[The Grand Canyon] is, of course, altogether valueless. It can be approached only from the south, and after entering it there is nothing to do but leave. Ours has been the first, and will doubtless be the last, to visit this profitless locality. It seems intended by nature that the Colorado River, along with the greater portion of this lonely and majestic way, shall be forever unvisited and undisturbed.

Lieutenant Joseph Ives (1861)

One could almost say, then, that the history of the Colorado River contains a metaphor for our time. One could say that the age of great expectations was inaugurated at Hoover dam - a fifty-year flowering of hopes when all things appeared possible. And one could say that amid the salt-encrusted sands of the river's dried up delta, we began to founder on the Era of Limits.

Marc Reisner
Introduction

- A stream is a channel flow of any size.
- Streams are responsible for many of our most spectacular landforms.
- The Colorado River is one of the most regulated streams in the U.S.
- Human actions have often caused changes in natural stream flow.
- By understanding stream actions and the factors that affect stream flow we can make wiser land use decisions and protect people from flooding.

A *stream* is a channel flow of any size. Geologists use the term stream to refer to the smallest creek or the largest river. Streams bring water to irrigate crops and to supply our domestic needs. We have dammed streams to create reservoirs, polluted waterways with industrial and agricultural wastes, and altered stream channels to ensure ease of transportation. In modifying stream systems we have often discovered belatedly that the original natural system worked best.

No U.S. stream is as regulated as the *Colorado River* (Fig. 1), an almost iconic feature of the western landscape. Steep canyon walls along much of its length created a physical barrier for early travelers to whom the river represented a tantalizing yet inaccessible water source. The canyon country of the Southwest was among the last to be mapped in the U.S. The region was explored by Major John Wesley Powell, a one-armed U.S. Civil War veteran, and the first person to lead a party of men through the treacherous rapids of the Grand Canyon in 1869. The river was increasingly eyed as a potential water supply source as population in the Southwest, particularly California, increased.

Rising above 3,000 meters (10,000 feet) in the shadow Long's Peak, in Rocky Mountain National Park, *Colorado*, the river flows west until it is joined by the Green River and turns south to carve a series of deep sinuous canyons in the arid plateaus of southern Utah and northern Arizona (Fig. 1). The river eventually finds the sea in the *Gulf of California*, forming a broad delta. The river drops over 3 km (2 miles) in elevation over its 2,320 km length (1,450 miles) with an average *gradient* of a little over 1 meter per kilometer. The next section examines the *stream profile*, how stream characteristics change from the relatively steep and narrow channels near the
stream source to the gentle gradients and broad channels near the river’s mouth.

Eventually, much of the lower course of the river was corralled behind massive dams. Structures such as the Hoover Dam (Fig. 1) were among the largest constructed features in the world at the time they were built. One consequence of dam building was the alteration of the physical environment downstream from the largest dams. Regulated flows are much lower than the peak stream flow prior to dam construction. Under pre-dam conditions, spring floods eroded sand bars from the channel and formed beaches along the canyon walls. The rapid flows cleared the stream of obstructions created by boulders deposited at the mouths of tributary streams. These
processes and the ecological environments they created disappeared following dam construction.

In a spectacular experiment, scientists with the U.S. Geological Survey utilized *controlled floods* downstream from Glen Canyon Dam to restore some of the pre-dam channel characteristics (Fig. 2). The sections on *stream profiles* and *channel migration* investigate the role of stream velocity in controlling erosion and deposition of sediment within and adjacent to stream channels.

The Colorado River *drainage basin* (Fig. 1), the area drained by the river and its tributaries, occupies 626,777 square kilometers (243,000 square miles) in seven states (Wyoming, Colorado, Utah, New Mexico, Arizona, Nevada, California). The basin has been artificially divided into two halves, the upper and lower Basins. The boundary between the basins crosses the river at Lee's Ferry, a few miles downstream from Glen Canyon Dam (Fig. 1). As the only major stream flowing through the southwest, the Colorado River represents a rare water source in an otherwise dry land. Today water diversion structures siphon off the river's water to ensure a steady supply of water for cities as far away as San Diego and to provide water to irrigate the winter vegetable crops of the Imperial Valley, southern California.
Natural variations in streamflow in the Colorado and other rivers are monitored daily by a nationwide network of stream gaging stations. The section on streamflow examines how scientists measure variations in flow of streams and links readers to real-time data from online gaging stations for the Cuyahoga River, northern Ohio.

Figure 3. Streamflow hydrographs for the Colorado River at Lee's Ferry before (1957, top) and after (1997, bottom) construction of Glen Canyon dam. Graph of 1983 (middle) reflects a surge in flow following excessive snowmelt. Data from USGS.
Variations in streamflow in the lower Colorado River (downstream from Lee's Ferry, Fig. 1) were minimized following construction of the big dams (Fig. 3). However, even the most regulated systems are subject to surprises. Heavier than normal snowfall in the winter of 1982/1983 melted the following spring causing a rapid filling of reservoirs on the lower Colorado. Discharge from Glen Canyon Dam had to be increased to maximum capacity to avoid Lake Powell overtopping the dam and causing it to fail (see 1983 graph, Fig. 3). As it was, the increased flow ripped out chunks of bedrock from spillway tunnels, threatening the survival of the dam. Rapid snowmelt is one cause of flooding, others are described in the section on floods and the widespread Mississippi River flood, 1993, the most devastating flood in U.S. history, is singled out for special attention in a separate section.

Large dams are effective agents for flood control as long as floodwaters can be stored in reservoirs to be released slowly when the threat of flooding has receded. This plan works as long as there is sufficient storage capacity to accommodate excess runoff. Dams and other flood control structures were built along the lower Colorado River to generate hydroelectric power, provide a stable water supply, create reservoirs for recreation, and to protect against potential floods.

Flooding wouldn't seem to be a big issue in the desert Southwest but the entire flow of the Colorado broke through an irrigation canal in 1905 and was redirected into the Imperial Valley in southern California. The floods turned the low-lying Salton sink into the Salton Sea (Fig. 4), forming an inland lake that evaporation has subsequently rendered saltier than the nearby Gulf of California. The Salton Sea is the largest body of water in California. Another major flood in the lower Colorado in 1916 prompted the initial steps toward construction of the Hoover Dam (Fig. 1). Construction of the dam, the first major dam on the river, began in 1933 and was completed in 1935.

Figure 4. The Salton Sea was formed as a result of flooding of a low-lying area in southern California by the Colorado River in 1905. Image from USBR Lower Colorado Regional office photo library.
Today the water of the Colorado River does not reach its delta. Water is extracted through irrigation canals (Fig. 5) and aqueducts to supply agriculture and cities both within and beyond the river basin. So much water is removed that the modest remainder evaporates in the desert of northern Mexico short of the Gulf of California.

Figure 5. Irrigation canal, southern Arizona. Similar canals transport water from the Colorado River to irrigate fields throughout Arizona and southern California. Image from the Bureau of Reclamation's Lower Colorado Regional office photo library.

Think about it . . .
Create a concept map that illustrates the potential history of precipitation falling as snow in a mountainous area in the watershed (drainage basin) of the Colorado River.

Stream Profile

- Stream gradient represents the change in elevation of a stream over a given horizontal distance.
- Stream gradient decreases downstream.
- High-gradient streams often occupy steep-walled V-shaped valleys.
- Low-gradient streams are characterized by broad curves called meanders.
- Velocity decreases as the length of the wetted perimeter (channel banks and bed) increases.
- A floodplain is a broad, flat plain adjacent to a stream channel.
- Riparian wetlands are located on floodplains alongside stream channels.
- Streams deposit sediment to form a delta when velocity decreases.
Stream gradient, the change in elevation over a specific horizontal distance, gradually decreases along the length of a stream channel (Fig. 6). The steepest gradients are found in steep-sided mountain stream valleys that may drop 40 to 60 meters per kilometer (210-320 feet/mile). Streams at lower elevations typically have a sinuous course characterized by numerous broad curves (meanders). Streams approaching the river mouth may decrease in elevation by as little as a few centimeters over 1 kilometer. The rapids downstream from Lee's Ferry in the lower Colorado River mark a segment of the stream channel with a gradient of 4 meters per kilometer. In contrast, near the river's mouth the gradient diminishes to a gentle 0.1 meter per kilometer.

If all other factors were equal, stream velocity would be greatest in streams with the steepest gradients. However, these streams are also characterized by boulder-strewn channels that generate turbulence and frictional drag on stream flow, lowering stream velocity. This characteristic is channel roughness (Fig. 7). The irregular flow generated by obstructions in the stream channel is the principal reason that flow in high-gradient stream channels has lower velocity than flow in the meandering channel of a stream's lower course where channel roughness is at a minimum.

The channel banks and bed in contact with the stream are termed the wetted perimeter (Fig. 7). The frictional effects of drag from the wetted perimeter reduce stream velocity. If all other factors are equal, the channel with the smallest wetted perimeter will exhibit the highest stream velocity. The wetted perimeter length can vary for streams with similar cross sectional areas. Typically, deep narrow channels will have...
longer perimeters than broad shallow channels (Fig. 7). Stream velocity increases downstream even as stream gradient decreases. Velocity increases because stream size increases because of the addition of water from tributary streams and the relative length of the wetted perimeter decreases.

Broad flat lands alongside the stream channel are termed **floodplains**. Floodplains have often been considered prime sites for development (Fig. 8) because of their low relief, fertile soils, and ready access to water. Today floodplains are home to more people and development than ever before. Modern weather satellites and stream monitoring techniques can help protect people's lives but the damage caused by flooding has increased in step with population.

All streams transport sediment (Fig. 9); the muddier the stream the greater the sediment load. Sediments are deposited when stream velocity drops. Streams with high sediment loads may form **braided channels** as sediment is deposited to form sand bars and islands that divide the main channel into multiple smaller channels (Fig. 9).

The Mississippi delivers 200 million tons of sediment to the Gulf of Mexico each year. Rivers dump much of their sediment where they enter the relatively quiet waters of an ocean or lake;
the landform that is created is a delta (Fig. 10). The form of the delta is largely dependent on the volume of transported sediment and the actions of coastal currents that may redistribute the sediment.

Figure 9. View of the confluence of Amazon River and Rio Negro in Amazon basin near Manaus, Brazil. Note the contrast between the brown sediment-laden Amazon River and its darker sediment-lite tributary. Flow is from bottom of image toward the top. Original image courtesy of NASA.

Figure 10. Mississippi River delta, Louisiana. Note plume of sediment (white line) dumped by the distributary channels that form a "bird's-foot" delta. Constant dredging is required for oceangoing ships to navigate the main channel of the river. Click on image for larger view. Original image courtesy of NASA.
Channel Migration

- Stream velocity varies around curves in stream channels.
- Velocity is greatest on the outside of curves, least on the inside.
- Erosion occurs in areas of higher velocity near the outside of stream curves and deposition takes place in regions of low velocity on the inside of curves.
- Concurrent erosion and deposition cause stream channels to migrate laterally.
- Velocity decreases as the length of the wetted perimeter (channel banks and bed) increases.
- A floodplain is a broad, flat plain adjacent to a stream channel.

The lowermost sections of most stream channels have a sinuous course and stream velocity varies within the channel relative to bends in the stream. Maximum velocity occurs toward the outside of bends in the stream channel; stream velocity is least on the inside of bends (Figs. 11, 12).

Erosion of the channel occurs on the outer banks of streams (cut banks) where velocity is greatest and deposition occurs on inner banks (forming point bars) where velocity is least (Figs. 12, 13). The stream channel slowly migrates across the valley floor in the direction of the erosion. The interplay of erosion and deposition serves to exaggerate curves in the stream channel to form long, looping bends termed meanders (Figs. 13, 14).

Development on the floodplain (see Stream Profile) may be threatened by the lateral migration of stream channels. Cut banks may be supplemented with large rocks (riprap) in an effort to prevent further erosion and protect adjacent structures (Fig. 15).
Figure 13. Deposition and erosion around a curve in a small stream in Wyoming, showing relative positions of point bars, cut banks and maximum stream velocity (blue arrows) in a stream channel.

Figure 14. Four stages in the lateral migration of a stream channel. The meander bend grows relatively slowly (top left to top right). As the neck between the opposite banks narrows (bottom left) the stream cuts across the neck (bottom right), abandoning the curve as an oxbow lake.

Figure 15. Riprap (gray rocks) placed along the outside of a meander bend in the Cuyahoga River to prevent erosion of the stream bank and undermining of the adjacent road. Photograph taken during high flow.
Channel migration occurs by a combination of two processes, **accretion** and **avulsion** (Fig. 16). Accretion allows the point bars to grow slowly as the meander bend becomes more exaggerated. Avulsion results in rapid, dramatic changes when the river cuts through the narrow neck of a fully developed meander.

The law recognizes that it is unrealistic to try to compensate owners for the slow loss of land by erosion on the outer banks of meanders. The lost soil would be transported downstream and added to someone else's property along a point bar. It would be impossible to trace the constituent parts and to lay claim to them once they settled on a channel bank further downstream. This is the **rule of accretion** and applies as meander bends progressively migrate across valley floors. In contrast, the **rule of avulsion** concedes that ownership of land originally encircled by a meander does not change if a sudden shift in the stream channel isolates the property on the opposite bank of the stream.

**Think about it . . .**

1. Complete the Venn diagram found at the end of the chapter to compare and contrast the characteristics of streams near their origins and near their mouths.

2. Examine the image of the lower course of the Mississippi River at the end of the chapter and make some interpretations and predictions about the past and future path of the river.
Drainage Networks

- The area drained by a stream and its tributaries is a drainage basin or watershed.
- The Mississippi River drainage basin covers approximately half of the conterminous U.S.
- Drainage basins are separated by high ground termed a divide.
- Drainage patterns are governed by the underlying geology of a region.

Approximately two-thirds (68%) of Earth’s land surface contains rivers that drain to the ocean. Land that is permanently covered by ice (Antarctica) or that is characterized by hot, dry deserts typically lack stream systems.

A **drainage basin** or watershed is the area drained by a stream and its tributaries (Fig. 17). The size of the drainage basin typically increases as the size of the stream increases. The drainage basin for the Mississippi River occupies approximately half the land area of the U.S. The two principal tributaries of the Mississippi are the Missouri and Ohio Rivers. The drainage basins for each of these (and other) rivers are included within the larger Mississippi drainage basin (Fig. 17).

![Diagram of drainage basins for major tributary streams to the Mississippi River. Image modified from a map at the National Watershed Network.](image)

The Mississippi River is separated from streams that drain to the west by a **drainage divide** represented by the Rocky Mountains. Streams west of the Rockies flow to the Pacific Ocean or Gulf of California. Streams in the eastern U.S. flow to the Gulf of Mexico or the Atlantic Ocean. Drainage divides separate neighboring drainage basins (Fig. 18).
In Ohio (Fig. 19) a drainage divide separates streams that drain northward to the Great Lakes from streams that flow south to the Ohio River. The city of Akron in northeast Ohio straddles the divide between the Cuyahoga and Tuscarawas Rivers. The Cuyahoga River is part of the Great Lakes Basin and drains to the north. The nearby Tuscarawas River is a tributary of the Muskingum River. Both rivers are in the Ohio River watershed, a major tributary of the Mississippi River.
Drainage Patterns

The pattern of drainage in a basin is largely determined by the underlying geology (Fig. 20). Streams typically follow the path of least resistance, forming valleys where rock is most readily eroded or following the steepest slope gradient. Consequently, stream patterns often provide clues to the geology of the drainage basin. Dendritic drainage is characteristic of areas where the geology is relatively uniform, for example, where rock layers are horizontal. Dendritic patterns are typical of Ohio streams and of much of the Colorado River basin (Fig. 1). Streams intersect with a characteristic V-pattern in map view in dendritic drainage systems. The tip of the V points downstream.

Streams intersect at right angles in both trellis and rectangular drainage patterns. Trellis drainage is characteristic of areas with alternating parallel valleys and ridges (e.g., central Pennsylvania). Streams occupy the valleys, flowing parallel to the ridges but occasionally cutting across the geologic grain at water gaps. Rectangular patterns distinguish regions where the bedrock exhibits well-developed joints or fractures. The streams exploit the fractures as lines of weakness. Finally, radial drainage patterns are typically found on the slopes of volcanoes, where streams flow downslope, parallel to the slope gradient.

Figure 20. The four principal types of drainage pattern are related to the underlying regional geology.
Streamflow

- Discharge is the volume of water that flows past a given point in a given time.
- Stage measures the depth of water in the stream channel relative to a standard value.
- The USGS has over 7,000 stream gaging stations. Data from over half of which are available online.
- Stream gages measure the depth of water in a stream channel and the velocity of flow.
- The recurrence interval is the average time in years between floods of the same size.
- A hydrograph illustrates discharge over time.
- We can view current streamflow conditions for three sites along the Cuyahoga River and compare them to hydrographs that illustrate annual discharge.

Stream flow varies with the season and provides a key measure of the potential for flooding. Streamflow is measured as discharge or stage.

Stream stage measures the depth of water in the stream channel relative to a standard datum, an arbitrary starting point for measurement - not necessarily the bottom of the channel.

Discharge is the volume of water that flows past a given point in a given time. The volume is calculated by multiplying the area water in the stream channel (depth x width) by the velocity (distance/time) of the stream flow (Fig. 21). The

---

**Think about it . . .**

1. Go to this EPA site [http://www.epa.gov/surf2/locate/](http://www.epa.gov/surf2/locate/) and locate your watershed (drainage basin) using a place name, your zip code, or the maps provided. What is the acreage and total length of perennial river miles for your watershed?
2. Examine the image of the Nile River at the end of the chapter and interpret the type of drainage pattern represented.
dimensions of the stream channel are expressed in feet or meters and velocity is measured in feet or meters per second. Consequently the units of discharge are cubic meters (or feet) per second, i.e., discharge is the volume (cubic meters or cubic feet) of water that passes a given point in one second.

A record of "normal" stream flow is required to understand the potential risk from flooding. The United States Geological Survey (USGS) records stream flow conditions from over 7,000 gaging stations (Fig. 22) across the country (go here for a map showing locations of U.S. gaging stations). Data from over 4,000 of these stations is relayed back to the USGS using satellites. Stream gages measure the depth of water in a stream channel and the velocity of flow.

Data on stream stage is relatively straightforward to collect, because it simply requires knowledge of the height (depth) of water in the stream channel. Information on discharge is affected by stream width, a factor that is not measured by the gages. Discharge is typically estimated from established stage/discharge relations. Gaging station locations are measured periodically to ensure the stream width has remained uniform.

Figure 21. Right: Discharge can be calculated by multiplying the area of the stream channel (width x depth) by the distance traveled in a given time (velocity). Left: Measurements of stage and discharge can be used to construct a stage-discharge plot. Stage readings are then converted to discharge values using the graph data. Graph modified from original at USGS.

Figure 22. A stream gage installation on the Cuyahoga River, Akron, Ohio. View downstream from gage (left). Stream gage instrument (right) updates streamflow data several times each day via satellite.
During the massive 1993 Mississippi flood, new maximum values were established for discharge at 36% of the gaging stations in the flooded area and for flood stage at 47% of the stations. More stations recorded higher flood stages because channels had been altered to protect surrounding areas from flooding. Many of the alterations created narrower stream channels resulting in greater depths for similar discharge values.

The **recurrence interval** is the average time in years between floods of the same size (Fig. 23). Knowledge of how frequently large floods will occur provides agencies the opportunity to construct structures of sufficient scale to prevent future flood damage. However, city planners should also realize that recurrence intervals are only averages. A 100-year flood happens on average once every 100 years but from 1800-2000, two "one-hundred year" floods could have occurred in 1899 and 1901, or in 1801 and 1999.

Historical stream flow data are available for all gaging stations. Even though the length of the record varies the data can be used to illustrate seasonal or annual variability of discharge. A graph that illustrates discharge over time is termed a **hydrograph** (Fig. 24).
Cuyahoga River: Current Conditions

Current stream flow conditions are measured several times a day at three gaging stations along the Cuyahoga River (Fig. 25; Hiram Rapids, Akron, Independence). Visit each station’s website and complete the information requested. Each site contains graphs that display streamflow (discharge) and stage for the last week, and tables of data on historical flow and stage values.

Figure 24.
Hydrograph of discharge at Akron, Ohio, gaging station on the Cuyahoga River from January 1992 to December 1996. Note that discharge peaks in late winter/early spring, and minimum flows occur during the summer. Discharge is measured in cubic feet per second (CFS).

Figure 25.
Locations of three stream gaging stations on the Cuyahoga River, Ohio, that provide real-time online data on streamflow.
Floods

- Discharge is the volume of water that flows past a given point in a given time.
- A flood is the temporary overflow of a river onto adjacent lands not normally covered by water.
- The 1993 Mississippi flood was the worst in U.S. history and covered 17,000 square miles in nine states.
- Many factors may contribute to flooding, for example, torrential rains or prolonged steady precipitation, rapid snowmelt, saturated ground, urbanization, alteration of natural systems, collapse of manufactured structures.

Introduction

A riverine flood may be defined as the temporary overflow of a river onto adjacent lands not normally covered by water (Fig. 26). This definition does not take into account coastal

Think about it . . .

1. What is the discharge of a stream in a rectangular channel that is 10 meters wide, 6 meters deep, 40 kilometers long, and has a velocity of flow of 5 meters per second?
   a) 21 cubic meters per second
   b) 300 cubic meters per second
   c) 1200 cubic meters per second
   d) 2400 cubic meters per second

2. Go to the USGS real-time water data page located at http://water.usgs.gov/realtime.html, select the "state map" option (look left, under map), click on your state and find the nearest stream gaging station to your location.

3. Try the Virtual River - Discharge exercise (http://vcourseware4.calstatela.edu/VirtualRiver/index.html) that provides a detailed discussion of streamflow and guides users through the determination of stream discharge. Print the certificate upon completion of the exercise.
floods can happen anywhere. Some of the counties with the most flood declarations are located in arid southwestern states (Fig. 27) where floods are more likely to result from brief intense storms rather than prolonged rainfall. Flooding is related to the magnitude and timing of precipitation, evaporation rates, the characteristics of snowmelt, the capability of the ground to absorb water, and modifications of the physical landscape.

The most devastating flood in U.S. history occurred in the summer of 1993 when all large midwestern streams (including the Mississippi, Missouri, Kansas, Illinois, Des Moines, and Wisconsin Rivers) overflowed their banks (Fig. 28). Seventeen thousand square miles of land were covered by floodwaters in a region covering all or parts of nine states (North Dakota, South Dakota, Minnesota, Iowa, Wisconsin, Illinois, Missouri, Kansas, and Nebraska). The flood led to widespread damage, loss of life, and economic losses. It is estimated that the direct costs of the flood were over $15 billion.
Causes of Flooding

Floods occur where water on the land surface exceeds the volume of water that can be transported in stream channels and absorbed by the surrounding soil. The sudden addition of large volumes of water from heavy storms is the most common cause of flooding (Fig. 29).

Alternatively, if the long-term precipitation is greater than normal the streamflow will gradually increase until flooding occurs. Midwestern states received higher-than-normal precipitation prior to the 1993 Mississippi flood (Fig. 30). Much of the area received over 150% of normal rainfall and parts of North Dakota, Kansas, and Iowa received more than...
double their typical rainfall. The excess precipitation filled storage reservoirs and saturated the ground throughout the Midwest.

Heavy precipitation in the form of snow and ice may simply delay the flooding until temperatures rise sufficiently to cause rapid snowmelt. An abrupt prolonged rise in temperatures may be all that is necessary to cause widespread flooding. The effects of flooding are exaggerated when broken ice blocks form ice dams that block the stream channel. This situation is especially true for north-flowing streams because upstream (southern) meltwaters may rise when blocked by downstream (northern) ice dams. The spring 1997 flood of the Red River was caused by unseasonally high temperatures and submerged towns in Minnesota and North Dakota before flowing north into Canada.

Some precipitation will be absorbed by soils and will infiltrate into the earth to be taken up by plants or to add to the groundwater system. However, if the ground is saturated the excess water will be added to stream discharge. During the 1993 flood (Fig. 31), much of the midwestern lands were already saturated because of cooler-than-normal conditions during the previous year (less evaporation) so less rainfall was absorbed by soils and more runoff into streams.
Construction of roads and buildings results in paving over of natural surfaces with an **artificial impervious cover** designed to rapidly transport rainfall through storm sewers to streams. In addition, development may also **replace natural wetland reservoirs** with agricultural fields or housing projects. Riverine wetland systems act as storage reservoirs for floodwaters. Wetlands absorb floodwaters and release them slowly after the flood crest has passed. Much of the Mississippi river system had been altered over the previous century by the draining of wetlands. States bordering the Mississippi River have lost two-thirds of their original wetlands; Iowa has lost 89% of its natural wetlands, mostly to agriculture.

Finally, the collapse of constructed dams has resulted in disastrous floods around the world. Flooding following the collapse of a dam in Johnstown, Pennsylvania, on May 31, 1889, killed over 2,200 people. Several days of heavy rains caused a series of dams to burst causing widespread flooding in Henan Province, China in August 1975. Estimates are that as many as a quarter of a million people were drowned or died from disease or starvation following the floods. The flood was kept secret by the Chinese government for the next 20 years.

**Think about it . . .**
Try the on-line Virtual River - Flooding exercise (http://vcourseware4.calstatela.edu/VirtualRiver/Flooding/index.html) that provides a detailed discussion of factors associated with flooding. Print the certificate upon completion of the exercise.

**Mississippi River Flood, 1993**

- The 1993 Mississippi flood was the worst in U.S. history and covered 17,000 square miles in nine states.
- Flooding was caused by abnormal weather patterns resulting in higher-than-normal rainfall over the Midwest through June and July.
Flooding occurred along the Upper Mississippi River basin, between the river's source and the confluence with the Ohio River south of St. Louis.

Flooding did not occur in the Lower Mississippi River as it is much wider and was supplied by tributaries from areas with less rainfall.

Forty-eight people died because of the effects of the flooding and damages were estimated as $15 to 20 billion.

Introduction

The most devastating flood in U.S. history occurred in the summer of 1993 when many of the largest midwestern streams in the Missouri and Upper Mississippi drainage basins overflowed their banks. Damages from the flood event were estimated at $21 billion. All large midwestern streams including the Mississippi, Missouri, Kansas, Illinois, Des Moines, and Wisconsin Rivers flooded. Over seventeen thousand square miles of land were covered by floodwaters in a region covering all or parts of nine states (Fig. 28; North Dakota, South Dakota, Nebraska, Kansas, Missouri, Iowa, Wisconsin, Minnesota, Illinois).

Weather Conditions

The abnormal rainfall was attributed to a weather system formed when warm moist air from the Gulf of Mexico collided with cold, dry air from Canada over the Midwest. When the warm Gulf air cooled it lost the moisture it carried as rain. Normally this rainfall would have been distributed throughout the northeastern states but a stalled high-pressure system over the Southeast blocked the flow of the jet stream bringing a

Figure 32. Weather conditions for midwestern flooding, late spring and early summer, 1993.
constant stream of storms over the Midwest (Fig. 32). For nearly two months (June, July) weather patterns in the U.S. were dominated by this stationary high-pressure system.

Mississippi River System

The Mississippi River is divided into two parts. The Upper Mississippi runs from it source to Thebes, southern Illinois, where the Ohio River meets the Mississippi (Fig. 33). The Lower Mississippi runs downstream from Thebes to the Gulf of Mexico. Flooding was confined to the Upper Mississippi because the river channel widens considerably south of Thebes, and the Lower Mississippi received lower than average inflow from tributaries. The effects of the flooding were exaggerated where the waters of the Missouri River entered the Mississippi north of St. Louis (Fig. 33). The width of the combined rivers at their confluence increased to over 30 km (20 miles) in places in St. Charles County, Missouri. Over half the county was under water at the height of the flood.

People and the Flood

Nearly 50 people died as a result of the flooding, 26,000 were evacuated, and over 56,000 homes were damaged. Economic losses that are directly attributable to the flooding totaled $10 to 12 billion. Indirect losses in the form of lost wages and
production cannot be accurately calculated. The consequences of flooding were determined by land use patterns.

- The greatest economic losses occurred in cities on the floodplain. Des Moines, Iowa, located in the center of the flood region, became the largest U.S. city to lose its water supply when its water treatment plant flooded. More than 250,000 people lost drinking water for 12 hot summer days. Water pipes, contaminated by floodwaters carrying sewage and agricultural chemicals, had to be flushed out before the municipal water supply was reconnected. Economic losses in Des Moines totaled approximately $716 million.

- Hundreds of miles of roads built on the flat, wide floodplain were closed (Fig. 34). Flooding is estimated to have cost $500 million in road damage.

- The flooding submerged eight million acres of farmland (Fig. 35). Production of corn and soybeans were down 5 to 9% as a result and corn prices rose by $0.15 per bushel. Floods deposited thick layers of sand in some fields. The U.S. Soil Conservation Service spent $25 million to buy flood-prone farmlands for conversion to natural conditions (e.g., wetlands). Conversion of natural lands to farmlands

Figure 34. Flooding along Mississippi River at Quincy, Illinois, closed two bridges connecting Illinois and Iowa. Image courtesy of FEMA.

Figure 35. Corn crop destroyed by flooding, Missouri. Image courtesy of FEMA.
has resulted in greater runoff and exaggerated the effects of flooding. Modern farming methods leave plant residue on the surface and reduce runoff.

- The Mississippi River itself is a crucial part of the Midwest’s economic infrastructure. Barge traffic normally moves goods through a system of 29 locks between Minneapolis and St. Louis. Barges carry 20% of the nation’s coal, a third of its petroleum, and half of its exported grain (Fig. 36). Barge traffic was halted for two months because of flooding; carriers lost an estimated $1 million per day. Some power plants along the river saw their coal stocks dwindle from a two-month supply to enough to last just 20 days.

Figure 36. Barge traffic on the Mississippi River. Image courtesy of the U.S. Army Corps of Engineers Digital Images Library.

Think about it . . .
Use peak flow data for the Mississippi River at Keokuk, Iowa, to estimate the recurrence interval for the 1993 flood event. Go to the end of the chapter to complete the exercise.

Flood Control

- Two strategies for protecting people and property from flooding are prevention and adjustment.
- Prevention is the attempt to stop flooding from taking place by building structures in the floodplain to control streamflow.
• Engineers have attempted to control the flow of rivers by constructing levees or diversion channels, and building reservoirs to store floodwaters.
• Adjustment recognizes that flooding is inevitable and changes human activity to lessen the impact of floods.
• Adjustment measures include purchasing flood insurance or seeking help from the Federal Emergency Management Agency (FEMA) following a flood event.

The Mississippi River is one of the most heavily engineered natural features in the U.S. The character of the floodplain has changed to accommodate agriculture and urbanization. Approximately 80% of the original wetlands along the river were drained since the 1940s. The river channel itself has been artificially constrained by levees and floodwalls. These structures serve to increase the volume of water that can be held in the channel and thus increase the size of the flooded area if the levee breaks.

We can either attempt to stop natural hazards from occurring (prevention) or recognize that they will happen and modify our life styles to deal with them (adjustment).

Prevention

There are three principal ways that engineers have attempted to control the flow of rivers in the Mississippi River basin and elsewhere:
• Build levees or floodwalls to contain rising stream levels.
• Construct a floodway channel to divert floodwaters.
• Build reservoirs on tributary streams to store floodwaters for later release.

The U.S. Army Corps of Engineers was given directions to construct flood control structures (dams, reservoirs, levees) on the Mississippi River following disastrous floods in the 1930s. 

Levees. raised embankments along the stream bank (Fig. 37), may fail because the floodwater rises over the top of the structure or the levee collapses under the weight of the water. Levees and floodwalls protect people on the floodplain from most floods. However, they may not protect against the largest floods with recurrence intervals of more than 100 years. Floodplain residents may experience a false sense of security that can lead to more extensive development of flood-prone lands (the "levee effect").
Over 9,300 km of levees were damaged following the 1993 flood in the Mississippi River basin. Only 17% of federal levees were damaged, but up to 77% of locally constructed levees failed. Most levee breaks occurred south of St. Louis. St. Louis was protected by a massive floodwall. The wall developed a leak but held up over the length of the flood. Over 50 propane tanks containing over a million gallons of gas in south St. Louis presented the threat of a massive explosion. A levee break south of the city allowed the river level to drop around St. Louis and reduced pressure on the propane tanks. Many of smaller levees in rural areas failed.

An alternative to building up the banks of the river is to build a floodway or diversion channel that will transport floodwaters away from inhabited areas. Winnipeg, Canada, completed a 47 km (29 mile) floodway around the city in 1968 (Fig. 38). The floodway takes water from the Red River south of the city and loops around the developed region before dumping the water back into the river further downstream. Winnipeg was unaffected by the 1997 Red River flood while cities upstream in North Dakota (Fargo, Grand Rapids) were severely damaged by flooding.
The construction of dams for flood control follows the premise that floodwaters can be stored in reservoirs to be released slowly when the threat of flooding has receded (Fig. 39). This plan works as long as there is sufficient storage capacity to accommodate excess runoff. Unfortunately, reservoirs were already near capacity following higher-than-normal precipitation in 1993 and were largely ineffective in preventing flooding.

Large dams and reservoirs on the Mississippi River would hinder transportation. Therefore, the majority of flood control structures in the Upper Mississippi River basin are located in the Missouri River basin. The Missouri basin can be further subdivided and most of the dams are located in a southern sub-basin, the Kansas River basin. Approximately 85% of stream flow in the Kansas basin is controlled, i.e., it flows through dams (Fig. 40).
Adjustment

Steps taken to adjust to flood events include:

- Purchase insurance through the National Flood Insurance Program.
- Seek assistance from the Federal Emergency Management Agency (FEMA) following a flood event.
- Move residents and structures from floodplains and/or restore natural riverine environment.

Typical residential home insurance does not cover losses associated with flooding. The National Flood Insurance Program was established in 1968 by the federal government to provide some financial protection for floodplain residents. Approximately 10% of midwestern residents living in flood-prone areas had flood insurance prior to the 1993 floods. Over 11 million buildings are located in flood-prone areas in the U.S. but only 19% of owners have purchased flood insurance.

FEMA was created in 1979 to provide financial assistance to people and areas affected by natural disasters. Not all areas affected by flooding are declared disaster areas (Fig. 27). Residents who don’t buy flood insurance must gamble that they will receive disaster aid from FEMA to help cover cleanup costs.

Two recent examples illustrate that the tide in flood control appears to be turning from prevention measures toward adjustment. Following the 1993 flood the residents of Valmeyer, Illinois, decided to relocate their town to a bluff overlooking its original location on the floodplain 6 km (4 miles) from the river. In Napa, California, voters approved a sales tax increase to fund a project that would modify land use...
patterns in the floodplain of the tidal Napa River. The plan will remove some levees and restore wetlands along the riverbank where it loops through downtown Napa. In addition a floodway will be added to reroute discharge during big floods.

Think about it . . .

1. Examine the map of U.S. flood declarations by county (Fig.27) and suggest possible explanations for the high incidence of floods in different regions of the map. Why do some counties have no flood declarations?

2. The National Flood Insurance Program developed a rating system that evaluates community efforts to better manage the floodplain. Citizens of participating communities receive reductions in their flood insurance rates. Create your own evaluation rubric for floodplain management activities. Go to the end of the chapter to complete the exercise.

Summary

1. What is a stream?
A stream is a channel flow of any size. Geologists use the term stream to refer to the smallest creek or the largest river. The size and number of streams increase with precipitation.

2. What is stream gradient?
Stream gradient is the change in elevation of a stream over a specific horizontal distance. Gradient decreases along the length of a stream channel from its source to its mouth. The steepest gradients are found in steep-sided mountain stream valleys that may drop 40 to 60 meters per kilometer. Streams approaching the river mouth may decrease in elevation by as little as a few centimeters per kilometer.

3. What factors affect stream velocity?
Stream velocity is determined by stream gradient (steeper = faster), channel roughness (more roughness = less velocity), length of the wetted perimeter (stream bank and channel floor; in streams of equal cross section area, less wetted perimeter =
Stream velocity increases downstream because of decreasing channel roughness and an increase in stream discharge.

4. How does stream velocity vary within a stream channel? Stream velocity varies within the channel relative to curves (meanders) in the stream. Maximum velocity occurs toward the outside of curves in the stream channel; stream velocity is least on the inside of curves.

5. How does channel migration occur? Channels migrate laterally across a floodplain because of the interplay of erosion and deposition associated with meanders. Erosion occurs in areas of higher velocity (outside of meanders) and deposition is associated with areas of lower velocity (inside of meanders). The stream channel slowly migrates across the valley floor in the direction of the erosion.

6. What are avulsion and accretion? Channel migration occurs by a combination of accretion and avulsion. Accretion represents the addition of material to point bars as the meander bend becomes more exaggerated. Avulsion results in rapid, dramatic changes when the river cuts through the narrow neck of a fully developed meander.

7. What landforms are associated with stream systems? High-gradient streams are often characterized by relatively narrow V-shaped valleys. Stream channels may have waterfalls where the stream flows over a resistant rock. Low-gradient streams exhibit sinuous channels characterized by meanders. Point bars are formed by deposition on the inside of meanders and erosion forms cut banks on the outside of a meander. Flat land adjacent to streams is termed the floodplain. Streams with a high sediment load may have a braided form, with several smaller channels flowing around sand bars. Most streams build a delta at their mouth as sediment is deposited when the stream enters the relatively calm waters of a lake or ocean.

8. What is a drainage basin? A drainage basin or watershed is the area drained by a stream and its tributaries. The size of the drainage basin typically increases as the size of the stream increases. For example, the drainage basin for the Mississippi River occupies approximately half the land area of the U.S. Drainage basins are separated by drainage divides.
9. How is the flow of water in a stream measured?
Stream flow can be measured as discharge or stream stage.
Discharge is the volume of water that flows past a given point in a given time. The volume is calculated by multiplying the area of the stream channel (depth x width) by the velocity (distance/time) of the stream flow. Stream stage represents the depth of water in the stream channel relative to a standard datum (an arbitrary starting point for measurement - not the bottom of the channel).

10. Where is stream flow measured?
Stream flow is measured at over 7,000 stream gage stations across the U.S. Data are collected on stream stage by measuring the depth of water in the stream channel relative to some fixed marker. Discharge is typically estimated from established stage/discharge relations.

11. What is the recurrence interval of a flood?
The average time in years between floods of the same size. Unfortunately many stream gage records do not extend back before the beginning of this century (most don't even come close) so the record used to determine the average value is really too short to estimate the recurrence interval for "100"-year floods.

12. What are the principal causes of flooding?
Flooding of streams can be defined as the temporary overflow of a river onto adjacent lands not normally covered by water. Factors that may contribute to flooding include: (a) heavy storms adding large volumes of water over a short time interval; (b) above normal long-term precipitation; (c) rapid snowmelt, especially in north-flowing rivers; (d) Saturated soils; (e) natural vegetation replaced by impervious cover (roads, buildings); (f) storm sewers transport run-off more rapidly to streams; (g) loss of wetlands; and, (h) collapse of constructed structures (dams).

13. What is the most expensive flood in U.S. history?
The 1993 midwestern flood on the Mississippi River and its tributary streams was the most expensive flood in U.S. history. The flood covered 17,000 square miles in nine states. Flooding was caused by abnormal weather patterns resulting in higher-than-normal rainfall over the Midwest through June and July. Flooding occurred along the Upper Mississippi River basin, between the river's source and the confluence with the Ohio River south of St. Louis. Flooding did not occur in the Lower
Mississippi River because it is much wider and was supplied by tributaries from areas with less rainfall.

14. What methods can be employed to stop flooding? Prevention measures, methods to control the amount of water in a stream include; (a) levees or floodwalls (common on the Mississippi River); (b) floodway channels to divert floodwaters (e.g. Red River floodway, Winnipeg); (c) dams and reservoirs on tributary streams to store water for later release (common on the Missouri River).

15. Are there any alternatives to construction of massive structures? You bet. Adjustment represents an alternative strategy to move people or structures out of the path of potential floods or to seek financial assistance to deal with the costs of flooding. Federal programs such as the National Flood Insurance Program or agencies like the Federal Emergency Management Authority can provide insurance against flooding or disaster aid to affected home owners. Recently residents in flood-prone areas have either moved their town (Valmeyer, IL) or voted to restore floodplain wetlands (Napa, CA) in an effort to lessen the effects of later flooding.
Venn Diagram: Stream Characteristics

Use the Venn diagram, below, to compare and contrast the similarities and differences between streams near their origins and near their mouths. Consider a stream like the Colorado or a river near where you live and think about how it changes character along its length. Print this page and write features unique to either group in the larger areas of the left and right circles; note features that they share in the overlap area in the center of the image.
Image Analysis: Mississippi River Radar Image

Examine the image of part of the lower course of the Mississippi River on the next page. This picture was taken by the Spaceborne Imaging Radar aboard the Space Shuttle. The long axis of the image is approximately 40 km in length. North is to the top right. (Image courtesy of NASA's Visible Earth site). This section of the river represents part of the state border between Arkansas, Louisiana, and Mississippi. Louisiana and Arkansas lie above (west of) the river and Mississippi is below (east of) the river. This region is characterized by rich farmland (purple) where a variety of crops are grown. The green regions bordering the river are undeveloped forested areas. The river is the black band that curves across the image from the top right-hand corner.

1. Interpret the image and discuss (below) the history of this section of the river.

2. Identify where erosion and deposition are occurring along the stream channel and label those locations E (erosion) and D (deposition) on the blank map on the right.

3. Use the blank map to the right of the image to draw an earlier course of the channel.

4. Describe how velocity and depth changes between points X and Y on the image and plot how you expect velocity and depth to vary from X to Y on the graphs below.

5. Predict where the river will be if we were to revisit this area 50 years from now.
Image Analysis: Nile River

Examine the two images, below, of part of the Nile River as it flows through the Sudan. The lower picture was taken by the Spaceborne Imaging Radar aboard the Space Shuttle. The long axis of the image is approximately 50 km in length. North is to the top right corner of the images. The river flows from left to right.

The thick, white band in the top right of the radar image is an ancient channel of the Nile that is now buried under layers of sand. This channel cannot be seen in the upper photograph and its existence was not known before this radar image was processed.

1. What drainage pattern is represented by these images?  
2. Interpret the history of this section of the river.

Image courtesy of NASA's Visible Earth site.
Flood Recurrence Interval: Mississippi River, Keokuk

The table below presents peak flow data for the Mississippi River at Keokuk, Iowa, 1943-1992. This data set ends the year prior to the 1993 Mississippi River flood. We will use these data to estimate the recurrence interval for the 1993 flood event.

1. Complete the table below by calculating the remaining recurrence intervals (RI) for the flood events of 1965, 1969, 1976, and 1972.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Date</th>
<th>Discharge (ft$^3$/sec)</th>
<th>RI=(N+1)/rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1973</td>
<td>344,000</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>1965</td>
<td>327,000</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1960</td>
<td>289,500</td>
<td>16.7</td>
</tr>
<tr>
<td>4</td>
<td>1986</td>
<td>268,000</td>
<td>12.5</td>
</tr>
<tr>
<td>5</td>
<td>1951</td>
<td>265,100</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>1974</td>
<td>260,000</td>
<td>8.3</td>
</tr>
<tr>
<td>7</td>
<td>1979</td>
<td>257,000</td>
<td>7.1</td>
</tr>
<tr>
<td>8</td>
<td>1944</td>
<td>256,000</td>
<td>6.2</td>
</tr>
<tr>
<td>9</td>
<td>1952</td>
<td>253,800</td>
<td>5.5</td>
</tr>
<tr>
<td>10</td>
<td>1969</td>
<td>253,000</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1975</td>
<td>252,000</td>
<td>4.5</td>
</tr>
<tr>
<td>12</td>
<td>1947</td>
<td>245,700</td>
<td>4.2</td>
</tr>
<tr>
<td>13</td>
<td>1986</td>
<td>241,000</td>
<td>3.8</td>
</tr>
<tr>
<td>14</td>
<td>1948</td>
<td>233,600</td>
<td>3.6</td>
</tr>
<tr>
<td>15</td>
<td>1982</td>
<td>225,000</td>
<td>3.3</td>
</tr>
<tr>
<td>16</td>
<td>1962</td>
<td>224,100</td>
<td>3.1</td>
</tr>
<tr>
<td>17</td>
<td>1983</td>
<td>224,000</td>
<td>2.9</td>
</tr>
<tr>
<td>18</td>
<td>1946</td>
<td>223,300</td>
<td>2.8</td>
</tr>
<tr>
<td>19</td>
<td>1967</td>
<td>221,200</td>
<td>2.6</td>
</tr>
<tr>
<td>20</td>
<td>1976</td>
<td>214,000</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1972</td>
<td>192,000</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1954</td>
<td>181,400</td>
<td>1.67</td>
</tr>
<tr>
<td>40</td>
<td>1970</td>
<td>140,000</td>
<td>1.25</td>
</tr>
<tr>
<td>49</td>
<td>1977</td>
<td>79,800</td>
<td>1.02</td>
</tr>
</tbody>
</table>

N = number of readings (49)  
Rank = order of readings
2. Plot the discharge vs. RI for *at least* 10 points on the graph provided. Draw a straight line through the plotted points with RI values of 2 or more and estimate the size of 100-year and 500-year floods for this gaging station.

3. Compare the predicted flood discharge against the discharge of the 1993 Great Mississippi flood (446,000 ft³/sec). How frequently do floods of this magnitude occur at this site?
Community Flood Management Evaluation Rubric

Communities must meet some basic requirements for citizens to receive purchase insurance policies from the National Flood Insurance Program (NFIP). The NFIP developed a community rating system (CRS) to encourage additional community activities that would lead to a further reduction in flood losses. One goal of the program is to reduce the money spent by the NFIP to help cities recover from flood events. The CRS evaluates community efforts to better manage activities in the floodplain. Over 900 communities currently participate in this program. CRS communities fall into 1 of 10 classes. Citizens of highly-rated class 1 communities would receive insurance rate reductions of 45% whereas class 10 communities receive no reduction in their rates.

Create your own evaluation rubric for floodplain management activities that identifies some of the potential steps a community could take to increase its status in the CRS. Identify at least one potential activity from each of the following four categories: Public Information, Mapping and Data Collection, Flood Damage Reduction, and Flood Preparedness and Regulation. Note: none of these activities should involve building new flood protection structures.

Briefly describe each activity in the table on the next page and assign it a points value. The maximum total score for your rating system is 100. Some activities will be more useful than others so award points accordingly. One activity has been completed as an example.
<table>
<thead>
<tr>
<th>Activity</th>
<th>Category</th>
<th>Description</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard disclosure</td>
<td>Public information</td>
<td>Make sure that potential purchasers of flood-prone properties are aware of the hazard.</td>
<td>1</td>
</tr>
</tbody>
</table>

**Total Score**: 100