Introduction to Groundwater and Aquifer Properties

I. Matter and Energy (basic physical properties)

A. Energy: capacity to do work, implies overcoming resistance to movement

1. Kinetic Energy: $E_k=0.5mv^2$ (units:kg-m^2/sec^2 = joule)
2. Potential Energy: $E_p = mgh$ (units:kg-m^2/sec^2 = joule)

B. Force: initiates work

F = ma F = force, m = mass, a = acceleration

units = kg-m/sec^2 = 1 newton

C. Work: force applied to fluid to initiate fluid flow

W = FD W = work, F = force, D = distance

units: N-m = kg-m^2/sec^2 = joule

D.

	SI system of units	English System
1.	mass = kg	Slug
2.	length = meter	foot
3.	time = sec	second
4.	Force = Newton	pound
5.	Acceleration = m/sec/sec	ft/sec/sec

E. Weight: gravitational force exerted on a mass

w = mg w = weight, m = mass, g = grav. acceleration
g = 9.8 m/sec/sec = 32 ft/sec/sec

weight units SI = newton, English = pound
1 N = 1 kg m/sec^2 1 lb = 1 slug ft/sec^2

F. Density D = m/V D = density, m = mass, V = volume

1. Units: kg/m^3

G. Specific Weight = weight per unit volume = w/V = Dg
units: N/m^3 lb/ft^3

H. Pressure: force applied to a unit area perpendicular to the direction of force.
P = F/A P = pressure, F = Force, A = area

units: english lb/ft^2 SI: N/m^2 = Pa

1. Standard atmospheric pressure (25 C at sea level) =
1.013×10^5 Pa = 2116 lb/ft. sq. = 1.013×10^3 millibar

II. Introduction to Groundwater

A. Introduction

1. Water contained within cracks, fractures and pore spaces of soil, sediment and rocks beneath the surface of the earth

2. Groundwater is much more voluminous and ubiquitous than surface water, commonly found within 2500 feet depth below land surface.

3. Groundwater flow path: atmospheric precipitation percolates into soil/bedrock directly or from surface lakes and streams, and generally flows downward under the force of gravity until it reaches some sort of physical barrier or impermeable zone, which either severely impedes flow or stops it altogether.

4. Types of Groundwater

a. Meteoric Water: water recently circulated from atmospheric cycle

b. Connate Water: water that is entrapped with sediments when they are deposited, and subsequently gets buried and lithified with the sediments in form of sedimentary rock.

(1) i.e. connate water = fossil water.

c. Juvenile Water: water freshly derived from deep within the interior of the earth via volcanic processes.

III. Porosity of Earth Materials

1. Porosity: ratio, in per cent, of the volume of void space to the total volume of sediment or rock

$$P\ (\%) = \frac{\text{total volume - volume of solids}}{\text{total volume}} \times 100$$

a. Porosity is the primary governing factor influencing the ability of rock or sediment to store fluids (e.g. groundwater or hydrocarbons)

b. Types of Porous Openings

(a) Intergranular Porosity = primary pore spaces present between particles of a sediment or rock deposit

i) Intergranular Porosity influenced by:
a) sorting
b) grain packing
c) grain size

(b) Fractured Porosity
(c) Solution Cavities
(d) Vesicles

c. Effective porosity: considers the extent to which pore spaces are interconnected in a deposit, as well as the force of hydrostatic attraction that binds water molecules to the surfaces of grains/pore spaces

(1) Hygroscopic Water = high suface tension of water creates tendency to coat pores with electrostatically-bound film of water
(a) effectively reduces porosity of rock/material, represents the porosity available for fluid flow.

d. Secondary Porosity: can impart a secondary or "overprint" porosity on a rock unit via structural fracturing and chemical dissolution.

e. Lithologic Control on Porosity
(1) Porosity of Unconsolidated Sediments
(a) function of grain size and packing

i) uncompacted clay and silt = very high porosity (up to 50%)

**compacted clay and silt = decreased porosity to 15%

ii) sand and gravel: porosity of 20-30% typically

(2) Porosity of Sedimentary Rocks
(a) Primary vs. Secondary Porosity

(b) Sandstone and conglomerate may possess relatively high porosities (30%)

(c) Limestone and carbonates may be low or high depending on solution
i) dissolved limestone ---- high secondary porosity
ii) hard, dense limestone ----- low primary porosity

(3) Porosity of Crystalline Plutonic and Metamorphic Rocks
(a) Very low primary porosity
(b) Secondary "structural porosity"
i) joints, fractures, faults -----porous zones
a) may achieve 5-10% on avg, up to 50% porosity in some instances

(4) Porosity of Volcanic Rock

(a) Vesicles and columnar jointing may create relatively high porosities
(b) Inter-flow fluvial deposits
(c) brecciated horizons

IV. Specific Yield

a. Specific Yield and Specific Retention
(1) Specific Yield of Aquifer

S.Y. = Vol. of Water Drained Under Gravity
Total Volume of Rock in Aquifer

(2) Specific Retention

S.R. = Vol. of Water Retained as Water Film
Total Volume of Rock in Aquifer

** Porosity = S.Y. + S.R. **

(3) Specific Retention > with < grain size
i) Pendular Water- moisture that clings to soil particles because of surface tension.

A. Ranges of Specific Yield and Earth Materials
1. Clay = 0-5%, sand = 10-35%, Gravel = 12-26%

V. Hydraulic Conductivity of Earth Materials

1. Permeability: the degree of interconnectedness between pore spaces and fractures within a rock or sediment deposit. A measure of the capacity of a porous material to transmit fluids

a. Permeability (K) is largely a function of:
(1) grain size, size of pore space
(2) shape of grains/shape of pore space
(3) degree of interconnected pore space

b. Hydraulic Conductivity = permeability in a horizontal direction in aquifer

(1) Measure of rate of tranmission of fluids horizontally through aquifer, essentially another term for permeability (modification of Darcy's Law)

$$Q = -KIA$$

Where Q = discharge (L^3/T)
K = hydraulic conductivity (permeability) (L/T)
I = hydraulic gradient (vertical head distance between two points of observation) (decimal ratio)
A = cross-sectional area through which flow occurs (L^2)

(a) Vertical Conductivity = capacity to transmit fluids in vertical direction
(b) Horizontal Conductivity = capacity to transmit fluids in horizontal direction

c. Darcy's Law

$$Q = \frac{KA(P_2-P_1)}{uL}$$ where,

Q = Volume Discharge Rate (cm^3/sec)
K = Permeability (millidarcy = mD)
A = Cross-sectional area at perpendicular to flow (cm^2)
L = length along which press. diff. is measured (cm)
(P_2-P_1)= pressure difference (atm) between two points separated by distance L
u = viscosity of fluid (centipoises)

Generally, well sorted sand and gravel display high porosity and permeability, however, a poor sorted sand with much matrix material will have a low permeability.

Unpacked clay, may have a very high porosity but very low permeability.

Generally clay/shale make for good permeability barriers, while sand and gravel readily transmit fluids. However secondary overprints such as structural deformation and diagenetic alteration (post-depositional changes in mineralogy) can drastically influence permeabiltiy and porosity.

A. Hydraulic Conductivity

1. By rearranging Darcy's Law (above):

$$K = \frac{-Q}{A(I)}$$

where K = hydraulic conductivity
A = cross-sectional area
I = dh/dL = gradient ("rise over run")

2. Intrinsic Permeability (Ki)

a. Modified K that considers the properties of the porous medium, shape of the pore openings

$Ki = Cd^2$ where C = shape constant, d = diameter of grains

standard units in civil engineering = sq^2
standard units in petroleum eng. = darcy

1 darcy = 9.87×10^{-9} cm^2

3. Relationship of K to Ki

a. Hydraulic conductivity then is a function of both pore throat geometry and physical nature of the fluid

K = Ki(pg/u) where

K = hydraulic conductivity, Ki = intrinsic permeability, p = density of fluid, g = acceleration due to gravity, and u = visosity of the fluid.

B. Permeameters

1. Defined: lab device to measure hydraulic conductivity of earth materials (see figure included with the note set)

a. Involves a holding chamber for the seds/soil, and a head of water is established in the medium. The head is known, the length of the material medium is known, discharge is measured.

b. Equation for solution of constant head permeameter test:

K = QL/(Ah)

where K = hydraulic conductivity (cm/sec), L = length of sample (cm), A = cross-sectional area of sample (cm^2), h = hydraulic head (cm), Q = discharge (cm^3/sec)

c. Equation for solution of falling head permeameter test:
See attached equation sheet.

C. Permeability Vs. Lithology

(1) Permeability of Unconsolidated Sediments
(a) Relationships to Grain Size
i) Perm < with < Grain Size (and vice versa)
ii) Perm < with < sorting (and vice versa)

a) Hence well sorted coarse sediment (sand, gravel) display the highest permeability

b) Poorly sorted or very fine sediment (clayey sand, or clay) generally display lowest permeability

c) Permeability of Lithified Rocks

(b) Function of interconnected nature of pore spaces

i) Sandstone, Conglomerate = high primary permeability

ii) Limestone = low primary permeability

a) Dissolved Limestone ----- high secondary permeability

iii) Shale and Well-cemented Siltstone = low primary permeability

a) Fractured Shales and Siltstones = high secondary permeability

b) Crystalline Igneous and Metamorphic Rocks = low primary permeabiltiy

c) Fractured Shales and Siltstones = high fractured (secondary permeability

iv) Volcanic Rocks = high primary permeability associated with columnar jointing

D. Limestone Solution Processes: A Special Aquifer Consideration

1. Calcium Carbonate System

a. <u>pH Defined</u>

(1) pH Defined: the "activity" of hydrogen ions in a solution; defines the concepts of acidity and alkalinity.

(a) "activity" = essentially equivalent to the effective concentration of a given ion in solution.

(b) By definition, a pure substance such as water, or a solid mineral, has an activity = 1.0.

(c) The lower the overall concentration of ions in solution, the closer activity= concentration.

i) As concentration of dissolved ions increases, e.g. seawater, activity of a given ion is generally < than its conentration.

ii) activity accounts for resistive interference of given ions to reaction, by other electrostatically charged ions in solution.

(d) Hence pH = negative log base 10 of hydrogen ion activity of a solution:

$pH = -\log_{10}[H+]$

H activity = 0.0001 = 10^{-4} pH = $-Log_{10}$ (10^{-4}) = 4 (acidic)
H activity = 10^{-14} pH = $-Log_{10}$ (10^{-14}) = 14 (basic)

2. Calcium Carbonate Stability as Function of pH

a. Definitions:

(1) Ion Solubility: the relative ability of ionic/elemental species to dissolve into solution. High Solubility = very dissolvable

(2) Mineral Precipitation: the crystallization of solid compounds from ionic species in a solution.

(3) Solution Equilibria

(a) "Saturated" Solution: a condition in which the rate of precipitation = rate of dissolution for a given set of ionic species.

(b) "Undersaturated" Solution: a condition in which a solid mineral species or compound will readily dissolve into solution, if soluble.

(c) "Supersaturated" Solution: a condition in which a ionic species will readily combine to precipitate out of solution.

3. Important reactions involving CO_2, H_2O, $CaCO_3$, and pH.

a. Dissolution of Carbon Dioxide (gas) in water results in production of Carbonic Acid, which subsequently dissociates into free H^+ ions and the bicarbonate anion
(HCO_3^-), hence increasing hydrogen ion activity, and by definition decreasing pH (becoming more acidic).

$CO_2 + H_2O$ ------ H_2CO_3

H_2CO_3 ------- H+ + HCO_3-

$CO_2 + H_2O$ ---- H+ + HCO_3-

b. As Calcium Carbonate (solid) reacts with water in presence of free hydrogen ions, the solid Calcium Carbonate dissolves forming free Ca^{+2} ions and free bicarbonate ions, hence consuming free hydrogen ions, decreasing hydrogen ion activity, and by definition increasing pH (becoming more basic). i.e. Calcium Carbonate acts to neutralize or buffer the solution by consuming hydrogen ions.

$CaCO_3 + H_2O + CO_2$ ------ $Ca_{+2} + 2HCO_3$-

c. Dissolution of Calcium Carbonate as a Function of pH

d. General relationship: as Carbon Dioxide content of water increases, hydrogen ion actvity increases, pH decreases (more acidic)------solid Calcium Carbonate undergoes dissolution

(1) Dissolved Carbon Dioxide content is temperature dependent, as T >, Carbon Dioxide content <, hence hydrogen ion activity decreases, pH increases (conducive to calcium carbonate precipitation)

As T <, Carbon Dioxide content >, hence hydrogen ion activity increases, pH decreases (conducive to calcium carbonate dissolution)

Hence >T, <P, <CO2, >pH, Calcium Carbonate Precipitation
<T, >P, >CO2, <pH, Calcium Carbonated Dissolution

e. In Sum: carbon dioxide in water creates carbonic acid and limestone dissolves
(1) If carbon dioxide is decreased (lossed) in groundwater system, pH > and calcite precipitates

VI. Aquifers

A. Subsurface Hydrologic Zones

1. Zone of Aeration or Vadose Zone:

a. the uppermost portion of the groundwater environment, extends from a few cm's to hundreds of meters.

(1) Zone contains mixture of moisture and air held in pore spaces by molecular attraction.

b. Much water flows downward through this zone into the underlying layer.

2. Zone of Saturation: or phreatic zone: zone below zone of aeration, in which all pore spaces, fractures and cracks are filled or saturated with water. (i.e. groundwater).

a. Water table: the top surface of the saturated zone, open to atmospheric pressure conditions via the vadose zone above.

b. Ground water flow: groundwater flows along permeable zones under the force of gravity, taking the path of least resistance. Ground water flows along porous paths from areas of higher water table elevation to areas of lower water table elevation.

c. Water table configuration: water table generally follows the surface topography of the land above, rising to higher elevations beneath hills, and lower elevations beneath valleys, generally water table deeper beneath hills, and coming closer to surface beneath valleys.

(1) intersection of water table with surface of the earth results in surface flow of water in form of springs or seeps, or perhaps manifested as a lake or swamp.

d. Pressure Relationships: the level of the water table is generally a surface of constant pressure or hydrologic head.

(1) A well dug to intersect the water table, will fill with water to the level of the water table, unless under some kind of hydrostatic pressure (artesian conditions)

(2) Groundwater Maps: elevations of top of water table can be mapped and contoured

i) Ground water elevations derived from measuring water levels in wells

ii) Hydraulic Gradient = rise/run or slope of water surface = (vertical difference/horizontal distance)

a) Groundwater flow generally parallel to lines of gradient (i.e. perpendicular to contour lines in downgradient direction under force of gravity)

(3) Cone of depression- if water is pumped from a well faster than it can be replaced, the level of the water table will be drawn down in the shape of an inverted cone.

B. Aquifer Types

1. Definitions

a. Aquifer: porous rock/sediment units that have a capacity to contain water, pores can be formed by openings between grains (primary porosity) or by cracks and fractures in the rocks (secondary porosity)

(1) Common Aquifers: unconsolidated sand and gravel, sandstone, dissolved/fractured limestone, lava flows, fractured crystalline rocks.

b. Aquiclude: Impermeable layers which will not transmit or store groundwater, tend to form the upper or lower boundaries of aquifers

c. Aquitard = "leaky" aquiclude: low permeability layers which transmit groundwater at very slow rates in both vertical and/or horizontal directions.
(1) More permeable than aquiclude

d. Aquifuge: effectively impermeable body of rock or unconsolidated material

2. Unconfined Aquifers: aquifers in vertical and hydraulic continuity with land surface.
a. Water Table Aquifers = Unconfined Aquifers

(1) Water of saturated zone in open contact with atmopheric pressures
(2) Water percolates through vadose zone to phreatic zone
(3) Capillary Zone: layer immediately above water table where water moves upward under high surface tension and capillary forces

3. Confined Aquifers: aquifers that are separated from atmospheric pressures by impermeable zones or confing layers (water not referred to as "water table")

a. Confined aquifer and artesian conditions, relative to hydrostatic pressure

(1) Potentiometric surface: analogous to water table, but is elevation of water of confined aquifer that rises to equilibrium in open well penetrating confined aquifer

(a) may contour elevations to form potentiometric contour map
i) confined aquifer groundwater flow generally perpendicular to contour of potentiometric surface.

(b) confined aquifers commonly under hydrostatic pressure in response to rock compaction and pore fluid pressures

b. Artesian Aquifer: identified as water in a well that rises under pressure above the saturated confined aquifer horizon

(1) Conditions of formation:
(a) confined aquifer between two impermeable layers
(b) exposure of aquifer to allow recharge/infiltration
(c) hydraulic flux into the aquifer from water cycle

c. Free-flowing artesian aquifer
(1) Artesian aquifer in which pressures are such that water freely flows out onto the ground surface.

d. Perched Aquifers: localized zone of upper level groundwater occurrence "perched" above a laterally discontinous aquitard.

(1) forms a localized occurrence of groundwater above regional water table system (hybrid of confined and unconfined systems)

C. Water Table and Potentiometric Surface Maps

1. From well water level records, contour maps of the water table (unconfined aquifer) or potentiometric surface (confined aquifer) can be constructed.

a. Data
(1) Elevations of surface measuring points at wells
(2) Depth to water from surface measuring point
(3) Surface El. - DTW = Water Elevation
(4) Plot elevations according to location on map
(5) Contour at appropriate contour interval

b. Resultant Information of Water Level Maps
(1) Geometric orientation of water table/pot. surface
(2) Hydraulic gradient perpendicular to contours
(3) Groundwater flow directions along hydraulic grad.
(4) "upgradient" and "downgradient" relationships

VII. Aquifer Characteristics

A. Transmissivity- measure of the amount of water that can be transmitted horizontally through an aquifer unit by the full saturated thickness of the aquifer under a hydraulic gradient of 1

$T = Kb$ T = Transmissivity, K = hydraulic Conductivity, b = saturated thickness of aquifer

Units T = L sq./T, b = L, K = L/T

B. Storativity = storage coefficient

1. Volume of water that a permeable unit will or absorb or expel from storage per unit surface area per unit change in head
a. a dimensionless ratio

C. Specific Storage = amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the mineral skeleton and the pore water per unit change in head.

** S.S. applied to both confined and unconfined aquifers**

** see equation sheet for details ***

S.S. = $pg(\alpha + n\beta)$ S.S. unit = m^{-1}

S.S. = specific storage
p = density of water (kg/m^3)
g = acceleration due to gravity (m/sec^2)
α = compressibility of aquifer skeleton (m^2/N) = volume change per unit force
n = porosity (decimal fraction)
β = beta = compressibility of the water (4.6×10^{-10} m^2/N) = volume change per unit force

D. Relationship of storativity to specific storage

1. Confined Aquifer

$S = b(S.S.)$ (units L/L = dimensionless)

where S = storativity, b = aquifer thickness (m), S.S. = specific storage (m^{-1})

2. Unconfined Aquifer

$S = S.Y. + h(S.S.)$

where S = storativity, S.Y. = specific yield, h = thickness of saturated zone (m), S.S. = specific storage (m^{-1})

** Since S.Y. is several orders of magnitude > h(S.S.) then for all practical purposes: S = S.Y. in unconfined aquifers**

3. Determination of the volume of water drained from an aquifer as head is lowered:

$V_L = SA(\Delta H)$

V_L = volume loss, S = storativity, A = surface area of aquifer drained (m^2), ΔH = Head Decline = drop in head or water level (m)

VIII. Homogeneity and Heterogeneity of the Aquifer

A. Homogeneous Hydraulic Unit

1. A homogeneous porous medium with uniform hydraulic properties in 3-dimensions (X,Y,Z)
   a. T, S, K of similar value vertically and horizontally in all directions
   b. e.g. uniform, porous sandstone of constant thickness

B. Heterogeneous Hydraulic Unit

1. A heterogeneous porous medium with non-uniform hydraulic properties (vary according to X,Y,Z directions)

2. T, S, K vary vertically and horizontally according to direction

a. e.g. fractured granite (can be quite complicated)

C. Directional Permeability Control

1. Isotropic Medium: intrinsic permeability same in all directions (3-D)

(1) Kv = Kh vertical and horizontal permeability equal

2. Anisotropic Medium: intrinsic permeability varies according to preferred orientations

(1) Kv not equal to Kh vertical and horizontal perm. not equal

IX. Groundwater and Environmental Concerns

A. Resource Development

1. Groundwater use for urban and domestic needs prevalent throughout North America

a. Residential use in rural areas off "plumbing grid" of public water supplies

b. Residential and Industrial use in arid and semi-arid portions of U.S.

(1) Groundwater useage very prevalent throughout the Mid-west and far-west.

B. Environmental Hazards

1. Groundwater Contamination

a. Industrial/Government Facilities

b. Sewage/bacteria

(1) Mining

(2) Landfills

2. Ground Subsidence and Subsurface Fluid Withdrawal

a. Extensive withdrawal of subsurface fluids

(1) groundwater

(2) Petroleum

b. Fluid withdrawal results in decrease in pore pressure, leading to subsidence of land areas under lithostatic pressure