The Earth as a System: The Hydrologic Cycle

- Earth is unique in the solar system
  - Right size and distance from the Sun to have liquid water
  - Mantle convection brings water to Earth's surface through volcanism
- The hydrologic cycle describes the movement of water through Earth's four spheres
  - Geosphere, hydrosphere, atmosphere, biosphere

The Earth as a System: The Hydrologic Cycle

- Movement Through the Hydrologic Cycle
  - Water evaporates from the oceans, plants, and soil and moves through the atmosphere
  - Water leaves the atmosphere via precipitation
  - Precipitation either
    - Soaks into the ground (infiltration),
    - Runs over the surface (runoff),
    - Evaporates, or
    - Is stored as part of a snowfield or glacier
  - The Hydrologic Cycle is balanced:
    - Water is constantly moving from one reservoir to another, but the total amount on earth remains the same

Distribution of Earth's Water

- Total global water: 96.5%
- Freshwater: 2.5%
- Surface water and other freshwater: 1.3%
- Groundwater: 30.1%
- Lakes: 20.1%
- Glaciers and ice sheets: 68.6%
- Snow and ice: 73.1%
- Atmosphere: 0.22%
- Biological water: 0.22%
- Rivers: 0.46%
- Swamps: 2.53%
- Soil moisture: 3.52%

The Hydrologic Cycle
The Earth as a System: The Hydrologic Cycle

• Movement Through the Hydrologic Cycle
  – Transpiration involves water absorbed by plants and later transferred to the atmosphere
  – As evaporation and transpiration both move water from the surface to the atmosphere, they are often considered a combined process called evapotranspiration

Running Water

• The difference between runoff and infiltration depends on
  – Intensity and duration of rainfall
  – The amount of water already in the soil
  – The type of soil
  – Slope of the land
  – Nature of the vegetative cover
• When the surface is impermeable or saturated, runoff is dominant
  – Runoff is high in urban areas due to buildings, roads and parking lots

Running Water

• Runoff Will Start as Sheet Flow
  – Sheet flow develops into tiny channels called rills
  – Rills meet to form gullies
  – Gullies join to form brooks, creeks, or streams
  • A stream is any water that flows in a channel, regardless of size
  • A river carries a substantial amount of water and has many tributaries

Running Water

• Drainage Basins
  – A stream drains an area of land called a drainage basin or watershed
  – The imaginary line separating one basin from another is called a divide
    • Sometimes visible as a high ridge in a mountainous region
    • Sometimes hard to determine in subdued topography
  – A continental divide splits a continent into different drainage basins
  – If you observed streams over several years, you would see many lengthen their courses by headward erosion

Drainage Basin and Divide

Mississippi River Drainage Basin
River Systems
- Rivers drain much of the land area
  - Exceptions: extremely arid or polar regions
  - The variety of rivers that exist is a reflection of the different environments they are found in
  - Climate differences and human intervention influence the character of a river
- River systems can be divided into three zones
  - Sediment production (erosion dominates)
  - Sediment transportation
  - Sediment deposition

Sediment production
- Zone where most sediment is derived
- Located in the headwater region of a river system
- Sediment generated by
  - Bedrock broken into smaller pieces
  - Bank erosion
  - Scouring of the channel bed

Sediment deposition
- When a river reaches a large body of water, the energy decreases and the river deposits sediments
- Typically only fine sediments are deposited in oceans

Zones of a River
Drainage Patterns

- Drainage systems are patterns of the interconnected network of streams in an area
  - Common drainage patterns
    - **Dendritic**
      - The most common
      - Uniform underlying material
    - **Radial**
      - Typically forms on volcanic cones or domes
    - **Rectangular**
      - Bedrock is jointed or faulted
    - **Trellis**
      - Bedrock consists of alternating bands of resistant and weak strata

Drainage Patterns

- **Formation of a Water Gap**
  - A water gap is a notch where a river cuts through a ridge that lies in its path
  - Two possible methods of formation:
    - **Antecedent stream**
      - Stream existed before the ridge was uplifted
    - **Superposed stream**
      - Stream was eroded into a preexisting structure buried beneath layers of relatively flat lying strata

Superposed Stream

Streamflow

- Water Moves in a River Channel Under the Influence of Gravity
  - Water slowly flowing in a nearly straight path is called **laminar flow**
  - Water moving quickly in an erratic fashion (both horizontal and vertical movement) is called **turbulent flow**
  - Streams typically exhibit turbulent flow
### Streamflow

#### Factors Affecting Flow Velocity
- **The slope, or gradient, of the stream**
  - A steeper gradient has more gravitational energy to drive channel flow
- **Channel shape**
  - The **wetted perimeter** is the area where the river is in contact with the channel
  - The most efficient channel has a small wetted perimeter compared to its cross-sectional area
    - A narrow, deep channel has a small wetted perimeter, less frictional drag, and will flow more efficiently
- **Water depth affects frictional resistance**
  - Maximum flow velocity occurs when a stream is bankfull
- **An increase in channel size will increase the cross-sectional area to wetted perimeter ratio, thus increasing channel efficiency**
- **Rough channels (boulders, etc.) create turbulence and decreased velocity**

#### Changes Downstream
- **A longitudinal profile** is a cross-sectional view of a stream
  - **Head or headwater** is the source of the stream
  - **Mouth** is the downstream point where the stream empties into a larger body of water
  - Most longitudinal profiles have a concave shape
- **Discharge increases toward the mouth**
- **Channel size and velocity also increase toward the mouth**
- **Slope decreases downstream**
- **Volume increases downstream**

#### Influence of Channel Shape on Stream Velocity

- **Discharge** is the volume of water flowing past a certain point in a given unit of time
  - When discharge increases, the width, depth, and flow velocity increase predictably
- **Monitoring streamflow**
  - The U.S. Geological Survey (USGS) measures flow velocity, discharge, and river stage (height of water surface relative to a fixed point)
    - USGS network of 7500 stream gaging stations
    - These data are useful for resource management
Longitudinal Profile

Channel Changes from Head to Mouth

The Work of Running Water

- Stream Erosion
  - Erosion related to slope, discharge, and bed/bank sediments
    - Sand-sized particles are easily eroded
    - Silt/clay-sized particles and gravels are harder to erode
      - Channels with cohesive silty bottoms are typically narrower than sandy channels
  - Streams cut channels by quarrying, abrasion, and corrosion
    - Quarrying involves removing large blocks from the channel bed
      - Aided by fracturing of bedrock

- Potholes
  - Transport of Sediment by Streams
    - All streams transport some sediment
    - Sediment load is transported in three ways:
      - Dissolved load (in solution)
      - Suspended load (in suspension)
      - Bed load (sliding, skipping, or rolling along the bottom)
Transport of Sediments

- **Dissolved load**
  - Most of the dissolved load is brought to a stream **via groundwater**
  - Dissolved load is not affected by stream velocity
  - Dissolved minerals precipitate when water chemistry changes
    - When organisms create hard parts
    - When water enters an inland “sea” where the evaporation rate is high

- **Suspended load**
  - The largest part of a stream’s load is carried in **suspension**
    - Usually only fine sand, silt, and clay are carried this way
    - During a flood stage, larger particles can also be carried in suspension
  - Amount of material carried in suspension is controlled by stream velocity and settling velocity of sediments
    - **Settling velocity** is the speed at which a particle falls through a still liquid

- **Bedload**
  - Coarse sands, gravel, and boulders move along the stream bed by **saltation** (skipping or jumping)
  - Larger particles slide or roll along the bottom
  - Less rapid and more localized than transport via suspended load
  - Coarse gravels may only be moved during times of high flow while boulders move only during exceptional floods

---

### The Work of Running Water

- **Transport of Sediment by Streams**
  - **Dissolved load**
  - **Suspended load**
    - The largest part of a stream’s load is carried in **suspension**
      - Usually only fine sand, silt, and clay are carried this way
      - During a flood stage, larger particles can also be carried in suspension
    - Amount of material carried in suspension is controlled by stream velocity and settling velocity of sediments
      - **Settling velocity** is the speed at which a particle falls through a still liquid
  - **Bedload**
    - Coarse sands, gravel, and boulders move along the stream bed by **saltation** (skipping or jumping)
    - Larger particles slide or roll along the bottom
    - Less rapid and more localized than transport via suspended load
    - Coarse gravels may only be moved during times of high flow while boulders move only during exceptional floods

- **Capacity and competence**
  - Describes a stream’s ability to carry solid particles
    - **Capacity** is the maximum load of solid particles a stream can carry per unit time
      - The greater the discharge, the greater the capacity
    - **Competence** is the maximum particle size a stream can transport
      - Streams with a faster velocity have a higher competence
The Work of Running Water

- Deposition of Sediment by a Stream
  - Deposition occurs when a stream’s velocity is less than the settling velocity
  - Particles of the same size are deposited at the same time in a process called sorting
    - Larger particles settle out first
  - Sediments deposited by streams are called alluvium

Stream Channels

- Bedrock Channels
  - Bedrock channels are cut into the underlying strata
    - Typically form in the headwater region where streams have a steep slope
    - Energetic flow tends to transport coarse particles that actively abrade the bedrock channel
    - Steps and pools are common features of bedrock channels
    - Channel pattern is controlled by the underlying geology

Stream Channels

- Alluvial Channels
  - Alluvial channels form in sediment previously deposited in the valley
    - Typically associated with a floodplain
    - Channels can change shape as material is eroded and transported
    - Channel shape is affected by the average size of sediment, gradient, and discharge
    - Channel patterns reflect the stream’s ability to transport load at a uniform rate while expending the least amount of energy

Stream Channels

- Meandering Channels
  - Streams transport suspended sediment in broad, sweeping bends called meanders
    - Relatively deep, smooth channels, primarily transporting mud
    - Meandering channels evolve over time
      - The outside of a meander (cutbank) is a zone of active erosion
      - The inside of a meander (point bar) is a zone of deposition
      - Through time, the bends in a channel can also migrate and eventually join together
        - A meander that has been cut off from joined bends is called a cutoff oxbow lake

Formation of Cut Banks and Point Bars

Formation of an Oxbow Lake
Stream Channels

- Alluvial Channels
  - Braided channels
    - A braided channel is a complex network of converging and diverging channels that thread among numerous islands or gravel bars
    - A large portion of the load is coarse material
      - Bank material is easily eroded and reworked
    - Stream has a highly variable discharge
      - Commonly form at the toe of a glacier

Braided Stream

Shaping Stream Valleys

- A stream valley is the channel and the surrounding terrain that directs water to the stream
  - Alluvial channels have wide valley floors
  - Bedrock channels have narrow V-shaped valleys
    - In arid climates, narrow valleys have nearly vertical walls—called slot canyons

Slot Canyon

Shaping Stream Valleys

- Base Level and Graded Streams
  - The base level is the lowest point to which a stream can erode
    - Ultimate base level is sea level
    - Local or temporary base level includes lakes, resistant layers of rock, and large rivers
      - All limit a stream’s ability to downcut its channel
  - Changing conditions causes readjustment of stream activities
    - Raising base level causes deposition
    - Lowering base level causes erosion

Building a Dam
Shaping Stream Valleys

• Base Level and Graded Streams
  – A graded stream only transports sediment
    • Has the necessary slope and other channel characteristics to maintain the minimum velocity required to transport the sediment supplied to it
    • No net erosion or deposition of sediment
  – Consider displacement by a fault along a graded stream:
    • Raises a layer of resistant rock
    • Forms a waterfall—concentrates energy here
    • Serves as a temporary base level
    • Called a knickpoint

Changes in Base Level

Shaping Stream Valleys

• Valley Deepening
  – A steep gradient and channel far above base level leads to downcutting of the channel
    • Lowering of the streambed toward base level
    • V-shaped valleys with steep sides are the result of severe downcutting
    • Rapids and waterfalls are prominent features in V-shaped valleys
      – Occur where the stream’s gradient increases significantly

Yellowstone River

The Retreat of Niagara Falls

Niagara Falls ("American" Falls)
**Shaping Stream Valleys**

- **Valley Widening**
  - As a stream approaches a graded condition, the shape changes to a meandering pattern
  - Downcutting is less dominant
  - More energy is directed laterally (side to side)
  - Continuous erosion from moving meanders produces a floodplain (flat valley floor)
  - The floodplain will be inundated when the stream overflows its banks
  - Erosional floodplain (floodplain is being formed)
  - Depositional floodplain (produced by major fluctuations in base level or climate conditions)

**Development of an Erosional Floodplain**

**Shaping Stream Valleys**

- **Incised Meanders and Stream Terraces**
  - **Incised meanders** are meanders flowing through steep, narrow bedrock valleys
  - Meanders first develop on a floodplain
  - Base level drops causing the meanders to start downcutting
  - Once the river has adjusted to the new base level, it will produce a new floodplain below the old one
  - The flat remnants of the old flood plain are called terraces

**Incised Meanders**

- Before uplift of the Cretaceous Plateau, the river was streamlining as a floodplain.
- During uplift of the plateau, the meanders drowned because of the streamlining process.

**Stream Terraces**

- **Multiple terraces along the Bow River, Cochrane, Alberta**
Deltas

- Deltas form when sediment-charged streams reach a temporary or ultimate base level and enter a relatively still body of water
  - The stream’s forward velocity decreases, lowering its carrying capacity
  - Sediments are deposited by the dying current and produce three types of beds
    - Foreset beds
    - Topset beds
    - Bottomset beds

Depositional Landforms

- Size of sediment varies in the delta
  - Coarse sediments are deposited close to the river mouth (foreset beds)
  - Fine sediments are deposited at the outer edge of the delta (bottomset beds)
  - As a delta grows outward, the stream’s gradient continually decreases
    - The channel becomes choked with sediment
    - River seeks shorter, steeper routes to base level
    - The main channel divides into several smaller channels in the delta called distributaries

Formation of a Delta

- The Mississippi River Delta
  - History and Structure
    - The Mississippi River Delta is actually a series of seven coalescing deltas
    - Present delta, called a bird-foot delta, formed over the past 500 years
    - The river is trying to cut through to the Atchafalaya River
      - The river would abandon its current course through New Orleans and the lowermost 500 km of its channel
      - Engineering structures currently keep the river from migrating

Growth of the Mississippi River Delta

- Natural Levees
  - Natural levees are raised areas adjacent to the channel formed during flood events
    - Water overtops banks and flows out like a flat sheet, loses velocity instantly and drops coarse material near the banks
    - Fine material is laid out on the valley floor
  - Following a flood event, levees prevent water from returning to the stream channel
    - Poorly drained back swamps form in the flood plain
    - Yazoo tributaries flow in the back swamp area before reaching the main stream channel
Formation of a Natural Levee

Depositional Landforms

- Alluvial Fans
  - Alluvial fans are fan-shaped deposits of sediments at the base of mountain fronts
  - The stream emerges onto a flat lowland, the gradient drops, and sediment is deposited
  - More prevalent in arid climates
  - Mountain streams carry mostly sand and gravel, thus alluvial fans are composed of the same material
  - Fan shape is produced in much the same way as a delta—the flow divides into distributary channels

Alluvial Fan in Death Valley

Floods and Flood Control

- A flood occurs when the stream exceeds the capacity of its channel
  - The most common and most destructive geologic hazard
- Common types of floods:
  - Regional floods
  - Flash floods
  - Ice-jam floods
  - Dam-failure floods

Floods and Flood Control

- Regional floods
  - Seasonal floods that typically result from spring rains or rapid melting of snow
  - Example: 2011 in the Mississippi River

Floods and Flood Control

- Flash floods
  - Occur with little to no warning
  - Produce rapid rises in water levels and can have devastating flow velocities
  - Mountainous areas are extremely susceptible due to steep slopes
  - Example: August 2011 flash floods in upstate New York and Vermont from Hurricane Irene
**Flash Floods in Vermont**

- **Ice-jam floods**
  - Ice forms in rivers creating dams that will break when temperatures rise
  - Common problem with north-flowing rivers in the northern hemisphere

- **Dam-failure floods**
  - Dams designed to contain small or moderate floods face a larger volume flood event
  - Dams fail and release large amounts of water as a flash flood
  - Example: Johnstown Flood of 1889

**North Flowing Siberian Rivers**

- **Flood Recurrent Intervals**
  - An estimate of how often a flood of a given size can be expected to occur
  - A “25-year event” would be much smaller but four times more likely to occur than a “100-year flood”
  - “100-year flood” means that there is a 1 percent probability in a given year for a flood of that size
  - Stream gage data must be collected for 20–30 years to make a reasonable calculation

**Floods and Flood Control**

- **Flood Control**
  - **Artificial levees**
    - Most commonly used stream-containment structures
    - Earth mounds built on river banks to increase the capacity of the channel
      - Not built to withstand, and often fail in floods
      - When exceptional floods threaten, openings are created to divert water out of the channel and into floodways
  - **Channelization**
    - Altering a stream channel to make flow more efficient
    - Can make the stream straighter or deeper
      - Accelerates erosion

**Birds Point-New Madrid Floodway**
Floods and Flood Control

- Flood Control
  - Flood-control dams
    • Built to store floodwater and release it slowly (in a controlled manner)
    • Typically provide water for irrigation and hydroelectric power
  - Nonstructural approach
    • Best approach to flood control is to limit development within floodplains of high-risk flood areas