Missouri Highway and Transportation Department.

FLOODS AND HUMAN INTERACTIONS

The material that is contained on the following pages was reprinted from the text entitled *Natural Hazards and Disasters* by Donald Hyndman and David Hyndman. In their book the focus is on Earth and atmospheric hazards that appear rapidly, often without significant warning. With each topic they emphasize the interrelationships between hazards, such as the fact that building dams on rivers often leads to greater coastal erosion and wildfires generally make slopes more susceptible to floods, landslides, and mudflows. By learning about the dynamic Earth processes that affect our lives, the reader should be able to make educated choices about where to live, build houses, business offices, or engineering projects. People do not often make poor choices willfully but through their lack of awareness of natural processes.

Effects of Development on Floodplains

Long before Europeans arrived in North America, Native Americans built their houses on high ground or, lacking that, built mounds to which they could retreat in times of flood. European descendants, however, built levees to hold back the river. In spite of extensive high levees, more than 70,000 homes in the Mississippi River basin flooded in 1993, predominantly those of poor people living on the floodplains where the land is less expensive. Outside the area covered by the floodwaters, life went on almost untouched, but those nearby worried about flooding if the levees failed.

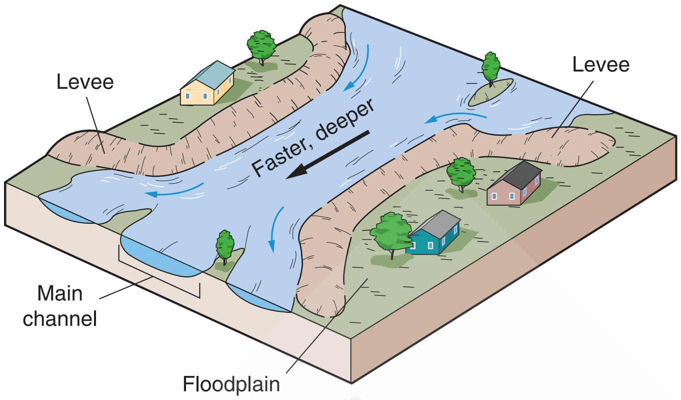


FIGURE 12-1. Levees that constrict the flow of a stream cause water to flow faster and deeper past levees. This causes flooding both upstream and downstream.

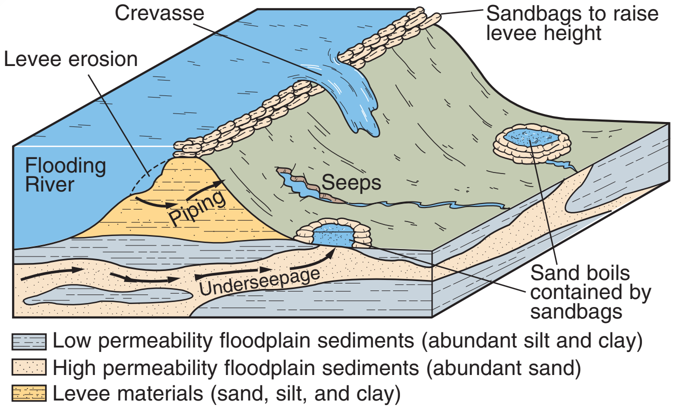
Levees

Most **levees** are constructed from fine-grained sediments dredged from the river channels or the floodplains. Different materials have different advantages. Compacted clay resists erosion and is nearly impermeable to floodwater but can fail by slumping. Crushed rock is permeable but less prone to slumping. During the1993 floods across the Mississippi River basin, locals, National Guard personnel, and others dumped loads of crushed rock and filled sandbags to raise the height of critical levees across the region. For days and weeks on end, it seemed that the work would never stop. As the higher levees raised river levels, they became saturated, causing slumping. Crushed rock in the levees minimized that. People inspecting a levee would sound an alarm if they found a leak. Cloudy water indicated that soil was being washed out of the levee through a process called **piping.** Wave erosion, slumping, or piping damaged or caused the failure of more than two-thirds of the levees in the upper Mississippi River drainage.

Levees did save some towns from flooding, but it is the levees themselves that created much of the problem. Every levee keeps floodwater from spreading out over its floodplain. All of the floodwater that should have spread over the floodplain is confined between the levees, causing the flood flow to be many times deeper and faster. A few towns on the floodplain are not protected by levees. When the water rises, people merely move out, then clean up afterward. Grafton, Illinois, at the confluence of the Illinois River with the Mississippi, is such a place, but after six big floods in twenty years, some people began to think about a change. When finished, they will have moved much of the town to higher ground with the help of funds from various federal agencies. Small towns such as Cedar City and Rhineland, Missouri, accepted a governmental buyout of their flood-damaged homes and moved off the floodplain. The homes were bulldozed to create public parkland.

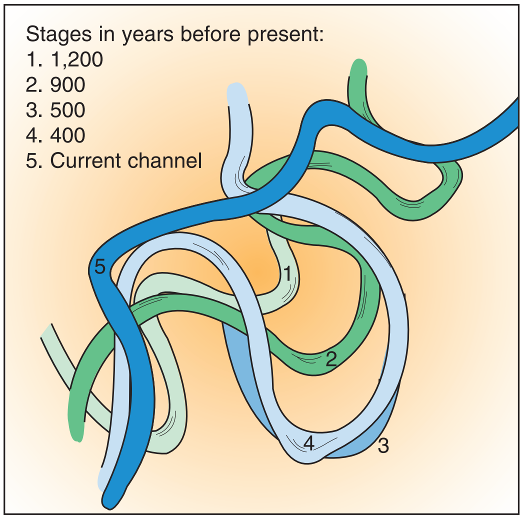
People's typical response to unwanted action by a stream is to treat the symptoms and not consider the consequences of such treatments. Individuals, municipalities, states, and even the U.S. Army Corps of Engineers commonly try to "protect" floodplain areas from floods by building levees and then higher levees. Historically, levees were typically built on top of original **natural levees,** which are at the edge of the stream channel. Although a levee or dike may be initially of sufficient height to constrain a 100-year flood, the stream will eventually overtop the levee in a larger flood. Changes such as urbanization, levee construction, or channelization in the upstream drainage basin can cause flooding both upstream and downstream of the constricted river stretch that is "protected" by levees (▶Figure 12-1). Upstream of the channelized section, water levels rise because the flow is constricted, causing flooding. Immediately downstream, the water level is higher because it is deeper within the constricted area. Flooding will thus commonly occur both upstream and downstream where it would not have occurred before the levees were built.

Most people feel safe when they live on floodplains that they believe are protected by levees. They think flooding can only occur behind a levee if it is overtopped. Over-



U.S. Army Corps of Engineers.

FIGURE 12-2. A levee may fail by overtopping, seeping through, or piping.



Modified from Farrell.

▶**FIGURE 12-3.** The Mississippi River at False River, Louisiana, shows gradual migration of meanders before the formation of a cutoff in an oxbow lake. The river flows from upper right to lower left.

California Department of Water Resources.

▶**FIGURE 12-4.** A California Conservation Corps crew places sandbags around sand boils at the Sacramento River, at north Andrus Island, in the delta area southwest of Sacramento on January 4, 1997.

topping or **breaching** of levees does frequently occur in major floods. Other common failures are caused by bank erosion from river currents or waves, slumps into the channel, piping, or seepage through old gravels beneath the levee (▶Figure 12-2). Or, if a flood is prolonged, lateral seepage beneath the levee may raise the groundwater level, which then floods surrounding areas behind the levee.

Levees are always built on floodplains, which often are composed of old permeable sand and gravel channels surrounded by less permeable muds. The floodplain muds beyond the current channel are sediments that were left behind by the river where it spilled over a natural levee to flow on the floodplain.

The river migrates across all parts of that floodplain over a period of hundreds or thousands of years. Under a mud-capped floodplain, the broad layers of sand and gravel deposited in former river channels interweave one another (▶Figure 11-19b, page 279; and Figure 12-3). These permeable layers provide avenues for transfer of high water in a river channel to lower areas behind levees on a floodplain.

Rising floodwater in a river increases water pressure in the groundwater below; this can push water to the surface on the floodplain, where it can potentially rise to nearly the water level in the river. With prolonged flooding, that water often reaches the surface as **sand boils** (▶Figures 12-2 and 12-4). The water, under pressure, gurgles to the surface to build a broad pile of sand a meter or more across. Workers defending a levee generally pile sandbags around sand boils to prevent the loss of the piped sand (▶Figure 12-4). They leave an opening in the sandbags to let the water flow away and reduce water pressure under the levee.

Artificial levees damage not only homes and businesses when they fail but also fertile cropland on floodplains. A flooding river without artificial levees spills slowly over its floodplain, first dropping the coarser particles next to the main channel to form low natural levees. Farther out on the floodplain, mud settles from the shallow, slowly moving water to coat the surface of the floodplain and replenish the topsoil. When artificial levees fail, cropland on the floodplain is often damaged by both deposition and erosion. The floodplain areas adjacent to a levee breach are commonly buried under sand and gravel from the flood channel. Farther away, the faster flow from the breach may gully other parts of the floodplain and carry away valuable topsoil.

The Great Mississippi River Basin Flood of 1993

August 1993 had the largest upper Mississippi flood on record, larger than a 100-year event (▶Figures 12-5, 12-6, and 12-7). River flow reached 29,000 cubic meters per second at St. Louis, 160 percent of the average flow at New Orleans near the mouth of the river. Twenty-five thousand square kilometers of floodplain was underwater. Fifty people died, and damages exceeded $22 billion,* the worst flood disaster in U.S. history. More people died in the previous record flood on the lower Mississippi River in 1927, primarily because flood forecasting and warning systems then were less advanced. In 1993, highways, roads, and railroads were submerged for weeks on end, along with homes, businesses, hospitals, water-treatment plants, and factories (▶Figures 12-8 and 12-9). Almost 100,000 square kilometers, much of it productive farmland, lay underwater for months. Wells for towns and individual homes were flooded and contami-

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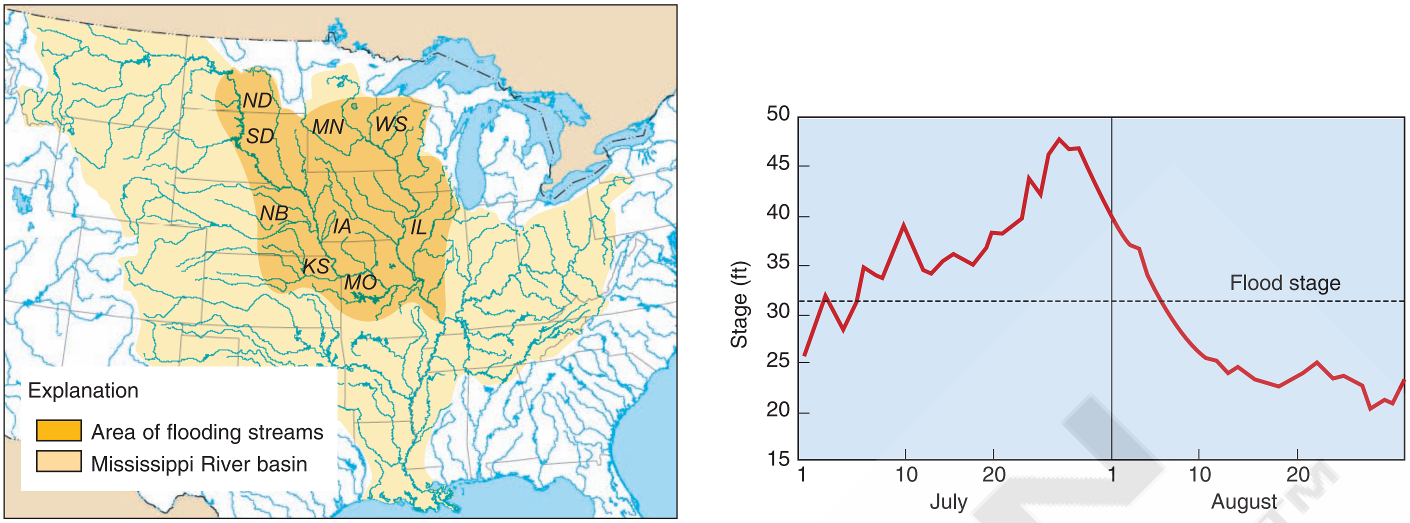
*Note: All costs are in 2002 dollars.



C. Parrett, USGS.

U.S. Army Corps of Engineers.

(a)

(b)

FIGURE 12-5. **(a)** This map shows the Mississippi basin and the general area of flooding streams during the summer of 1993. Heavily affected states are labeled with their abbreviations. **(b)** The flood hydrograph for the 1993 flood event shows that the Mississippi River was above flood stage for more than one month.

nated, requiring boiling of domestic tap water. The U.S. Army Corps of Engineers halted all river barge traffic on the Mississippi north of Cairo, Illinois, in late June because it could no longer operate the locks and dams along the river.

Rivers across the basin overtopped or breached numerous levees as the flood crest reached them. Of 1,576 levees on the upper Mississippi River, 1,043 of the 1,347 that were built by local or state agencies were damaged. Only thirty-nine of the 214 that were federally constructed were dam-

Sidebar 12-1 Discharge Estimated from Cross Section and Water Slope

Specifically,

$\mathbf{Q} = \mathbf{4.0A^{1.21}S^{0.28}}$ for bankfull stage,

or

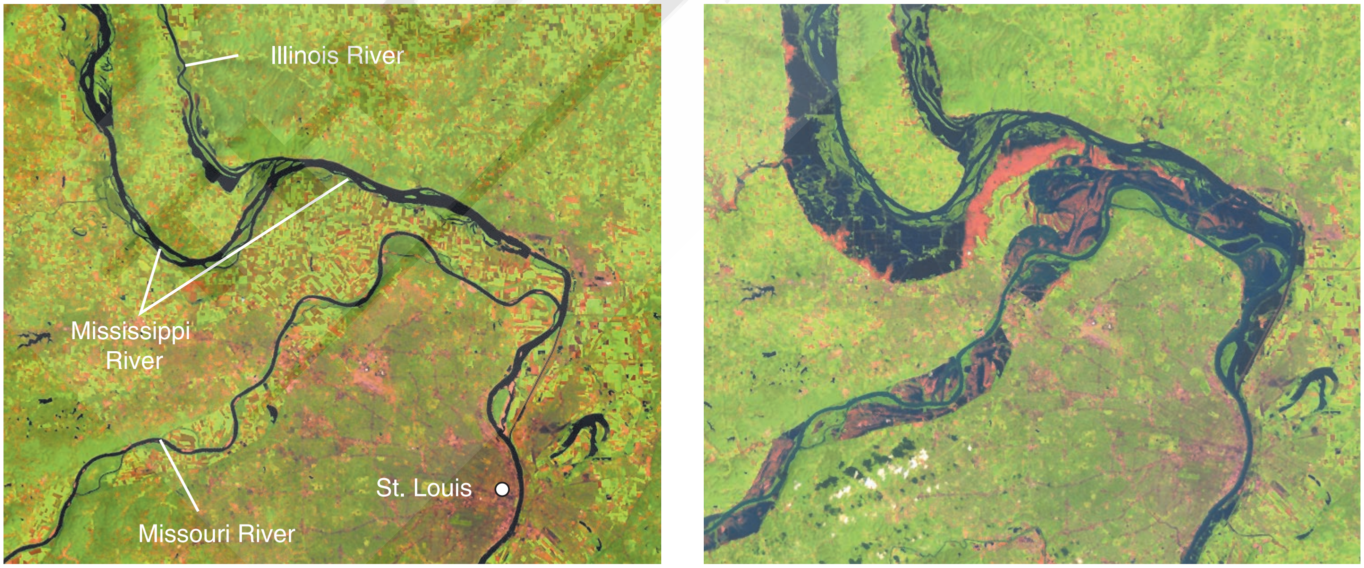
$= \mathbf{3.4A^{1.30}S^{0.32}}$ (to ± 20%),

where

Q = water discharge (in m^3/sec.)

A = average cross-sectional flow area (in m^2)

S = water-surface slope (along the channel)



NASA images.

(a)

(b)

FIGURE 12-6. The Mississippi River flood of 1993 can be clearly seen by comparing satellite images taken **(a)** before and **(b)** during the flood. Note that the river fills its floodplain except in the channelized St. Louis reach.

U.S. Army Corps of Engineers.

FIGURE 12-7. In the breach of this levee during the 1993 flood on the Mississippi, the river (on the left) spills through two breaches to cover the floodplain (right). A second levee at the right edge of the photo provides temporary relief.

Missouri Highway and Transportation Department.

FIGURE 12-8. The Missouri River flooded, filled its floodplain, and submerged this freeway near Jefferson City, Missouri, in late July 1993.

U.S. Army Corps of Engineers.

FIGURE 12-9. The 1993 flood left a large number of homes deeply submerged in floodwaters for an extended period of time.

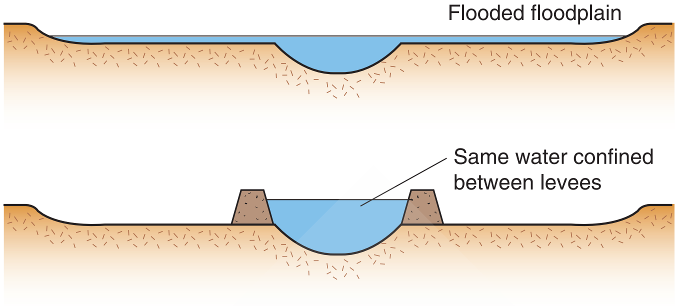


FIGURE 12-10. Levees confine at least the same amount of water between levees as could spread out over the floodplain.

aged. Levees failed from north of Quincy, Illinois, to south of St. Louis, Missouri, and on the Missouri River from Nebraska City, Nebraska, south through Kansas and Missouri to St. Louis. Once a river breached a levee, it would flush sand and gravel over previously fertile fields, flood the area behind the levee, and flow downstream outside the main channel (see Figures 12-7 and 12-8). Each levee breach would lower the river level, sparing downstream levees, at least for a while. Even large cities were affected. Des Moines, Iowa, had no drinking water and no electric power for almost two weeks. The Mississippi River at St. Louis was above flood stage from June 26 to late August, then again from September 13 to October 5. Clearly, the upper Mississippi River levee system only provided limited control of the 1993 flood.

Every time we build a new levee to protect something on a floodplain or to facilitate shallow-water navigation, we reduce the width of that part of the river and raise the water level during flooding (Figure 12-10). (See also Sidebar 12-1.)

A study conducted for the U.S. Congress in 1995 showed that if levees upriver had been raised to accommodate the 1993 flood, the water level in the middle Mississippi would have been 2 meters higher than it was. In fact, the increase in flood stages, for constant discharge, has increased 2 to 4 meters in the last century in the parts of the Mississippi River with levees. This rise in flood level is mostly the result of building the levees. The upper Missouri and Meramec rivers do not have levees and show no increase in flood levels.

Navigational dikes or **wing dams** constrict the river channel at St. Louis and other locations to increase river depth for barge traffic at low discharges (Figure 12-11). Even at high discharges when the river flow tops the wing dams, these structures increase resistance to flow near the river banks, which slows the velocity and raises the water level. As a result, for the same flood discharge, the stage or water height increases. This artificial increase in stage clearly affects the inferred recurrence interval for any huge flood such as the 1993 event on the Mississippi. The 1993 peak stage lies well above the recurrence interval curve adjusted for river flow without the wing dams.

The adjusted recurrence interval for the 1993 flood at

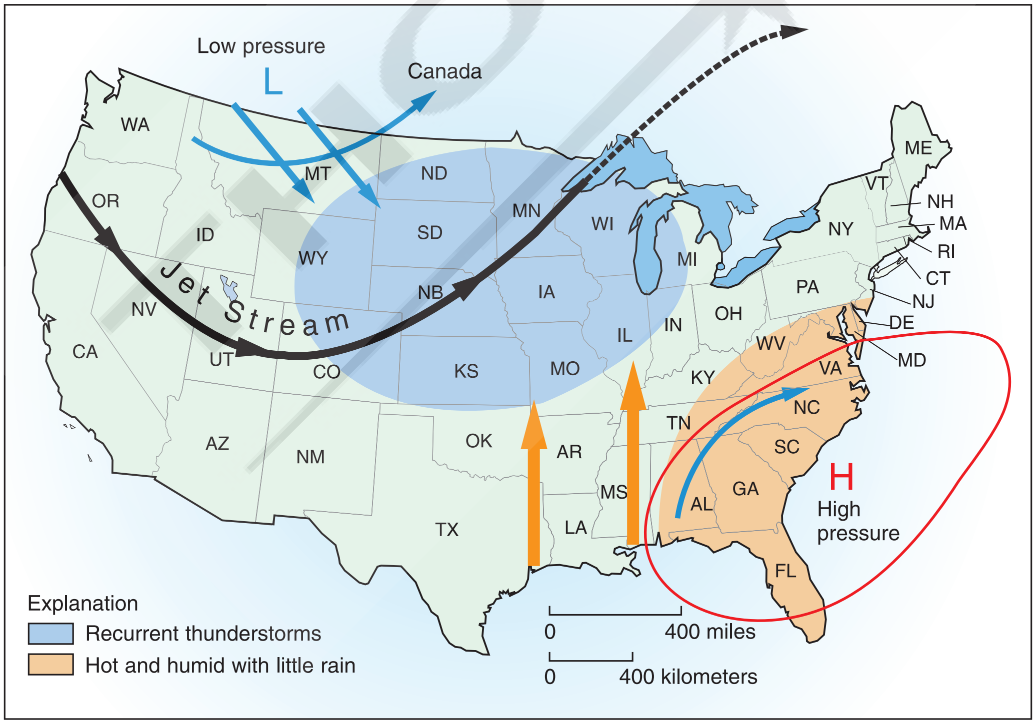
FIGURE 12-11. Wing dams on the Mississippi River, halfway between the Missouri and Ohio rivers, slow the flow at flood stages but provide a deepwater central channel for shipping at lower water.

U.S. Army Corps of Engineers.

St. Louis is 100 years or less, rather than previous estimates of up to 500 years. Recall that any new record flood changes previous recurrence intervals because the previous largest flood is now the second largest in the **recurrence interval** formula. This can have significant consequences for 100-year-event floodplain maps. Properties that were outside the 100-year flood hazard area are now within it; flood-protection structures that appeared to provide an adequate margin of safety no longer do so.

Some houses lay for weeks in water as much as halfway up the second story. After the lengthy flood, putrid gray mud coated floors and walls, and plaster was moldy to the ceiling because it and the insulation wicked it up. Belongings that could not be moved in time had to be thrown out and carted away. For those who expected the levees to hold, losses were higher because they made less effort to move their belongings. Not all the damage occurred within the floodplain. Many other areas with saturated soils had flooded basements and backups of sewers and drain fields.

As in some previous major floods, the preceding winter and the first half of 1993 were 50 to 100 percent wetter than average, so most of the ground was saturated with water. Along with the usual melting of winter snow in the upper parts of the Mississippi basin, water levels in rivers of the basin rose as they usually do. However, 1993 was different, es-



Modified from Wahl & others, 1993.

FIGURE 12-12. The dominant weather pattern for June and July 1993 that created the Mississippi River floods included a stationary low over western Canada and a persistent high off the Southeast coast.

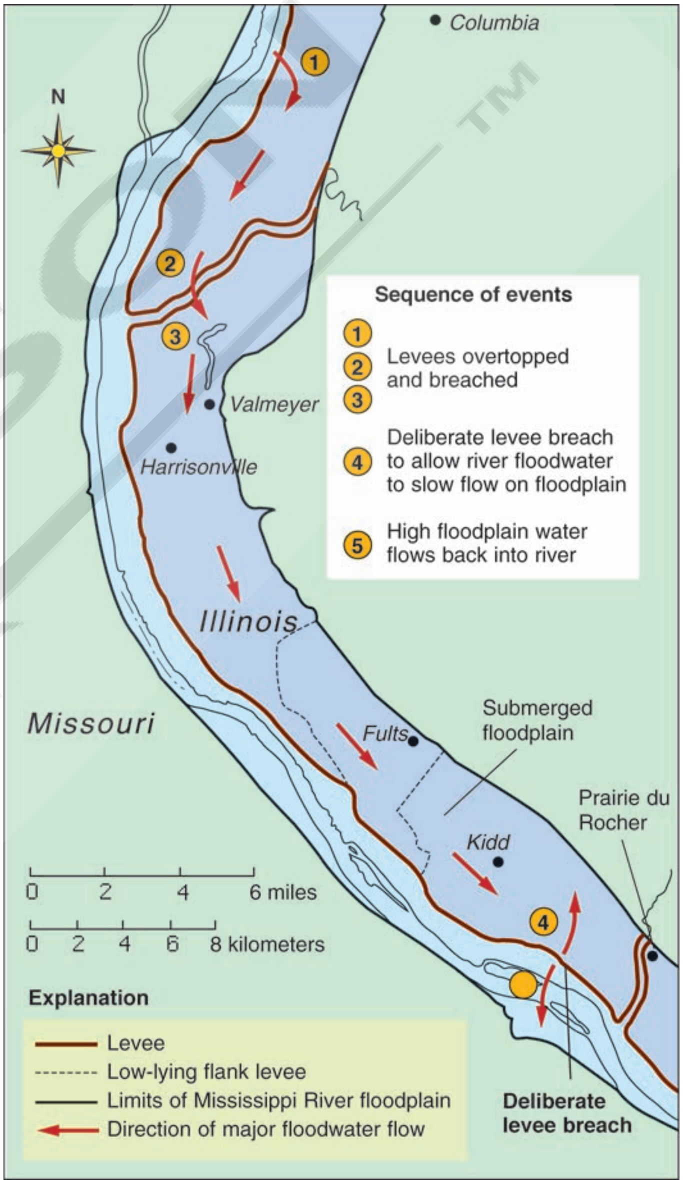
pecially in late June and July. The jet stream moved farther south, bringing cool, dry air from Canada and circulating around a low pressure system in southwestern Canada. That part of the jet stream swept northeastward from Colorado toward northern Wisconsin. At the same time, warm, moist air pulled into the central United States from the Gulf of Mexico collided with the cool, dry air to produce persistent low pressure cells and northeast-trending lines of thunderstorms centered on Iowa and the surrounding states (▶Figure 12-12). Even this was not a particularly unusual weather pattern. What was unusual was its coincidence with a persistent high pressure system that stalled over the Southeast coast. That high kept the storms from moving east as they would normally have done.

For the July 5 storm, for example, a stationary front extended northeast from northern Missouri to southeastern Wisconsin (▶Figure 12-12). A series of cold fronts rotated counterclockwise around a low in southwestern Manitoba. Each cold front colliding with the warm, moist air over Iowa lifted the warm air to cause condensation and thunderstorms. A strong vortex in the middle atmosphere, some 5 kilometers above the surface, created additional lift for the thunderstorms. Strong upper-atmosphere winds of the jet stream created a chimney effect that created additional updraft.

By late June, flood-control reservoirs in the upper Mississippi basin were full or nearly so. The storms kept forming in the same area; it rained and rained, literally for months. The soil was still saturated from heavier than normal winter and spring precipitation, but torrential rains continued as high water arrived from upstream. Most of the area was drenched with 0.6 meter of rain between April and August; areas in central Iowa, Kansas, and northern Missouri received more than 1 meter. On June 17–18, 7 to 18 centimeters of rain fell in southern Minnesota, Wisconsin, and northern Iowa. In late June, flooding in Minnesota was the worst in thirty years. The flood crest moved downstream while it continued to rain. Compounding the problem, storms in Iowa on July 4–5 and 8–9 dumped 5 to 12, and 20 centimeters, respectively. Other major storms, on July 15–16, and 22–24, dumped an additional 12 and 33 centimeters of rain on various parts of the region.

The flood wave moved downstream at approximately 2 kilometers per hour, so it was relatively simple to predict when the maximum height of the flood would reach any area. In reality, however, other factors came into play. Tributaries added to the flow and broad areas of floodplain that were not blocked by levees removed flow to release it more gradually to the river. Tributaries backed up and locally even flowed upstream. Most places had multiple flood crests. Between Minneapolis and Clinton, Iowa, high bluffs confine the river to a narrow floodplain. From Clinton down to St. Louis, the floodplain is wider, and various agencies have built levees of different heights. From St. Louis down to Cairo, Illinois, they channelized the Mississippi River to maintain dikes for an average river depth of 7 meters. The river crested at nearly 6 meters above flood stage in St Louis.

In most places in the upper Mississippi River drainage, the recurrence interval of the flood was thirty to eighty years. In the lower Missouri River drainage basin in Nebraska, Iowa, and Missouri, the peak discharge was greater than a 100-year event. Large portions of the upper Mississippi River basin were declared federal disaster areas.



Modified from Illinois State Geological Survey.

▶**FIGURE 12-13.** This map shows the Mississippi River, levees, and floodplain in the Valmeyer–Prairie du Rocher area of Illinois. The sequence of events can be followed from the breach of the main levee, flow south along floodplain, to deliberate breach to release water near Prairie du Rocher. This diagram shows the flow through a breach and downstream on a floodplain outside the channel levee.

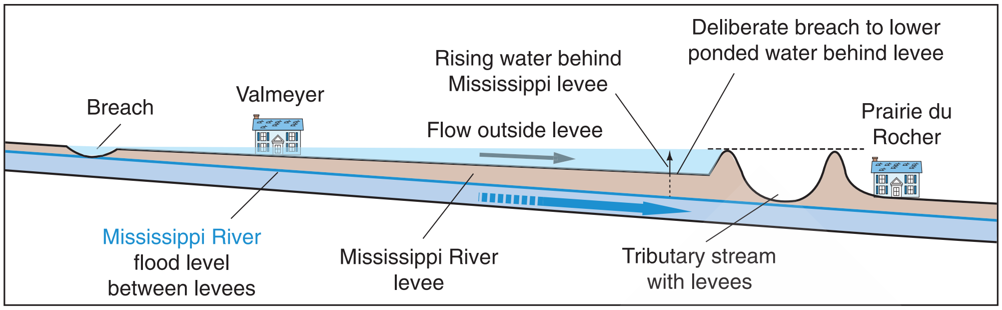


FIGURE 12-14. This vertical cross section through the area shown on Figure 12-13, shows that the water will gradually rise to the level of water at the breach upstream if that flow is blocked downstream.

Intentional Levee Breaks

Individuals, towns, and government agencies go to great lengths to maintain and raise levees to protect towns from floods. So why would levee district officials and the U.S. Army Corps of Engineers intentionally sever a Mississippi River levee during the flood of 1993? They did just that in southwestern Illinois on August 1, 1993, to save the town of Prairie du Rocher (Figure 12-13). Fifteen kilometers north of Valmeyer, Illinois, a levee failed, permitting Mississippi River water to flow onto the floodplain on the east side of the river. There it began flowing south, soon overtopping a pair of levees on a tributary stream and continuing south behind the main levee to flood Valmeyer (Figures 12-13 and 12-14). Twenty-seven kilometers south of Valmeyer, another tributary stream flanked by levees of its own would stop the floodplain water and protect the town of Prairie du Rocher unless they also were overtopped. However, water in part of a floodplain enclosed by levees will gradually rise to the level of the inflow breach upstream (Figure 12-14). The Mississippi River, of course, decreases in elevation downstream; levees protecting Prairie du Rocher were high enough to keep out the advancing flood but not as high as the Mississippi River at the breach 42 kilometers upstream. That means that the "lake" behind the main Mississippi River levee would rise well above the flood level on the Mississippi and flood Prairie du Rocher.

The solution was to deliberately breach the main Mississippi River levee 1 kilometer upstream from Prairie du Rocher to permit the "lake" behind the levee to flow back into the Mississippi River. Officials and the Corps of Engineers breached the levee before the floodplain flood reached Prairie du Rocher so the backflood of Mississippi water would cushion the oncoming wall of water on the floodplain. When the "lake" behind the floodplain rose higher than the Mississippi River, it again flowed back into the river.

Levees, Safety, and Costs

More and more people built homes and businesses in the Mississippi floodplain behind the supposed safety of the levees. The 1993 floods, however, completely submerged seventy-five towns. Are the costs of more levees and dams more than the value of the buildings they protect? Should taxpayers pay for flood losses for people who build in the flood-

Andrea Booher, FEMA.

FIGURE 12-15. Davenport, Iowa, also on the Mississippi River floodplain, was again underwater during the 2001 event.

plain? As noted above, federal relief funds are increasingly restricted to only those who move to higher elevations outside the floodplains or raise the floor level of their homes.

The **National Flood Insurance Program** (NFIP) made insurance available to those living on designated floodplains at modest cost (see "Floodplains and 100-Year Floodplains" in Chapter 11, page 292). In spite of that, only 5.2 percent of households in the Mississippi flood-hazard area had purchased flood insurance; those who did not probably believed that their floodplain property was protected by the levees. Some communities were again flooded in 2001 (▶ Figure 12-15).

One important outcome of the widespread failure of levees and flooding behind them was a general consensus that rebuilding in flood-prone areas was not acceptable. Where flood insurance funds were used for reclamation or rebuilding, the work had to conform to NFIP standards. For insured buildings, the structure had to suffer loss of more than 50 percent of its value, and the rebuilt lowest floor had to be above the level of the 100-year flood level. Some 10,000 homes and businesses were approved for removal or nonrebuilding from more than 400 square kilometers of floodplain. A 1994 committee of federal experts recommended that levees along the lower Missouri River be moved back from the river by 600 meters to give the river room to meander and spill over its floodplain during high water.

Avulsion

What happens if a stream flooding outside its levees never returns to the main channel? This process is called **avulsion.** The most famous and catastrophic cases have occurred on the Yellow River in China many times over the past several thousand years. Details of these cases are described in "Case in Point: Yellow (Huang-Ho) River of China" below. Meandering streams follow paths through their floodplains, gradually shifting position as each meander erodes its outside bank and deposits on the point bar of its inside bank. If the meander belt remains in one place for a long time, such as between artificial levees, deposition of sediment gradually raises the channel elevation. Large floods often breach levees.

Initially, water crossing a levee breach is relatively clear and below its sediment load capacity, so it erodes vigorously. As the breach erodes deeper, the floodwater carries more sediment and the water-surface slope decreases, ultimately bringing the breach flow into equilibrium and limiting further erosion. If floodplain flow is ponded locally, the breach flow will slow, sediments will deposit, and the breach or crevasse will stop flowing. Levee breaches near Quincy, Illinois, along the Mississippi River in 1993, ranged from 100 meters to 1 kilometer in width and continued for seven to fifteen hours before deposited sediment stopped the breach flow.

If the floodplain flow is unrestricted downstream to lower elevations and the flood level remains high, the breach flow may continue to erode, ultimately diverting the main channel through the breach and causing avulsion. The stream moves to a new lower-elevation path on the floodplain. Because the new path is lower, the stream does not return to its original path.

At high flood levels, water may break through a crevasse in a levee where the floodplain lies lower than the streambed. The stream may abandon its channel and form an entirely new one. The Mississippi River did this locally in the 1993 flood. In the 1870s, the Bear River in California shifted to a new path following channel aggradation caused by hydraulic gold mining. The social and economic consequences of avulsion on a major river such as the Mississippi can be severe (see "Case in Point: New Orleans").

Channelization

Confining a stream within a concrete-lined channel causes the flow velocity to increase by making the stream deeper and straighter, as well as by reducing channel roughness. For hundreds of years, European cities such as Florence and Pisa, Italy, have sought protection from floods by build-

David Gatley photo, FEMA.

▶**FIGURE 12-16.** The Los Angeles River runs through a straight section of concrete channel with angled energy dissipation structures.

(Text continues on page 311.)

CASE IN POINT Yellow (Huang-Ho) River of China

The Future of the Mississippi?

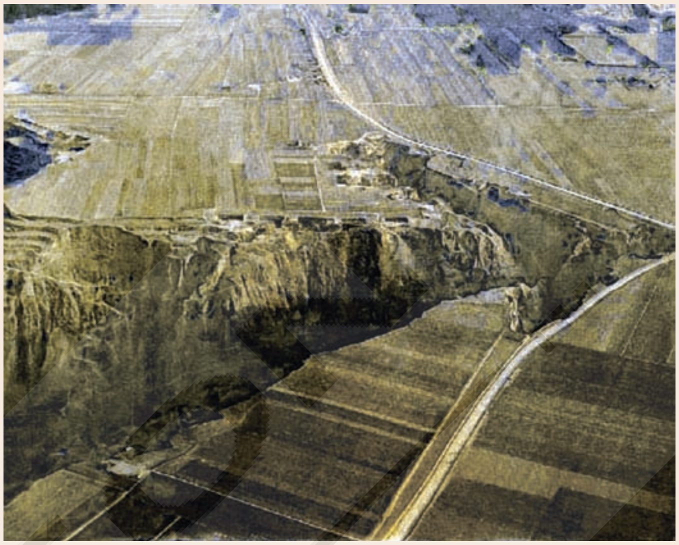
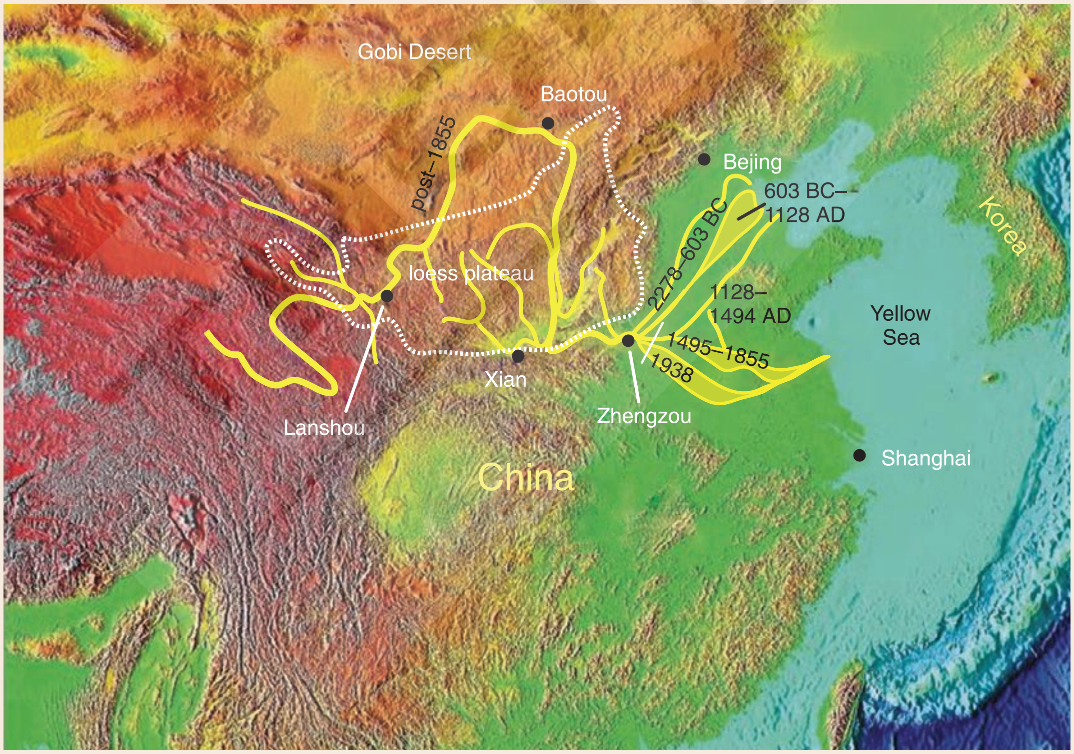

George Leung photo.

FIGURE 12-18. The largest remaining area of loess tableland at Dongzhiyuan in Gansu, China, is being rapidly eroded. The size of the view can be inferred from the road around the end of the deep canyon.

The 4,845-kilometer-long Yellow River (Huang Ho) drains most of northern China, an area approximately 945,000 square kilometers. That is a similar length but less than one-third the drainage area of the Mississippi River (▶Figure 12-17). The upper reach, flowing generally east from the Tibetan highlands, carries relatively clear water through mountains and grasslands for more than half the river's length. The middle reach south from Baotou and the deserts and plains of Inner Mongolia drains a broad region of yellowish wind-deposited silt or loess originally blown from the Gobi Desert in Mongolia to the northwest.

Sediment supply to the river from the loess plateau is vigorous because of vast arid to semi-arid, hilly areas of easily eroded silt. Before heavy agricultural use of the loess plateau beginning in 200 B.C., the plateau was mostly forested and the sediment load fed to the river would have been one-tenth of the current load. After the tenth century A.D., agriculture had largely destroyed the natural vegetation. Silt supplied by sheetwash and gully erosion (▶Figure 12-18) is so abundant that floods often carry hyperconcentrated loads of yellow-colored sediment that gives the river its name. Average sediment load during a flood is generally greater than 500 kilograms per cubic meter, which is some 50 percent by weight or 20 percent by volume.

The lower reach of the Yellow River, downstream from Zhengzhou, flows across a densely populated and cultivated alluvial plain, one affected repeatedly by flooding for more than 4,000 years. As the river gradient decreases and the river spreads out over a width of several kilometers, sediment deposits and progressively raises the channel bottom; that regularly requires raising the levees. Near Zhengzhou, siltation raises the river bottom at an average of 6 to 10 centimeters per year, aggravates flooding, and rapidly fills the reservoirs behind dams.



Topography from NOAA.

FIGURE 12-17. The middle reach of the Yellow River drains the easily eroded loess plateau. During the last 4,000 years, the lower Yellow River of China changed its course many times.

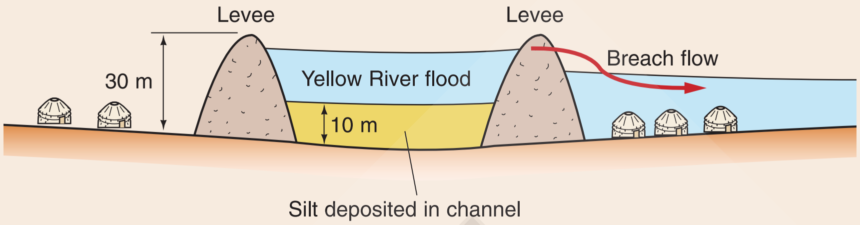


FIGURE 12-20. Siltation in the channel of the Yellow River, between levees, has raised the channel some 10 meters. Even with 30-meter levees, breaches often lead to avulsion and abandonment of the main channel.

As early as 4,000 years ago, Emperor Yu dredged the channel and dug nine separate diversion channels to divert floodwaters. In 7 B.C., Rhon Gia advised evacuating people rather than fighting the river, but people did not follow his wise suggestion. After a disastrous flood in 1344 A.D., people used a combination of river diversion, river dredging, and dam construction. After each flood, they plugged breached dikes and raised existing dikes. With the channel raised by siltation, some breaches drained the old channel and followed an entirely new path to the sea—that is, by river avulsion. Unfortunately, as with most rivers, levees here are built from the same easily eroded silt that fills the channel; the river erodes the levees just as it does the loess plateau. Downstream from a breach, the riverbed between levees is left dry, a serious problem for those who are dependent on its water.

In 1887, the river topped 20-meter-high levees and followed lower elevations to the south to reach the East China Sea at the delta of the Yangtze River at Shanghai. The flood drowned people and their crops; the flood and resultant famine killed more than 1 million people. Official government policy since 1947 has been to contain floods by flood-control dams and by artificial levees along the channel. However, these structures are only designed to control a flood with a recurrence interval of sixty years, clearly not a long-term solution. The bed of the river is now as much as 10 meters higher than the adjacent floodplain (Figures 12-19 and 12-20). Because the riverbed is well above the surrounding landscape, the lower 600 kilometers of the river receives no water from either surface runoff or groundwater.

In 1960, the Chinese completed the San-men Gorge Dam, 122 meters high and more than 900 meters wide. Its 3,100 square kilometer reservoir that is designed to collect water and silt probably will be filled with sediment by 2006. At the same time, a major effort was launched to plant trees and irrigate huge areas of the silt plateau to reduce the amount of silt reaching the Yellow River. Unfortunately, most of the trees died. As with droughts, construction of reservoirs and extraction of water for irrigation and other uses leads to low downstream flow, especially since 1985. Flood stage in 1996 was an all-time high even though the discharge was much lower than the 1958 and 1982 floods.

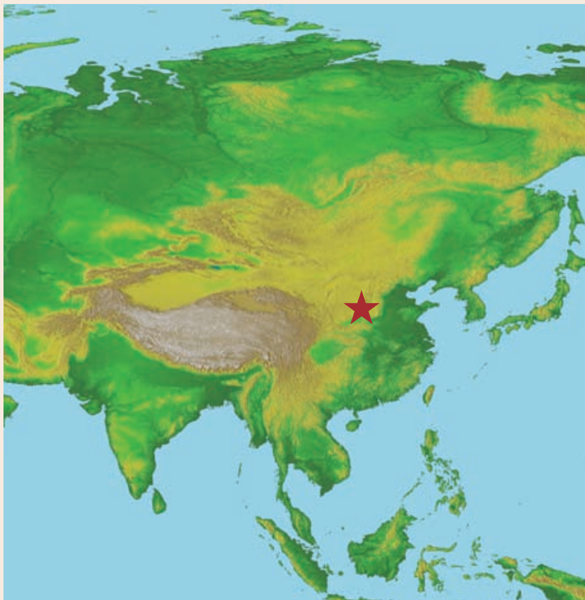
Repeated construction of levees over the last 2,500 years has not prevented catastrophic floods and river course changes. The lower 800-kilometer stretch of the Yellow River has repeatedly shifted its course laterally by hundreds of kilometers (Figure 12-17). Although the Mississippi drainage basin does not include either desert or active wind-blown loess in its headwaters, its riverbed rises higher with each year. Is this the future of the Mississippi River as people continually raise levees in response to each major flood?


China Environmental Science Press.

FIGURE 12-19. Levees of the Yellow River stand high above the surrounding floodplain.

What Went Wrong?

China has lived with the Yellow River and its floods for thousands of years and have tried to control the floods with levees just as we do. It has not worked. Levees broke and killed thousands of people. Avulsion dramatically changed the river course several times. With each flood, they built the levees higher and the levees still failed. There should be a message here; our levees fail just about as frequently.



CASE IN POINT New Orleans

In addition to permanently flooding and eroding large floodplain areas, the disruptions to a city that depends on river shipping for its economic livelihood can be severe. Avulsion of the Mississippi River above New Orleans would be economically catastrophic for the city. The Yellow River avulsion in 1855 took only one day. Avulsion of the Saskatchewan River in the 1870s turned more than 500 square kilometers of its floodplain into a belt of braided channels and small lakes. Avulsion there occurred at the outside of a large meander and apparently evolved over a period of several years.

New Orleans Flood History

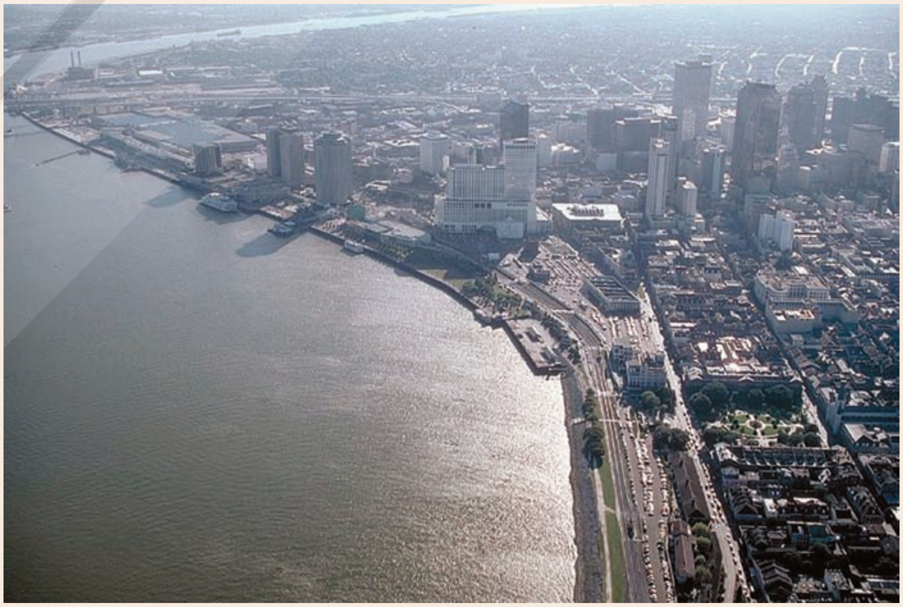
Originally settled in 1718 as a French colony on a natural levee of the Mississippi River and 4.5 meters above sea level, New Orleans soon built low artificial levees to protect itself in times of flood. By 1812, the levees extended 114 kilometers upstream. New Orleans has battled the river ever since. With each large flood, the levees were built higher to protect the town. Major levees built in 1879 to contain floods around New Orleans broke in 1882 in 284 places. In 1927, with 2,900 kilometers of levees, the flood broke through in 225 places. In the 1973 record flood, the river submerged 50,000 square kilometers of floodplain.

By 1900, the city began to spread north into the swamps of the floodplain by building canals and draining them with pumps. Soggy peat on the floodplain began to compact because of dewatering and the weight load of roads and buildings, so the city began to settle. Parts of it are now almost 4 meters below sea level, even farther below the Mississippi River that flows along the dikes right next to the core of downtown (▶Figure 12-21). Ships on the Mississippi look down on the city. High capacity pumps capable of pulling 1,100 cubic meters per second keep the groundwater at bay and the ground free of water, even after torrential rains.

Each additional dike further confines the river, which aggravates its tendency to flood downstream. Each time, the river rises higher during flood and flows faster. Instead of permitting the river to spread over its floodplain to shallow depths during flood, levees along the Mississippi and tributaries exacerbate the problem by raising the river level well above the natural floodplain.

The Atchafalaya River Problem

As the Mississippi River carries sediment to the Gulf of Mexico, it builds its delta seaward, thereby decreasing the river's slope in the depositional delta area. At the same time, the river builds both its bed and natural levees higher. During a major flood, the river breaches the natural levees, and its water heads down a steeper, shorter, lateral path to the sea. Because water flows faster on the steeper slope, it will begin to carry more of the river's flow, gradually taking over to become the new main channel. Sixty to seventy years ago, a new distributary channel, the Atchafalaya River, formed and began to sap some of the flow from the main channel (▶Figure 12-22).



Marli Miller photo.

▶**FIGURE 12-21.** New Orleans, the major shipping center on the lower Mississippi River, is protected by levees so that the river now stands 4 meters above the downtown area.

FIGURE 12-22. In Louisiana, the Mississippi River takes a long gentle path to the Gulf of Mexico. The Atchafalaya River drains part of the flow of the Mississippi upstream from Baton Rouge, taking a shorter and therefore steeper path.

Unfortunately New Orleans is located on the main channel downstream from where the Atchafalaya splits off. For New Orleans to be left high and dry without its river would destroy its key role as a shipping center for the whole Mississippi basin.

In the 1960s, recognizing the problem, the U.S. Army Corps of Engineers built the Old River control structure to permit 30 percent of the flow to enter the Atchafalaya, keeping 70 percent in the main channel through New Orleans. The idea was to regulate flow so that floodwaters could be channeled into the Atchafalaya to save New Orleans and other towns from flooding. Some of the sediment carried by a flood could also be channeled off to minimize further siltation of the main channel through New Orleans. The 1973 Mississippi River flood almost destroyed the Old River control structure, thereby channeling the main flow into the Atchafalaya River.

New Orleans is now at the mercy of the river. If a catastrophic flood should breach levees in the area, much of the city would be drowned in as much as 7 meters of water, along with a thick layer of sand and mud brought in through the breach. Could it happen? It was not supposed to happen in the upper Mississippi in 1993. A catastrophic flood could also destroy the Old River control structure, leading to dominance of the Atchafalaya River over the current Mississippi course through New Orleans. Or the U.S. Army Corps of Engineers could decide to deliberately breach the barrier at the Old River control structure to save New Orleans. Either way the city loses. If the Atchafalaya takes most of the flow, the city is left high and dry without the river that is critical to its future.

How long can the U.S. Army Corps of Engineers keep the Mississippi confined and prevent it changing course to the straighter, steeper path to the ocean along the Atchafalaya River? The long-term effect of using levees to confine a river such as the Mississippi can be tragic as seen by comparing the history of the Yellow River in China.

CASE IN POINT A Channelized Old World River

The Arno River, Florence, Italy, November 4–5, 1966

Like many other old European towns, multistory buildings are built right next to the channel of the Arno River. The river itself is channelized through the city, with vertical walls raised only a little above street level. In the seventeenth century, walls almost 9 meters high were built on the riverbanks, reducing the bankfull channel width from 300 meters to its current 150 meters. Even at low water, the river reaches both walls in many places. Although the surrounding region is hilly, the old part of town, including most of its most famous museums and churches, is on a broad, flat floodplain 1 to 2 kilometers wide, primarily on the north bank of the river.

In Florence, the Arno is only 160 kilometers from its headwaters but has a record of catastrophic floods including those in 1117 and 1333 that decimated the city and its bridges. Two years before the disastrous flood of 1547 that killed more than 100 people, Bernardo Segni pointed out that cutting so many trees for timber in the mountains upstream permitted water to erode the soil and to silt up the beds of the rivers. Thus, humans had contributed to the flood. In spite of major floods averaging one per twenty-six years, Florence remained unprepared.

The largest flood ever on the Arno River was recorded on November 3, 1966. Coincidentally, the largest previous flood was on the same day in 1333. Following an exceptionally wet October that saturated soils, a heavy storm on November 3 dumped 48 centimeters of rain on Florence and the Arno headwaters, a third of the average annual rainfall. Discharge reached 2,580 cubic meters per second and overfilled reservoirs. The flood tore through small towns upstream, continued down river at almost 60 kilometers per hour into its narrow, concrete-lined river channel within Florence. At 2:30 A.M. on November 4, floodwaters rapidly rose to a depth of 6.2 meters, 2 meters higher than the 1333 flood. By 4 A.M., water invaded the main square and was soon 1.5 meters deep in the Piazza Duomo.

The raging floodwaters rose to the roadway of the famed Ponte Vecchio, threatening the famous bridge that has spanned the Arno River in one form or another since Roman times; it was previously destroyed by floods in 1117 and 1333 and rebuilt each time. A bus carried downriver by the raging torrent crashed into the bridge during the 1966 flood, opening a huge hole. Ironically, that permitted water to pass, easing pressure on the bridge, and probably saving it from complete destruction. By 7 A.M. on November 4, water 1 to 2 meters deep completely covered the central part of the city. Water was 6 meters deep in parts of town—up to third-floor levels. Heating oil from thousands of basement tanks flushed to the surface and was carried along with the floodwaters to contaminate everything it touched. For a city whose claim to fame is one of Europe's most valuable centers of culture and art, the effect was disastrous, with damage from mud and polluted water and the destruction of many priceless medieval and Renaissance paintings, sculptures, and books, many of which were stored in basements. Twenty-nine people died.

A significant part of the blame for these devastating floods was attributed to the residents. Since pre-Roman settlement in the region, they had stripped natural vegetation from the hills for centuries. That produced an annual cycle of winter floods and summer droughts. The 1966 problem was compounded by the failure to gradually release water from two hydroelectric dams upstream from Florence during heavy October rains. Late on November 3, the dam operators realized they had a problem, so they released a huge mass of water from the upstream dam, which in turn required immediate opening of the downstream dam, unleashing a wall of water.

In the last few decades, the extraction of gravel from the Arno River channel for construction materials and the construction of reservoirs upstream have caused increased channel erosion. Little has been done to rectify the basic causes, but most vulnerable art works are now kept on the upper floors of buildings and out of range of future floods.

What Went Wrong?

The Arno River, channelized since the seventeenth century, is bordered by multistory buildings. Deforestation permitted erosion of the drainage basin and deposition of sediment in the river channel. A major storm dumped 48 centimeters of rain on already saturated soils. Operators of two dams upstream failed to gradually release water to lower reservoirs during the rainy period that preceded the major storm, so they were not able to collect water behind the dams during the flood.

ing walls lining rivers that run through them (see "Case in Point: A Channelized Old World River"). In other cases, such as the upper Rhine valley of Germany, levees were constructed to deepen the flow to permit year-round navigation. The intended results were as anticipated. Those walls raised flood water levels and increased the water velocity. Unfortunately, such changes also enhanced erosion, both in the channeled reach and downstream where the river is not confined to the channel. Floods also pass through more rapidly, resulting in much higher downstream flood crests. Urban Los Angeles provides an extreme example of **channelization** (▶Figure 12-16).

In another example, part of the Tia Juana River drains northwestward from Mexico to the ocean through a small corner of San Diego. A 4.3-kilometer section of the river is channelized to protect the city of Tijuana from flooding just before it enters San Diego. To protect agricultural land on the California side from severe flooding and erosion, and to permit groundwater recharge, the U.S. Army Corps of Engineers built an energy-dissipating structure and sedimentation area to slow the water and deposit excess sediment. They used levees to protect built areas on both flanks.

Flood Control and Multipurpose Dams

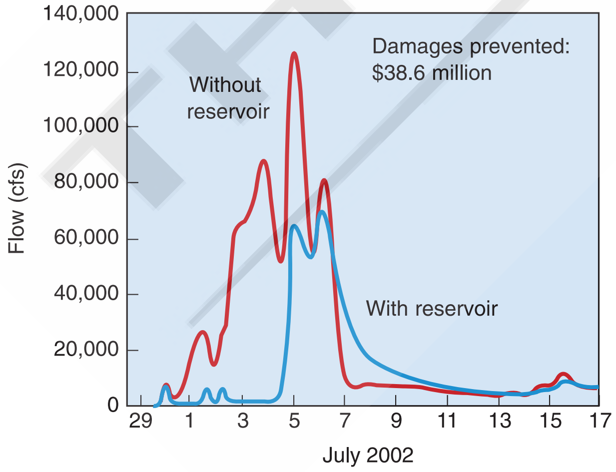
Some dams are built to trap floodwaters upstream and then release that water more slowly once the flood has passed (▶Figure 12-23). One of the most serious problems with dams is a more subtle one. Many are designed and financially justified as **multipurpose dams** to provide electric power, flood control, water for irrigation, and recreation.

These are desirable attributes, but the timing of their needs often clashes. For example, winter is California's wet season, so reservoirs and rivers fill and flood then or in spring as rainfall overlaps snowmelt. Summer is dry, but because that is the growing season, irrigation water is in high demand. Electricity use is also highest in summer, primarily because of air conditioning. Dam officials try to fill reservoirs as full as possible in the winter to prepare for summer irrigation and electric power needs. In contrast, reservoirs need to be kept as low as possible to provide maximum capacity to contain a potential flood. Thus, the dilemma: predict rainfall well enough in advance to fill the reservoirs but keep them low enough to contain possible floods. Unfortunately, predicting the weather is not entirely reliable, especially weeks in advance. Immense floods that inundated much of the Central Valley of California, including several cities, in the winter of 1997–98 demonstrated the consequences of multiuse management based on unreliable weather predictions (see "Case in Point: Sacramento–San Joaquin Valley, California").

Floods Caused by Failure of Human-Made Dams

Federal agencies or states own only 7.8 percent of dams, local agencies and public utilities own 18.5 percent, and private companies or individuals own 59 percent. Thus, care in siting, design, construction quality, and maintenance of dams is highly variable.

Many dams serve their intended purpose, in theory, until the reservoir behind the dam is filled with sediment or, fortunately not often, the dam fails. When the U.S. Army Corps of Engineers studied more than 8,000 U.S. dams in 1981, they found that one-third of them were unsafe. The hazard to people living downstream depends on the volume of



U.S. Army Corps of Engineers.

▶**FIGURE 12-23.** This flood hydrograph shows the Guadalupe River with Canyon Lake Reservoir (blue) and a calculation of what it would have been without the reservoir (red).

Perry Rahn photo.

▶**FIGURE 12-24.** Damages from the June 10, 1972, flood at Rapid City, South Dakota, were extensive. Cars were mangled, and all that is left of a nearby house is the tangle of boards in the lower right.

CASE IN POINT Sacramento-San Joaquin Valley, California

Flood of January 5, 1997

When the State of California proposed limiting new development in flood-prone areas on low ground near the confluence of the Feather and Yuba rivers north of Sacramento, the California Building Association and California Association of Realtors fought the restrictions, arguing that it would take away people's property rights. The State Department of Natural Resources responded that such building is not in the public interest because property owners expect the government to use public tax dollars to bail them out when disaster strikes.

▶FIGURE 12-25. Failed Feather River levees left only rooftops of homes showing above floodwaters on the floodplain north of Sacramento on January 4, 1997.

Norm Hughes photo, California Department of Water Resources.

▶FIGURE 12-26. A levee of the Feather River was eroded and breached at a country club north of Sacramento, California, on January 3, 1997.

Norm Hughes photo, California Department of Water Resources.

From December 29, 1996, through January 4, 1997, a "pineapple express" accompanying El Niño brought one of a series of five warm, subtropical rainstorms from the central Pacific Ocean (▶Figure 12-25). Heavy, warm rains fell on a Sierra Nevada snowpack that was almost double the average, causing record stream flow, but torrential rains made up 85 percent of these flows. Ground saturated from earlier rains and snowmelt amplified the runoff, causing streams to rise to record levels.

Levees failed on the Cosumnes, Mokelumne, Tuolumne, and Feather rivers (▶Figure 12-26). The Mokelumne River levee failure swept a marina and 230 boats downstream to crash into a bridge. Multipurpose reservoirs filled up, and erosion and mudslides severed U.S. Highway 50 across the Sierra Nevada in five places. Floodwaters covered 650 square kilometers, killed at least eight people, damaged or destroyed 16,000 homes, and caused damages of more than $1.8 billion (in 2002 dollars).

The worst event of the flood was failure of a problem-plagued levee on the lower Feather River, out on the broad Sacramento River valley, where water rose to a depth of 23.5 meters during the night of January 2. This flooded 39 square kilometers of farmland, killed three people, displaced 80,000 more, and caused $225 million in damages (▶Figures 12-26 and 12-27). The disaster would have been much worse if the new city of Plumas Lakes that was approved in 1993 had been built. Developers and politicians planned it on the floodplain as a Sacramento bedroom community for as many as 30,000 people. By 2001, the Plumas Lakes development had all the basic approvals for an initial 700 homes. All of these sites were partly or entirely flooded in the 1997 storm.

On January 3, authorities deliberately breached the levee downstream near the confluence with the Bear River to permit some of the floodplain water to flow back into the Feather River and relieve pressure on the levee. Parts of the site were still under 2.5 meters of water two months after the flood.

Voters rejected another group of planned towns for 100,000 people just upstream from Sacramento in 1993, but the developers continue to challenge the rejection in the courts. Downstream near Stockton, other developments for 29,000 people have been approved by city councils but also are being fought in court by opponents who are concerned about future flooding and long-term costs to the public.


Norm Hughes photo, California Department of Water Resources.

FIGURE 12-27. Flooding from the Feather River extended far off to the horizon in some places.

Flooding on the Sacramento River downstream was ranked as approximately a fifty-year event. Damages reached almost $2.2 billion, including flood-control sites, homes, small businesses, private irrigation systems, highways and other roads, buildings, fences, and crops. This figure did not consider the large losses in income from businesses and tourism. Some 775 square kilometers flooded as levees failed in more than eighty places. In some cases, water flowing through old river gravel channels under the levees eroded the base of the levees. Developers and local officials still insist that the planned cities will be safe from floods when levees are upgraded. Developers are lured by the huge development profits; cities want the tens of thousands of new jobs and tens of millions of dollars in new annual tax revenues. Unfortunately, taxpayers pay for the consequences when things don't go as planned.

The recurrent arguments on one side are that people should not be denied the right to build on their own property, that development will bring new jobs and new tax revenues. They also insist that flood-control dams, levees, and levee improvements, many as yet not built, will provide ample safety. Opponents argue that levees and dams have proven inadequate and unsafe again and again and that property owners expect the government and therefore the public to pay for cleanup, repairs, and rebuilding after any natural disaster. Flood experts doubt that levee upgrades will prevent flooding. Even if levees do not fail, water will flow through subsurface gravels to flood areas behind the levees (Figures 12-2 and 12-4).

Multipurpose Dams

The demands on many multipurpose dams in the Sierra Nevada compounded the flooding problem in 1997. Engineers rationalized building of the dams by adding up the total benefits of irrigation, electric power, recreation, and flood control. Unfortunately, some of these are mutually incompatible.

On a positive note, a broad consensus among federal, state, and county agencies noted that rivers need more space to "do their own thing." Even the U.S. Army Corps of Engineers, which built most of the levees and dams, is having second thoughts. Instead of building levees adjacent to river channels, the corps suggests a 30-meter corridor on either side of the channel where development is not allowed and where the river is permitted to meander and develop riffles. This would minimize flood damage, reduce construction and maintenance costs, and provide a small area of natural flood plain and a "nice river corridor."

What Went Wrong?

Large dams were built to serve several distinctly different purposes that were not compatible. The water level in reservoirs behind the dams needed to be low enough to provide protection from floods in wet springs but high enough to provide water for irrigation and electric power in hot, dry summers. Weather prediction was not accurate enough weeks in advance to adjust the reservoir heights and prevent overtopping of the dams.

water released, the height of the dam, the valley topography, and the distance downstream. Calculations show that a dam-failure flow rate in a broad open valley would likely drop to half of its original rate in 60 kilometers or so, but in a steep narrow valley this level of drop in flow rate requires 130 kilometers.

Flooding on Rapid Creek in the Black Hills of South Dakota provided dramatic evidence of why it is dangerous to live downstream of a multiuse dam (▶Figure 12-24). In just six hours in June 1972, 37 centimeters of rain fell over the Rapid Creek drainage basin. Southeast winds carrying warm, moist air from the Gulf of Mexico banked up against the Black Hills where it encountered a cold front from the northwest. Pecola Dam, 16 kilometers upstream, was built on Rapid Creek just twenty years earlier for irrigation and flood control after an earlier flood. Building of this and other dams made people feel secure from floods, so they built homes along the creek downstream.

During the intense flood of 1972, the creek's typical flow of a few cubic meters per second became a torrent of 1,400 cubic meters per second within a few hours. With rising water, authorities began ordering evacuation of the low-lying area close to the creek at 10:10 P.M., and the mayor urged evacuation of all low-lying areas at 10:30. The spillway of a dam just upstream from the city became plugged with cars and house debris from upstream, raising the lake level by 3.6 meters. At 10:45 P.M. the dam failed, releasing a torrential wall of water into Rapid Creek that flows through Rapid City. The flood just after midnight killed 238 people, destroyed 1,335 homes and 5,000 vehicles, and caused $690 million in damages. More than 2,800 other homes suffered major damage (▶Figures 12-24 and 12-28).

In this case, the lesson was learned—at least for now. The city used $207 million in federal disaster aid to buy all of the floodplain property and turned it into a greenway, a park system, a golf course, soccer and baseball fields, jogging and bike paths, and picnic areas. Since then, building in the floodplain has been prohibited. However, decades later, pressure increases to build shopping centers and other structures in the greenbelt. The decision rests in a politically divided city council—the usual struggle between developers or "jobs" versus long-term costs, aesthetics, and safety.


Perry Rahn photo.

▶**FIGURE 12-28.** This house was carried off its foundation onto the road by the 1972 Rapid City flood.

More than 3,300 high and hazardous dams are located within 1.6 kilometers of a downstream population center. Few local governments consider the hazard of upstream dams when permitting development. Major floods from dams in narrow valleys have occurred for a variety of reasons:

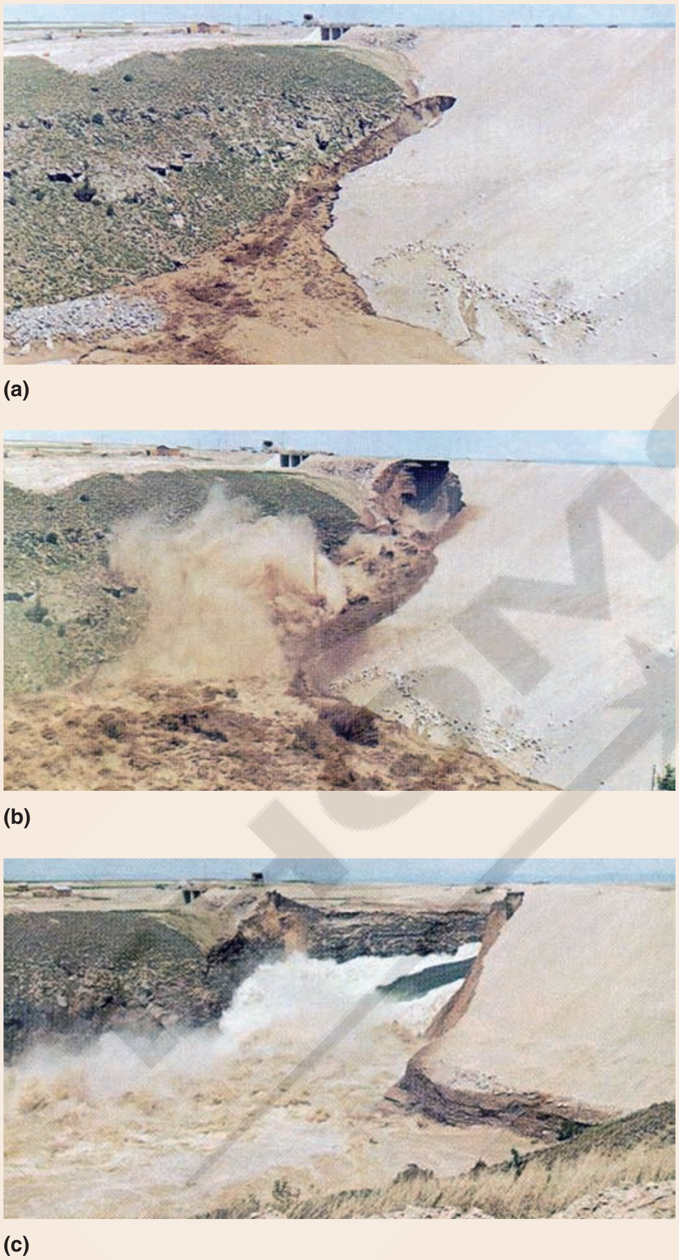
- Overtopping a reservoir after prolonged rainfall, as in the 1972 flood in Rapid City, South Dakota. Although most dams could be built higher, the cost increases rapidly with height, in large part because a dam's length also increases rapidly with its height.
- Seepage of water under a dam leads to piping and erosion of the dam foundations, resulting in catastrophic dam failure. The Teton Dam in eastern Idaho that failed on June 5, 1976, took eleven lives and caused more than $3.2 billion in damages (see "Case in Point: Failure of the Teton Dam, Idaho").
- Subsurface erosion along faults or other weak zones in the foundation rock below the dam.
- Poor design and engineering standards of a privately owned slag-heap dam at Buffalo Creek, West Virginia, resulted in a 1972 failure that drowned 125 people.
- Improper maintenance of a dam, including failure to remove trees, repair internal seepage, or properly maintain gates and valves.
- Negligent operation, including failure to remove or open gates during high flows, as in the 1966 flood on the Arno River in Florence, Italy.
- Landslides into reservoirs that cause a surge and overtopping of the dam, as in the Vaiont Dam in northeastern Italy that killed 2,600 in 1963. Filling the reservoir behind the dam increased pore-water pressure in sedimentary rocks sloping toward the reservoir. A catastrophic landslide into the reservoir displaced most of the water to drown more than 2,500 people downstream (see "Case in Point: The Vaiont Landslide" in Chapter 8, pages 210—211).
- Earthquakes that weaken earth-fill dams or cause cracks in their foundations. The Van Norman Dam, owned by the city of Los Angeles and less than 10 kilometers from the epicenter of the 1971 San Fernando Valley earthquake, is immediately upstream from thousands of homes. It is an earthen structure that was thirty years old when the earthquake struck. The earthquake caused a large landslide in its upstream face and so drastically thinned the dam that it seemed likely to fail. Operators were fortunately able to lower the water to a safe level so that the dam did not fail, but authorities evacuated 80,000 people from the area downstream until they could lower the water level.

CASE IN POINT Failure of the Teton Dam, Idaho

The Teton Dam, near Rexburg in eastern Idaho, was built by the U.S. Bureau of Reclamation to provide not only irrigation water and hydroelectric power to east-central Idaho but also recreation and flood control. After dismissal of several lawsuits by environmental groups, construction began in February 1972, and filling of the reservoir behind the completed dam began in October 1975. The dam was an earth-fill design 93 meters high and 945 meters wide, with a thin "grout curtain" or concrete core to prevent seepage of water through the dam.

On June 3, 1976, workers discovered two small springs just downstream from the dam. On June 5 at 7:30 A.M., a worker discovered muddy water flowing from the right abutment (viewed downstream). Although mud in the water indicated it was carrying sediment, project engineers did not believe there was a problem. By 9:30 A.M., a wet spot appeared on the downstream face of the dam and quickly began washing out the embankment material. The hole expanded so rapidly that two bulldozers trying to fill it could not keep up and were themselves lost into the hole. At 11:15 A.M., project officials told the county sheriff's office to evacuate the area downstream. At 11:55, the crest of the dam collapsed; two minutes later, the reservoir broke through and rushed downstream (▶Figure 12-29). The flood obliterated two small towns and spread to a width of 13 kilometers over Rexburg, with a population of 14,000, and continued downslope at 16 to 24 kilometers per hour.

The flood killed eleven people and 13,000 head of livestock, and the federal government paid more than $530 million (in 2002 dollars) in claims. The cause of failure was never settled, but numerous flaws came to light. After construction started, U.S. Geological Survey geologists expressed concern about pressures from a filled reservoir and loading that could cause movement around the dam, as well as internal shearing, endangering the dam.



U.S. Army Corps of Engineers.

▶**FIGURE 12-29.** Progressive failure of Teton Dam, eastern Idaho, June 5, 1976: **(a)** At 11:20 A.M., muddy water pours through the right abutment of the dam. **(b)** At 11:55 A.M., the right abutment begins to collapse and a large volume of muddy water pours through the dam. **(c)** In the early afternoon, the dam fails and the reservoir floods through it.

What Went Wrong?

An expert's review panel blamed design and construction flaws for the dam's failure. A modern dam was built on bedrock with open joints that were not cemented as specified. Fill settled away from the cracked rock, causing internal deformation of the structure. A concrete wall inside the dam, which was designed to block water flow, was built too thinly and cracked under the high water pressure at the base of the dam.

http://earthscience.brookscole.com/hyndman

FEMA.

▶FIGURE 12-30. This flood in the Midwest in June 1994 certainly made roads impassible.

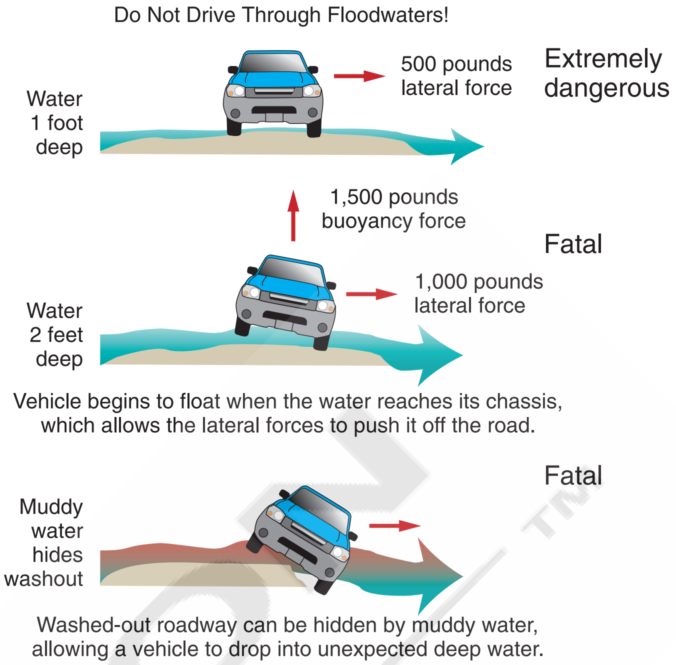
Urbanization

Flash floods also materialize wherever roads or buildings cover the ground and where drainage channels are built to handle the runoff, because water cannot soak into materials such as pavement. Increasing **urbanization** in many parts of the world causes increasing numbers of flash floods and higher flood levels. In urban areas, floods often create problems for those who think they can wait out the rising waters. When they realize they really do have to evacuate, the roads have become impassable, preventing evacuation (▶Figure 12-30).

Streams in all but arid regions are fed mostly by groundwater. Even during floods, a large proportion of the flow commonly moves through the subsurface. The saturation of near-surface soils is necessary before significant surface runoff begins. Exceptions include conditions with especially heavy rains or ground that has been frozen or sealed by wildfires. Small drainage basins have higher, narrower hydrographs than those of large basins, and their floods arrive sooner after a major rainstorm. Paved streets and parking lots, houses, and storm sewer systems carry runoff quickly to streams and result in a significantly higher hydrograph flow in a shorter length of time. The stream discharge rises and falls much faster than in rural areas.

Flash Flood Hazards

Any type of flood can be dangerous, but flash floods are especially so because they often appear unexpectedly and water levels rise rapidly. Deaths are frequent because of little warning and because of their violence. Even under a clear blue sky, floodwaters may rush down a channel from a distant storm. On many occasions, people have been caught in a narrow, dry gorge because they were not aware of a storm upstream. At night, people in their homes have been swept away.



Vehicle begins to float when the water reaches its chassis, which allows the lateral forces to push it off the road.

Washed-out roadway can be hidden by muddy water, allowing a vehicle to drop into unexpected deep water.

Modified from USGS.

▶FIGURE 12-31. Even shallow floodwaters can lift a vehicle and wash it downstream.

Driving through a flooded roadway can be dangerous or even fatal. Even though water may appear shallow, the force of its flow against the wheels, or worse against the side of the car, can wash it downstream. Shallow fast-moving water can erode a deep channel that may not be visible. Fast-moving water only 1 foot deep exerts more than 500 pounds of force against the wheels and is extremely dangerous (▶Figure 12-31). Water 0.6 meters deep and above the vehicle floorboards can exert 700 kilograms of buoyancy and 450 kilograms laterally to push the vehicle off the road and potentially drown the occupants. Driving into apparently shallow muddy water that hides a washed-out roadway can drop the vehicle into deep water and drown the occupants. Even where water is still or hardly moving, liquefaction or settling of part of a roadway can cause unexpected deep water. Cars seem heavy, but their weight is generally much less than the volume of water to fill a car. Most cars will float in water—that is, until water seeps in and they sink. If trapped in a partly submerged and sinking car, it will be difficult to open the doors to escape. Either lower a window or kick out the windshield to climb out.

Even after a storm passes, stay away from downed power lines. Be wary of broken tree limbs that may fall unexpectedly. If you smell gas in a building, extinguish any open flames, turn off the main gas valve, open windows and doors, and evacuate the building.

Coarse material in a stream is supplied by erosion of bedrock or from landslides that enter the channel. In most cases, debris flows on steeper slopes supply that coarse debris to the streams; steep stream gradients are also needed to transport the coarse material. High-gradient bedrock channels generally have deep, narrow cross sections that carry deep, turbulent flows that are highly erosive during floods. Their turbulence makes them capable of transporting large boulders as bedload and even in suspension. Bedload boulders impact and abrade the channel sides, severely damaging roads and bridges.

Changes Imposed on Streams

Increased stream sediment load requires a steeper slope for transport. With excess sediment supplied to a stream, more than the stream can carry, sediment drops out to choke the channel. The stream generally becomes braided, and the channel becomes steeper. Examples include a landslide or mudflow filling the channel, or deforestation by fire, heavy logging, or overgrazing of a watershed, all of which cause excessive erosion and lead to the dumping of large amounts of sediment into a channel.

Forest Fires and Range Fires

In vegetated areas, rain droplets impact leaves rather than landing directly on the ground. Rich forest soils soak up water almost like a sponge, providing a subsurface sink for rainwater that can then be used by the vegetation. Fire removes that soil protection, permitting the droplets to strike the ground directly and run off the surface. Intense fire also tends to seal the ground surface by sticking the soil grains together with resins developed from burning organic materials in the soil. This decrease in soil permeability reduces water infiltration, forcing a large proportion of the rain to directly run off the surface. This can carve deep gullies into steep hillsides and feed large volumes of sediment to local streams (see Chapter 16 for further discussion and pictures of fire-related gullies).

Logging and Overgrazing

Logging by clear-cut methods can promote significant erosion. Perhaps the most destructive method involves "tractor yarding" in which felled trees are skidded downslope to points at which they are loaded on trucks. The method leaves skid trails focused downslope to a single point like tributaries leading to a trunk stream. Skidding logs along the ground removes brush and other vegetation, leaving the ground vulnerable to erosion. Logging roads tend to intercept and collect downslope drainage, permitting the formation of gullies, increased erosion, and the addition of sediment to streams.

Cattle and sheep grazing on open slopes similarly remove surface vegetation that formerly protected the ground. Rainfall running off the poorly protected soil is more likely to erode gullies, thereby carrying more sediment to the streams. Once gullies begin, the deeper and faster water causes rapid gully expansion and destruction of the area for most uses (▶ Figure 12-32). Animals grazing near streams also break down stream banks, causing more rapid bank erosion and heavier stream sediment loads.

Donald Hyndman photo.

▶ **FIGURE 12-32.** Heavy sheep grazing has encouraged deep erosion in a steep slope south of Lake Wakatipu, New Zealand. The broader valley in the upper right is a more extreme stage of the same process.

Vegetation removal also decreases evapotranspiration, the evaporation of rain from leaves and the transpiration of moisture from the living cells of leaves, which naturally pulls water from the soil via roots. This reduction in evapotranspiration permits more water to soak into the ground and to run off the ground surface. Evapotranspiration can drop to 50 percent after clear-cutting. More water penetrating a slope tends to promote landslides, which in some areas contributes as much as 85 percent of the sediment supplied to a stream. Increased runoff and erosion on slopes also carries more sediment into streams. That upsets the balance of the stream, causing increased sediment deposition in the channel and increased flooding downstream.

Hydraulic Placer Mining

The historic practice of hydraulic placer mining in California during the 1860s and 1870s provided a classic case history of how rivers respond to large volumes of added sediment load. Gold miners originally panned gold or separated it from sand and gravel in streambeds with small sluice boxes fed by water diverted from the stream. As those river gravels became depleted, the miners discovered gold in high-level terrace gravels above the streams. To separate that gold, they used high pressure jets of water from higher elevations to hose down the gravels into large sluice boxes at stream level (▶ Figure 12-33). The accumulated loose gravel was picked up by the streams during flood and washed down-


USGS.

FIGURE 12-33. Hydraulic placer gold mining in California in the 1860s contributed to heavy gravel accumulations in the rivers of the western Sierra Nevada mountain range.

stream. The Bear River in the western Sierra Nevada, for example, built up its bed by as much as 5 meters in response to hydraulic gold mining upstream.

The first big flood from heavy rainfall in the Sierra Nevada in January 1862 flushed much of the placer gravel from tributaries into the main rivers, and in turn out through the mouths of their canyons into the edge of California's Central Valley. The rivers became choked with sediment because they could not carry it all; channels filled with gravel, and the flood spread far beyond where it should have. Previously productive farmland was covered with gravel, making it unusable. Cities were not much better off. The next catastrophic floods, in 1865, turned the Central Valley into an "inland sea" 20 miles wide by 250 miles long, submerging farms and towns. Similar floods occurred in the following thirty to forty years.

Hydraulic mining was finally outlawed in 1884, but by then the damage was done. Landowners and governments tried to deal with the floods by the usual means of treating the symptoms. Build levees near the river to contain the flood; when those are topped during a subsequent flood, build them higher. Channelize and straighten the river to carry the water through more quickly and to prevent the water from backing up to form a lake. Build dams to contain the floods. These actions, however, made matters worse downstream. Floodwaters raced right down the channel rather than spreading out across floodplains to slowly drain back into channels as the flood waned. Flood levels between the levees were much higher, so water flowed faster. All that water created greater flood levels downstream.

Although downstream towns built levees to protect themselves, the sediment-choked channels contained so much new sediment that their beds in some cases built up higher than the towns behind the levees. On January 19, 1875, a modest flood along the Yuba River breached a levee at Yuba City north of Sacramento, sending a flood of gravel through the town, all but destroying it.

The hydraulic placer-mining fiasco may be past, but other landscape alterations can lead to similar results. Deforestation from fire or vegetation stripping by overgrazing may lead to rapid erosion in hilly terrain. Sediment from such erosion is carried to stream channels, choking them and leading to heavy sediment deposition. In some areas, the result is braided streams.

Dams and Stream Equilibrium

Building dams removes sediment from streams because the velocity in reservoirs behind the dams drops to virtually zero. Downstream of the dam, the stream carries little or no sediment, so it erodes its channel more deeply during flood (▶ Figure 12-34).

Dams are built for different competing purposes, as noted below in the discussion of flood control and multipurpose dams. According to the 1994 National Inventory of Dams,

- more than 31 percent of dams were built to provide recreation,
- 23.5 percent were built to collect water for water supply or irrigation use during dry seasons,
- 14.6 percent were designed to control flooding downstream from storm or high-water runoff, and
- 2.9 percent were built to generate hydroelectric power.

Flood-control dams are built to stop flooding of floodplains. The intent is not to allow people to build on floodplains, but that is often the effect. People may feel protected by a dam, but that is a false sense of security.

Flood-control dams are built high enough to contain a certain magnitude of expected flood, perhaps a 100-year flood. The ability of a dam to contain such a flood depends on how full the reservoir is just before the flood, as well as changes in management of the upstream land such as deforestation or urbanization. In addition, the reservoirs behind dams eventually fill. At some point, the dam may not be adequate, and in extreme cases the dam may fail.

Most of the largest dams are built by states, the U.S. Army Corps of Engineers, or the Bureau of Reclamation with funds supplied by the federal government. Most of the

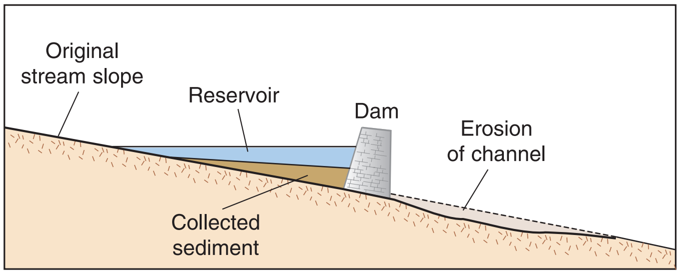


FIGURE 12-34. Trapping of stream sediment in the reservoir behind a dam causes erosion downstream.

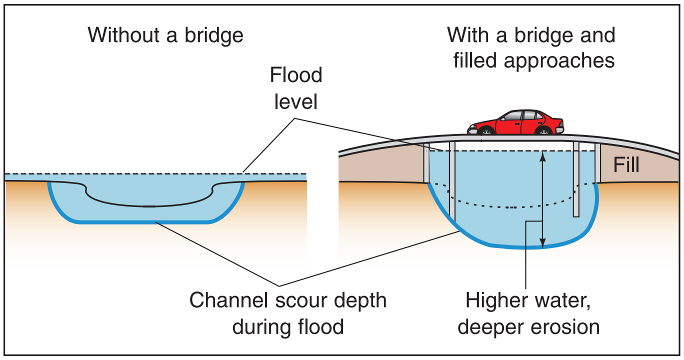


FIGURE 12-35. This diagram shows the effect of a bridge on a flood.

money comes from public taxes. For Congress to appropriate funds for a large dam, the corps must justify the cost weighed against perceived benefits. The benefits might include flood control, hydroelectric power generation, water stored for irrigation, and recreation. Often the cost is justified by adding together all of the perceived benefits even though some are often incompatible with others. Because the public pays for the dam through its taxes, Congress must be convinced of the importance of the benefits.

Bridges

The road or railroad approaches to bridges commonly cross floodplains by raising the roadway above some planned flood level. Most commonly this involves bringing in fill and effectively creating a partial dam across the floodplain so that river flow is restricted to the open channel under the bridge (▶ Figure 12-35). Where roadway approaches restrict flow, floodwater upstream is slowed and becomes deeper. Deeper water flowing under the bridge flows faster, causing erosion of the channel under the bridge. In major floods, the channel deepening may undermine the pilings supporting the bridge, causing the bridge to fail. Where more enlightened planners or engineers design the bridge—or where better funding is available—the approaches may be built on pilings to permit floodwater to flow underneath the roadway. Even where planners are aware of the problem, fill may be used to reduce construction cost.

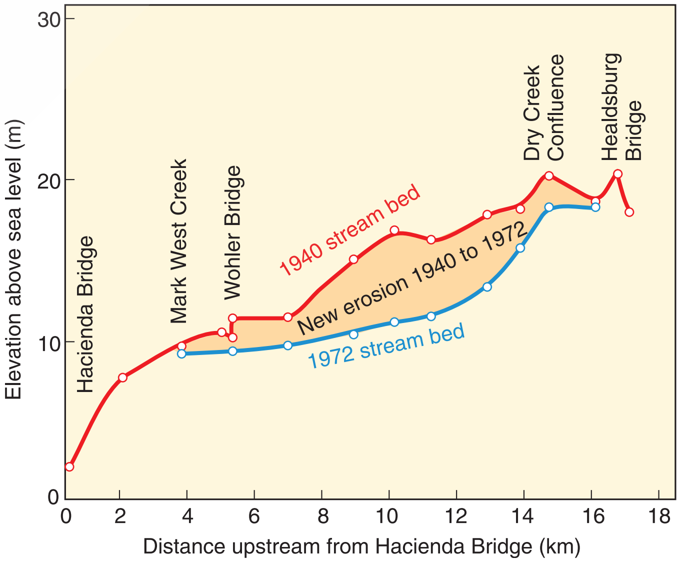
Mining of Stream Sand and Gravel

Large amounts of sand and gravel are used in construction materials for roads, bridges, and buildings. Much of that sand and gravel is mined from streambeds or floodplains. At first glance, that might seem like a harmless thing to do. After all, won't the stream merely bring in more gravel to replace that which was mined? Actually, removal of sand or gravel from a streambed has the same downstream effect as a dam; supply of sediment in the stream decreases. Because the water flow in the stream is unchanged, the decrease in sediment load leaves the stream downstream from the mining area with excess energy that it uses to erode its channel deeper. Deepening a channel can severely damage roads and bridges. It also typically lowers the water table because more groundwater flows into the deeper stream channel; as a result, water supplies are damaged. Where gravel is mined from pits on the floodplain, temporary barriers are often used to channel the stream around the pit (▶ Figure 12-36). Later, rising water may erode the barriers. Water entering the pit from upstream slows and deposits sediment in the upper end of the pit, eventually filling it.


Donald Hyndman photo.

FIGURE 12-36. Now flooded, these gravel pits along the South Platte River near Denver, Colorado, are only separated from the river by thin gravel barriers.

Although such mining may appear, therefore, to exploit a renewable resource, the gravel removed from flood flow by deposition is not being carried farther downstream. The increased energy of the stream downstream amplifies the erosion. In one prominent court case, it was shown that mining of gravel from stream bars has resulted in deepening of the channel by as much as 3 meters for many kilometers



Modified from Shulman & Slosson.

FIGURE 12-37. Downcutting of part of the Russian River channel between 1940, before gravel mining began, and 1972 as a result of gravel-mining operations downstream along the Russian River in northern California.

downstream from Healdsburg, California (Figure 12-37). The change threatened several bridges, destroyed fertile vineyard land, and lowered groundwater levels.

Streambed mining can affect nearby and upstream structures such as roads and bridges. As water nears a deepened gravel pit, its velocity increases, in many cases eroding the upstream lip of the pit and washing that gravel down into the pit. That lip migrates upstream. The deepening channel undercuts roads, bridge piers, and other structures, destroying them. The cost to repair or replace such structures often exceeds the value of the mined gravel. (See "Case in Point: Channel Deepening and Groundwater Loss from Gravel Mining.")

EFFECT OF RIVER GRAVEL MINING ON COASTAL EROSION Removal of sediments from a stream often has far-reaching consequences where a river dumps its sediment at the coast. Normally, much of the sediment deposited in the river delta is carried up or down the coast by longshore drift. The sands and gravels that form beaches are supplied by such longshore drift and may gradually move along the coast for hundreds of miles. When the sediment supply is reduced because of gravel mining or an upstream dam, the longshore movement of sediment along the coast continues but is not replenished. Beaches erode and may even disappear. Waves that normally break against the beach then break against the beach-face dunes or sea cliffs, causing severe erosion (See Chapter 13 for a detailed discussion of coastal erosion.)

Paleoflood Analysis

A major problem in estimating the sizes and recurrence intervals of potential future catastrophic floods in North America is that we only have a short record of stream flow data; the measurement of flood magnitudes is not much more than 100 years, even less in the West. The record is better in civilizations such as China and Japan that have written records extending a few thousand years, and to a lesser extent in Europe. We can project graphical data on magnitudes and their recurrence intervals to less-frequent larger events. However, as outlined above, any record-sized event can dramatically change the estimate of recurrence intervals. **Paleoflood analysis** uses the physical evidence of past floods that are preserved in the geological record to reconstruct the approximate magnitude and frequency of major floods in order to extend the record into the past and to recognize larger floods. Even where the paleoflood magnitudes cannot be determined reliably from the evidence, the flood height can often be fairly well determined. By itself, this can provide critical information on the minimum hazard of a past flood.

Early Postflood Evidence

The nature and magnitude of a flood is most obvious immediately after it occurs. Streams in different environments and different climates, however, are highly variable. Most usable evidence comes from meandering streams, not braided or straight streams. Unfortunately, most studies have been in single regions such as the west-central United States that may not apply well to other regions.

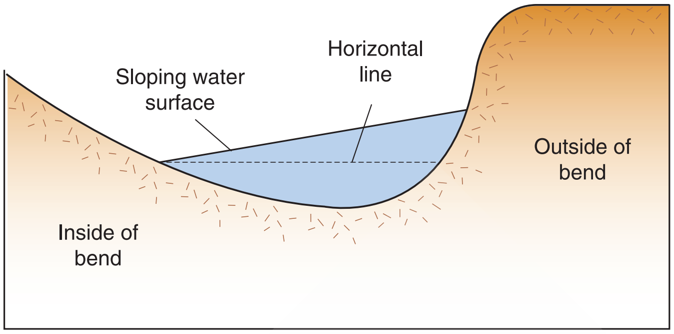


FIGURE 12-38. This diagram shows water-surface inclination at a bend.

The best reaches of a stream for paleoflood analysis are those with narrow canyons in bedrock, slack water sites, and areas with high concentrations of suspended sediment. Useful features include the following (see also Figure 12-41):

- **high-water marks,** which can provide the elevation and width of the high-water surface;
- **cross-sectional area,** if a cross section is exposed (assuming no post-peak scour or channel fill);
- **mean flood depth** (equal to cross-sectional area divided by water-surface width);
- **estimated water velocity,** which can be calculated (± 50%) from the inclination of the water surface as it flows rapidly around a bend (Figure 12-38);
- **mean flow velocity,** which can also be estimated (± 25–100%) from the size of the largest boulders that were moved;
- water **discharge** for high within-bank flows, which can be estimated from cross-sectional flow area and water slope along the channel (Sidebar 12-1);
- **meander wavelength,** which approximately equals 1.63 × meander belt width or 4.53 × meander radius of curvature (Figure 12-39);

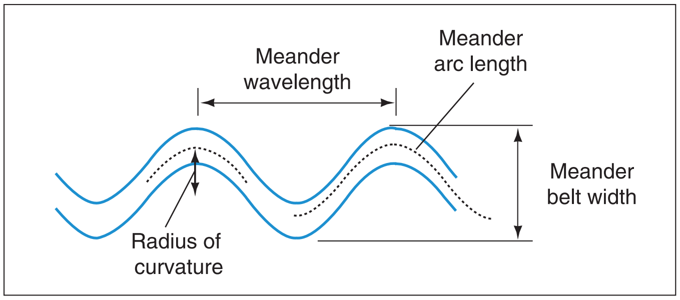


FIGURE 12-39. This diagram shows the relationship between meander characteristics.

CASE IN POINT Channel Deepening and Groundwater Loss from Gravel Mining

The Russian River, Northern California

The Russian River downstream from Healdsburg, California, north of San Francisco, provides an excellent example of the consequences from river-channel gravel mining. Beginning in 1946, both the region's population and large construction projects increased the need for sand and gravel mined from the Russian River watershed. By 1978, private companies were mining 4.06 million metric tons per year of sand and gravel along the Russian River, mostly downstream from Dry Creek. Of this, 80 percent came from stream terraces and 10 percent by draglines from within the stream channel. Draglines excavated gravel in pits as deep as 18 meters below water level in a stream that is typically less than 1 meter deep.

Recall that the slope of a stream strives to remain in equilibrium with the amount and grain size of supplied sediment, and the erodibility and cross section of the channel (see "Dams and Stream Equilibrium," page 318). If any of these factors change, the others will adjust to help bring the stream back toward equilibrium. In the early 1970s, Byron Olson and other fruit farmers along Dry Creek, upstream from Healdsburg, noticed that riverbanks were eroding, steepening, and collapsing more rapidly in storms than they had in the past. The channels eroded more deeply, and the streams became wider at the expense of adjacent orchards and vineyards.

Local farmers blamed the gravel miners for the increased erosion and filed suit for damages. Detailed stream studies followed that eliminated large storms, fire or flood events, and land use changes as causes for the observed increase in discharge and erosion. The total deepening of the Russian River streambed upstream from its confluence with Dry Creek ranged, by 1972, from 2 meters at the confluence to 5.7 meters some 5 kilometers upstream and 2 meters some 9 kilometers upstream. Dry Creek eroded its bed 3.3 meters deeper for some 10 kilometers upstream from the confluence (▶ Figure 12-37). It also undercut and threatened bridge supports (▶ see Figure 12-40).

The removal of so much gravel left Dry Creek with much less bedload to carry, locally increased the channel gradient into the deep mining pits, and increased turbulence. This resulted in more aggressive downcutting all the way from the mining areas into Dry Creek.

F. M. Mann Jr., courtesy of Byron Olson.

▶ **FIGURE 12-40.** Dry Creek bridge supports near Healdsburg, California, have been severely undercut by stream-bed gravel mining downstream.

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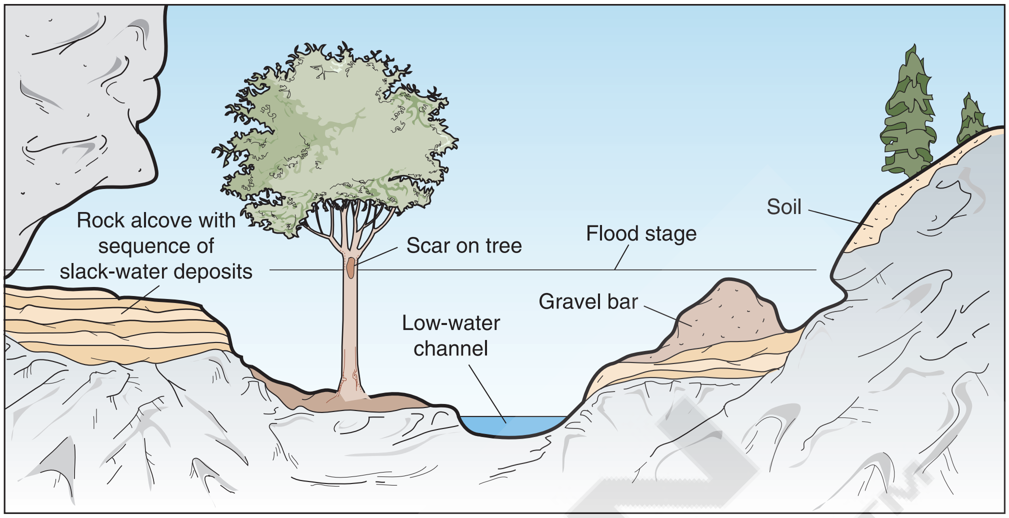
▶**FIGURE 12-41.** This idealized sketch shows the paleoflood features that are used to determine flood level.



Jarrett & England, USGS.

- **meander belt width,** which approximates 2.88 × meander radius of curvature (▶Figure 12-39); and
- **length of a meander arc,** which is related to the bankfull channel width and depth (▶Figure 12-39).

Note that many numerical relationships hold for interrelated variables across all stream sizes. This emphasizes the need to maintain those relationships if any artificial changes are imposed on a stream. These relative proportions of meander wavelength, radius of curvature, and meander belt width hold regardless of the stream size. It does not matter whether it is a small stream only 2 meters across or the lower Mississippi River 1,000 meters across.

Paleoflood Markers

DRIFTWOOD AND SILT LINES Organic debris including leaves, twigs, logs, and silt carried in floodwaters tends to collect at the edges of the flow, including in back eddies (▶Figure 12-41). These provide perhaps the best evidence for maximum flood height, though they may not be preserved long after the flood and driftwood is likely to be well below the maximum water level. Debris may pile up on bridges, providing a minimum height of the flood (▶Figure 12-42). More commonly, floods will leave behind drift lines that show the high-water mark for a short period of time until it erodes away with the next rainstorm (▶Figure 12-43).

TREE RING DAMAGE Individual trees may preserve effects of damage during a flood, indicating the number of years since the flood (▶Figure 12-44). Scars on a tree trunk or branch remain at their original height during tree growth. The height of the damage generally indicates the minimum stage of a flood, though it could be somewhat above the flood height if vegetation piles up.

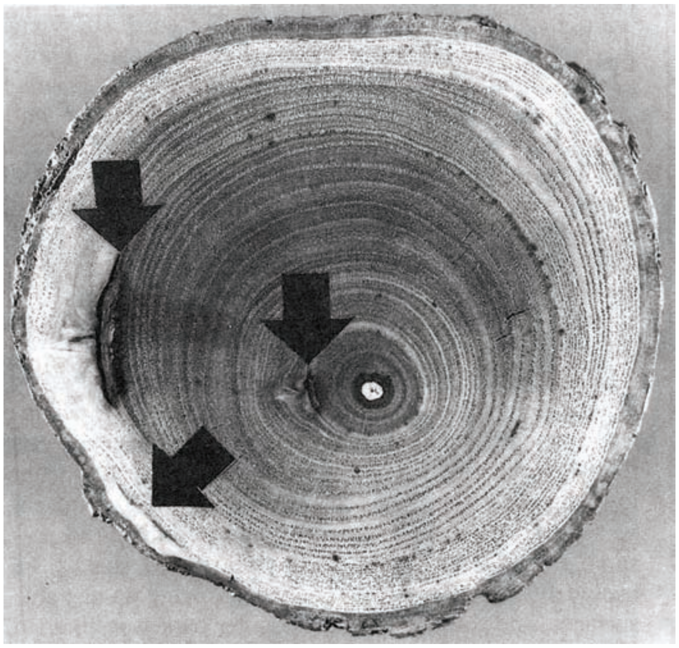
The age of trees growing on a new flood-deposited sand or gravel bar indicates the minimum age since the flood that produced the bar. When all of the oldest trees on the

Donald Hyndman photo.

▶**FIGURE 12-42.** A catastrophic flood on this small stream, Shoal Creek, in Austin, Texas, on November 15, 2001, overtopped the bridge deck and left branches tangled in its railings, evidence of the previous flood height. The high water also deeply eroded the channel and undercut the supports, causing the bridge deck to sag.

Donald Hyndman photo.

▶**FIGURE 12-43.** This organic drift line marks the high water along Shoal Creek in Austin, Texas, from a flood that followed an intense rain storm that dropped 7.5 centimeters of rain in one and one-half hours.


D. Usher photo, USGS.

▶FIGURE 12-44. The number of tree growth rings after the point of damage indicates the number of years since damage occurred.

deposit are of roughly equal age, then that age is probably close to the age of the deposit.

SLACK WATER DEPOSITS During a flood, silt and fine sand can be deposited on sheltered parts of floodplains, the mouths of minor tributaries or shallow caves in canyon walls in bedrock canyons, or downstream from major bedrock obstructions (▶Figure 12-45). These provide information on the maximum water height in a flood.

Organic material in silt and mud layers on floodplains can be dated with radiocarbon methods to indicate the dates of former floods. Bounds can be placed on the heights of former floods even if the specific heights cannot be determined.

Boulders are often deposited where flood velocity decreases, such as where a channel abruptly widens or gradient decreases. These provide a minimum height for a flood.

Review of Factors that Influence Floods

- Floods appear to be more frequent and severe with time, partly because our measurement record is so short. The longer the record, the greater chance of recognizing larger floods. Gauging stations in the United States were not used until 1895. Global climate change is another factor, but human influences such as urbanization are in many cases much more important.


Donald Hyndman photo.

▶FIGURE 12-45. These Lake Missoula slack water sands were deposited over coarse, darker cross-bedded Lake Missoula flood deposits near Starbuck in eastern Washington state.

- Floods are generally natural, although they are commonly aggravated by changes imposed by humans. Rivers cover their floodplains during flooding. "Damage" reflects injury to humans and their structures. That damage is not caused by nature but by peoples' choices of where to live. If you build on a floodplain, your house will eventually be flooded.
- Flood damage costs rise year after year because of population growth, more expensive property, and people moving into less suitable areas.
- The probability of a 100-year flood is the same every year, regardless of how many years it has been since the last 100-year flood.
- However, following any new record flood, the 100-year floodplain is likely to get larger; the recurrence interval for the existing mapped floodplain will get shorter. Therefore, the 100-year floodplain area mapped some years ago is *not* correct—it is almost always larger because of human activity. In other words, the correct 100-year average flood level is higher and covers a greater area than the mapped level.

Hydrologic conditions and basin characteristics that can lead to rapid rise and high level of floodwaters include:

- moderate to heavy rainfall over an extended period over a large area (a series of storms or a stalled storm);
- extremely heavy rainfall as a major storm carries heavy moisture onshore because water cannot soak in quickly enough;
- heavy rainfall on frozen or already water-saturated ground;
- rapid snowmelt from prolonged high temperatures or heavy rainfall on a warm snowpack;
- large drainage area above a site;
- low-order streams so that there are few tributaries to spread out the flow;

- steep channel gradients;
- narrow, deep channels and narrow or missing floodplains;
- lack of vegetation as in an arid climate, after an intense fire, or after clear-cut logging with numerous roads;
- thin or fine-grained, nearly impervious soils that minimize the ability of water to soak in;
- increased runoff because of upstream urbanization, including paving, houses, storm drains, and levees or channelization of upstream valleys leading to constricted and rapid flow;
- failure of a human-made dam or a landslide dam; or
- some combination of the above.

Complexity, or "Coincident Criticality" and Floods

With all of the influences that can lead to flooding, it is overlapping, generally unrelated events that often lead to the most extreme floods. Examples include:

- heavy rainfall on already saturated or frozen ground;
- heavy warm rainfall on a deep snowpack;
- rapid melting of snow over frozen ground;
- heavy rainfall filling a reservoir and causing failure of its dam; and
- earthquake-caused failure of an earth-fill dam, leading to catastrophic flooding downstream.

KEY POINTS

- ✓ Most stream levees are built on top of the natural levees, adjacent to the stream channel from fine-grained sediments dredged from the stream channel. Because levees confine the stream to the main channel rather than permitting floodwaters to spread over the floodplain, the levees dramatically raise water levels during a flood. **Review pp. 297–298; Figures 12-1 and 12-10.**
- ✓ Although people feel safe behind a levee, levees fail by overtopping or breaching, bank erosion, slumps, piping, or seepage through old river gravels below the levee. **Review pp. 298–299; Figures 12-2 and 12-4.**
- ✓ The Mississippi River in 1993 remained above flood level for more than one month—in some places, for two months. Approximately two-thirds of the levees on the upper Mississippi River were damaged, and many were breached. **Review p. 299.**
- ✓ Mississippi River flood levels, for a constant discharge, have become higher each time levees were constructed or raised. **Review pp. 300–301.**
- ✓ Some Mississippi River levees were deliberately breached to decrease flood levels and protect critical areas downstream. In one case, the breach permitted rising water in the "lake" outside the levee to flow back into the river. **Review pp. 303–304; Figure 12-13 and 12-14.**
- ✓ Many people living on floodplains are eligible for national flood insurance but are not aware that they live on a floodplain; nor are they aware that they may be flooded even though there is a levee between them and the river. **Review p. 304.**
- ✓ Avulsion occurs when a breach flow does not return to the river but follows a new path. The consequences for some river-dominated cities such as New Orleans would be catastrophic. The Yellow River of China is an excellent example of repeated avulsion over more than 2,000 years and its devastating consequences. **Review pp. 304–309; Figures 12-17 and 12-22.**
- ✓ Rivers are often channelized to protect adjacent towns, pass floods through more quickly, and increase water depth for shipping. **Review pp. 305, 310–311; Figure 12-16.**
- ✓ Multipurpose dams are built on rivers to provide electric power, flood control, water for irrigation, and recreation. Unfortunately, the demand to keep reservoir levels low enough for flood control often does not coincide with demands to keep levels high enough for electric power generation, irrigation, and recreation. **Review pp. 311–313.**
- ✓ Floods caused by the failure of human-made dams are worst in steep, narrow valleys. Some fail during floods, others because of seepage and erosion under the dam, some by poor design and construction, and others by major landslides into the reservoir upstream. **Review pp. 311 and 314; Figure 12-29.**
- ✓ Urbanization aggravates the possibility of flash floods because it hastens surface runoff to streams. Cars driven into a flooded roadway with water above their floorboards are often pushed off the road, which can cause their occupants to drown. Most vehicles will float until they fill with water and sink. **Review pp. 314 and 316; Figure 12-31.**

- ✓ A dam on a stream or mining of stream gravel removes sediment so that the excess stream energy causes erosion downstream. **Review pp. 318–320; Figures 3-34 and 3-37.**
- ✓ Paleoflood analysis, the study of the magnitude and timing of past floods, includes indications of high-water marks, cross-sectional area, meander wavelength, among other factors. **Review pp. 320–323; Figures 12-38 to 12-45.**

IMPORTANT WORDS AND CONCEPTS

Terms

avulsion, p. 305
breaching, p. 298
channelization, p. 305
deliberate breach, p. 312
evapotranspiration, p. 317
levee, p. 297
multipurpose dams, p. 311
National Flood Insurance Program, p. 304
natural levee, p. 298
paleoflood analysis, p. 320
piping, p. 298
recurrence interval, p. 301
sand boil, p. 299
streambed mining, p. 320
urbanization, p. 314
wing dams, p. 301

QUESTIONS FOR REVIEW

1. Roughly what depth of flowing stream is dangerous to drive through?
2. What non-natural changes imposed on a stream cause more flooding and more erosion?
3. Aside from protecting the adjacent stream bank, what effects do levees have on a stream?
4. What are the negative effects of mining sand or gravel from a streambed?
5. Aside from storing water for irrigation or water supply, flood control, hydroelectric power, and irrigation, what negative physical effects do dams have?
6. What negative physical effect do most bridges have on the streams they cross?
7. What process can lead to the failure of a river levee?
8. What process can lead to flooding of the floodplain behind a levee (of a flooding river) if the levee does not fail?
9. What is a common sign of seepage under a levee?
10. Under what circumstance (or for what purpose) might a levee be deliberately breached?
11. What catastrophic problems may arise with a multipurpose dam that a single-purpose dam should not have? Why?
12. How would a hydrograph for a drainage basin change if major urban growth were to occur upstream? Be specific.
13. What specific evidence can be used to estimate the maximum water velocity in a prehistoric flood?

FURTHER READING

Assess your understanding of this chapter's topics with additional quizzing and conceptual-based problems at:

http://earthscience.brookscole.com/hyndman.