HYDROLOGY/WATER RESOURCES

NRCS (SCS) Rainfall-Runoff

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

$$S = \frac{1{,}000}{CN} - 10$$

$$CN = \frac{1{,}000}{S + 10}$$

P = precipitation (inches)

S = maximum basin retention (inches)

Q = runoff (inches)

CN = curve number

Rational Formula

$Q = CIA$, where

A = watershed area (acres)

C = runoff coefficient

I = rainfall intensity (in./hr)

Q = peak discharge (cfs)

Darcy's Law

$Q = -KA(dh/dx)$, where

Q = discharge rate (ft^3/sec or m^3/s)

K = hydraulic conductivity (ft/sec or m/s)

h = hydraulic head (ft or m)

A = cross-sectional area of flow (ft^2 or m^2)

$q = -K(dh/dx)$

q = specific discharge (also called Darcy velocity or superficial velocity)

$v = q/n = -K/n(dh/dx)$

v = average seepage velocity

n = effective porosity

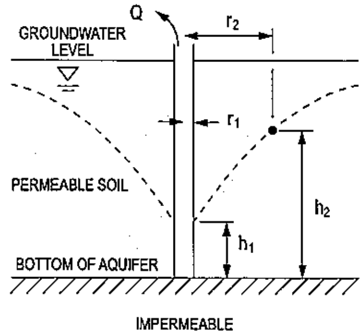
Unit hydrograph: The direct runoff hydrograph that would result from one unit of runoff occurring uniformly in space and time over a specified period of time.

Transmissivity, T: The product of hydraulic conductivity and thickness, b, of the aquifer (L^2T^{-1}).

Storativity or storage coefficient of an aquifer, S: The volume of water taken into or released from storage per unit surface area per unit change in potentiometric (piezometric) head.

Well Drawdown

Unconfined aquifer



Dupuit's Formula

$$Q = \frac{\pi k \left(h_2^2 - h_1^2\right)}{\ln\left(\frac{r_2}{r_1}\right)}$$

where

Q = flow rate of water drawn from well (cfs)

k = coefficient of permeability of soil (fps)

h_1 = height of water surface above bottom of aquifer at perimeter of well (ft)

h_2 = height of water surface above bottom of aquifer at distance r_2 from well centerline (ft)

r_1 = radius to water surface at perimeter of well, i.e., radius of well (ft)

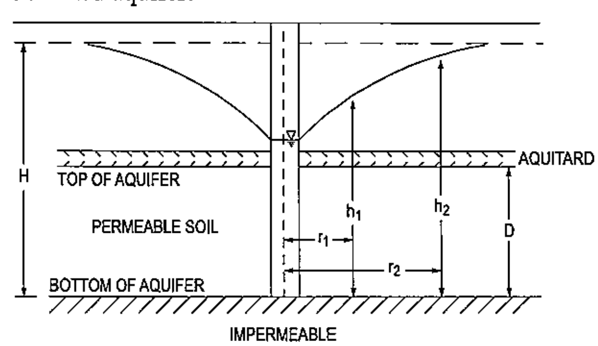
r_2 = radius to water surface whose height is h_2 above bottom of aquifer (ft)

ln = natural logarithm

Q/D_w = specific capacity

D_w = well drawdown (ft)

Confined aquifer:



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

where

T = KD = transmissivity (ft^2/sec)

D = thickness of confined aquifer (ft)

h_1, h_2 = heights of piezometric surface above bottom of aquifer (ft)

r_1, r_2 = radii from pumping well (ft)

ln = natural logarithm

GROUNDWATER FLOWS

- FLOWS IN PORES & FRACTURES OF AQUIFERS
- FLOW IS INDUCED BY HYDRAULIC GRADIENTS
- FLOW IS IN DIRECTION OF DECREASING HEAD, h,

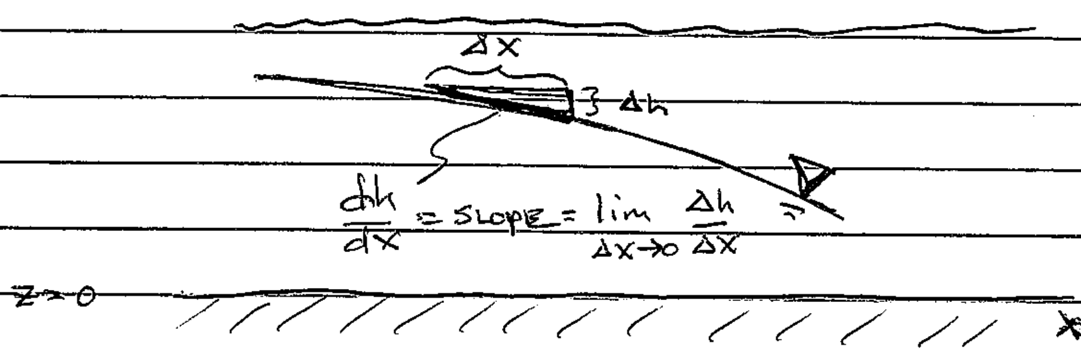
REMINDER: head = pressure head + elev.

$$h = \frac{P}{\rho g} + z$$

- FLOW VELOCITY IS PROPORTIONAL TO THE HYDRAULIC GRADIENT = $\frac{\text{CHANGE IN head}}{\text{CHANGE IN DISTANCE}}$

$$i_x = \frac{\Delta h}{\Delta x} = \frac{dh}{dx} = \frac{\partial h}{\partial x}$$

$$\vec{i_t} = i_x \vec{i} + i_y \vec{j} + i_z \vec{k}$$



$$\frac{dh}{dx} = \text{SLOPE} = \lim_{\Delta x \to 0} \frac{\Delta h}{\Delta x}$$

DARCY'S LAW REPRESENTS SPECIFIC DISCHARGE

LIMITATION: APPLIES FOR LAMINAR FLOW

$$\frac{\text{GROUNDWATER FLOW}}{\text{AREA PERPENDICULAR TO FLOW}} = \text{SPECIFIC DISCHARGE} \sim \text{DARCY VELOCITY}$$

$$q_x = \frac{Q}{A} = -K\frac{dh}{dx} = -K i_x$$

NOTE: THE NEGATIVE SIGN IS BECAUSE FLOW IS IN THE DIRECTION OF DECREASING HEAD (i.e., A NEGATIVE HYDRAULIC GRADIENT)

K ~ HYDRAULIC CONDUCTIVITY

$$K \equiv \underbrace{\left(\text{INTRINSIC PERMEABILITY}\right)}_{\text{PROPERTIES OF THE GEOLOGIC FORMATION}}\left(\text{FLUID PROPERTIES}\right)$$

$$K \equiv K_i \frac{\rho g}{\mu}$$

WHERE: ρ ~ MASS DENSITY OF THE FLUID

g ~ GRAVITATIONAL ACCELERATION

μ ~ DYNAMIC VISCOSITY OF THE FLUID

K_i ~ INTRINSIC PERMEABILITY

DIMENSIONS: $$\frac{\text{Length}}{\text{Time}} = (\text{Length})^2 \left(\frac{\frac{\text{MASS}}{\text{Length}^3} \cdot \frac{\text{Length}}{\text{Time}^2}}{\frac{\text{MASS}}{\text{Length} \cdot \text{Time}}}\right)$$

INTRINSIC PERMEABILITY, K_i (L^2)

MOST IMPORTANT PROPERTIES AFFECTING THE MAGNITUDE OF K_i INCLUDE

1) SIZES & NUMBERS OF PORES.
"PACKING" → 2) PORE SHAPE & "CONNECTEDNESS"
3) SURFACE TEXTURE.

$$K_i \propto (\text{diameter})^2$$

$\boxed{K_i \text{ MIGHT BE HIGHER FOR HIGHER } n\text{, BUT NOT NECESSARILY, e.g., CLAYS.}}$

"GENERAL" VALUES FOR d & K_i

MATERIAL	MEDIAN SIZE (cm)	K_i (cm^2)
FINE SAND	0.02 cm	10^{-8}
MEDIUM SAND	0.04 cm	10^{-7}
COARSE SAND	0.08 cm	10^{-6}

RANGES ARE ± 2 ORDERS OF MAGNITUDE!

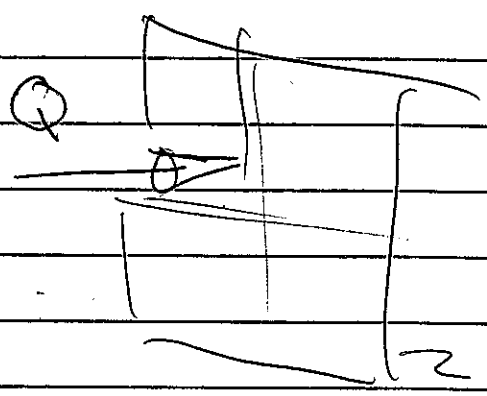
$\rho \approx 1\ g/cm^3$, $g = 981\ cm/s^2$,
& $\mu = 0.012\ g/cm \cdot s$

$$\therefore \quad K = \frac{10^{-7}\ cm^2 \cdot 1\ g/cm^3 \cdot 981\ cm/s^2}{0.012\ g/cm \cdot s} = 0.0082\ cm/s$$

SEEPAGE VELOCITY, v

USED FOR WATER SUPPLY (VOLUME) — q ~ DARCY VELOCITY OR SPECIFIC DISCHARGE
i.e, FLOW PER TOTAL AREA

OF INTEREST FOR CONTAMINANT TRANSPORT & GEOTECHNICAL PROBLEMS UNDER DAMS — v ~ AVERAGE PORE OR SEEPAGE VELOCITY, WHICH REFLECTS THE AVERAGE VELOCITY OF GROUNDWATER IN PORE SPACES.



PLANE ⊥ Q OF AREA A

$$Q = q\,A = n\,v\,A$$

n ↑ POROSITY

$$\therefore \quad q = n v \quad \text{or} \quad v = q/n$$

AQUIFERS: GEOLOGICAL FORMATIONS THAT ARE SATURATED WITH WATER

$$S, \text{ DEGREE OF SATURATION} \equiv \frac{\text{VOLUME OF WATER}}{\text{VOLUME OF VOIDS}}$$

"SATURATED" MEANS, $S \equiv 1$ (OR 100%)

$$n, \text{ POROSITY} \equiv \frac{\text{VOLUME OF VOIDS}}{\text{TOTAL (BULK) VOLUME}}$$

VOLUMETRIC WATER CONTENT, θ, WILL EQUAL POROSITY, n, WHEN THE DEGREE OF SATURATION IS 100% (SATURATED)

GROUNDWATER FLOW OCCURS IN PORES & FRACTURES

- UNCONSOLIDATED SYSTEMS ARE COMPOSED OF BROKEN ROCK PIECES & PORES ARE THE SPACES BETWEEN THE GRAINS/PIECES
- CONSOLIDATED SYSTEMS ARE WHOLE ROCK FORMATIONS & PORES CAN EXIST AMONG THE CEMENTED GRAINS THAT FORM ROCKS OR AS FRACTURES/CRACKS THAT SUBSEQUENTLY OCCUR AS A RESULT OF TECTONICS &/OR WEATHERING.

- UNCONSOLIDATED FORMATIONS ARE USUALLY MORE POROUS & MORE PERMEABLE (higher K) & DARCY'S LAW OFTEN APPLIES
- FLOWS IN MANY CONSOLIDATED FORMATIONS OCCURS PRIMARILY IN FRACTURES/CONDUITS & DARCY'S LAW OFTEN DOES NOT APPLY

WELL HYDRAULICS (IDEAL)

GOVERNING EQN FOR GWF FOR A CONFINED AQUIFER

$$K\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right) = S_s \frac{\partial h}{\partial t}$$

FOR A SINGLE WELL @ X=0, Y=0; THIS CAN BE REWRITTEN IN TERMS OF r, THE DISTANCE FROM THE CENTER OF THE PUMPING WELL:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t}$$

WHERE $S \equiv S_s b$

$T \equiv K \cdot b$

$b \sim$ AQUIFER THICKNESS

$S_s = \rho g(\alpha + n\beta)$

$\alpha \sim$ AQUIFER COMPRESSIBILITY

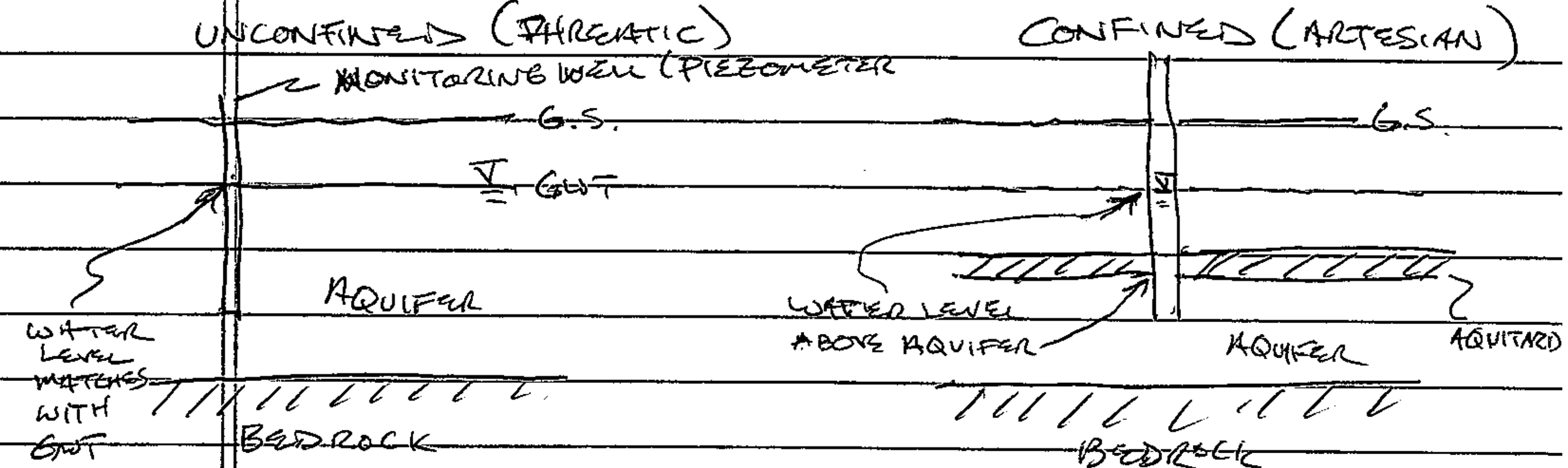
$\beta \sim$ FLUID (WATER) COMPRESSIBILITY

UNDER STEADY STATE CONDITIONS, ie, $\frac{\partial h}{\partial t} \equiv \emptyset$

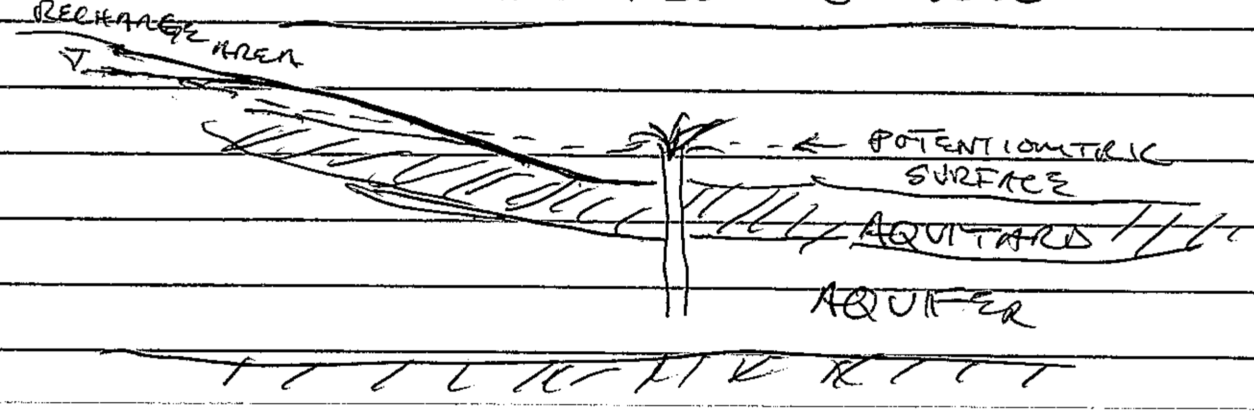
$$\frac{d^2 h}{dr^2} + \frac{1}{r}\frac{dh}{dr} = \emptyset$$

AQUIFER BEHAVIOR

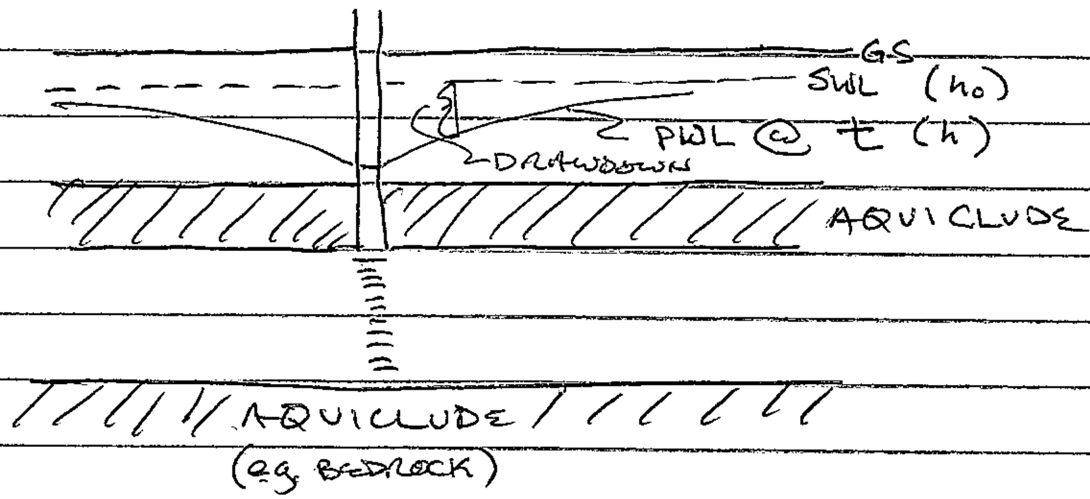
- UNCONFINED AQUIFERS HAVE A "FREE" WATER SURFACE OR GROUNDWATER TABLE, WHICH IS AT ATMOSPHERIC PRESSURE & BELOW WHICH THE PRESSURES ARE NORMALLY HYDROSTATIC
- CONFINED AQUIFERS ARE OVERPRESSURED & THE POTENTIOMETRIC SURFACE IS ABOVE THE TOP OF THE AQUIFER. THE TOP OF THE AQUIFER IS A CONFINING UNIT (AQUITARD OR AQUICLUDE)



SPECIAL CASE: FLOWING WELL



SOLUTIONS TO THE GWFE FOR A SINGLE PUMPING WELL IN A FULLY CONFINED AQUIFER



DRAWDOWN, s, $\equiv$ Δ POTENTIOMETRIC SURFACE FROM STATIC (UNPUMPED, INITIAL) LEVEL

$$s(r,t) \equiv h_0 - h(r,t)$$

ASSUMPTIONS

HOMOGENEOUS, ISOTROPIC PROPERTIES

NO BOUNDARIES, UNIFORM THICKNESS

CONSTANT PUMPING RATE

FULLY CONFINED, FULLY PENETRATING

FLAT SWL ($h(r,t=0)=h_0$)

SOLUTION: THEIS

$$s(r,t) = h_0 - h(r,t) = \frac{Q}{4\pi T} W(u)$$

WHERE: $u = \dfrac{r^2 S}{4Tt}$ $\quad \boxed{\begin{matrix} T = Kb \\ S = S_s b \end{matrix}}$

$$\text{FOR } u \leq 1: \quad W(u) \equiv -0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} \ldots$$

(UNITS!)

COOPER - JACOB APPROXIMATION: $u \leq 0.05$ (SAY)

$$s(r,t) = h_0 - h(r,t) \cong \frac{Q}{4\pi T}\left[-0.5722 - \ln u\right]$$

$$= \frac{2.303\,Q}{4\pi T}\log\left(\frac{2.25\,Tt}{r^2 S}\right) \quad (\text{error} \leq u \cdot 100\%)$$

$u \downarrow$ AS $t \uparrow$ OR AS $r \downarrow$

THEIS

$$s(r,t) = \frac{Q}{4\pi T}W(u)$$

NEED TABLE OR GRAPH OF "WELL" FUNCTION

VALID FOR ALL t

~~AS~~

COOPER - JACOB

$$s(r,t) = \frac{2.3\,Q}{4\pi T}\log\left(\frac{2.25\,Tt}{r^2 S}\right)$$

ERROR DIMINISHES AS $t \uparrow$ (or $r \downarrow$)

~~eg $Q = 10\ m^3/min$~~

EXAMPLE: FULLY CONFINED AQUIFER PUMPED @ $1\ m^3/min$

GIVEN:

POROSITY, $n = 0.20$

AQUIFER THICKNESS, $b = 10\ m$

AQUIFER COMPRESSIBILITY, $\alpha = 10^{-8}\ m^2/N$

WATER COMPRESSIBILITY, $\beta = 4.6(10^{-10})\ m^2/N$

INTRINSIC PERMEABILITY, $K_i = 10^{-7}\ cm^2 = 10^{-11}\ m^2$

WATER DENSITY, $\rho = 1\ g/cm^3 = 1000\ kg/m^3$

WATER VISCOSITY, $\mu = 0.012\ g/cm\cdot s = 0.0012\ kg/m\cdot s$

$g = 9.81\ m/s^2$

FLOW RATE, $Q = 1\ m^3/min$

CALCULATE: T, S, $s(r,t)$ @ $r = 100\ m$, $t = 1000\ min$

$$T \equiv K \cdot b, \quad K \equiv \frac{K_i \rho g}{\mu} = \frac{10^{-11} m^2 \cdot 1000 \frac{kg}{m^3} \cdot 9.8\ m/s^2}{0.0012\ kg/m\cdot s}$$

$$K = 8.2(10^{-5})\ m/s = 0.00495\ m/min$$

$$\therefore T = 0.00495 \frac{m}{min} \cdot 10\ m = 0.0495 \frac{m^2}{min} \approx 0.05 \frac{m^2}{min}$$

$$S \equiv S_s b, \quad S_s \equiv \rho g(\alpha + n\beta) = 1000 \frac{kg}{m^3} \cdot 9.81 \frac{m}{s^2}\left(10^{-8} \frac{m^2}{N} + 0.2 \cdot 4.6(10^{-10}) \frac{m^2}{N}\right)$$

$$S_s = 9.9(10^{-5})\ m^{-1}$$

$$\therefore S = 9.9(10^{-5})\ m^{-1} \cdot 10\ m = 0.00099 \cong 0.001$$

$$u = \frac{r^2 S}{4Tt} = \frac{(100\ m)^2\ 0.001}{4 \cdot 0.05 \frac{m^2}{min} \cdot 1000\ min} = 0.0495 \cong 0.05$$

EXAMPLE CONTINUED

THEIS APPROACH:

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + \ldots$$

$$= -0.5772 - \ln 0.05 + 0.05 - \frac{(0.05)^2}{2 \cdot 2 \cdot 1} + \frac{(0.05)^3}{3 \cdot 3 \cdot 2 \cdot 1} - \ldots$$

$$= -0.5772 + 3.0058 + 0.05 - 6.2(10^{-4}) + 3.5(10^{-6}) - \ldots$$

$$= 2.478$$

$$\therefore \quad s(r = 100\,m, t = 1000\,min) = \frac{1\,m^3/min}{4\pi\, 0.05\,\frac{m^2}{min}} \cdot 2.478 = 3.98\,m$$

COOPER JACOB APPROXIMATION:

$$s(r=100, t=1000) = \frac{2.303 \cdot 10}{4\pi\, 0.05} \log\left(\frac{2.25 \cdot 0.05 \cdot 1000}{(100)^2 \cdot 0.001}\right)$$

$$= 3.85\,m \quad (\text{error from THEIS} \sim 3\%)$$

SPECIAL CONDITION: STEADY STATE (EQUILIBRIUM)

IN ADDITION TO THE ASSUMPTIONS FOR THE THEIS SOLUTION (i.e., IDEAL AQUIFER & PUMPING CONDITIONS), ASSUME THAT THE POTENTIOMETRIC SURFACE HAS STABILIZED. IN THIS CASE, THE THIEM SOLUTION APPLIES, WHICH COMES FROM INTEGRATING DARCY'S LAW FOR AXISYMMETRIC FLOW TO THE PUMPING WELL

$$\frac{Q}{A} = \frac{Q}{2\pi r \cdot b} = K \frac{dh}{dr}$$

WHICH YIELDS:

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

TO USE THIS SOLUTION, MUST BE GIVEN VALUES OF h_2 @ r_2, Q, & T.

SAY THAT ONE KNOWS r_0, h_0, THEN

$$s(r) = h_0 - h(r) = \frac{Q}{2\pi T} \ln \frac{r_0}{r}$$

FOR THE PW, $r = r_w$, $\therefore$ $s_w = \frac{Q}{2\pi T} \ln \frac{r_0}{r_w}$

SPECIFIC CAPACITY, $Q/s_w = \frac{2\pi T}{\ln (r_0/r_w)}$

APPLICATION OF THIEM SOLUTION TO AN UNCONFINED AQUIFER:

DARCY'S LAW: $\frac{Q}{A} = \frac{Q}{2\pi r h} = K \frac{dh}{dr}$

WHICH YIELDS:

$$h_2^2 - h_1^2 = \frac{Q}{\pi K} \ln \frac{r_2}{r_1} \quad \text{(DUPUIT FORMULA)}$$

SPECIAL CASE FOR A PUMPING WELL:

$r_0 \sim$ DISTANCE WHERE PUMPING IS NOT "FELT"

i.e., $h_2 = h_0$ @ $r_2 = r_0$

DRAWDOWN IN PW, $s_w \equiv h_0 - h_w$, h_w @ $r = r_w$

$$h_0^2 - h_w^2 = \frac{Q}{\pi K} \ln \frac{r_0}{r_w}$$

$$h_w = \sqrt{h_0^2 - \frac{Q}{\pi K} \ln \frac{r_0}{r_w}}$$

$$s_w = h_0 - h_w = h_0 - \sqrt{h_0^2 - \frac{Q}{\pi K} \ln \frac{r_0}{r_w}}$$

EXAMPLE OF STEADY STATE WELL HYDRAULICS:

GIVEN:

$b = 10\,m$ (CONFINED)

$h_o = 10\,m$ (UNCONFINED)

$r_o = 1000\,m$

$K = 0.05\,m/min \Rightarrow T = Kb = 0.05\,m/min \cdot 10\,m = 0.5\,m^2/min$

$r_w = 0.25\,m$

$Q = 1.0\,m^3/min$

CALCULATE: SPECIFIC CAPACITY $\left(Q/s_w\right)$ FOR CONFINED & UNCONFINED

CONFINED: $s_w = \dfrac{Q}{2\pi T} \ln \dfrac{r_o}{r_w} = \dfrac{1\,m^3/min}{2\pi\,0.5\,m^2/min} \ln \dfrac{1000\,m}{0.25\,m} = 2.64\,m$

$\therefore \dfrac{Q}{s_w} = \dfrac{1.0\,m^3/min}{2.64\,m} = \dfrac{0.379\,m^3/min}{m} = \dfrac{380\,lpm}{m}$

NOTE: FOR CONFINED AQUIFER, $\dfrac{Q}{s_w} = \text{CONSTANT} = \dfrac{2\pi T}{\ln r_o/r_w}$

UNCONFINED: $h_o^2 - h_w^2 = \dfrac{Q}{\pi K} \ln \dfrac{r_o}{r_w} = \dfrac{1\,m^3/min}{\pi\,0.05\,m/min} \ln \dfrac{1000\,m}{0.25\,m} = 52.8\,m^2$

$h_w = \sqrt{h_o^2 - 52.8\,m^2} = \sqrt{(10\,m)^2 - 52.8\,m^2} = 6.87\,m$

& $s_w = h_o - h_w = 10\,m - 6.87\,m = 3.13\,m$

$\therefore Q/s_w = \dfrac{1\,m^3/min}{3.13\,m} = \dfrac{0.320\,m^3/min}{m} = \dfrac{320\,lpm}{m}$

SOIL & GROUNDWATER REMEDIATION

CONTAMINANT PHASES:

1) PURE ~ "NEAT" OR "FREE" OR "NONAQUEOUS"
(e.g., GASOLINE OR FUEL OIL)
2) DISSOLVED OR AQUEOUS
3) VAPOR OR GASEOUS (FOR VOLATILE CONTAMINANTS)
4) SORBED

SITES THAT POSE A THREAT TO PEOPLE, EITHER BECAUSE CONCENTRATIONS EXCEED DRINKING WATER STANDARDS (MCLs ~ MAX CONTAMINANT LEVELS) OR OTHER EXPOSURES (e.g., CONTACT, INHALATION, etc.), OR TO THE ENVIRONMENT, SUCH AS DISCHARGE TO SURFACE WATER, MUST UNDERGO CORRECTIVE ACTION (REMEDIATION OR "PLUME CONTROL")

PLUMES CAN BE CAPTURED ("PUMP & TREAT")
SOURCE ZONES CAN BE CLEANED UP (SOURCE CONTROL) USING FLUSHING OR ENHANCED FLUSHING TECHNIQUES &/OR CHEMICAL TREATMENT (e.g., ADVANCED OXIDATION) & BIOREMEDIATION.