Groundwater Chemistry: Properties of Water, Water Quality and Groundwater Contamination

Groundwater

Groundwater Chemistry: Properties of Water, Water Quality and Groundwater Contamination

United Nations Educational, Scientific and Cultural Organization · International Centre for Water Security and Sustainable Management

Aims & Objectives

This chapter starts with the chemical properties of water and the formation of water quality.

The parameters representing the characteristics of water quality are presented in this chapter.

Natural and anthropogenic factors that influence the formation of water quality are to be investigated.

Water quality standards, water pollution, and sources of contamination are to be discussed with the remediation of contaminated groundwater.

Contents

1. Properties of water

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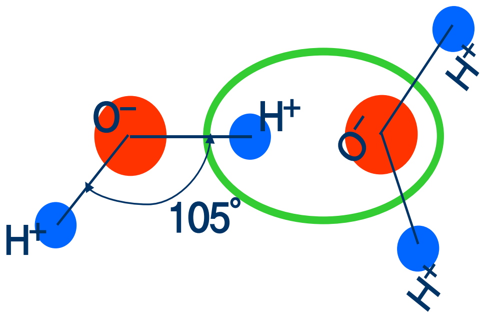
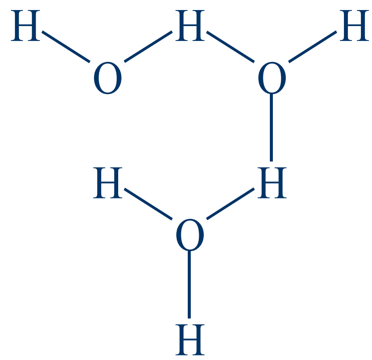
Properties of Water



Water molecule has a positive and a negative end. Molecules can attract one another to form a hydrogen bond.

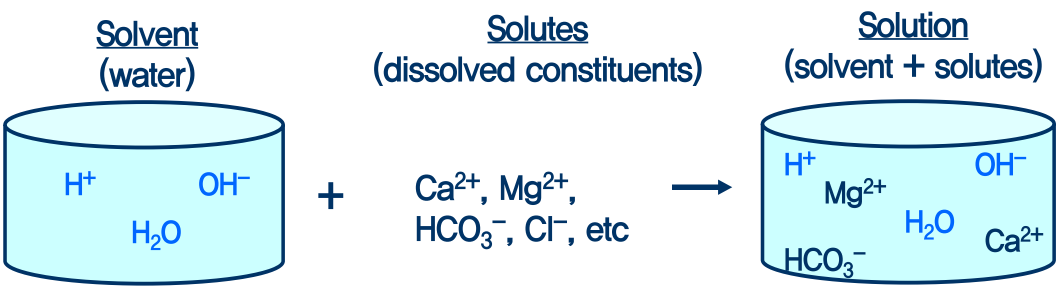
Hydrogen bonding causes the following properties of water:

- high boiling point & melting point
- The maximum density is at 4C.
- Ice is less dense than the liquid water protecting benthic ecosystems.



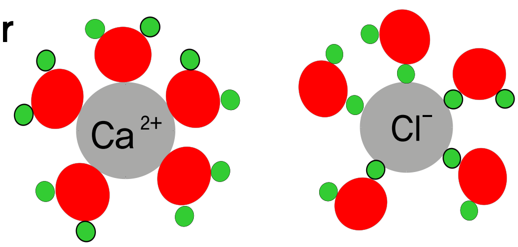
Properties of Water

Solvent : Water dissolves some amount of solid or gas.



Because of the polar nature of water, ions will be surrounded by water dipoles in solution (hydration).

Hydration isolates the ions from their neighbors and neutralizes the attractive forces that hold minerals together.



Concentration Units

Molality:
Number of moles of solute dissolved in a 1-kg mass of solution. This is an SI unit with the symbol mol/kg.

Molarity:
Number of moles of solute in 1 m3 of solution. The SI unit for molarity is designated as mol/m3. 1 mol/m3, equals 1 mmol/ℓ . Moles per liter, mol/ℓ , is commonly used in groundwater studies.

Mass concentration:
kg/m3, g/ℓ is a permitted SI unit. The most common mass concentration unit reported in the groundwater literature is milligrams per liter (mg/ℓ).

2. Chemical reaction and equilibrium

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The Law of Mass Action

The driving force of a chemical reaction is related to the concentrations of the reactants and the products of the reaction.

For the reaction,

$$bB + cC \leftrightarrows dD + eE$$

b, c, d, and e: the number of moles of chemical constituents B, C, D, and E

$$K = \frac{[D]^d[E]^e}{[B]^b[C]^c}$$

K: thermodynamic equilibrium constant
[ ]: thermodynamically effective concentration (activity)

The condition of chemical equilibrium

The condition of chemical equilibrium can be defined as

Σ free-energy: products − Σ free-energy: reactants = 0

The standard free energy of formation, ΔG^0, is defined as the free energy of the reaction to produce 1 mol of a substance from the stable elements under conditions that are specified as standard-state conditions

The standard free-energy change of reaction, ΔG_r^0, is the sum of the free energies of formation of the products in their standard states minus the free energies of formation of the reactants in their standard states:

$$\Delta G_r = \Delta G_r^0 + RT\ln\frac{[D]^d[E]^e}{[B]^b[C]^c}$$

$$\Delta G_r^0 = -RT\ln K$$

Polyprotic Acids in groundwater

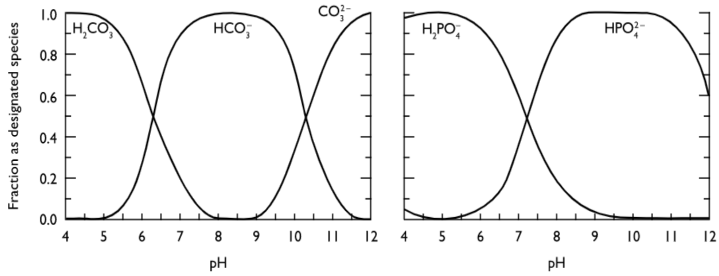
Carbonic acid (H2CO3) in groundwater:

Carbonic acid (H2CO3) forms when carbon dioxide (CO2) combines with water. Carbonic acid dissociates by transferring hydrogen ions (protons):

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \quad \rightarrow \quad HCO_3^- \Leftrightarrow H^+ + CO_3^{2-}$$

Phosphoric acid (H3PO4) in groundwater

$$H_3PO_4 \Leftrightarrow H^+ + H_2PO_4^- \rightarrow H_2PO_4^- \Leftrightarrow H^+ + HPO_4^{2-} \rightarrow HPO_4^{2-} \Leftrightarrow H^+ + PO_4^{3-}$$



Distribution of major species of dissolved inorganic carbon and inorganic phosphorus in water at 25° C (from Freeze and Cherry, 1979)

Hydrogen Ion Activity (pH)

Dissociation of Water :

$$H_2O \leftrightarrow H^+ + OH^-$$

The corresponding equilibrium expression for this reaction is

$$K = \frac{[H^+][OH]^-}{[H_2O]}$$

where K = equilibrium constant
[ ] = molar concentration

we assume $[H_2O]$ is unity and don't bother to include it explicitly in the equations

$$K_W = [H^+]\,[OH^-]$$

where K_w = equilibrium constant for water

Hydrogen Ion Activity (pH)

The positive ions in solution must be balanced by the negative ions.

$$[H^+] = [OH^-]$$

$$K_W = [H^+]\,[OH^-] \text{ substituting for } [OH^-]$$

$$K_W = [H^+]^2$$

$$-\log[H^+] = -\frac{1}{2}\log K_W$$

pH represents − log [H^+], it is convenient to use pK to represent − log [K]

$$pH = -\log[H^+] = -\frac{1}{2}\log K_W = \frac{1}{2}pK_W$$

In dilute aqueous solution at 25℃, $K_W = 10^{-14}$

⇒The pH of pure water is 7.0

Water quality and pH

pH (Hydrogen Ion Activity) affects aqueous complexation, mineral solubility, adsorption properties, gas solubility, & biochemical reactions.

A sample of GW ~ originally in equilibrium with calcite at P_{CO2} = 0.1 atm

⇒ allowed to equilibrate with atmosphere (P_{CO2} = 0.0003 atm)

Large change in pH (pH 6.5 → 8.4) would have a major effect on the solubility of minerals.

Water quality and Temperature

Temperature should be measured in the field.
Temp affects a number of water quality parameters.

When temp increased,

- Chemical & biochemical reaction rates increase
- Gas solubility decreases (specially impact on oxygen)
- Mineral solubility increases
- Growth rates of aquatic organisms increases

The equilibrium constants must be recalculated using the temp of the aquifer.

$$\log\frac{K_2}{K_1} = \frac{\Delta H_R^0}{2.303R}\left(\frac{T_2 - T_1}{T_2 T_1}\right)$$

Where K_2 = equilibrium constant at temp of interest, T_2
K_1 = equilibrium constant at 25° C, T_1
ΔH^0_R = change in the enthalpy of the reaction (cal/mole)
R = gas constant (1.987 cal/° mole)

Redox Potentials (Eh)

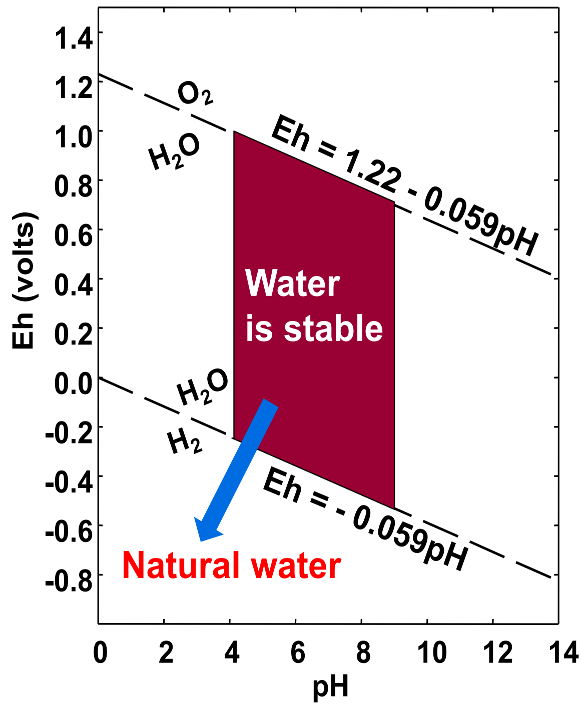
Redox Potential can be measured
using Redox tester on site.

Redox Potential (Eh) by the Nernst equation:

$$\mathrm{Eh} = \mathrm{E}^0 + \frac{\mathrm{RT}}{\mathrm{nF}}\ln \mathrm{K_{sp}} \qquad \mathrm{Eh} = \mathrm{E}^0 - \frac{0.0592}{1}\log\frac{\mathrm{P}_{\mathrm{H2}}^{1/2}}{\mathrm{a}_{\mathrm{H+}}}$$

where E^0 = standard potential (at 25° C & 1 atm pressure)
R = gas constant (kcal/(mol•K)
T = temperature (kelvins)
F = Faraday constant (23.1 kcal/V)
n = number of electrons
K_{sp} = solubility product ($\log K_{sp} = \frac{-\Delta_r G^0}{2.303RT}$)

Eh–pH Diagram



- This diagram shows the stability limits of water at 25°C and 1 bar.
- At conditions above the top dashed line, water is oxidized to O_2; at conditions below the bottom dashed line, water is reduced to H_2. No natural water can persist outside these stability limits for any length of time.
- Water in nature is usually between pH 4 and pH 9.

$CO_2 - H_2O$ System And Carbonate Equilibrium

Carbonic acid is a weak acid of great importance in natural waters.
The first step in its formation is the dissolution of $CO_2(g)$ in water according to:

$$CO_2(g) \leftrightarrow CO_2(aq)$$

At equilibrium we have:

$$K_{CO_2} = \frac{a_{CO_2}}{P_{CO_2}}$$

Once in solution, $CO_2(aq)$ reacts with water to form carbonic acid:

$$CO_2(aq) + H_2O(l) \leftrightarrow H_2CO_3^0$$

$CO_2 - H_2O$ System And Carbonate Equilibrium

In practice, $CO_2(aq)$ and $H_2CO_3^0$ are combined and this combination is denoted as $H_2CO_3^*$.

It' s formation is dictated by the reaction:

$$CO_2(g) + H_2O(l) \leftrightarrow H_2CO_3^*$$

For which the equilibrium constant at 25℃ is:

$$K_{CO_2} = \frac{a_{H_2CO_3^*}}{P_{CO_2}} = 10^{-1.46}$$

Most of the dissolved CO_2 is actually present as $CO_2(aq)$; only a small amount is actually present as true carbonic acid $H_2CO_3^0$

$CO_2 - H_2O$ System And Carbonate Equilibrium

In water exposed to the atmosphere,

$$CO_2(g) + H_2O = CO_2(aq)$$

The concentration of aqueous carbon dioxide is determined by CO_2 pressure.

$$CO_2(aq) + H_2O \Leftrightarrow H_2CO_3$$
$$CO_2(aq) + H_2CO_3 = H_2CO_3^*$$

The equilibrium constant pK_{CO2} for the solution of carbon dioxide in water to produce carbonic acid is 1.46.

The carbonic acid will dissociate in two steps.

(1) $H_2CO_3^* = H^+ + HCO_3^-$

(2) $HCO_3^- = H^+ + CO_3^{2-}$

The first dissociation constant pK_1 = 6.35

The second dissociation constant pK_2 = 10.33

Calculation Distribution Of Mass Between Species

Ex) at pH 7 given $[CO_2]_T = 10^{-3}$ M.

$$[CO_2]_T = [H_2CO_3^*] + [HCO_3^-] + [CO_3^{2-}]$$

$$pH = 7 \text{ therefore } [H^+] = 10^{-7}$$
$$[OH^-] = K_w / [H^+] = 10^{-14} / 10^{-7} = 10^{-7}$$

$$[HCO_3^-] = [H_2CO_3^*] (K_1 / [H^+])$$
$$= [H_2CO_3^*] (10^{-6.35} / 10^{-7}) = [H_2CO_3^*] (10^{0.65})$$

$$[CO_3^{2-}] = [HCO_3^-] (K_2 / [H^+])$$
$$= [H_2CO_3^*] (K_1 / [H^+]) (K_2 / [H^+])$$
$$= [H_2CO_3^*] (10^{0.65}) (10^{-10.33} / 10^{-7})$$
$$= [H_2CO_3^*] (10^{-2.68})$$

Calculation Distribution Of Mass Between Species

$$[CO_2]_T = [H_2CO_3^*] + [HCO_3^-] + [CO_3^{2-}]$$
$$[CO_2]_T = [H_2CO_3^*] + [H_2CO_3^*] (10^{0.65}) + [H_2CO_3^*] (10^{-2.68})$$

$$[CO_2]_T = [H_2CO_3^*] (1 + 10^{0.65} + 10^{-2.68})$$
$$[CO_2]_T = [H_2CO_3^*] (5.47)$$

$$[H_2CO_3^*] = [CO_2]_T / (5.47)$$
$$[H_2CO_3^*] = 10^{-3} / 5.47 = 10^{-3.74}$$

$$[HCO_3^-] = [H_2CO_3^*] K_1 / [H^+] = 10^{-3.74}(10^{-6.35} / 10^{-7}) = 10^{-3.09}$$

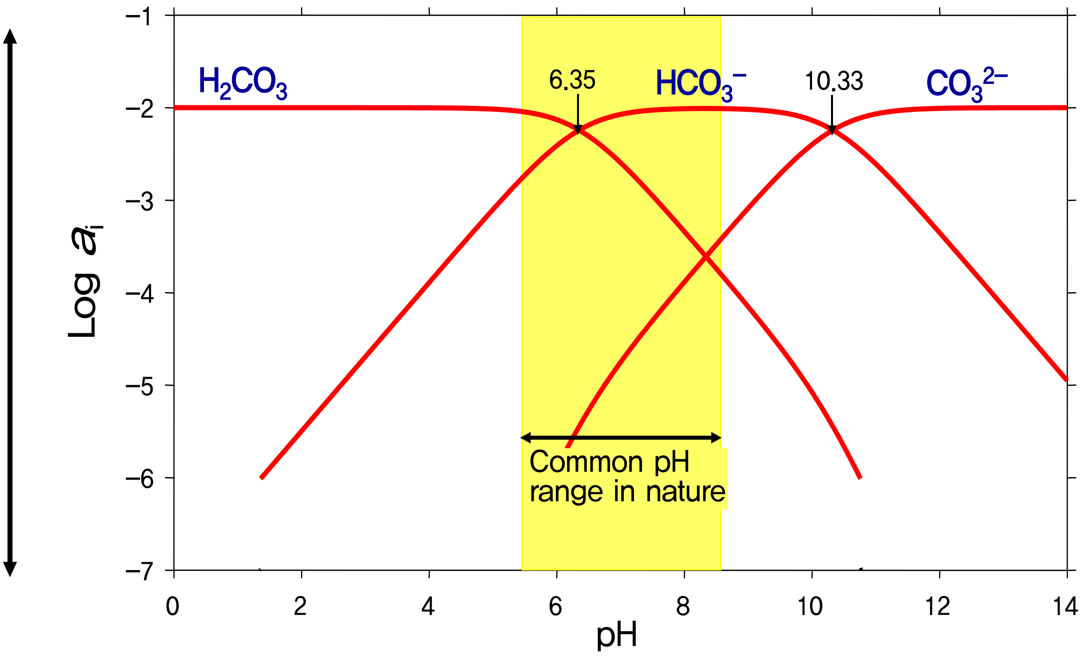
$$[CO_3^{2-}] = [HCO_3^-] K_2 / [H^+] = 10^{-3.09}(10^{-10.33} / 10^{-7}) = 10^{-6.42}$$

The carbonate species $[H_2CO_3^*]$, $[HCO_3^-]$ and $[CO_3^{2-}]$ have concentrations of $10^{-3.74}$, $10^{-3.09}$ and $10^{-6.42}$ M at pH 7.

Bicarbonate is the dominant ion.

Calculation Distribution Of Mass Between Species

Bjerrum plot showing the activities of inorganic carbon species as a function of pH for a value of total inorganic carbon of 10^{-3} mol L^{-1}.



In most natural waters, bicarbonate is the dominant carbonate species

Dissolved Inorganic Constituents in Groundwater

Major constituents (greater than 5mg/l)		Minor constituents (0.01 ~ 10.0mg/l)	
Bicarbonate	Silicon	Baron	Nitrate
Calcium	Sodium	Carbonate	Potassium
Chloride	Sulfate	Fluoride	Strontium
Magnesium	Carbonic acid	Iron	

Trace constituents (less than 0.1mg/l)			
Aluminum	Cobalt	Molybdenum	Thallium
Antimony	Copper	Nickel	Thorium
Arsenic	Gallium	Niobium	Tin
Barium	Germanium	Phosphate	Titanium
Beryllium	Gold	Platinum	Tungsten
Bismuth	Indium	Radium	Uranium
Bromide	Iodide	Rubidium	Vanadium
Cadmium	Lanthanum	Ruthenium	Ytterbium
Cerium	Lead	Scandium	Yttrium
Cesium	Lithium	Selenium	Zinc
Chromium	Manganese	Silver	Zirconium

Major Ions And Charge Balance

More than 90% of the dissolved solids in ground water can be attributed to eight ions: $Na^+, Ca^{2+}, K^+, Mg^{2+}, SO_4^{2-}, Cl^-, HCO_3^-, and\ CO_3^{2-}$
These ions are usually present at concentrations greater than 1 mg/L.
Silica, SiO_2, a nonionic species, is also typically present at concentrations greater than 1 mg/L. Direct analysis can be done for the first six ions.
As a check on the chemical analysis, a cation-anion balance is usually performed. This is accomplished by converting all the ionic concentrations to units of equivalents per liter. The anions and cations are summed separately, and the results are compared.
If the sum of the cations is not within a few percent of the sums of the anions, then either there is a problem with the chemical analysis or one or more ionic species that have not been identified are present in significant amounts.
An alternative method is to calculate the charge balance error (CBE).
The charge balance error can be found from the following equation.

$$CBE\% = \frac{\sum z \times m_c - \sum z \times m_a}{\sum z \times m_c + \sum z \times m_a}$$

Hydrochemical Processes in the Soil Zone

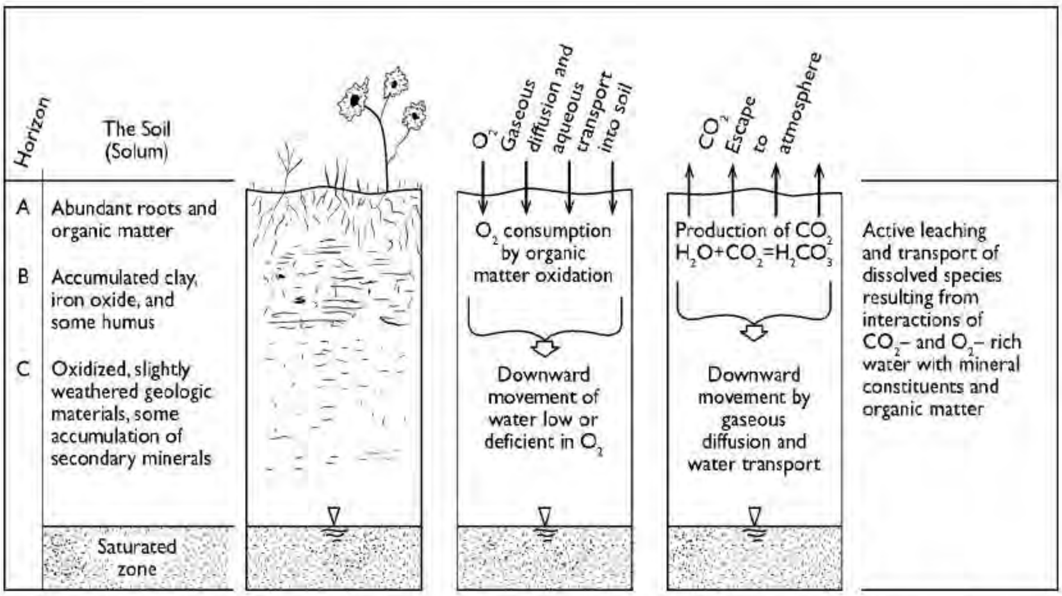


Figure 7.1 Schematic representation of major hydrochemical processes in the soil zone of recharge areas.

From Freeze and Cherry (1979)

Constituents in Natural Water and Origin

Origin	Positive Ions	Negative Ions
Contact of water with minerals, soils, and rocks	Ca^{+2}, Fe^{+2} Mg^{+2}, Mn^{+2} K^{+}, Na^{+}, Zn^{+2}	HCO_3^-, CO_3^{-2} Cl^-, F^-, NO_3^- PO_4^{-3}, OH^-, SO_4^{-2} $H_2BO_3^-$, H_3SiO_4
The atmosphere, in rain	H^+	HCO_3^-, Cl^-, SO_4^{-2}
Decomposition of organic matter in the environment	NH_4^+, H^+, Na^+	Cl^-, HCO_3^-, OH^-, NO_2^-, NO_3^-, HS^- Organic radicals
Municipal, industrial, and agricultural sources and other human activity	Inorganic ions, including a variety of heavy metals	Inorganic ions, organic molecules, color

3. Water quality and water quality standards

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Water Quality

Water quality: the condition of the water, including chemical, physical, and biological characteristics; a measure of the suitability of water for a particular use (drinking, bath, swimming, etc) based on selected physical, chemical, and biological characteristics.

Water quality is controlled by concentrations of organic and inorganic chemicals, and additional chemical parameters such as pH and dissolved oxygen; and physical parameters, including water temperature, conductivity, and turbidity.

Water Quality Standards

MCLG (maximum contaminant level goal):
the concentration of a contaminant that is considered to be safe for human consumption. MCLG is based only on health considerations and does not consider factors such as cost or feasibility.

MCL (maximum contaminant level):
the maximum permissible level of a contaminant in water which is delivered to any user of a public water system. MCL is legally enforceable standard and is set as close as practicable to the MCLG when we consider cost and feasibility.

Primary standards:
legally enforceable regulations based on protection of human health.

Secondary standards:
recommendations or guidelines that are not legally enforceable and are based on aesthetics of the water, like taste, odor, and color

Water Quality Standards Examples

U.S. EPA
National Primary Drinking Water Regulations

Volatile Organic Chemicals (VOCs)	MCL, in mg/L
Benzene	0.005
Carbon Tetrachloride	0.005
1,2-Dichloroethylene	0.005
Trichloroethylene	0.005
p-Dichlorobenzene	0.075
1,1-Dichloroethylene	0.007
1,1,1-Trichloroethane	0.2
Vinyl Chloride	0.002
cis-1.2-Dichloroethylene	0.07
1,2-Dichloropropane	0.005
Ethylbenzene	0.7
Chlorobenzene	0.1
o-Dichlorobenzene	0.6
Styrene	0.1
Tetrachloroethylene	0.005
Toluene	1
trans-1,2-Dichloroethylene	0.1
Xylenes (Total)	10
Dichloromethane	0.005
1,2,4-Trichlorobenzene	0.07
1,1,2-Trichloroethane	0.005

Water Quality Standards Examples

U.S. EPA
National Primary Drinking Water Regulations

Inorganic Chemicals	MCL, in mg/L
Antimony	0.006
Arsenic	0.005
Asbestos	7Million Fibers/Liter
Barium	2
Beryllium	0.004
Cadmium	0.005
Chromium	0.1
Cyanide	0.2
Fluoride	0.4
Mercury	0.002
Nitrate (as N)	10
Nitrite (as N)	1
Total Nitrate/Nitrite (as N)	10
Selenium	0.05
Thallium	0.002

Radionuclides	MCL
Gross alpha particle activity	15 pCi/L
Combined radium-226 and radium-228	5 pCi/L
Tritium	20,000 pCi/L
Strontium	8 pCi/L
Beta particle and photon radioactivity	4 millirem/year
Radioactivity (Total, for 2 or more radionuclides)	4millirem/year
Radon (proposed for regulatoin in drinking water; action level for indoor air is 4pCi/L	

Other Contaminants	MCL
Total Coliform Bacteria (depends on system size; includes repeat sampling requirements for fecal coliform bacteria)	No more than 1 sample or 5% of monthly
Total Trihalomethanes, annual average of four quarterly samples (only for systems serving ≥ 10,000	0.10 mg/L

Water Quality Standards

Secondary Drinking Water Standards are not MCLs, but unenforceable federal guidelines regarding taste, odor, color and certain other non-aesthetic effects of drinking water.
EPA recommends them to the States as reasonable goals, but federal law does not require water systems to comply with them. States may, however, adopt their own enforceable regulations governing these contaminants. To be safe, check your State' s drinking water rules.

U.S. EPA
National Secondary Drinking Water Standards

Contaminants	Suggested Level
Aluminum	0.05-0.2 mg/L
Chloride	250 mg/L
Color	15 color units
Copper	1 mg/L
Corrosivity	Non-corrosive
Fluoride	2.0 mg/L
Foaming agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 threshold odor numbe
pH	6.5-8.5
Silver	0.1 mg/L
Sulfate	250 mg/L
Total dissolved solids (TDS)	500 mg/L
Zinc	5 mg/L

4. Presentation of water chemical data

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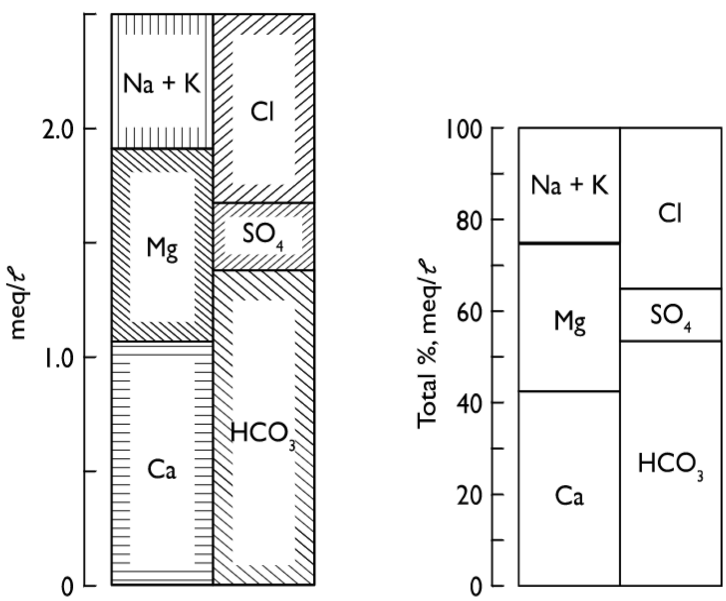
Visualizing Chemical Data

- There are a large number of plots used to visualize ion abundances:
  - Bar graph
  - Circular diagram
  - Stiff Diagram
  - Radial Diagram
  - Schoeller diagram

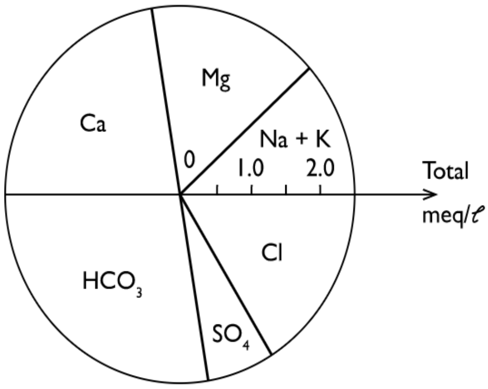
- Piper Diagram is used to group waters and interpret their origins

Graphical Methods Representing Water Quality

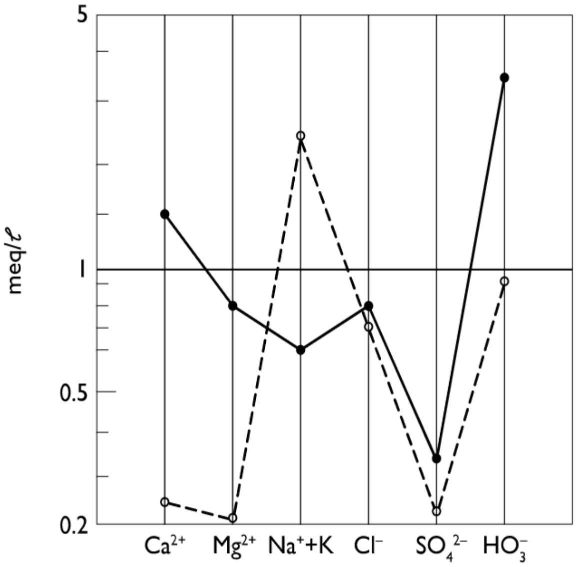


Bar graphs (from Freeze and Cherry, 1919)

Graphical Methods Representing Water Quality

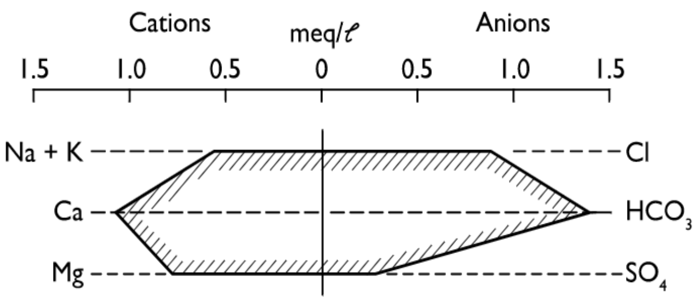


Circular diagram



Schoeller semilogarithmic diagram

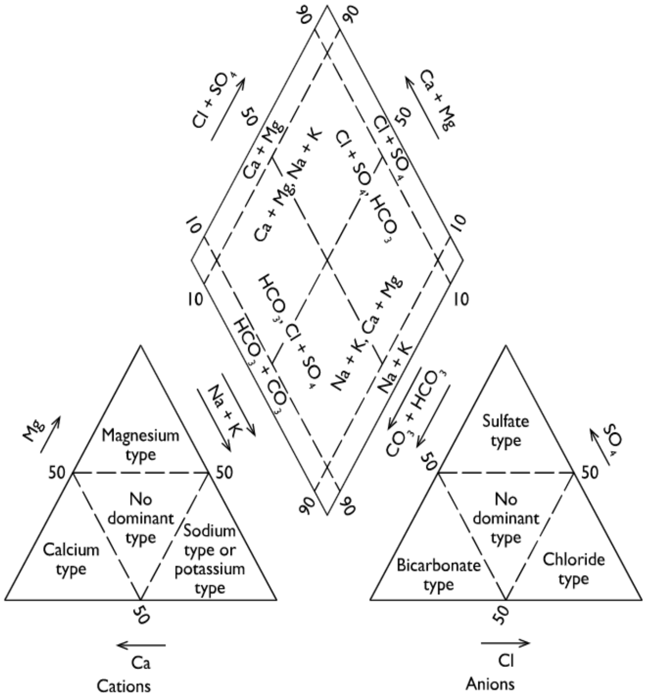
Graphical Methods Representing Water Quality



Stiff diagram

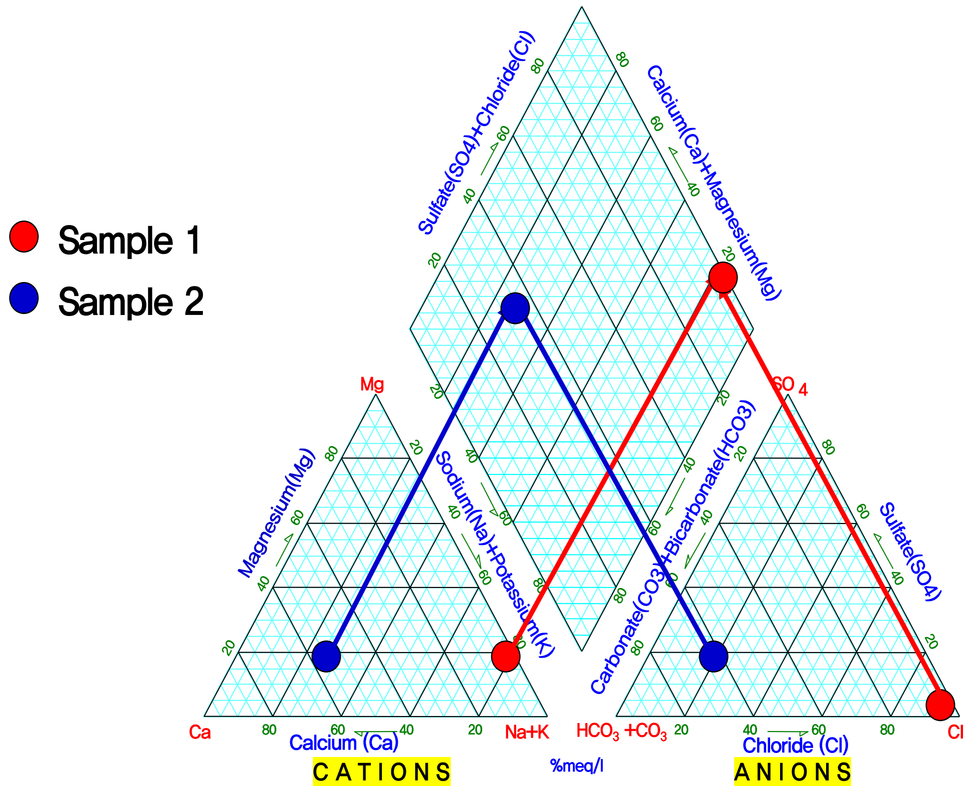
Example 넣기… 재연 논문에서…

Graphical Methods Representing Water Quality

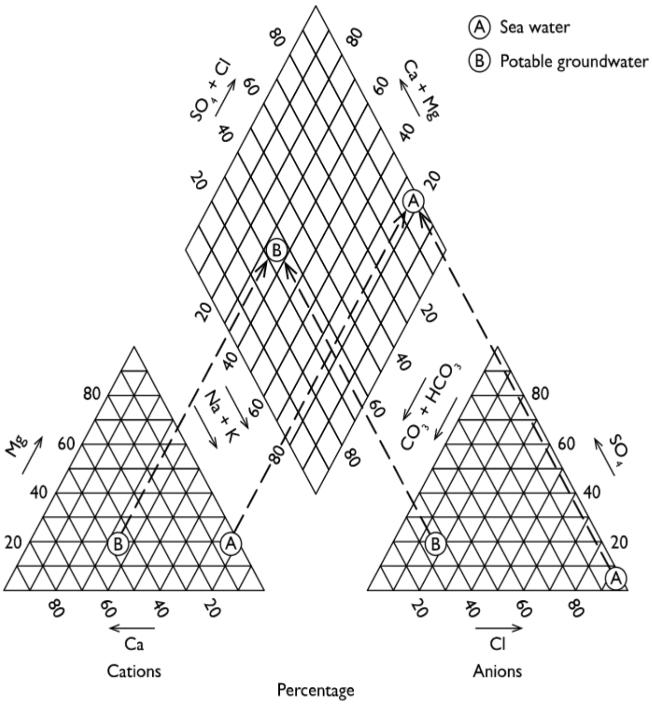


Piper Diagram (from Freeze and Cherry, 1919)

Plotting On A Piper Diagram

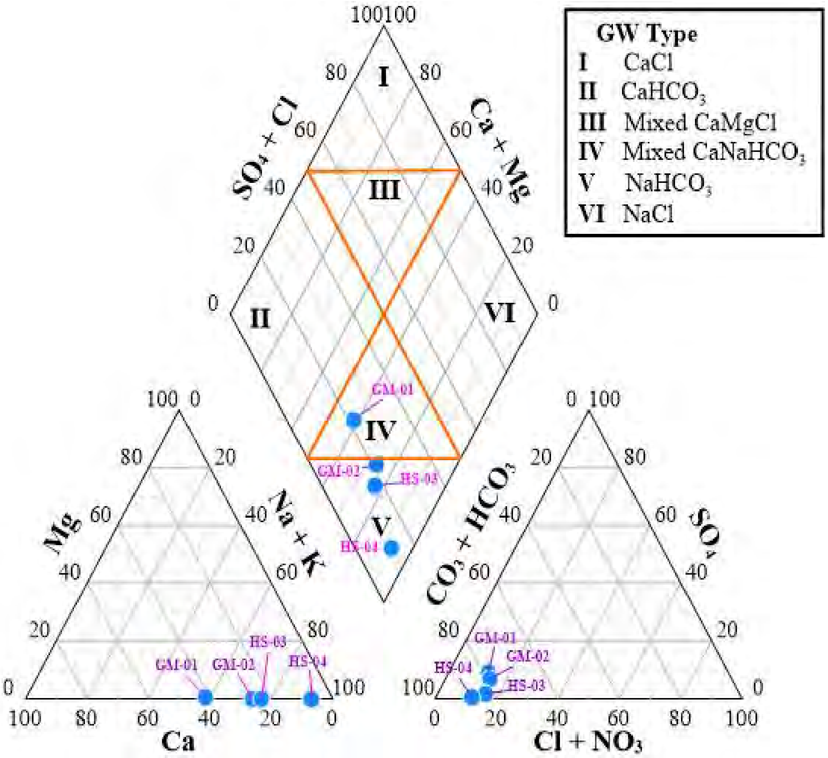


Graphical Methods Representing Water Quality



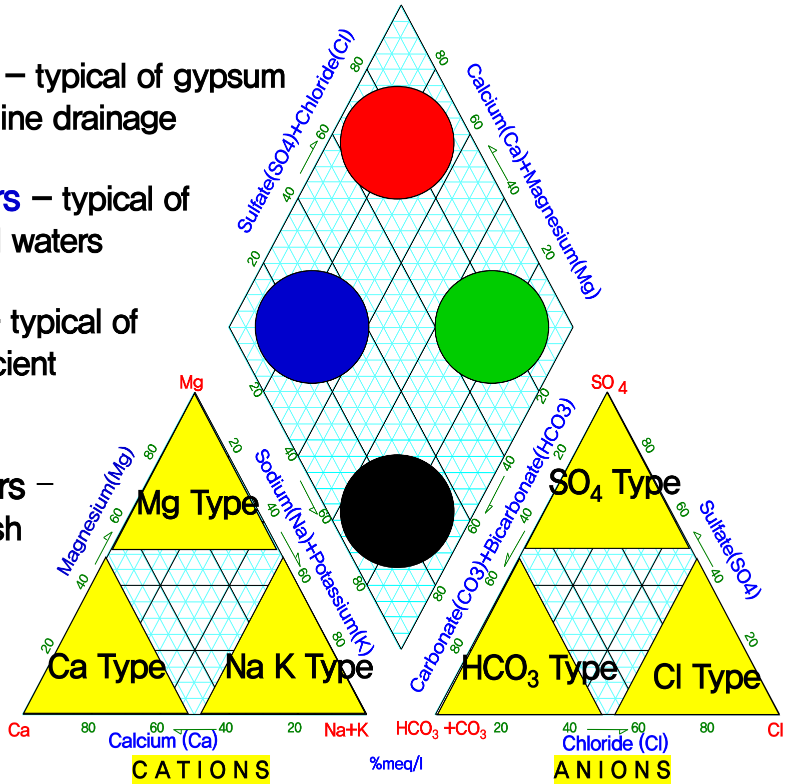
From Freeze and Cherry (1979)

Graphical Methods Representing Water Quality



Classification of Water

- **Ca–SO_4 waters** – typical of gypsum ground waters and mine drainage
- **Ca–HCO_3 waters** – typical of shallow, fresh ground waters
- **Na–Cl waters** – typical of marine and deep ancient ground waters
- Na–HCO_3 waters – typical of deeper fresh ground waters influenced by ion exchange



5. Groundwater contamination and remediation

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Sources Of Groundwater Contamination (From "Contaminant Hydrogeology (2008) By C.W. Fetter)

Category 1: Sources designed to discharge substances
- Spetic tanks and ceespools
- Injection wells
- Land application (of treated or untreated waste water, sludge, wastes from refining operations, etc)

Category 2: Sources designed to store, treat and/or dispose of subtances
- Landfills
- Open dumps
- Residential disposal
- Surface impoundments
- Mine wastes
- Material stockpiles
- Graveyards
- Animal burials
- Above-ground storage tanks (ASTs)
- Underground storage tanks (USTs)
- Containers (containers of chemical and waste produces)
- Open incineration and detonation sites
- Radioactive waste disposal sites

Sources of groundwater contamination (from "Contaminant Hydrogeology (2008) by C.W. Fetter)

Category 3: Sources designed to retain substances during transport
- Pipelines
- Material transport and transfer (by moving vehicles)

Category 4: Sources discharging substances as a consequence of other planned activities
- Irrigation
- Pesticide applications
- Fertilizer application
- Farm animal wastes
- Salt application for load deicing
- Urban runoff
- Percolation of atmospheric pollutants
- Mine drainage

Sources of groundwater contamination (from "Contaminant Hydrogeology (2008) by C.W. Fetter)

Category 5: Sources providing a conduit for contaminated water to enter aquifers
- Production wells
- Monitoring wells and exploration borings
- Construction excavation

Category 6: Naturally occurring sources whose discharges is created and/or exacerbated by human activity
- Groundwater-surface water interactions
- Natural leaching
- Saltwater intrusion

Chemicals And Contaminants In Groundwater (From USGS)

1. Inorganic Contaminants Found In Groundwater (1)

Contaminant	Sources to groundwater	Potential health and other effects
Aluminum	Occurs naturally in some rocks and drainage from mines.	Can precipitate out of water after treatment, causing increased turbidity or discolored water.
Antimony	Enters environment from natural weathering, industrial production, municipal waste disposal, and manufacturing of flame retardants, ceramics, glass, batteries, fireworks, and explosives.	Decreases longevity, alters blood levels of glucose and cholesterol in laboratory animals exposed at high levels over their lifetime.
Arsenic	Enters environment from natural processes, industrial activities, pesticides, and industrial waste, smelting of copper, lead, and zinc ore.	Causes acute and chronic toxicity, liver and kidney damage; decreases blood hemoglobin. A carcinogen.
Barium	Occurs naturally in some limestones, sandstones, and soils in the eastern United States.	Can cause a variety of cardiac, gastrointestinal, and neuromuscular effects. Associated with hypertension and cardiotoxicity in animals.
Beryllium	Occurs naturally in soils, groundwater, and surface water. Often used in electrical industry equipment and components, nuclear power and space industry. Enters the environment from mining operations, processing plants, and improper waste disposal. Found in low concentrations in rocks, coal, and petroleum and enters the ground and	Causes acute and chronic toxicity; can cause damage to lungs and bones. Possible carcinogen.
Cadmium	Found in low concentrations in rocks, coal, and petroleum and enters the groundwater and surface water when dissolved by acidic waters. May enter the environment from industrial discharge, mining waste, metal plating, water pipes, batteries, paints and pigments, plastic stabilizers, and landfill leachate.	Replaces zinc biochemically in the body and causes high blood pressure, liver and kidney damage, and anemia. Destroys testicular tissue and red blood cells. Toxic to aquatic biota.
Chloride	May be associated with the presence of sodium in drinking water when present in high concentrations. Often from saltwater intrusion, mineral dissolution, industrial and domestic waste.	Deteriorates plumbing, water heaters, and municipal water-works equipment at high levels. Above secondary maximum contaminant level, taste becomes noticeable.
Chromium	Enters environment from old mining operations runoff and leaching into groundwater, fossil-fuel combustion, cement-plant emissions, mineral leaching, and waste incineration. Used in metal plating and as a cooling-tower water additive.	Chromium III is a nutritionally essential element. Chromium VI is much more toxic than Chromium III and causes liver and kidney damage, internal hemorrhaging, respiratory damage, dermatitis, and ulcers on the skin at high concentrations.
Copper	Enters environment from metal plating, industrial and domestic waste, mining, and mineral leaching.	Can cause stomach and intestinal distress, liver and kidney damage, anemia in high doses. Imparts an adverse taste and significant staining to clothes and fixtures. Essential trace element but toxic to plants and algae at moderate levels.
Cyanide	Often used in electroplating, steel processing, plastics, synthetic fabrics, and fertilizer production; also from improper waste disposal.	Poisoning is the result of damage to spleen, brain, and liver.
Dissolved solids	Occur naturally but also enters environment from man-made sources such as landfill leachate, feedlots, or sewage. A measure of the dissolved "salts" or minerals in the water. May also include some dissolved organic compounds.	May have an influence on the acceptability of water in general. May be indicative of the presence of excess concentrations of specific substances not included in the Safe Water Drinking Act, which would make water objectionable. High concentrations of dissolved solids shorten the life of hot water heaters.
Fluoride	Occurs naturally or as an additive to municipal water supplies; widely used in industry.	Decreases incidence of tooth decay but high levels can stain or mottle teeth. Causes crippling bone disorder (calcification of the bones and joints) at very high levels.
Hardness	Result of metallic ions dissolved in the water; reported as concentration of calcium carbonate. Calcium carbonate is derived from dissolved limestone or discharges from operating or abandoned mines.	Decreases the lather formation of soap and increases scale formation in hot-water heaters and low-pressure boilers at high levels.

Chemicals And Contaminants In Groundwater (From USGS)

1. Inorganic Contaminants Found In Groundwater (2)

Contaminant	Sources to groundwater	Potential health and other effects
Iron	Occurs naturally as a mineral from sediment and rocks or from mining, industrial waste, and corroding metal.	Imparts a bitter astringent taste to water and a brownish color to laundered clothing and plumbing fixtures.
Lead	Enters environment from industry, mining, plumbing, gasoline, coal, and as a water additive.	Affects red blood cell chemistry; delays normal physical and mental development in babies and young children. Causes slight deficits in attention span, hearing, and learning in children. Can cause slight increase in blood pressure in some adults. Probable carcinogen.
Manganese	Occurs naturally as a mineral from sediment and rocks or from mining and industrial waste.	Causes aesthetic and economic damage, and imparts brownish stains to laundry. Affects taste of water, and causes dark brown or black stains on plumbing fixtures. Relatively non-toxic to animals but toxic to plants at high levels.
Mercury	Occurs as an inorganic salt and as organic mercury compounds. Enters the environment from industrial waste, mining, pesticides, coal, electrical equipment (batteries, lamps, switches), smelting, and fossil-fuel combustion.	Causes acute and chronic toxicity. Targets the kidneys and can cause nervous system disorders.
Nickel	Occurs naturally in soils, groundwater, and surface water. Often used in electroplating, stainless steel and alloy products, mining, and refining.	Damages the heart and liver of laboratory animals exposed to large amounts over their lifetime.
Nitrate (as nitrogen)	Occurs naturally in mineral deposits, soils, seawater, freshwater systems, the atmosphere, and biota. More stable form of combined nitrogen in oxygenated water. Found in the highest levels in groundwater under extensively developed areas. Enters the environment from fertilizer, feedlots, and sewage.	Toxicity results from the body's natural breakdown of nitrate to nitrite. Causes "bluebaby disease," or methemoglobinemia, which threatens oxygen-carrying capacity of the blood.
Nitrite (combined nitrate/nitrite)	Enters environment from fertilizer, sewage, and human or farm-animal waste.	Toxicity results from the body's natural breakdown of nitrate to nitrite. Causes "bluebaby disease," or methemoglobinemia, which threatens oxygen-carrying capacity of the blood.
Selenium	Enters environment from naturally occurring geologic sources, sulfur, and coal.	Causes acute and chronic toxic effects in animals--"blind staggers" in cattle. Nutritionally essential element at low doses but toxic at high doses.
Silver	Enters environment from ore mining and processing, product fabrication, and disposal. Often used in photography, electric and electronic equipment, sterling and electroplating, alloy, and solder. Because of great economic value of silver, recovery practices are typically used to minimize loss.	Can cause argyria, a blue-gray coloration of the skin, mucous membranes, eyes, and organs in humans and animals with chronic exposure.
Sodium	Derived geologically from leaching of surface and underground deposits of salt and decomposition of various minerals. Human activities contribute through de-icing and washing products.	Can be a health risk factor for those individuals on a low-sodium diet.
Sulfate	Elevated concentrations may result from saltwater intrusion, mineral dissolution, and domestic or industrial waste.	Forms hard scales on boilers and heat exchangers; can change the taste of water, and has a laxative effect in high doses.
Thallium	Enters environment from soils; used in electronics, pharmaceuticals manufacturing, glass, and alloys.	Damages kidneys, liver, brain, and intestines in laboratory animals when given in high doses over their lifetime.
Zinc	Found naturally in water, most frequently in areas where it is mined. Enters environment from industrial waste, metal plating, and plumbing, and is a major component of sludge.	Aids in the healing of wounds. Causes no ill health effects except in very high doses. Imparts an undesirable taste to water. Toxic to plants at high levels.

Remediation Of Contaminated Groundwater

Various in-situ and ex-situ methods are available and appropriate methods should be selected

Example: The Remediation Technologies Screening Matrix (US EPA)

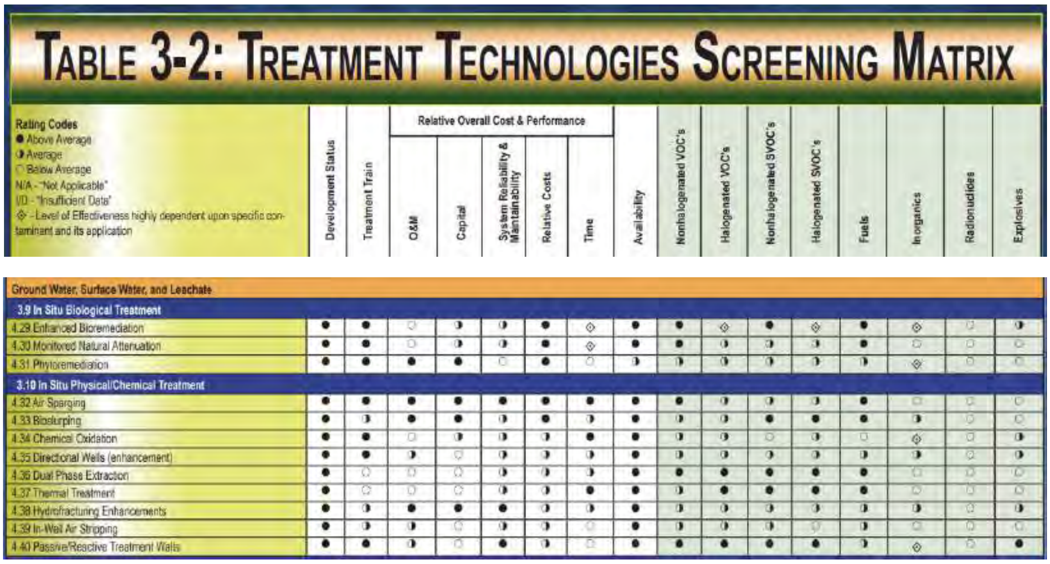

TABLE 3-2: TREATMENT TECHNOLOGIES SCREENING MATRIX

Rating Codes
● Above Average
◑ Average
○ Below Average
N/A - "Not Applicable"
I/D - "Insufficient Data"
◈ - Level of Effectiveness highly dependent upon specific contaminant and its application

Ground Water, Surface Water, and Leachate	Development Status	Treatment Train	Relative Overall Cost & Performance: O&M	Capital	System Reliability & Maintainability	Relative Costs	Time	Availability	Nonhalogenated VOC's	Halogenated VOC's	Nonhalogenated SVOC's	Halogenated SVOC's	Fuels	Inorganics	Radionuclides	Explosives
3.9 In Situ Biological Treatment																
4.29 Enhanced Bioremediation	●	●	○	◑	◑	●	◈	●	●	◈	●	◈	●	◈	○	◑
4.30 Monitored Natural Attenuation	●	●	○	◑	◑	●	◈	●	●	◑	◑	◑	●	○	○	○
4.31 Phytoremediation	●	●	●	●	○	●	○	◑	◑	◑	◑	◑	◑	◈	○	○
3.10 In Situ Physical/Chemical Treatment																
4.32 Air Sparging	●	●	●	●	●	●	●	●	●	◑	◑	◑	●	○	○	○
4.33 Bioslurping	●	◑	●	●	◑	●	◑	●	◑	◑	●	●	●	◑	○	○
4.34 Chemical Oxidation	●	●	○	◑	◑	◑	●	●	◑	◑	○	◑	○	◈	○	◑
4.35 Directional Wells (enhancement)	●	●	◑	○	◑	◑	◑	●	◑	◑	◑	◑	◑	◑	○	◑
4.36 Dual Phase Extraction	●	○	○	○	◑	◑	◑	●	●	●	●	●	●	○	○	○
4.37 Thermal Treatment	●	○	○	○	◑	◑	●	●	◑	●	●	●	●	○	○	○
4.38 Hydrofracturing Enhancements	●	◑	●	●	●	◑	◑	●	◑	◑	◑	◑	◑	◑	○	◑
4.39 In-Well Air Stripping	●	◑	◑	○	◑	◑	○	●	◑	◑	◑	○	◑	○	○	○
4.40 Passive/Reactive Treatment Walls	●	●	◑	○	●	◑	○	●	●	●	●	●	◑	◈	○	●


Thank you very much

Solute Transport & Tracer Test

Groundwater

Solute Transport & Tracer Test

UNESCO
United Nations Educational, Scientific and Cultural Organization
i-WSSM
International Centre for Water Security and Sustainable Management

contents

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1. Solute transport

3

Mechanisms of solute transport

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Major mechanisms for solute transport

- **Advection**: transport by the velocity of groundwater
- **Molecular diffusion:** transport due to random movements of solutes, not accounted by the velocity
- **Dispersion**: combined effect of advection and molecular diffusion making particles to spread out due to variations in flow velocity and pathways.
- **Sorption**: the adhesion of atoms, ions or molecules to a surface of aquifer material (adsorption) and the release of those from the surface (desorption)
- **Chemical/biological reaction or radioactive decay** : precipitation, biodegradation, oxidation-reduction, radioactive decay

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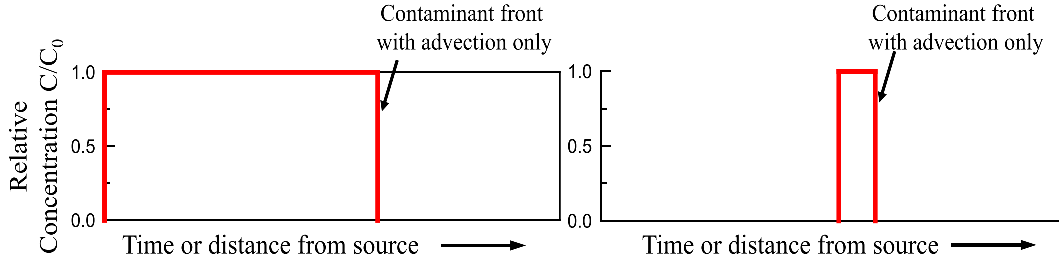
Advection; convection

- The transport of solute by bulk motion of a fluid at the same velocity with groundwater flows
- 1-D Advection Equation

$$\bar{v} = \frac{Ki}{n_e}$$

$$\frac{\partial C}{\partial t} = -\bar{v}\frac{\partial C}{\partial x}$$

$\bar{v}$ = average linear velocity, [m/s])
K = hydraulic conductivity*([m/s])
n_e = effective porosity C = Concentration
i = hydraulic gradient t = time
x = distance to the flow direction



〔 solute transport by advection (left: continuous injection, right: pulse injection) 〕

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Hydrodynamic dispersion and molecular diffusion

- **Hydrodynamic dispersion** : combined effect of mechanical dispersion and molecular diffusion
- Mechanical dispersion

$$\text{Mechanical dispersion} = \alpha \bar{v}$$

α =dispersivity, [m]

$\bar{v}$ = avg. linear velocity, [m/s]

  - Microscopic dispersion
  - Macroscopic dispersion
- Molecular diffusion
- scale effect of dispersivity

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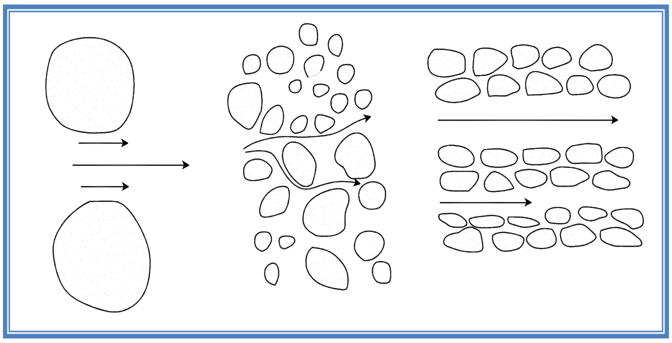
Microscopic dispersion

- **Friction in pore throat:**
  - Variation in velocity due to different friction of pore channel
  - High friction along with pore wall and lower friction to the center of the pore channel
- **Tortuosity**
  - Different pathways
- **Pore size:**
  - Variation in velocity due to different friction of pore size



[Mechanical dispersion in microscopic scale]

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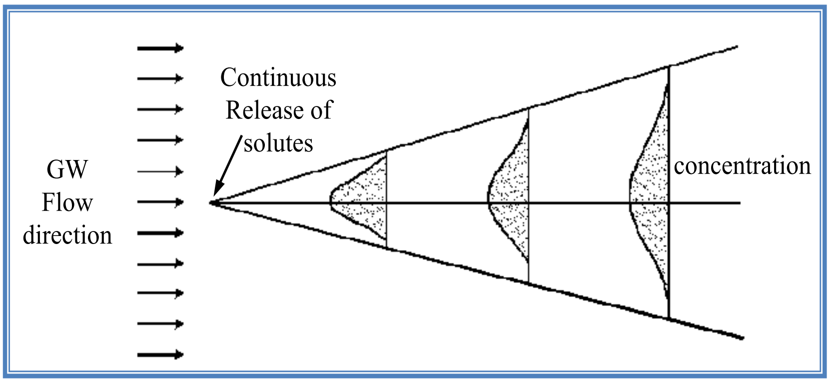
Macroscopic dispersion

- Longitudinal dispersion:
  - Some of the contaminants will be "behind" or "ahead" the mean groundwater, giving rise to a longitudinal dispersion
- Transverse dispersion:
  - some will be "to the sides of" the pure advective groundwater flow, leading to a transverse dispersiv



〔 dilution caused by hydrodynamic dispersion in porous media〕

- Dispersion is a kind of mixing process and longitudinal dispersion is generally 10 to 20 times higher than transverse dispersion

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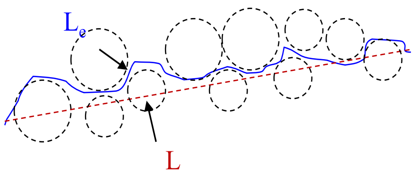
Molecular diffusion

- A fundamental physical phenomenon, which Albert Einstein characterized as Brownian motion, that describes the random thermal movement of molecules and small particles in gases and liquids
- Molecular diffusion coefficient in groundwater (D^*): Molecules in porous media has longer diffusion path than that in water body causing slower diffusion

$$D^* = \varpi D_0$$

ϖ = proportionality constant
D_0 = Ion diffusion coeff. (~10^{-6} cm^2/sec)

- ω : proportionality constant related with tortuosity; $T = L_e/L > 1$



- Perkins & Johnson(1963) : ω =0.7
- Freeze & Cherry(1979) : ω =0.5~0.01

cations	H^+	9.31×10^{-9} m^2/sec
	Na^+	1.33×10^{-9} m^2/sec
	K^+	1.96×10^{-9} m^2/sec
	Mg^+	7.05×10^{-10} m^2/sec
	Ca^{2+}	7.93×10^{-10} m^2/sec
	Mn^+	6.88×10^{-10} m^2/sec
	Fe^{2+}	7.19×10^{-10} m^2/sec
	Fe^{3+}	6.07×10^{-10} m^2/sec
	Cr^+	5.94×10^{-10} m^2/sec
anions	OH^-	5.27×10^{-9} m^2/sec
	F^-	1.46×10^{-9} m^2/sec
	Cl^-	2.03×10^{-9} m^2/sec
	HCO_3^-	1.18×10^{-9} m^2/sec
	SO_4^{2-}	1.07×10^{-9} m^2/sec
	CO_3^{2-}	9.55×10^{-10} m^2/sec

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Concentration breakthrough curves by hydrodynamic dispersion

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

$$D = \alpha\bar{v} + D^*$$

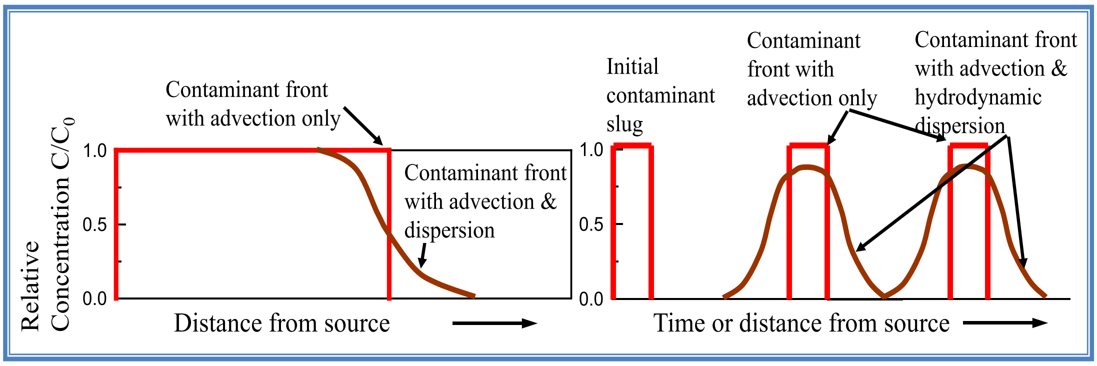
D = hydrodynamic dispersion

α = hydrodynamic dispersivity

$\bar{v}$ = avg. linear velocity (Darcy velocity)

D^* = Molecular diffusion coeff.

$\alpha\bar{v}$ = mechanical dispersion by advection



〔 solute transport by A+ hydrodynamic dispersion (left: continuous injection, right: pulse injection) 〕

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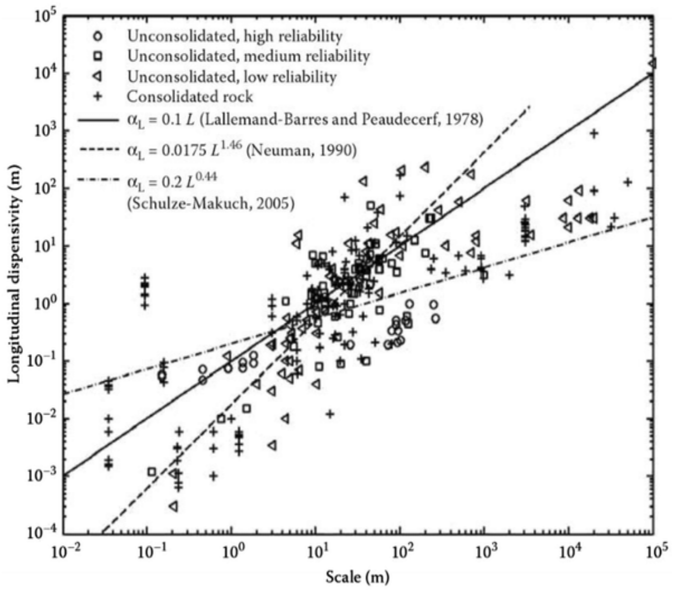
Scale effect of hydrodynamic dispersion

- Hydrodynamic dispersion increases as solute moves longer (Gelhar, 1985; Domenico and Schwartz, 1990)

  → Contaminant could spread out more as it transport further



Source: Thibodeaux and Mackay, 2011

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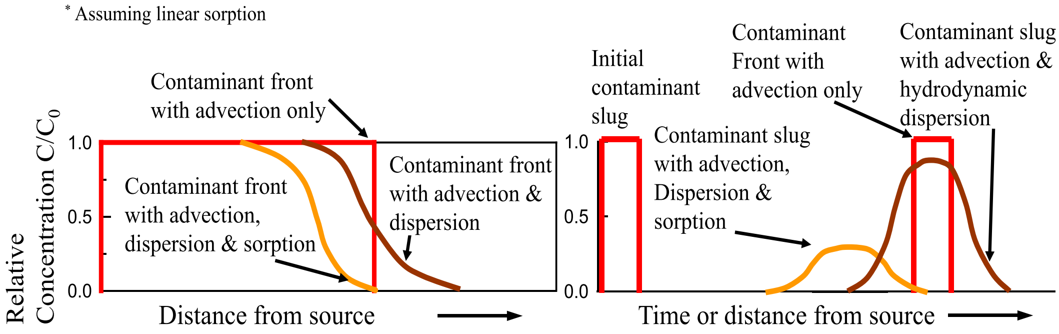
Sorption

- Sorption makes solutes to retard behind average groundwater velocity

$$R = \frac{v_x}{v_c} \left(= 1 + \frac{\rho k_d}{n}\right)^*$$

R = retardation factor
v_x = avg. linear gw velocity
v_c = transport velocity of solute
ρ = density
k_d = distribution coeff.
n = porosity

* Assuming linear sorption



[solute transport by A+D+sorption (left: continuous injection, right: pulse injection)]

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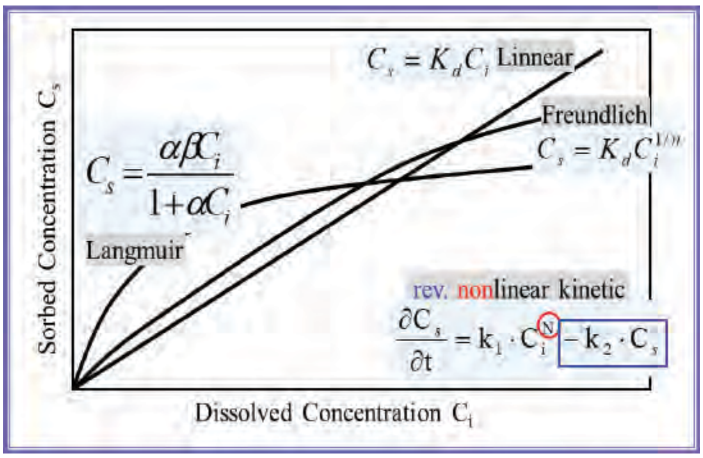
Sorption isotherm

- Various sorption isotherm
  - Equilibrium sorption model : sorption process is fast enough rather than groundwater flows
    - Linear isotherm: applicable when concentration is lower than half of the solubility
    - Freundlich isotherm: applicable to very low concentration and limited sorption site
    - Langmuir isotherm: sorption increase with linear at low concentration and is constant at high concentration
  - Non-equilibrium sorption model : sorption process is slow so that the groundwater flows can affect on the process
    - Kinetic model: The solute transport equation is linked with a equation explaining the kinetic sorption-desorption ratio



C_i = concentration in water
C_s = concentration on solid
Kd(distribution coeff.),
α(constant related to the free adsorption energy),
β(adsorption capacity)

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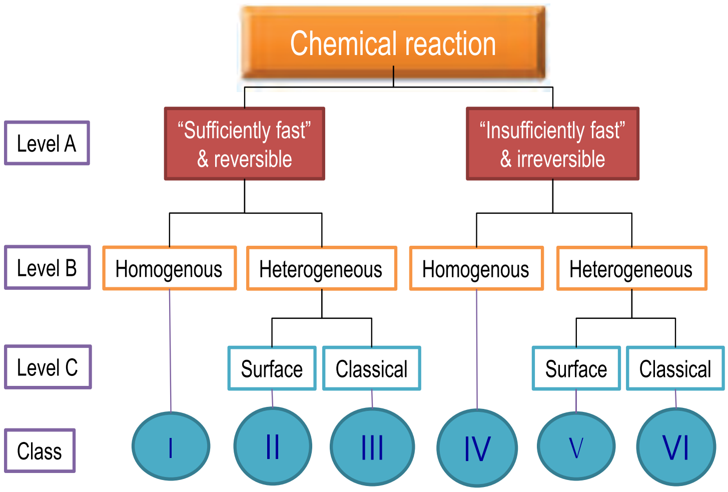
Chemical reactions in subsurface

- Classification : Rubin(1983)

- Rev.: Sufficiently fast, LEA (local equilibrium assumption) system
- Irrev.: Insufficiently fast, kinetic system

- Homo: take place within liquid phase
- Hetero: within solid and liquid phase

- Surface: hydrophobic adsorption, ion exchange
- Classical chemical rxn: precipitation, dissolution



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Homogenous Reaction I (Class I) – Chemical equilibrium

- Reactions take place entirely within the liquid phase
- If the reactions are reversible and proceed rapidly enough, local chemical equilibrium
- Reversible & chemical equilibrium

$$aA + bB \Leftrightarrow cC$$

- a, b, c : number of molecules of each compound that are needed to balance the reaction
- An equilibrium constant(K_{eq})

$$K_{eq} = \frac{[C]^c}{[A]^a[B]^b}$$

- Sufficient time to proceed to the point of equilibrium
- Class I reaction

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Homogenous Reaction II (Class IV) – Chemical kinetics

- Reactions take place entirely within the liquid phase
- If enough time for reaction is nor provided, irreversible rxn
- Irreversible & chemical kinetics
  - disappearance time of the reactants A and B
  - appearance time of the products C

$$R_A = -\frac{d[A]}{dt} = \kappa[A]^p[B]^q$$
$$R_B = -\frac{d[B]}{dt} = \kappa'[A]^p[B]^q$$
$$R_C = \frac{d[C]}{dt} = \kappa''[A]^r$$

$R_A, R_B = reaction\ rate\ for\ the\ disappearance\ of\ A\ \&\ B$
$R_C = reaction\ rate\ for\ the\ appearance\ of\ C$
$[A],[B],\&[C] = measured\ con'c$
$\kappa, \kappa', \kappa'' = reaction\ rate\ constants$
$p,q,\&r = reaction\ order\ of\ reactant\ or\ product$

- p, q & r = 0 ; zero-order $\quad [A] = [A]_o - \kappa t$
- P, q & r = 1 ; first-order $\quad [A] = [A]_o e^{-\kappa t}$
- p, q & r = 1 or 0 ; more difficult to analyze

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Radioactive decay

- If radionuclides enter the groundwater system, those which are cations, are possibly subjected to retardation on soil surfaces
- In addition they will undergo radioactive decay, which will reduce the concentration of radionuclides in both the dissolved and sorbed phases.

Radioactive decay

$$\left(\frac{\partial C}{\partial t}\right)_{decay} = -\frac{\ln 2}{\lambda} C$$
$$\because \lambda = the\ half-life\ of\ the\ radionuclide$$

- The reaction rate constant : first-order decay process

$$\kappa = \ln\frac{2}{\lambda}$$
$$\because [C] = [C_1]e^{-(\ln 2/\lambda)t}$$

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Biodegradation

- There are numerous microorganisms in subsurface, which can degrade hydrocarbons.
- Aerobic biodegradation : the microbes require oxygen in their metabolism
  - Monod function

$$\frac{dH}{dt} = -M_t h_u \left(\frac{H}{K_h + H}\right)\left(\frac{O}{K_o + O}\right)$$

$$\frac{dO}{dt} = -M_t h_u G \left(\frac{H}{K_h + H}\right)\left(\frac{O}{K_o + O}\right)$$

$$\frac{dM_t}{dt} = M_t h_u Y \left(\frac{H}{K_h + H}\right)\left(\frac{O}{K_o + O}\right) + k_c Y C_{oc} - b M_t$$

H = hydrocarbon con'c
O = oxygen con'c
M_t = total aerobic microbial con'c
h_u = Max. hydrocarbon utilization rate per unit mass of aerobic microorganism
Y = microbial yield coef.
K_h = hydrocarbon half − saturation constant
K_o = oxygen half − saturation constant
k_c = first − order decay rate of natural organic carbon
C_{oc} = natural organic carbon con'c
b = microbial decay rate
G = ratio of oxygen to hydrocarbon consumed

- Anaerobic biodegradation : the microbes can degrade hydrocarbon in the absence of oxygen
  - another electron acceptor (Nitrate, nitrite, sulfate, iron, methane etc.)
  - Anaerobic decomposition of hydrocarbon can be described by another variation of the monod function
  - Two-step catalytic chemical reactions

$$\frac{dH}{dt} = -M_a h_{ua} \left(\frac{H}{K_h + H}\right)$$

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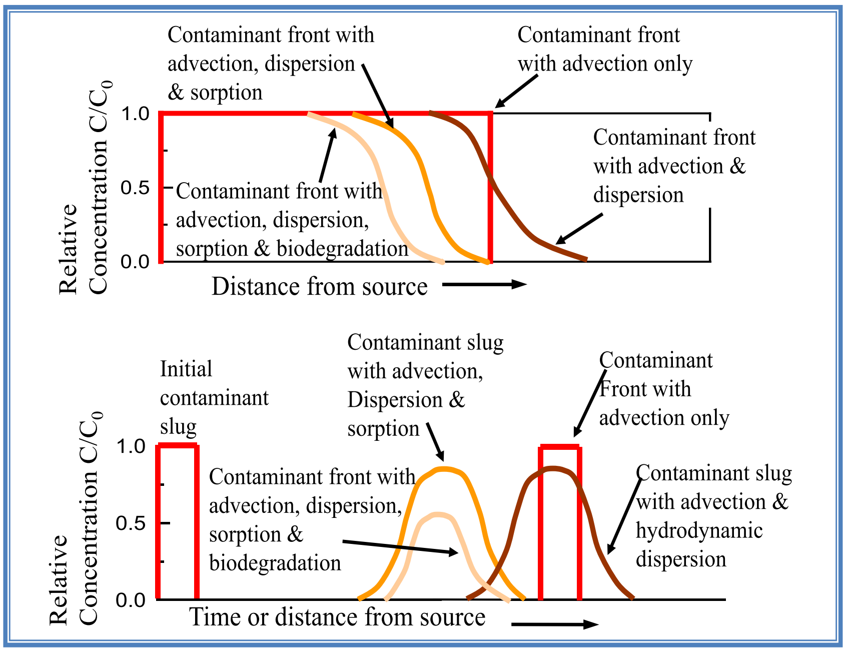
Biodigradation



〔 solute transport by A+D+S+biodegradation
(left: continuous injection, right: pulse injection) 〕

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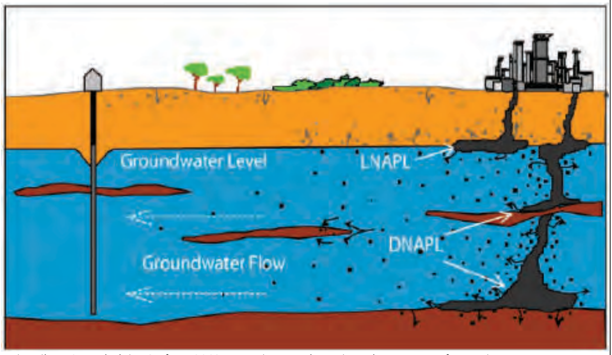
multiphase transport

- Nonaqueous Phase Liquids (NAPLs)
  - Organic liquid contaminants that do not dissolve in, or easily mix with, water (hydrophobic) like oil, gasoline and petroleum products
  - D-NAPLs
    - Denser than water, so sink downward
    - Solvents such as TCE, PCE, TCA, etc
  - L-NAPLs
    - Lighter than water, so float on water table
    - Fuels such as gasoline, Diesel, etc



Liu, Lihua & Haderlein, Stefan. (2013). A review on the aging phenomena of organic components and their mass transfer through the NAPL interfacial phase. Chinese Journal of Geochemistry. 32. 252-260. 10.1007/s11631-013-0630-6.

- Multiphase
  - Saturated zone : 2 phase flow (Water , NAPLs)
  - Unsaturated zone : 3 phase flow(Air, Water, NAPLs)
  - NAPLs transport are governed by interfacial tension and capillary pressure

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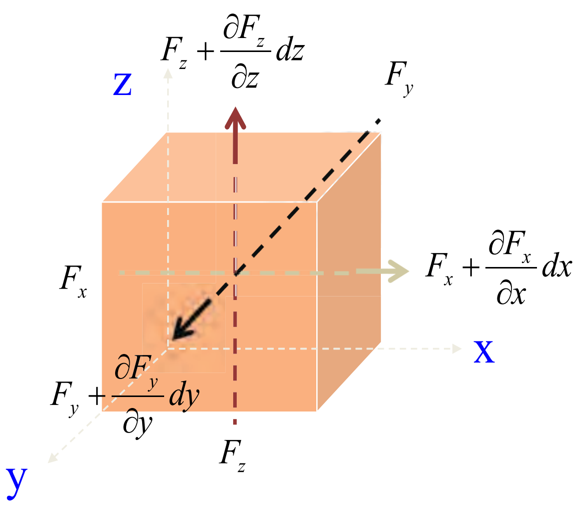
Governing equation for solute transport

The law of the conservation of mass

Total mass change of solute in the unit REV volume	=	Total mass out from the unit REV volume	−	Total mass in from the unit REV volume	±	Total mass change due to reactions



Assumptions
- Porous medium
- Homogeneous
- Isotropic
- Saturated
- Steady state flow
- Darcy's law applicable

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Non-reactive solute transport

- **non-reactive solute**: Solute entering into aquifer does not react with aquifer materials
- **Types of non-reactive solute**: H^{3+}, Cl^-, Br^-, I^-, NO_3^- , etc
- **Transport mechanism**: advection and hydrodynamic dispersion

Governing A-D equation

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

D_x = dispersion coefficient
v_x = avg. linear velocity (seepage velocity)

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Reactive solute transport

- **Reactive solution**: Solute that may sorb onto or react with aquifer materials, resulting that mass of solute changes with time and space
- **Reaction procedure in the subsurface environment**
  - Retarding reaction
    - Adsorption, absoprtion & desorption
  - Mass changing reaction
    - precipitation)
    - oxidation-reduction rxn
    - biodegradation
    - radioactive decay

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Reactive solute transport – sorption, chemo-biological rxns

- Chemical retardation: Solute reacts with the porous media and its rate of movement is retarded relative the advective groundwater velocity
- Governing eqn. for reactive solute transport

$$\frac{\partial C}{\partial t} = D_l \frac{\partial^2 C}{\partial x^2} - \bar{v}_x \frac{\partial C}{\partial x} - \frac{r_d}{n}\frac{\partial S}{\partial t} + \left(\frac{\partial C}{\partial t}\right)_{rxn}$$

C = solute concentration in water

t = time

D_l = longitudinal dispersion coeff.

$\bar{v}$ = avg. linear velocity

n = porosity

r_d = unit bulk dry mass of media

S = mass of solute adsorbed per unit bulk dry mass of porous media

rxn = chemical or biological reactions excluding adsorption

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Reactive solute transport – radioactive decay

Radionuclide may decay and adsorbs onto media

Governing equation for adsorptive and radioactive decay

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

R = retardation factor

$$R\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} - kC$$

k = 1st order decay rate

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2. Outlines of Tracer tests

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Tracer test application

- To find out connectivity between points or areas of concern
  - Connectivity through fractures, conduit in karst aquifer, checking leakage
- To estimate physical/chemical/biological parameters to characterize the solute transport procedure in the aquifer of contaminated area, radioactive waste disposal site, landfill and so on.
  - Average linear velocity (=seepage velocity, Darcy velocity)
  - Dispersion coefficient (or dispersivity)
  - Retardation factor
  - Reaction kinetics relating adsorption, distribution coefficient, precipitation, redox reaction and so on.

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Types of tracer

types	remarks
Ions	• Have been used extensively to determine flow paths, residence time, and other aquifer properties. • Selection based on the purpose, types of aquifer system (karst, fractured rock, porous media), aquifer properties (degree of heterogeneity, extent of clay lenses), natural background concentration, analytical methods avaiable • Anions as conservative tracer, Cations could react (ion exchange) with clay minerals under low pH • Ionic tracers: Cl^-, Br^-, I^-, SO_4^{2-}, Li^+, NH_4^+, Mg^{2+}, K^+, organic anions (such as benzoate), alcohols, etc
dyes	• Inexpensive, simple to use, and effective to tracing surface water and groundwater • Green (Fluorescein, Pyranine, Lissamine FF), Orange (Rhodamine B, Rhodamine • WT, Sulfo Rhodamine B), Blue (Optical brighteners such as Photine CU, Amino G acid)
Others	• Temperature • Spores • Bacteria as common biological tracers (Escherichia coliform(E.coli), Streptococcus faecalis, Bacillus stearothermophilus, Serratia marcescens, etc)

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Ion tracers

In most situations, anions are not affected by the aquifer medium whereas cations will react frequently by ion exchange with minerals.

Chloride (Cl^-)	• where to avoid density effect(inj. Conc. 3000 ppm and lower) and low clay minerals (not good for coastal area) •Conservative, inexpensive, safe • detection: ion selective electrode, electrical conductivity meter
Bromide (Br^-)	• natural background concentration is lower than 1 ppm • most commonly used ion tracer • stable in biological reaction, precipitation, adsorption • detection: ion selective electrode, electrical conductivity meter, LC
Iodide (I^-)	• natural background concentration is lower than 0.01 ppm • tends to be sorbed to a greater extent than bromide or chloride and affected by microbiological activity

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Dye Tracers

- Inexpensive, simple to use, effective to trace surface water and groundwater
- Been used since the late 1800's, extensively used around 1960
- Very high detectability, rapid field analysis, and relatively low cost and low toxicity

Rhodamine WT	• One of the most useful tracers for quantitative studies • Orange dye, conservative, very low detection limit 0.1 ppb. • low photochemical and biological decay rate and adsorption • the most conservative dye for stream and karst tracing
Fluorescein	•Green dye called as uranin, sodium fluorescein, pthalien • Low sensitivity of analyses due to high natural background fluorescence • High photochemical decay rate compared to other dyes • affected by pH (it becomes colorless in acidic conditions) and salinity (decrease with increasing salinity) •Affected by suspended sediment load, temperature, pH, CaCO3 content, salinity, etc.

Criteria for tracer selection

- Test objectives
  - For identifying flow path – all kind of tracers applicalbe
  - For estimating transport parameters (velocity, porosity, dispersion coefficient) – conservative tracer
  - Distribution coefficient with velocity – reactive tracer
  - Groundwater recharge – environmental tracer such as ^{36}Sr, ^{18}O, etc
  - Age of groundwater – radioactive tracers (^{3}H), CFC

- Types of media
  - Karst aquifer – dyes, spores, tritium
  - Porous aquifer – all kind of tracers but not particle tracers
  - Fractured rock aquifer – all kind of tracers but very rarely, particle tracers

Criteria for tracer selection

- Detectability
  - Background concentration, dilution by mixing and dispersion determined by injection method (pulse/const.), distance btw inj.-obs. wells, dispersivity, posority, hydraulic conductivity of media
  - detection limit of measuring apparatus
  - Interference by other tracers or natural matters
- Method of sample collection and analysis
  - Availability of the in-situ or onsite measurement devices
  - in case of off-site analysis, sample collection, storage, and delivery method are taken into consideration
  - Expense for sample collection and analysis

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Criteria for tracer selection

- Tracer properties
  - Density effect : Too high concentration of tracer (e.g., Ion tracers over 2,000 mg/L) could sink downward before mixing vertically well in the borehole
  - Conservative tracer should be used when to know the advective and dispersive properties of the media
  - If the purpose of the tracer test is to know the such kinetic properties of the media as ion exchange, adsorption/desorption, biodegradation, radioactive decay, then use those kind of reactive tracers
- Toxicity
  - Toxicity to human body and environment is most priority criteria when choosing tracer
  - Some bacteria, radioactive nuclides, ions should follows related regulations (E. coli., bromide)
  - e.g. Bromide (Br^-) : Dangerous when mass in adult's blood is over 2.4 g

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3. Performing Tracer test

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Types of tracer tests

- Single-Well Tracer Tests
  - Sing-well injection-withdrawal test
  - Drift-pumpback test
  - Point-dilution test
- Multi-Well Tracer Tests
  - Natural gradient tracer test
  - Forced gradient tracer test
    - Divergent flow tracer test
    - Convergent flow tracer test
    - Recirculation tracer test

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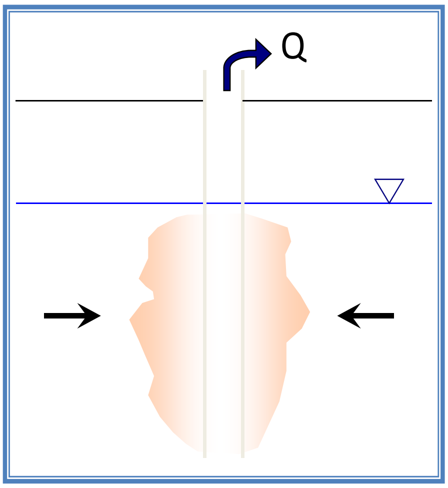
Sing-well injection-withdrawal test

- Introduced first to study the patterns of solute spreading in sandy aquifer (Mercado, 1996)
- Assumption :
  - Groundwater flows in radially divergent and then convergent.
  - Natural groundwater velocity is very low so as to be negligible

- Test procedure
  1) Inject tracer solution of constant concentration into a well at a constant rate – record injection concentration, injection rate, injection period, injection volume
  2) Pump out water from the same well at the same rate of injection right after the injection phase
  3) Monitor the change of concentration with time during pumping phase



[plumes at the beginning of withdrawal phase]

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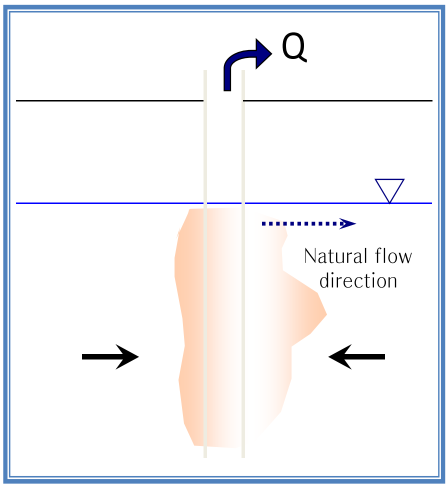
Drift & pump-back test

- Inject the tracer solution *slowly enough not to disturb a natural groundwater flow system*
- Useful test only at close area from the well (Pickens and others, 1981)
- Borehole should be fully penetrated and vertical flow is negligible

- Test procedure
  1) Measure the water table and well depth
  2) Insert the injection tube (or pipe) to the bottom of the well and wait till the water level is back to original position
  3) Inject slowly a tracer solution of the same volume with the submerged part of the tube
  4) Withdraw the tube slowly and then let the tracer solution drift out from the borehole for a certain time
  5) Pump back after a certain time and measure the concentration change with time



[plumes at the beginning of pump-back phase]

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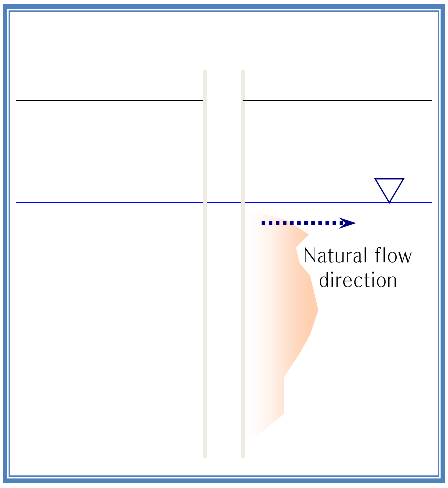
Point-dilution test

- May give useful information when performing before other tracer tests
- Monitor the change of concentration profile with depth, and then estimate the hydraulic conductivity profile around the test well
- Assumptions :
  - Negligible vertical mixing within the borehole when horizontal flow is dominant
- Test procedure
  1) Measure the water table and well depth
  2) Insert the injection tube (or pipe) to the bottom of the well and wait till the water level is back to original position; measure the recovery time
  3) Inject slowly a tracer solution of the same volume with the submerged part of the tube
  4) Withdraw the tube out of the borehole after waiting for the recovery time
  5) Monitor the change of concentration profile with depth by sampling or in-situ proper sensors with time



[plumes during point dilution test]

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Natural gradient tracer test

- Introduce tracer solution with low rate into the aquifer so that natural flow system is not disturbed during the whole test period
- One injection well and one or more observation wells
- Need to plan detailed sampling network in horizontally and vertically
- Hard to perform when the distance btw inj. and obs. well is great
- Typical case studies
  - Borden Landfill Site (Canada), Cape Cod Site (USA)
- Observation wells are suggested to be arranged parallel to the natural groundwater flow direction

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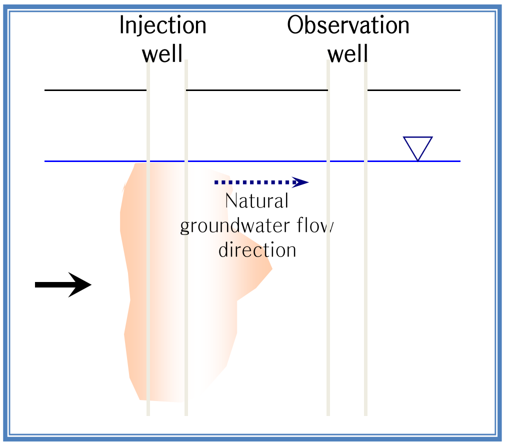
Natural gradient tracer test

- Test procedure
  1) Prepare tracer solution
  2) Introduce the tracer solution slowly, not disturbing natural flow system, by same method like single well tracer test such as drift and pump-back test or point dilution test.
  3) Monitor the concentration change at the observation well(s).

✓ When pumping out groundwater to measure the concentration, try to minimize the sample volume not to disturb the flow system.

✓ Small pump is recommended to take samples when there is no in-situ sensor because bailer can disturb and induce vertical mixing during taking samples.



[plumes during natural gradient tracer test]

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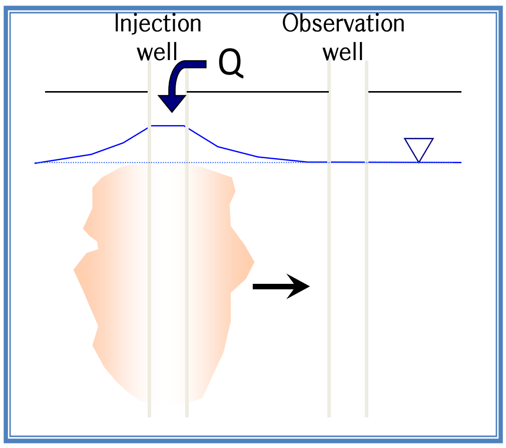
Forced gradient tracer test - Divergent flow

- Inject tracer solution constantly into injection well located at the center of the test area
- Monitor the concentration with time at the observation wells located radially around the injection well
- Need to prepare large volume of water during entire test period

- Test procedure
  1) Prepare tracer solution in water tank. Sometimes, two or more water tanks are need to prepare tracer solution during tracer injection from one tank.
  2) Inject tracer solution constantly through injection well. Sometimes, chaser fluid, whose concentration is same as background, are recommended to use save tracer solution.
  3) Monitor the concentration change at the observation wells

  ✓ Divergent flow field are recommended to be established before tracer injection



[plumes during divergent forced gradient tracer test]

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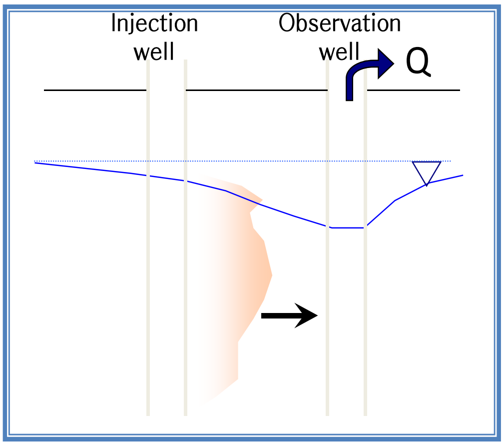
Forced gradient tracer test - Convergent flow

- Pump groundwater from pumping well located at the center of the test area
- Inject tracer solution through injection well located around the pumping well
- Can perform with pumping test

- Test procedure
  1) Pump groundwater from the pumping well (=observation well) to establish steady state convergent flow field. Take the collected groundwater to make tracer solution. Record pumping rate.
  2) Pumped water should discharge to the downgradient point to avoid the return flow.
  3) Injection tracer solution slowly into injection well when steady state.
  4) Monitor the concentration change at the pumping(observation well)



[plumes during convergent forced gradient tracer test]

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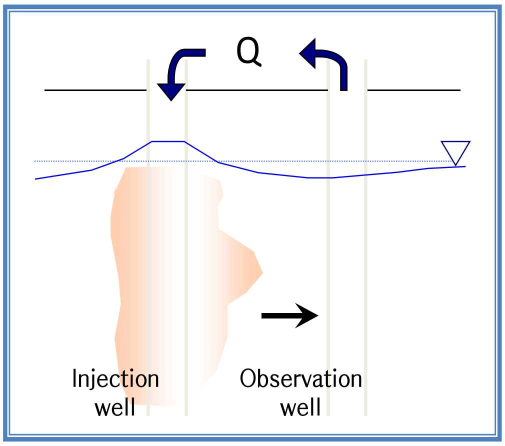
Forced gradient tracer test - recirculation flow

- To establish st. st. flow field, pump at one well and injection into the other well at the same rate
- Inject tracer into injection well and monitor the concentration at pumping well
- Applicable to hundred meters of test area if the aquifer is very permeable
- Applicable to a single fissure between two wells using packers

- Test procedure
  1) Establish st. st. flow field by pumping at one well and injection into the other well at the same rate
  2) Tracer solution is introduced to the injection well through injectin pipe line when steady state.
  3) Monitor the concentration of the pumped water with time through sampling port on the pumping-injection pipe line



[plumes during recirculating forced gradient tracer test]

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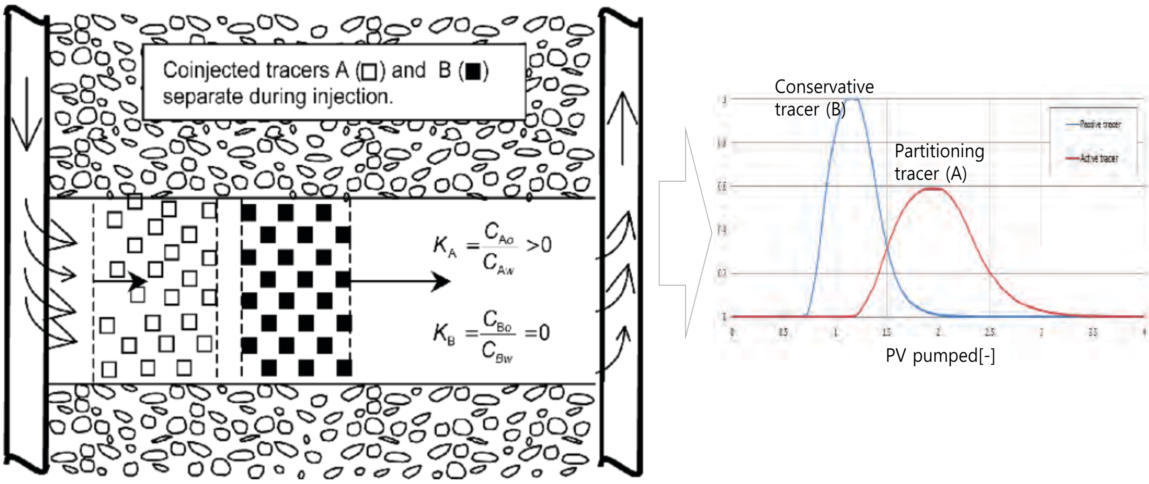
Partitioning (interwell) tracer test (PITT)

- To find out the existence and estimate the mass of organic contaminant
- Co-inject a conservative tracer with partitioning tracers at the same time



Source: S. Busch, 2016, Sensitivity analysis of the partitioning inter-well tracer test for oil saturation determination, mathematics

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Partitioning (interwell) tracer test (PITT)

- Use retardation process of partitioning tracers compared to conservative tracer.
- Bromide and Chloride are used as conservative tracer and several alcohol tracers (2,4-dimethyl-3-pentanol, 6-methyl-2-heptanol , n-hexanol) are used as partitioning tracer.
- Maintain the injection rate of the cocktail of tracer solutions and pumping rate at observation well
- The saturation and mass of the total organic matters existing in the stream lines between injection and observation well

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Step 1 and 2 : parameters and feasible method

Methods			Required information to interpretation	Estimation equations	Parameters to be estimated				
					Av. Linear velocity	dispersivity		Effective porosity	others
						Longi.	Trans.		
Single	Single injection-withdrawal test	BT curve at withdrawal well	Effective porosity, aquifer thickness	$\alpha = \frac{3U_I^{1/2}[\Delta(U_P/U_I)]^2}{32\pi^{3/2}(b\theta)^{1/2}}$		○			
		BT curve at obs. well	Distance to obs well	$\alpha = \left(\frac{3r}{16\pi}\right)\left(\frac{\Delta t}{t_{1/2}}\right)^2$		○			
	Drift & pump-back test		Effective porosity, aquifer thickness	$v = \left(\frac{Q}{\pi b n_e}\right)^{1/2} \frac{t^{1/2}}{T}$	○				
			aquifer thickness, K, Hydraulic gradient	$v = \frac{Qt}{\pi b T^2 KI}$ $n_e = \frac{\pi b K^2 I^2 T^2}{Qt}$	○			○	
	Point dilution test		Effective porosity	$v = \frac{-V}{n_e \xi A t} \ln\left(\frac{C}{C_0}\right)$	○				
Multi-well	Natural gradient tracer test	1-D, Pulse or constant inj.	aquifer thickness, Distance to obs well	Type-Curve matching or Method of Moment	○	○		○	Reaction coeff.
		2-D, Pulse or constant inj.	aquifer thickness, Hydraulic gradient, Coordinate of obs. well	Type-Curve matching or Method of Moment	○	○	○	○	Reaction coeff.
	Convergent forced gradient	Pulse inj.	Distance to obs well	Type-Curve matching	○	○			Reaction coeff.
	Partitioning tracer test	Pulse or constant inj.	Partitioning coeff.	$S_n = \frac{R-1}{K_n-(R-1)}$	○	○		○	NAPL saturation

Step 3: tracer and detection method

- Types of tracer
  - Physical (Temperature), Biological (Spores, Bacteria), Chemical (Ion, Dye, Gas, Alcohol)
- Ion
  - Chloride, Bromide, Iodide
  - EC as an alternative measure of ion concentration
  - Ex-situ(ISE), In-situ(CTD sensors, Hydronet sensor)
- Dye
  - Sulphorhodamine B, Fluorescein
  - Very low detection limit
  - Ex-situ (Spectrofluorophotometer), In-situ (SCUBA®)
- Multi-level monitoring owing to vertical heterogeneity

Step 4: tracer injection

- Injection Method
  - Continuous -Natural Injection
    - High detection potential and low experimental error
    - Large volume of source water and reservoir tank
  - Instantaneous-Forced Injection
    - Vice versa

- Injection Concentration

$$C_{inj} = [V_{test\ area} \times C_{limit}] / [V_{inj} \times R_{recovery}]$$

4. Interpreting Tracer Tests

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Single well injection-withdrawal tracer test

1) Estimation of longitudinal dispersivity using BT curves at injection-withdrawal well

- Longitudinal dispersivity for the entire aquifer thickness (α) : Breakthrough (BT) curves during withdrawal phase (x-axis=U_p/U_I)

$$\alpha = \frac{3U_I^{1/2}[\Delta(U_P/U_I)]^2}{32\pi^{3/2}(b\theta)^{1/2}}$$

U_I = total inj. volume [m^3]
U_P = pumped volume with time [m^3]
b = aquifer thickness [m]
θ = porosity [-]

$\Delta(U_p/U_I)$ = dimensionless increment of pumped volume between the intersections of the tangent line at $0.5C_0$ and lines of C/C_0=0.0 and 1.0 [-]

- Solution for the relative concentration at the injection-withdrawal well (Gellhar and Collins, 1971)

$$\frac{C}{C_0} = \frac{1}{2} erfc\left\{\left(\frac{U_P}{U_I}-1\right) \Big/ \left[\frac{16}{3}\frac{\alpha}{R}\left(2-\left|1-\frac{U_P}{U_I}\right|^{1/2}\left(1-\frac{U_P}{U_I}\right)\right)\right]^{1/2}\right\}$$

$R(=(Qt/\pi b\theta)^{1/2})$= average location of radial front at the end of injection phase [m]

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Single well injection-withdrawal tracer test

2) Estimation of dispersivity using BT curves at observation well, if any

- Longitudinal dispersivity (α) : estimated using BT curves obtained at observation well during injection phase

$$\alpha = (3r/16\pi)(\Delta t/t_{0.5})^2$$

Δt = time increment between the intersections of tangent line at $0.5C_0$ and the lines of C/C_0=0.0 and 1.0 [day]

$t_{0.5}$ = time when relative concentration is half of injection concentration at the distance of r from the injection well [day]

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Dirft and pump-back tracer test

1) Estimation of advection velocity when knowing aquifer thickness(b) and effective porosity(n_e)

- When ambient groundwater flow can be negligible

$$v = (Qt_p / \pi b n_e)^{1/2} / t_*$$

Q = pumping rate [m^3/s]
n_e = effective porosity [-]
T_* = drift time [day]
t_p = elapsed time since pumping when center of mass is recovered [day]

- Ambient groundwater flow is high enough not to be negligible

$$v = \frac{(Q/\pi b n)^{1/2} t^{1/2}}{T}$$

$t = t_a - t_p$
$T = t_a - t_i$
t_a = elapsed time when center of mass is recovered [day]
t_p = time when pumping started [day]
t_i = time when tracer injection [day]

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Drift and pump-back tracer test

2) Estimation of average linear velocity (v) and effective porosity (n_e)

- Effective porosity can be change with vertical location and the porosity estimated using the core samples is generally total porosity instead effective porosity.
- When use Darcy's equation ($v = KI / n_e$), two equations are derived as follows for average linear velocity and effective porosity

$$v = \frac{Qt}{\pi b T^2 KI}$$

$$n_e = \frac{\pi b K^2 I^2 T^2}{Qt}$$

v = av. Linear velocity [m/day]
Q = Pumping rate [m^3/s]
$t = t_a - t_p$
$T = t_a - t_i$
b = aquifer thickness [m]
K = hydraulic conductivity [m/d]
I = hydraulic gradient [-]
n_e = effective porosity [-]

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Point dilution test

1) Average linear velocity

$$v^* = -(V/At)\ln(C/C_0)$$

$$v^* = v n_e a$$

V = volume of the test interval[m^3]
A = x-sectional area of the test interval [m^3]
t = time [day]
C = tracer concentration when time is t [mg/L]
C_0 = initial tracer concentration [mg/L]
v = av. Linear velocity [m/day]
a = flow distortion factor [-]

- Flow distortion factor : groundwater flowlines are distorted from outside to inside of borehole because the hydraulic conductivity of the open borehole is higher than ambient aquifer
- The flow distortion factor should be known to estimate average linear velocity, but it is assumeb to be constant because it is hard to be estimated.

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Natural gradient trace test

1) Average linear velocity, effective porosity, longitudinal dispersivity

- Type curve matching to the solution
- Matching programs: CATTI (Sauty and Kinzelbach, 1992), CXTFIT (US DOA, 1999), TRAC (Gutierrez, et al., 2011)
- 2-D solution for the breakthrough concentration at a observation well located to the direction of natural groundwater flow

$$C(x,y,t) = \frac{\Delta M}{4\pi m n_e \sqrt{\pi D_L D_T t}} \exp\left[-\frac{(x-ut)^2}{4D_L t} - \frac{y^2}{4D_T t}\right] \exp(-\lambda t)$$

ΔM = mass of tracer injected per unit area [kg]
x = distance btw inj. obs. well [m]
A = x-sectional area of groundwater flow [m^2]
D_L (=α_Lu) = longitudinal dispersion coeff. [m^2 /s]
α_L = longitudinal dispersivity [m]
λ = decay rate [1/s]
u = average linear velocity [m/s]
α_T = transverse dispersivity [m]
D_T (=α_Tu) = transverse dispersion coeff. [m^2 /s]
m = aquifer thickness [m]

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Forced gradient tracer tests

- Divergent gradient tracer test:
  - No analytical solution. Should be numerically interpreted.
  - Case study: Numerical analysis for the solute transport through single fissure under divergent tracer test (Novakowski et al., 1994)
- Convergent gradient tracer test:
  - Laplace transform solution, an approximation solution, is suggested by Moench (1989)

$$C(r,t) = \frac{\Delta M}{2Q\sqrt{\pi D_L u t^{3/2}}} \exp\left(-\frac{(r-ut)^2}{4D_L t}\right)\exp(-\lambda t)$$

ΔM = mass of tracer injected per unit area [kg]	λ = decay rate [1/s]
r = radial distance [m]	u = average linear velocity [m/s]
A = x-sectional area of groundwater flow [m^2]	Q = pumping rate [m^3/s]
D_L (=$\alpha_L u$) = longitudinal dispersion coeff. [m^2 /s]	α_L = longitudinal dispersivity [m]

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Partitioning tracer test

- NAPL saturation or volume using retardation factor of partitioning tracer

$$R = 1 + \frac{\rho_b K_d}{\theta_w} + \frac{S_n K_n}{(1-S_n)}$$

$$V_p = \frac{m}{M}\frac{Qt_c}{1-S_n}$$

$$V_n = S_n \cdot V_p$$

R : retardation factor

ρ_b : bulk density

θ_w : volumetric water content

K_d : sorption coefficient

K_n : partition coefficient

S_n : NAPL saturation

t_c : mean arrival time for conservative tracer

M : total tracer mass injected

m : tracer mass produced from extraction well

V_p : tracer-swept pore volume

V_n : NAPL volume

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Estimation of retardation factor using the Method of Moment

- Method of Moment of tracer breakthrough curves (Yu et al, 1990)
- advantages : don't need physical model
- Moment

$$M_n = \frac{m_n}{m_0} = \frac{\int_0^\infty t^n C(z,t)dt}{\int_0^\infty C(z,t)dt}$$

M_n = n^{th} generalized moment
m_n = n^{th} moment
t = time
C_0 = injection concentraton
z = distance btw inj and obs well

$$m_n = \int_0^\infty t^n C(x,t)dt$$

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Method of Moment

- For the pulse injection of tracer test
  - First moment($\tau(z)$) = average of breakthrough curve, 2^{nd} central moment ($\mu_2(z)$) = dispersion of the breakthrough curve

First moment

$$\tau(z) = M_1 = \frac{\int_0^\infty tC(z,t)dt}{\int_0^\infty C(z,t)dt}$$

2^{nd} central moment

$$\mu_2(z) = \frac{\int_0^\infty (t-\tau)^2 C(z,t)dt}{\int_0^\infty C(z,t)dt} = M_2 - M_1$$

Average linear velocity(v)

$$v = \frac{z}{M_1 - t_0/2}$$

Dispersion coefficient (D)

$$D = (\mu_2 - \frac{t_0}{12})\frac{v^3}{2z}$$

z = distance btw inj and obs well [L] t_0 = injection period [T]

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Method of Moment

- For the constant injection tracer test

First moment

$$\tau(z) = M_1 = \frac{\int_0^\infty t \frac{\partial C_1}{\partial t} dt}{\int_0^\infty \frac{\partial C_1}{\partial t} dt} = \frac{\int_0^1 t dC_1}{\int_0^1 dC_1} = \int_0^1 t dC_1$$

2nd central moment

$$\mu_2(z) = \int_0^\infty (t - M_1)^2 \frac{\partial C_1}{\partial t} dt = \int_0^1 (t - M_1)^2 dC_1$$

Average linear velocity(v)

$$v = \frac{z}{M_1}$$

Dispersion coefficient (D)

$$D = \frac{\mu_2 z v}{2\tau^2} = \frac{\mu_2 v^3}{2z}$$

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Thank you very much

Geophysical Surveys for the Diagnosis of Groundwater Systems

Groundwater

Geophysical Surveys for the Diagnosis of Groundwater Systems

Aims and objectives

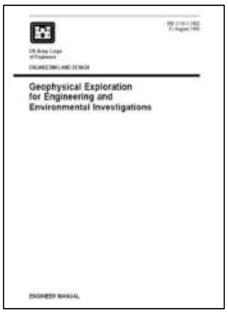
- The aims of the course are to:

  (1) promote to trainees a good understanding of the necessity of geophysical surveys to delineate hydrogeological structure and properties under subs urface environment.
  (2) understand to trainees the fundamental principles of geophysical surveys regarding groundwater system.

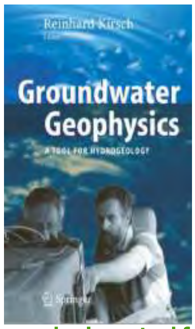
- The objectives are that trainees will understand:

  (1) geophysical methods related to hydrogeology
  (2) how to choose geophysical surveys suitable for hydrogeological objectives
  (3) geophysical well logging using groundwater wells
  (4) advantages of geophysical approaches

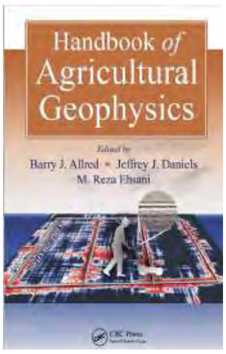
References



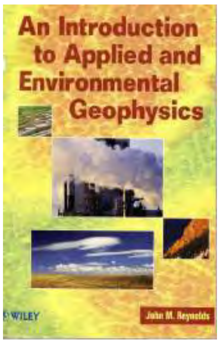
Geophysical exploration for engineering and Environmental investigation(USACE)



Groundwater geophysics: a tool for hydrogeology



Geophysical methods applied to agriculture



Introduction to environmental geophysics

Contents

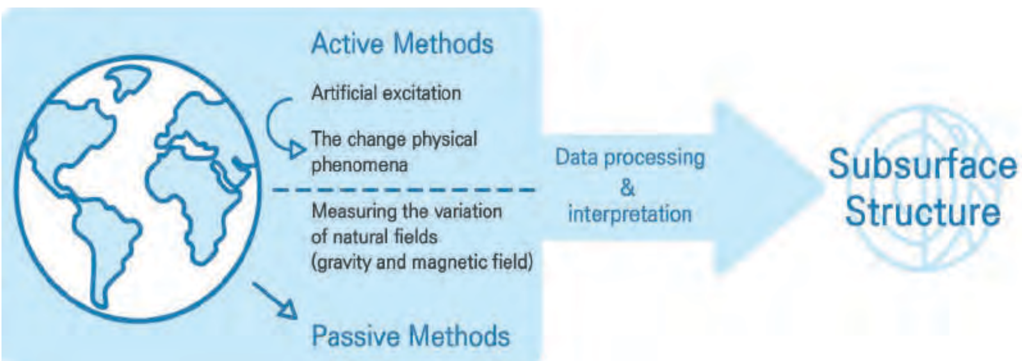
1. Geophysics related to hydrogeology
2. Geophysical methods
   - Electrical survey
   - Electromagnetic survey
   - Seismic survey
   - GPR survey
3. Geophysical well logging
4. Conclusions

1. Geophysics related to hydrogeology

1. Geophysics
2. Geophysical methods for hydrogeology
3. Objectives of geophysical methods
4. Decision matrix for field applications

1.1 Geophysics

- **(Definition) The non-invasion investigation of subsurface conditions through measuring, analyzing and interpreting physical field at the surface**
  - Imaging technologies of subsurface structures by using the changes of physical phenomena due to the contrast of physical properties
  - The change of physical phenomena is manifestation of earth's responses to natural fields or artificial excitations



[Active and passive methods]

1.2 Geophysical methods for hydrogeology

- **(Definition) Geophysical methods for hydrogeology are derived from conventional principal areas of subsurface investigation including p etroleum and mineral exploration.**
  - Determination of geophysical method will provide the optimal results.
  - All methods as noted in below will not be applicable in target area, therefore, it is critical to care fully assess which methods are most likely to provide information relevant to the problem of inte rest.

Methods		Target Properties	Physical Phenomena
Active methods	Electrical Method	Electrical conductivity	Change of electrical potential
	Electromagnetic Methods	Electrical conductivity Magnetic susceptibility	Change of intensity and phase of electric or magnetic field
	Seismic Method	Elastic moduli, density	Reflection, Refraction, etc.
Passive methods	Radioactive method	Contents of radioactive elements	Gamma ray activity
	Gravity method	Density	Change of gravitational acceleration
	Magnetic method	Magnetic susceptibility	Change of magnetic field

1.3 Objectives of geophysical methods

- **(Definition) The benefit of geophysics are non-destructive, efficiency, c omprehensiveness, cost-effective, and proven to be helpful to decision-makers who face complex hydrogeological objectives.**
  - Generally, geophysical methods consist of field surveys conducted along oriented lines or grid lines over the desired area of interest.
  - All characterization methods related to each attribute are most commonly employed by practitioners for various objectives as noted in below.

Characterization Methods	Attributes	Example hydrogeological objectives
Seismic refraction	P-wave velocity	Mapping top of bedrock, **water table**, and fault
Seismic reflection	P-wave reflectivity and velocity	Mapping stratigraphy, top of bedrock, delineation of **faults/fracture zone**
Electrical resistivity	Electrical resistivity	Mapping aquifer zonation, water table, top of bedrock, **fresh-salt water interface** and plume boundaries, estimation of hydraulic anisotropy, estimation/monitoring of water content and quality
Electromagnetic	Electrical resistivity	Mapping aquifer zonation, water table, fresh-salt water interface, estimation of hydraulic anisotropy, estimation/monitoring of **water content and quality**
GPR	Dielectric constant and contrast	Mapping stratigraphy, water table, estimation/monitoring of water content

(Rubin and Hurbbard, 2005)

1.4 Decision matrix for field application

- **(Definition) Decision matrix table will provide relevant information to determine optimal geophysical methods for the desired area of interest.**
  - For example, identification of the scope or size of the required geophysical coverage.

Characterization Methods	Attributes	Field application									
		1	2	3	4	5	6	7	8	9	10
Gravity	Density	P	P	s	s	s	s			s	
Magnetic	Magnetic susceptibility	P	P	P	s						
Self-Potential	Potential difference			P		P					
Seismic refraction	Elastic moduli, density	P	P		P	s	s				
Seismic reflection	Elastic moduli, density	P	P								
Electrical resistivity	Electrical resistivity			P	P	P	P	P	s	P	
Electromagnetic	Impedence, EC	s	P	P	P	P	P	P	P	P	
GPR	Dielectric constant, EC				P	P	P	s	P	P	P

Field applications

1. **Hydrocarbon(coal, petroleum, gas et cetera) exploration**
2. **Regional geologic mapping(wide area for several hundreds of km^2)**
3. **Mineral exploration**
4. **Site characterization and infrastructure**
5. **Hydrogeological survey**
6. **Subsurface cavity mapping**
7. **Leachate and contamination plume mapping**
8. **UXO(Unexploded Ordnance) detection**
9. **Archeology**
10. **Forensics(i.e., illegal burials)**

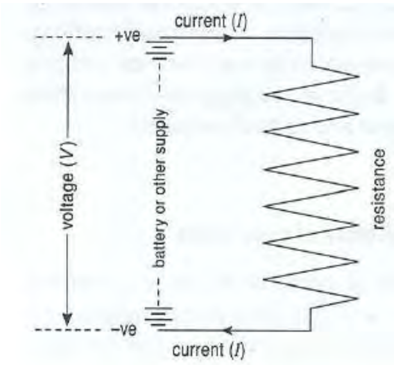
P: primary s : secondary

2. Geophysical method

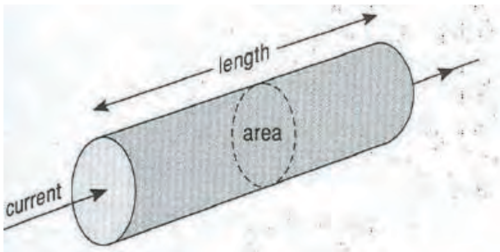
1. Electrical resistivity survey
2. Electromagnetic survey
3. Seismic survey
4. GPR survey

2.1 Electrical resistivity survey

- **(Definition) to determine resistivity distribution in the earth measuring potential differences be generated by artificial electric currents**
  - Measuring the potential changes created by galvanic current due to the contrast of electrical properties governed by ohm's law.
  - Resistivity(ρ) is intrinsic properties of material independent of shape and complex function of mineral type, porosity, pore fluid, etc.
  - Dependency on pore fluid is good indicator for hydrogeological application.



$$\frac{V}{I} = R \ (\Omega)$$



$$R = \rho\frac{L}{A}$$

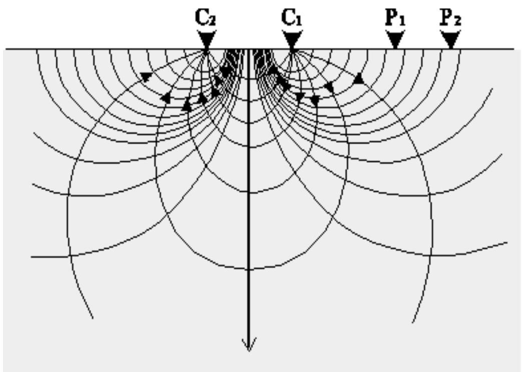
2.1 Electrical resistivity survey

- **Electrical resistivity depends on influencing factors including porosity, pore fluid resistivity, water saturation, water content, and clay content.**
  - Electrical resistivity, the reciprocal of electrical conductivity, is an intrinsic properties of a material that measures how strongly it resists electric current.

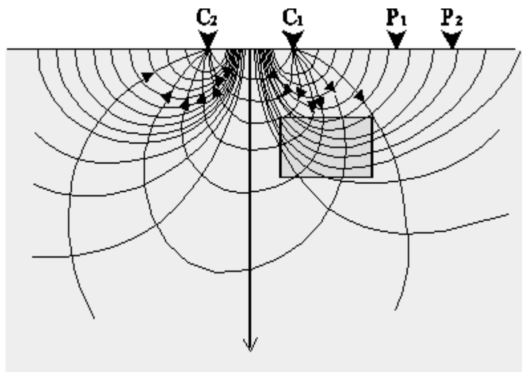
Influencing factors		Degree of influence Low --------------- High	Geological conditions of rock mass
Porosity	**Saturated**	**Large ----------- Small**	Weathered and fault fractured zones
	Unsaturated	Small ----------- Large	
Pore fluid resistivity (Groundwater)		Low -------------- High	Components of groundwater
Water saturation		Large ----------- Small	Groundwater table
Water content (Porosity & water saturation)		Large ----------- Small	Weathered and fault fractured zones
Clay content		Much ----------- Little	Weathered and altered zones

2.1 Electrical resistivity survey

- **Imaging resistivity distribution of subsurface by measuring the potential differences caused by artificial introduced current.**
  - A changes of electrical resistivity introduces channeling of galvanic current and thus a potential differences.
  - Detects horizontal and vertical discontinuities, 3-D bodies of anomalous conductivity.



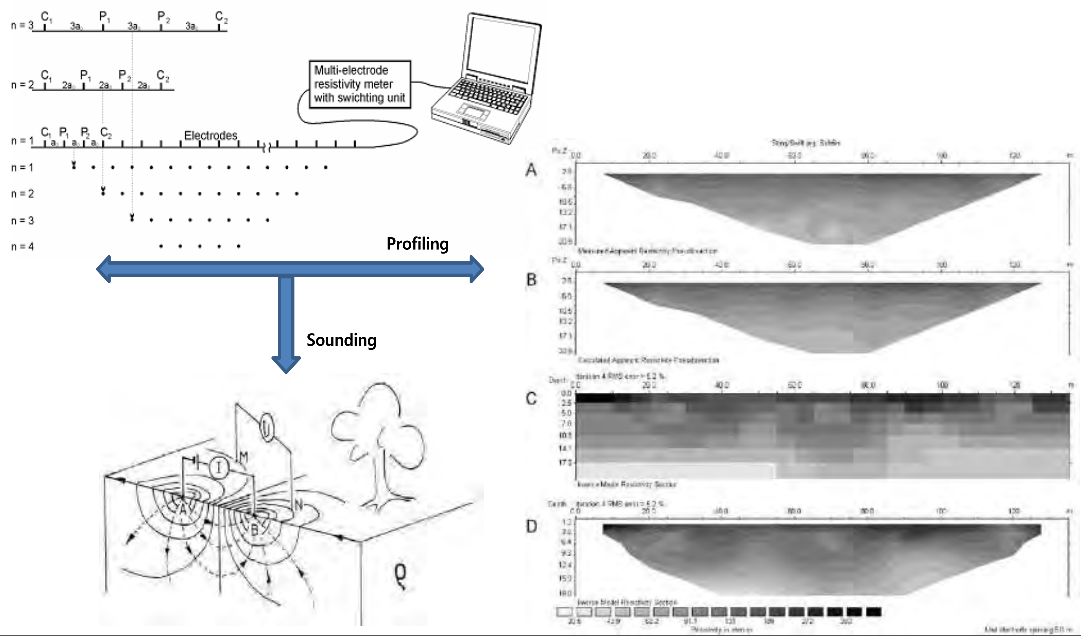
$$\rho = G\frac{\Delta V}{I}$$



$$\rho_a = G\frac{\Delta V}{I}$$

2.1 Electrical resistivity survey

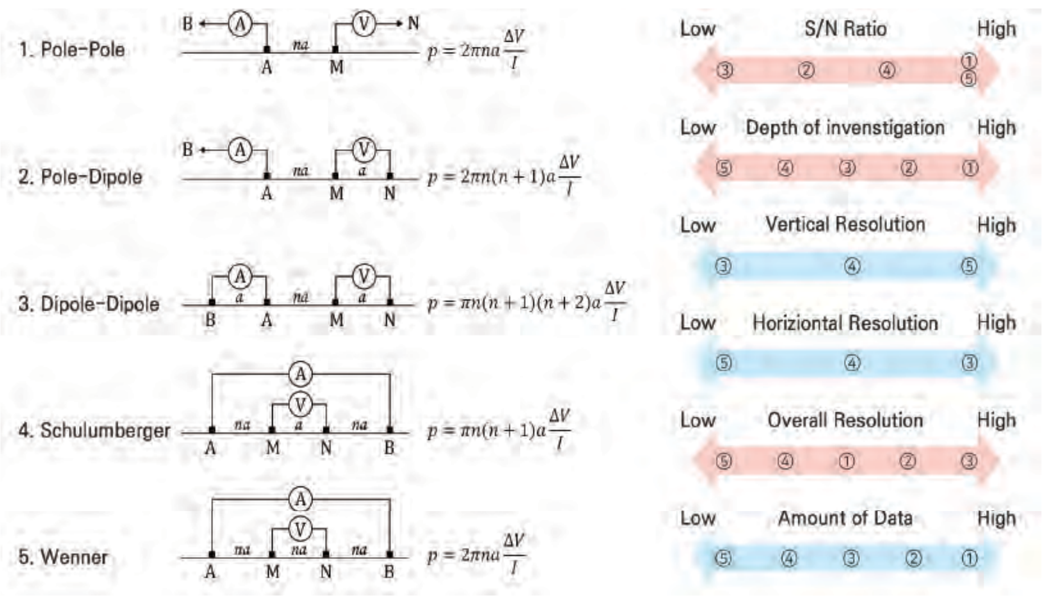
- **Data acquisition and inversion**
  - Measured apparent resistivity data were processed and inverted to produce subsurface vertical and lateral resistivity distribution section using inversion.



2.1 Electrical resistivity survey

▪ Electrode array

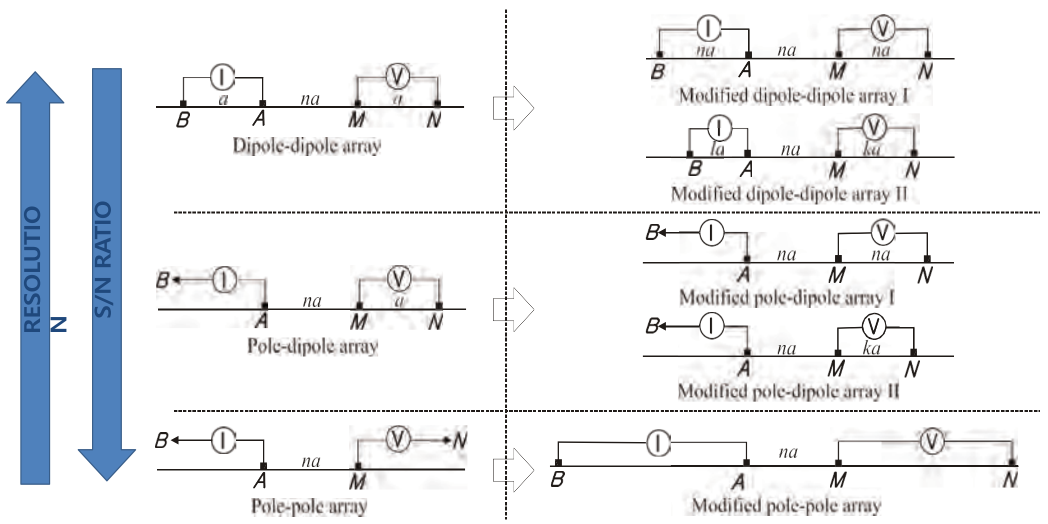
- Electrical resistivity survey is a geophysical method where two current electrodes are used to inject an current into the ground and potential difference is measured between two potential electrodes.
- Based on measured potential and array geometry, apparent resistivity can be computed.



2.1 Electrical resistivity survey

▪ Modified electrode array

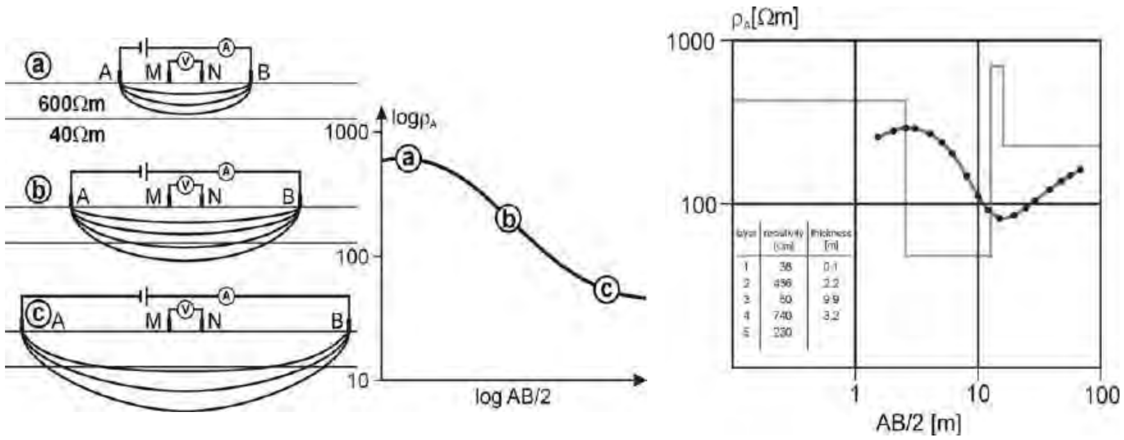
- Modified arrays were designed to enhance the signal-to-noise ratio of the conventional electrode array through boosting up the measured potential difference.



2.1 Electrical resistivity survey

▪ Vertical electrical sounding (VES)

- An electrical method of geometrical sounding based on one-dimensional(1 D) assumption.
- It is suitable for regional survey in efficiency.



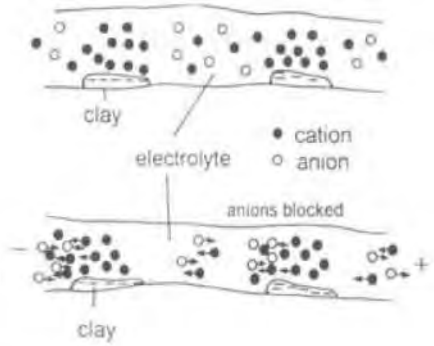
Source: Groundwater Geophysics(Kirsch,2006)

Schulumberger Sounding : Acquisition scheme, sounding curve, and inversion result

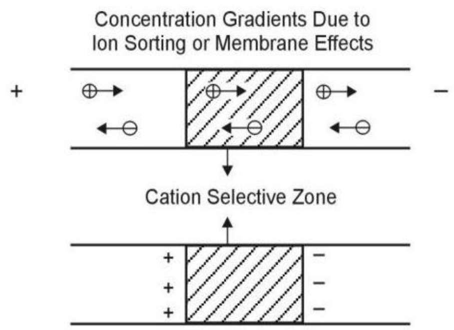
2.1 Electrical resistivity survey

▪ Induced polarization (IP)

- makes use of the capacitive action of the subsurface to located zones where conductive materials are disseminated within host rock.
- is prospective method in hydrological application because of the dependency of IP on the existence and size of mineral, clay contents, and et cetera.



Membrane Polarization



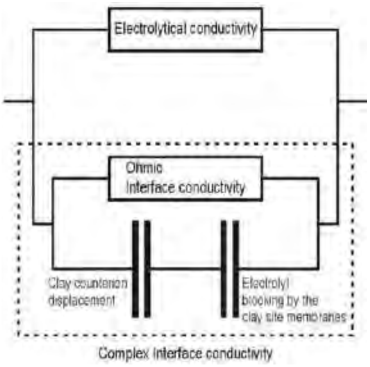
Electrode Polarization

2.1 Electrical resistivity survey

▪ Induced polarization (IP)

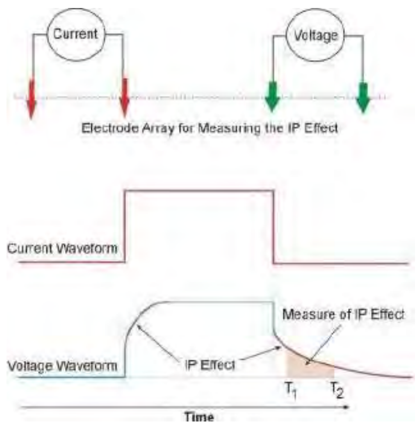
- is a geophysical imaging technique used to identify the electrical chargeability of subsurface materials.
- provides additional information about the spatial variation in lithology and grain-surface chemistry because capacitive properties of the subsurface materials are determine in addition to resistivity measurement.

Electrical Analogy and Complex Conductivity



$$J^*(\omega) = (\sigma_{eff} + i\omega\varepsilon_{eff})E(\omega)$$

$$\sigma_{eff} + i\omega\varepsilon_{eff} = \sigma^* = \sigma'(\omega) + i\sigma''(\omega)$$

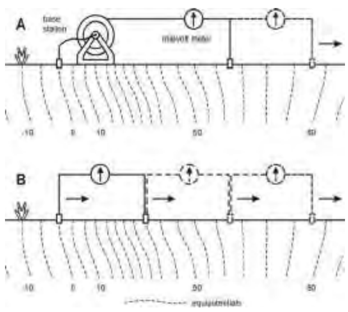


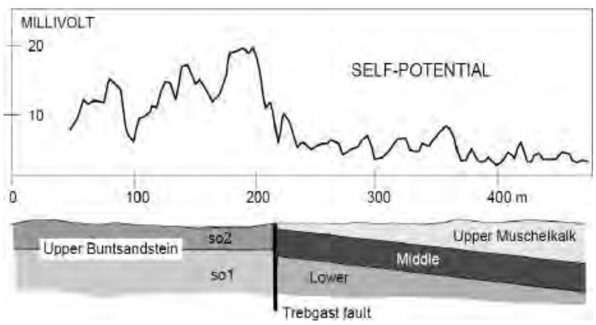
IP Effect and Measurement

2.1 Electrical resistivity survey

▪ Spontaneous potential (SP)

- make use of SP originating from various electro-chemical, electro-physical, and bio-electrical processes.
- can classified to mineralization potential due to reduction and oxidation, electro-chemical potential from ion flow, thermo-electrical potential by heat flow, and streaming potential from groundwater flow.



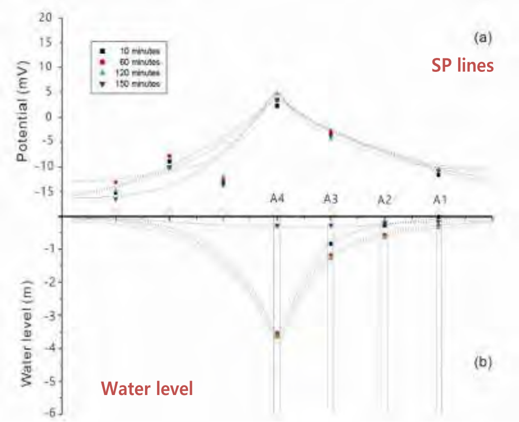


Source: Groundwater Geophysics(Kirsch,2006)

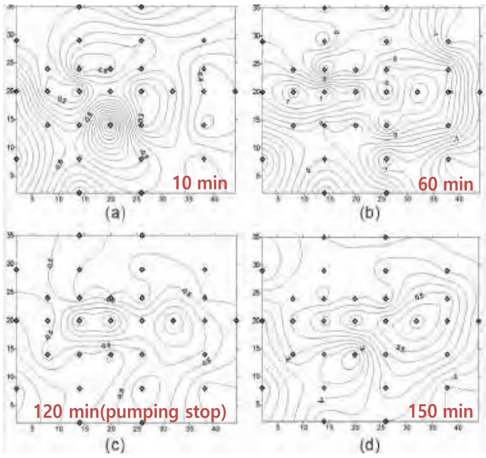
2.1 Electrical resistivity survey

- **Spontaneous potential (SP)**
  - Streaming potential originates when an electrolyte is driven by a pressure gradient through a channel or porous plug with charged walls.
  - provides a reliable information on the anisotropy of aquifer in the pumping test at single well using equi-potential map.

SP variation and drawdown curve due to pumping



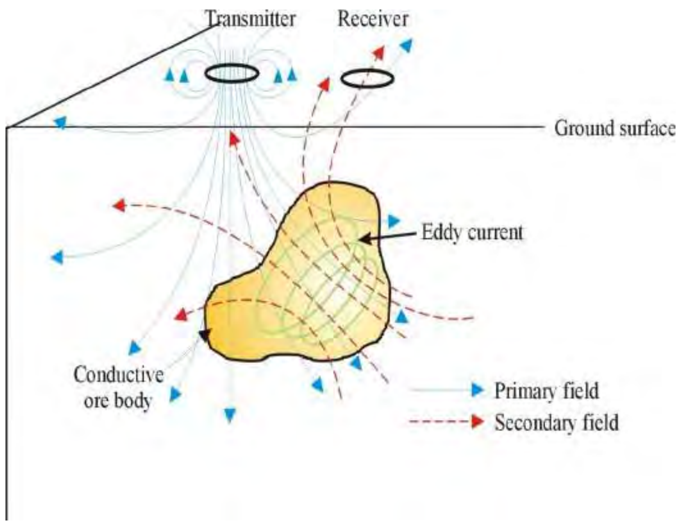
Equi-potential lines during pumping test indicate anisotropy



Source: Economic and Environmental Geology(Song and Yong, 2003)

2.2 Electromagnetic survey

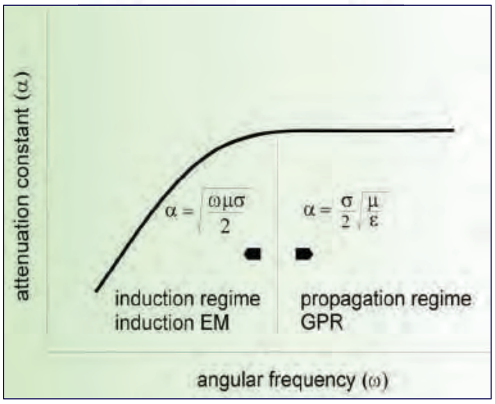
- **(Definition) is based on the response of the ground to the propagation of EM field composed of an alternating electric intensity and magnetic fields.**
  - Imaging the earth's interior measuring secondary or total field induced by primary field natural or artificially induced.
  - Magnitude od secondary field depends on electrical conductivity of material and governed by Ampere's law and Faraday's law.



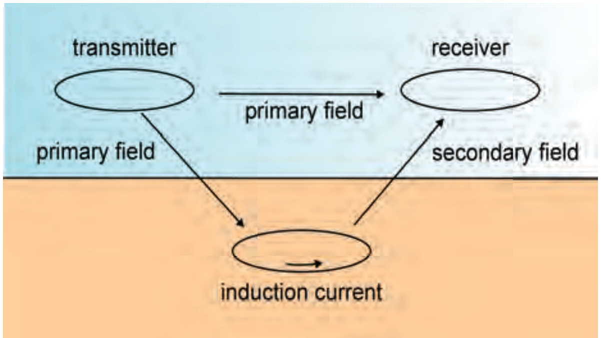
2.2 Electromagnetic survey

- **Electromagnetic attenuation decreases the intensity of EM radiation due to absorption or scattering of photons.**
  - EM induction method is based on the measurement of the change in mutual impedance between a pair of coils on or above the earth's surface.

Attenuation of EM field



Schematic diagram of EM induction method



2.2 Electromagnetic survey

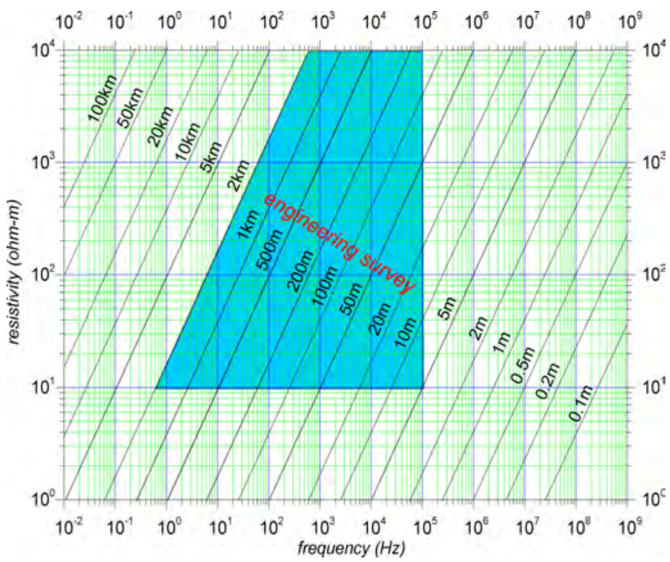
- **Skin depth is defined as the depth up to which the magnetic field penetrates inside the conductor form the top of its surface.**
  - Attenuation defines the rate of amplitude loss an EM wave experiences at it propagate
  - Skin depth defines the distance a wave must travel before its amplitude has decayed by a factor of 1/e.

Skin depth (δ)

$\delta = 50$

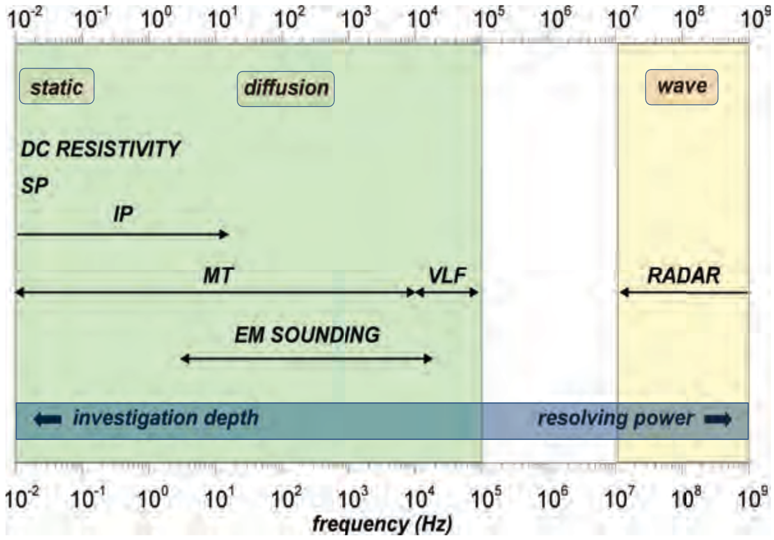
ρ: **resistivity of the ground (ohm-m)**

f: **frequency (Hz)**



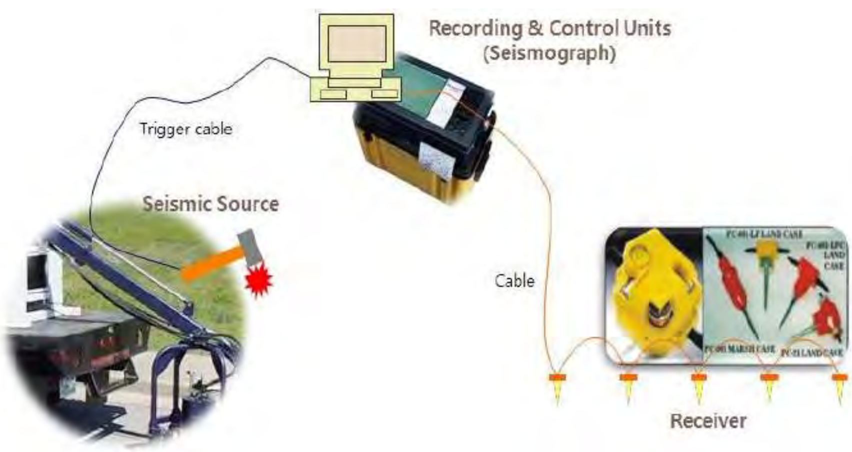
2.2 Electromagnetic survey

- **Electromagnetic spectrum is the range of frequencies of EM radiation and their respective wavelengths and photon energies.**
  - Wavelength of EM spectrum increase from approximately 10^{-2} m to 10^{9} m, and this corresponds to frequencies decreasing from 10^{-2} Hz to 10^{9} Hz .
  - Survey methods are classified to MT, EM sounding, VLF, and Radar from low to high frequency.



2.3 Seismic survey

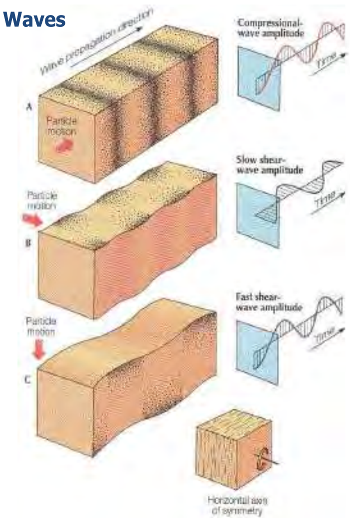
- **(Definition) is low impact, non-invasive method of gathering information about the characteristics of geological structures beneath ground surface.**
  - Seismic survey is the most commonly conducted geophysical survey for engineering investigation.
  - Imaging subsurface geologic structures using reflection, refraction, and diffraction phenomena of elastic wave propagating subsurface.
  - Such wave phenomena depend on mostly velocity, which depends on elastic modulus and density of material, porosity, pore fluid, and etc.



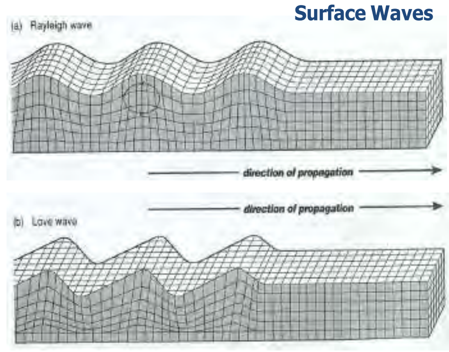
2.3 Seismic survey

- **Seismic waves are waves of energy that travel through Earth's layer, and are a result of earthquake, volcanic eruption, and man-made explosions.**
  - Body waves travel through the interior of the Earth.
  - Surface waves travel across the surface, which decay more slowly with distance than body waves traveling in three dimensions.
  - Particle motion of surface waves is larger than that of body wave, so they can cause more damage.

Body Waves



Surface Waves

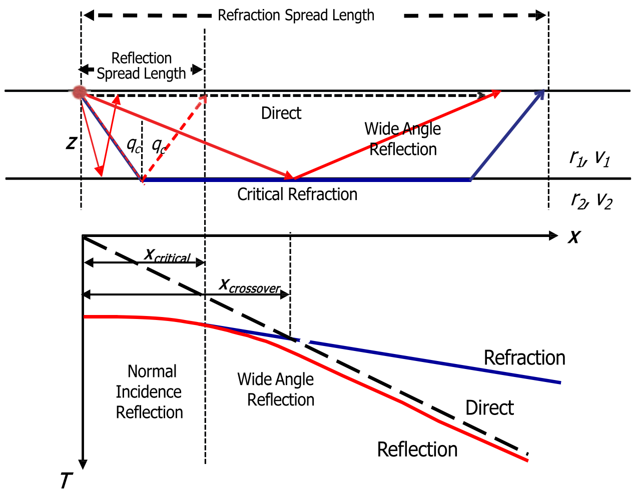


P-velocity $V_P = \sqrt{\dfrac{\kappa + \frac{4}{3}\mu}{\rho}}$ change of shape and volume

S-velocity $V_S = \sqrt{\dfrac{\mu}{\rho}}$ change of shape only

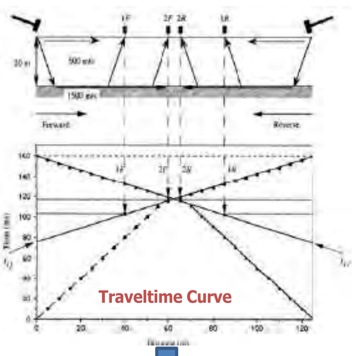
2.3 Seismic survey

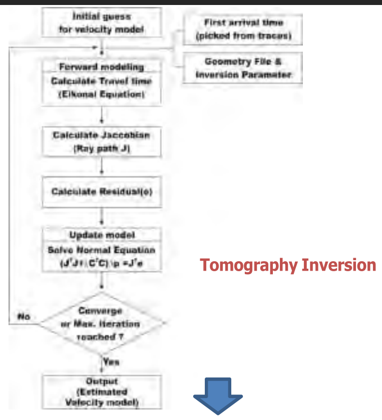
- **Seismic survey line is a set of seismographs for the purpose of recording reflections and refractions of waves from velocity discontinuities within the earth.**
  - The purpose of reflection method is to estimate the properties of ground surface from reflected seismic waves.
  - The seismic refraction method utilizes the refraction of waves by rock or soil layers to characterize the subsurface geologic conditions and geologic structure.



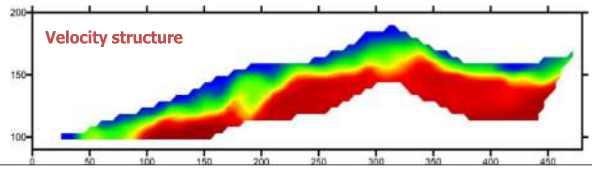
2.3 Seismic survey

- **Seismic refraction is a geophysical principle governed by Snell's law of refraction.**
  - The waves are refracted when they cross the boundary between different types of soil or rock.
  - The method enable the general soil types and the approximate depth to strata boundaries(i.e., bedrock) to be determined.



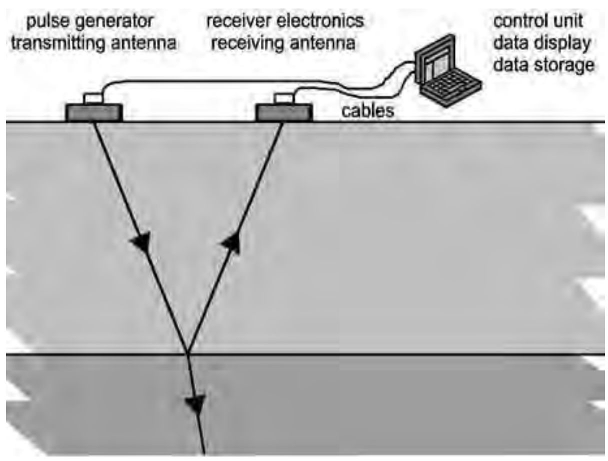


- Simple calculation
- Delay time method
- Hale's method
- Generalized Reciprocal method (GRM)



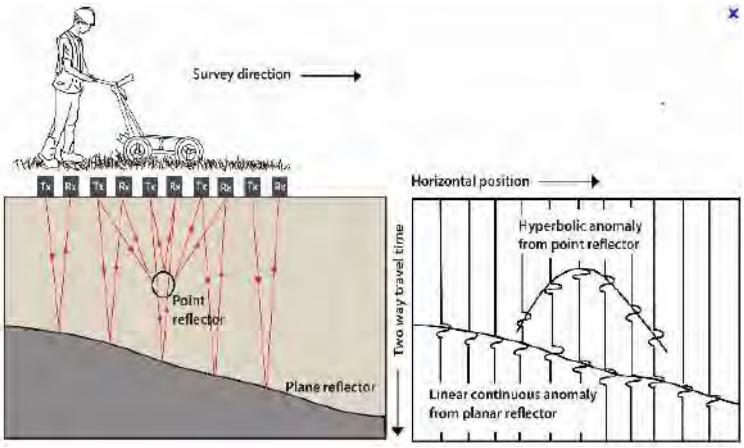
2.4 GPR (ground penetration radar) survey

- **(Definition) is a geophysical method that uses radar pulses to image the subsurface utilities including metals, pipes, cables or masonry.**
  - This non-destructive uses EM radiation in the microwave band of radio spectrum and detects the reflected signals from subsurface structure.
  - EC of the ground, the transmitted center frequency, and the radiated power may limit the effective depth range of GPR investigation.



2.4 GPR (ground penetration radar) survey

- **GPR antennas are generally in contact with the ground for the strongest signal strength.**
  - The velocity wave depends on dielectric permittivity, the ability of a substance to hold an electrical charge, which depends on water contents of the ground.
  - Cross borehole GPR has developed within the field of hydrogeophysics to be a valuable means of assessing the presence and amount of soil water.



(http://www.indicomet.com)

3. Geophysical well logging

3. Geophysical well logging

- **(Definition) is the practice of making a detail record of the geologic formation penetrated by a borehole.**
  - Well logging is performed in boreholes drilled for the oil, groundwater, mineral, geothermal exploration and environmental studies.

Logging system

(http://www.robertson-geo.com)

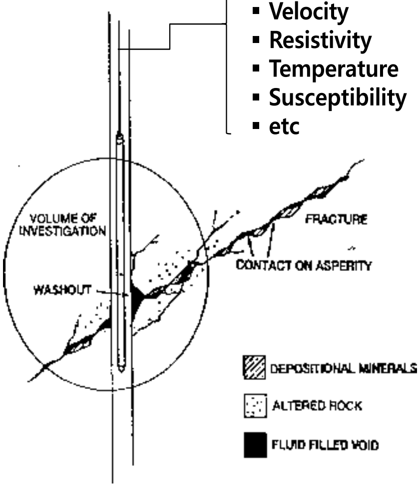
Winch system

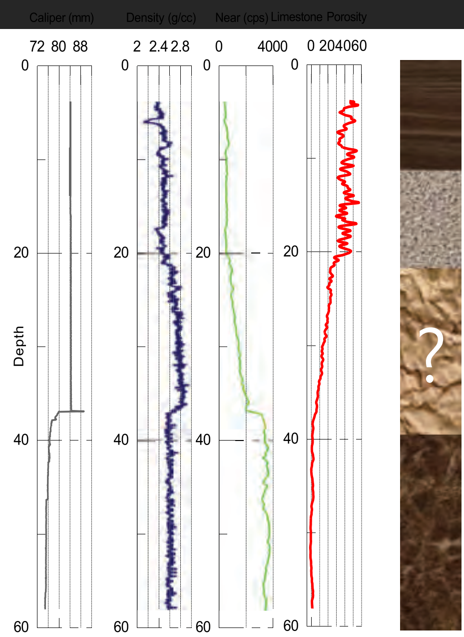
(http://www.mountsopris.com)

3. Geophysical well logging

- **Geophysical well logging is a set of borehole investigation methods that are based on various and special logging tools.**
  - The purpose of well logging is to measure the depth and thickness of formation, porosity, water saturation, temperature, permeability, and etc.

- Caliper
- Density
- Porosity
- Velocity
- Resistivity
- Temperature
- Susceptibility
- etc

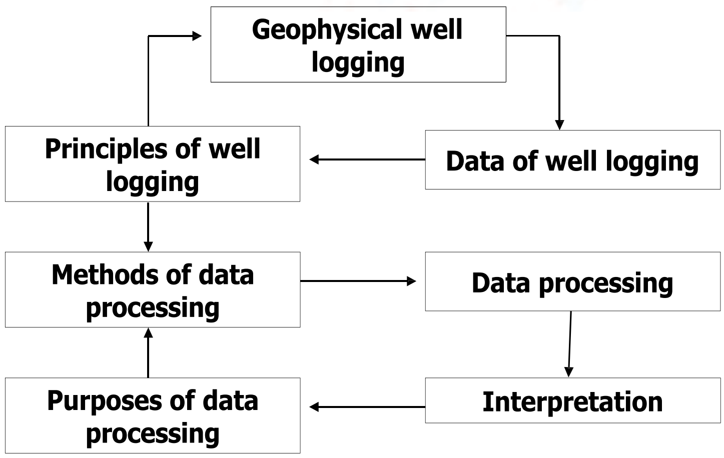


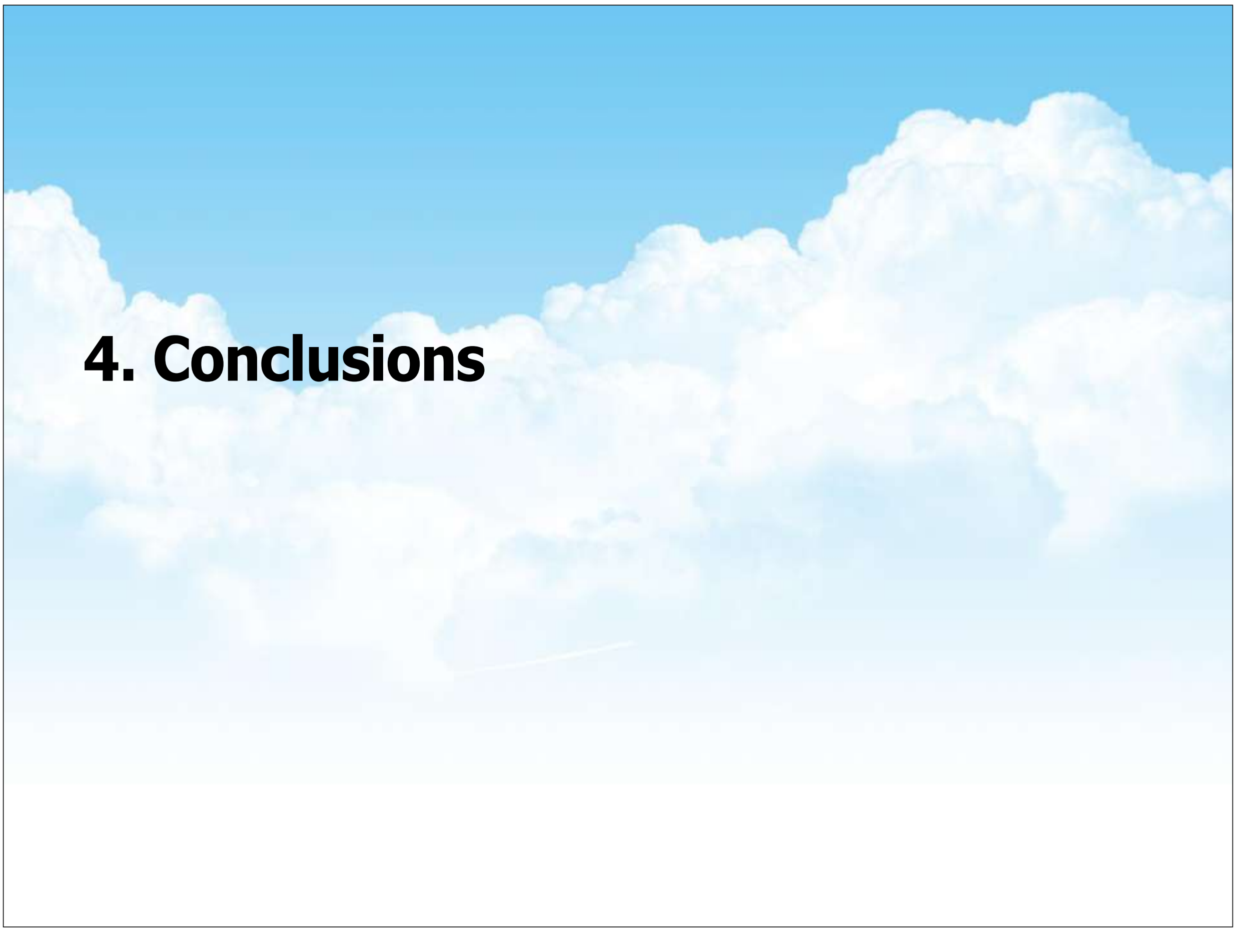


3. Geophysical well logging

- **Processing and interpretation of geophysical well logging data of wells are based on the use of all available logging data.**
  - The preprocessing or data preparation is potentially the most-consuming part of a logging project.
  - Data preparation is usually conducted in order which may vary slightly because of personal preference and the nature of available computer programs.

Understaing data processing





4. Conclusions

- **Advantages of geophysical approach**
  - Geophysics including surface and borehole offers advantages over conventional point-wise sampling to hydrogeologist because of:

• High data sampling density

• Relatively lower cost of measurements

• Minimally invasive – may allow investigations without affecting the hydrology of the system

• Larger measurement volume – more consistent with modeling needs

(Binley, 2006)

4. Conclusions

- **Groundwater geophysics**

• Use of geophysical methods and technologies to characterize, monitor, and investigate the hydrogeological parameters and processes.
  – Mapping subsurface features like fault an fracture zone which is possible water deposits and water reservoirs.
  – Water table mapping

• Geophysical approach mainly focused on hydrological objectives are newly termed as Hydrogeohysics, a expended concept of groundwater geophysics.
  – Estimating (hydraulic) properties, water contents/quality
  – Monitoring hydrological processes such as water resources, contaminant transport, and ecological and climate investigation

4. Conclusions

▪ Applicability to groundwater problems

- Groundwater conditions at a location are mainly described through the distribution of permeable layers like sand, gravel, fractured rock and i mpermeable or low-permeable layers like clay, till, and solid rock.
- Hydrological conditions like water contents and quality provides sufficient contrast of petrophysical properties for geophysical imaging.
- Seismic velocity, electrical conductivity, and dielectric constant are the most relevant petrophysical properties for geophysical groundwater e xploration.

4. Conclusions

▪ Hydrogeological objects and geophysics

- Are closely related to various results including hydrologic mapping, hydrologic parameter estimation, and monitoring of hydrologic processes.

- **Hydrogeologic mapping**
  - Geometry of subsurface units or interfaces (aquifer geometry, fault/fracture zone, permeable or impermeable zonation)
  - Water table, Top of bedrock
  - Fresh-salt water interface, Plum boundaries
- **Hydrological parameter estimation**
  - Water content/quality, permeability or hydraulic conductivity
  - Hydrogeological spatial correlation parameters
- **Monitoring of hydrological processes**
  - Water content and quality
  - Groundwater flow


Thank you very much

Groundwater Well Drilling & Development

Groundwater

Groundwater Well Drilling & Development

UNESCO | i-WSSM
United Nations Educational, Scientific and Cultural Organization | International Centre for Water Security and Sustainable Management

Aims & Objectives

- The aims of the course are to:

  (1) Understand the process of groundwater development, and be aware of precaution when developing groundwater

  (2) Understand the history of groundwater development in Korea, and understand that groundwater development is carried out according to the development of the country

- The objectives are that trainees will understand:

  (1) Groundwater development procedure

  (2) Groundwater development history

Contents

1. Groundwater development

4

1.1 Groundwater development procedure

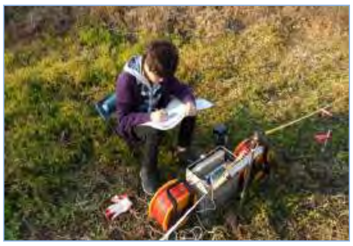
◆ Groundwater development procedure

- Drilling for investigation
- Groundwater impact assessment
- Drilling for production well
- Installing the water use facilities

5

1.1 Groundwater development procedure

◆ Drilling for investigation


Geophysical survey


Drilling machine


Casing installation


Anti-pollution grouting


Drilling


Air surging

Source) Korea Rural Community Corporation

6

1.1 Groundwater development procedure

◆ Groundwater impact assessment


Predrilled well investigation


Pollution source investigation


On–site water quality survey


Water quality sampling


Water level measurement


Pumping test

7

Source) Korea Rural Community Corporation

1.1 Groundwater development procedure

◆ Drilling for production well


Drill bit for well development


Install well screen


Install well pipe


Groundwater production Well


Air–surging


Install gravel

8

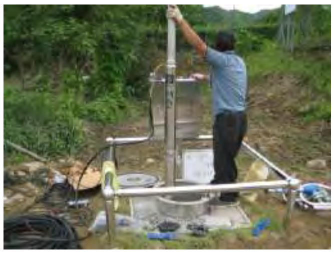
Source) Korea Rural Community Corporation

1.1 Groundwater development procedure

◆ Installing the water use facilities


Submersible motor pump


Installing of pipe


Installing submersible pump


Completed well facility


Inside of the well facilities


Installing well protection guide

9

Source) Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ Drilling well location

- The location of groundwater development should be a location away from the source of pollution or a location where no source of pollution is expected in the future

Groundwater development

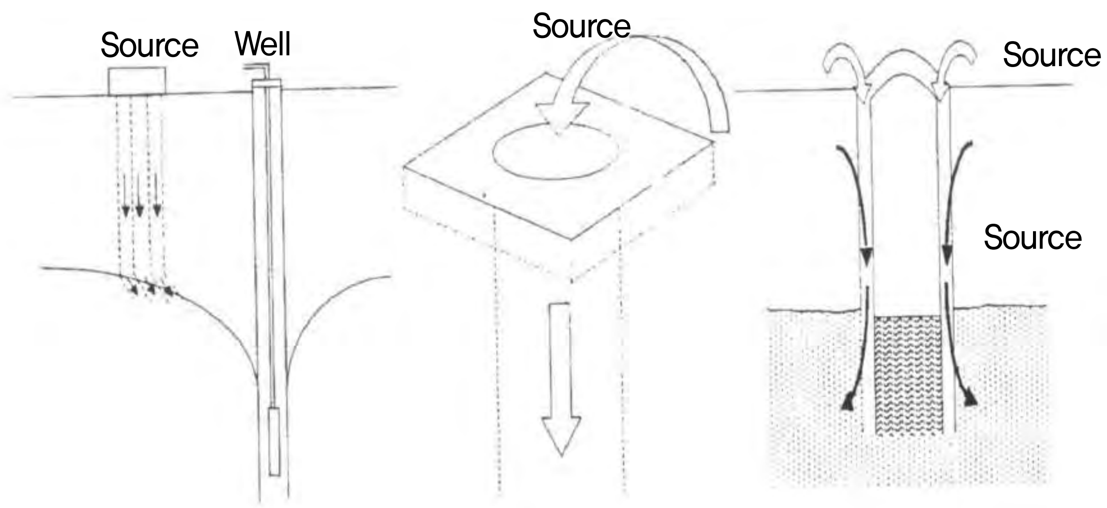
1. Installing the casing
2. Drilling the bedrock
3. Installing the well screen
4. Air-surging
5. Pumping test

10

Source) Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ Case of contamination



1. Pollution by inflow of nearby pollutants

2. Contamination due to poor upper protection facilities

3. Contamination due to poor grouting

11

Source) Modified by Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ Casing installation

- Casing is installed to prevent collapse of the unconsolidated alluvial layer
- Grouting is made to the depth where the casing is installed to prevent the inflow of surface pollutants through the hollow wall

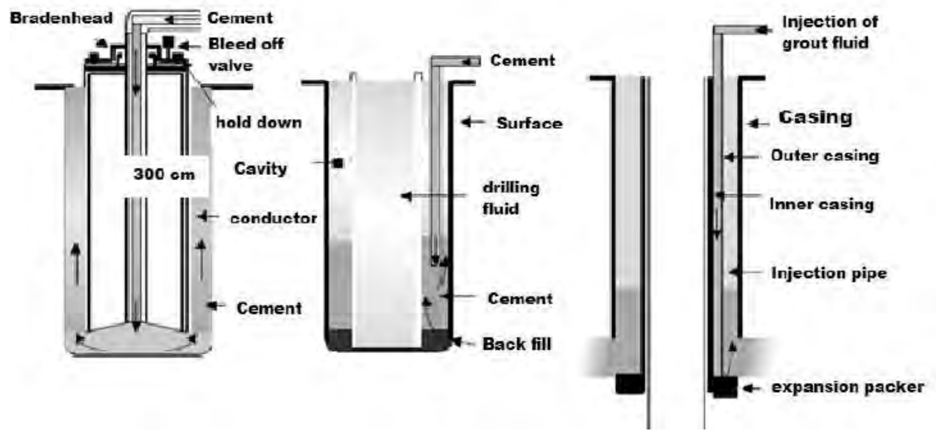
12

Source) Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ Grouting method

- Purpose : Prevention of inflow of surface pollutants(up to 1 – 2 m in bedrock)
- Construction method : Bradenhead, Grout pipe, Packer grouting method
- Grouting is effective in the case of groundwater contamination due to nitrate nitrogen in the upper part of the surface



1. Bradenhead method 2. Grout pipe method 3. Packer grouting method

13 Source) Modified by Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ Installing of well screen

- Air surging is an in-cavity cleaning operation performed using an air compressor to clean the wall of the hole and prevent the sedimentation of slime and mud that has fallen during drilling
- After air-surging, the well material is installed : filling the space between the hollow wall and the well material with fine gravel of 10 – 20 mm (※ Gravel filling : partial increase in permeability and suppression of inflow of fine particles → prevent failure of submersible motor pump)

14 Source) Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ Pre-construction inspection

〈Good case〉


Confirmation of installation materials


Installation of good screen


Well connection condition

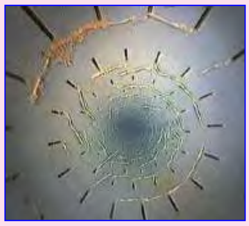

Well material end point

〈Wrong case〉


Sight is bad condition


Well material rust


Damage to well material


Unsuitable well materials

15

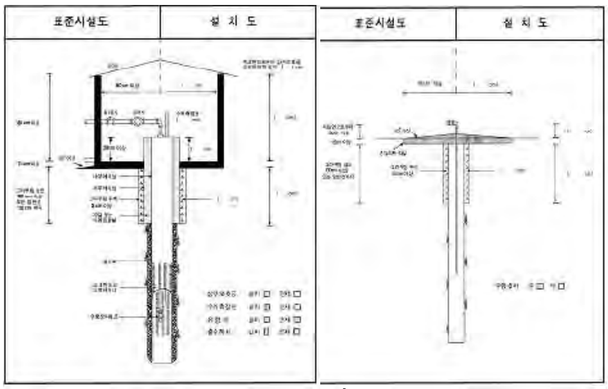
Source) Korea Rural Community Corporation

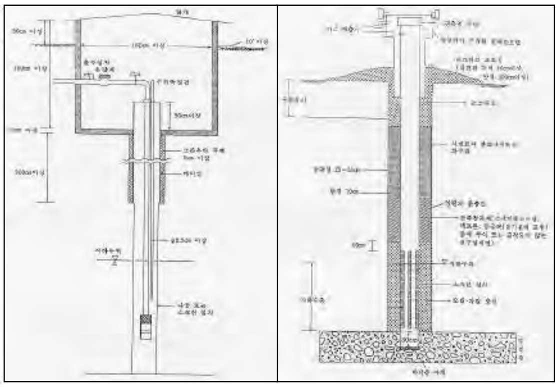
1.2 Groundwater well drilling

◆ Upper well guard installation

– Groundwater well protector : Surface pollutant inflow prevention facility
– Enforcement rules of the Groundwater Act : Chapter 4, Article 8
- Groundwater development/utilization facilities

– Rules for conservation of groundwater quality : Chapter 2
- Groundwater pollution prevention facility


Groundwater development/utilization facilities


Groundwater pollution prevention facility

16

Source) Groundwater Act

1.2 Groundwater well drilling

◆ Well facilities

Groundwater pollution prevention facility

Well pipe and utility facilities

17

Source) Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ Enclosed protection facility

– Enclosed protection facility
  - Installed in protection house or outside the house
– Advantage : Completely block contaminants
  - Easily clean the wells and replace the submersible motors

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Source) Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ **Poor protection facilities**

– Poor management and abandoned groundwater wells acts as a pathway for groundwater contamination

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Source) Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ **Water quality testing**

1) Purpose

- To maintain the water quality within the groundwater law
- Under the Groundwater law, Groundwater users must undergo regular water quality testing.

2) Law

- Groundwater Act : Article 20 (Water quality testing)
- Rules for conservation of groundwater quality : Article 10 (Water quality testing
- Drinking water management Act : Article 5 (Water quality for drinking water)

3) Water quality testing subject and cycle

- Domestic water : more than 30 tons of pumping rate per day : 3 year
- Industrial water : more than 30 tons of pumping rate per day : 3 year
- Agricultural water : more than 100 tons of pumping rate per day : 3 year

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1.2 Groundwater well drilling

◆ Well facility inspection

Inspection of pipe

Switchboard inspection

Check of well house

Check the water level measuring pipe

21

Source) Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ Well restoration

– Definition

- Restoring the facility or properly backfilling the land to prevent the inflow of pollutants into the facility or land subject to restoration and to not endanger human health and safety

– Abandoned well

- Wells that have failed in use, but are not properly backfilled or buried naturally, and are missing or neglected from the management target, causing concerns about groundwater contamination

22

Source) Korea Rural Community Corporation

1.2 Groundwater well drilling

◆ Well restoration procedure


Abandoned well


Backfill material


Insert backfill material into well


Casing drawing


Impervious material injection


Impervious material injection


Backfill processing


Clean up around

23

Source) Korea Rural Community Corporation

1.3 Large scale radial collector well

◆ Install the caisson


Selection of location


Install the sue steel sheet


Install the rebar and reinforced concrete


Completion of installation


Install the caisson

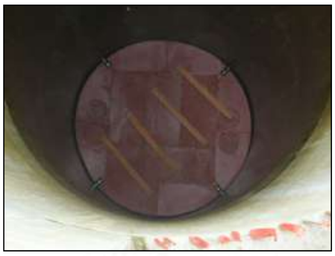

Excavation & settlement

24

Source) Daju Company, modified by KRC

1.3 Large scale radial collector well

◆ **Horizontal drilling for arm**



Install the guide

Drilling machine

Drilling horizontal hole

Completed facilities

Finishing the horizontal hole

Installing the well screen

25

Source) Daju Company, modified by KRC

1.4 Well development

◆ **Well Development for Drilled Wells**

- Part of the normal well drilling procedure
- Takes place right after well drilling and before the final disinfection

- **Purpose of well development procedures:**
  - Maximising the **well yield** after construction
  - Optimising the filter capacity of the gravel pack

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Source: www.ssswm.info

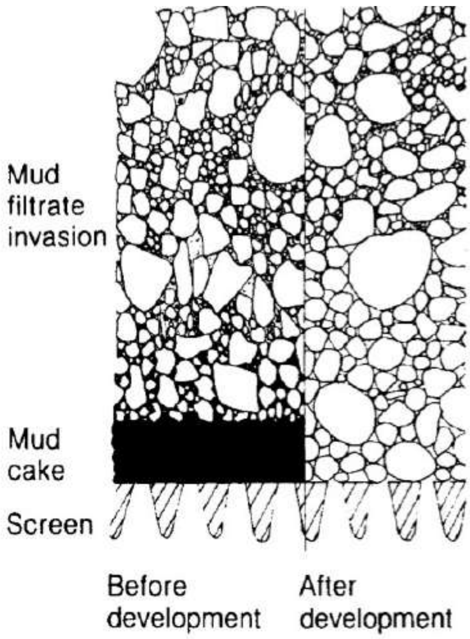
1.4 Well development

◆ Improving the Well Yield right after Construction

- **Well drilling procedures** alter the hydraulic in the vicinity of the well

  → Fines and drilling fluid additives originating from the drilling process remain in the borehole and block the pores of the surrounding aquifer.
- **Well Development techniques** aim to remove these fines (mud cake) and to let consolidate the gravel pack.

Results: - Higher yield
- Less sand intrusion



Source: CLARK (1988)

27

Source: www.ssswm.info

1.4 Well development

◆ **Most Common Well Development Techniques**

Over-pumping → Pumping the well at a higher rate than usually.

Surging → By moving a surge block up and down the well, water is forced into and out the aquifer, and mobilising the fines.

Jetting → Injection of high-pressure air or water through the screen to remove fines and drilling fluids.

→
- **Higher yield**
- **Higher filter capacity**
- **Less sand intrusion**

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Source: www.ssswm.info

2. History of groundwater development

2.1 Groundwater development history of Korea
2.2 Groundwater development in agriculture

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2.1 Groundwater development history of Korea

◆ 1960's ~ 1970's

1960's

Humans dig the ground to develop groundwater

1970's

Development of alluvial layer with depth of 20 m

First groundwater development on Jeju Island

30

Source) Korea Rural Community Corporation

2.1 Groundwater development history of Korea

◆ 1980's ~ 1990's

1980's

Develop subsurface dam

Development of rock wells

1990's

Upland water development

Rural domestic water
Hot spring, deep groundwater development

31

Source) Korea Rural Community Corporation

2.1 Groundwater development history of Korea

◆ 2000's ~ 2010's

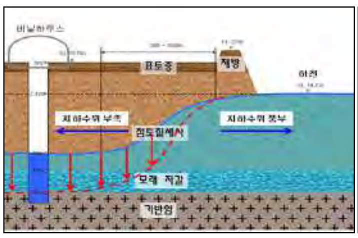
2000's

Groundwater conservation Management

Groundwater contamination

Groundwater observation

2010's



Large-capacity groundwater

Artificial recharge

Smart control of groundwater

Groundwater development for drought

Source) Korea Rural Community Corporation

2.2 Groundwater development in agriculture

◆ 1963 ~ 1967 (The begging of groundwater development

- Feasibility investigation for groundwater by USOM(United States Operation Mission) (1963)
- Develop 3 alluvial wells by Ministry of Agriculture and Forest (1964)
- Development of agricultural water supply plan (for rice field 70,000ha)
- Started well–development project by Korean government (1965–1967)

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Source) Korea Rural Community Corporation

2.2 Groundwater development in agriculture

◆ Established groundwater development corporation (1969)

- Newly started groundwater management organization in Ministry of agriculture for big drought in 1967
- Established groundwater development corporation in 1969 by government
  – establish 7 branches in 7 provinces

❖ Drought situation at that time

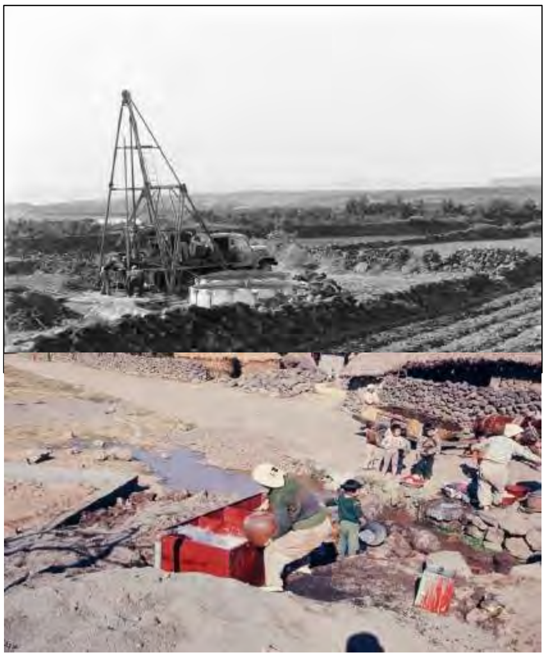
- 1967 : May~July precipitation 307mm (decrease rice production 8%)
- 1968 : May~July Precipitation 122mm (decrease rice production 18%)

34

Source) Korea Rural Community Corporation

2.2 Groundwater development in agriculture

◆ **The first successful groundwater development in Jeju island(1970)**



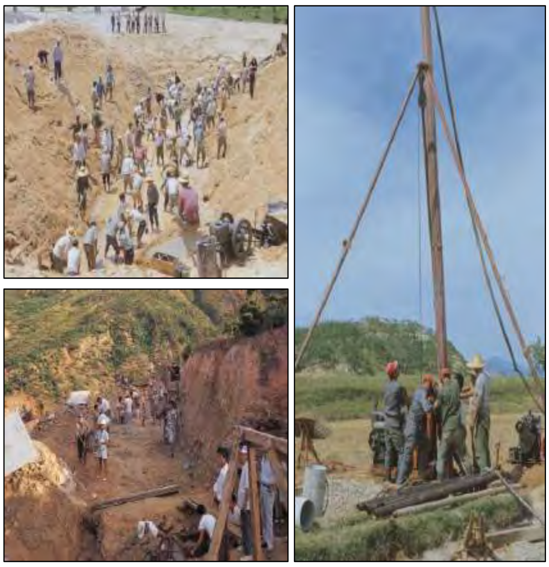
- Successfully developed the first deep well for the agricultural water In Jeju island (1970.2~5)
  - located northern part of Jeju island
  - depth of well : 30m, pumping rate : 2,000㎥/day
- After success of deep well installation, established groundwater survey and development plan for juju island

35

Source) Korea Rural Community Corporation

2.2 Groundwater development in agriculture

◆ Groundwater development in alluvial aquifer (1971~1980))



- Maintenance of alluvial wells
  - Inspection of groundwater facilities
  - Observational survey of existing public wells
- Groundwater development for drought condition
  - Well development for extreme drought
  - Well development for horticultural complex
  - Well development for emergency water

36

Source) Korea Rural Community Corporation

2.2 Groundwater development in agriculture

◆ Bedrock groundwater development (1981`)

- Started development of bedrock groundwater
  - 1st bedrock groundwater well drilled in 1981
  - well depth : 50m, pumping rate: 500m^3/day
- Successfully implanted 8 bedrock groundwater wells
  - After that, bedrock wells are installed instead of alluvial wells
- Deep groundwater development project started 1991
  - well depth : more than 1,000m

37

Source) Korea Rural Community Corporation

2.2 Groundwater development in agriculture

◆ Development of underground dams and radial collection wells (1983~)

- Purpose : Large-scale agricultural groundwater development
- Facility : underground dam and radial collection wells
- history
  - 1983: 1st underground dam is installed
  - length of dam : 230m
    - · radial collection wells : 4
  - After that, 4 underground dams are installed

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Source) Korea Rural Community Corporation


Thank you very much

Groundwater Monitoring Networks in Korea

Groundwater

Groundwater Monitoring Networks in Korea

Aims and objectives

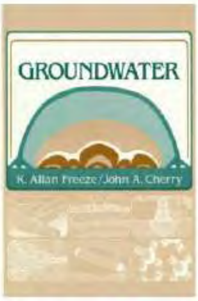
- The aims of the course are to:

  (1) promote to trainees a good understanding of the necessity of groundwater monitoring network to monitor long-term general trends in water-level fluctuations and in groundwater quality.
  (2) understand to trainees the installation procedures for developing groundwater monitoring wells and the equipment composing the groundwater monitoring system.

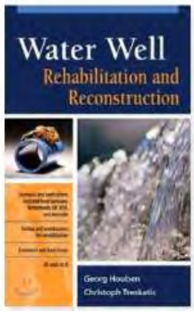
- The objectives are that trainees will understand:

  (1) the necessity of groundwater monitoring network
  (2) the equipment composing the groundwater monitoring system
  (3) the frameworks of time-series data analysis technique
  (4) the installation procedures for developing groundwater monitoring wells

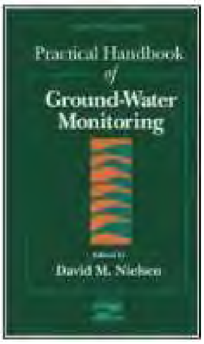
References



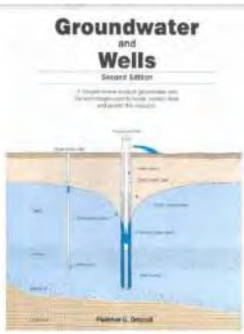
Groundwater
(Freeze and Cherry, 1979)



Water well
Rehabilitation and reconstruction



Practical handbook of
Groundwater monitoring



Groundwater and wells

Contents

1. Groundwater resources in Korea
   - Characteristics of groundwater resources in Korea
   - Groundwater monitoring networks in Korea
1. Groundwater Monitoring Networks
   - National level groundwater monitoring networks
   - Regional level groundwater monitoring networks
   - Seawater intrusion monitoring networks
   - Public services
3. Conclusions

1. Groundwater resources in Korea

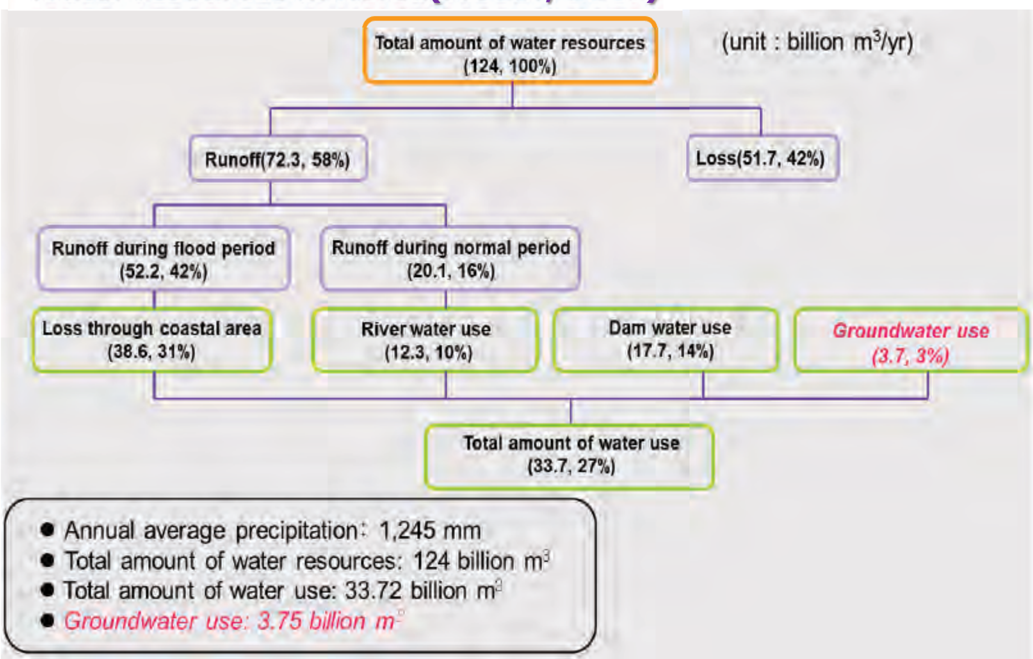
1.1 Characteristics of groundwater resources in Korea

1.2 Groundwater monitoring networks in Korea

1.1 Characteristics of groundwater resources in Korea

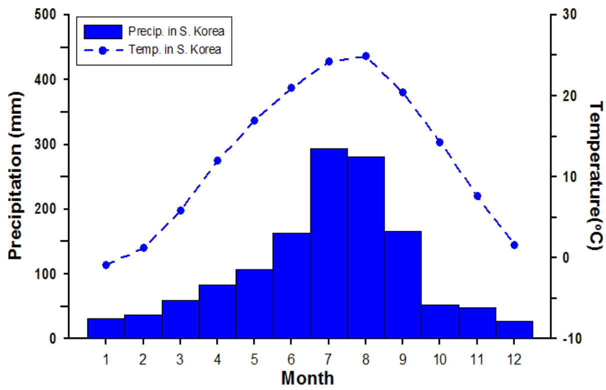
Characteristics of groundwater resources in Korea

Water resources in Korea(MOLIT, 2017)



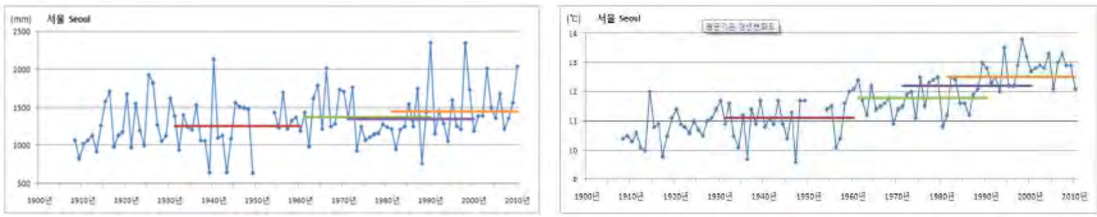
1.1 Characteristics of groundwater resources in Korea

Characteristics of groundwater resources in Korea



Monthly mean hydrologic data in Korea

Variation of monthly mean hydrologic values for precipitation and temperature during each 30 year period

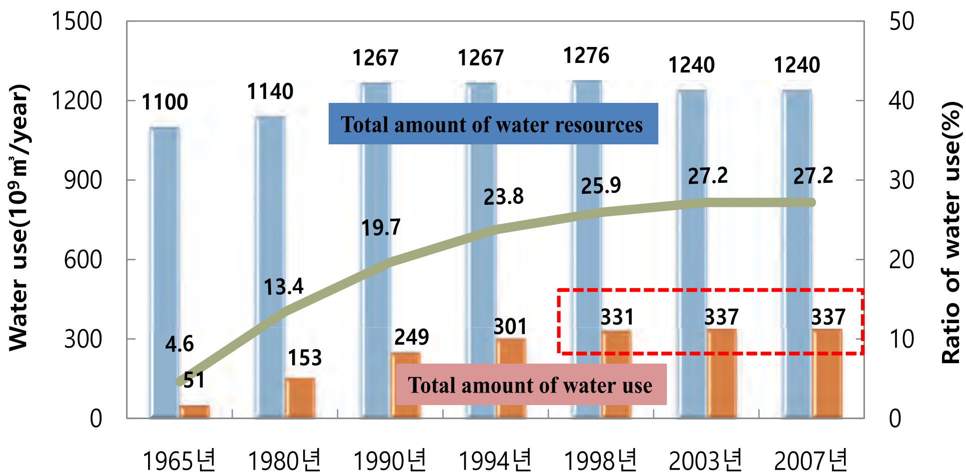


1.1 Characteristics of groundwater resources in Korea

Characteristics of groundwater resources in Korea

Variation of total amount of water use

: no significant change after 1998

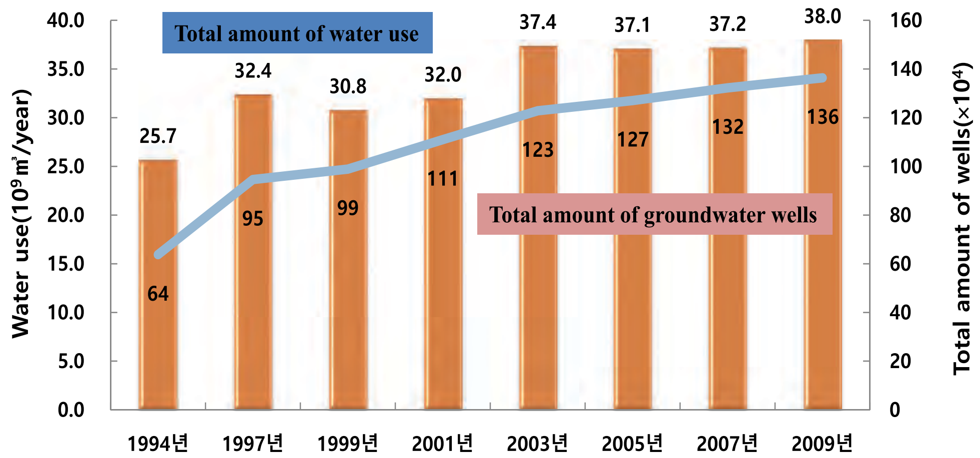


1.1 Characteristics of groundwater resources in Korea

Characteristics of groundwater resources in Korea

Variation of total amount of groundwater use

: showing the increase trend of total amount of wells and water use

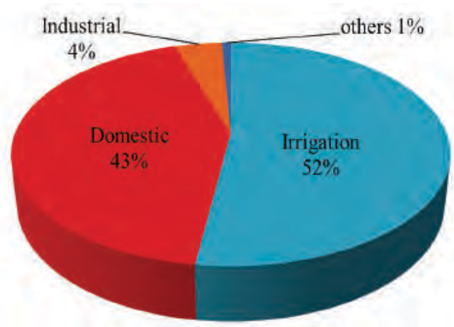


1.1 Characteristics of groundwater resources in Korea

Characteristics of groundwater resources in Korea

Groundwater use in Korea(MOLIT, 2017)

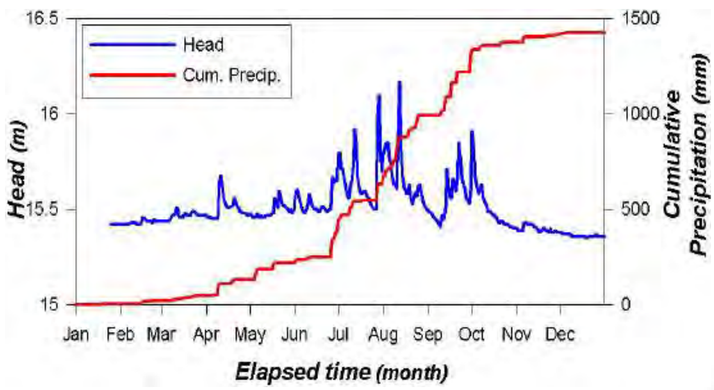
	Total	Domestic	Industry	Irrigation	Etc.
Wells	1,657,800	866,500	13,600	774,100	3,600
Use(MCM/yr)	4,043	1,736	177	2,109	32

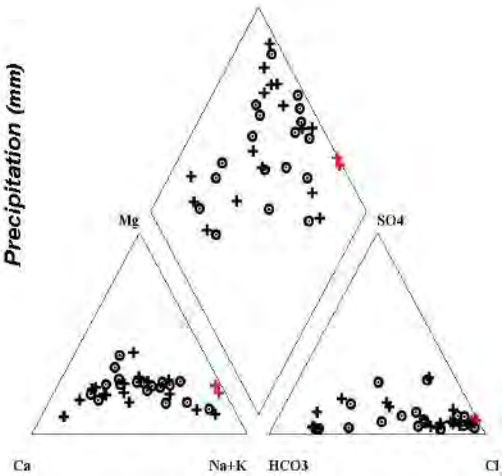


1.2 Groundwater monitoring networks in Korea

(Definition) are observing the fluctuation trend of groundwater level and quality to prevent hazards; groundwater depletion, contamination, land subsidence, seawater intrusion, and etc.

- Groundwater level, temperature, and electrical conductivity (EC) are measured automatically every hour in field and they are transferred to web server periodically.
- Groundwater quality is analyzed in a laboratory for main cation and anion one/twice every year according to the purpose of monitoring networks.





1.2 Groundwater monitoring networks in Korea

Installation procedure for developing groundwater monitoring well

1.2 Groundwater monitoring networks in Korea

(Monitoring system) The effectiveness of groundwater monitoring can be considerably increased by carefully attention to system implementation.

- Appropriately-constructed observation and abstraction wells must be used.
- Field equipment and laboratory facilities must be appropriate to objectives.
- Complete operational protocol and data handling system must be established.
- Groundwater and surface water monitoring should be integrated where applicable.

Groundwater monitoring networks

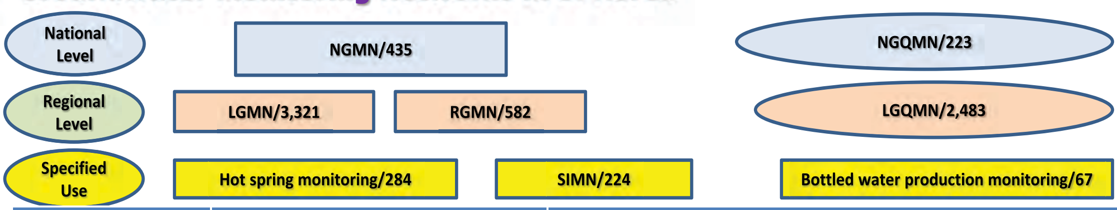
Establishment of monitoring sensor and power supply

Multi-level sensor

1.2 Groundwater monitoring networks in Korea

Groundwater monitoring networks are composed of NGMN and NGQMN for national level, LGMN, LGQMN and RGMN for regional level, and SIMN for specific use, respectively.

Groundwater monitoring networks in S. Korea



Ministry (management)	Name	Description
Ministry of Environment (K-WATER)	National Groundwater Monitoring Network (NGMN)	- To monitor groundwater level, temp., and EC - Evenly distributed in South Korea - 435 stations (2020.12)
Local Government	Local Groundwater Monitoring Network (LGMN)	- Similar purposes to National Groundwater M.N. - Quantity managements by local governments - 3,321 Stations (2018.09)
Ministry of Agriculture, Food, and Rural Affairs (KRC)	Seawater Intrusion Monitoring Network (SIMN)	- To protect crops from the hazard by irrigating saline groundwater in coastal areas - 224 stations (2020.12)
	Rural Groundwater Management Network (RGMN)	- To manage groundwater quantities and qualities for sustainable irrigation - 582 stations (2020.12)
Ministry of Environment (Local governments)	National Groundwater Quality Monitoring Network (NGQMN)	- To monitor groundwater quality and contamination - 223 stations (2020.12)
	Local Groundwater Quality Monitoring Network (LGQMN)	- Quality monitoring & managements by local governments - 2,483 stations (2016.12)
Commercial Companies	Drinking Groundwater/Hot(Thermal) Springs	- Commercial purpose of business companies and corporations

2. Groundwater monitoring system

2.1 National level groundwater monitoring networks

2.2 Regional level groundwater monitoring networks

2.3 Seawater intrusion monitoring networks

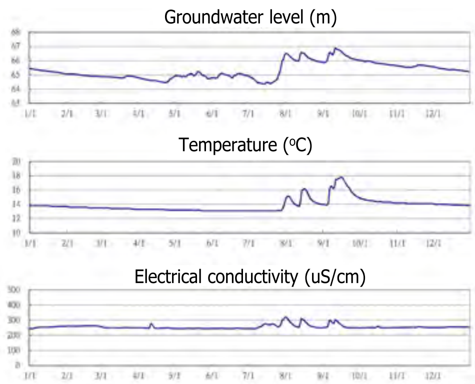
2.4 Public services

2.1 National level groundwater monitoring networks

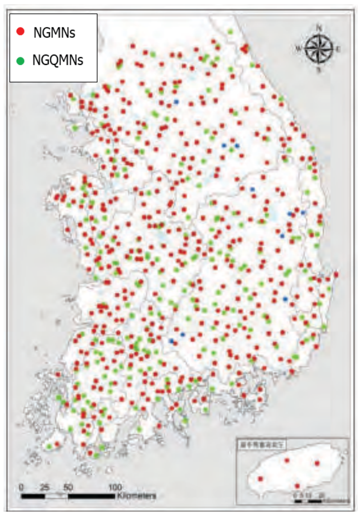
(Role) NGMNs and NGQMNs are the key station in acquiring groundwater hydrological data and groundwater quality in Korea, respectively.

- Each groundwater monitoring well in NGMNs is composed of two wells for bedrock aquifer and the alluvial aquifer.
- Groundwater monitoring wells in NGQMNs are managing for monitoring water quality change in concerning area by sampling groundwater periodically.

Location of groundwater monitoring wells in NGMNs and NGQMNs



Yeoncheon monitoring well in Gyunggi-Province

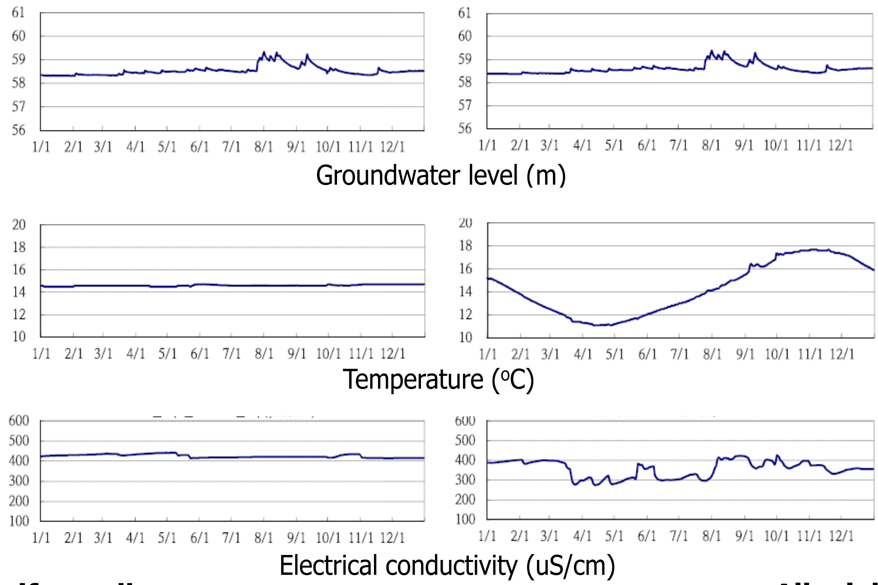


Source: MOE and K-water(2020)

2.1 National level groundwater monitoring network

(NGMNs) Three items are monitored in each well for bedrock aquifer and the alluvial aquifer.

Gapyoung monitoring wells in Gyunggi-Province



Bedrock aquifer well

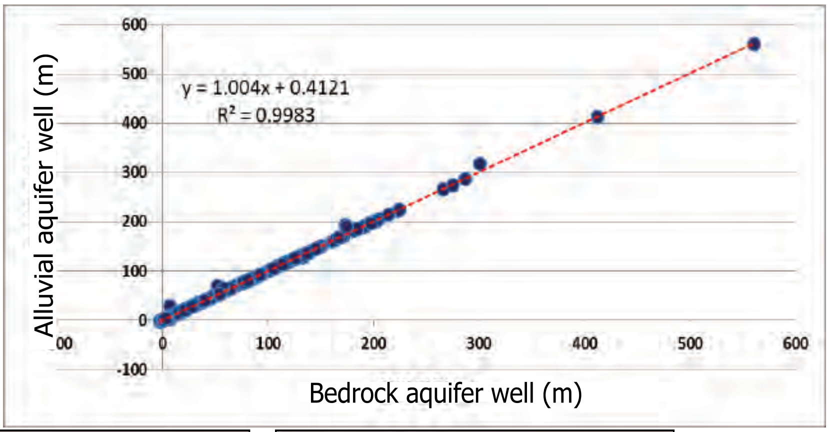
Source: MOE and K-water(2020)

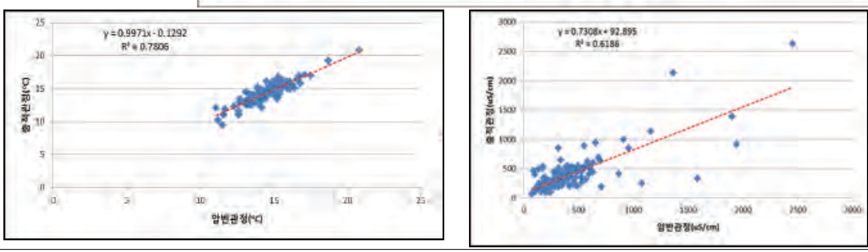
Alluvial aquifer well

2.1 National level groundwater monitoring network

(Hydraulic characteristics) Hydraulic connectivity between the two wells for bedrock aquifer and the alluvial aquifer is found to be very close.

175 samples from NGMNs; bedrock and alluvial aquifer



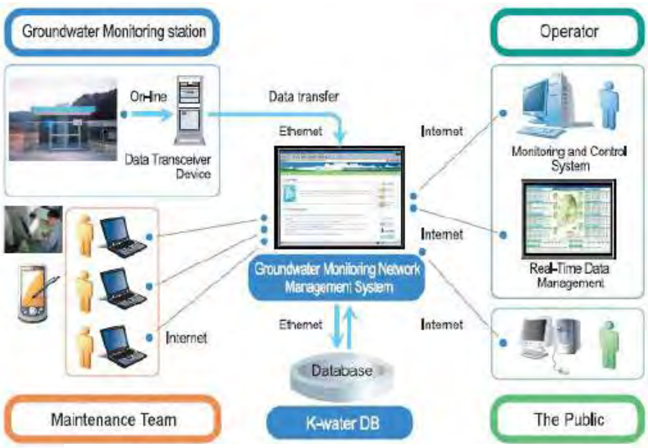


Source: Song et al., (2018)

2.1 National level groundwater monitoring network

Management system for NGMNs is established for the monitoring data remote transceiver system.

- (purposes) Improvement of reliability of observed data and minimization of missing data by regular check them up.
- (purposes) Analysis of real-time monitoring data by the NGMN management system and provision of it through the telecommunication.



Management system for NGMNs Reference: www.gims.go.kr

2.2 Regional level groundwater monitoring network

(Role) The groundwater monitoring data are obtained by installing an observation wells at a point where the wells in NGMNs and NGQMNs are insufficient.

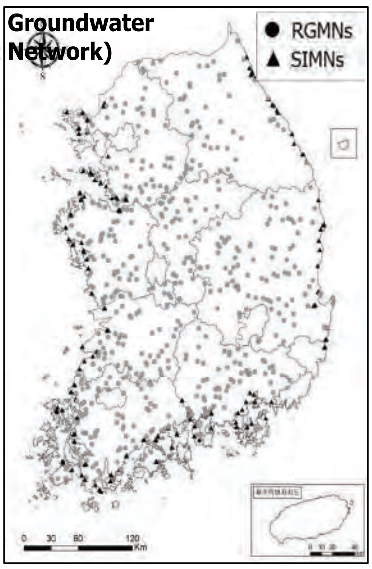
- Groundwater monitoring wells in LGMNs are installed in areas where the wells in NGMNs are insufficient, and some of them are installed in areas of concern for water contamination.

LGMNs (Local Groundwater Monitoring Networks)

● RGMNs
▲ SIMNs

● LGMNs
▲ Pollution

RGMN (Rural Groundwater Management Network)



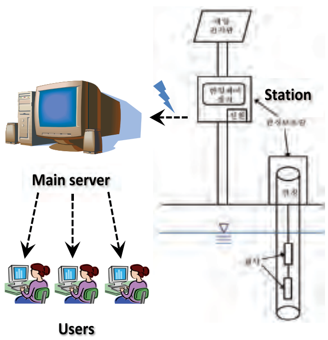
Source: MOE and K-water(2020)

2.2 Regional level groundwater monitoring network

(RGMNs) It is used for rational use and conservation of groundwater resources through the analysis of long-term monitoring data for groundwater level and quality.

- Establishment of groundwater monitoring sensors after constructing well
- Observation of real-time groundwater level and quality (temp. and EC)
- Analysis of water quality data and well logging
- Analysis of groundwater reserves based on groundwater level fluctuation

RGMNs

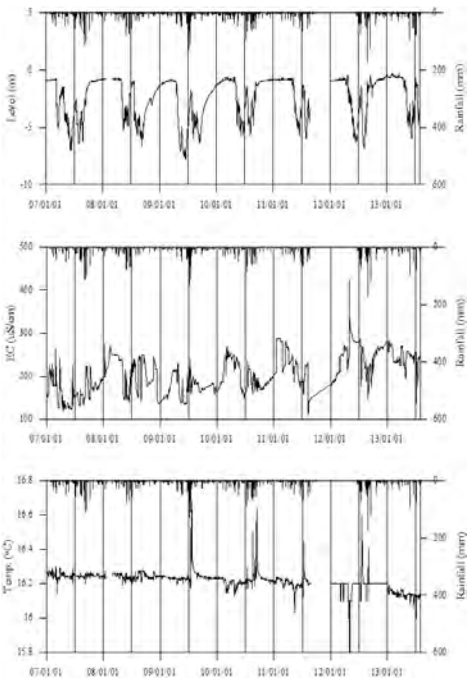


All-in-one sensors invented by RRI
It collects three physical properties such as groundwater level, temperature, and electrical conductivity every hour.

2.2 Regional level groundwater monitoring network

(RGMNs) Effect of groundwater use in cropping periods

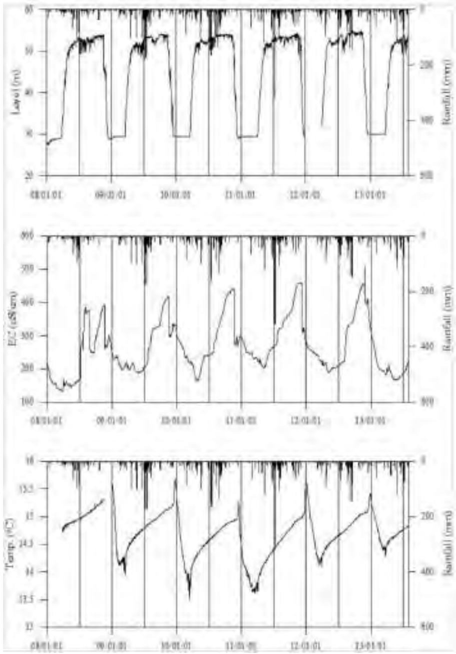
E-chon station
(Typical pattern of rural GW)



2.2 Regional level groundwater monitoring network

(RGMNs) Excessive pumping of groundwater in a greenhouse facilities zone

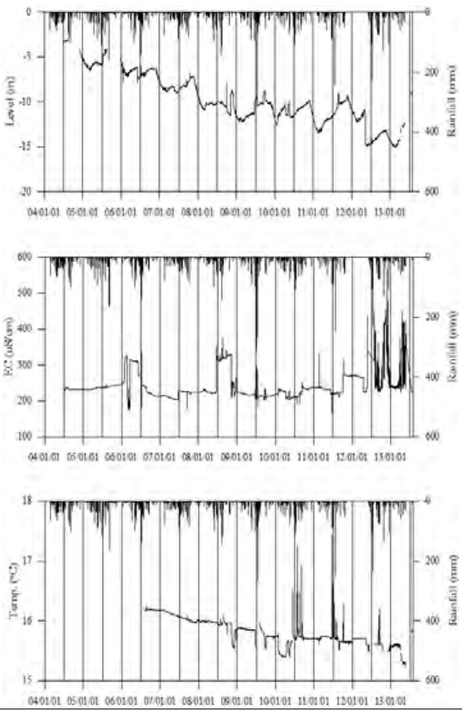
Jin-ju station



2.2 Regional level groundwater monitoring network

(RGMNs) Excessive pumping of groundwater from plants near farm lands

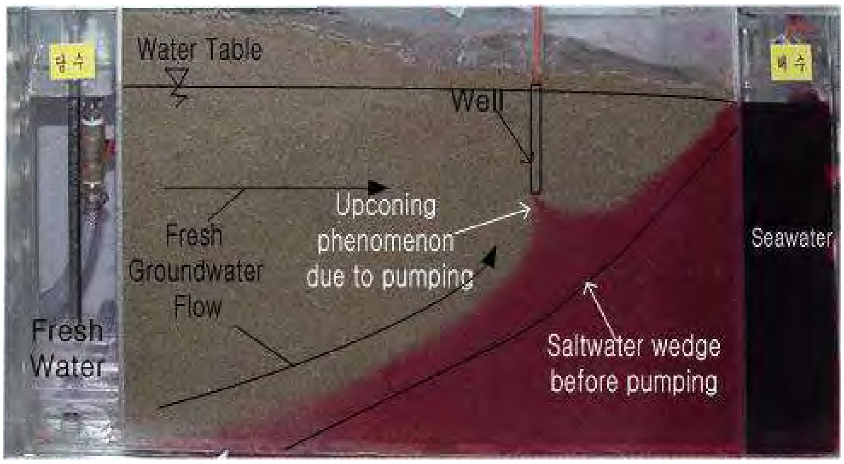
Kim-hae station



2.3 Seawater intrusion monitoring networks

(Definition) Seawater intrusion is the movement of seawater into fresh water aquifers due to natural processes or human activities.

- When groundwater is pumped from aquifer that are in hydraulic connection with the sea, the gradients that are set up may induce a flow of salt water from the sea toward the well.
- This migration of salt water into freshwater aquifers under the influence of groundwater development.



Reference: Namsik Park (2003)

2.3 Seawater intrusion monitoring networks

(Seawater intrusion monitoring networks)

- An around-the-clock monitoring system for seawater intrusion in coastal areas is installed to protect the hazard on farmlands by irrigating relatively saline groundwater in coastal areas.
- The groundwater wells in SIMNs is monitoring various items: groundwater level, temperature, and electrical conductivity which are measured by multi-level sensors.

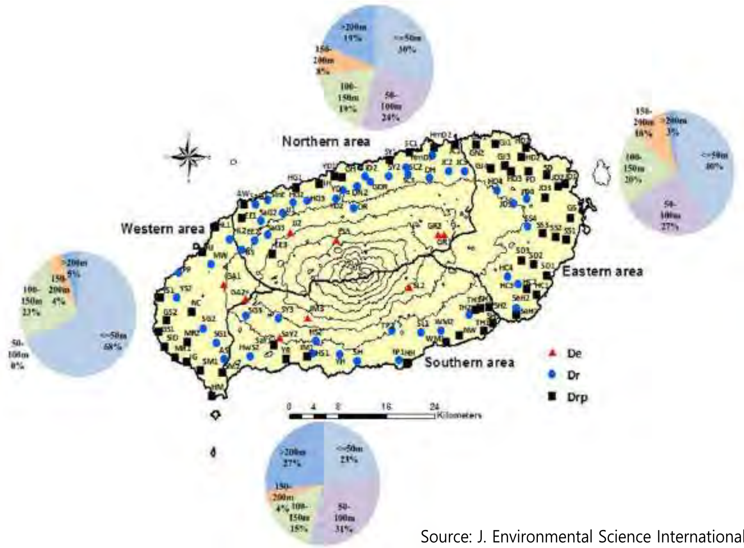
SIMNs

Multi-level sensors invented by RRI
one level sensor is placed just below the lowest groundwater level and two EC sensors are designated to be placed onto and above transition zone between saline water and freshwater, respectively.

2.3 Seawater intrusion monitoring networks

(Case of seawater intrusion monitoring from SIMNs in Jeju Island)

- Regional classification for 115 groundwater monitoring wells with three representative variation types; Dr (affected by rainfall only), Drp (affected by rainfall and pumping, simultaneously), and De (no special factors)

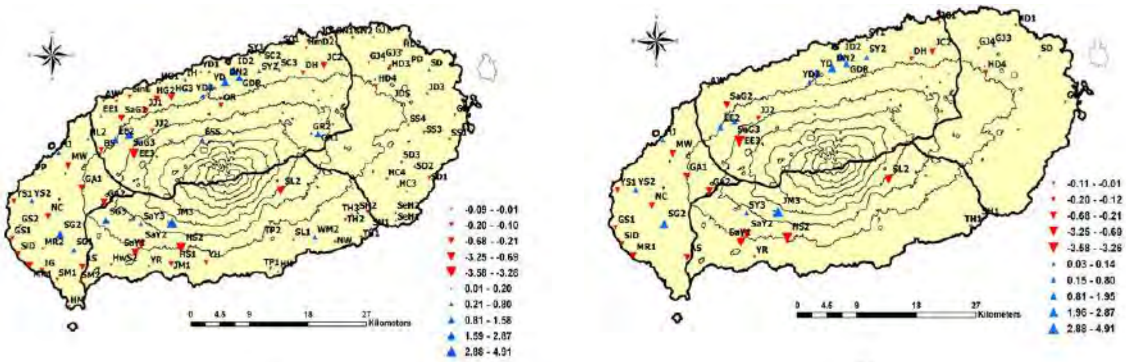


Source: J. Environmental Science International (Song et al., 2013)

2.3 Seawater intrusion monitoring networks

(Case of seawater intrusion monitoring from SIMNs in Jeju Island)

- Distribution of trend analysis of groundwater levels using linear regression method (a) and non-parametric method (b)



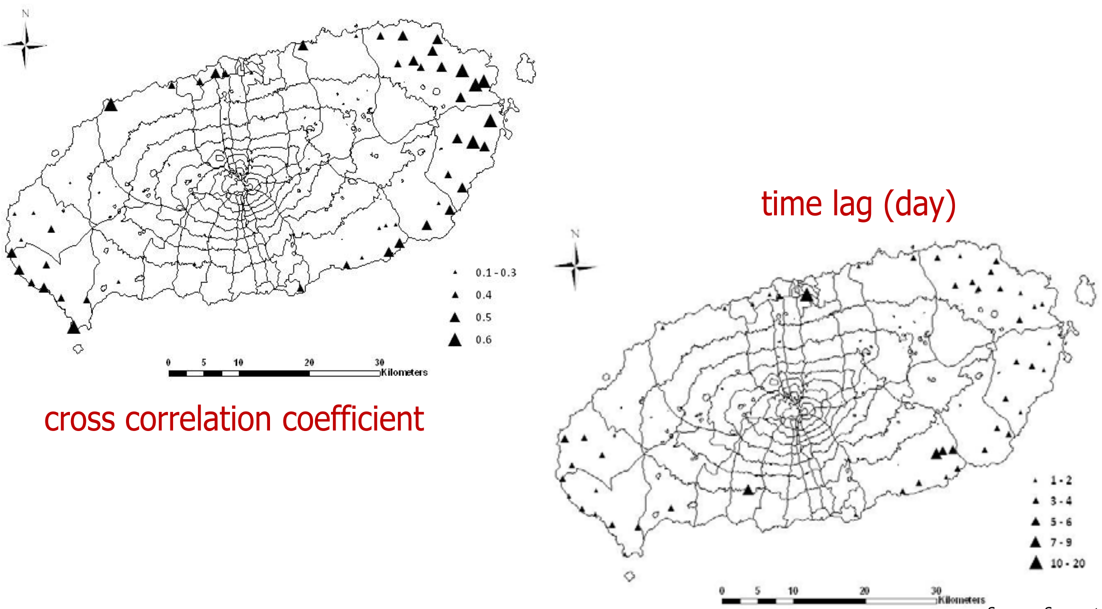
(a) (b)

Source: J. Environmental Science International (Song et al., 2013)

2.3 Seawater intrusion monitoring networks

(Case of seawater intrusion monitoring from SIMNs in Jeju Island)

- Distribution of cross correlation coefficient and time lag (day) for variation of groundwater level due to the rainfall for tidal affected wells (n=57)

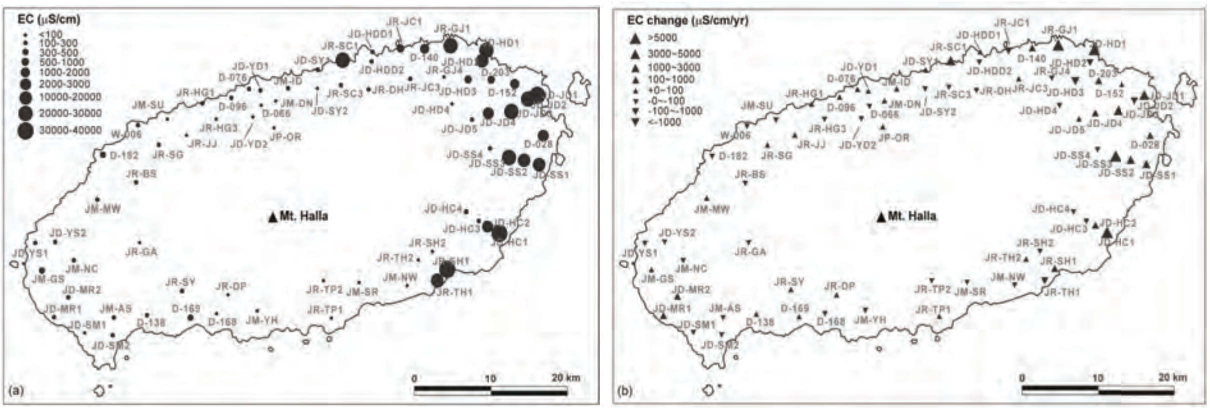


Source: Song et al., (2018)

2.3 Seawater intrusion monitoring networks

(Case of seawater intrusion monitoring from SIMNs in Jeju Island)

- Distribution of the mean of EC (a) and changing rates (b)
- The highest EC levels (30,000-40,000 μS/cm) are observed at the eastern part.
- The large EC values along the coast line indicate gradual encroachment of seawater.
- Interestingly, areas with high EC levels or high EC increasing rates are not identical to those with high water level decreasing rates.



Source: J. Korean Earth Science Society (Lee et al., 2007)

2.4 Public services

(Definition) The networks have a total of over 4,000 monitoring wells and majority of them are now equipped with automatic data loggers and remote terminal units.

- Most of the monitoring data are available to the public through internet websites.

URL: www.groundwater-m.or.kr
www.gims.go.kr

3. Conclusions

3. Conclusions

The purpose of groundwater monitoring networks is to prevent land subsidence, groundwater depletion, and groundwater contamination through continuous monitoring of groundwater level and water quality fluctuations.

- **Monitoring networks in Korea are composed of**
  - National level monitoring networks; NGMNs, NGQMNs
  - Regional level monitoring networks; LGMNs, LGQMNs, RGMNs
  - SIMNs for specific use
- **Monitoring items**
  - Groundwater level, temperature, and electrical conductivity (EC)
  - Groundwater quality is analyzed in a laboratory for main cation and anion
- **Public services**
  - Monitoring data are available to the public through internet websites.

    URL: www.groundwater-m.or.kr
    www.gims.go.kr

Groundwater Monitoring Network Practice

Groundwater

Groundwater Monitoring Network Practice

United Nations Educational, Scientific and Cultural Organization · i-WSSM International Centre for Water Security and Sustainable Management

Aims & Objectives

- **The aims of the course are to:**

  (1) Study with the factors required for designing an observation well
  (2) Understand the procedure for setting up an observation well
  (3) Understand the checking procedure of the observation well installed in the field

- **The objectives are that trainees will understand:**

  (1) Designing factors for observation well;
  (2) Well materials for observation well
  (3) Checking point for installed observation well

Contents

1. Monitoring well design

1.1 Criteria for monitoring well design
1.2 Site investigation for well installation
1.3 Considering factor before well installation
1.4 Designing the detection monitoring well

4

1.1 Criteria for monitoring well design

◆ Monitoring well installation

- Construct the well with minimum disturbance to the formation
- Construct the well of materials that are compatible with the anticipated geochemical and chemical environment
- Properly complete the well in the desired zone
- Adequately seal the well with materials that will not interfere with the collection of representative water–quality samples
- Sufficiently develop the well to remove any additives associated with drilling and provide unobstructed flow through the well

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1.1 Criteria for monitoring well design

◆ Key factors for well installation

- Intended purpose of the monitoring well
- Placement of the well to achieve accurate water levels and/or representative water-quality samples
- Adequate well diameter to accommodate appropriate tools for well development, aquifer testing equipment and water-quality sampling devices
- Surface protection to assure no alteration of the structure or impairment of the data collected from the well

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1.1 Criteria for monitoring well design

◆ Key factors for well installation

- Achieving the purpose of the installation of the well
- Place the well to achieve accurate water levels and/or representative water-quality samples
- Adequate well diameter to accommodate appropriate tools for well development, aquifer testing equipment and water-quality sampling devices
- Surface protection to assure no alteration of the structure or impairment of the data collected from the well

7

1.1 Criteria for monitoring well design

◆ Key factors for well installation

- Geologic and Hydrogeologic conditions
  -> Affect the occurrence and movement of ground water and contaminant transport in the subsurface
  -> Significantly influence the design and construction techniques used to install a monitoring well
- Characterizing the hydrogeology of a site
  -> Site Investigation

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1.2 Site investigation for well installation

◆ Key factors for site investigation

- Characterization of subsurface materials including
  - The lateral and vertical extent of the uppermost aquifer
  - The lateral and vertical extents of upper and lower confining units/layers
  - The geology at the owner/operator' s facility (e.g., stratigraphy, lithology, structural setting)
  - The chemical properties of the uppermost aquifer and its confining layers relative to local ground-water chemistry and hazardous wastes managed at the facility

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1.2 Site investigation for well installation

◆ Key factors for site investigation

- Characterization of Groundwater flow including
  - The vertical and horizontal directions of ground-water flow in the uppermost aquifer
  - The vertical and horizontal components of hydraulic gradient in the uppermost aquifer
  - The hydraulic conductivities of the materials that comprise the uppermost aquifer and its confining units/layers
  - The average linear horizontal velocity of ground-water flow in the uppermost aquifer

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1.3 Considering factor before well installation

◆ Considering factor before installation of wells

- exploratory borings and related subsurface tests must usually be made to define the geology beneath the site and to assess ground–water flow paths and velocity
- Formation samples and other data collected from this work are needed to define the hydraulic characteristics of the underlying materials
- The logs of these borings are used to correlate stratigraphic units across the site
- An understanding of the stratigraphy, including the horizontal continuity and vertical thickness of formations beneath the site, is necessary to identify zones of highly permeable materials or features such as bedding planes, fractures or solution channels

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1.3 Considering factor before well installation

◆ Considering factor before installation of wells

- Because the occurrence and movement of groundwater in the subsurface are closely related to the geology, the geologic conditions at the site influence the location, design and methods used to install monitoring wells
- The required depth of a monitoring well is determined by the depth to one or more water–bearing formations that need to be monitored. Where two or more saturated zones occur beneath a site and the intent of the monitoring program is to monitor water quality in the lower zone, the monitoring well may require surface casing to "seal–off" the upper water–bearing formation prior to drilling deeper.

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1.3 Considering factor before well installation

◆ Considering factor before installation of wells

- The formations at the site, whether consolidated or unconsolidated, also influence the type of well completion
  - -〉 In unconsolidated deposits, screened intakes are typically designed.
  - -〉 The well may have either a naturally developed or artificially-emplaced filter pack, depending on the grain-size distribution of the water-bearing materials.
  - -〉 Artificial filter packs and screened intakes are also often required in poorly-consolidated formations to minimize potential caving of the borehole and/or to reduce turbidity in water samples collected from the completed well

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1.3 Considering factor before well installation

◆ Considering factor before installation of wells

- Drilling methods must be chosen based at least in part on geologic considerations.
  - -〉 Hard, consolidated formations restrict or eliminate certain drilling methods
  - -〉 For example, in karstic formations, cavernous openings create significant problems in maintaining circulation and in protecting drilling equipment
  - -〉 Unconsolidated deposits can also present severe limitations for various drilling methods

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1.3 Considering factor before well installation

◆ Considering factor before installation of wells

- Drilling methods must be chosen based at least in part on geologic considerations.
  - -〉 Some drilling techniques cannot be used where large boulders are present
  - -〉 Conversely, cohesive geologic deposits and the resultant stability of the borehole may expand drilling options
  - -〉 Variations in equipment, drilling techniques and installation procedures may be necessary to overcome specific limitations when using particular drilling methods

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1.3 Considering factor before well installation

◆ Considering factor before installation of wells

- Consideration of the hydrogeology at the site is also important when selecting a drilling method
  - -> The depth to which the well must be drilled to monitor a selected water-bearing zone may exceed the practical depths of a particular drilling technique
  - -> In addition, certain saturated geologic materials, under high hydrostatic pressures, may either 1) impose increased frictional resistance (i.e. expanding clays) which limits the practical depths reached by some drilling methods or 2) create unstable borehole conditions (i.e. heaving sands) that may preclude the use of some drilling methods for installation of the monitoring well

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1.4 Designing the detection monitoring well

◆ **Designing procedure**

- STEP 1 Define the data that are required from a regulatory perspective, and develop technical objectives to meet those requirements
- STEP 2 Perform a preliminary investigation.
  - –Comprehensive review of existing information relating to the site
  - –Thorough review of available literature and existing field data
  - –Characterize the hydrogeology of the region and the site
  - –Gather information that will be useful in planning field investigations.
  - –Characterizing the chemical and physical properties of the wastes or constituents of concern to the extent that this information is available.

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1.4 Designing the detection monitoring well

◆ **Designing procedure**

- STEP 3 Develop a conceptual model of site hydrogeology
  - – Based on the regional hydrogeology and on the preliminary investigation
  - – Used as the basis for designing field investigations at the site.
- STEP 4 Perform field investigations at the site.
  - – Include one or more of the following techniques:
    - · Subsurface boring programs;
    - · Laboratory analyses of soil, unconsolidated material, and rock samples;
    - · Geologic and hydrogeologic analyses;
    - · Mapping programs;
    - · Electric cone penetrometer surveys; and
    - · Geophysical surveys.

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1.4 Designing the detection monitoring well

◆ **Designing procedure**

- STEP 5 Continue to develop and refine a conceptual model of the site based on the field investigations
  - Form the basis for the design of the ground-water monitoring system
  - Based on information of sufficient amount and quality to ensure that the monitoring system will fulfill the established regulatory requirements and technical objectives.
  - The quantity of data required will vary with the hydrogeologic complexity of the site.
  - Facilities located in complex hydrogeologic settings require more hydrogeologic data than facilities located in less complex settings.

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1.4 Designing the detection monitoring well

◆ **Designing procedure**

- STEP 6 Design a detection monitoring system consisting of both downgradient monitoring wells that intercept and monitor the potential pathways of contaminant migration, and background (e.g., upgradient) monitoring wells that provide representative samples of background ground–water quality.
- STEP 7 Install downgradient monitoring wells and background (e.g., upgradient) monitoring wells.
- STEP 8 Collect and analyze ground–water samples from downgradient and background monitoring wells (and from springs or the vadose zone, when appropriate) at the frequency specified in the facility permit.

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1.4 Designing the detection monitoring well

◆ **Designing procedure**

- STEP 9 Evaluate the ground-water monitoring system with respect to the regulatory requirements, the technical objectives, and the accuracy of the conceptual model. Refine the ground-water monitoring system, if necessary

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2. Monitoring well construction

2.1 Drilling procedure
2.2 Well materials

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2.1 Drilling procedure

◆ Drilling method

- Factors be considered when choose the drilling method
  - Versatility of the drilling method;
  - Relative drilling cost;
  - Sample reliability (ground-water, soil, unconsolidated material, or rock samples);
  - Availability of drilling equipment;
  - Accessibility of drilling site;
  - Relative time required for well installation and development;
  - Ability of the drilling technology to preserve natural conditions;
  - Ability to install well of desired diameter and depth; and
  - Relative ease of well completion and development, including ability to install well in the given hydrogeologic setting

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2.1 Drilling procedure

◆ Drilling procedure

- The guidance to assist in the selection of drilling procedures for installing monitoring wells as follows:
  - Preserves the natural properties of the subsurface materials;
  - Contamination of ground water and aquifer materials should be avoided;
  - Allow for the collection of representative samples of rock, unconsolidated materials, and soil;
  - Allow the owner/operator to determine when the appropriate location for the screened interval has been encountered;

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2.1 Drilling procedure

◆ Drilling procedure

- The guidance to assist in the selection of drilling procedures for installing monitoring wells as follows:
  - Allow for proper placement of the filter pack and annular sealants. The borehole should be at least 100 mm larger in diameter than the nominal diameter of the well casing and screen to allow adequate space for placement of the filter pack and annular sealants;
  - The drilling method should allow for the collection of representative groundwater samples. Drilling fluids (including air) should be used only when minimal impact to the surrounding formation and ground water can be ensured.

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2.2 Well materials

◆ Casing and screen materials

- Monitoring well casing and screen materials should meet the following performance specifications:
  - Monitoring well casing and screen materials should maintain their structural integrity and durability in the environment in which they are used over their operating life;
  - Monitoring well casings and screens should be resistant to chemical and microbiological corrosion and degradation in contaminated and uncontaminated waters

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2.2 Well materials

◆ Casing and screen materials

- Monitoring well casing and screen materials should meet the following performance specifications:
  - · Able to withstand the physical forces acting upon them during and following their installation, and during their use -- including forces due to suspension in the borehole, grouting, development, purging, pumping, and sampling, and forces exerted on them by the surrounding geologic materials; and
  - · Should not chemically alter ground-water samples, especially with respect to the analytes of concern, as a result of their sorbing, desorbing, or leaching analytes.

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2.2 Well materials

◆ Casing and screen materials

- The selection of the most suitable well casing and screen materials should consider site specific factors, including:
  - – Depth to the water-bearing zone(s) to be monitored and anticipated well depth;
  - – Geologic environment;
  - – Geochemistry of soil, unconsolidated material, and rock over the entire interval in which the well is to be cased;
  - – Geochemistry of the ground water at the site, as determined through an initial analysis of samples from both background wells and downgradient wells and including:
    - · natural ground-water geochemistry,
    - · nature of suspected or known contaminants, and
    - · concentration of suspected or known contaminants; and
  - – Design life of the monitoring well.

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3. Monitoring well checking

3.1 Groundwater level measurement
3.2 Monitoring well checking procedure

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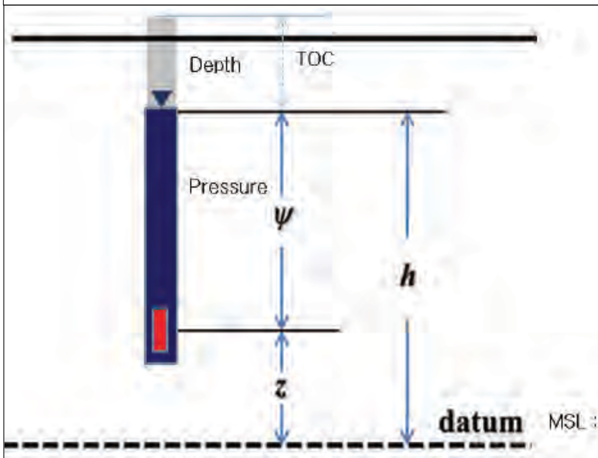
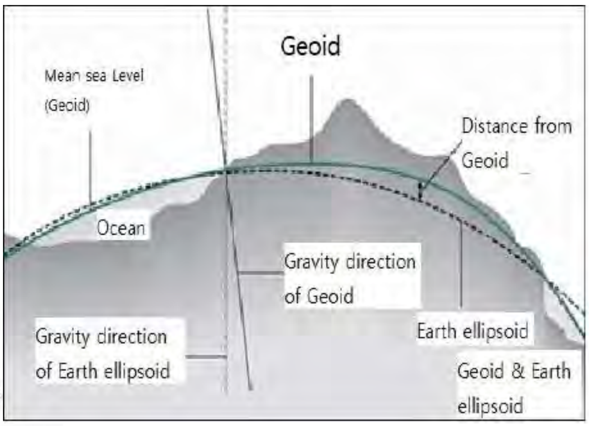
3.1 Groundwater level measurement

◆ **Concept of groundwater level measurement**

- TOC (Top of casing)
- DTW (Depth to water)
- MㄴI (Mean sea level)





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3.2 Monitoring well checking procedure

◆ Manual groundwater level checking

- Check the error between the manual water level value and the automatic water level value
- The automatic water level measurement value is corrected according to the manual measurement value

Groundwater level measurement using manual equipment

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3.2 Monitoring well checking procedure

◆ Checking RTU(Remote Terminal Unit_

- Check the time, temperature of water, voltage
- Check the telecommunication device

Remote Terminal Unit installed at Korea

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Thank you very much