

1 Introduction to Aquifer Testing

1.1 Notation

- Physical Properties

- Aquifer thickness, b
- Aquitard thickness, b'
- Aquifer porosity, $n = \frac{V_v}{V_b} = n_e + n_i$
 - * Volume of voids, V_v
 - * Bulk volume, V_b
 - * Aquifer effective porosity, n_e
 - * Immobile zone porosity, n_i
- Bulk density, $\rho_b = (1 - n) \rho_s$
- Skeletal density, $\rho_s = 2.65 \text{ g/cm}^3$
- Water content, $\theta = \frac{V_w}{V_v}$
- Relative saturation, $\Theta = \frac{\theta}{n} = \frac{V_w}{V_b}$

- Conductance Parameters

- Aquifer hydraulic conductivity, $K = k \frac{\gamma}{\mu}$
 - * Intrinsic permeability, $k \propto d^2$
 - * Pore diameter, d
 - * Fluid specific weight, $\gamma = \rho_w g = 9807 \text{ Pa/m}$
 - * Fluid density, $\rho_w = 1 \text{ g/cm}^3$
 - * Fluid dynamic viscosity, $\mu = 0.001 \text{ Pa} \cdot \text{s}$
- Aquifer transmissivity, $T = K_h b$
- Horizontal component of hydraulic conductivity, K_h
- Vertical component of hydraulic conductivity, K_v or K'
- Anisotropy ratio, $m = \frac{K_h}{K_v} = \frac{K}{K'}$
- Hydraulic conductance, $C = \frac{K_v}{b'} = \frac{K'}{b'}$
- Hydraulic resistance, $c = \frac{1}{C} = \frac{b'}{K'}$
- Aquitard leakance, $L = \sqrt{T} c = \sqrt{\frac{T}{C}} = \sqrt{\frac{K b b'}{K'}} = \sqrt{m b b'}$
- Hydraulic conductivity tensor, $\underline{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$

- Flow Parameters

- Hydraulic head, $h = z + \frac{p}{\gamma} + \frac{v^2}{2g}$
 - * Elevation, z
 - * Fluid pressure, p
 - * Fluid specific weight, $\gamma = \rho g$
 - * Fluid density, ρ
 - * Gravitational constant, $g = 9.807 \text{ m/s}^2$
- Hydraulic gradient vector, $\mathbf{i} = [i_x, i_y, i_z] = \text{grad}h = \left[\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}, \frac{\partial h}{\partial z} \right]$
- Fluid flux vector, $\mathbf{q} = \frac{Q}{A} = [q_x, q_y, q_z] = -\underline{K} \nabla h$
 - * Fluid flow, $Q = \frac{\Delta V_w}{\Delta t}$

* Cross sectional area, A

– Richards' equation, $q = -D \nabla \theta$

– Aquitard flux, $q' = -K' \frac{\Delta h}{b'} = -L \Delta h$

• Storage Parameters

– Specific storativity, $S_s = -\frac{\partial \theta}{\partial h} = -\frac{\partial \left[\frac{V_w}{V_b} \right]}{\partial h} = \frac{V_w}{V_b^2} \frac{\partial V_b}{\partial h} - \frac{1}{V_b} \frac{\partial V_w}{\partial h} = \frac{V_w}{V_b} \left[\frac{1}{V_b} \frac{\partial V_b}{\partial h} - \frac{1}{V_w} \frac{\partial V_w}{\partial h} \right] =$

$\gamma n (\beta_w - \beta_s) = \gamma (\alpha + n \beta_w)$

– Water compressibility, $\beta_w = -\frac{1}{V_w} \frac{\partial V_w}{\partial p} = 4.4 \times 10^{-10} Pa^{-1} = 5 \times 10^{-6} m^{-1}$

– Aquifer compressibility, $\alpha = -\frac{1}{V_b} \frac{\partial V_b}{\partial p}$

– Effective stress, p

– Bulk volume, V_b

– Skeletal compressibility, β_s

– Barometric efficiency, $BE = n/S_s$

– Tidal efficiency, $TE = 1 - BE$

– Aquifer storativity, $S = b S_s$

– Aquifer hydraulic diffusivity, $D = K/S_s = T/S$

– Specific yield, $S_y = b \frac{\partial \theta}{\partial h} = b \frac{\partial \theta}{\partial h}$

• Transport Parameters

– Solute effective dispersion coefficient, $D_e = D_o + \alpha v$

– Molecular diffusion coefficient, D_o

– Solute dispersivity, α

– Average fluid pore velocity, v

– Retardation factor, $R = 1 + \frac{\rho_b}{n} K_d$

– Distribution coefficient, K_d

– Cation exchange capacity, CEC

– Anion exchange capacity, AEC

– Organic carbon content, OC

– Specific surface area, S_a

– Sorption kinetic parameter, k

• Additional Aquifer Parameters

– Specific capacity, $C_p = Q/s$

– Pumping rate, Q

– Aquifer drawdown, s

– Recharge rate, R

– Deep percolation rate, DP

1.2 Definitions of Hydraulic Properties

- Anisotropic: hydraulic conductivity is different in different directions. We must represent the hydraulic conductivity, K , using a tensor
- Anisotropy ratio: Ratio of hydraulic conductivity in one principal direction to the hydraulic conductivity in another principal direction.
- Aquiclude: A geologic formation in which negligible fluid flow is possible
- Aquifer: A geologic formation that transmits appreciable quantities of water to a well
- Aquifer Compressibility: reciprocal of bulk modulus of elasticity of aquifer where is the effective stress. ranges from $10^{-6} Pa^{-1}$ for clays, to $10^{-10} Pa^{-1}$ for rock
- Aquitard or confining layer: geologic formation that resists the movement of water between two aquifers. The layer has material properties K' and b' to distinguish them from aquifer properties. Flow through a confining layer can be assumed to be vertical:
- Conductance: hydraulic conductivity of resistive layer (K') per unit thickness of the resisting layer (b'):
- Darcian flux: see flux
- Darcy's Law: relates hydraulic flux to hydraulic gradient and hydraulic conductivity
- Dimension of Flow:
 - Cartesian Flow: flux is different in each of the three cartesian directions
 - Planar Flow: flux is different in two directions, but zero in one cartesian direction
 - Linear Flow: flux is different in one cartesian direction, but zero in the other two
 - Radial or Cylindrical Flow: flux is planar, radiating inward or outward from a central axis.
 - Spherical Flow: flux is radiating uniformly in all three directions from a point
- Discharge: Water moving from the subsurface to the surface across the earth's surface
- Drawdown: water level decline due to pumping from well, where h_i is baseline (initial) water level before pumping and h is observed water level during aquifer test.
- Flux: Volume of water (V_w) flowing per unit area (A) per unit time (t)
- Homogeneous Media: K is a constant in space
- Hydraulic Resistance: the reciprocal of the conductance (C)
- Hydraulic conductivity: Measure of ability of geologic media to transmit water, related in a general way to pore size and shape:
 - C = constant of proportionality
 - d = median pore or grain size
 - γ specific weight of fluid used to measure total head
 - μ = water dynamic viscosity
- Hydraulic Diffusivity: ratio of hydraulic conductivity to specific storage, or, equivalently, of transmissivity to the storage coefficient
- Hydraulic Gradient: Change in total head per unit distance (h)
- Infiltration: Water passing across the earth's surface into the subsurface
- Isotropic: hydraulic conductivity is the same in all directions. It can be represented as a scalar

- Leakance, or Leakage factor
- Microporosity or matrix porosity: pores too small to see, such as voids between mineral grains or clay platelets.
- Macroporosity: visible pores, such as fractures, voids or vugs
- Nonlinear: K is not constant for all values of total head or fluid potentials
- Percolation: Water moving through the unsaturated zone
- Porosity: volume of voids (V_v) per unit bulk volume (V_b), ranging from 10^{-5} for dense granites to over 0.70 for volcanic tuffs.
- Precipitation: Water falling on the surface of the earth
- Recharge: Water moving across the water table from the unsaturated zone into the saturated zone
- Relative Saturation: Water content of material relative to saturated water content:
- Richards' Equation: relates hydraulic flux to change in volume of water in storage
- Specific Capacity: water discharge from well divided by amount of drawdown
- Specific Storage: A measure of the volume of water released (or added) to storage, per unit volume of aquifer, per unit increase (or decrease) in fluid pressure. It is the sum of the aquifer plus water compressibilities: where α is the fluid specific weight, β is the bulk compressibility, β_w is the compressibility of water, and $-\alpha n$ is the compressibility of the mineral skeleton.
- Specific Yield: volume of water released (or added) from an unconfined aquifer per unit area of aquifer per unit decline (rise) in water table position. Similar to the storage coefficient for confined aquifers.
- Storage Coefficient: water released from storage for a given thickness of aquifer (b).
- Storativity: Identical to the storage coefficient
- Total Head: sum of elevation, pressure, velocity, osmotic and other potentials
- Transmissivity: Total hydraulic conductivity for a given aquifer thickness
- Water Compressibility: reciprocal of bulk modulus of elasticity of water where p is the water pressure.
- Water Content: volume of water (V_w) per bulk volume of aquifer (V_b)

1.3 Common Errors

- DANGER #1: q and v are not the same!
 - q is specific flux (units of velocity)
 - v is groundwater velocity (units of velocity)
- DANGER #2: Darcy's Law is not always valid!
 - Darcy's law is only appropriate for laminar, and not turbulent flow, turbulent conditions arise in large voids (fractures, caves, etc.), and where velocities are high, such as near boreholes.
 - The Reynolds number helps to define the conditions for laminar flow d is void opening, is kinematic viscosity (approximately $10^{-6} \text{ m}^2/\text{s}$), R is the ratio of inertial to viscous forces.
 - When the inertial forces are too great, such as when $R > 1$, then flow can become turbulent.
 - For turbulent conditions, the flow rate varies with the square root of the gradient.
- DANGER #3: The Universal Confining Layer (by P. Stone):

An unrecognized protector of our ground water

There is a unique geological unit – economically critical, hydrologically essential, extremely widespread (ubiquitous among some investigated environments) – that amazingly has not been formally recognized and described as an interrelated unit, and not named according to the rules for stratigraphic nomenclature.

This unit, whose lithology and thickness varies among sites but is always highly impermeable, even when very thin, is found to lie atop the first "usable" drinking-water aquifer apparently virtually everywhere. Or, perhaps one should say, it is found in virtually every place where there has been some shallow stratigraphic and geo-hydrologic investigation that could reveal it; these of course being at sites where actual, or suspected, or potential, ground-water contamination has prompted such investigation. Surprisingly, this unit almost always perches some completely unconnected, sometimes ephemeral, always minor and inconsequential, zone or ground water atop it, that being the contaminated zone where present. Or else no water table whatsoever reportedly exists above the confining layer for the underlying aquifer in hydraulic nature even though it often occurs at an uncommonly shallow depth for such an aquifer.

This formation and confining layer is unique not only because of its near ubiquity among the widely scattered investigated sites, but because it encompasses various different geologic formations and, astoundingly, completely different geologic provinces also. What other geologic formation in the shallow subsurface encompasses both Appalachian Piedmont and Atlantic Coastal-Plain provinces, of vastly different ages and especially origins? Host materials range from soft sediments to residua from hard crystalline rocks (curiously, the same condition, if not the layer itself, is commonly reported for fractured hard-rock aquifers also). One might conjecture that this layer relates somehow to alluvial deposition, stream valleys certainly being one of the few depositional environments to span both Piedmont and Coastal-Plain geologic provinces. Or perhaps it is some unrecognized sub- "C" soil horizon or phenomenon, formed in-place. Will close examination of contamination-site investigations from other geologic provinces, in other parts of the country, reveal this same formation? Is it found still further afield, at least at sites where there is some exploratory interest able to find it?

The economic importance of this stratum cannot be overestimated. By universally isolating the uppermost "true" aquifer from the host of dangerous materials at the ground surface above, or especially those dissolved in the shallowest "perched" or "ephemeral" ground water so nearby above, the environmental Cleanup costs that are avoided, or deemed unnecessary, are astronomical in their cumulative total, and represent some very considerable sum at any given site also.

Other distinctive distributional characteristics include (I thank a colleague for this observation) the apparent tendency, judged from reported contaminant-plume geometry, for the confining unit to rise near property boundaries. Incidentally, I hope the identification of this physical mechanism lays to rest the suspicious sometimes voiced concerning the numerous ground-water contaminant plumes that seem never to migrate out from the responsible party's property to another's, ending

instead somewhere near the boundary. The averted costs in liabilities add another vast value to this unit.

One accepts as obvious that this geographic coincidence of property boundaries and contaminant plumes and their controlling stratigraphy cannot be random coincidence and that property lines themselves cannot influence the underground. Could there in any way be some nonapparent control made by the underground environment on the boundaries? At first glance, of course, this would seem to be impossible. But perhaps it involves unknowing influence on decisions in plating, somewhat like the suspected subconscious reading of subtle topographic and other surficial signs by "water witchers" who then truly believe that they feel the divining rod move as they pass over an underground "stream". What other reasonable explanation can there be for these fortuitously placed natural "liners", and even natural "slurry walls", containing the future spread of ground-water contaminants at the many sites that so desperately need them?

How did the extremely widespread occurrence of this single stratum, or at least an analogous stratigraphic sequence, escape geologic investigation's attention prior to the proliferation of contamination-site hydrologic investigation? Dare one put forth an outrageous hypothesis? Could some action of the contaminants themselves "create" this layer, say perhaps by somehow chemically reducing permeability. What other physical or cultural characteristic of ground-water contamination, or of such sites, might cause or explain this prevailing presence? This remains as grist for future research. In any case, if this important zone exists almost everywhere – and a host of apparently irrefutable professional sources have identified it at scores of sites – it should be recognized and named formally, as are all significant geologic units no matter how emplaced.

I have sought advice from colleagues regarding a descriptive or distinctive name for the layer or formation, with a diversity of suggestions received: From the artificial constructs "Nofurac" or "Commonly Formations" (no further action or continued monitoring only), to the Linnean binomial "Confinus Maximus", to the Victorian-era-sounding "The glorious [or "great" or "grand"] hydraulic impedance". My personal favorite, and therefore the winner, is the "Nocostus Aquitard", and thus it is given.