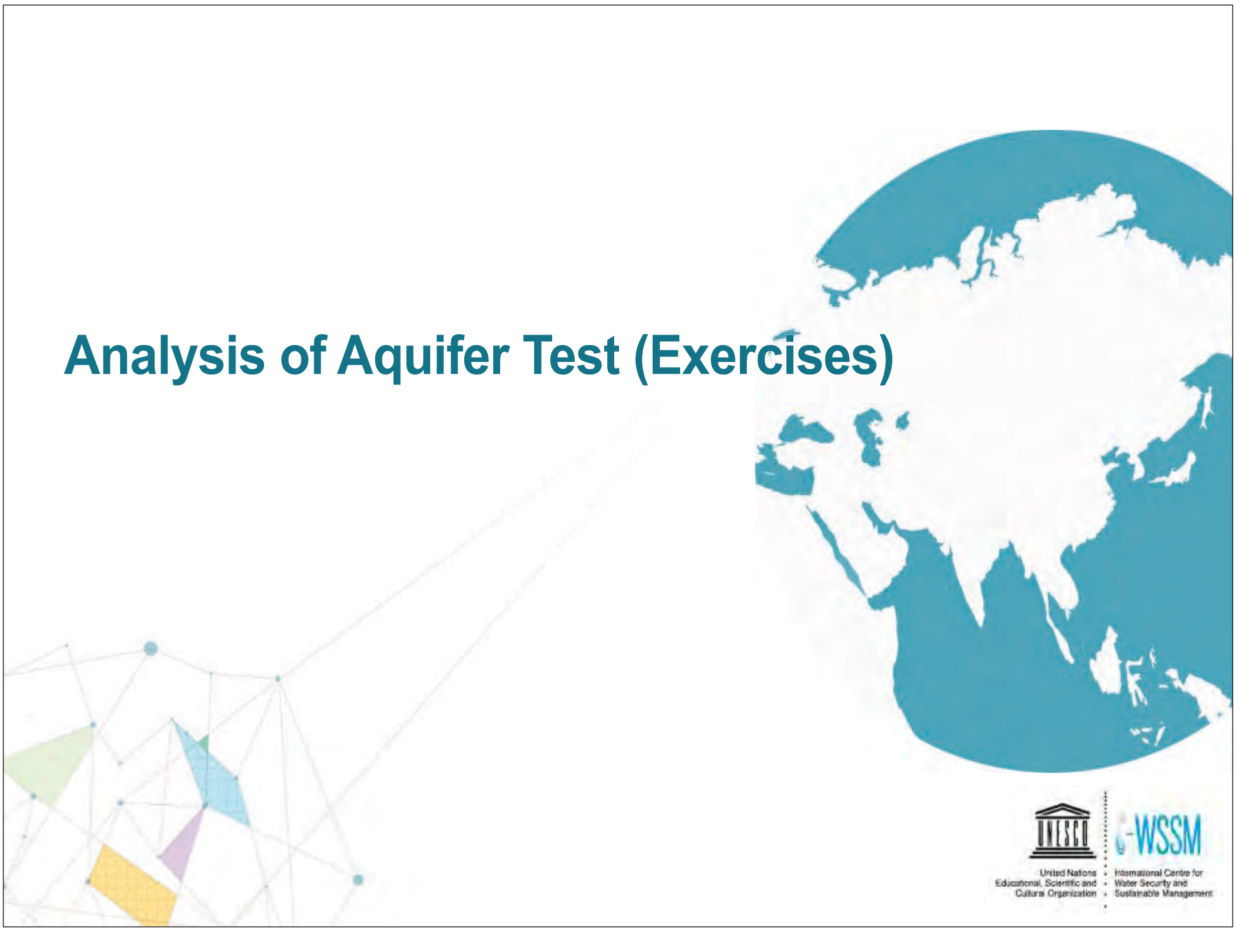
  - Exercise in the next module

Thank you very much



Analysis of Aquifer Test (Exercises)

Groundwater



Analysis of Aquifer Test (Exercises)

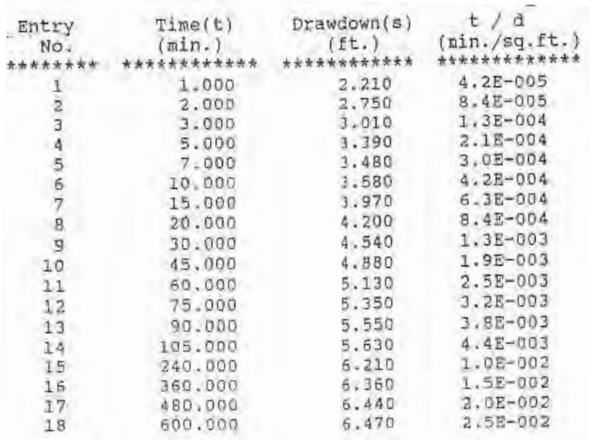
AQTESOLV

- Software for the analysis of aquifer tests (pumping tests, constant-head tests and slug tests)
- Glenn M. Duffield, HydroSOLVE, Inc., USA
- Features in AQTESOLV
  - Solution for Unconfined Aquifer with 3D Saturated/Unsaturated Flow
  - Constant-Head Tests
  - Solutions for Nonuniform Aquifers
  - Generalized Radial Flow Model
  - Solution for a Water-Table Aquitard
  - Underdamped Slug Tests with Partially Penetrating Wells
  - Horizontal Wells
  - Single-Fracture Solutions
  - Step-Drawdown Test in Leaky Aquifer
  - Confined Two-Aquifer System
  - Automatic Image Well Generation
  - Delayed Observation Well Response
  - Dagan's Slug Test Method for Wells Screened Across Water Table
  - Slug Tests in Fractured Aquifers
  - Distance-Drawdown Analysis
  - Groundwater Mounding
  - Diagnostic Flow Plots
  - Active Type Curves

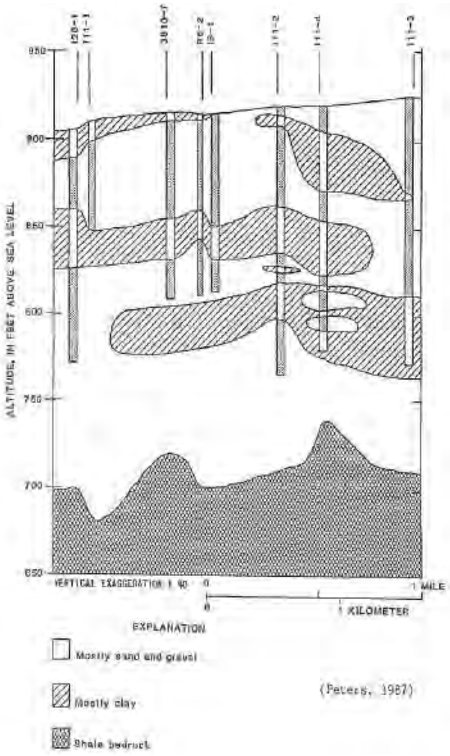
Pumping test outline

	Pumping Well (I6-1)	Obs. Well (R6-2)
Well depth (ft)	105	105
Water level depth (ft bgl*)	5	5
Screen Length (ft)	20	3
Well diameter (ft)	1	1/6
Pumping rate (ft3/d)	108,760	
Distance from pumping well (ft)		154
Aquifer thickness (ft)	21	

* bgl = below ground level



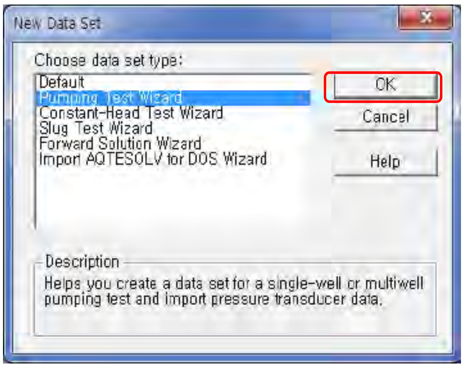
```
 Entry       Time(t)      Drawdown(s)       t / d
  No.         (min.)         (ft.)      (min./sq.ft.)
********  ************  ************  *************
   1           1.000          2.210        4.2E-005
   2           2.000          2.750        8.4E-005
   3           3.000          3.010        1.3E-004
   4           5.000          3.390        2.1E-004
   5           7.000          3.480        3.0E-004
   6          10.000          3.580        4.2E-004
   7          15.000          3.970        6.3E-004
   8          20.000          4.200        8.4E-004
   9          30.000          4.540        1.3E-003
  10          45.000          4.880        1.9E-003
  11          60.000          5.130        2.5E-003
  12          75.000          5.350        3.2E-003
  13          90.000          5.550        3.8E-003
  14         105.000          5.630        4.4E-003
  15         240.000          6.210        1.0E-002
  16         360.000          6.360        1.5E-002
  17         480.000          6.440        2.0E-002
  18         600.000          6.470        2.5E-002
```



(Peters, 1987)

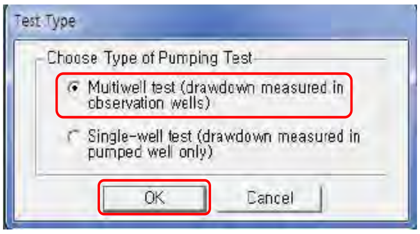
Open, Choose data set and test type

- Open AQTESOLV.exe
- File – New – Choose "Pumping test wizard" for data set type
- Choose "Multiwell test" for test type



Description

Helps you create a data set for a single-well or multiwell pumping test and import pressure transducer data.



Choose Type of Pumping Test

● Multiwell test (drawdown measured in observation wells)

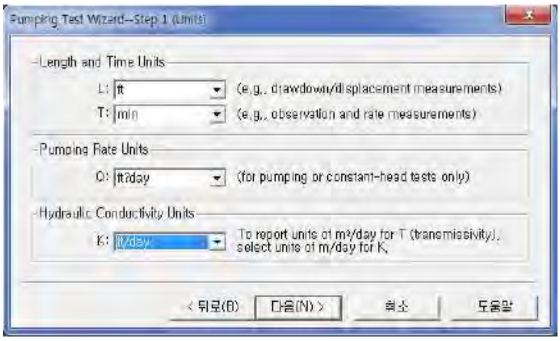
○ Single-well test (drawdown measured in pumped well only)

Data set type

- Default
- Pumping test
  - Data set for a single- or multi-well test
- Constant-head test
- Slug test
- Forward solution
  - Predictive simulation of a pumping test
- Import AQTESOLV for DOS
  - Import data set created with a DOS ver. Of AQTESOLV

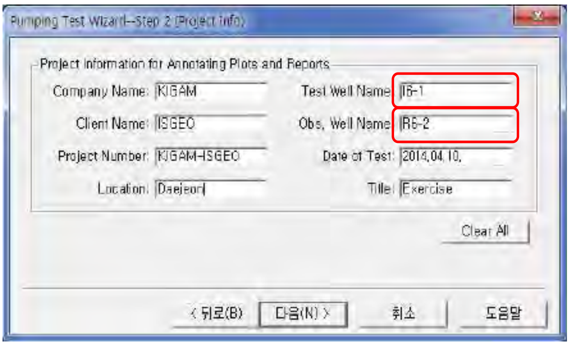
Unit, Project Information

- Pumping Test Wizard—Step 1 (Unit-ft, min, ft^3/day, ft/day)
- Pumping Test Wizard—Step 2 (Project Information)



Length and Time Units
L: ft (e.g., drawdown/displacement measurements)
T: min (e.g., observation and rate measurements)
Pumping Rate Units
Q: ft?day (for pumping or constant-head tests only)
Hydraulic Conductivity Units
K: ft/day To report units of m²/day for T (transmissivity), select units of m/day for K.

< Unit >

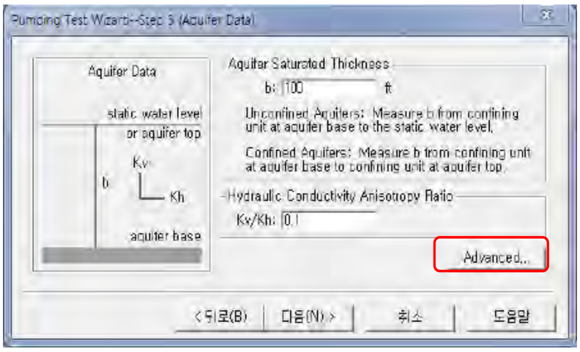


Project Information for Annotating Plots and Reports
Company Name: KIGAM
Client Name: ISGEO
Project Number: KIGAM-ISGEO
Location: Daejeon
Test Well Name: I6-1
Obs. Well Name: R6-2
Date of Test: 2014.04.10.
Title: Exercise

< Project Info >

Pumping well Information

- Pumping Test Wizard—step 3 (Aquifer Data)
  - Thickness: 100 ft, Kv/Kh: 0.1



Aquifer Saturated Thickness

b: 100 ft

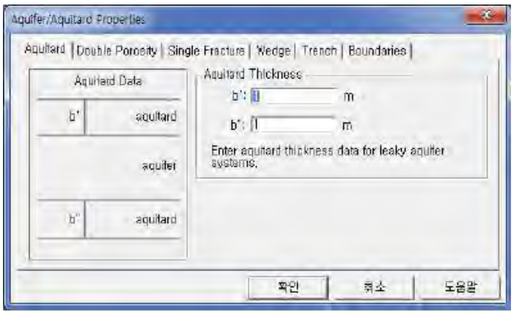
Unconfined Aquifers: Measure b from confining unit at aquifer base to the static water level.

Confined Aquifers: Measure b from confining unit at aquifer base to confining unit at aquifer top.

Hydraulic Conductivity Anisotropy Ratio

Kv/Kh: 0.1

< Aquifer data >

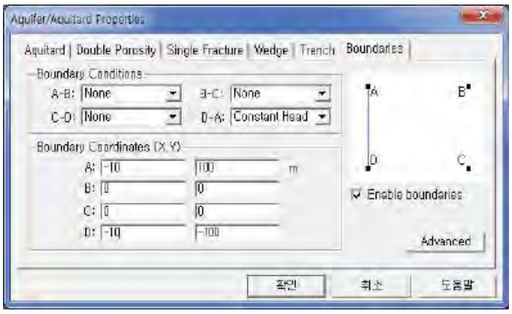


Aquitard Thickness

b': 0 m

b'': 1 m

Enter aquitard thickness data for leaky aquifer systems.



Boundary Conditions

A-B: None B-C: None

C-D: None D-A: Constant Head

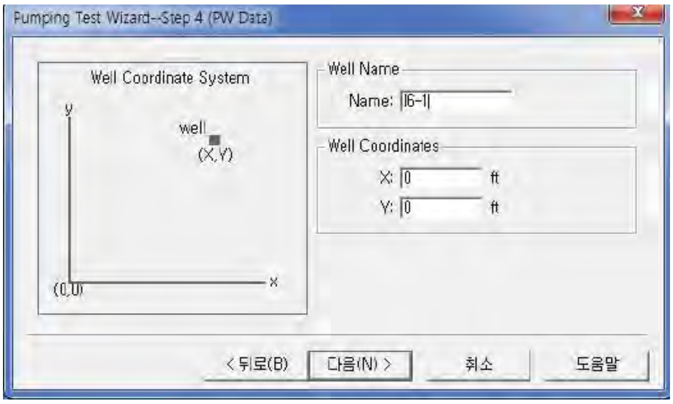
Boundary Coordinates (X, Y)

	X	Y	
A:	-10	100	m
B:	0	0	
C:	0	0	
D:	-10	-100	

☑ Enable boundaries

Pumping well Information

- Pumping Test Wizard—step 4 (PW Data)
  - Name: I6-1, (x,y): (0,0)



Well Name

Name: I6-1

Well Coordinates

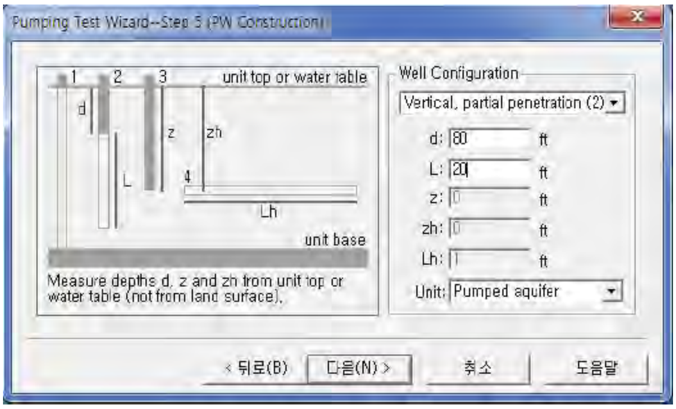
X: 0 ft

Y: 0 ft

< well Location>

Pumping well Information

- Pumping Test Wizard—step 5 (PW Construction)
  - Select "vertical, partial penetration(2)" for well configuration
  - d: 80 ft, L: 20 ft, Unit: pumped aquifer



Pumping Test Wizard--Step 5 (PW Construction)

Measure depths d, z and zh from unit top or water table (not from land surface).

Well Configuration: Vertical, partial penetration (2)

d: 80 ft

L: 20 ft

z: 0 ft

zh: 0 ft

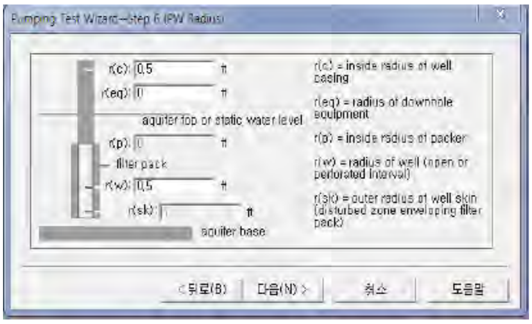
Lh: 1 ft

Unit: Pumped aquifer

< PW Construction >

Pumping well Information

- Pumping Test Wizard—step 6 (PW Radius)
  - r(c)=r(w): 0.5 ft, r(eq): 0 ft
- Pumping Test Wizard—step 7 (PW Rate Data)
  - Insert Row or Add Rows of 1
  - Type "0" -> enter -> type "108760" -> enter
  - Type "600" -> enter -> type "108760" -> finalize by clicking mouse



Pumping Test Wizard--Step 6 (PW Radius)

r(c): 0.5 ft

r(eq): 0 ft

r(p): 0 ft

r(w): 0.5 ft

r(sk): 1 ft

r(c) = inside radius of well casing

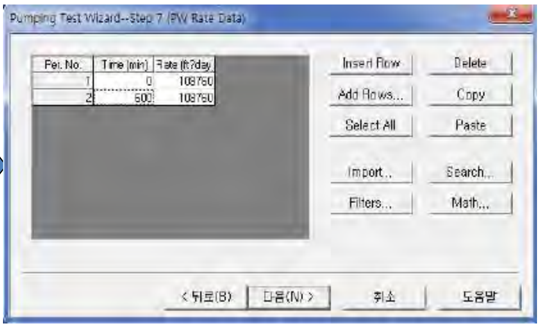
r(eq) = radius of downhole equipment

r(p) = inside radius of packer

r(w) = radius of well (open or perforated interval)

r(sk) = outer radius of well skin (disturbed zone enveloping filter pack)

< PW Radius >



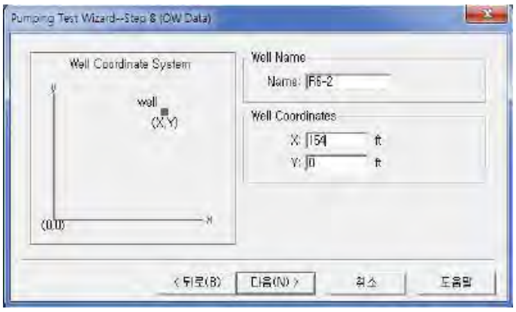
Pumping Test Wizard--Step 7 (PW Rate Data)

Per. No.	Time (min)	Rate (ft?day)
1	0	108760
2	600	108760

< PW Rate data >

Observation well Information

- Pumping Test Wizard—step 8 (OW Data)
  - Name: R6-2, (x,y): (154,0)
- Pumping Test Wizard—step 9 (OW Construction)
  - Select "vertical, partial penetration(2)" for well configuration
  - d: 97 ft, L: 3 ft, Unit: pumped aquifer



Pumping Test Wizard--Step 8 (OW Data)

Well Name

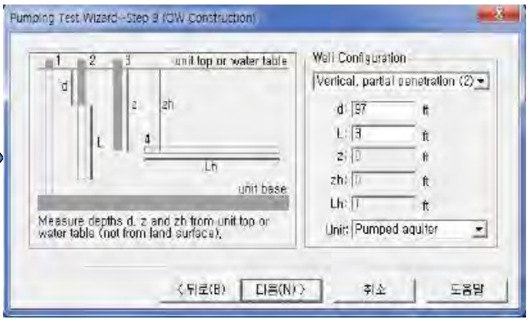
Name: R6-2

Well Coordinates

X: 154 ft

Y: 0 ft

< Obs. Well Location >



Pumping Test Wizard--Step 9 (OW Construction)

Well Configuration: Vertical, partial penetration (2)

d: 97 ft

L: 3 ft

z: 0 ft

zh: 0 ft

Lh: 1 ft

Unit: Pumped aquifer

Measure depths d, z and zh from unit top or water table (not from land surface).

< Obs. Well Construction >

Observation well Information

- Pumping Test Wizard—step 10 (OW Radius)
  - r(c)=r(w): 0.1667 ft, r(eq): 0 ft

Pumping Test Wizard--Step 10 (OW Radius)

r(c): 0.1667 ft

r(eq): 0 ft

r(p): 0 ft

r(w): 0.1667 ft

r(sk): 1 ft

r(c) = inside radius of well casing

r(eq) = radius of downhole equipment

r(p) = inside radius of packer

r(w) = radius of well (open or perforated interval)

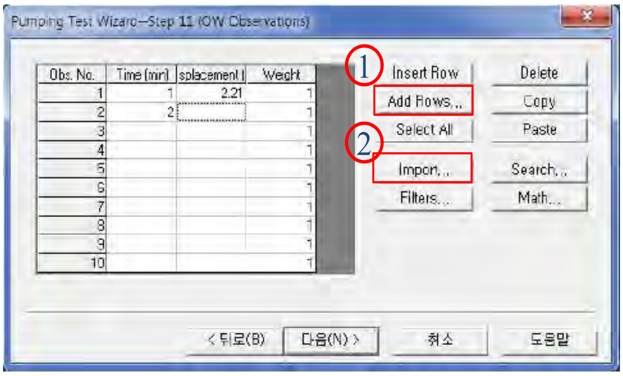
r(sk) = outer radius of well skin (disturbed zone enveloping filter pack)

< Obs. Well Radius >

< Input data>

Pumping Test Wizard—step 11 (OW Observations)

❖ Input method 1: Add Rows and then type the data



Pumping Test Wizard—Step 11 (OW Observations)

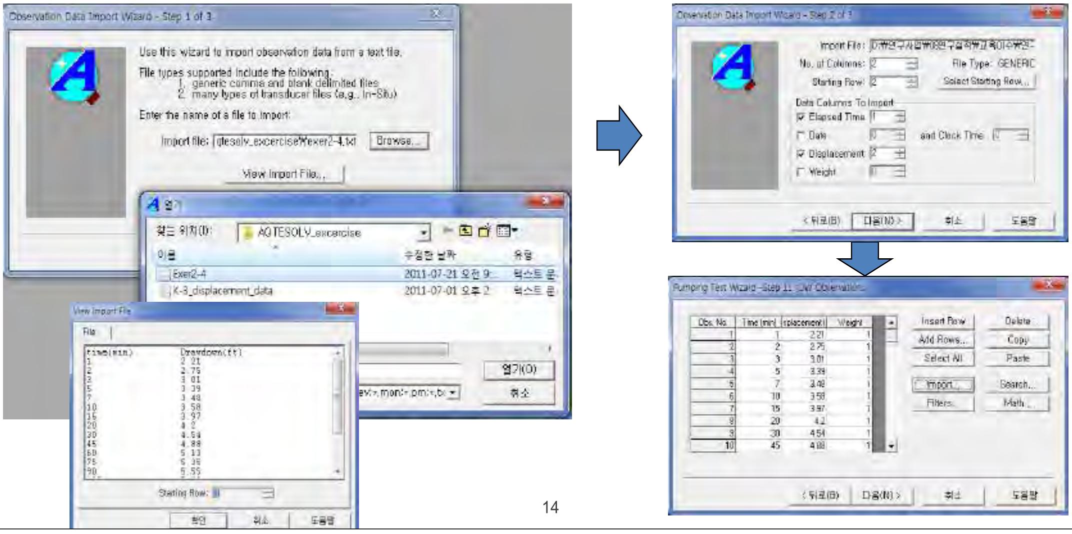
Obs. No.	Time (min)	splacement (	Weight
1	1	2.21	1
2	2		1
3			1
4			1
5			1
6			1
7			1
8			1
9			1
10			1

< Observation data >

Pumping Test Wizard—step 11 (OW Observations)

❖ Input method 2: Import file (.txt, .csv, .dat, .lev, .mon…)

- Step 1 of 3: Click "import file" -> Click "Browse" -> Select and open the file "Exer2-4" -> Click "View import file"
- Step 2 of 3: Columns= 2, starting row=2 -> check the box of "Elapsed time" and select '1" -> Check the box of "displacement" and select "2"
- Step 3 of 3: Skip this step -> The imported data are shown on the window



Observation Data Import Wizard - Step 1 of 3

Use this wizard to import observation data from a text file.

File types supported include the following:
1. generic comma and blank delimited files
2. many types of transducer files (e.g., In-Situ)

Enter the name of a file to import:

Import file: qtesolv_excercise₩exer2-4.txt

찾는 위치(I): AQTESOLV_excercise

이름	수정한 날짜	유형
Exer2-4	2011-07-21 오전 9:	텍스트 문
K-3_displacement_data	2011-07-01 오후 2	텍스트 문

View Import File

```
time(min)            Drawdown(ft)
1                    2.21
2                    2.75
3                    3.01
5                    3.39
7                    3.48
10                   3.58
15                   3.97
20                   4.2
30                   4.54
45                   4.88
60                   5.13
75                   5.35
90                   5.55
```

Observation Data Import Wizard - Step 2 of 3

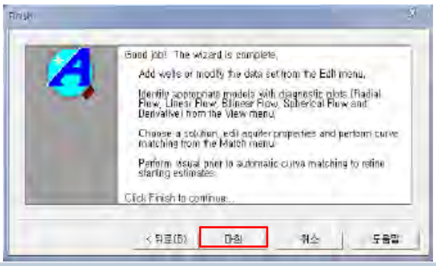
Import File: D:₩연구사업₩08연구집적₩교육이수₩연:
No. of Columns: 2
File Type: GENERIC
Starting Row: 2

Data Columns To Import
☑ Elapsed Time 1
☐ Date 0 and Clock Time 0
☑ Displacement 2
☐ Weight 0

Pumping Test Wizard—Step 11 (OW Observations)

Obs. No.	Time (min)	splacement (	Weight
1	1	2.21	1
2	2	2.75	1
3	3	3.01	1
4	5	3.39	1
5	7	3.48	1
6	10	3.58	1
7	15	3.97	1
8	20	4.2	1
9	30	4.54	1
10	45	4.88	1

Finalize Pumping Test Wizard, Check the Error log



Good job! The wizard is complete.

Add wells or modify the data set from the Edit menu.

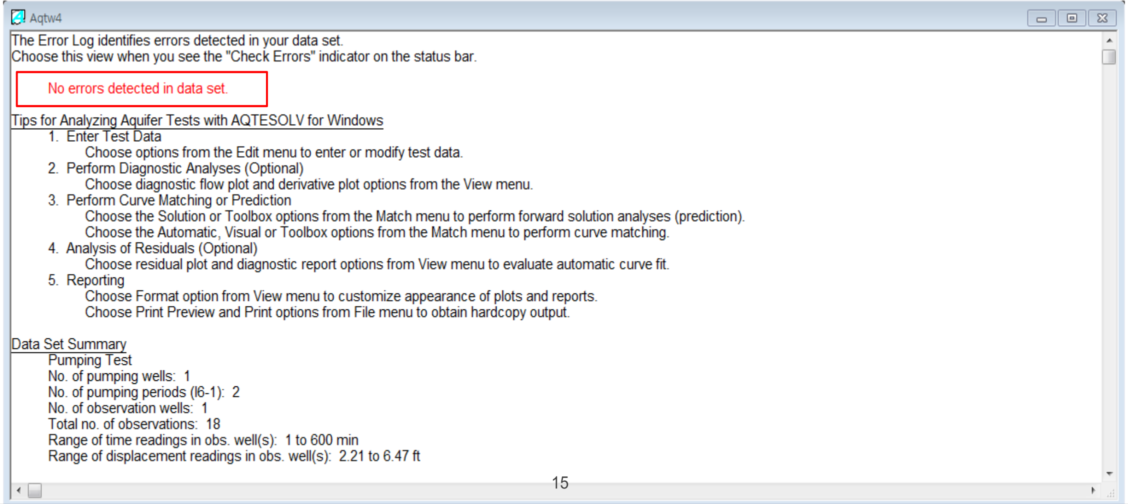
Identify appropriate models with diagnostic plots (Radial Flow, Linear Flow, Bilinear Flow, Spherical Flow and Derivative) from the View menu.

Choose a solution, edit aquifer properties and perform curve matching from the Match menu.

Perform visual prior to automatic curve matching to refine starting estimates.

Click Finish to continue...

No errors detected in data set!!!



The Error Log identifies errors detected in your data set.
Choose this view when you see the "Check Errors" indicator on the status bar.

No errors detected in data set.

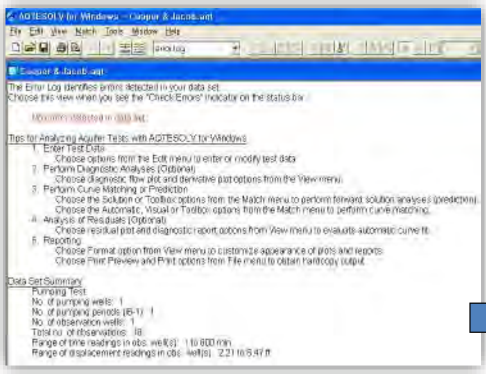
Tips for Analyzing Aquifer Tests with AQTESOLV for Windows

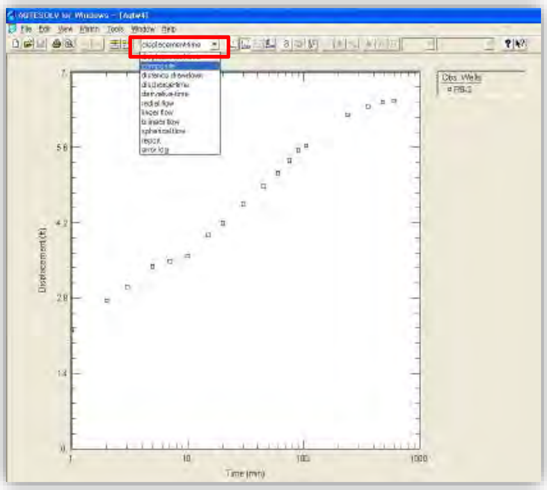
1. Enter Test Data
   Choose options from the Edit menu to enter or modify test data.
2. Perform Diagnostic Analyses (Optional)
   Choose diagnostic flow plot and derivative plot options from the View menu.
3. Perform Curve Matching or Prediction
   Choose the Solution or Toolbox options from the Match menu to perform forward solution analyses (prediction).
   Choose the Automatic, Visual or Toolbox options from the Match menu to perform curve matching.
4. Analysis of Residuals (Optional)
   Choose residual plot and diagnostic report options from View menu to evaluate automatic curve fit.
5. Reporting
   Choose Format option from View menu to customize appearance of plots and reports.
   Choose Print Preview and Print options from File menu to obtain hardcopy output.

Data Set Summary
Pumping Test
No. of pumping wells: 1
No. of pumping periods (I6-1): 2
No. of observation wells: 1
Total no. of observations: 18
Range of time readings in obs. well(s): 1 to 600 min
Range of displacement readings in obs. well(s): 2.21 to 6.47 ft

Display data plot

- Error log

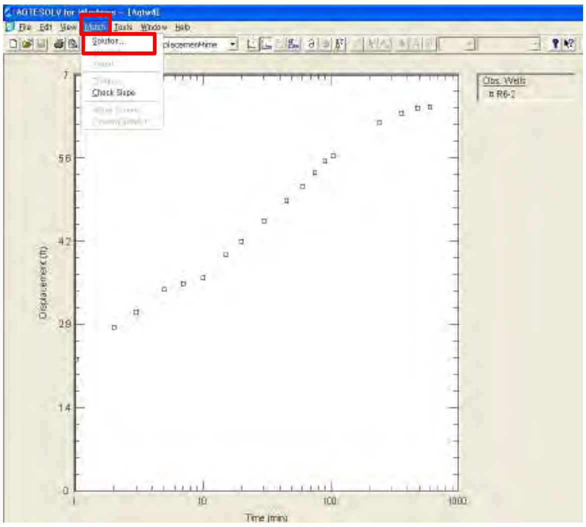


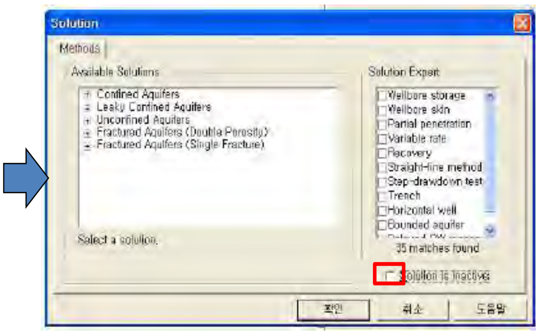


- Select “Displacement-time” at drop-down menu

Choose match solution

❖ Click “Match” on menu and “Solution”





1. uncheck the box “solution is inactive”
2. Choose Aquifer type
   - “unconfined” for example
3. Choose solution
   - “Theis” for example

Solutions in AQTESOLV

- Solutions for Pumping Tests
  - Confined Aquifer
    - Moench-Prickett (1972) : confined aquifer undergoing conversion to water-table conditions.
    - Butler (1988) : nonuniform aquifer.
    - Dougherty-Babu (1984) : confined aquifer with partially penetrating wells, wellbore storage and wellbore skin.
    - Hantush (1962) : confined wedge-shaped aquifer.
    - Murdoch (1994) : confined aquifer with an interceptor trench.
    - Daviau et al. (1985) : confined aquifer with a uniform-flux or infinite-conductivity horizontal well.
    - Barker (1988) generalized radial flow solution for a pumping test in a single-porosity confined aquifer with wellbore skin and nonintegral flow dimension.
  - Leaky confined Aquifer
    - Cooley-Case (1973) : leaky confined aquifer overlain by a water-table aquitard.
    - Neuman-Witherspoon (1969) : leaky confined two-aquifer system.
  - Unconfined Aquifer
    - Tartakovsky-Neuman (2007) : unconfined aquifer with 3D flow in the saturated and unsaturated zones.
  - Fractured Aquifer
    - Gringarten-Witherspoon (1972) : fractured aquifer with a uniform-flux vertical fracture.
    - Gringarten-Ramey-Raghavan (1974) : fractured aquifer with an infinite-conductivity vertical fracture.
    - Gringarten-Ramey (1974) : fractured aquifer with a horizontal fracture.
    - Barker (1988) generalized radial flow solution for a pumping test in a double-porosity fractured aquifer with slab shaped or spherical blocks, fracture skin, wellbore storage, wellbore skin and nonintegral flow dimension.

Solutions in AQTESOLV

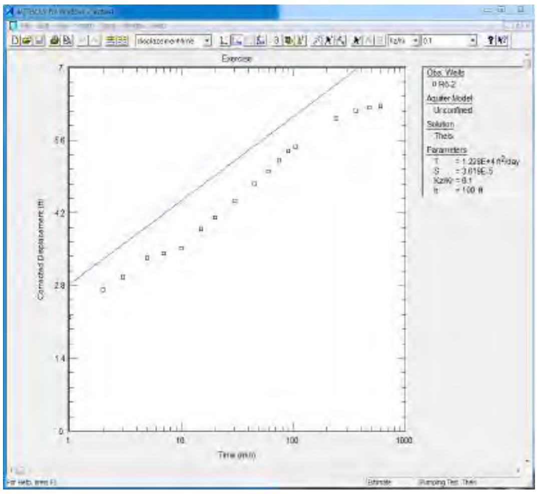
- Solutions for Slug Tests
  - Confined Aquifer
    - Dougherty-Babu (1984) : confined aquifer with partially penetrating wells and wellbore skin.
    - Butler (1998) : confined aquifer with partially penetrating well and underdamped (oscillatory) response.
    - Butler-Zhan (2004) : confined aquifer with partially penetrating wells and underdamped (oscillatory) response.
  - Unconfined Aquifer
    - Springer-Gelhar (1991) : unconfined aquifer with partially penetrating well and underdamped (oscillatory) response.
    - Dagan (1978) : unconfined aquifer with a well screened across the water table.
  - Fractured Aquifer
    - Barker-Black (1985) : double-porosity fractured aquifer with slab-shaped blocks.

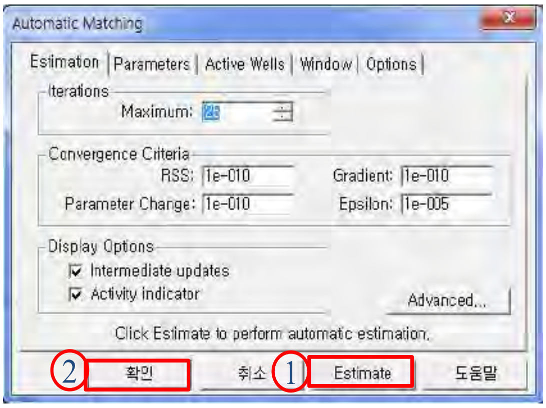
Solutions in AQTESOLV

- Solutions for Constant-Head Tests
  - Confined Aquifer
    - Jacob-Lohman (1952) : confined aquifer.
    - Hurst-Clark-Brauer (1969) : confined aquifer with wellbore skin.
    - Dougherty-Babu (1984) : confined aquifer with partially penetrating wells and wellbore skin.
    - Barker (1988) : single-porosity confined aquifer with wellbore skin and nonintegral flow dimension.
  - leaky Aquifer
    - Hantush (1959) : leaky aquifer.
    - Moench (1985) : leaky aquifer with wellbore skin and storage in the aquitard(s).
  - Fractured Aquifer
    - Barker (1988) generalized radial flow solution for a constant-head test in a double-porosity fractured aquifer with slab shaped or spherical blocks, fracture skin, wellbore skin and nonintegral flow dimension.
    - Ozkan-Raghavan (1991) : fractured aquifer with a uniform-flux or infinite-conductivity vertical fracture

Curve Matching – Automatic method

- Click "Match" on menu and select "Automatic"
- Click "Estimate" on the pop-up window
- Click "Confirm" if the solution is converged





Automatic Matching

Estimation | Parameters | Active Wells | Window | Options

Iterations

Maximum: 20

Convergence Criteria

RSS: 1e-010　Gradient: 1e-010

Parameter Change: 1e-010　Epsilon: 1e-005

Display Options

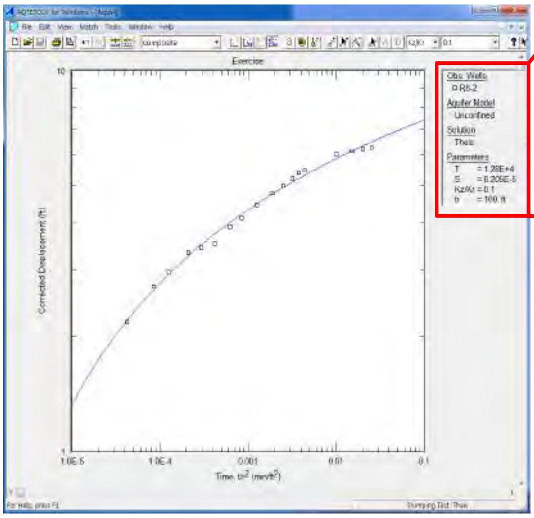
☑ Intermediate updates

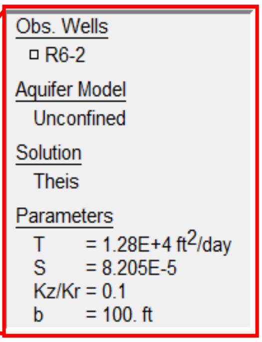
☑ Activity indicator

Click Estimate to perform automatic estimation.

Curve Matching – Automatic method

- Parameter Estimation Results





Obs. Wells

□ R6-2

Aquifer Model

Unconfined

Solution

Theis

Parameters

T = 1.28E+4 ft²/day

S = 8.205E-5

Kz/Kr = 0.1

b = 100. ft

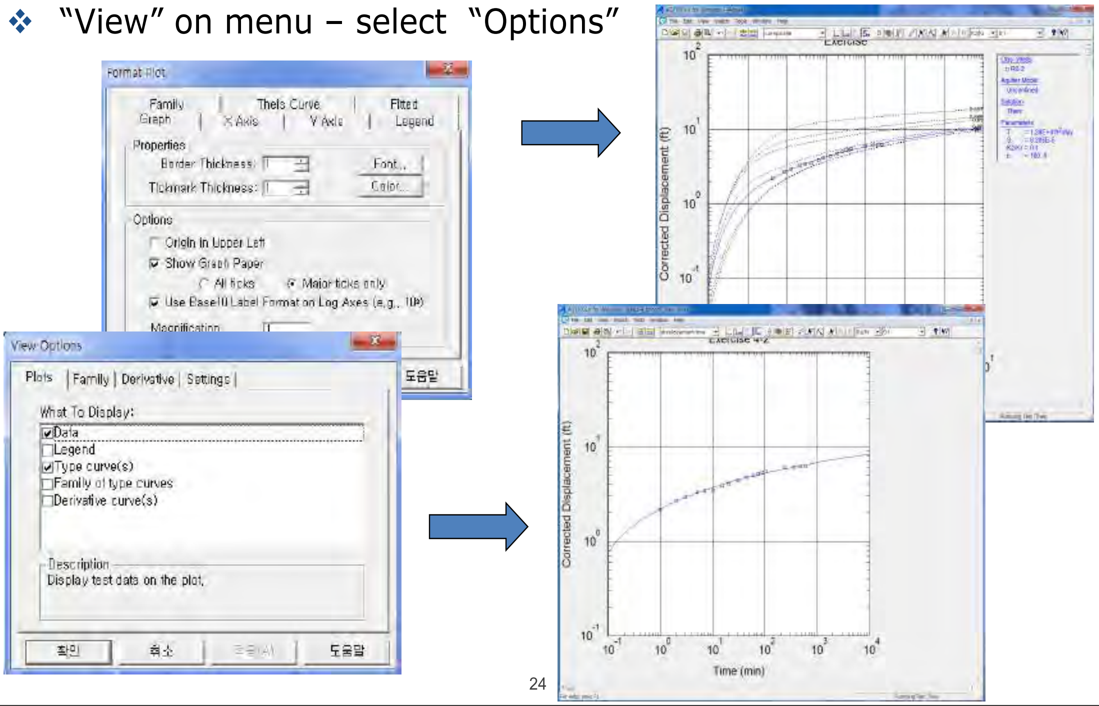
- Unconfined aquifer – Theis solution
- K(=T/b) = 128.0 ft/day
- S = 8.205x10^{-5}

Curve Matching – Visual method

- Choose “Visual” from the “Match” menu.
- Drag the left mouse button on the graph to match the type curve with data
- Release the left mouse button when you have finished matching the type curve.

Format & Options

- “View” on menu – select “format”
- “View” on menu – select “Options”



Format Plot

Family | Theis Curve | Fitted | Graph | X Axis | Y Axis | Legend

Properties

Border Thickness: 1

Tickmark Thickness: 1

Options

☐ Origin in Upper Left

☑ Show Graph Paper

○ All ticks ● Major ticks only

☑ Use Base10 Label Format on Log Axes (e.g., 10³)

Magnification: 1

View Options

Plots | Family | Derivative | Settings

What To Display:

☑ Data

☐ Legend

☑ Type curve(s)

☐ Family of type curves

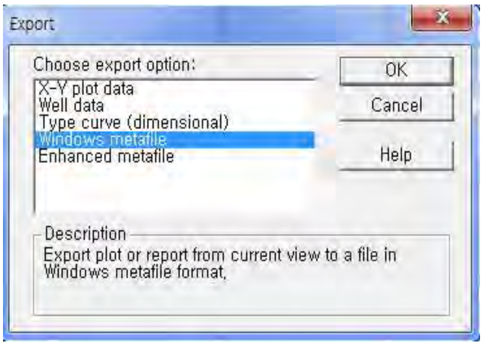
☐ Derivative curve(s)

Description

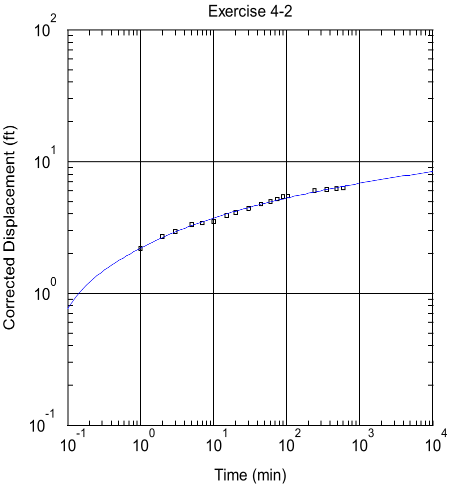
Display test data on the plot.

Export Results

- ❖ “File” on menu – Select “Export”
- ❖ X-Y plot data, well data, Type curve, Graph figure file



Export plot or report from current view to a file in Windows metafile format.

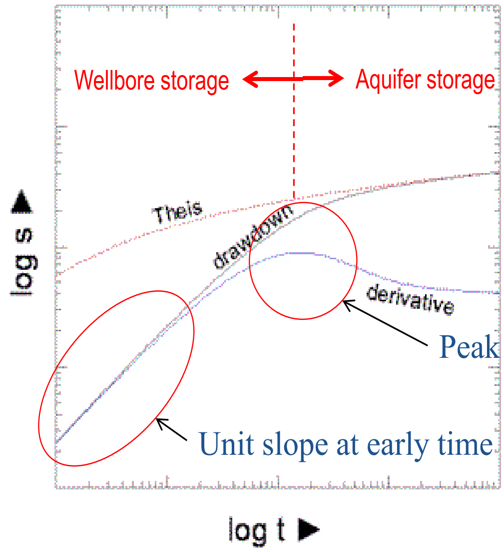


Pumping test example II

- Single-well test in a confined aquifer
- with wellbore storage and wellbore skin

Wellbore storage

- Initial source of pumped water from a storage in the well casing
- Delayed drawdown compared to predicted response
- Disappear as pumping continues



Peak near the end of wellbore storage period

Unit slope at early time

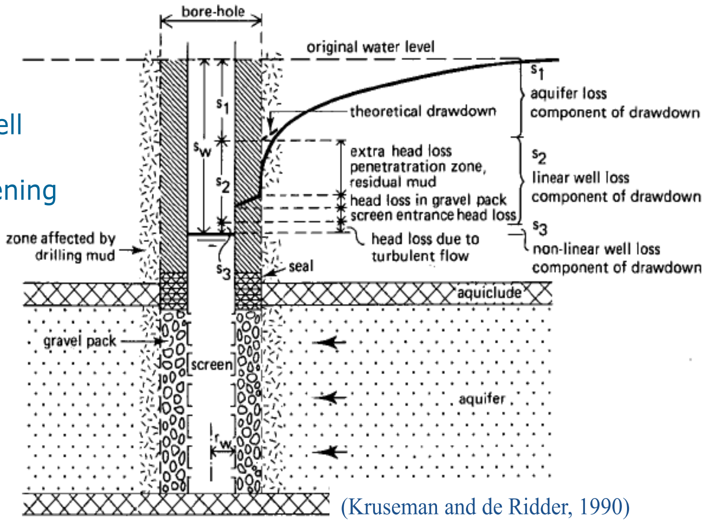
❖ diagnosis – radial flow plot
- On radial (log-log) plot, early-time data showing a unit slope
- A characteristic peak in the derivative curve near the end of the wellbore storage period

Wellbore skin

- Results from a zone of altered permeability near the wellbore
  - Positive skin : lower permeability in a damaged skin zone
    - Mud infiltration, screen bridging by coarse particles, mineral ppt, improper screen size(smaller than sorounding pores)
    - $r_{we} < r_w$

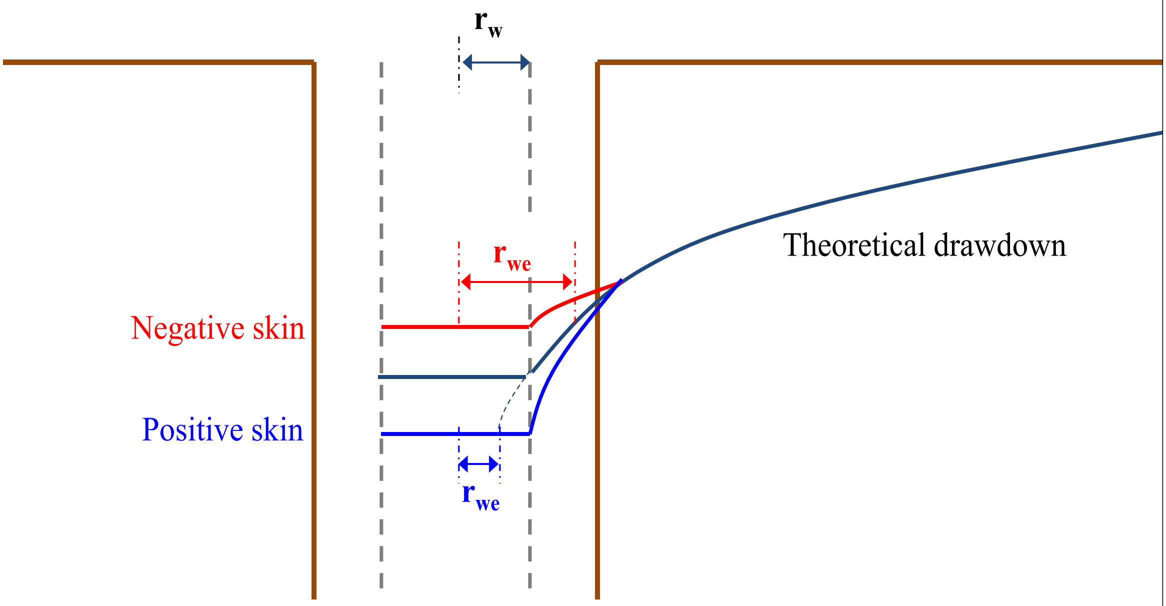
- Negative skin : Enhanced permeability
  - Hydraulic fracturing, well development, natural fracture or solution opening
  - $r_{we} > r_w$

❖ $r_{we} = r_w e^{-Sw}$
- r_w: norminal well radius
- r_{we}: effective well radius
- s_w : wellbore skin factor



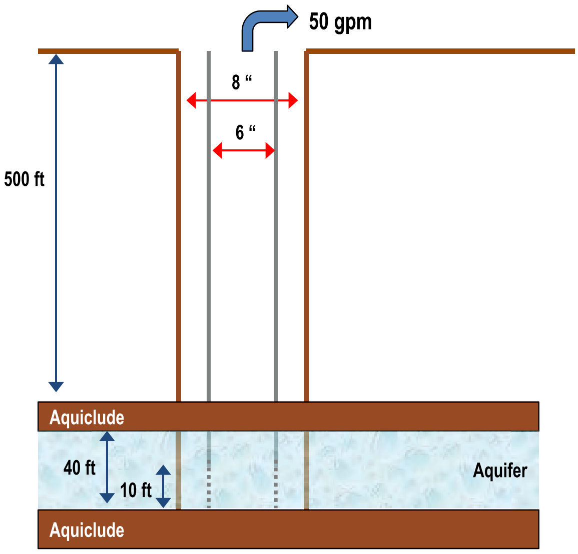
(Kruseman and de Ridder, 1990)

Wellbore skin

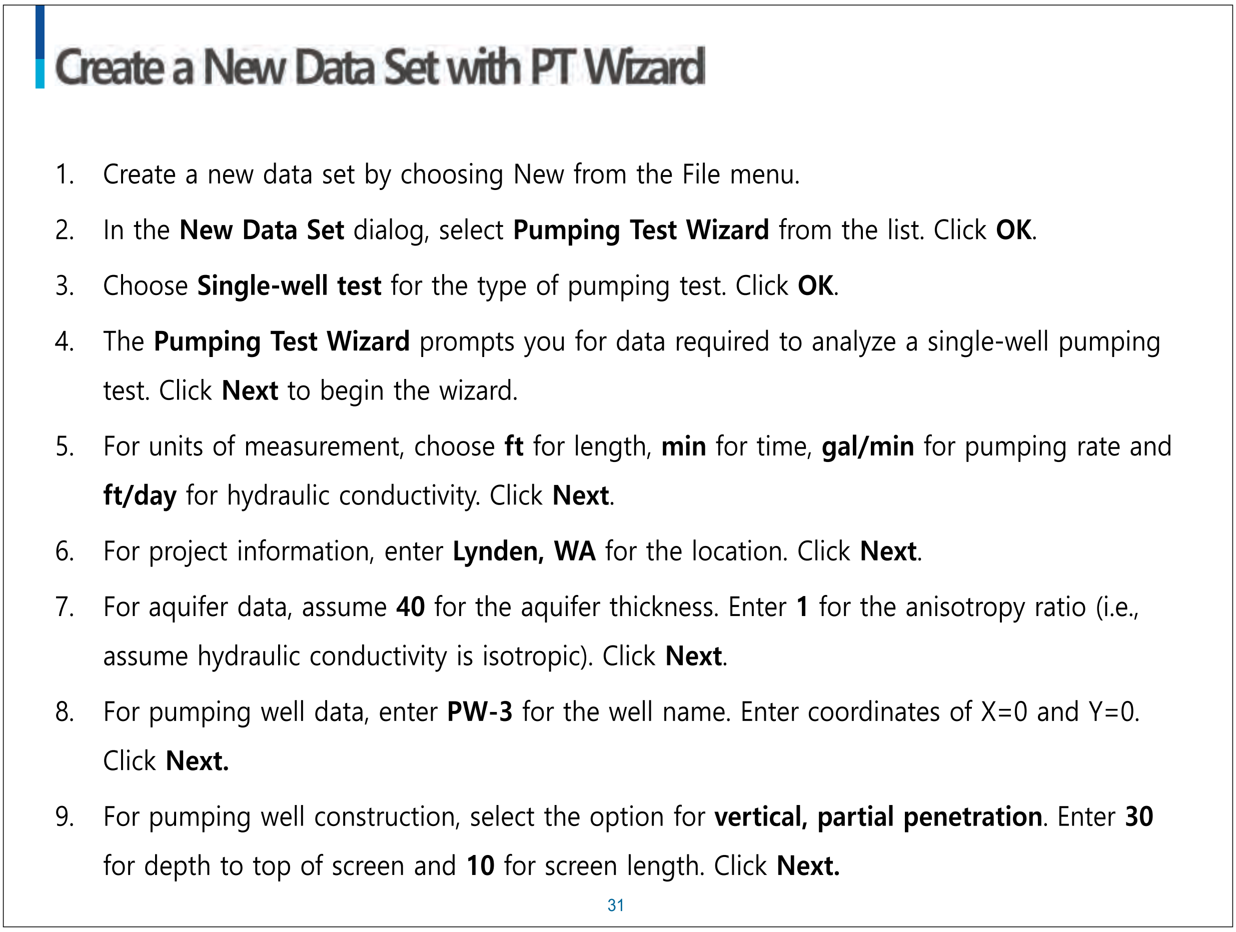


Site and Test Overview

- Constant-rate test in pumped well (single-well test) with wellbore storage and skin in a nonleaky confined aquifer, Lynden, WA

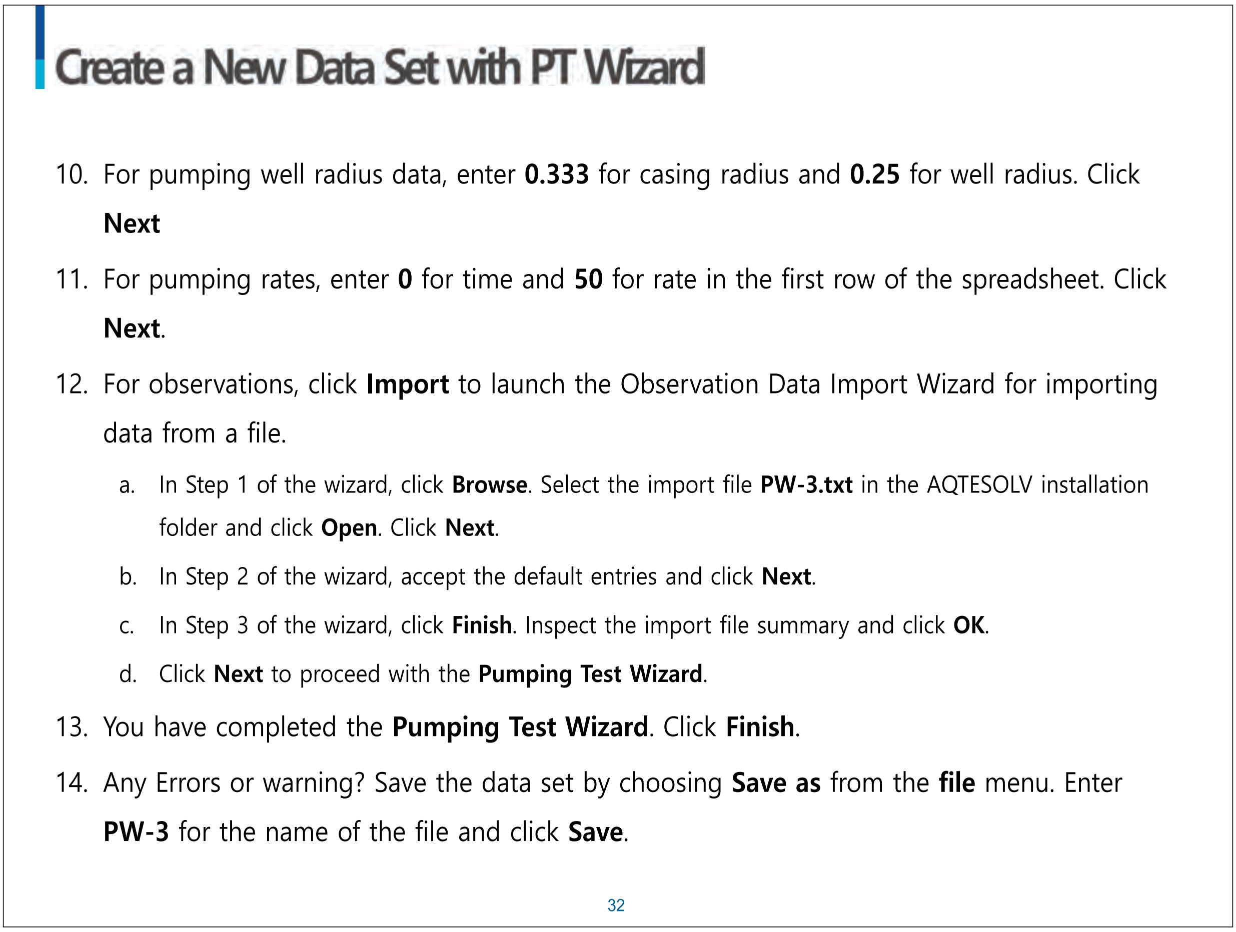


❖ In this example, you will analyze data from a single-well pumping test conducted in a <u>500-ft deep confined aquifer</u> near Lynden, Washington. <u>The six-inch diameter test well</u> was constructed in an <u>eight-inch borehole</u>. The well is <u>screened</u> over the <u>lower 10 feet</u> of the sand and gravel comprising the <u>40-ft thick aquifer</u>. Pumping continued for more than two weeks at a constant rate <u>of 50 gpm</u>. Time and drawdown measurements were recorded <u>in minutes and feet</u>, respectively.



Create a New Data Set with PT Wizard

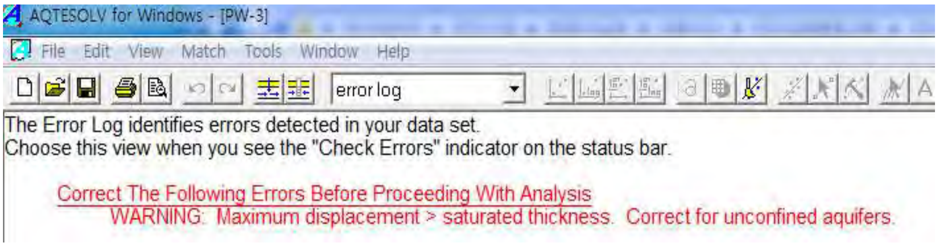
1. Create a new data set by choosing New from the File menu.
2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.
3. Choose **Single-well test** for the type of pumping test. Click **OK**.
4. The **Pumping Test Wizard** prompts you for data required to analyze a single-well pumping test. Click **Next** to begin the wizard.
5. For units of measurement, choose **ft** for length, **min** for time, **gal/min** for pumping rate and **ft/day** for hydraulic conductivity. Click **Next**.
6. For project information, enter **Lynden, WA** for the location. Click **Next**.
7. For aquifer data, assume **40** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.
8. For pumping well data, enter **PW-3** for the well name. Enter coordinates of X=0 and Y=0. Click **Next.**
9. For pumping well construction, select the option for **vertical, partial penetration**. Enter **30** for depth to top of screen and **10** for screen length. Click **Next.**



Create a New Data Set with PT Wizard

10. For pumping well radius data, enter **0.333** for casing radius and **0.25** for well radius. Click **Next**
11. For pumping rates, enter **0** for time and **50** for rate in the first row of the spreadsheet. Click **Next**.
12. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.
    a. In Step 1 of the wizard, click **Browse**. Select the import file **PW-3.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
    b. In Step 2 of the wizard, accept the default entries and click **Next**.
    c. In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.
    d. Click **Next** to proceed with the **Pumping Test Wizard**.
13. You have completed the **Pumping Test Wizard**. Click **Finish**.
14. Any Errors or warning? Save the data set by choosing **Save as** from the **file** menu. Enter **PW-3** for the name of the file and click **Save**.

Warning



The Error Log identifies errors detected in your data set.
Choose this view when you see the "Check Errors" indicator on the status bar.

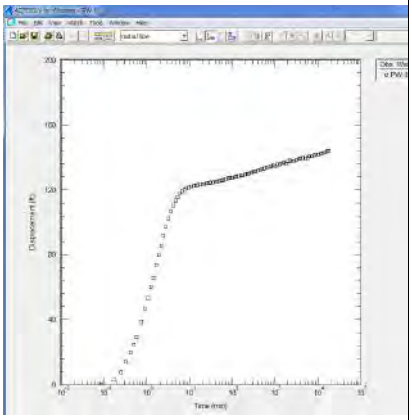
Correct The Following Errors Before Proceeding With Analysis
WARNING: Maximum displacement > saturated thickness. Correct for unconfined aquifers.

It is ok because it is a confined aquifer!

In case of an unconfined aquifer, change the aquifer saturated thickness or check the unit of the displacement

1.Choose aquifer data from the edit menu to change the aquifer property
2.Choose units from the edit menu to change units

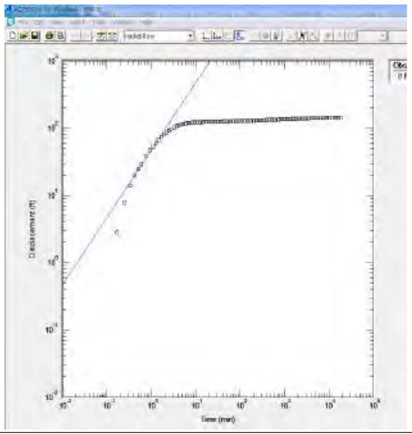
Inspect Diagnostic plots



- Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

- Choose **Radial Flow** from the **View** menu to display a radial flow plot **on log-linear** axes.

  Late-time data plotting as a straight line indicate radial flow conditions in an infinite-acting aquifer.



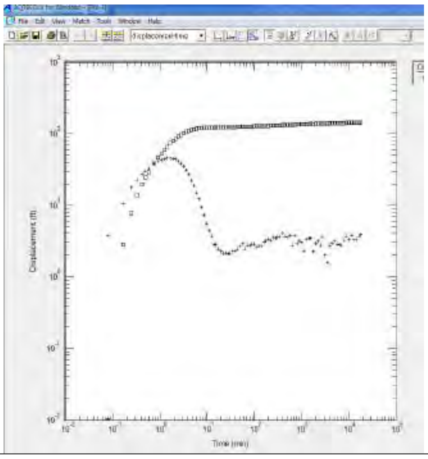
- Choose Log Axes from the View menu to display the radial flow plot on log-log axes.
- Choose Visual from the Match menu. Click the mouse over the second data point on the plot to display a line with unit slope over the early-time data.

  Early-time data with unit slope on a radial flow plot with log-log axes is characteristic of wellbore storage.

Inspect Diagnostic plots

- **Derivative analysis** is another useful diagnostic tool for evaluating aquifer conditions.
- Choose **Displacement-Time** from the **View** menu to display a plot of the test data.
- Choose **Log Axes** from the **View** menu to display the data on log-log axes.
- Choose **Wells** from the **Edit** menu. Select **PW-3** from the list and click **Modify**.
  - In the **Symbols** tab, remove the check from **Use data symbols properties** and select **cross** for the derivative symbol.
  - In the **Curves** tab, remove the check from **Use type curve properties**. Click **Color** for the derivative curve properties, change the color to **red**, and click **OK**.
  - Click **OK** and then **Close**.
- Select **Options** from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the Derivative tab, select the option for **Bourdet** and enter a differentiation interval of **0.4**. Click **OK**.

The peak on the derivative plot is characteristic of wellbore storage. At intermediate to late time, the derivative approaches a constant value when the aquifer is infinite acting.

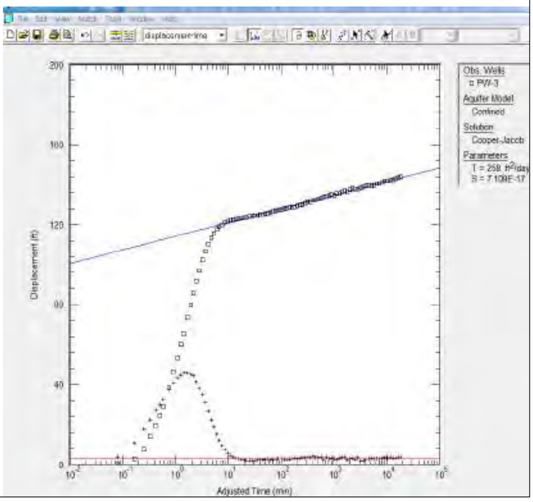


Preliminary Estimate Aquifer Properties

- From the radial flow and derivative plots, we have know that test was performed in confined aquifer with wellbore storage
- Preliminary estimates of T using Cooper-Jacob (1946) solution

1. Choose **Solution** from the **Match** menu to select a method for analyzing the data.
2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Cooper-Jacob (1946)** and click **OK**.
3. Choose **Displacement-Time** from the **View** menu.
4. Choose **Visual** from the **Match** menu to perform visual curve matching with the Cooper-Jacob solution. Match the line to late-time data after the wellbore storage effect has dissipated.
5. Repeat the previous step as needed to achieve a satisfactory match to the late-time data. Your estimate of **T** should be on the order of **250 ft2/day**.

The low value of S that you obtain with the Cooper-Jacob solution is an indication of partial penetration effect and possibly wellbore skin effect at the pumped well.

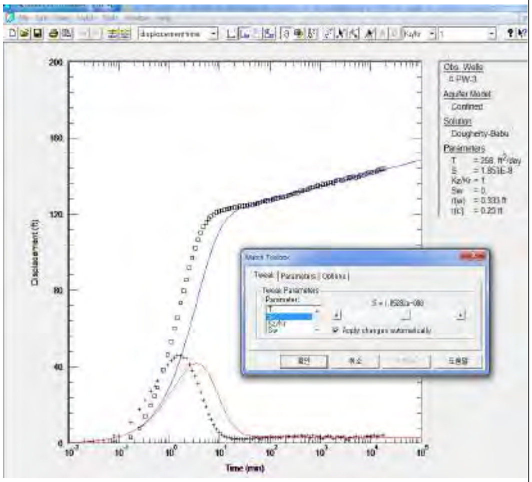


Accounting for partial penetration

1. Choose **Solution** from the **Match** menu to select a method for analyzing the data.
2. From the list of solutions for **Confined Aquifers**, select **Dougherty-Babu (1984)** and click **OK**.
3. Choose **Log-Linear Axes** from the **View** menu to view the data on log-linear axes.

4. Choose **Toolbox** from the **Match** menu. In the Tweak tab, select **S** from the list of parameters. Use the scroll bar to adjust the value of storativity to match the late-time data. You can set the range of storativity values by editing the minimum and maximum values for S in the **Parameters** tab.

The Dougherty-Babu solution accounts for partial penetration; however, the implausibly low value of S determined from this analysis indicates wellbore skin effect.



Obs. Wells
PW-3
Aquifer Model
Confined
Solution
Dougherty-Babu
Parameters
T = 258. ft²/day
S = 1.853E-8
Kz/Kr = 1
Sw = 0.
r(w) = 0.333 ft
r(c) = 0.25 ft

S = 1.8583e-008

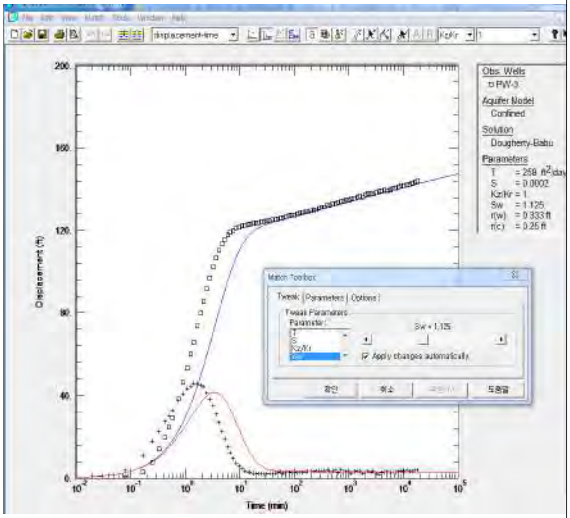
☑ Apply changes automatically

Accounting for wellbore skin

1. In the **Parameters** tab, enter 0.0002 for S as a plausible estimate of storativity in a confined aquifer. In the **Tweak** tab, select **Sw** (wellbore skin factor) from the list of parameters. Use the scroll bar to adjust the value of wellbore skin factor to match the late-time data. You can set the range of wellbore skin factor values by editing the minimum and maximum values for Sw in the **Parameters** tab.

It is not possible to estimate S and Sw simultaneously from a single-well test. If an estimate of S is available independently from an observation well, we may use it as a known value in the analysis of pumping well data; otherwise, we may assume a value of S based on local hydrogeologic conditions.

Partial penetration and wellbore skin can produce virtually identical effects in a pumping well's drawdown response. In this case, decreasing the penetration ratio, L/b, was equivalent to increasing the wellbore skin factor.



Obs. Wells
PW-3
Aquifer Model
Confined
Solution
Dougherty-Babu
Parameters
T = 258 ft²/day
S = 0.0002
Kz/Kr = 1
Sw = 1.125
r(w) = 0.333 ft
r(c) = 0.25 ft

Sw = 1.125

☑ Apply changes automatically

Accounting for wellbore storage

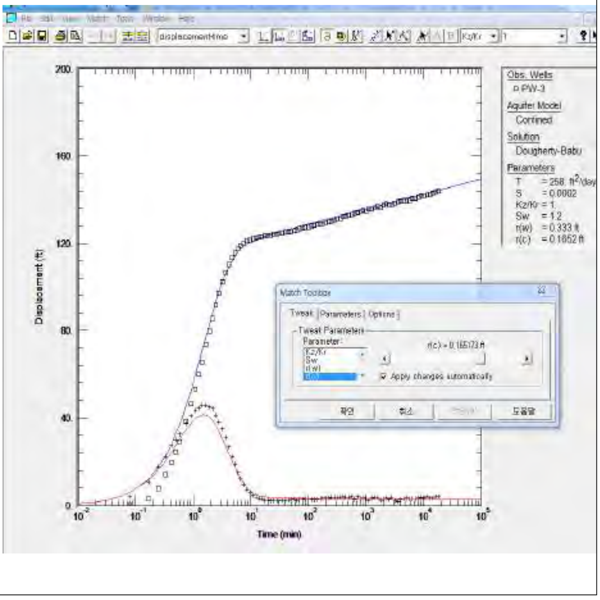
1. In the **Tweak** tab, select **r(c)** from the list of parameters. Use the scroll bar to adjust the value of casing radius to match the early-time data. You can limit the range of casing radius values by editing the minimum and maximum values for r(c) in the **Parameters** tab. After you have aligned the curve with the early-time data, click **OK**.

Adjust the casing radius value to match early-time data affected by wellbore storage. In many cases, the effective casing radius turns out to be less than the nominal value because of equipment in the well such as discharge tubing and transducer cable.

Final Estimate of Parameters

T ≈ 250 ft2/day
S = 0.0002
Kz/Kr = 1.0
Sw ≈ 1.2
r(w) = 0.333 ft
r(c) ≈ 0.165 ft

2. Choose **Save** from the **File** menu to save your work.



Obs. Wells
PW-3
Aquifer Model
Confined
Solution
Dougherty-Babu
Parameters
T = 258. ft^2/day
S = 0.0002
Kz/Kr = 1.
Sw = 1.2
r(w) = 0.333 ft
r(c) = 0.1652 ft

r(c) = 0.165173 ft

☑ Apply changes automatically

Curve Matching Tips

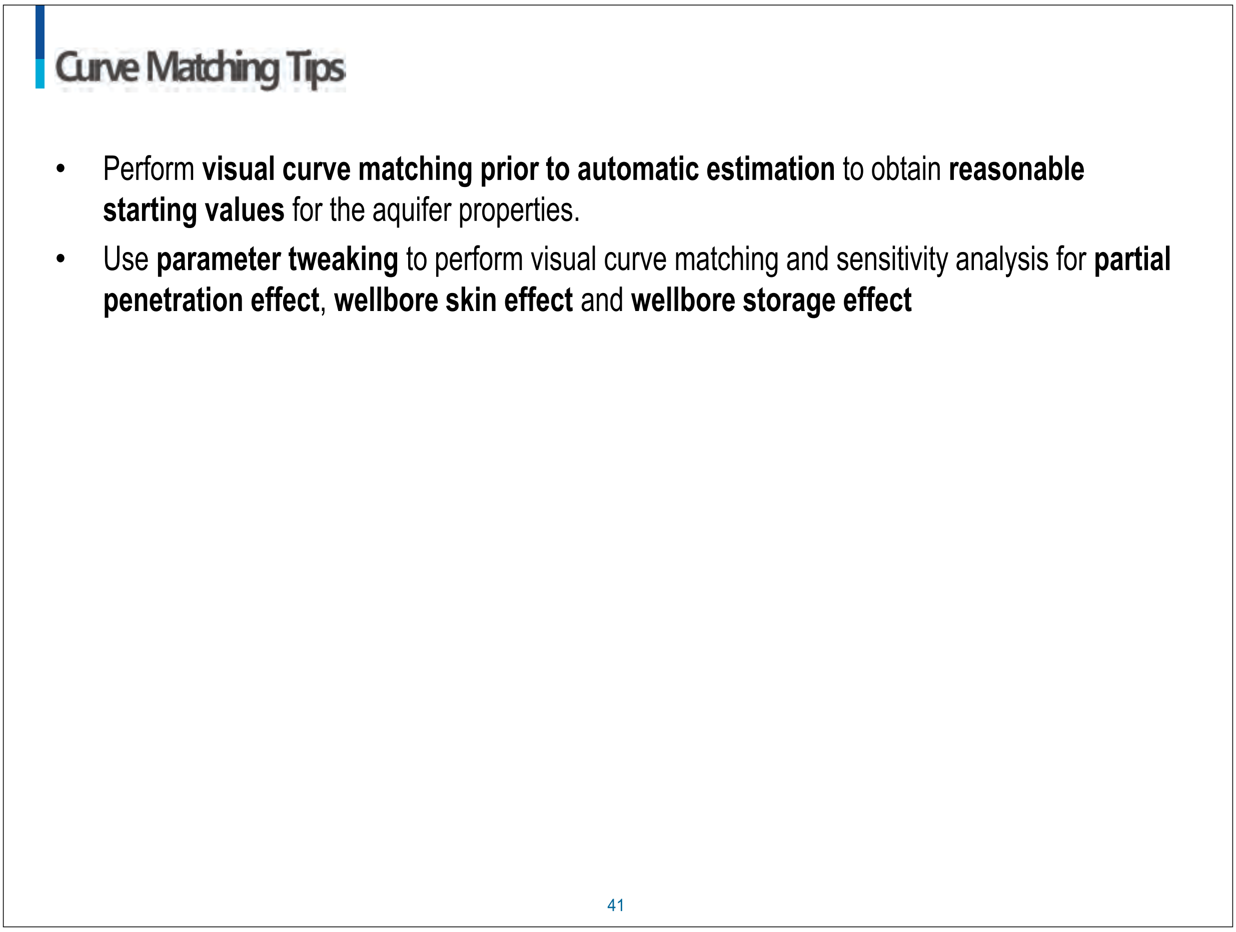
- Use **the Cooper-Jacbo (1946)** solution to obtain **preliminary estimates**
- **Examines the data using Diagnostic flow plots**

Summary of Drawdown Characteristics for Selected Flow Regimes

Regime	Diagnostic Flow Plot	Characteristic
Wellbore storage	radial flow plot (log axes)	unit (1:1) slope at early time
Infinite-acting radial flow	radial flow plot (semilog axes)	constant positive slope at late time
Infinite-conductivity fracture	linear flow plot (log axes)	unit (1:1) slope at early time
Finite-conductivity fracture	bilinear flow plot (log axes)	unit (1:1) slope at early time
No-flow boundary	radial flow plot (semilog axes)	slope doubles
Channel (strip) aquifer	linear flow plot (log axes)	unit (1:1) slope at late time
Closed aquifer	radial flow plot (log axes)	unit (1:1) slope at late time
Constant-head boundary	radial flow plot	zero slope at late time
Spherical flow	spherical flow plot (log axes)	negative unit (-1:1) slope

Occurrence of Flow Regimes

Early	Intermediate	Late (Boundaries)
• wellbore storage • linear flow (fracture) • bilinear flow (fracture)	• infinite-acting aquifer • spherical flow • Inter-porosity flow	• no-flow • recharge • channel aquifer • closed aquifer



Curve Matching Tips

- Perform **visual curve matching prior to automatic estimation** to obtain **reasonable starting values** for the aquifer properties.
- Use **parameter tweaking** to perform visual curve matching and sensitivity analysis for **partial penetration effect**, **wellbore skin effect** and **wellbore storage effect**

Thank you very much