Objective: To understand the inter-relationships of the principal hydrological processes in a watershed.

These are:
- Precipitation
- Evaporation
- & transpiration
- Depression storage
- Infiltration
- Overland flow
- Hortonian flow
- Saturated flow
- Interflow
- Throughflow
- Groundwater flow
- Streamflow generation
Consider "storage" in a stream.

\[ I - Q = \frac{dS}{dt} \]

Volumes of Mega-Reservoirs

<table>
<thead>
<tr>
<th>Item</th>
<th>Volume</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Oceans:</td>
<td>$1.32 \times 10^6$ km$^3$</td>
<td>97.3%</td>
</tr>
<tr>
<td>Icecaps &amp; glaciers</td>
<td>$29.2 \times 10^6$ km$^3$</td>
<td>2.14%</td>
</tr>
<tr>
<td>Groundwater</td>
<td></td>
<td></td>
</tr>
<tr>
<td>To 4000 m</td>
<td>$8.35 \times 10^6$ km$^3$</td>
<td>0.61%</td>
</tr>
<tr>
<td>To 800 m</td>
<td>$4.18 \times 10^6$ km$^3$</td>
<td>0.30%</td>
</tr>
<tr>
<td>Fresh-water Lakes</td>
<td>$0.125 \times 10^6$ km$^3$</td>
<td>0.0099%</td>
</tr>
<tr>
<td>Saline lakes &amp; inland seas</td>
<td>$0.104 \times 10^6$ km$^3$</td>
<td>0.008%</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>$0.067 \times 10^6$ km$^3$</td>
<td>0.005%</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>$0.013 \times 10^6$ km$^3$</td>
<td>0.001%</td>
</tr>
<tr>
<td>Rivers</td>
<td>$0.00125 \times 10^6$ km$^3$</td>
<td>0.0001%</td>
</tr>
</tbody>
</table>

Accessible Fresh Water (above 800 m): $4.39 \times 10^6$ km$^3$ or $1.16 \times 10^{18}$ gal.

*Of which 95% is groundwater.*
Fluxes to/out of Mega-Reservoirs

Water Balance for North America & the World
(Flux units are in km³/yr)

<table>
<thead>
<tr>
<th>Hydrological Element</th>
<th>North America</th>
<th>World</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land area (millions of sq km)</td>
<td>20.7</td>
<td>132.2</td>
</tr>
<tr>
<td>Precipitation (P)</td>
<td>13,910</td>
<td>110,303</td>
</tr>
<tr>
<td>Infiltration &amp; soil moisture (I)</td>
<td>9,690</td>
<td>83,360</td>
</tr>
<tr>
<td>Evaporation &amp; transpiration (ET)</td>
<td>7,950</td>
<td>71,475</td>
</tr>
<tr>
<td>Surface water runoff (QS)</td>
<td>4,220</td>
<td>26,945</td>
</tr>
<tr>
<td>Groundwater runoff (QG)</td>
<td>1,740</td>
<td>11,885</td>
</tr>
</tbody>
</table>

(Global view of the water mass balance.)

Concept of "Residence Times"

Paradigm: If we know the storage volume, $S$ (in units of m³), of a steady-state reservoir, and the flux, $Q$ (in units of m³/day), then the volume $S$ would be replaced in a total time $T$ such that

$$QT = S$$

Thus, an order-of-magnitude estimate of the residence time of a particle of fluid in the storage volume is given by

$$T = \frac{S}{Q}$$
\[ T = \frac{S}{Q} \]

An example (Residence time of fresh water)

Accessible Fresh Water (above 800 m): \(4.39 \times 10^6 \text{ km}^3\)
Continental Precipitation (P): \(110,303 \text{ km}^3\text{/yr}\)

*Residence Time of Fresh Water = 40 years*

In this course, the following terms might serve as synonyms in appropriate cases:

**Synonyms:**
- *Residence Time*
- *Characteristic Time*
- *Time Constant*

---

**Table: Summary of residence times**

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<tr>
<th>Type</th>
<th>Time Scale</th>
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<tr>
<td>Oceans</td>
<td>(\approx 4000 \text{ yrs})</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>(\approx 10 \text{ days})</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>(\approx 2 \text{ weeks to } 1 \text{ year})</td>
</tr>
<tr>
<td>Rivers &amp; streams</td>
<td>(\approx 2 \text{ weeks})</td>
</tr>
<tr>
<td>Lakes &amp; reservoirs</td>
<td>(\approx 10 \text{ years to } 100 \text{ years})</td>
</tr>
<tr>
<td>Groundwater</td>
<td>(\approx 10 \text{ years and more}) (From hours to 1000's of years)</td>
</tr>
</tbody>
</table>
The Water Cycle
(A Fundamental Relation of Hydrology)

A mass balance relation between the principal physical components of a hydrological system. (Also known as the “Hydrological Cycle”.)

Hydrological components of the water cycle:
- Precipitation
- Evaporation & transpiration
- Infiltration
- Overland flow
- Interflow
- Groundwater flow
- Streamflow

Quantifying watershed processes.
\[ P + Q_{swi} + G_{in} - (ET + G_{out} + Q_{swo}) = \Delta S/\Delta t \]
## Water Balance for North America & the World

(Flux units are in km³/yr)

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Note (for example):

\[ P = I + Q_S \]

Oftentimes, a water balance relation reflects the hydrologist’s point of view regarding a particular physical process. (What’s this “point of view”?)
Water Balance for North America & the World
(Flow units are in km³/yr)

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Note (for example):

\[ P = I + Q_S \]

or

\[ ET = I - Q_G \]
A classic problem in the "response" of physical systems.

The transfer function of a system allows one to predict the expected output process due to a specified input process.

The Thesis: Historically, streamflow shows a strong correlation with precipitation. Knowing the nature of this relationship, we can predict stream discharge from known or predicted precipitation.
Changes in the streamflow of the Pawcatuck River for a specific precipitation event.

Example of a single "event". (We want to explore "cause & effect" in a watershed system.)

Changes in the streamflow of the Pawcatuck River for a specific precipitation event.

Precipitation
Evapo-transpiration
Water Table
Subsurface flow
Stream
Surface Runoff
Baseflow

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We next look at the time and space sequencing of precipitation, surface runoff, groundwater flow and streamflow generation.

(Note: No precipitation for an extended period. Groundwater table in "equilibrium" with stream level.)
Storm (precipitation) begins.

No subsurface flow

Surface becomes wet, and depression storage develops.

(Ground becomes "wet")
Precipitation

Evapo-transpiration

Surface Runoff

Water Table

No subsurface flow

Overland flow (direct runoff) develops.

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Stream

Precipitation

Evapo-transpiration

Surface Runoff

Water Table

No subsurface flow

Stream begins to rise; surface "wetting" begins to infiltrate

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(Note development of “bank storage”.)

Stream begins to rise; surface “wetting” begins to infiltrate

Groundwater mounding begins, subsurface flow develops; stream level rises.
Mounding spreads laterally.

Enhanced subsurface and overland flow.
Precipitation

Evapo-transpiration

Water Table

Surface Runoff

Subsurface flow

Soil water content increases in unsaturated zone.

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Evapo-transpiration

Water Table

Surface Runoff

Subsurface flow

Precipitation stops.

© John F. Hermance
Evapo-transpiration

Surface runoff slows

Water Table

Subsurface flow

Surface runoff slows; mounding spreads.

Stream

© John F. Hermance

Evapo-transpiration

Surface runoff slows

Water Table

Subsurface flow

Stream level drops; mounding spreads.

© John F. Hermance
Evapo-transpiration

"Baseflow" to stream now dominates. Stream level continues to fall.

Evapo-transpiration

Baseflow continues to sustain streamflow. Stream level continues to fall.
Evapo-transpiration

Water Table

Subsurface flow

Stream

Modest groundwater flow continues.

Evapo-transpiration

Water Table

No subsurface flow

Stream

Normal equilibrium is restored.
This is only one of many scenarios for the time-space interaction of precipitation and runoff.

A more typical “initial condition” for a stormflow event follows.
The Thesis: Historically, streamflow shows a strong correlation with precipitation. Knowing the nature of this relationship, we can predict stream discharge from known or predicted precipitation.
The composite effect of *longitudinal flow* to a stream along its axis.
We want consider how these discrete “slices” provide an aggregate streamflow.

Surface runoff and baseflow act in parallel to feed streamflow.
This lateral contribution is comprised of local Horton and saturated overland flow, return flow from seepage, and baseflow (groundwater).

Use this symbol to denote the sum total of all surface runoff and baseflow delivered by this slice.
Other "slices" or 2D elements also contribute to streamflow. Which integrates to the composite aggregate stream discharge, Q.
Plan view illustrating the longitudinal integration of lateral inputs to streamflow.

The thickness of the arrow is used to denote the local magnitude of stream discharge. The basic idea is that streamflow is generated by the integrated contributions of surface runoff and baseflow along its length.

Summary: The Paradigm: Longitudinal stream development is the composite effect of lateral flow to a stream along its axis. We saw an example of lateral input from a discrete 2D element. We assumed that each 2D “slice” provides a discrete contribution to the total streamflow. The superposition of transverse surface and subsurface flow from these discrete slices is what we term the “longitudinal integration of lateral inputs” to generating and sustaining streamflow.

Streamflow discharge (Q) progressively increases downstream due to lateral inflow from surface runoff, interflow and groundwater base flow.
A Caveat: Longitudinal stream attenuation

Gaining versus Losing Stream

Note: Streams can *lose* water along their channel, or reach, as well as *gain* water.

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