The Hydrologic Cycle

What is the hydrologic cycle?

- Plato and other Greek philosophers believed that springs and rivers originated from purified sea water transported underground.
- Aristotle improved the theory by suggesting vapor transport through caverns from the sea and condensation at springs.
- With a few exceptions these theories were maintained until the 17th century.
- First person to demonstrate that precipitation originated from runoff was Pierre Perrault in 1674.
  - measured precipitation near Paris for 3 years
  - estimated discharge of Seine
  - multiplied precipitation by drainage basin area and found the volume was 6 times the runoff!!

$\Rightarrow$ Conclusion: Precipitation is more than adequate to account for runoff.

Perrault’s work was strongly supported by that of Edme Mariotte (1620-1694): similar experiments, but better measurement techniques earned him the nickname

In 1693, Edmund Halley measured evaporation, demonstrating the evaporation of sea water was sufficient to account for observed precipitation.
Groundwater and the Hydrologic Cycle

The endless circulation of the water between ocean, atmosphere, and land is called the hydrologic cycle:

(Fitts, 2002)

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Volume (%)</th>
<th>Residence time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans and Seas</td>
<td>96.5</td>
<td>~4000 years</td>
</tr>
<tr>
<td>Lakes and reservoirs</td>
<td>0.013</td>
<td>~10 years</td>
</tr>
<tr>
<td>Swamps</td>
<td>&lt;0.01</td>
<td>~1 – 10 years</td>
</tr>
<tr>
<td>Rivers</td>
<td>&lt;0.01</td>
<td>~2 weeks</td>
</tr>
<tr>
<td>Soil water</td>
<td>&lt;0.01</td>
<td>~2 wk – 1 year</td>
</tr>
<tr>
<td>Groundwater</td>
<td>1.6</td>
<td>~2 wk – 10,000 yr</td>
</tr>
<tr>
<td>Ice and snow</td>
<td>2</td>
<td>~10-1,000 years</td>
</tr>
<tr>
<td>Atmospheric water</td>
<td>&lt;0.01</td>
<td>~10 days</td>
</tr>
<tr>
<td>Biospheric water</td>
<td>&lt;0.01</td>
<td>~1 week</td>
</tr>
</tbody>
</table>

(Fitts, 2002)
How much of the FRESH water on earth is in various reservoirs?

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice and snow</td>
<td>69.6</td>
</tr>
<tr>
<td>Groundwater</td>
<td>30.1</td>
</tr>
<tr>
<td>Surface water</td>
<td>0.3</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>0.05</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.04</td>
</tr>
<tr>
<td>Biosphere</td>
<td>0.003</td>
</tr>
</tbody>
</table>

So, nearly ______ of FRESH, LIQUID water on earth is groundwater!

Local water balance

Infiltration - Evaporation - Discharge - Underflow
Types of water

Some seawater is trapped at the time of sediment deposition

Some water is produced inside the earth by outgassing caused by heat of accretion

Water derived from precipitation

Recall that:

\[ \text{Infiltration} - \text{ET} - \text{Discharge} - \text{Underflow} = \Delta \text{Storage} \]

- What is the ultimate cause of fluid movement?
  - Energy gradients, especially gradients of mechanical energy
- We quantify the mechanical energy of a fluid using the fluid potential—
Components of fluid potential ($\Phi$)

- $d$ – depth below water surface
- $z$ – height above datum (a point of given total mechanical energy)
- $p$ – pressure
- $v$ – velocity

The reference blob is at rest at the datum, so it has a fluid potential of $\boxed{0}$.

What kinds of mechanical energy can a fluid have?

1) Potential energy (gravitational; reflects the work to lift mass from elevation $z = 0$ to $z$):

$$\text{PE} = mgz$$

2) Kinetic energy (energy required to accelerate fluid from rest to observed velocity)

3) Elastic energy (compressional; work done in raising fluid pressure from $p_0$ to $p$)
\[ \text{EE} = m \int_{p_0}^{p} \frac{dp}{\rho} \]

If fluid is only slightly compressible, \( \int_{p_0}^{p} \frac{1}{\rho} dp \approx \frac{1}{\rho} \int_{p_0}^{p} dp \)

\[ \Rightarrow \text{EE} = \frac{m}{p} \int_{p_0}^{p} dp = m \frac{p - p_0}{\rho} \]

These are the components of \( \Phi \) [total mechanical energy per unit mass]:

\[ \Phi = \frac{PE + EE + KE}{m} \]

\[ \Phi = mgz + m \frac{p - p_0}{\rho} + \frac{1}{2} mv^2 \]

\[ \Phi = g z + \frac{p - p_0}{\rho} + \frac{1}{2} v^2 \]

In groundwater flow, \( v \) is normally very small; \( v^2 \) is very, very small

\[ \Rightarrow \frac{v^2}{2} \to 0 \]

Thus, \( \Phi = gz + \frac{p - p_0}{\rho} \)

Can we express \( p \) in terms of \( h \)?

\[ d = h - z \]

\[ \text{Datum} (z = 0) \]
\( \rho \) is equal to weight of water at depth \( d \), plus \( p_0 \)
\[
p = \rho gd + p_0
\]
\[
= \rho g(h - z) + p_0
\]
\[
\Phi = gz + \frac{\rho g(h - z) + p_0 - p_0}{\rho}
\]
\[
= gz + g(h - z)
\]
\[
= gz + gh - gz
\]
\[
\therefore \Phi = gh
\]

Does “\( g \)” vary much over the surface of the earth?

Therefore \( h \), the hydraulic head, is directly related to the fluid potential. Water flows from areas of higher head to lower head.

\[h_1 > h_2\], so water will flow from Well 1 toward Well 2

Recall that our conclusion that \( h \) is representative of \( \Phi \) is based on two major assumptions:
Finally, from earlier diagrams, recall that the dimensions of h are \[ \text{ } \]

Now we have a means of determining and predicting the direction of flow. Let’s see if we can describe the rate of flow next.