Groundwater Development (AE5108)

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References


Hydrogeology / Geohydrology

- It is the area of geology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust (commonly in aquifers).
What is groundwater

- Water occupying all the voids within a geological stratum
- It is a saturated zone
- It is a renewable mineral resource
- It is a part of hydrologic cycle
Aquifers

- Formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs
- Meaning, ability to store and transmit water.
- Also known as
  - groundwater reservoir
  - water-bearing formation
Types of confining beds

- **Aquiclude**
  - Saturated but relatively impermeable; eg. clay
- **Aquifuge**
  - Relatively impermeable; eg. rock
- **Aquitard**
  - Saturated but poorly permeable; eg. Sandy clay
Fig. 2.5 Divisions of subsurface water.
Unconfined and confined aquifers

Fig. 2.11  Schematic cross section illustrating unconfined and confined aquifers.
Semi-confined or leaky aquifers

Fig. 2.13 Sketch of a leaky, or semiconfined, aquifer.

Impermeable strata
Perched water table

Fig. 2.12. Sketch of perched water tables.
Springs
Father of groundwater studies in Ceylon

Late Mr. C. H. L. Sirimanne (1909 – 1970) (Geologist)
Deputy Director of the Geological Survey of Ceylon
State institutions involved in groundwater study

- Water Resources Board (WRB)
- National Water Supply and Drainage Board (NWS & DB)
Groundwater resources of Sri Lanka

- Shallow Karstic aquifer of Jaffna Peninsula
- Deep confined aquifer of the northwest
- Coastal sand aquifer
- Alluvial aquifer of flood-plains and river valleys
- Shallow Regolith aquifer of hard-rock region
- Lateritic (cabock) aquifer of southwest
Groundwater resources of Sri Lanka
Karstic aquifer of Jaffna Peninsula

Figure 1.2: Groundwater conditions in the Peninsula (After C.H.L. Sirimanne, 1952)
(a) Red Earth, (b) Jaffna Limestone, (MSL) mean sea level, (GWL) groundwater level,
(FWZ) zone of fresh water saturation, (BWZ) probable zone of brackish water; (1) Dry
Well (2) Well of Puttur type, (3) Ordinary successful well, (4) Spring of Keerimalai type,
(5) Solution cavern
Keerimalai spring
Deep confined aquifer of the northwest

Deep Confined Aquifers of the Sedimentary Limestone and Sandstone Formations
Coastal sand aquifer

Figure 1.4(a): The aquifer in the Kalpitiya Peninsula on a coastal spit.

Figure 1.4(b): Schematic cross section of Nilaveli coastal aquifer.
Alluvium Aquifer

GROUNDWATER HYDROLOGY

Stream
Ground surface
Water table
Alluvium
Impermeable strata

1000 m
50 m
Shallow regolith aquifer of hard-rock region
Behaviour of groundwater table (Panabokke, 1959)
Present level of understanding

<table>
<thead>
<tr>
<th>Topic</th>
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<td>Documents on Groundwater - Miscellaneous</td>
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Source: Panabokke and Perera (2005)
Distribution of tube-well sites
Distribution of abstraction points
Total supply of surface and groundwater
(Source: NWS&DB and WRB databases)

<table>
<thead>
<tr>
<th>District</th>
<th>Total supply of surface and groundwater resources (m³/day)</th>
<th>Supply of groundwater resources (m³/day)</th>
<th>Percentage of groundwater supply (%)</th>
<th>Percentage of surface water supply (%)</th>
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<tbody>
<tr>
<td>1.Ampara</td>
<td>12457.0</td>
<td>329.0</td>
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<td>1021.0</td>
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Objectives of Government subsidy agro-well program by the ADA (1989)

- Assuring stable income to the farmers
- Protecting the environment by arresting *chena* cultivation
Requirements for agro-well
(Defined by ADA for subsidy scheme)

- Circular well
- Internal DM > 5 m
- Depth > 8 m
- 3 m depth of water at the beginning of yala (dry season).
Achievements by the end of year 2000

- 18,338 wells subsidized
- Benefited 6000 ha
- Raised cropping intensity to 200%
- Anuradhapura & Kurunegala benefitted the most
Distribution of subsidy agro-wells by districts by the end of year 2001.
Yearly progress in the construction of subsidy agro-wells
Figure 1. Funding source of agro-wells (Anuradhapura district) - 1998.
Table 3. Land extent available under agro-wells and extent cultivated using agro-wells Kurunegala district.

<table>
<thead>
<tr>
<th>Land size (ac)</th>
<th>Land extent available under agro-wells (ac)</th>
<th>Land extend cultivated during yala 1999.</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>No. of farmers</td>
<td>%</td>
<td>No. of farmers</td>
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<tr>
<td>&lt; 0.5</td>
<td>410</td>
<td>8</td>
<td>1658</td>
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<tr>
<td>0.5 - 1</td>
<td>1188</td>
<td>23</td>
<td>1681</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>610</td>
<td>12</td>
<td>487</td>
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<tr>
<td>1.5 - 2</td>
<td>1503</td>
<td>29.5</td>
<td>590</td>
</tr>
<tr>
<td>2 - 2.5</td>
<td>468</td>
<td>9</td>
<td>115</td>
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<tr>
<td>&gt; 2.5</td>
<td>944</td>
<td>18.5</td>
<td>334</td>
</tr>
<tr>
<td>Total</td>
<td>5123</td>
<td>100</td>
<td>4865</td>
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</table>

Source: HARTI agro-well census (1999).
Table 5. Recuperation time of wells after pumping in Kurunegala district (months of July/August 1999) - No. of farmer responses.

<table>
<thead>
<tr>
<th>Time range (hrs)</th>
<th>For 50% recuperation</th>
<th>%</th>
<th>For 100% recuperation</th>
<th>%</th>
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<tr>
<td>0-24</td>
<td>3817</td>
<td>72.24</td>
<td>1955</td>
<td>37</td>
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<tr>
<td>24-48</td>
<td>531</td>
<td>10.05</td>
<td>1118</td>
<td>21.19</td>
</tr>
<tr>
<td>48-70</td>
<td>100</td>
<td>1.89</td>
<td>295</td>
<td>3.58</td>
</tr>
<tr>
<td>70-90</td>
<td>80</td>
<td>1.51</td>
<td>248</td>
<td>4.69</td>
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<tr>
<td>&gt; 90</td>
<td>104</td>
<td>1.97</td>
<td>375</td>
<td>7.09</td>
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<tr>
<td>Not reporting</td>
<td>652</td>
<td>12.34</td>
<td>1293</td>
<td>24.47</td>
</tr>
<tr>
<td>Total</td>
<td>5284</td>
<td>100%</td>
<td>5284</td>
<td>100%</td>
</tr>
</tbody>
</table>

Source: HARTI agro-well census (1999).
Facts on agro-wells by end of year 2000

- Total no. 50,000 (except in N & E)
- 65% lined
- 20% tube wells
- 80% in A’pura, K’negala & Puttalam
- More than 50% located in highland
- 0.2 – 0.8 ha cultivated
- Density of 64/100 ha in Puttalam and 35/100 ha in A’pura
- 45% under subsidy schemes
- Chilli, onion, vegetables & banana
Few more facts

- Oct., Nov., Dec. replenishment of surface & GW
- 10% RF goes as GW recharge
- Imperfectly and poorly drained areas occupies 40% and suitable to locate agro-wells
Status in the North

• By 1969; 100,000 dug wells in the Jaffna peninsula depths ranging from 5 to 10 m
Aspects neglected

• Proper sitting
• Safe intensity
• Sustainable abstraction
• Follow-up action
Problems in hard rock areas

- Drying of wells in mid-season
- Low recovery rates
- Interference between wells
- Salinity
Recommendations

- Well distance 100 m
- Well density 7 – 8 / 100 ha
- Safe to use 75% of the storage
- Imperfectly drained area is best suited for well location
Objectives of Government subsidy micro-irrigation program by the ADA (2000)

• Doubling the cultivated extent by increasing the irrigation efficiency
• Increasing cropping intensity to 300%
• Improving the quality of produces
• Reducing groundwater pollution
What is conjunctive use

- Simultaneous use of surface water and groundwater to meet crop demand.
Benefits of conjunctive use

- Managing the demand based on the availability
- Water quality management
Conjunctive use of tank and groundwater

- Hydrologically interconnected
- Cascade level management
- Utilization of rainfall
- Utilization of residual moisture
Conjunctive use plan

- Rainwater for land preparation & raising nursery
- Selection of crop
- Staggered planting
- Non traditional season
- GW recharge through tank rehabilitation
- Soil moisture conservation
- Water saving irrigation techniques
 Conjunctive use plan

- Basin perspective
- Institutional reform
- Monitoring and information system
- Public-private partnership
- Rehabilitation and hardware improvement
- Farmer participation
- Farmer training
Issues

- Technical
- Financial
- Legal
- Environmental
- Socio-economical
Technical Aspects
Interstices (voids / pores)

(a) Well-sorted sedimentary deposit
(b) Poorly sorted sedimentary deposit
(c) Pebbles that are themselves porous
(d) Mineral deposits in the interstices
(e) Rocks rendered porous by solution
(f) Rock rendered porous by fracturing
Porosity ($\alpha$)

- Ratio between volume of pores and bulk volume

$$\alpha = \frac{V_v}{V}$$

$V_v$ – volume of voids
$V$ – total volume
Specific retention ($S_r$)

- Ratio of the volume of water a soil will retain after saturation against the force of gravity to its own volume

$$S_r = \frac{W_r}{V}$$

- $W_r$ – volume occupied by the retained water
- $V$ – bulk volume
Specific yield ($S_y$)

• Ratio of the volume of water that, after saturation, can be drained by gravity to its own volume

$$S_y = \frac{W_y}{V}$$

$W_y$ – volume water drained
$V$ – bulk volume

$$\alpha = \frac{(W_r + W_y)}{V} = S_r + S_y$$
<table>
<thead>
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<th>Material</th>
<th>Specific Yield, percent</th>
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<td>Gravel, coarse</td>
<td>23</td>
</tr>
<tr>
<td>Gravel, medium</td>
<td>24</td>
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<tr>
<td>Gravel, fine</td>
<td>25</td>
</tr>
<tr>
<td>Sand, coarse</td>
<td>27</td>
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<tr>
<td>Sand, medium</td>
<td>28</td>
</tr>
<tr>
<td>Sand, fine</td>
<td>23</td>
</tr>
<tr>
<td>Silt</td>
<td>8</td>
</tr>
<tr>
<td>Clay</td>
<td>3</td>
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<tr>
<td>Sandstone, fine-grained</td>
<td>21</td>
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<tr>
<td>Sandstone, medium-grained</td>
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<tr>
<td>Limestone</td>
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<tr>
<td>Dune sand</td>
<td>38</td>
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<td>Loess</td>
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<td>Peat</td>
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<td>Schist</td>
<td>26</td>
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<td>Siltstone</td>
<td>12</td>
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<tr>
<td>Till, predominantly silt</td>
<td>6</td>
</tr>
<tr>
<td>Till, predominantly sand</td>
<td>16</td>
</tr>
<tr>
<td>Till, predominantly gravel</td>
<td>16</td>
</tr>
<tr>
<td>Tuff</td>
<td>21</td>
</tr>
</tbody>
</table>
Storage coefficient \((S)\)

(Storativity)

- Volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to that surface

In most confined aquifers \(0.00005 < S < 0.005\)

\[ S = 3 \times 10^{-6} \text{b} \]  (rule-of-thumb)
Specific storage ($S_s$)

- Volume of water a unit volume of saturated aquifer releases from storage for a unit decline in hydraulic head

\[ S = S_s \times b \]

- \( S = \) Storage coefficient
- \( b = \) aquifer thickness
Illustrative sketches for defining storage coefficient of (a) confined and (b) unconfined aquifers.
Groundwater flow

- Henry Darcy (1803 – 1858) – a French hydraulic engineer
- Darcy’s Law (1856)
  - Flow rate through porous media is proportional to the head loss and inversely proportional to the length of the flow path.
Darcy’s law (1856)

- $Q = -KA \frac{dh}{dl}$
- $V = \frac{Q}{A} = -K \frac{dh}{dl}$
  
  $K$ – hydraulic conductivity

  $V$ – Darcy velocity

  $\frac{dh}{dl}$ – hydraulic gradient

  (-) ve sign indicates that the flow is in the direction of decreasing head

- $V_{\alpha} = \frac{V}{\alpha}$

  $V_{\alpha}$ – average interstitial velocity

  $\alpha$ – porosity
Experimental verification

Apply Bernoulli equation at the entrance and exit
Bernoulli equation

\[
\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + h_L
\]

Neglecting velocity head:

\[
h_L = \left(\frac{p_1}{\gamma} + z_1\right) - \left(\frac{p_2}{\gamma} + z_2\right)
\]

- \(p\) - pressure
- \(\gamma\) - specific weight of water
- \(v\) - velocity
- \(g\) - acceleration due to gravity
- \(z\) – elevation
- \(h\) – head loss
Permeability

- **Hydraulic conductivity (K)**
  \[ K = - \frac{v}{(dh/dl)} = \frac{(m/day)}{(m/m)} = m/day \]
  
  \( V \) – Darcy velocity
  \( dh/dl \) – hydraulic gradient

- **Transmissivity (T)**
  \[ T = Kb = (m/day)(m) = m^2/day \]
  
  \( b \) – saturated thickness of the aquifer
Determination of hydraulic conductivity

- **Laboratory method (Permeameter)**
  - Constant head
  - Falling head

- **Field method**
  - Tracer method
  - Augur hole method
  - Pumping test method
Laboratory methods

\[ K = \frac{V L}{A t h} \]

\[ K = \frac{r_t^2 L}{r_c^2 t} \ln \frac{h_1}{h_2} \]
Tracer method

Fig. 3.5 Cross section of an unconfined aquifer illustrating a tracer test for determining hydraulic conductivity.
\[ V_\alpha = \frac{Kh}{L\alpha} \]

Where; \( K \) - Hydraulic conductivity
\( \alpha \) - Porosity
\( h \) and \( L \) are shown in the diagram.

Also, \( V_\alpha = \frac{L}{t} \)

\( t \) – travel time of tracer

\[ K = \frac{\alpha L^2}{ht} \]
Limitations of tracer test:

- Holes must be close together to reduce travel time
- Flow direction must be known
- Not applicable for stratified aquifer
Auger hole method

\[ K = C \frac{dy}{dt} \]

\( \frac{dy}{dt} \) – rate of rise

\( C \) – obtained from the table
<table>
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<tr>
<th>$L_{wp}/r_w$</th>
<th>$y/L_{wp}$</th>
<th>$y/L_{wp}$ for Impermeable Layer</th>
<th>$y/L_{wp}$ for Infinitely Permeable Layer</th>
</tr>
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<td>0.1</td>
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<td>423</td>
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<td>5.91</td>
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<td>6.27</td>
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<td></td>
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<td>7.34</td>
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<td>50</td>
<td>1</td>
<td>1.25</td>
<td>1.18</td>
</tr>
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<td>0.75</td>
<td>1.33</td>
<td>1.27</td>
</tr>
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<td></td>
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<td>1.64</td>
<td>1.57</td>
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<td>100</td>
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<td>0.37</td>
<td>0.35</td>
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<td>0.75</td>
<td>0.40</td>
<td>0.38</td>
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<td>0.5</td>
<td>0.49</td>
<td>0.47</td>
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### TABLE 3.1 Representative Values of Hydraulic Conductivity
(after Morris and Johnson⁴⁵)

<table>
<thead>
<tr>
<th>Material</th>
<th>Hydraulic Conductivity, m/day</th>
<th>Type of Measurement¹</th>
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<tr>
<td>Gravel, coarse</td>
<td>150</td>
<td>R</td>
</tr>
<tr>
<td>Gravel, medium</td>
<td>270</td>
<td>R</td>
</tr>
<tr>
<td>Gravel, fine</td>
<td>450</td>
<td>R</td>
</tr>
<tr>
<td>Sand, coarse</td>
<td>45</td>
<td>R</td>
</tr>
<tr>
<td>Sand, medium</td>
<td>12</td>
<td>R</td>
</tr>
<tr>
<td>Sand, fine</td>
<td>2.5</td>
<td>R</td>
</tr>
<tr>
<td>Silt</td>
<td>0.08</td>
<td>H</td>
</tr>
<tr>
<td>Clay</td>
<td>0.0002</td>
<td>H</td>
</tr>
<tr>
<td>Sandstone, fine-grained</td>
<td>0.2</td>
<td>V</td>
</tr>
<tr>
<td>Sandstone, medium-grained</td>
<td>3.1</td>
<td>V</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.94</td>
<td>V</td>
</tr>
<tr>
<td>Dolomite</td>
<td>0.001</td>
<td>V</td>
</tr>
<tr>
<td>Dune sand</td>
<td>20</td>
<td>V</td>
</tr>
<tr>
<td>Loess</td>
<td>0.08</td>
<td>V</td>
</tr>
<tr>
<td>Peat</td>
<td>5.7</td>
<td>V</td>
</tr>
<tr>
<td>Schist</td>
<td>0.2</td>
<td>V</td>
</tr>
<tr>
<td>Slate</td>
<td>0.00008</td>
<td>V</td>
</tr>
<tr>
<td>Till, predominantly sand</td>
<td>0.49</td>
<td>R</td>
</tr>
<tr>
<td>Till, predominantly gravel</td>
<td>30</td>
<td>R</td>
</tr>
<tr>
<td>Tuff</td>
<td>0.2</td>
<td>V</td>
</tr>
<tr>
<td>Basalt</td>
<td>0.01</td>
<td>V</td>
</tr>
<tr>
<td>Gabbro, weathered</td>
<td>0.2</td>
<td>V</td>
</tr>
<tr>
<td>Granite, weathered</td>
<td>1.4</td>
<td>V</td>
</tr>
</tbody>
</table>

¹H is horizontal hydraulic conductivity, R is a repacked sample, and V is vertical hydraulic conductivity.
Horizontal flow in an alluvial aquifer

K = 75 m/day and i = 10 m/1000 m
V = ? Q = ?
Example

- A sandy aquifer has the following characteristics:
  - hydraulic conductivity 0.0001 m/s
  - porosity of 26%
  - Width 5000 m
  - Thickness 10 m
  - Hydraulic gradient 5 m/100m

i. How much water will be transmitted in a day in m³/day?

ii. How many days it will take to travel from the point of recharge to a point 2 km downstream?
Answer

i. Cross sectional area = $10 \times 5000 = 50000 \text{ m}^2$
   Hydraulic gradient = $5/100 = 0.05$
   $K = 0.0001 \times 3600 \times 24 = 8.64 \text{ m/day}$
   $Q = 8.64 \times 5000 \times 0.05 = 21600 \text{ m}^3/\text{day}$

ii. Darcy velocity = $21600/50000 = 0.43 \text{ m/d}$
   Interstitial velocity (seepage velocity) = $0.43/0.26 = 1.65 \text{ m/day}$
   Time to travel 2 km = $2 \times 1000 / 1.65$
   = 1212 days = 3.32 years
Homogeneous aquifer

- Hydrologic properties are identical everywhere.

Isotropic aquifer

- Hydraulic properties do not vary with direction.

These are called idealized aquifers
Fig. 3.7 Diagram of two horizontal strata, each isotropic, with different thicknesses and hydraulic conductivities.
Anisotropic aquifers

- Horizontal average “$K$”

$$K_x = \frac{K_1 z_1 + K_2 z_2 + \ldots + K_n z_n}{z_1 + z_2 + \ldots + z_n}$$

- Vertical average “$K$”

$$K_z = \frac{z_1 + z_2 + \ldots + z_n}{\frac{z_1}{K_1} + \frac{z_2}{K_2} + \ldots + \frac{z_n}{K_n}}$$
Vertical flow into a leaky aquifer

Fig. 3.9 Diagram illustrating application of Darcy’s law for vertically downward flow.
General flow equation - Laplace equation

Fig. 3.24 Diagram of horizontal flow through a square element of an aquifer.
General flow equation

\[ V = -K \frac{\partial h}{\partial s} \]

- distance along the average direction of flow

\[ q_{x,i} = -T_x W \left( \frac{\partial h}{\partial x} \right)_i \quad \text{and} \quad q_{x,o} = -T_x W \left( \frac{\partial h}{\partial x} \right)_o \]

- transmissivity in the x direction
- length of a side of the square

\[ (q_{x,i} - q_{x,o}) + (q_{y,i} - q_{y,o}) = -SW^2 \frac{\partial h}{\partial t} \]

- storage coefficient
where \( S \) is the storage coefficient. It follows that

\[
-T_x \frac{(\partial h/\partial x)_i - (\partial h/\partial x)_o}{W} - T_y \frac{(\partial h/\partial y)_i - (\partial h/\partial y)_o}{W} = -S \frac{\partial h}{\partial t} \tag{3.75}
\]

If the value of \( W \) becomes infinitesimally small, the derivatives on the left side become the second derivatives of \( h \), so

\[
T_x \frac{\partial^2 h}{\partial x^2} + T_y \frac{\partial^2 h}{\partial y^2} = S \frac{\partial h}{\partial t} \tag{3.76}
\]

This is the general partial differential equation for unsteady flow of groundwater in the horizontal direction.

For three dimensions, employing an elemental cube rather than a square, it can be shown that

\[
K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} = S_s \frac{\partial h}{\partial t} \tag{3.77}
\]

where \( S_s \) is the specific storage, defined as the volume of water a unit volume of saturated aquifer releases from storage for a unit decline in hydraulic head.*
If the flow is steady, \( \partial h / \partial t = 0 \); therefore,

\[
K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} = 0
\]  

(3.78)

and for homogeneous and isotropic aquifers, Eq. 3.78 reduces to

\[
\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0
\]  

(3.79)

which is the Laplace equation for potential flow.\textsuperscript{28,29}
Well hydraulics

Steady flow

• Dupuit equation
• Thiem equation
  – Confined aquifer
  – Unconfined aquifer

Unsteady flow

• Theis equation
Steady unidirectional flow in a confined aquifer of uniform thickness.

Can assume that the head decreases uniformly in the flow direction and apply Darcy’s equation.
Steady flow in an unconfined aquifer between two water bodies with vertical boundaries.
Dupuit assumption

- Velocity of the flow is proportional to the tangent of the hydraulic gradient
- Flow is horizontal and uniform everywhere
Dupuit equation

flow per unit thickness;

\[ q = -KH \frac{dh}{dx} \]

Integrating;

\[ qx = -\frac{K}{2} h^2 + C \]

if \( h = h_0 \) where \( x = 0 \), then the Dupuit equation;

\[ q = \frac{K}{2x} (h_0^2 - h^2) \]
Steady flow to two parallel streams from a uniformly recharged unconfined aquifer.
Dupuit equation

flow per unit thickness;
\[ q = -Kh \frac{dh}{dx} \]

by continuity;

\[ q = Wx \]

by combining;

\[ h^2 = h_a^2 + \frac{W}{K} (a^2 - x^2) \]
from symmetry and continuity;

\[ Q_b = 2aW \]

Where \( Q_b \) is the base flow entering each stream per unit length of stream channel.

If \( h \) is known at any point \( Q_b \) or \( W \) can be computed provided \( K \) is known.
Steady radial flow to a well penetrating a confined aquifer on an island.
Radial flow to a well penetrating an extensive confined aquifer.
Radial flow to a well penetrating an unconfined aquifer.
Steady Radial Flow in a Confined Aquifer

Assume:
- Aquifer is confined (top and bottom)
- Well is pumped at a constant rate
- Equilibrium is reached (no drawdown change with time)
- Wells are fully screened and is only one pumping
Consider Darcy’s law through a cylinder, radius $r$, with flow toward well.

\[ Q = K \frac{dh}{dr} 2\pi rb \] and rearrange as \[ dh = \frac{Q}{2\pi K b} \frac{dr}{r} \]

Integrate from $r_1$, $h_1$ to $r_2$, $h_2$

\[ \int_{h_1}^{h_2} dh = \frac{Q}{2\pi K b} \int_{r_1}^{r_2} \frac{dr}{r} \]

\[ h_2 - h_1 = \frac{Q}{2\pi K b} \ln \frac{r_2}{r_1} \]

or noting that $T = Kb$

\[ T = \frac{Q}{2\pi (h_2 - h_1)} \ln \frac{r_2}{r_1} \]

this is the Thiem equation
Steady Radial Flow in an Unconfined Aquifer

Assume:

- Aquifer is unconfined but underlain by an impermeable horizontal unit.
- Well is pumped at a constant rate
- Equilibrium is reached (no drawdown change with time)
- Wells are fully screened and
- There is only one pumping well
Radial flow in the unconfined aquifer is given by

\[ Q = K(2\pi rh) \frac{dh}{dr} \]

and rearrange as

\[ hdh = \frac{Q}{2\pi K} \frac{dr}{r} \]

Integrate from \( r_1, h_1 \) to \( r_2, h_2 \)

\[
\int_{h_1}^{h_2} hdh = \frac{Q}{2\pi K} \int_{r_1}^{r_2} \frac{dr}{r}
\]

\[
\frac{h_2^2 - h_1^2}{2} = \frac{Q}{2\pi K} \ln \frac{r_2}{r_1}
\]

or noting that \( T = Kb \)

\[
K = \frac{Q}{\pi(h_2^2 - h_1^2)} \ln \frac{r_2}{r_1}
\]

this is the **Thiem equation for unconfined conditions** (K not T, \( h^2 \) not h, no 2)
Specific capacity

- Discharge rate per unit drawdown
- This is a measure of productivity of a well

Specific capacity = Discharge rate / Drawdown in the well
Specific Capacity of a Well – Roughly estimating T

Specific Capacity = Discharge Rate/Drawdown in the well

1. A well is pumped to approximate equilibrium.
2. A good well would be 50 gpm per foot of drawdown, or 20 feet of drawdown at 1,000 gpm.
3. $h_e$ and $r_e$ are the head and corresponding distance from a well where drawdown is effectively zero.
4. Specific capacity = $T = \frac{Q}{(h_e - h_w)} = \ln \frac{T}{527.7 \log \frac{r_e}{r_w}}$
5. Rule of Thumb – $T \sim 1,800 \times$ Specific Capacity
6. What is $r_e$? It doesn’t matter that much.
   - $r_e = 1,000 \times r_w \quad \log \frac{r_e}{r_w} = 3$
   - $r_e = 10,000 \times r_w \quad \log \frac{r_e}{r_w} = 4$
7. Case A $\Rightarrow T = \text{Specific Capacity} [527 \times 3] = 1,581 \times \text{SC}$
   Case B $\Rightarrow T = \text{Specific Capacity} [527 \times 4] = 2,108 \times \text{SC}$
8. If you use $T \sim 1,800 \times$ Specific Capacity you are not too far off. SC is gpm/ft and T is gpd/ft.
Flow net

- It is a graphical representation of two-dimensional steady-state groundwater flow through aquifers
- Consists of flow lines and equipotential lines
Flow net (contd...)

Fig. 3.10 Portion of an orthogonal flow net formed by flow and equipotential lines.
Consider the portion of a flow net shown in Fig. 3.10. The hydraulic gradient $i$ is given by

$$i = \frac{dh}{ds}$$  \hspace{1cm} (3.46)

and the constant flow $q$ between two adjacent flow lines by

$$q = K \frac{dh}{ds} dm$$  \hspace{1cm} (3.47)

for unit thickness. But for the squares of the flow net, the approximation

$$ds \approx dm$$  \hspace{1cm} (3.48)

can be made so that Eq. 3.47 reduces to

$$q = K dh$$  \hspace{1cm} (3.49)

Applying this to an entire flow net, where the total head loss $h$ is divided into $n$ squares between any two adjacent flow lines, then

$$dh = \frac{h}{n}$$  \hspace{1cm} (3.50)

If the flow is divided into $m$ channels by flow lines, then the total flow

$$Q = m q = \frac{K mh}{n}$$  \hspace{1cm} (3.51)

Thus, the geometry of the flow net, together with the hydraulic conductivity and head loss, enables the total flow in the section to be computed directly.
• streamlines and equipotentials meet at right angles
• diagonals drawn between the cornerpoints of a flownet will meet each other at right angles
• streamtubes and drops in equipotential can be halved and should still make squares
• flownets often have areas which consist of nearly parallel lines, which produce true squares
• many problems have some symmetry (e.g., radial flow to a well)
• the sizes of the squares should change gradually; transitions are smooth and the curved paths should be roughly elliptical or parabolic in shape.
In this example, we have $N_f = \text{the number of flow tubes} = 5$, and $N_d = \text{the number of equipotential drops} = 5$.

Suppose that the permeability of the underlying soil is $k = 10^5 \text{ m/sec}$ (typical of a fine sand or silt), then the flow per unit width of dam is:

$$Q = 15 \times 10^{-5} \text{ m}^3/\text{sec} \text{ (per m width)}$$

and if the dam is 25m wide the total flow under the dam:

$$Q = 25 \times 15 \times 10^{-5} \text{ m}^3/\text{sec}$$
Fig. 3.12 Flow nets for seepage from one side of a channel through two different anisotropic two-layer systems. (a) $K_u/K_L = 1/50$. (b) $K_u/K_L = 50$. The anisotropy ratio for all layers is $K_z/K_z = 10$ (after Todd and Bear58).
Fig. 3.12 Flow nets for seepage from one side of a channel through two different anisotropic two-layer systems. (a) $K_u/K_L = 1/50$. (b) $K_u/K_L = 50$. The anisotropy ratio for all layers is $K_x/K_z = 10$ (after Todd and Bear\textsuperscript{58}).
Fig. 3.14 Contour map of a groundwater surface showing flow lines.
Fig. 3.15 Contour map of the piezometric surface near Savannah, Georgia, 1957, showing closed contours resulting from heavy local groundwater pumping (after USGS Water-Supply Paper 1611).
Refraction of flow lines

**Fig. 3.18** Refraction across layers of coarse and fine sand with a hydraulic conductivity ratio of 10 (after Hubbert\textsuperscript{28}; copyright © 1940 by the University of Chicago Press).
Groundwater Recharge
Methods of estimation

• Borehole hydrograph
  \[ \text{Recharge} = \text{Hydrographic Rise} \times \text{Specific Yield} \]

• River hydrograph
  \[ \text{Change in base flow} = \text{Precipitation recharge} \]

• Salt balance method

• Infiltration method

• Water balance

• Empirical method
  \[ \text{e.g. } R = 0.15 \text{ Pe; site specific} \]
Artificial recharge

- Maintain or augment the natural groundwater
- Coordinate operation of surface and groundwater
- Combat adverse conditions
  - GW depletion, saline water intrusion, etc.
- Provide subsurface storage for surface water
Recharge methods

- **Water spreading**
  - Basin, stream channels, furrow, pond, well, flooding, etc.

- **Unintentional recharge**
  - Irrigation, septic tanks, seepage from channels and reservoirs, seepage from sewerage systems, etc.
Groundwater Pollution
Definition, Sources and Implications

- Artificially induced degradation of natural groundwater quality
- Originates from disposal of waste (septic tank to irrigated agriculture)
  - Organic and inorganic chemicals, biological, physical and radiological types
- Difficult to detect, difficult to control and may persists for decades
- Creates toxicity or spread disease
Groundwater quality of Sri Lanka (Assignment)

1. Nitrate in Jaffna
2. Nitrate in Kalpittiya
3. Quality of Hard rock aquifer
4. Occurrence of dental fluorosis
5. CKDu – possible link with groundwater
6. Problem of Ca, Mn and Fe