CHAPTER 1

GROUNDWATER HYDROLOGY
GROUNDWATER HYDROLOGY

• Role of Groundwater
  – Water Supply
  – Drainage; Seepage, excavations, and foundations;
  – Subsidence of land; Special problems
    • sea water intrusion, artificial recharge, waste disposal, pollution
GROUNDWATER HYDROLOGY

• Role of Groundwater
  – Water management – (concerned with) underground storage, conservation, minimum cost, quantity available, quality available, time and space variations.
GROUNDWATER HYDROLOGY

- Groundwater and other applications
  - Geology: oil, gas, salt deposits, fresh water mining
  - Petroleum Engineering
  - Agriculture: irrigation, drainage, soil moisture
  - Soil Science (Agronomy): soil-plant-water relations
GROUNDWATER HYDROLOGY

• Groundwater and other applications
  – Public Health
  – Law: groundwater rights, RCRA, CERCLA, SARA, LUST
  – Economics: natural resources (G.W.), agriculture (G.W.)
  – Geography
  – Political Science: between nations and states
GROUNDWATER HYDROLOGY

• Groundwater in Hydrologic cycle:
GROUNDWATER HYDROLOGY

• Hydrologic Budget:
GROUNDWATER HYDROLOGY

• Hydrologic Budget:

\[ P + Q_{in} - Q_{out} + Q_g - E_s - T_s - I = \Delta S_s \]

\( P \) = is the precipitation,  
\( Q_{out} \) = out surface water flow  
\( E_s \) = surface evaporation  
\( I \) = infiltration  
\( Q_{in} \) = into surface water flow  
\( Q_g \) = into groundwater  
\( T_s \) = transpiration  
\( \Delta S_s \) = change of water storage
GROUNDWATER HYDROLOGY

EXAMPLE 1.6.1

During 1996, the water budget terms for Lake Annie in Florida\(^6\) included precipitation (\(P\)) of 43 inch/yr, evaporation (\(E\)) of 53 inch/yr, surface water inflow (\(Q_{\text{in}}\)) of 1 inch/yr, surface outflow (\(Q_{\text{out}}\)) of 173 inch/yr, and change in lake volume (\(\Delta S\)) of –2 inch/yr. Determine the net groundwater flow (the groundwater inflow minus the groundwater outflow).

\[
G = \Delta S - P + E - Q_{\text{in}} + Q_{\text{out}}
\]

\[
= -2 - 43 + 53 - 1 + 173
\]

\[
= 180 \text{ inch/yr}
\]

EXAMPLE 1.6.2

During January 1996, the water-budget terms for Lake Annie in Florida\(^6\) included precipitation (\(P\)) of 1.9 inch, evaporation (\(E\)) of 1.5 inch, surface water inflow (\(Q_{\text{in}}\)) of 0 inch, surface outflow (\(Q_{\text{out}}\)) of 17.4 inch, and change in lake volume (\(\Delta S\)) of 0 inch. Determine the net groundwater flow for January 1996 (the groundwater inflow minus the groundwater outflow).

The water budget equation to define the net groundwater flow for the lake is

\[
G = \Delta S - P + E - Q_{\text{in}} + Q_{\text{out}} = 0 - 1.9 + 1.5 - 0 + 17.4 = 17 \text{ inch for January 1996}
\]
GROUNDWATER HYDROLOGY

• Sources of GW
  – Precipitation
  – Natural recharge
  – Artificial recharge
GROUNDWATER HYDROLOGY

• Disposal of Groundwater
  – Outflow – stream, spring, lake, ocean
  – Use of water – wells, drains
  – Evapotranspiration
GROUNDWATER HYDROLOGY

• Groundwater as Resource
  – “Renewable” natural resource
  – Largest fresh water source
    • concerned with its development and management
GROUNDWATER HYDROLOGY

• Groundwater Occurrence
  – GW occurs in saturated and unsaturated zones, but GW supply tapped from saturated zones.
GROUNDWATER HYDROLOGY
GROUNDWATER HYDROLOGY

• Infiltration – water entering the ground.
• Percolation – water movement within the ground
• Unsat. Zone – water percolates vertically downward
• Sat. Zone – water percolates horizontally and may move in any direction depending on the boundaries of the aquifer.
GROUNDWATER HYDROLOGY

• Historical Background
  – Water Development
    • Groundwater development described from 800 BC
    • Dug Well

Fig. 1.1 Vertical cross section along a qanat (after Beaumont).
GROUNDWATER HYDROLOGY

• Kanat (Qanat)
  – Iran and Egypt
  – Avg. Length = 5km
  – \( Q = 400 \text{ l/s} = 35000 \text{ m}^3/\text{d} = 6420 \text{ gpm} \)
  – No. = 35,000
  – Water runs to waste due to continuous flow in canals.
GROUNDWATER HYDROLOGY

• 17th Century
  – Perrault – rainfall and runoff estimates for a river basin
  – Mariotte – infiltration theory
  – Halley - evaporation
GROUNDWATER HYDROLOGY

• 18th Century
  – Fundamentals of geology established with a basis for understanding the occurrence and movement of groundwater.
GROUNDWATER HYDROLOGY

• 19th Century
  – Henry Darcy
    • Darcy’s Law
    • Well Drilling
  – Groundwater Hydraulics – Boussinesq, Dupuit, Forcheimer, Thiem
GROUNDWATER HYDROLOGY

• 20th Century
  – USGS: data collection in the U.S.
GROUNDWATER HYDROLOGY

- Groundwater use in the U.S.

<table>
<thead>
<tr>
<th>Year</th>
<th>B.G.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1935</td>
<td>10</td>
</tr>
<tr>
<td>1945</td>
<td>20</td>
</tr>
<tr>
<td>1960</td>
<td>50</td>
</tr>
<tr>
<td>1975</td>
<td>80</td>
</tr>
<tr>
<td>1985</td>
<td>110</td>
</tr>
</tbody>
</table>
GROUNDWATER HYDROLOGY

- G.W. / T.W. = 20% and increasing (US)
- G.W. / T.W. = 87% (Kansas)
- G.W. / T.W. = 63% (Oklahoma)
GROUNDWATER HYDROLOGY

• Relative use of Groundwater in the US
  – Irrigation 65%
    • 91% in 17 western states.
  – Industry 21%
  – Public Supply 10%
  – Rural Supply 4%
GROUNDWATER HYDROLOGY

• Top Industrial Uses of Groundwater
  – Oil Refinery
  – Paper Manufacturing
  – Metal Manufacturing
  – Chemical Manufacturing
  – Air Conditioning and Refrigeration Plants
  – Distilling
  – Ice Manufacturing
  – Food Processing
  – Food Processing
  – Nuclear Power Plants
World’s water distribution – Table 1.1

<table>
<thead>
<tr>
<th></th>
<th>% of total water</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Surface water</td>
<td></td>
</tr>
<tr>
<td>Salt water in oceans</td>
<td>97.2</td>
</tr>
<tr>
<td>Salt water in lakes + inland areas</td>
<td>0.008</td>
</tr>
<tr>
<td>Fresh water in lakes</td>
<td>0.009</td>
</tr>
<tr>
<td>Fresh water in streams</td>
<td>0.0001</td>
</tr>
<tr>
<td>Fresh water in glaciers + icecaps</td>
<td>2.15</td>
</tr>
<tr>
<td>Water in biomass</td>
<td>0.004</td>
</tr>
<tr>
<td>(2) Groundwater</td>
<td>0.625</td>
</tr>
<tr>
<td>Unsaturated zone</td>
<td>0.005</td>
</tr>
<tr>
<td>GW within 0.8 km (shallow percolation)</td>
<td>0.31</td>
</tr>
<tr>
<td>GW 0.8 – 4.0 km (deep percolation)</td>
<td>0.31</td>
</tr>
<tr>
<td>(3) Atmospheric water</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>100.00%</td>
</tr>
</tbody>
</table>
GROUNDWATER HYDROLOGY

- Compare
  - Shallow GW 0.31%
  - Fresh water in lakes and streams 0.0091%
  - Fresh water in glacier icecaps 2.15%
GROUNDWATER HYDROLOGY

• Origins of Groundwater
  – Meteoric Water:
    – Water infiltrated from precipitation, lakes and streams
    – Part of the hydrologic cycle
    – Recent geologic time, generally good quality
GROUNDWATER HYDROLOGY

• Origins of Groundwater
  – Connate Water
    – Water entrapped in sedimentary rocks at the time of deposition
    – Isolated from the hydrologic cycle, though of atmospheric origin
    – Found in lower parts of deep GW
    – Highly mineralized; in contact with salt deposits
    – Much older than meteoric water
GROUNDWATER HYDROLOGY

• Origins of Groundwater
  – Juvenile Water
    – Formed within earth; of volcanic or magmatic origin
    – Can move up with volcanic activity
    – Not part of the hydrologic cycle
    – Highly mineralized; insignificant as a water resource
Fig. 2.1 Diagram illustrating relationships of genetic types of water (after White⁴⁹; courtesy The Geological Society of America, 1957).
GROUNDWATER HYDROLOGY

• Formations
  – Aquifer: permeable geologic formation capable of storing and transmitting significant quantities of water.
    • Ex. – alluvium, limestone, basalt, gravel
  – Aquiclude: impermeable formation containing water, but not capable of transmitting significant quantities
    • Ex. – clay
GROUNDWATER HYDROLOGY

• Formations
  – Aquifuge: impermeable formation capable of neither storing nor transmitting water
  • Ex. - Granite
GROUNDWATER HYDROLOGY

• Types of Aquifers
  – Unconfined Aquifer: WT as upper boundary
Fig. 2.11 Schematic cross section illustrating unconfined and confined aquifers.
GROUNDWATER HYDROLOGY

– Confined Aquifer: water under pressure greater than atmospheric pressure.

– When the confined aquifer is depleted such that the aquifer pressure is atmospheric, it behaves as an unconfined aquifer.
GROUNDWATER HYDROLOGY

– Semi-Confined Aquifer (Leaky):
  • WT > PS, water moves from UA to CA
  • WT < PS, water moves from CA to UA

![Diagram of a leaky or semiconfined aquifer](image-url)
GROUNDWATER HYDROLOGY

– Perched Aquifer: Upper WT of limited extent. False WT

Fig. 2.12 Sketch of perched water tables.