Well Hydraulics

I. Introduction
  A. The Well
    1. hydraulic structure utilized to access water-bearing aquifers

    2. Well is in direct hydraulic communication with aquifer conditions
      a. Allows estimation of aquifer hydraulic properties
      b. Provides direct access to ground water conditions
        (1) Sampling
        (2) Testing
        (3) Resource Extraction
        (4) Environmental Restoration

II. Well Hydraulics

  A. Process: ground water flow to well from aquifer system
    1. Controls
      a. Hydraulic Properties of Aquifer
        (1) Hydraulic Conductivity, Permeability
        (2) Transmissivity
        (3) Storativity
        (4) Hydraulic Gradient

      b. Design and construction of well assembly
        (1) Materials
        (2) Screen Depth
        (3) Hydrogeologic Conditions

    2. Well response a function of aquifer properties
      a. Character of well directly related to aquifer properties
      b. Aquifer testing and characterization conducted utilizing the "well"
        (1) Mathematical derivation of well/aquifer response models

    3. Complicating Factors To Aquifer Characterization
      a. Complex mathematical models that are not applicable to actual conditions
        (1) False (but necessary) base assumptions

      b. Complex geologic and hydrologic conditions
        (1) Multiple variable systems,
        (2) Spatial and temporal differential processes

          (a) Unsolvable with simplified mathematical models
          (b) Analytical solutions virtually unobtainable for some complex and variable hydrogeologic conditions

            i) Necessity: simplification and assumption
  B. Definition of Terms

1. Static Water Level (SWL)

    a. Equilibrium level of water in well (confined or unconfined aquifer) when no water is being removed from the aquifer via pumping or free flow

    b. Common expression: depth to water from surface measuring point
        (1) Artesian well: depth of water level above surface

    c. SWL in well at equilibrium with aquifer is a reflection of the total hydraulic head of the water table (unconfined) or potentiometric surface (confined)

2. Pumping Water Level (PWL)

    a. Level at which water stands in a well when pumping/removal is in progress
    b. aka "dynamic water level"

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.

4. Drawdown = (SWL - PWL) = s

    a. Length difference between the SWL (water table or potentiometric) and the PWL

    b. Head difference (drawdown) represents the force potential of aquifer that causes water to flow from the aquifer to the well at the rate of pumping/extraction

        (1) s < as force potential > (and vice versa)

    c. Unconfined/Water Table

        (1) head = actual water level on water table along the drawdown curve
        (2) Saturated thickness of aquifer decreases

    d. Confined/Potentiometric

        (1) Drawdown represents the pressure head at that point, as a sum of the aquifer force potential and the pumping interaction of the well
        (2) Saturated thickness of aquifer is not affected, on the potentiometric surface

5. Drawdown Curve
    a. Shape of depressed potentiometric surface/water table in 3-D

6. Residual Drawdown (Recovery Curve)
    a. After pumping ceases, water levels will recover in well as well equilibrates with natural aquifer conditions

    b. Residual Drawdown = (SWL - Recovery Level)

7. Falling Head Conditions
    a. Active pumping and drawdown in well

8. Rising Head Conditions
    a. Recovery of well and aquifer following cessation of pumping

9. Well Yield
    a. Volume of water per unit time discharged from a well by pumping or free flow

        (1) Units of discharge: Gallons/Minute or m^3/day

10. Specific Capacity
    a. S.C. = (Yield/Drawdown)
    b. Units: GPM/Ft or cu. m/day/m

11. Pumping Well
    a. Active pumping of well/extraction of ground water
    b. Active drawdown measuring point

12. Observation Well
    a. Well that is nearby pumping well, but is no actively undergoing pump/removal
    b. Passive drawdown measuring point

13. Unsteady Radial Flow = "Transient Flow Conditions"
    a. Flow to pumping well is unsteady, the head of the drawdown curve changes with time

    b. Flow to well assumed to be radial, equal flow from all directions, isotropic/homogeneous aquifer conditions

14. Steady Radial Flow = "Steady State Flow Conditions"
    a. Flow to pumping well is steady, the head and cone of depression are at equilibrium between pumping rate and aquifer properties

    b. Flow to well assumed to be radial, equal flow from all directions, isotropic/homogeneous aquifer conditions

C. Nature of Converging Flow (on a well)

1. Well Flow and Drawdown
    - a. Pump removes water from well
    - b. Zone of low pressure develops near well bore
    - c. Water flow from higher pressure aquifer to lower pressure well zone
    - d. Force Potential = Head
        - (1) Head difference outside well vs. inside well

    - e. Zone of influence

        - (1) Distance r away from well where pumping influence (drawdown) is negligible

        - (2) controls on Zone of Influence
            - (a) Pumping/Discharge Rate
            - (b) Hydraulic Conductivity/Transmissivity of Aquifer
            - (c) Storage Coefficient of Well

2. Unconfined vs. Confined Aquifers
    - a. Unconfined Aquifers
        - (1) Drawdown of water table and saturated zone of aquifer

    - b. Confined Aquifers
        - (1) Saturated zone of aquifer generally not affected
        - (2) Potentiometric surface is lowered (reduced head)

3. Radial Converging Flow

    - a. Under isotropic, homogeneous aquifer conditions ...
        - (1) Ground water will flow radially towards the pumping well from all directions

    - b. Darcy's Law and Cone of Depression
        - (1) As grad h >, velocity of flow >
        - (2) Cone of depression: grad h > in close proximity to well

            - (a) r = radius of influence

                - i) horizontal distance from the center of a well to the limit of the cone of depression

    - c. Controls on Shape of Cone of Depression
        - (1) Pumping rate
        - (2) Pumping duration
        - (3) Hydraulic Gradient
        - (4) Recharge from aquifer to well

(5) Aquifer Properties (K, T, S)

(a) S - Coefficient of Storage

i) Volume of water released from storage or taken into storage, per unit of aquifer storage area, per unit change in head

ii) Range in S
Unconfined Aquifers: 0.01-0.3
Confined Aquifers: 10^{-5} to 10^{-3}

(b) T - Coefficient of Transmissivity

i) Rate of water flow through vertical strip of aquifer 1 ft wide, through the full saturated thickness of the aquifer, under a hydraulic gradient of 1

$T = Kb$

where K = horizontal hydraulic conductivity, b = saturated thickness

ii) Range in T

<1000 GPD/Ft = domestic wells, low-yield wells
>10,000 GPD/Ft = industrial/agricultural production wells

** T = how much water will move through the formation; S = how much water can be removed by pumping or draining of the aquifer

(6) Examples of Influence on Cone of Depression

(a) High Transmissivity (High permeability)
i) Flattened cone of depression
ii) Drawdown at minimum

(b) Low Transmissivity (Low Permeability)
i) Steepened cone of depression
ii) Drawdown at a maximum at well

** moral of story: a steeper gradient is needed to move water at a given discharge through a less permeable aquifer relative to a more permeable aquifer (a la Darcy's Law)

d. Head Loss

(1) A change in head is needed to stimulate ground water flow to a well
(2) Measure of force required to overcome resistance to flow through porous medium

4. Dynamics of the Cone of Depression

   a. Pump on in well
   b. Initial discharge derived from well storage and immediate aquifer in vicinity of well
   c. Radius of influence and drawdown increases with distance away from well as pumping continues

      (1) expanding cone of depression
      (2) drawdown increases gradient, increases flow to well

   d. With > time, expansion of R and s < exponentially
      (1) > water volume available with > R

   e. Stabilization of Cone of Depression

      (1) Cone intercepts enough aquifer flow to equal pumping rate (equilibrium of cone with pumping rate)
      (2) Cone intercepts body of surface water
      (3) R > to point where vertical recharge = pumping rate
      (4) R > to point where vertical leakage = pumping rate

   f. Rate of drawdown and R expansion exponentially decays with time as pumping system approaches equilibrium with aquifer conditions
      (1) conditions vary for equilibrium: hours, days, never?

D. Basic Well Equations (Models of Flow to Wells)

1. Introduction
   a. Given pumping rate, T and S; drawdown conditions can be derived:
      (1) Drawdown in aquifer at distance r from pumping well
      (2) Drawdown in well at any time t after pumping begins
      (3) Interference patterns for multiple pumping wells
      (4) Efficiency of intake for a production well

$$\text{Well Efficiency} = \frac{\text{Rate of Well Delivery}}{\text{Rate of Aquifer Delivery Potential}} \times 100\ \%$$

      (5) Degree of drawdown in the aquifer at various pumping rates

   b. Well equations as tools for hydrogeologist
      (1) Well represents "window" to the aquifer system, basic analytical tool
      (2) Flow Equation Applications (in practical terms)

         (a) Given aquifer properties (T, K, S), solutions can be used to determine the predicted drawdown of the potentiometric surface or water table near a pumping well at distance r from the pumping well

(b) Given the drawdown characteristics of a "pumping test" on an aquifer, then unknown aquifer properties (T, K, S) can be estimated.

c. A number of equations have been derived to describe the flow of water to wells using integral calculus

(1) Application of Darcy's Law to ground water flow to a pumping well

2. Thiem Equation: Equilibrium Well Equation

a. Base Assumptions

(1) Radial flow to well, equal volume from all directions
(2) Pumping discharge rate is constant
(3) Drawdown, radius of influence, cone of depression at at equilibrium (static)
(4) Well is 100% efficient in extracting water
(5) Well fully penetrates the aquifer
(6) Water table or potentiometric surface has 0 slope initially
(7) Laminar flow conditions (low Reynolds No.) prevail

** although in reality assumptions not true, for all practical purposes they are "in the ballpark" **

b. Thiem Equation for Unconfined Aquifer

(Equation) English SI

$$Q = \frac{K\left(H^2 - h^2\right)}{1055 \, \mathrm{LOG}\left(R/r\right)} \qquad Q = \frac{1.36K\left(H^2 - h^2\right)}{\mathrm{LOG}\left(R/r\right)}$$

$$\left.\begin{array}{ll} Q = (L^3/t) & h = (L) \\ K = (L/t) & R = (L) \\ H = (L) & r = (L) \end{array}\right\} \text{DIMENSIONAL ANALYSIS}$$

Where Q = pumping rate/discharge, K = hydraulic conductivity, H = distance of SWL from base of aquifer, h = distance of static PWL from base of aquifer, R = radius of cone of depression at maximum extent from well, r = radius of well bore.

c. Thiem Equation for Confined Aquifers

(Equation) English SI

$$Q = \frac{Kb(H-h)}{528\ \mathrm{Log}(R/r)} \qquad Q = \frac{2.73\,Kb(H-h)}{\mathrm{Log}(R/r)}$$

$b = (L)$

Symbols same as above, except b = thickness of aquifer

3. Theis Equation: Nonequilibrium Well Equation for Confined Aquifers

a. Base Assumptions

(1) Aquifer isotropic, homogeneous (Ky=Kx=Kz)
(2) Aquifer of uniform thickness and infinite in extent
(3) Closed system with no recharge to aquifer (confined)
(4) Well fully penetrates saturated thickness of aquifer
(5) Water instantaneously released from storage in aquifer
(6) Well 100% efficient
(7) Laminar flow conditions (low Re No.)
(8) Water table/potentiometric surface = 0 slope initially
(9) Water levels, drawdown, cone of depression NOT stable (not at equilibrium)
(10) Well discharge is at constant rate

(Equation) English SI

$$S^{*} = \frac{114.6\,Q\,(W(u))}{T} \qquad S^{*} = \frac{1}{4\pi}\,\frac{Q}{T}\,W(u)$$

$S^{*} = (L)$
$Q = (L^3/t)$
$T = (L^2/t)$
$r = (L)$
$S' =$ DIMENSIONLESS

W(u) = Well FUNCTION

ENGLISH SI

$$\mu = \frac{1.87\,r^2 S'}{Tt} \qquad \mu = \frac{r^2 S'}{4Tt}$$

$S' =$ STORATIVITY t = time since pumping began

where s^{*} = drawdown, Q = pumping rate, T = transmissivity, W(u) = well function of u

where s = drawdown, Q = pumping rate, T = transmissivity, W(u) = well function of u (exponential integral of u derived from W(u) tables), r = distance of observation point from pumping well, S = storage coefficient, t = time since pumping began.

4. Cooper and Jacob Method: Modified Theis Equation (simplified version)

   a. Assumption: t is sufficiently large and r is sufficiently small, replaces W(u) exponential integral function by the logarithmic function

      (1) Replacement of W(u) makes equation easier to work with in field applications

(Equation)	English	SI
	$S^{*} = \frac{264Q}{T} \log\left(\frac{0.3Tt}{r^2S'}\right)$	$S^{*} = \frac{0.183Q}{T} \log\left(\frac{2.25Tt}{r^2S'}\right)$

Where s = drawdown at r distance from pumping well, Q = discharge of pumping well, T = transmissivity of aquifer, t = time since pumping began, r = distance of observation point from pumping well, S = coefficient of storage of aquifer

E. Modification of Basic Well Equations (Variations on the Theme)

1. Flow in a leaky confined aquifer

   a. Adds a term to the Theis non-equilibrium equation to account for vertical leakage through the confining layer

      (1) Adds a Kz term for aquitard
      (2) Hantush-Jacob method

2. Flow to well that only partially penetrates aquifer

   a. Screen or well boring does not fully penetrate the saturated thickness of the aquifer

   b. Uniform radial flow to aquifer modified from horizontal
   c. Base equations modified to account for reduced efficiency of flow from aquifer to well

      (1) Hantush Partial Penetration Method
      (2) Modifies drawdown-transmissivity relationships

III. Aquifer Testing Methods

A. Pump Tests

1. Use and applications
    - a. To determine performance characteristics of a well
    - b. To determine the hydraulic parameters of an aquifer

        - (1) T,K,S

2. Well Performance Tests
    - a. Pump from well at certain discharge level
    - b. Drawdown and yield monitored to derive specific capacity of well
        - (1) S.C. = yield/drawdown

    - c. Used to size pump relative to production capacity of well

3. Aquifer Testing/Characterization
    - a. To derive transmissivity and storage coefficient of aquifer
    - b. Predict the effets of withdrawls on existing wells (cone of depression)
    - c. Predict drawdowns in well at future discharge use levels
    - d. Predict the radius of the cone of depression at a given pumping rate

4. Aqufer Test Parameters
    - a. Pumping Well

        - (1) SWL at time 0
        - (2) Pump discharge rate
        - (3) drawdown/dynamic pumping levels
        - (4) time since pumping began
        - (5) Time pumping stopped
        - (6) Recovery/residual drawdown levels

    - b. Observation Well(s)

        - (1) Recording drawdown at observation wells
        - (2) time since pumping began
        - (3) Distance(s) of observation well(s) from pumping well
        - (4) Drawdown of observation well
        - (5) SWL at time 0
        - (6) Time pumping stopped
        - (7) Recovery/residual drawdown levels

    - c. Other Data
        - (1) Radius of pumping and observation well assemblies
            - (a) borehole/casing diameter

- (2) Hydrogeologic Data
    - (a) Geologic Log
    - (b) aquifer thickness
        - i) top, bottom of aquifer
    - (c) Well position with respect to aquifer
        - i) fully penetrating saturated thickness
        - ii) partially penetrating saturated thickness
    - (d) Confined vs. unconfined aquifer?

- d. Aquifer Test Types
    - (1) Constant-rate test
        - (a) pumping well is pumped for significant length of time at one discharge rate
        - (b) Duration: typically on order of 72 hours or more

            - i) to allow aquifer to come to equilibrium with well assembly

    - (2) Step-drawdown test
        - (a) Pumping well is pumped at successively greater discharges for relatively short duration intervals

    - (3) Single-Well Pump Tests (Pumping well only)
        - (a) Pumping and drawdown information recorded.

        - (b) Aquifer Analysis: Only transmissivity and specific capacity of well can be calculated with a single well test (not Storativity or geometry of cone of depression)

    - (4) Multiple well pump tests (pumping + observation wells)
        - (a) Aquifer analysis: transmissivity, specific capacity (pumping well), storativity, and 3-D geometry of cone of depression can be calculated.

5. Conducting Aquifer Tests
    - a. Conduct preliminary pump evaluation to predict anticipated drawdown-response behavior

        - (1) Are observation wells spaced close enough to detect drawdown??

    - b. Test Protocol
        - (1) Maintain constant yield during test
            - (a) provide accurate measuring method of discharge
                - i) weirs, flumes, volume collection
        - (2) Measuring drawdown/water levels in wells
            - (a) hand measuring devices (M-scope, electronic water level indicator)
            - (b) Pressure transducer + data logger

(3) Track drawdown readings a appropriate time intervals

- (a) well drawdown follows an exponential decay function
  - i) rapid drawdown at first
  - ii) slower rate of drawdown as cone of depression approaches equilibrium with discharge rate

(b) Recommended time intervals for data collection in pumping well

Time Since Pumping Started (Min)	Time intervals between readings (Min)
0-10	0.5-1
10-15	1
15-60	5
60-300	30
300-1440	60
1440-end	480 (8 hr)

(c) Recommeded time intervals for data collection in observation well

Time Since Pumping Started (Min)	Time intervals between readings (Min)
0-10	0.5-1
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60-300	30
300-1440	60
1440-end	480 (8 hr)

** Ideally pump test continued until equilibrium conditions are attained

(4) Corrections for atmospheric pressures, stream levels, tidal oscillations?

(5) Follow-up well recovery levels to corroborate pumping data
- (a) Recovery data recorded at time intervals similar to pumping/drawdown until wells have recovered to within 90% of original level

(6) Duration Recommended
- (a) Confined aquifer: 24 hours
- (b) Unconfined aquifer: 72 hours

c. Data Analaysis

(1) Graphical Plots: Semi-log plots of Drawdown vs. Time Since Pumping Began

(a) Y-axis: arithmetic scale of drawdown in feet
(b) X-axis: logrithmic scale of time since pumping began (Min)

0 +

10 +
Drawdown
(Ft) 20 +

30 +

40 + + + + +
1 10 100 1000 10,000

Time Since Pumping Began (Min)

x-axis log scaled in powers of ten, one power of 10 = 1 log cycle
(2) Graphical Plots: Semi-log plots of Drawdown (Ft) vs. Distance (Ft)

0 +

10 +
Drawdown
(Ft) 20 +

30 +

40 + + + + +
1 10 100 1000 10,000

Distance from Pumping Well (Ft)

(3) Graphical Plots: Theis Curve-Matching Solution Method: Log-Log Plot of Drawdown (Ft) vs. Time (Min)
(a) both x and y axis on log scale

standard 3 x 5 log cycle graph

100. +
Drawdown
(Ft) 10.0 +

1.0 +

0.1 + + + + +
0.1 1.0 10.0 100.0 1000.0

Distance from Pumping Well (Ft)

** graphical plots can be made easily using EXCEL graphing function, EXCEL will generate logrithmic and arithmetic plots, use the "graph" command tool. Specify x-axis data and y-axis data by column, and then select "axis type" (log or arithmetic) for each.

B. Slug Tests

1. Pump Tests: Disadvantages
    a. Multiple wells needed (expense of installation and testing)
    b. If water is contaminated:
        (1) High volume discharge, must dispose (expensive)

    c. Low permeability aquifers

        (1) aquifers that store and transmit water, but at slow rates
        (2) Pump tests may not be feasible, wells may be pumped dry immediately even at low discharge

    d. Small diameter monitoring wells
        (1) Large D wells expensive to install
        (2) Environmental applications commonly use small D wells (less expensive)
        (3) Small D wells have limits to pumps and rates that can be used

2. "Slug or Bail Down Tests"

    a. Alternative to pump test
    b. may be conducted on single well
    c. useful in low permeability conditions
    d. effective in small diameter monitoring wells
    e. May be used to estimate the T, S, and K of the aquifer in the immediate vicinity of the well

        (1) Disadvantage: not effective in aquifers with high transimissivity and rapid well recovery

3. Basic Technique

    a. Known volume of water (slug) is instantaneously added to or withdrawn from a monitoring well
        (1) Well hydraulics taken out of equilibrium with aquifer force potential (head pressures)
        (2) well responds to return to equilibrium

    b. Rising Head Slug Test
        (1) Slug withdrawn from well, water level rises in well to return to equilibrium with aquifer

c. Falling Head Slug Test

  (1) Slug injected in well, water level falls in well to return to equilibrium with aquifer

d. Data Collection

  (1) Initial Static Water Level before test
  (2) Time 0 at which slug is added or removed
  (3) Falling or rising recovery level in well taken at prescribed (and recorded) time intervals
  (4) Radius of well casing/boring diameter
  (5) Radius of well screen
  (6) Length of well screen

  (7) Hydrogeologic Conditions
    (a) Confined or unconfined aquifer?
    (b) Partial or fully penetrating well?
    (c) Is SWL within the screen interval or above the screen interval?

4. Cooper-Bredehoeft-Popadopulos Method
  a. Method of slug test for confined aquifer
  b. Data Plot
    (1) H/Ho ratio on Y-axis (arithmetic)

      (a) H = Height of water level above or below SWL at time t
      (b) Ho = Maximum height of water level above or below SWL at time t

    (2) Time (recovery) in seconds on X-axis (log scale)

  c. Curve matching process of test well with empirically derived set of "well function" curves used to define K, S and T

5. Hvorslev Slug Test Method
  a. Slug test method used for wells that do not fully penetrate an aquifer
  b. Data Plot
    (1) H/Ho ratio on Y-axis (logrithmetic)

      (a) H = Height of water level above or below SWL at time t
      (b) Ho = Maximum height of water level above or below SWL at time t

    (2) Time (recovery) in seconds on X-axis (arithmetic scale)

6. Bouwer and Rice Slug Test Method
  a. Unconfined or confined aquifers
  b. Wells fully or partially penetrating