CHAPTER 5
RIVERS

1. INTRODUCTION

1.1 On the continents, except in the most arid regions, precipitation exceeds evaporation. Rivers are the major pathways by which this excess water flows to the ocean. Over the continental United States the average annual rainfall is about 75 centimeters. Of this, about 53 centimeters is returned to the atmosphere by evaporation and transpiration. The remaining 22 centimeters feeds streams and rivers, either directly (by landing in the channels or running off across the surface) or indirectly, by passing through the shallow part of the Earth as groundwater first. This 22 centimeters represents an enormous volume of water: 5.2×10^8 cubic meters per day (1.4×10^{11} gallons per day).

1.2 Rivers are also both the means and the routes by which the products of weathering on the continents are carried to the oceans. Enormous quantities of regolith are produced on the land surface by weathering, and most of this material is transported by rivers to the sea, either as particles or in solution. The other two principal agents that transport this material to the ocean, glaciers and the wind, are minor in comparison.

1.3 ***Rivers*** and ***streams*** (which term you use is a flexible matter of scale) are *channelized flows of water on the Earth's surface*. The term ***overland flow*** is used for *non-channelized flows of water*, usually less than a few centimeters deep but very widespread. There is a pronounced dichotomy between non-channelized flow and channelized flow. Have you ever walked up a small stream channel to see what happens to it? Its termination is almost always well defined.

1.4 Rivers are enormously *diverse*, in:

- **size**: varies by many orders of magnitude
- **geometry**: highly variable
- **substrate**: bedrock or sediment
- **sediment type:** sediment size ranges from mud to gravel
- **stage of development**: young, with rugged topography and rapid change, to old, with gentle topography and slow change
- **climate**: ephemeral and flashy to very steady

1.5 No two rivers look exactly alike, but we can talk about many things that most if not all rivers have in common, like

- how to analyze the hydrology of rivers
- the dynamics of turbulent open-channel flow
- the dynamics of fluvial sediment transport

1.6 The classic areas of study of rivers are these:

- ***fluvial hydrology:*** the study of water *as water* in rivers
- ***fluvial hydraulics:*** the study of the flow of rivers
- ***fluvial sedimentation:*** the study of sediment movement and in rivers
- ***fluvial sedimentology:*** the study of sediments in rivers (overlapping strongly with the preceding field) and of fluvial sedimentary deposits
- ***fluvial geomorphology:*** the study of fluvial geomorphic processes (things like sediment movement, channel changes, broader river-valley processes, drainage-network development) and the long-term evolution of rivers, river valleys, and drainage systems

2. SOME BASIC CHARACTERISTICS OF RIVERS

- Rivers have a *wide range in size* (as measured by either water discharge, sediment discharge, or length).
- Rivers have a *wide range of water discharge* and an *even wider range of sediment discharge*, as a function of time.
- Rivers are *curvy*; they are seldom straight for a long distance.
- Rivers don’t stay in one place: they *shift laterally* in various ways and at various rates, so there’s at least temporary *deposition* at many places in the river system.

- Most medium to large rivers can *keep pace with crustal subsidence or uplift* in some reach of the river by erosion or deposition.
- Rivers have a *long history*. (How does a river start?)

3. FLUVIAL HYDROLOGY

3.1 Measurement of Streamflow

3.1.1 Two aspects of streamflow are typically monitored on all major streams and an enormous number of minor streams as a function of time on a regular basis (in United States, mostly by the U.S. Geological Survey):

3.1.2 Stage. The ***stage*** of a river is *the height of the water surface of the stream above an arbitrary datum*, usually either sea level or an elevation slightly below the channel bed (Figure 5-1). Stage is related to depth, but the two are not the same.

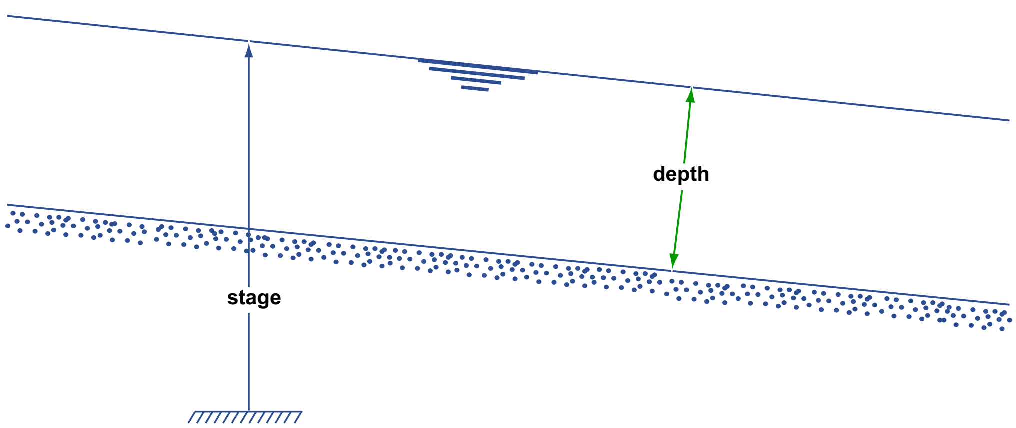


Figure by MIT OCW.

Figure 5-1. The stage and depth of a river.

3.1.3 The stage of a river is fairly easy to measure. Various kinds of *stream gauges* are in use. The simplest is a permanent vertical surface with vertical scale markings you read directly on a regular basis. What's more desirable, but also much more expensive, is an automatically and continuously recording gauge. There are various kinds of such gauges in use; most common is a float gauge, in a stilling well, connected to a strip-chart recorder (Figure 5-2).

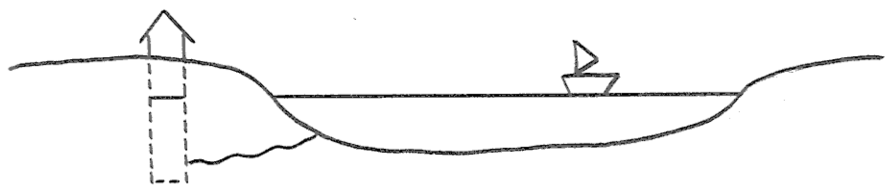


Figure 5-2. A stream-gauging station.

3.1.4 Discharge. The ***discharge*** of a river is *the volume rate of flow past a given cross section*, measured in cubic feet per second, cfs (cusecs) or cubic meters per second, m^3/s (cumecs). It's not nearly as easy to measure discharge as it is to measure stage. Most measurement of river discharge makes use of a simple equation that relates discharge Q past a cross section to the area A of the cross section and the mean velocity U of flow past that cross section:

$$Q = UA \tag{8.1}$$

3.1.5 If Equation 8.1 doesn't make sense to you immediately, just imagine that at a given instant you could magically mark the water that's passing through the given cross section and then watch that marked surface drift downstream for a unit interval of time (Figure 5-3). The distance traveled by that surface is, on the average, equal to the mean velocity U, because velocity is distance per unit time. The volume of water between the given cross section and the marked surface after that unit time, which by definition is just the discharge Q, is the product of the cross-sectional area A and the distance traveled by the surface during that unit time, which is equal to the velocity U, times 1, the unit of time.

3.1.6 So if you measure cross-sectional area and mean flow velocity you can solve for the discharge. This is easier said than done, but it's what's done in practice. There's an elaborate set of practical guidelines for doing this in natural streams; the procedure basically involves

- taking a large number of positions across the stream,
- measuring depth-averaged mean velocity (and depth), at each position, and then
- computing and averaging.

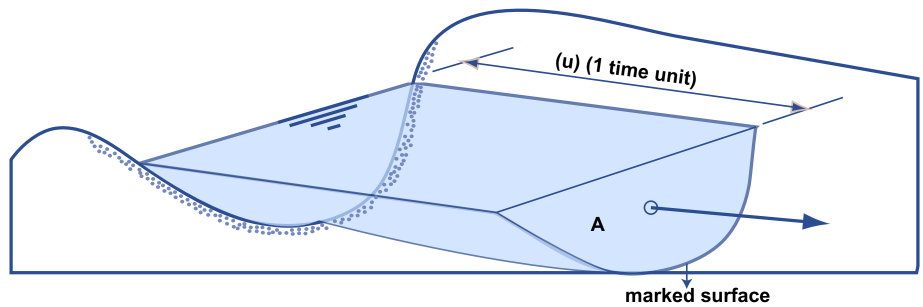


Figure 5-3. Seeing what is meant by Equation 8.1 for river discharge.

Obviously there's a certain unavoidable sloppiness to this, especially under difficult high-water conditions. It's done from bridges, cableways, or boats. The accuracy is something like 5% at best, 10–15% at worst. One tries to do it fast relative to change in stage and discharge.

3.1.7 Clearly, you can't measure the discharge continuously, or even often. But it's important to be able to know the discharge at times you don't (or can't) measure it. *How do you derive a continuous record of discharge?* The technique involves what is called a ***stage-discharge diagram***, often called a ***rating curve***. The rationale is that if downstream conditions don't change (for example, by aggradation or degradation occasioned by new structures built upstream, or the shifting of meander bends upstream) this curve is the same all the time, so once you have it you can find the discharge satisfactorily just by knowing the stage and going into the diagram. A lot of effort goes into deriving and checking rating curves. Rating curves are usually convex upward, as in Figure 5-4.

3.2 Hydrographs

3.2.1 It should seem natural to plot the results of streamflow measurements in the form of *a graph of stage vs. time or discharge vs. time*. The latter is most common and useful. Both kinds of graph are called ***hydrographs***. Time scales and discharge data used in hydrographs vary widely:

- To study individual floods, you need a "continuous" record of discharge for days or weeks (Figure 5-5A).
- A common longer-term hydrograph shows peak or mean daily discharge for a whole year (Figure 5-5B).

- Longer-term hydrographs show mean monthly or annual discharge over many years (Figure 5-5C). Hydrographs vary widely from river to river depending on climate and substrate. This reflects the circumstance that rivers can be *flashy* or *steady*.

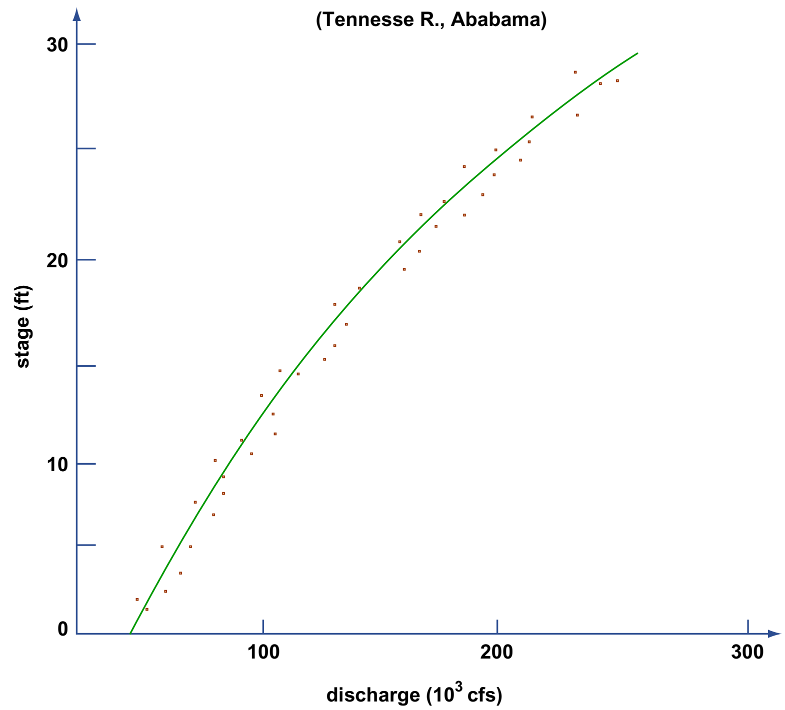


Figure by MIT OCW.

Figure 5-4. Example of a rating curve.

3.3.2 What is the characteristic or typical short-period hydrograph of a stream produced by a rainfall of given duration with given steady intensity? Refer to Figure 5-6.

AB: end of spell without rainfall; all surface runoff has ceased, and groundwater runoff is gradually decreasing.

B: surface runoff from a rainstorm reaches the channel.

BC: this is the ***rising limb*** of the hydrograph; surface runoff increases sharply.

C: this is the ***peak*** or ***crest*** of the hydrograph; surface runoff peaks.

CD: this is the ***falling limb*** or ***recession limb*** of the hydrograph. Groundwater runoff peaks here somewhere, then tails off slowly; surface runoff decreases to zero.

D: by this time there's no more surface runoff, only decreasing groundwater runoff.

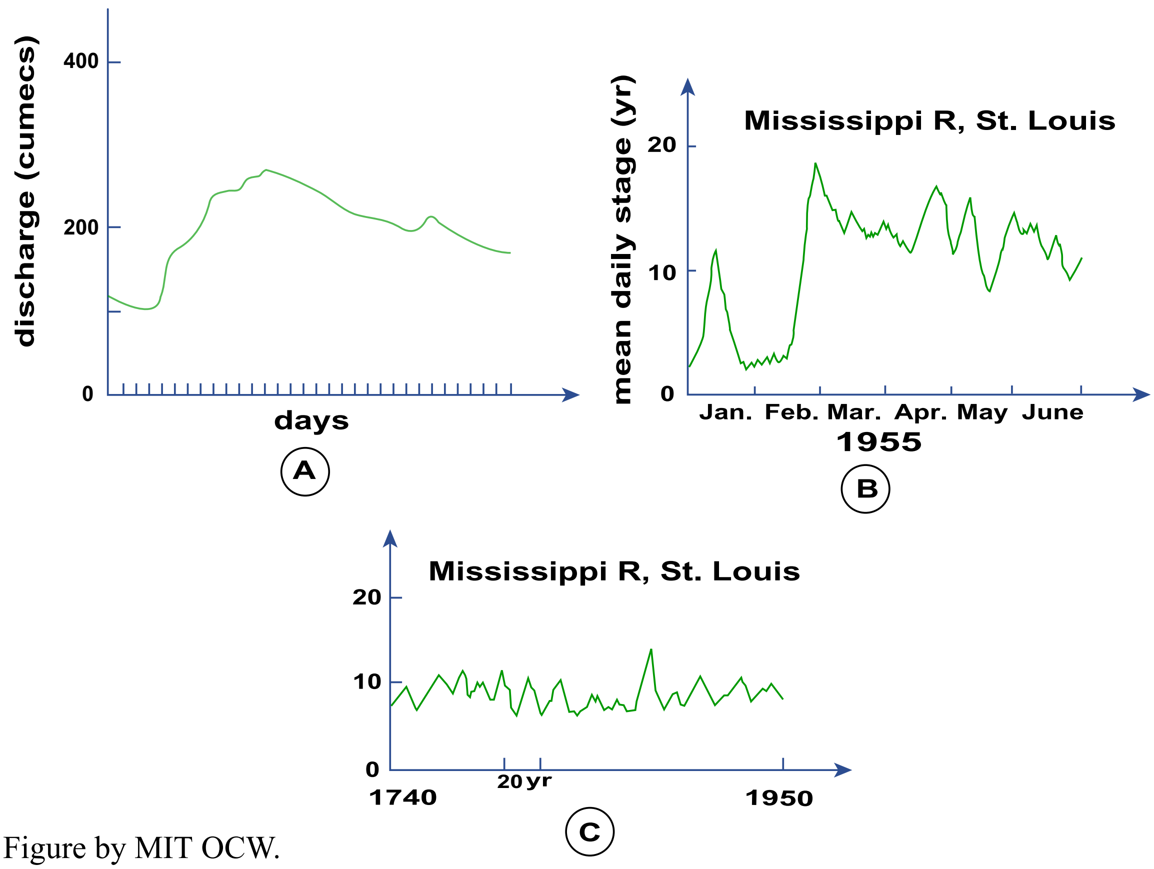


Figure by MIT OCW.

Figure 5-5. Examples of rating curves. A) Discharge hydrograph of n individual flood (conceptual). B) Stage hydrograph of the Mississippi River at St. Louis for an entire year. C) Stage hydrograph of the Mississippi River for over two centuries.

3.3.4 It's also possible to show both surface runoff and groundwater runoff on the same hydrograph (Figure 5-7). Note that sometimes groundwater flow actually goes negative, because of ***bank storage***: instead of the groundwater feeding the river, the river feeds the groundwater table.

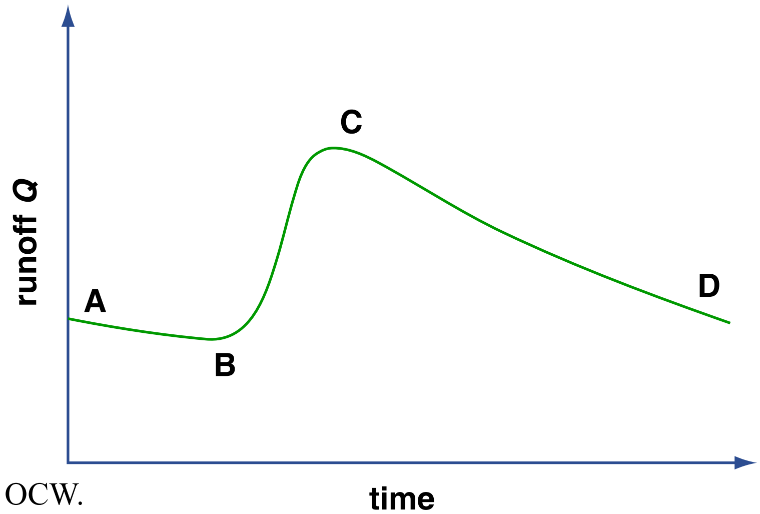


Figure by MIT OCW.

Figure 5-6. Characteristic short-period hydrograph of a stream, associated with a rainfall event of short duration and steady intensity.

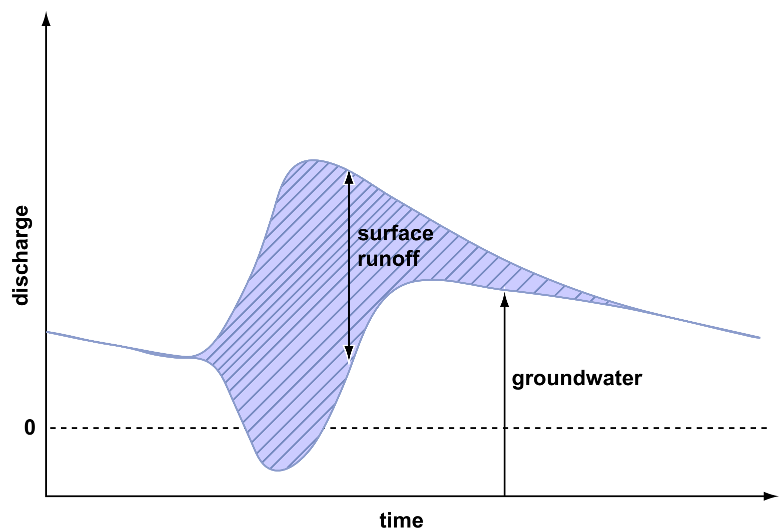


Figure by MIT OCW.

Figure 5-7. Showing surface runoff and groundwater runoff on the same hydrograph.

3.3.5 How does one account for the shape of the rising limb of the hydrograph? Think about a tiny "drop" of water falling on the watershed. Assume that it's not infiltrated or reevaporated but travels as surface runoff. At first it travels as ***overland flow***, and then later as ***channelized flow***. (In fact, watersheds can be classified as "small" or "large" depending on whether the ratio of time involved in overland flow to time involved in channel flow is large or small, respectively.) Eventually the drop passes a given station at the outlet of the drainage basin. This takes a certain average time. You can imagine a map of the drainage basin upstream of this point as being contoured by ***isochrons*** (curves of equal travel time) (Figure 5-8)—although it would be very difficult to compute or measure this in actual practice.)

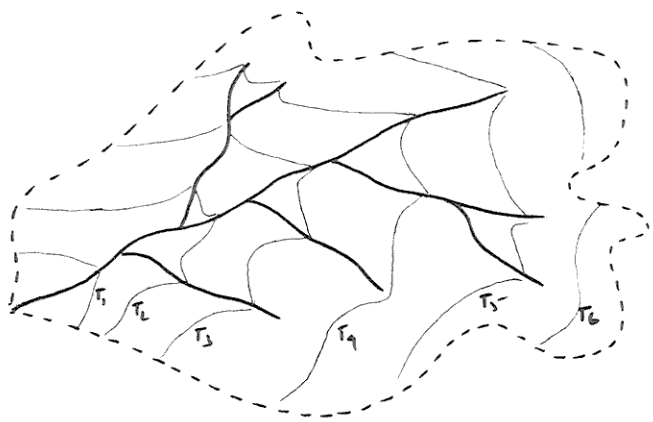


Figure 5-8. Map of a small drainage basin, showing isochrons of equal travel times of surface runoff to the outlet of the basin.

3.3.6 Assume a brief and uniform rainfall over the watershed (that is, the rain doesn't last long, and the rate of precipitation is the same everywhere in the basin). Surface runoff at our station can be accounted for by looking at cumulative area as a function of time (Figure 5-9). For our brief and uniform storm, this should be equivalent to the rising limb of the hydrograph for this storm if we make the transformation

Runoff = (rainfall depth) times (area)

It should make sense to you that the time it takes to reach the peak of the hydrograph thus derived (that is, the time it takes until all of the watershed area is now contributing to the discharge at the station) gets longer as the watershed area gets bigger. We haven't dealt with the falling limb of the hydrograph here, but, obviously, after the rain stops, less and less of the watershed area is contributing water, so the discharge past our station gradually decreases.

3.3.7 A hydrograph is this simple only for an ideal rainstorm in a very small watershed. Hydrographs of real rivers are invariably more complicated, for obvious reasons involving *unsteadiness* (varies with time) and *non-uniformity* (varies from place to place) of rainfall.

3.3.8 It's difficult to say anything striking about hydrographs at this point, but the differences in discharge reflected in the hydrographs are of paramount importance in both the channel pattern and the sedimentary processes in streams.

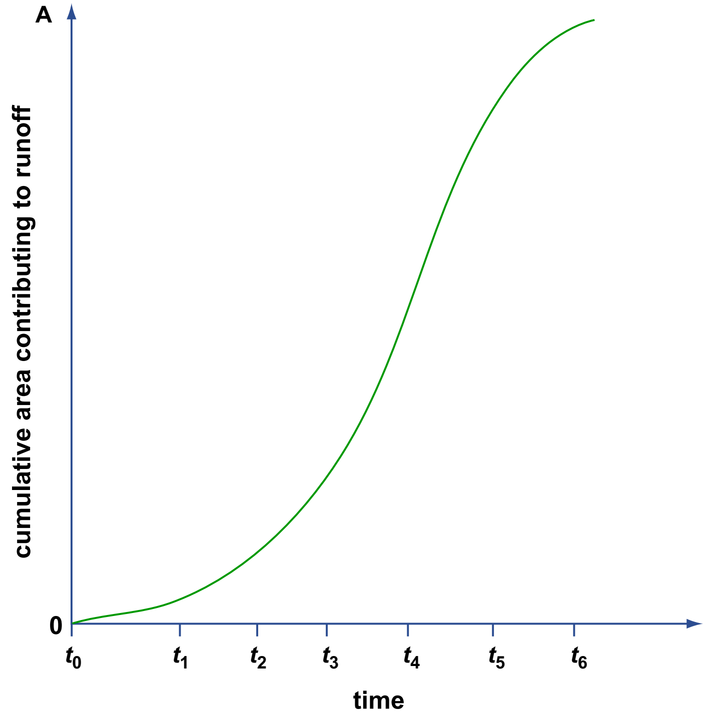


Figure by MIT OCW.

Figure 5-9. Graph of cumulative area as a function of time, for the rainfall event in the watershed shown in Figure 5-8.

3.3.9 In terms of *flashiness* (qualitative magnitude of change in discharge from time to time), one of the most important aspects of river behavior for sedimentation, you can plot a similar *diagram of discharge vs. percentage of time* (this is called a ***flow-duration curve*** (or a ***discharge-duration curve***) if you have a long record of discharge. Figure 5-10 shows such a curve for two medium-size streams in Ohio, of about the same size and discharge:

(1) Sandy Creek, Sandyville, Ohio: $A = 481$ mi^2, underlain by surficial sand and gravel, good porous aquifers;

(2) Rocky River, Berea, Ohio, $A = 269$ mi^2, glacial till and clay, highly impermeable material.

On the vertical axis is plotted Q/A instead of just Q, to normalize for the area of the drainage basin.

3.3.10 The curve for Rocky River shows greater peak flows and lesser base flows; this is described as *flashy* behavior. Sandy Creek, on the other hand, shows lesser peak flows and greater base flows; this kind of behavior is *steadier* and not as flashy.

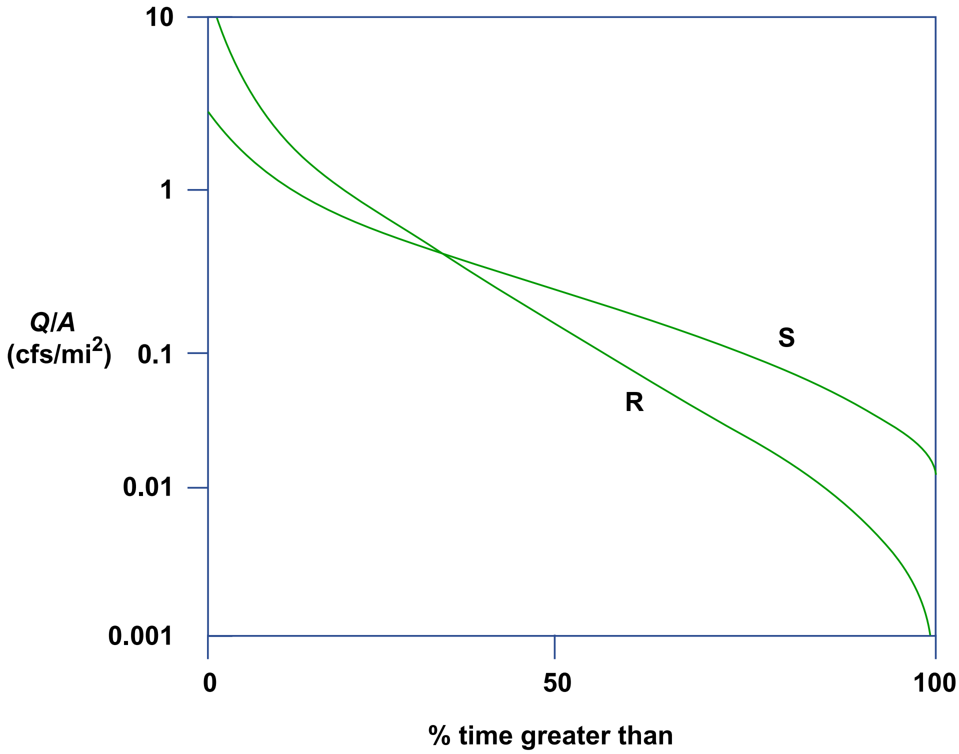


Figure by MIT OCW.

Figure 5-10. Discharge–duration curve for two small rivers in Ohio.

4. OPEN-CHANNEL HYDRAULICS

4.1 This would a good place to go back and review the material on open-channel flows in Chapter 1. Recall that in open-channel flows the presence of the free surface means that the geometry of the flow can change in the flow direction not just by being constrained to do so by the geometry of the boundaries but also by the behavior of the flow itself. This means that the acceleration of gravity can no longer be ignored, because the forces of gravity help shape the free surface. For example, gravity waves can be generated on the free surface. But the effect of gravity is more far-reaching than just that. Babbling brooks and white-water rivers clearly have complex free-surface geometries governed by bed relief, expansions and contractions of the channel, and, less obviously, upstream and downstream conditions. But all open-channel flows, even broad, majestic rivers like the Mississippi, are subject to such effects of gravity.

4.2 Here are three basic concepts in the hydraulics of open-channel flow I think you should know about:

bed shear stress:

The ***bed shear stress*** is *the force per unit area the flow exerts on the bed.* Actually the force per unit area varies strongly from point to point, depending on the details of the bed geometry, and the concept of boundary shear stress is built around the idea that you average over an area large enough to eliminate the effects of such things as sediment particles or local sediment topography. The importance of the bed shear stress lies in its role in moving the sediment particles resting on the river bed.

flow resistance:

The resistance to flow, or ***flow resistance***, is the force or drag the boundary exerts on the flow. You should recognize that in uniform flow, where the flow isn't accelerating or decelerating, Newton's third law tells us that this is just the opposite of the bed shear stress. The importance of the flow resistance is less easy to state. It has to do with the role of flow resistance in determining the particular combination of flow depth and flow velocity (out of an infinite number of possible combinations) with which the imposed water discharge is passed through a given reach of a river (Figure 5-11).

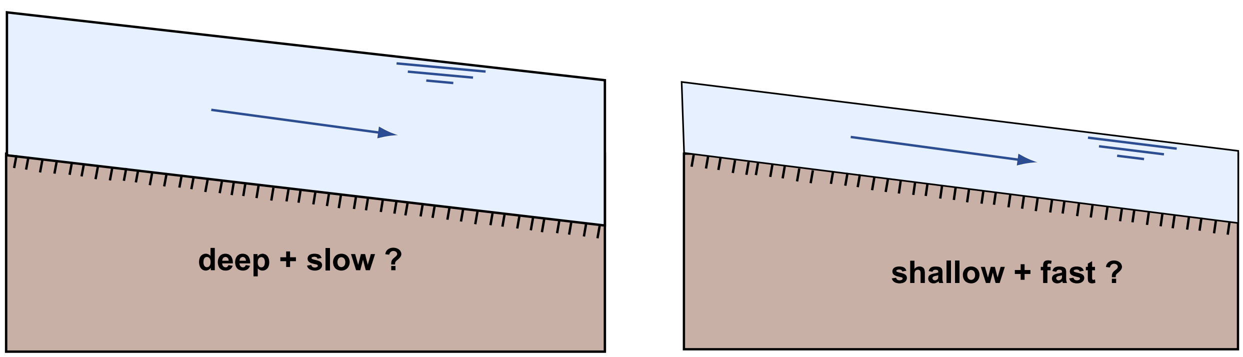


Figure by MIT OCW.

Figure 5-11. Which combination of depth and velocity to pass a given discharge through an open channel?

slope:

If rivers were always straight, the definition of the ***slope*** would be a straightforward concept: it's the difference in water-surface elevation between two stations along the river, divided by the horizontal distance be
stations (Figure 5-12). But if the river is curvy (as is usually the case, at least to some extent), then you have to measure the horizontal distance along the sinuous projection of the course of the river on a horizontal plane (Figure 5-13). The slope

can be measured in feet per mile (as in the U.S.) or in some metric units like meters per kilometer. Recalling some trigonometry, you might recognize the slope as the tangent of a slope angle. Measuring the slope of a river is not easy: you have to do some surveying to establish elevations, and you have to worry about what, exactly, is the course of the river.

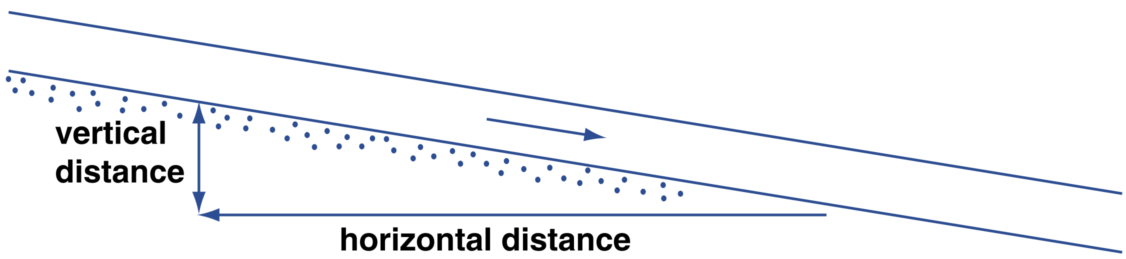


Figure by MIT OCW.

Figure 5-12. The slope of a river.

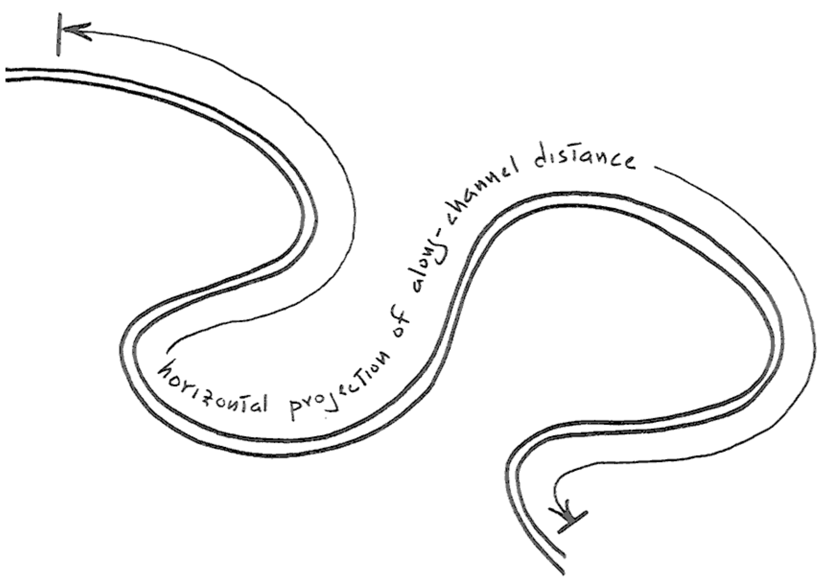


Figure 5-13. Measuring the horizontal component of the distance along a sinuous river.

ADVANCED TOPIC: THE RESISTANCE EQUATION FOR OPEN-CHANNEL FLOW

1. It's easy to derive a fundamental equation that relates the flow depth, the slope, and the bed shear stress of a river, if you are willing to assume that the flow in the river is about the same in cross-sectional shape and area at all cross sections (such rivers are said to have ***uniform flow***, which is often close to being the case).

2. Think about the water contained in a volume that's formed by the river bed, the free surface, and two cross sections a unit distance apart (Figure 5-18). One of the classic ways to get somewhere in the analysis of a problem in dynamics (and we're dealing with such a problem here) is to apply Newton's second law, $F = ma$, where F is the force on some body of matter, m is the mass of the body, and a is the acceleration of that body under the action of that force) to an appropriately chosen part of the dynamical system. What I want you to think about here are the forces that act on the water in the volume I just defined, which from now on I'll refer to as the "body". Because the flow is uniform, and the river discharge varies only slowly with time, it's a good assumption that the body is not accelerating. So Newton's second law tells us that the sum of all the forces acting on the body in the streamwise direction has to be zero.

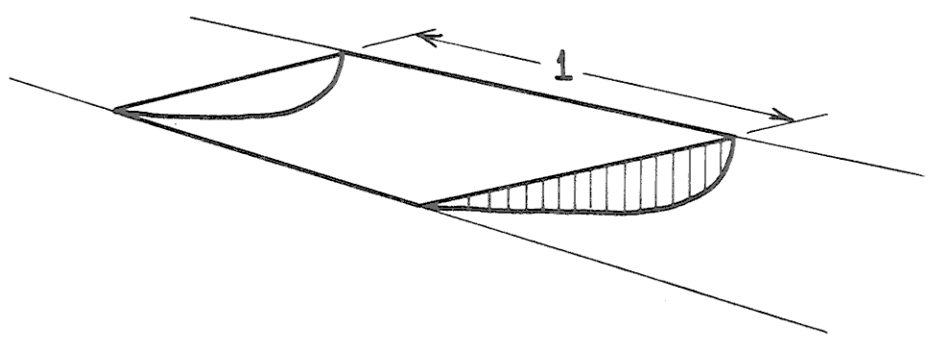


Figure 5-14. The water contained in a volume that is formed by the river bed, the free surface, and two cross sections a unit distance apart.

3. What are the forces acting on the body in the streamwise direction (Figure 5-15)? First of all there are hydrostatic fluid pressure forces on both the upstream and downstream faces of the body. We can forget about these, because they are the same upstream and downstream and they act opposite to each other. There's the weight of the body—that's a gravity force acting vertically downward—and a component of that weight acts in the downstream direction. It's this downstream component of the weight that pulls the water down the channel. If the weight per unit volume of the water is γ, and the cross-sectional area of the flow is A, and the slope angle is α, then the downstream component of the weight is $(1)(A)(\gamma)\sin\alpha$. Finally there's the upstream-directed frictional force exerted by the boundary on the moving body. It's this upstream-directed frictional force that resists the downstream-directed gravity force. If the wetted perimeter of the flow (that is, the total distance along the line of contact between the flow and the bed, as viewed in a cross section normal to the river flow) is P, then the frictional force is $(1)(P)(\tau_o)$. Writing the balance between the frictional force and the gravity force, we have

$$(1)(P)(\tau_o) = (1)(A)(\gamma)\sin\alpha \tag{8.2}$$

or, doing a little rearranging,

$$\tau_o = \gamma \frac{A}{P} \sin\alpha \tag{8.3}$$

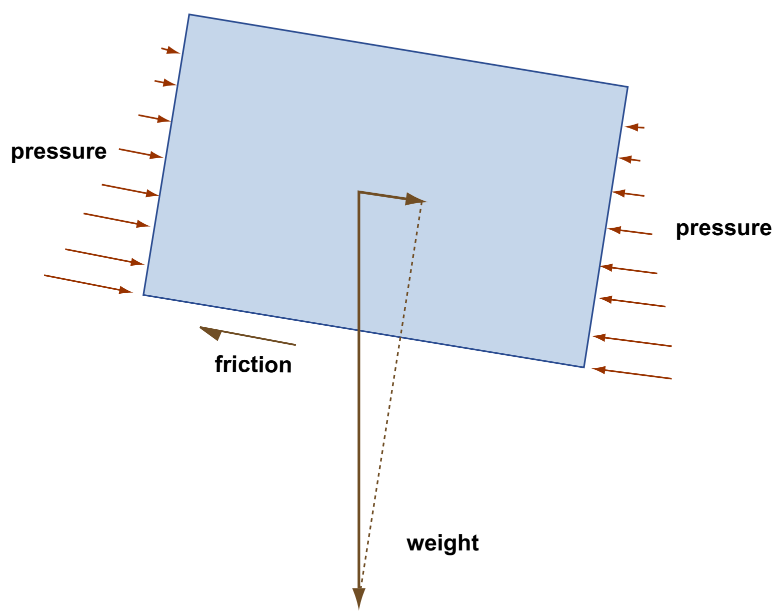


Figure by MIT OCW.

Figure 5-15. Streamwise forces acting on the body shown in Figure 5-14.

4. A slightly different and more specific way of obtaining a relationship like this is to assume that the width of the river is much greater than its depth, which is often the case. Then, if you look at a body that's like the one used above but is rectangular volume a unit length long and a unit length wide (Figure 5-16), the downslope component of the weight of the body is (1)(1)(d)sin α, where d is the flow depth, and the frictional force on the body is (1)(1)(τ_o), and the balance equation analogous to Equation 8.3 is

$$\tau_o = \gamma d \sin \alpha \qquad (8.4)$$

These two relationships, Equation 8.3 or Equation 8.4, are called ***the resistance equation for open-channel flow***. A simple result, no? Not many fundamentally important relationships in fluid dynamics are so easy to derive. One useful practical application of the resistance equation is that it gives you a way of finding the bed shear stress once you know the flow depth and the slope—and that's difficult to do, otherwise.

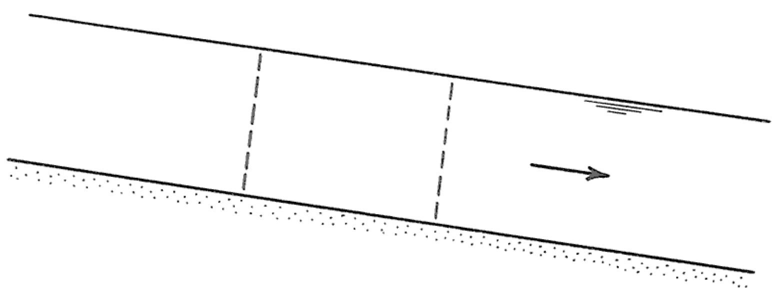


Figure 5-16. A body of water, in a river, that has unit length and unit width and extends from the river bed to the free surface.

4.4 Now I want to address two questions that get to the heart of how rivers actually operate. Neither of these questions is easy to deal with. The first is this: **What determines the slope of a river?** One way of answering this question is that the slope is determined by (1) the vertical and horizontal scales of broad crustal uplift that establish the topography that underlies the river system in the first place and (2) the subsequent general reduction in land elevation as the river wears down its drainage area. That's true, but there's more to the story, because rivers can meander within their valleys (as you will see in more detail later in this chapter) and thereby increase the length of their course without changing the elevation along their course. A meandering river has a considerably gentler slope than a straight river in the same river valley.

4.5 The other question is: **What determines the particular combination of flow depth and flow velocity associated with a given water discharge?** For any given discharge, there are an infinite number of such combinations; the river might flow fast and shallow, or slow and deep, and still transport the water discharge imposed from upstream. It's natural to pose this question at this point, but I think it's wise to postpone an attempt at an answer until we've dealt with bed configurations later in this chapter. See Section 8.7.

5. THE ENERGY OF RIVERS

5.1 The content of this section is a little less grandiose than the title would suggest. I would like to introduce some basic ideas about the energetics of rivers and then supply a calculation to show how much energy is actually expended by a representative large river.

5.2 Remember the "home experiment" on dropping a lump of modeling clay to demonstrate the nature of energy, back in Chapter 1? A river is a falling body too, in a very real sense; its fall is just constrained to be at a very low angle, by the gently sloping bed of the river.

5.3 When viewed as an energy system, a river is a converter of mechanical (potential) energy to thermal energy. The potential energy of the river water is converted to thermal energy by internal friction within the water. The kinetic energy of the river, however, remains nearly constant, because the flow isn't changing its speed much downstream. The nature of the internal friction is actually very complicated, because it depends on the details of the turbulence in the river.

5.4 When we obtain hydroelectric power from rivers, what we're doing is locally arranging the river, by building a dam and making a lake, so that the conversion of potential energy to heat energy is suppressed along some stretch of the river, and we convert the potential energy directly to electrical energy by turbines and generators instead.

5.5 It might interest you to think about the power expended by a large river. Let's make a very crude calculation of the rate of energy release by the lower Mississippi River, per square meter of the bed, as it flows downhill. One way of doing this is to think about a column of water above one square meter of the bed of the river, and how fast that column of water loses its potential energy as the river flows downslope. That loss of potential energy shows up as heat, via friction within the water column, owing to shear of the water, and at the bed of the river, as bottom friction. Think of this as the continuing degradation of the mechanical energy of the river into the thermal energy of the water. (Of course, the river doesn't keep on heating up: it's losing heat to its surroundings all the time at about the same rate that the heat is being produced by friction.)

5.5 You're likely to get confused about units here. In the mks (meter–kilogram–second) system of units in physics, the unit of force (including weight, which, remember, is a force) is the **newton** (N). The unit of energy is the **joule** (J), which is equal to one newton-meter.

BACKGROUND: WORK AND ENERGY

1. What comes to your mind when I mention work? Maybe what you do for a living, or things you have to do that are the opposite of fun. In physics, however, work has a very specific meaning: when a body of matter is acted upon and thereby moved by a force, the ***work*** done by the force on the body is equal to *the product of the component of the force in the direction of movement, and the distance the body moves*.

2. In physics, work is equivalent to energy. You probably have heard of Newton's second law of motion, mentioned in the background section on energy. It's not difficult to show, with some math, that Newton's second law can be recast into an equivalent form that says that *the work done on a body is equal to the change in kinetic energy of the body*. That's why the joule, the unit of energy in the mks system of units, is equal to one newton-meter.

5.6 In its lower reaches, the Mississippi is about ten meters deep, as a very round number, and its mean velocity is as much as a few meters per second. Let's assume, conservatively, one meter per second. The slope of the river is something like 10^{-4} (meaning that it drops about a tenth of a meter in one kilometer of downstream travel).

5.7 If our column of water is moving at one meter per second and drops a tenth of a meter in one kilometer of travel, it is losing elevation at a speed of 10^{-4} meters per second. (Think about that for a while, to convince yourself.) The weight of the unit-area column of water is equal to the weight of a cubic meter of water, times its height of ten meters. The mass of a cubic meter of water is (basically by definition!) one thousand kilograms. We have to multiply that by the value of the acceleration of gravity, about ten meters per second per second, to find its weight. Then we have to multiply by the height of the column, ten meters. The result is 10^5 newtons. That mass, with a weight of 10^5 newtons, is losing elevation at 10^{-4} meters per second, so the rate of loss of potential energy is ten newton-meters per second—or 10 joules per second, as per the definition of the joule in the background section above. That's the rate at which the unit-area column of water in the river loses its mechanical energy. One joule per second is called a ***watt*** (abbreviation: W). The grand final result is *ten watts per square meter of river bottom*. That doesn't sound like a lot (a ten-watt bulb is even dimmer than the classic dim bulb), but think of how many square meters there are on the bed of the Mississippi River (a few kilometers wide, and hundreds of kilometers long, even in just its lower reaches).

5.8 That long and involved computation above has relevance to hydropower. What a hydroelectric station does is convert the mechanical energy of the river directly into electrical energy. The falling water turns turbines connected to electrical generators, with minimal friction involved, instead of slowly losing its potential energy to heat by friction as it flows downstream.

6. THE MORPHOLOGY OF RIVERS

6.1 Figures 5-17 and 5-18 are simplified flow-transverse cross sections through a representative single-channel alluvial river of medium to large size. Figure 5-17 shows the entire stream valley, and Figure 5-18 shows details of the river channel itself. In the following paragraphs I will elaborate upon the various features shown in these figures the diagrams. I'll defer a description of the plan-form features of the river (that is, what you would see from the air, above the river) until later.

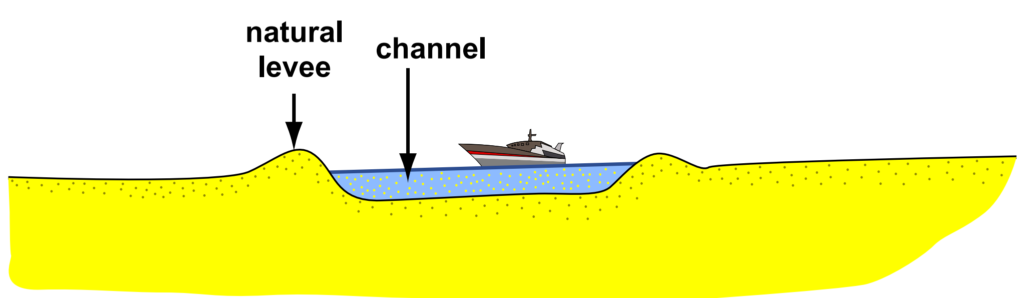


Figure by MIT OCW.

Figure 5-17. Simplified flow-transverse cross section through the valley of single-channel river of medium to large size.

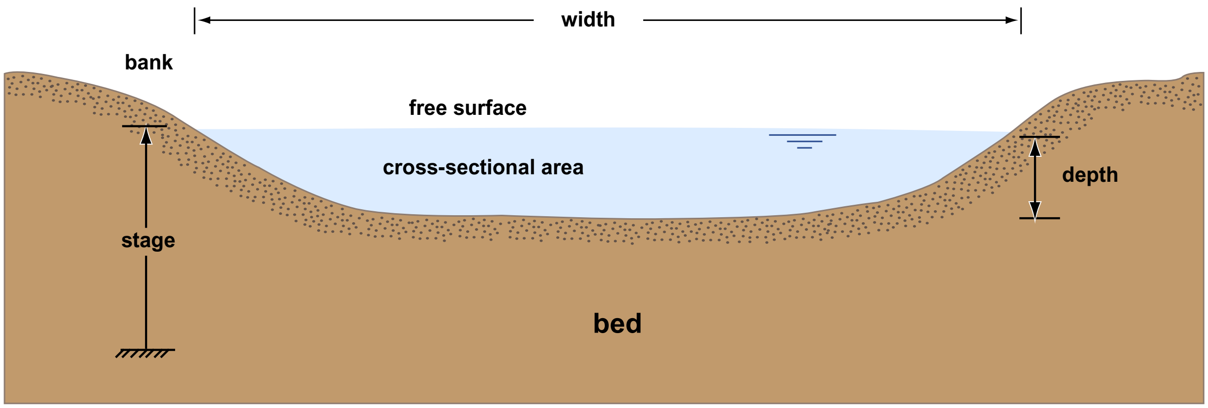


Figure by MIT OCW.

Figure 5-18. Simplified flow-transverse cross section through a representative river channel.

6.2 Most medium to large rivers flow on beds of sediment that they have deposited and can transport again; in a later section of this chapter, rivers of this kind will be called ***alluvial rivers.*** The unconsolidated sediment in the river valley, lying above the bedrock "basement" of the river, is called the ***valley fill***. Its thickness ranges from just a veneer to hundreds or even thousands of meters. In the case of rivers flowing across areas of the crust that have undergone substantial and prolonged subsidence, the valley fill is buried so deeply that it is at least partly lithified, and the material grades over into what would be considered the "ancient sedimentary record" (the term geologists use for sedimentary rocks that are very old by human standards).

6.3 The ***floodplain*** of a river is *an area of low relief adjacent to the river channel, which is inundated at times of high river stage*. During floods the floodplain receives a layer of fine sediment that settles out of suspension as the flood waters spread over the floodplain and decrease in velocity. If the river is not undergoing net aggradation (see below for what I mean by that), then the floodplain builds up to a level at which the rate of removal of fine sediment by erosion back into the main channel at times of low water is great enough to strike a balance with the rate of addition of fine sediment from suspension during floods. Most river floodplains are heavily vegetated, and, depending upon climate, are often dotted with shallow lakes and swamps (called ***backswamps***). Floodplains are among the best areas for agriculture, because they continually receive fresh influxes of fertile soil.

6.4 Alongside many river channels are low ridges called ***natural levees***, formed by deposition of the finer fraction of suspended sediment from flood waters passing across the river banks when the river is above flood stage. There's preferential deposition because the flood waters decelerate as they leave the main channel flow.

6.5 The river channel itself can be characterized most fundamentally by its cross-section shape and cross-section area. The ***width*** is the distance, normal to the local trend of the river, from bank to bank; obviously the width depends strongly on the river stage as well as on the average size of the river. The ***depth*** of the river varies from point to point across the section. A good way of encapsulating the lateral dimensions of the river is to specify the ***hydraulic radius***: the ratio of the cross-sectional area to the wetted perimeter at a given cross section. (To figure out the ***wetted perimeter***, you would use one of those distance-measuring wheels you can rent or buy. Start at the water line on one bank and walk straight across the river to the water line on the opposite bank. Whether you could do that without underwater breathing gear depends on the depth of the river.) For a very wide channel with a nearly rectangular cross section, with an approximately level bottom and steep banks, the hydraulic radius is nearly equal to the flow depth. (You might try figuring that out for yourself; ,it would take some careful thought and a bit of math.)

6.6 Another significant aspect of river geometry is the vertical profile. Imagine traveling up the river, keeping track of two things: the elevation of the riverbed above sea level, and the map distance from the mouth of the river. Then plot a graph with the riverbed elevation on the vertical axis and the upstream distance on the horizontal axis. Pass a smooth curve through the points. The result is what is called the ***longitudinal profile*** (or ***long profile***) of the river.

6.7 The longitudinal profiles of most rivers are *concave upward*, as shown in Figure 5-19. The reason is not difficult to understand. In the downstream direction, one tributary after another joins the river, each adding discharge. As the river grows larger, the ratio of cross-sectional area to wetted perimeter increases. Because the slope of the river depends, in large part, on the relative magnitude of the downslope driving force of gravity, which is affected by the whole volume of the river, and the upslope resisting force of friction, which is affected by the area of the riverbed, the slope decreases downstream.

6.8 The ***base level*** of a river is *the elevation of the water surface of the water body, either the world ocean or a lake along the river course, into which the river flows* (Figure 5-20). The base level changes with time: lake levels fluctuate as a consequence of variations in precipitation in the watershed of the river or because the outlet of the lake is eroded downward, and sea level changes, for various reasons and often very substantially, over a great variety of time scales, ranging from decades to tens of millions of years.

6.9 Think about what happens to the river as its base level changes. The concept to keep mind is that *the river has some equilibrium longitudinal profile*, in the sense that if conditions of precipitation, sediment supply, and base level remain constant the longitudinal profile stays the same. If a different set of conditions is imposed upon the river, the river adjusts its longitudinal profile accordingly toward a new equilibrium.

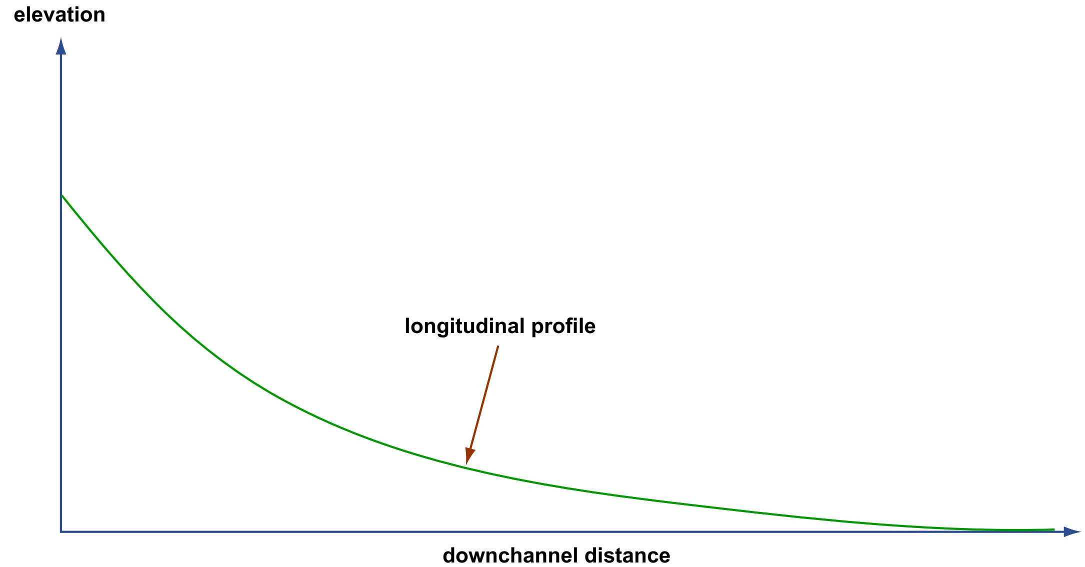


Figure by MIT OCW.

Figure 5-19. The longitudinal profile of a river.

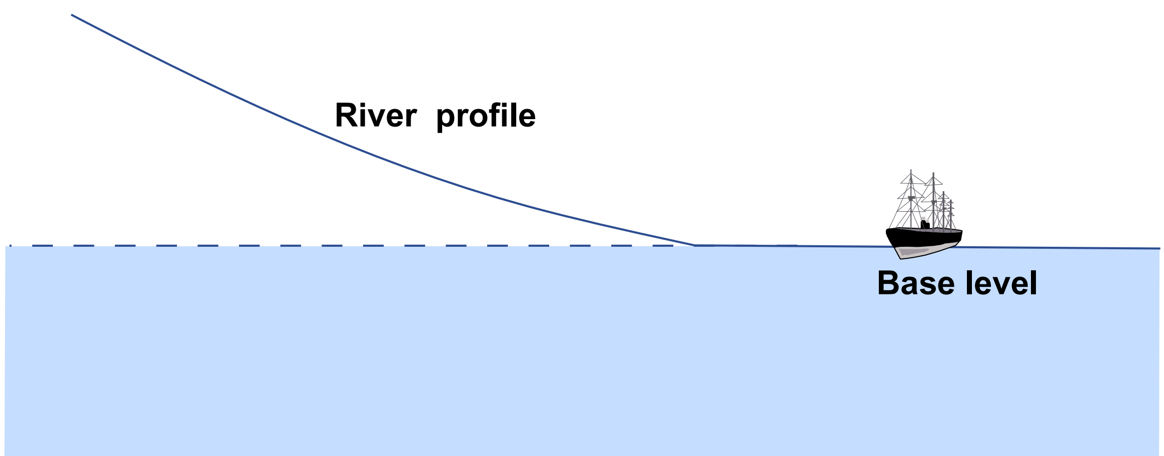


Figure by MIT OCW.

Figure 5-20. The base level of a river.

6.10 If base level rises, some of the sediment that's carried along by the river toward the river mouth is deposited along the way to raise the river bed, thereby establishing a new equilibrium longitudinal profile. If base level falls, the river erodes its bed to adjust toward a new, lower equilibrium profile.

6.11 There's more to be said, however, about what happens as the river erodes its bed as a consequence of a fall in base level. The erosion does not happen uniformly everywhere. all at the same time, but by upstream propagation of a point where the channel slope changes, from steeper downstream of the point to less steep upstream of the point. The point of change in slope is called a ***knickpoint*** (Figure 5-21). The position of a knickpoint is marked by a waterfall or rapids. Knickpoints migrate slowly upstream, thereby extending the new, lower longitudinal profile as the river eats its way upstream. If a floodplain has developed in the river valley, the old floodplain downstream of the knickpoint survives, for a long time, as a pair of terraces above the new, lower river channel Because the difference between old and new equilibrium profiles decreases upstream, other things being equal (the elevations of the highlands in the headwaters of the river are very conservative), the height of this knickpoint decreases as it migrates upstream. Often, if base level drops abruptly a number of times during some long period of time, more than one knickpoint is present along the river course, each slowly making its way upstream.

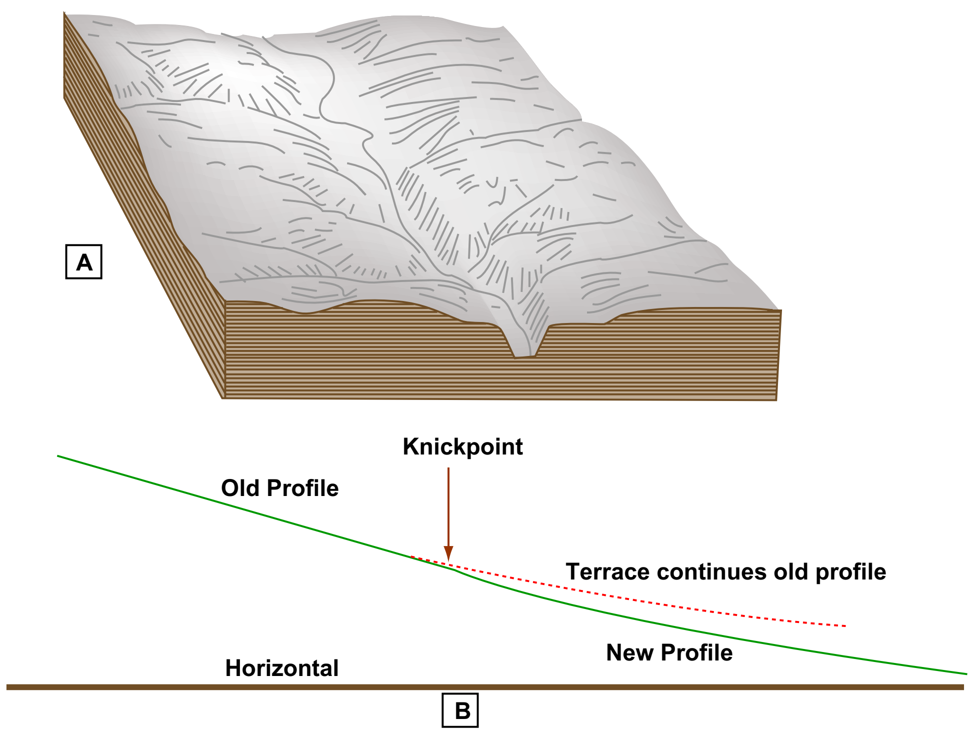


Figure by MIT OCW.

Figure 5-21. A knickpoint along a river course. A) Perspective view of a stream valley, showing a waterfall at a knickpoint. (From Thornbury, 1969.) B) Profile view of a stream in which a knickpoint is propagating upstream. (Modified from Holmes, 1965.)

6.12 As you will see in the later material on the plan-view features of rivers, rivers do not stay in one position but instead tend to shift laterally across their floodplains, by erosion at one bank and deposition at the other bank. (That's the basic reason why there are floodplains in the first place.) As the river lowers its bed in response to a fall in base level, and at the same time shifts its course laterally, it develops a new floodplain that's entrenched below the level of the old floodplain. The result is a pair of flat-topped ***river terraces***, one on either side of the river. The slopes at the edges of the modern floodplain retreat without much change in their shape, because they are continually being undercut along their bases rather than wearing away over their entire surface. Sometimes there is more than one set of such terraces.

7. CLASSIFYING RIVERS

7.1 Rivers are varied in so many ways that you should expect complexity in classification. Rivers can be classified in several ways:

- by the nature of their substrate
- by the percentage of time they flow
- by their relationship to the groundwater table
- by the kind of sediment load they carry
- by the dominant particle size of the bed sediment
- by their morphology

6.2 In the following I'll make some comments on classification of rivers in each of these ways. (But I'll defer discussion of classification of rivers by sediment load until later, after I've talked about the sediment load.)

Nature of Substrate:

Some rivers, especially small rivers in mountainous areas, flow directly on bedrock. Such rivers are called ***bedrock rivers***, or ***non-alluvial rivers*** (Figure 5-22A). Other rivers, especially large rivers, flow on *a bed a sediment they have deposited and can continue to transport*. Such rivers are called ***alluvial rivers*** (Figure 5-22B). Of course, some rivers lie in between, in that they have bedrock beds in some reaches and alluvial beds in other reaches (Figure 5-23). Alluvial rivers have held most of the problems, fascination, and importance for fluviologists, but if you're a white-water canoeing enthusiast I suppose you're more interested in bedrock rivers.

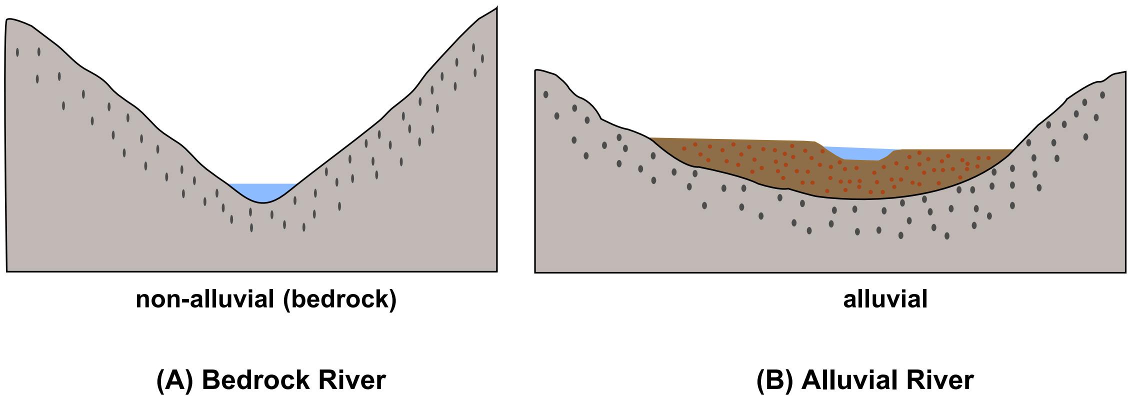


Figure by MIT OCW.

Figure 5-22. A) Bedrock rivers. B) Alluvial rivers.

Relationship to Groundwater Table:

Think about *the relative position of the water surface in the river and the local groundwater table*. If the water surface in the river lies *above* the local groundwater table in the river banks, then the river *loses water to its banks*. Such a river is said to be an ***effluent river*** (Figure 5-24A). On the other hand, if the water surface in the river lies *below* the local groundwater table in the banks, then the river *gains water from its banks*. Such a river is said to be ***influent river*** (Figure 5-24B). (These two terms are difficult to keep straight. It helps to think in terms of alternative terminology: an effluent river is also called a ***gaining river***, because it is gaining water from the adjacent substrate, and an influent river is called a ***losing river***.) Keep in mind that it's also possible for the groundwater table to lie entirely below the river bed (Figure 5-25). The river is still called an effluent river in that case.

Percentage of Time the River Flows:

Some rivers show a flow of water all the time, even long after the last rainstorm in the watershed. Such a river is called a ***perennial stream***. Other rivers flow for only a short time after a rainstorm, and for the rest of time, usually most of the time, their beds are dry. Such a river is called an ***ephemeral stream***. Some rivers lie between these two extremes: during the wetter part of the year they flow as a perennial stream, whereas during the drier part of the year they flow as an ephemeral stream. Such a river is called an ***intermittent stream***. Figure 5-

26 shows cartoon hydrographs of a perennial stream, an ephemeral stream, and an intermittent stream.

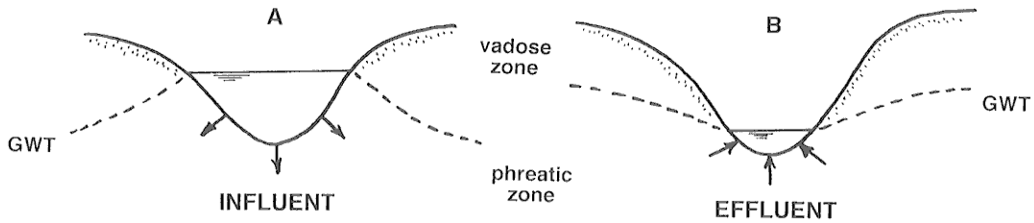


Figure 5-24. A) An influent river. B) An effluent river.

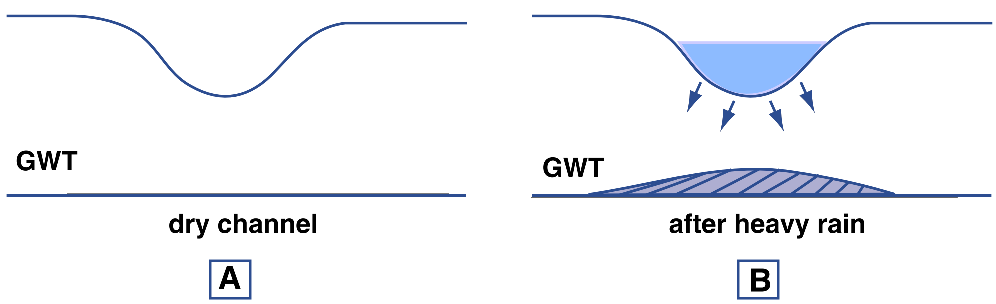


Figure by MIT OCW.

Figure 5-25. The groundwater table can lie entirely below the river bed. A) Before a heavy rain. B) After a heavy rain.

In an ephemeral stream, the water table always lies below the bed of the stream; the stream never receives any water from its bed or banks. In a perennial stream, the situation is more complicated. Think about the relationship between the river level and the groundwater table in some time period that starts in a dry spell, extends through a major rainfall event in the watershed, and ends during another dry spell. At the end of the first dry spell the river level lies below the groundwater table in the river banks (Figure 5-27A). After a heavy rainfall the river stage rises rapidly to lie well above the level of the groundwater table in the banks (Figure 5-27B). Groundwater is stored in the river banks, in the sense that the groundwater table is locally and temporarily higher there than in the surroundings. At the end of the rainy period both the river stage and the groundwater level are of about the same height and are about at their highest (Figure 5-27C). Then (Figure 5-27D) both the river stage and the groundwater table fall back to the dry-spell situation shown in Figure 5-27A. This sequence of events is called the ***runoff cycle***.

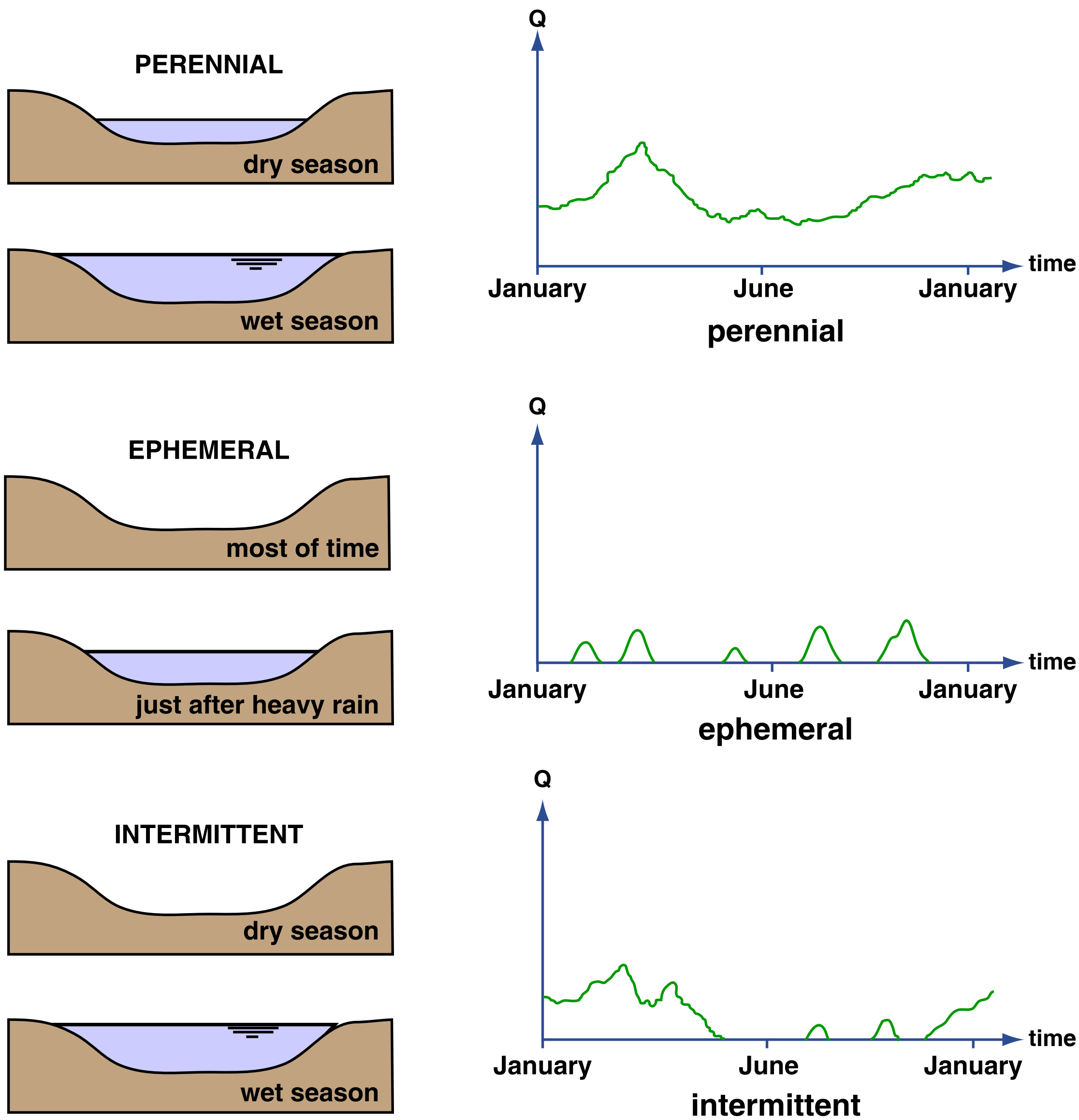


Figure by MIT OCW.

Figure 5-26. Perennial, intermittent, and ephemeral streams, and associated representative hydrographs.

Morphology:

The morphology of rivers, especially in plan view, varies enormously. The most common way to classify rivers is on the basis of their plan-view morphology. The morphology of rivers is bound up in a complex way with the nature of the sediment load, so a full appreciation of this section must await Section 8, on the sediment load of rivers.

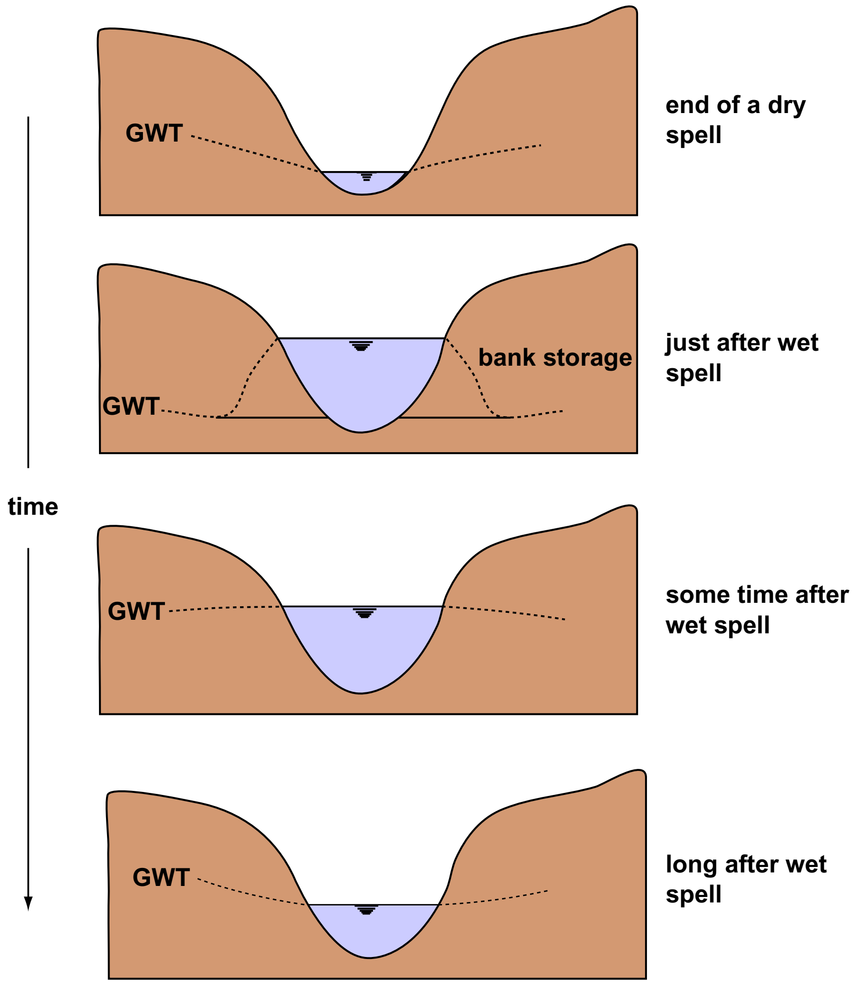


Figure by MIT OCW.

Figure 5-27. The runoff cycle.

Two characteristics are used in the classification of rivers by morphology: sinuosity and "multichanneledness". ***Sinuosity*** can be defined with respect to two arbitrary points along the river as *the ratio of the along-channel distance between the two points and the straight-line distance between the points* (Figure 5-28). The minimum sinuosity, for a straight river, is 1; the more sinuous the river, the greater its sinuosity. Very sinuous rivers can have values of sinuosity approaching 4. ***Multichanneledness***, an awkward but useful word, reflects *the number of individual flow channels shown by a river in a cross-stream traverse across the entire river system*. Many rivers have only one channel, except perhaps where an occasional island divides the channel into two. Other rivers show a large number of channels, all of about the same size and nature, separated by numerous bars and islands. The individual channels of such a river are called ***anabranches***.

Sinuosity and multichanneledness are to a large extent independent of one another, so it's natural to resort to a two-independent-variable pigeonhole classification with sinuosity along one axis and multichanneledness along the other axis (Figure 5-29). ***Straight*** rivers—those with sinuosity not much greater than 1—are surprisingly uncommon in nature. In fact, it's hard to keep rivers straight: humans straighten them out for their own purposes, and the rivers try to become sinuous again, by erosion and deposition on the banks. Both ***braided rivers*** *(low-sinuosity, multichanneled)* and ***meandering rivers*** *(high sinuosity, single-channeled)* are very common; more on them later. ***Anastomosing rivers*** *(high-sinuosity, multichanneled)* are much less common.

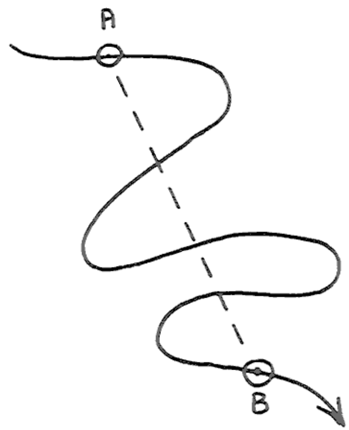


Figure 5-28. The sinuosity of a river.

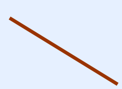
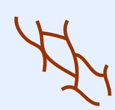
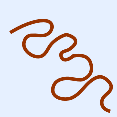
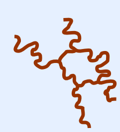
	Single channel	Multi-channel
LOW SINUOSITY	STRAIGHT 	BRAIDED 
HIGH SINUOSITY	MEANDERING 	ANASTOMOSING 

Figure by MIT OCW.

Figure 5-29. One way of classifying rivers.

8. VARIABLES INVOLVED IN RIVERS

Think about the variables that describe the characteristics and behavior of rivers. These fall into the broad categories of flow, sediment, geometry, and other. Here's a fairly inclusive list of such variables:

flow:

- cross section
- stage
- discharge
- velocity
- turbulence

sediment:

- bed-material properties
- load
- sediment discharge
- bed configuration
- slope or profile
- base level

geometry:

- width
- depth
- cross-section shape
- plan pattern

other:

- chemistry
- biota

Of these, some can be considered to be ***independent variables***, in the sense that they are imposed on the river and the river has to live with them, and other can be considered to be ***dependent variables***, in the sense that the river adjusts their values in response to the independent or imposed variables.

Independent variables:

temperature (almost entirely)
biota (mostly)
discharge (entirely)
sediment discharge (approximately, in the long term)
base level (entirely)
chemistry (almost entirely)
sediment characteristics (partly)
slope (in the short term but not in the long term)

9. FLUVIAL SEDIMENT TRANSPORT

9.1 Introduction

9.1.1 This section is a brief account of the nature of sediment transport in rivers. Regolith is produced by weathering of bedrock on the continents and is then transported away from the site of production as sediment (transported regolith), in both particulate and dissolved form. The oceans can be viewed as the repository for this sediment, although much is stored in sedimentary basins on the continents and recycled into new continental bedrock on time scales that may be a large fraction of geologic time.

9.1.2 *Rivers are by far the most important carriers of sediment on the continents*, although glaciers have been even more important at certain times and places. So although the essence of rivers is that they are flows of water, one of their most outstanding characteristics is that they are also transporters of sediment. I think it's fair to say that most of the interesting things about rivers are connected in some way with the sediment-transporting nature of rivers, either directly or indirectly. Fluvial sediment transport is an important area in several different disciplines: fluvial engineering, geomorphology, and sedimentology.

9.1.3 A big problem in gaining an appreciation for sediment transport in rivers is that it's generally difficult to observe sediment transport in real rivers, unless they are very shallow and not carrying much sediment. A good way to get around this difficulty, in part, is to build an artificial river in your backyard and watch from close up how the river transports its sediment.

9.1.4 It's not difficult to build a simplified small river that reproduces many of the essential aspects of fluvial sediment transport. Nail together a large wooden channel, open at the top and with a rectangular cross section (Figure 5-30). Caulk the seams and joints so they won't leak intolerably. (All such channels leak a little sometimes, even in the fanciest of laboratories.) The channel might best be about a meter wide and a few tens of meters long, but I realize that's a big order for backyard construction; you could get away all right with a channel no more than ten to twenty centimeters wide and five to ten meters long.

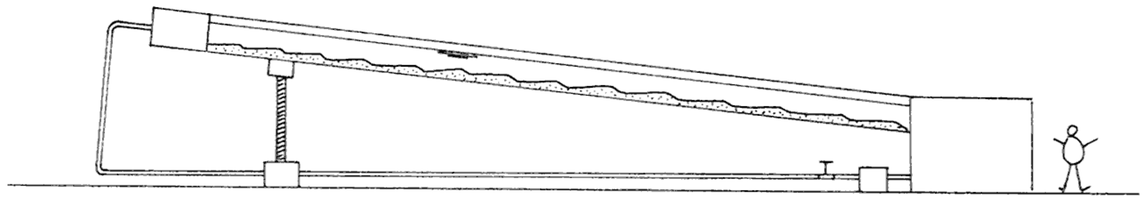


Figure 5-30. An experimental channel to model flow and sediment transport in rivers.

9.1.5 At its downstream end the channel should pass into a big open tank. Install a pump and some piping to take the water from the downstream tank and recirculate it to the upstream end of the channel. (This is by far the most expensive and, for most people, the most challenging part.) A valve in the return pipe lets you adjust the water discharge. You might mount the whole channel on a jack near the upstream end, so that you can change the slope of the channel easily, but that isn't really necessary. It would also be nice to make at least one sidewall of the channel out of glass or transparent plastic, for good viewing of the sediment transport. At the very least, install a few small subsurface portholes in the channel walls. Place a thick layer of sand on the floor of the channel. The mean size of this sand might be as fine as 0.1 mm or as coarse as 1 mm, but to see the widest range of phenomena and features use a sand with a mean size a little less than 0.5 mm.

9.2 Threshold of Movement

9.2.1 Now you are ready to make some experiments (flumologists— scientists and engineers who work with channels of the kind you just built in your back yard, which are called flumes— call them *runs*) in your channel. For each run, fill the tank and the channel with water to establish the depth of flow, turn on the pump, and adjust the valve for a certain water discharge and therefore (given the flow depth) a certain mean flow velocity. Arrange each run to have a flow depth as great as the flume will allow, ideally at least a large fraction of a meter.

9.2.2 The first thing you should do is study the beginning of sediment movement. (First, it would be good to smooth off the sand bed to be planar. That's not hard to do if you use an underwater scraper blade attached to a device that slides along the top edges of the channel walls.) Clearly, if the flow is too slow it won't move any sediment. As you gradually increase the flow velocity, however, at some point some sediment particles begin to move. That point is called the ***threshold of movement***. It may surprise you to find how difficult it is to define or locate the threshold, because there's weak movement or slight movement over a wide range of flow strengths. The problem of the threshold of movement reflects two questions that have long been recognized as important in fluvial sediment transport:

- How strong a flow is needed to initiate the transport of a given sediment?
- How coarse a sediment can be moved by a given flow?

9.2.3 The second question has to do with what's called the ***competence*** of a river. Just to give you some feel for the flow strength needed to move the sand in your channel, you would have to produce a current velocity of about 0.2 m/s to reach threshold conditions—depending on the sand size, of course, and on the water depth also.

9.3 The Sediment Load

9.3.1 Now make some runs with flow velocities greater than the threshold value, to study the modes of particle movement. *The aggregate of sediment particles which are transported by a flow at a given time* is called the ***sediment load***, or just the ***load***. The load can further be subdivided in three different ways: on the basis of

its physical nature;

its presence or absence in the bed; and

how it travels.

9.3.2 On the basis of its physical nature, the sediment load of rivers is conventionally subdivided into ***particulate load*** and ***dissolved load***. Does it surprise you that in general *the dissolved load is of the same order of magnitude as the particulate load*? Keep in mind that the concentration of the dissolved load doesn't depend greatly on the discharge, so there's a lot of dissolved load even at times of low discharge. In fact, there tends to be an inverse correlation between discharge and dissolved load, for the understandable reason that at times of high discharge most of the water in the river has run off the surface without spending a long time in contact with regolith and bedrock, where, by the variety of weathering processes you learned about in Chapter 2, the solutes of the dissolved load come from.

9.3.3 The load can also be divided into ***bed-material load***, which is *that part of the load whose sizes are represented in the bed in non-negligible percentages*, and ***wash load***, which is *that part of the load whose sizes are not present in the bed in appreciable percentages*. The wash load, which is always the finest fraction of the load (mainly clay or finest silt size), is carried through a long segment of a river without any exchange of sediment between the bed and the flow. Of course, you don't have any wash load in your backyard channel, unless you choose to dump in some water containing a suspension of fine clay.

9.3.4 In real rivers, much of the very finest fraction of the load has such a small settling velocity that it travels for long distances before settling to the bed, and even when it reaches the bed it tends to be resuspended immediately. So the finest fractions of the sediment are represented almost not at all in the bed material in the river channel. Only in overbank areas during floods, where the water velocities are small, is the wash load deposited. Even there, storage tends to be temporary, because shifting of the river channel tends eventually to re-erode the fine sediment that was previously deposited on the floodplain.

9.3.5 Finally, the load can be divided into ***bed load***, which *travels in direct contact with the bed or so close to the bed as not to be substantially affected by the fluid turbulence*, and ***suspended load***, which is *maintained in temporary suspension above the bed by the action of upward-moving turbulent eddies* (Figure 5-31). I hope it's clear from these definitions that

> bed load is always bed-material load, and suspended load is likely to be partly bed-material load and partly wash load, although in particular cases it could be all wash load, or all bed-material load.

This may sound confusing, but it makes sense. Figure 5-32 may or may not help.

9.3.6 The movement of bed load is sometimes called ***traction***. Bed-load movement can be by *rolling, sliding, or hopping* (Figure 5-33). It's not easy to observe bed-load movement in detail, but, if you're a good photographer and you made a high-speed close-up motion picture of bed load, you see that the particles characteristically take occasional excursions downstream, by rolling or hopping or bulldozing irregularly with brief stops along the way, and then come to rest for some time before being moved again. Once a grain is dislodged from a place of rest, it's susceptible to continued movement by the flow until it finally finds a rather sheltered position among the bed particles, at favorable sites called "pockets", and then it's not dislodged again until it's affected by an especially near-bottom eddy or until one or more of the bed particles sheltering it are themselves put into motion.

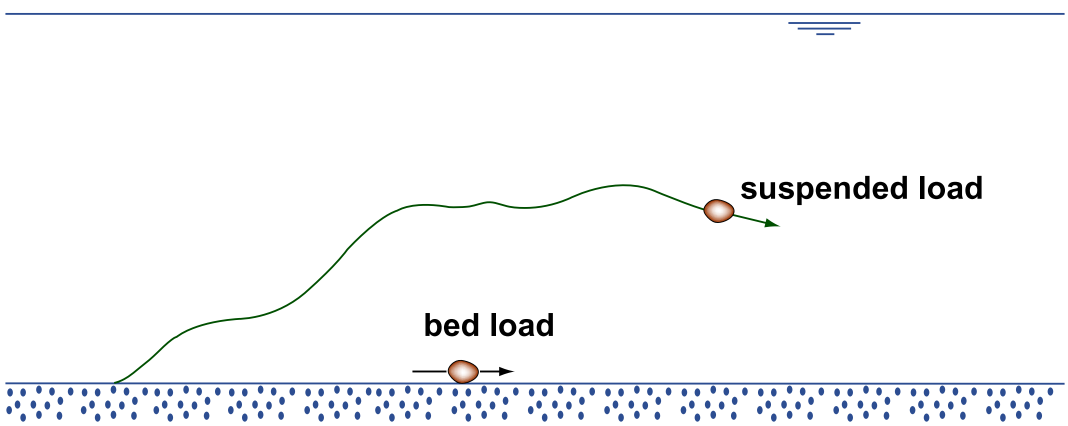


Figure by MIT OCW.

Figure 5-31. Bed load and suspended load.

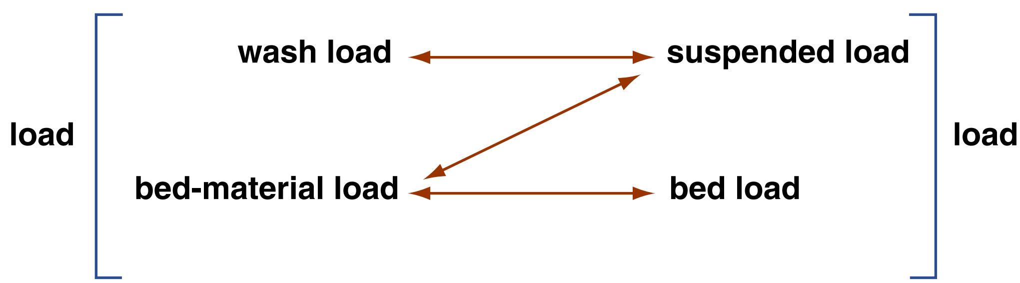


Figure by MIT OCW.

Figure 5-32. Relationships among bed-material load, wash load, bed load, and suspended load.

9.3.7 If you're a keen observer you would notice that *the set of particles that form the load keeps changing from time to time*, because particles are continually coming to rest and being set into motion again. Also, there's a problem in distinguishing between bed load and suspended load: **how far can a grain move up into the flow and still be considered bed load?** The standard criterion is *whether or not fluid turbulence has a substantial effect on the time and distance involved in the excursion*. Although the distinction between bed load and suspended load is a convenient one, there's no sharp break between bed load and suspended load. Also, a given particle can be part of the bed load at one moment and part of the suspended load at another moment, depending upon the time history of fluid forces and motions to which it is subjected. (And of course at still other times the same particle might not be moving at all.) Therefore, at any given time there's an appreciable overlap in the size distributions of the bed load and the suspended load, although clearly the suspended load tends always to be finer on the average than the bed load.

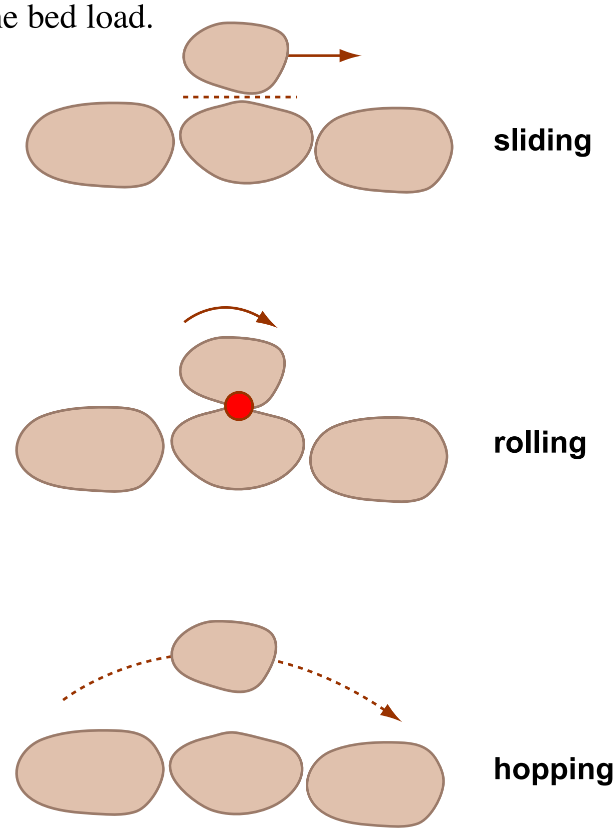


Figure by MIT OCW.

Figure 5-33. Modes of bed-load movement.

9.3.8 Particles moving as bed load are susceptible to being carried up into ***suspension*** when *the maximum vertical turbulent velocity fluctuations are greater in magnitude than the settling velocities of the particles*. If the conditions of the flow and the settling velocities of the particles fulfill that condition, then some of the moving bed-load particles occasionally find themselves caught in a strong upward-moving eddy, and the particle is carried for some distance above the bed. The particle is affected by a series of eddies as it moves downstream; depending on the motions of the individual eddies, the particle may rise only a short distance from the bed and travel only a short distance downstream before it settles back to the bed, or it may rise high above the bed, even almost to the water surface, and travel far downstream. Obviously, *the smaller the settling velocity and the stronger the turbulence, the greater the average height above the bed and the greater the distance of downstream travel by the particle*.

9.3.9 The sediment particles are not really suspended above the bed, in the way that a painting is suspended on a nail in the wall: they are always settling back toward the bed and will eventually return to the bed. Only particles of colloidal size, much finer than a micrometer, can be truly suspended. Such particles have such small mass that Brownian motions caused by the random collisions of molecules against the particle keep the particle in permanent suspension.

9.3.10 When the flow is relatively weak and/or the sediment is relatively coarse, the concentration of suspended sediment drops off rapidly upward, and the upper part of the flow may not have any suspended sediment at all (Figure 5-34A). When the flow is relatively strong and/or the sediment is relatively fine, however, suspended sediment is present throughout the entire depth of flow, and the concentration of suspended sediment drops off only slightly upward (Figure 5-34B).

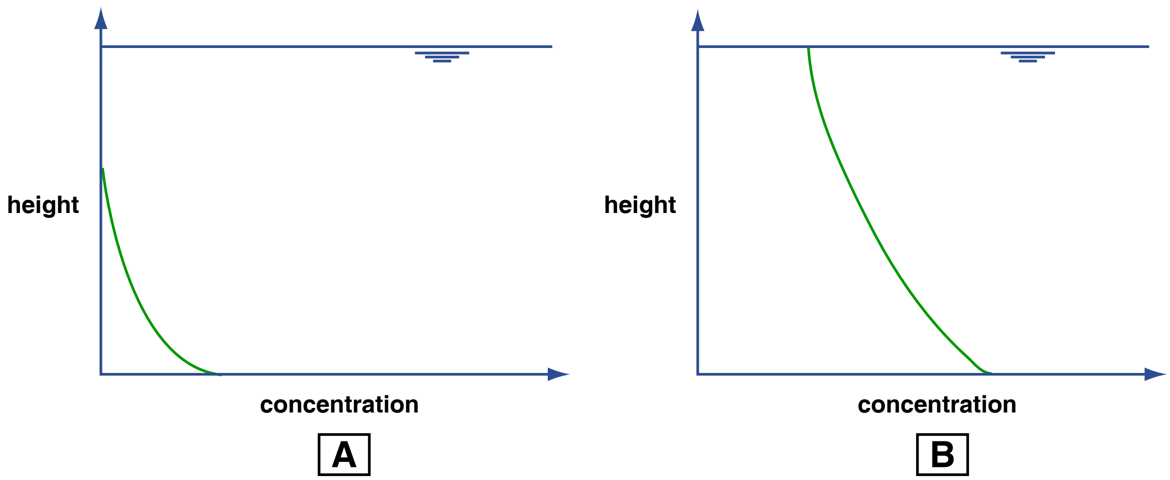


Figure by MIT OCW.

Figure 5-34. Vertical profiles of suspended-sediment concentration in a river.

9.4 Classification of Rivers by Sediment Load

9.4.1 It should seem natural to you that some rivers, especially those whose sediment sources consist mostly of coarse sand and gravel, carry mostly bed load. Such rivers are called, understandably, ***bed-load rivers***. On the other hand, the sediment sources of some rivers are mainly clay, silt, and fine sand. The sediment load of such rivers is mainly suspended load. Such rivers are called ***suspended-load rivers***. Finally, in a great many rivers both bed load and suspended load are important; such rivers are called ***mixed-load rivers***. Keep in mind that this classification is very loose, both because there's a continuous gradation in nature of sediment load from river to river and also because a given river carries its load in different ways, depending on its discharge at the given time.

9.4.2 You can also classify rivers by the dominant particle size of the bed material, into ***gravel-bed rivers***, ***sand-bed rivers***, and (much less common than the first two) ***mud-bed rivers***. (Of course, there are gradations among these three kinds.) In most sand-bed rivers, most of the bed-material sediment discharge on average is in the form of suspended load. In gravel-bed rivers, on the other hand, most of the sediment discharge is accounted for by bed-load transport.

9.5 Sediment Transport Rate

9.5.1 The rate at which sediment is moved past a cross section of the flow is called either the ***sediment transport rate*** or the ***sediment discharge***. It's related to the sediment load, but it's different, just because different fractions of the sediment load are transported at different rates. It can be measured in mass per unit time, or in weight per unit time, or in volume per unit time. For many decades hydraulic engineers have sought after formulas to predict the sediment discharge that's associated with some combination of flow conditions and sediment characteristics in some reach of a river. There are many such formulas, but none of them work gratifyingly well.

ADVANCED TOPIC: SEDIMENT DISCHARGE FORMULAS

1. To derive a sediment discharge formula, you try to think about the physics of sediment transport in a way that allows you to develop the form of some rational equation for transport rates, which contains within it one or more "adjustable parameters" whose values are assigned by analysis of selected data sets already at hand. It's a sad fact that the physics of sediment transport is so complicated that you can't develop an equation from the first principles of physics that contains no such adjustable parameters. It's almost no exaggeration to say that there are dozens of sediment discharge formulas in the hydraulic-engineering literature. The physical basis behind these formulas ranges widely, and none of them does a really good job.

2. Here's just the barest start at deriving a sediment discharge formula. Your common sense tells you that *the stronger the flow the greater the sediment transport rate*. And an important first-order fact of observation is that *the sediment transport rate is a very steeply increasing function of the flow strength*. Think about the simplest way to embody these important facts in a formula for the sediment transport rate per unit width of flow, usually written q_s. Perhaps the simplest approach to quantifying q_s is to write an expression like

$$q_S = A\tau_o{}^n \tag{8.6}$$

where A is a coefficient and n is an exponent much larger than one. Better yet, τ_o might be replaced with τ_o- τ_{oc}, where τ_{oc} is the threshold boundary shear stress for sediment movement. The trouble with Equation 8.6 is that it has no strong basis in the actual physics of the transport. The true situation must be much more complicated than Equation 8.6. But with A and n adjusted by use of observational data, Equation 8.6 can serve for very crude estimates of q_S.

9.5.2 Measuring the sediment transport rate is a notoriously difficult task. The suspended-load transport rate is usually measured by trapping small samples of the passing flow, with its suspended sediment, in a series of little catch bottles arranged vertically through the entire depth of the river, together with measurements of the local flow velocity along that vertical. Bed load is more difficult to measure. Usually bed load is measured with devices called *bed-load traps* or *bed-load samplers*. Think in terms of those pole-mounted dustpans that are used to sweep litter from paved surfaces—but with netting in the back of the pan to let the water flow through. They come in all sizes and geometries, but their purpose is to catch all the bed load that comes upon the trap from upstream—without catching too much or too little. Unfortunately there are many practical problems connected with bed-load traps.

9.6 Bed Configuration

9.6.1 Now you need to make a series of runs in your channel to study the bed configuration. By the term ***bed configuration*** I mean *the overall bed geometry that exists on the bed of the channel at a given time in response to the flow*. If you haven't had any experience with bed configurations, you may be thinking, "What's the big deal? Won't the sediment just move on a planar transport surface?" But it turns out that you would just as often be wrong about that than right. If the bed configuration is not planar, it's composed of *individual topographic elements* called ***bed forms***.

9.6.2 Make a series of runs with slightly increasing mean flow velocity above threshold conditions. In each run, let the flow interact with the bed long enough for the bed configuration to be statistically steady or unchanging. After that time the details of the bed configuration change constantly but the average characteristics remain the same. The time required for the flow and the bed to come into a new state of equilibrium might be as little as a few minutes to as long as several days, depending on the sediment transport rate, the size of the bed forms that develop, and the extent of modification of bed forms that were left over from the preceding run.

9.6.3 At low flow velocities, the bed becomes covered with ***ripples***: little ridges of sand with their crests and troughs oriented mostly transverse to flow but rather irregular in detail, with gentle upstream surfaces and generally angle-of-repose downstream surfaces (Figure 5-35A). Their spacings are 10–20 cm, and their heights are a few centimeters. They move slowly downstream, orders of magnitude slower than the flow velocity, by erosion of sand from their upstream sides and deposition on their downstream sides. Except at the highest speeds, you have to watch them closely to see them move. Ripples on real river beds look almost exactly like those you can produce in your backyard channel.

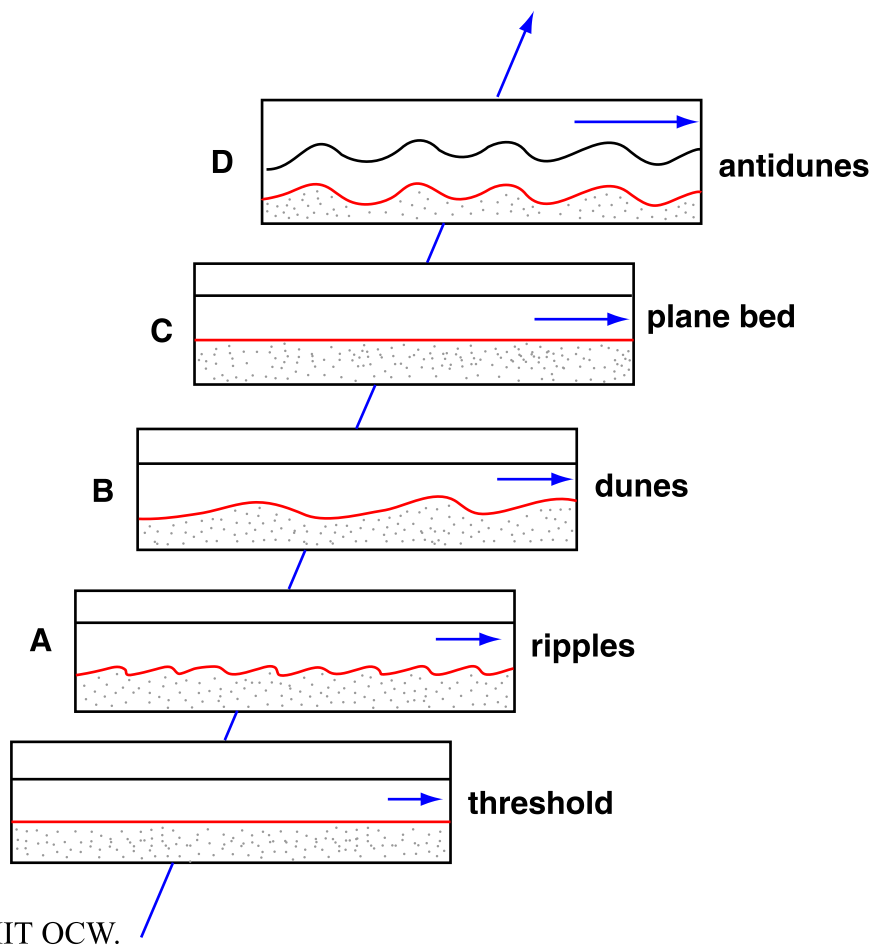


Figure by MIT OCW.

Figure 5-35. Sequence of bed configurations in open-channel flow over a bed of sand a few tenths of a millimeter in diameter.

9.6.4 At a flow velocity that's a moderate fraction of a meter per second, ripples are replaced by larger bed forms called ***dunes*** (Figure 5-35B). Dunes are fairly similar to ripples in geometry and movement, but they are at least an order of magnitude larger. The transition from ripples to dunes is complete over a narrow range of only a few centimeters per second in flow velocity. Dunes in large rivers can attain truly gigantic proportions: heights of over ten meters, and spacings of many hundreds of meters. Superimposed on such large dunes are one or more orders of smaller dunes, all the way down to little ripples.

9.6.5 As you increase the flow velocity further the dunes become lower and more rounded, over a fairly wide interval of flow velocity, until finally they disappear entirely, giving way to a planar bed surface over which abundant suspended load as well as bed load is transported (Figure 5-35C). Judging from the appearance of the bed after the flow is abruptly brought to a stop, the transport surface is strikingly planar: relief is no greater than a few grain diameters. But it's difficult to observe the mode of grain transport over the planar bed because the bed is obscured by abundant bed load and suspended load.

9.6.6 As you increase the flow velocity still further, subdued standing waves appear on the water surface, and the resulting pattern of higher and lower near-bed flow velocity causes the bed to be molded correspondingly into a train of waves that are in phase with the water-surface waves. Under certain conditions these coupled bed waves and surface waves increase in height and become unstable: they move slowly upstream and at the same time grow in height, until they become so steep that they break abruptly, throwing much sediment into suspension (Figure 5-35D). The bed and water surface then revert to a planar or nearly planar condition, whereupon the waves build again and the cycle is repeated. Because of their upstream movement these forms are called antidunes**.** Antidunes are important in shallow fast-flowing rivers but not in deep rivers. An excellent place to watch small antidunes in action is at the beach where a small stream, flowing fast and shallow, passes across the sandy beach to reach the sea.

9.7 More on Fluvial Hydraulics

9.7.1 Back in Section 4 I put off discussion of the following important question: **What determines the particular combination of flow depth and flow velocity associated with a given water discharge?** I can pick that up again, now that I've said some things about bed configurations.

9.7.2 The force the flow exerts on the bed of a river are of *two kinds*: skin friction and form drag:

> ***Skin friction*** (a term borrowed from aerodynamics of airplane wings) is the local friction force exerted on locally smooth areas of the river bed.
>
> ***Form drag*** is the force the flow exerts on a nonplanar part of the river bed, like a ripple or a dune, by exerting higher fluid pressure on the upstream side of the form than on the downstream side.

Just think back to the swimming-pool experiment with the tray or pizza pan, described in Chapter 1. In almost all river flows, *the form drag is much larger than the skin friction*.

9.7.3 It's easy to understand that the particular combination of depth and velocity for a given discharge in a river is mediated by the nature of the flow resistance: the greater the flow resistance, other things being equal, the deeper and slower the flow. And, as you can easily imagine given the ruggedness of ripples and dunes on a river bed, *the flow resistance is dominated by form drag whenever there are bed forms on the river bed*. So the most important factor in determining the combination of depth and velocity is the nature of the bed configuration.

8.7.4 This bed-configuration effect on the flow resistance has an important and beneficial consequence for the behavior of rivers during floods. As the discharge and therefore the flow velocity increases during a flood, the bed configuration is ripples and then rugged dunes, so the flow depth is relatively deep and the flow velocity is relatively low. As the velocity increases, however, eventually the dunes are washed out to a plane bed, and as the discharge continues to increase, the flow depth is then relatively low and the velocity is relatively high. (The word *relatively* in the last two sentences implies comparison with the same discharge but a different bed configuration.) The highest stage during the flood, when the bed is planar, is typically even greater than what it was at the time of transition from dunes to plane bed, but the important thing is that *the stage is much less than it would have been if this bed-configuration effect did not exist*—as in a bedrock river, for example.

9.8 The Sediment Yield

9.8.1 I need to introduce just one more thing about sediment in rivers. You should make a distinction between the sediment discharge and what's called the *sediment yield* of a river. The ***sediment yield*** is *the sediment discharge divided by the total drainage area of the river upstream of the cross section at which the sediment discharge is measured or estimated*. The sediment yield measures the rate, per unit area, at which sediment is removed from the watershed. It's important in studies of the long-term evolution of landscapes drained by rivers.

10. MORPHOLOGY AND DYNAMICS OF MEANDERING STREAMS

10.1 The two most characteristic plan patterns assumed by rivers are *meandering* and *braided*. First of all, keep in mind that the tendencies toward meandering and braiding are complementary rather than mutually exclusive, in the sense that many rivers show elements of both at the same time and within the same reach.

10.2 First, some descriptive stuff on the geometry of meandering rivers. Figure 5-36 shows most of the elements of a meandering river system. The *meander bends* or ***meander loops*** are never perfectly regular, but they are often described as if they were (Figure 5-37), in terms of ***wavelength*** and ***amplitude***. One can also think about a ***radius of curvature*** in the bend, but that's likely to vary from point to point in the bend. The narrow part of the meander bend, between adjacent reaches of the channel above and below the bend, is called the ***meander neck***.

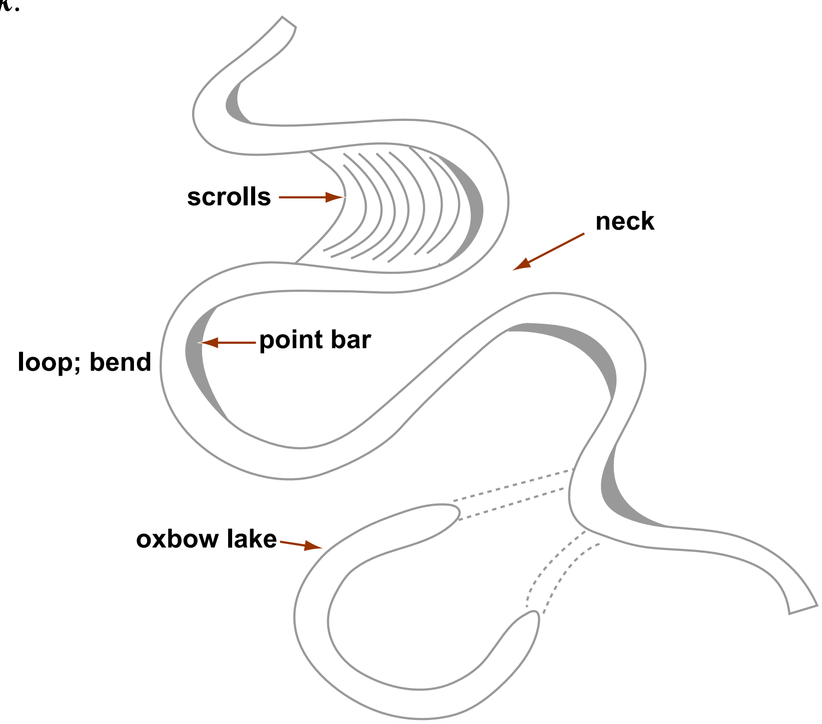


Figure by MIT OCW.

Figure 5-36. Elements of the plan-view features of a meandering river

10.3 On the inner, or convex, side of the meander bend is a fairly smooth and largely non-vegetated body of sand, sloping gently downward toward the center of the channel. This sand body, called a ***point bar***, lies everywhere below bank-full stage and is inundated by floods. Sediment is gradually accreted to the point-bar surface, causing the point bar to shift laterally. Point-bar deposits are for that reason called ***lateral-accretion deposits*** (because they accrete, laterally, onto the point-bar surface).

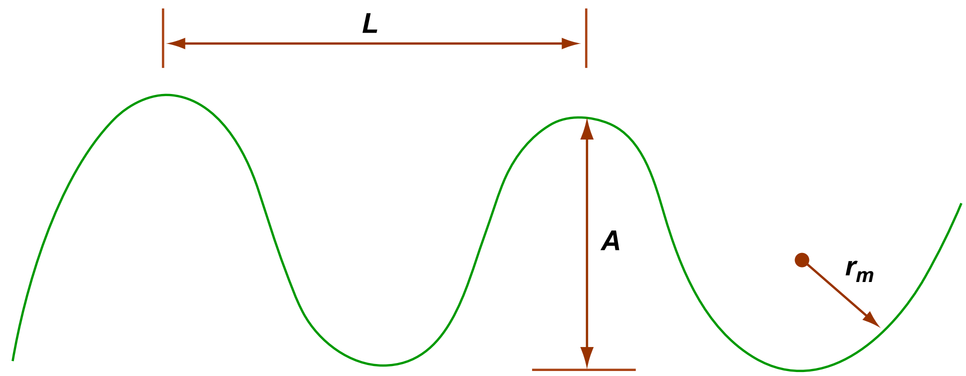


Figure by MIT OCW.

Figure 5-37. Idealized geometry of meander bends.

10.4 On the outer, or concave, side of the meander bend is a steep bank or cliff, often called a ***cut bank***, of consolidated or semiconsolidated sediment that is eroded during strong flows. The bank is eroded by various processes, the most important of which is undercutting low on the bank and collapse of large masses into the channel.

10.5 The flow-transverse profile of a meandering river is highly asymmetrical. The flow is deepest near the foot of the eroding outer bank, and it shoals gradually up the point-bar surface. The velocity of flow is highest in the region near the free surface and near the outer bank. Figure 5-38 is a cartoon of the flow-transverse profile, showing the characteristic pattern of isovels (lines of equal velocity). There's also a characteristic helical secondary circulation within the bend, such that the flow near the bed has a component inward toward the point bar, and the flow near the surface has a component outward toward the outer bank. This spiraling secondary circulation is readily explained by the differences in centrifugal force between the high-speed regions of the flow above and the low-speed regions of flow below. It's this secondary circulation that causes the accretion on the point-bar surface.

10.6 Meander bends generally have a tendency to change with time toward *larger amplitudes* and *narrower necks*. Eventually the river jumps across the narrow neck during a flood. Such an event is called ***meander cutoff***, or ***neck cutoff***. The river thereby straightens itself spectacularly in quantum jumps to offset the gradual amplification of the meander bends. Sometimes there's a less catastrophic variety of meander cutoff, whereby the river occupies an old slough that marks an earlier position of the bend; then the amplitude decreases, but not nearly to zero. Cutoffs of that kind are called ***chute cutoffs*** (because the river comes to occupy a chute between the two sides of the bend).

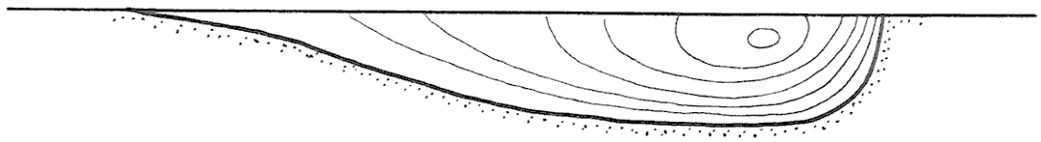


Figure 5-38. Flow-transverse section through a meander bend, showing isovels.

10.7 Point bars tend to be built episodically, during floods. The earlier positions of the top of the point bar are marked on the floodplain on the inner side of the meander bend by low and curving ridges arranged congruently within the meander bend (Figure 5-39). These curving ridges are called ***meander scrolls*** or ***meander scars***. One of the best kinds of evidence that the bend shifts in position as it grows is the truncation of earlier meander scrolls by the present channel.

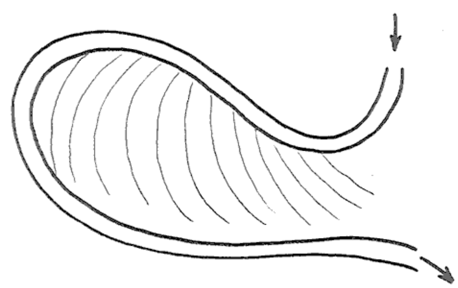


Figure 5-39. Meander scrolls.

10.8 The ends of an abandoned meander loop soon become plugged by fine sediment to form an ***oxbow lake*** (Figure 5-40). Oxbow lakes are filled in very slowly by deposition of fine sediment during overbank flows on the floodplain. Their outlines in the floodplain remain visible from the air long after they are filled, however, owing to slight differences in color and vegetation on the floodplain surface. The floodplains of meandering rivers show a complex pattern of several generations of truncated meander scars and partly or wholly filled oxbow lakes recording a long history of meandering.

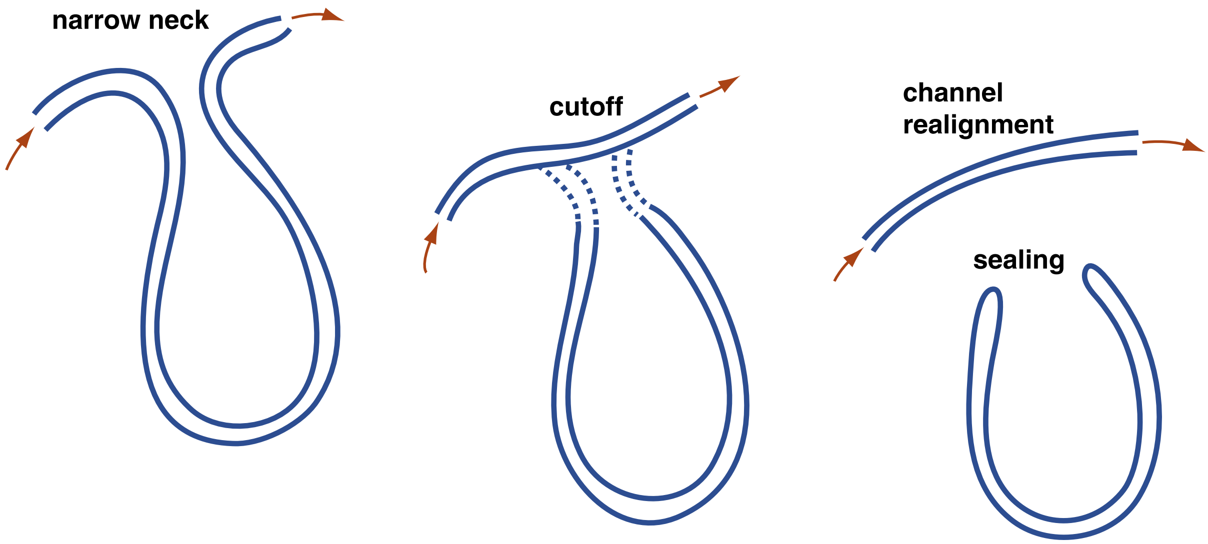


Figure by MIT OCW.

Figure 5-40. Development of an oxbow lake by meander cutoff.

10.9 Perhaps the best way to approach the problem of the dynamics of meandering and braiding is to think in terms of *the development of a meandering or braided pattern in a stream that is initially straight and regular and flowing within a homogeneous floodplain*. This kind of thing is easy to do in a wide flume in the laboratory (Figure 5-41): put the sediment in, homogenize it by hand, level it off, and then carve a regular channel in it. (You could fairly easily build apparatus in which to do this in your own backyard, which by now is getting rather crowded.) When a uniform sediment-moving flow is then started in the channel, the channel remains straight and regular for a long time, but eventually, after hours or even tens of hours, the inevitable little irregularities of the initial channel lead to an alternating pattern of erosion and deposition along the banks and therefore to increase in sinuosity of the channel.

10.10 If the banks of the laboratory stream are freely erodible (that is, if they consist of loose sand and gravel, rather than cohesive muds) then *the channel pattern is at first regularly sinuous but eventually becomes highly irregular and braided*. It's not nearly as easy to do this experiment in cohesive materials, but what's been done shows that in cohesive banks the braiding does not develop, but instead a statistically steady process of meander growth and cutoff develops.

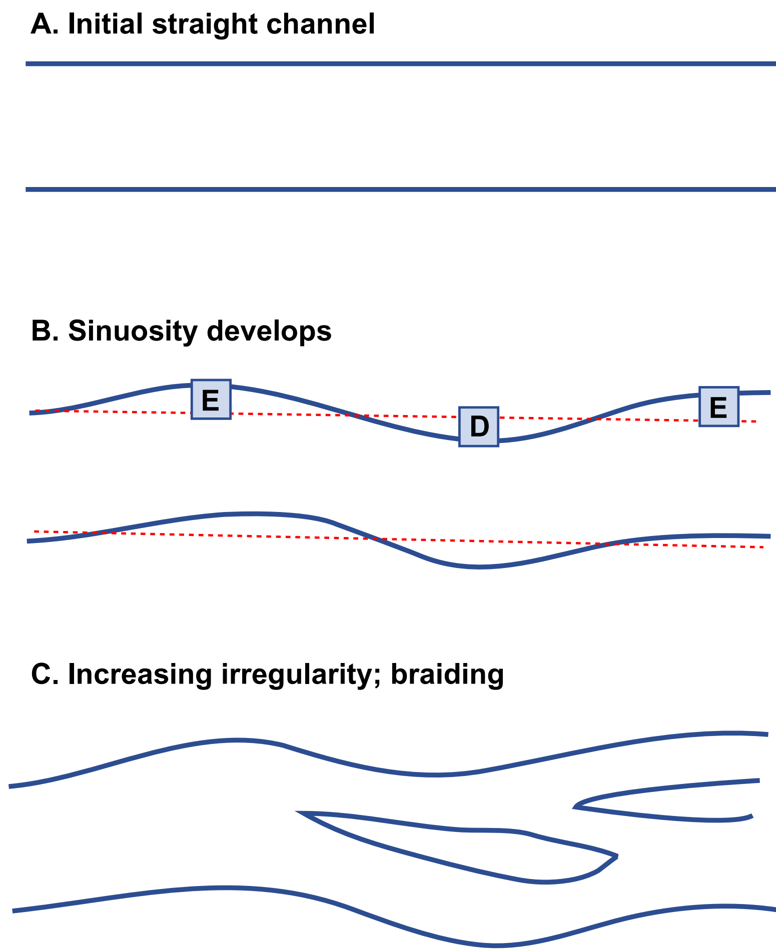


Figure by MIT OCW.

Figure 5-41. Development of braiding.

10.11 So you can see that a natural approach to the dynamics of meandering is to treat meandering as what the experts call a *stability problem*. In such an approach one attempts to capture the physics of the process, in terms of the interaction between the flow and the sediment transport, in the form of a set of equations, and then one attempts to linearize those equations in order to apply them to the behavior of a very-small-amplitude perturbation of an originally straight channel. *If the perturbation is damped, then the straight channel is stable; if the perturbation is amplified, then the straight channel is unstable*. The fastest-growing wavelength of the disturbance is the one that should specify the scale of the resulting meanders. Although the full equations may not be workable for determining the evolution of the meandering pattern once the disturbances have a finite amplitude, various other lines of attack have been brought to bear on particular aspects of finite-amplitude meanders, with considerable success.

10.12 On a more concrete note, it's widely agreed that the most important factor in determining whether a river meanders is *bank stability*. A floodplain with a large percentage of fine, cohesive sediment in it is conducive to meandering, as is a dense cover of vegetation. If the sediment is noncohesive and freely erodible, and the climate is inconducive to vegetation, the river braids rather than meanders. Incidental note: before the Silurian, when there were no land plants, there is no evidence of meandering streams, only braided streams.

11. DRAINAGE NETWORKS

11.1 Introduction

11.1.1 Given an area of land on which rain falls, there are always streams, even if they are only ephemeral. The entire area can be parceled exhaustively and mutually exclusively into sub-areas such that each sub-area is the drainage area of a single stream (Figure 5-42, which is a repeat of a figure shown back in Chapter 3). Such areas are called the ***drainage basins*** or ***watersheds*** or ***catchments*** of those streams. You learned some things about drainage basins in the earlier chapter on topography. Recall from Chapter 3 that the boundaries between adjacent drainage basins are called ***divides***. Just think of standing straddling the divide and pouring a glass of water from one hand into one drainage basin and from the other hand into the other drainage basin. Here the emphasis is on the network of streams in the drainage basin. The ***drainage network*** of a drainage basin is *the collection of all of the channels in a given drainage basin*: the main stream, often called the ***trunk stream***, and all of the tributaries, as well as the tributaries of tributaries, and so on.

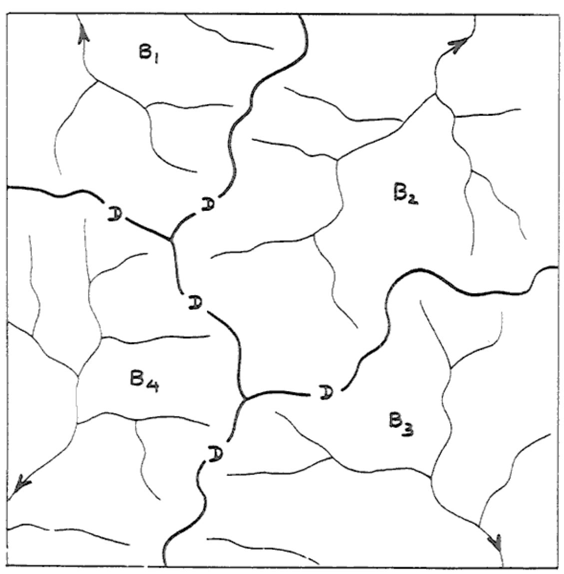


Figure 5-42. Drainage networks and drainage basins.

11.2 Drainage Patterns

11.2.1 By ***drainage pattern*** I mean *the spatial relationships of individual streams in the drainage basin.* The drainage pattern is a reflection of several factors:

- stage of development
- initial slope
- rock hardness
- rock structure
- recent tectonism

The pattern of each of the drainage networks shown in Figure 5-41 is what you would expect to see in a region that is underlain by fairly uniform materials—that is, materials that are about the same in their characteristics, in particular their susceptibility to erosion, from place to place.

11.2.2 Because an area responds to denudation (by ***denudation*** I mean *lowering of the land surface by weathering, erosion, and removal of the resulting regolith*) in a way that reflects the underlying geology, you can tell a lot about the geology of an area by looking at a map of the drainage pattern. Here are some of the common drainage patterns (Figure 5-43), with a few words on the bedrock controls:

Dendritic. This pattern, by far the most common, involves irregular branching of tributary streams in many directions and at almost any angle, though usually less than 90°. A dendritic pattern develops on rocks of uniform resistance, and without structural control. It is most likely to be found on flat-lying sedimentary rocks or massive igneous rocks. The drainage networks shown in Figure 5-41 could be described as dendritic.

Trellis. A system of subparallel streams, usually aligned along the strike of rock formations or between parallel or nearly parallel topographic features deposited by wind or ice. The main streams often make nearly right-angle bends to cross major ridges. The primary tributary streams are usually at right angles to the main stream, and the secondary tributaries are usually themselves at right angles to the primary tributaries, i.e., parallel to the main streams. Trellis patterns are most common in folded mountain belts like the Appalachians, where alternating folded weak and strong layers have been truncated by stream erosion.

Rectangular. Both the main stream and its tributaries show right-angle bends. This reflects control exerted by joint or fault systems. Where the joint or fault systems intersect at acute angles, an ***angulate*** pattern develops.

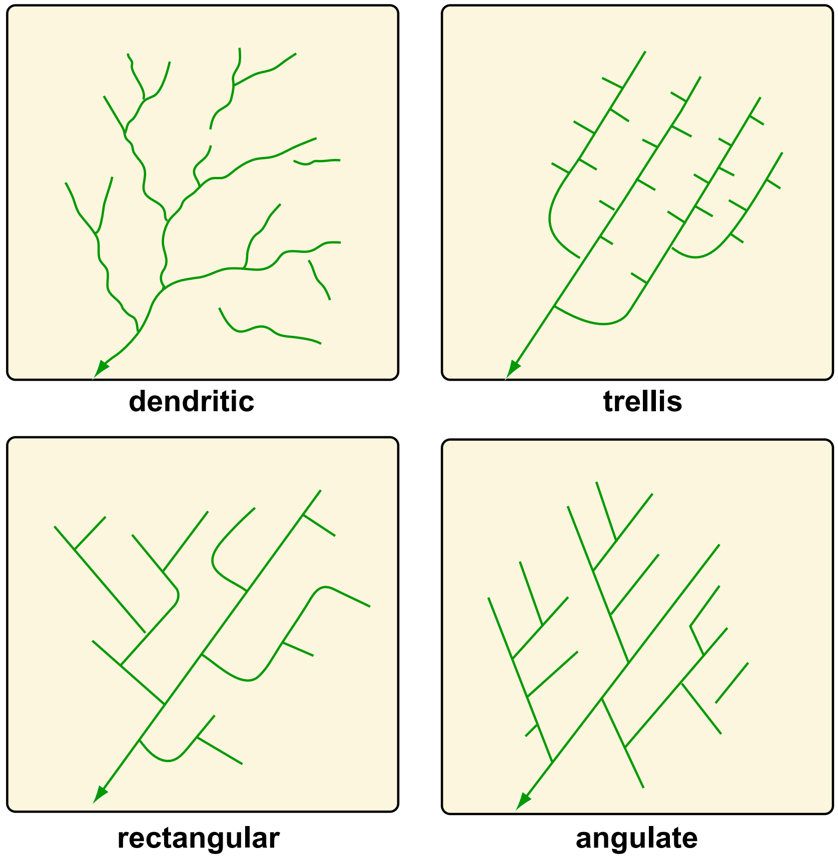


Figure by MIT OCW.

Figure 5-43. Common drainage patterns.

11.2.3 Some other patterns (Figure 5-44) are less common:

Centripetal. Drainage lines converge into a central depression, like a sinkhole, crater, or other basin.

Radial. Streams diverge from a central elevated tract: domes, volcanic cones, isolated conical hills.

Parallel. Found where there is a strong slope control, leading to regular spacing of parallel or nearly parallel streams.

Angular. Around maturely dissected domes which have alternating belts of strong and weak rock around them.

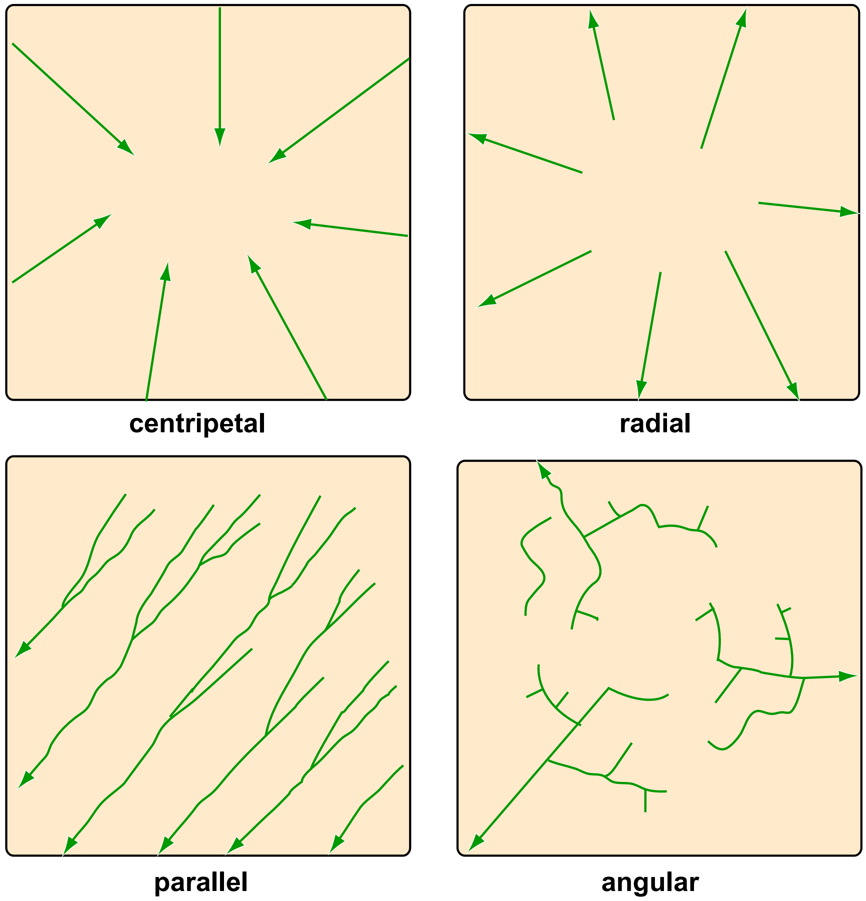


Figure by MIT OCW.

Figure 5-44. Other, less common drainage patterns.

ADVANCED TOPIC: FLUVIAL MORPHOMETRY

1. ***Fluvial morphometry*** is the term used to describe the analysis of the topological characteristics of drainage networks..

2. Here are some things you could measure about a drainage network:

- *configuration* or topological properties
- *linear* properties: analysis of a branching system of one-dimensional curves in plan.
- *areal* properties: analysis of areas of drainage basins, again in plan.
- *relief* properties: analysis of slope of channels or drainage areas.

Each one of these properties has been subjected to extensive study by the techniques discussed below. We'll examine only the first here.

3. First we need to define the concept of the ***order*** of a stream. To do that, look at a representative drainage network, and concentrate on its topology. The stream-channel network can be subdivided into segments lying between confluences, together with ***fingertip streams*** lying upstream of any confluences (Figure 5-45). One can develop a hierarchy of stream orders based on the tributary relationships of the channels, in the following way.

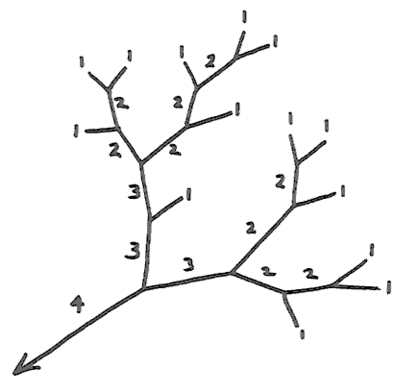


Figure 5-45. An example of stream orders.

4. The convention is that the fingertip channels (those with no tributaries) are called ***first-order streams***. The junction of two first-order streams produces a ***second-order stream***, and the junction of two second-order streams produces a third-order stream, and so on. Another convention is that the junction of a stream of given order with a stream of lower order doesn't change the order of a higher-order stream. The trunk stream of the drainage basin—the one by which the given drainage basin is actually defined, by choosing a given point on that stream—is the highest-order stream associated with that drainage basin.

5. The various relationships between stream order and length, area, and number properties of drainage basins have come to be known as ***Horton's laws***. Horton's law of stream orders states that

> The numbers of streams of different orders in a given drainage basin tend closely to approximate an inverse geometric series in which the first term is unity and the ratio is the bifurcation ratio.

(The ***bifurcation ratio*** is *the ratio of the number of streams of a given order to the number of streams of the next highest order*.) By the nature of a geometric series, this means that when you plot the logarithm of the number of streams of a given order against the stream order you tend to get a straight line (Figure 5-46). Graphs of this kind are called ***Horton diagrams***. Most of the curves in Horton diagrams tend actually to be slightly concave upward rather than being a straight line. Analysis of all the studies that have been published shows that this is a strong tendency. There are similar laws for other characteristics of the drainage network: the length of stream segments between confluences, and the drainage areas of stream segments.

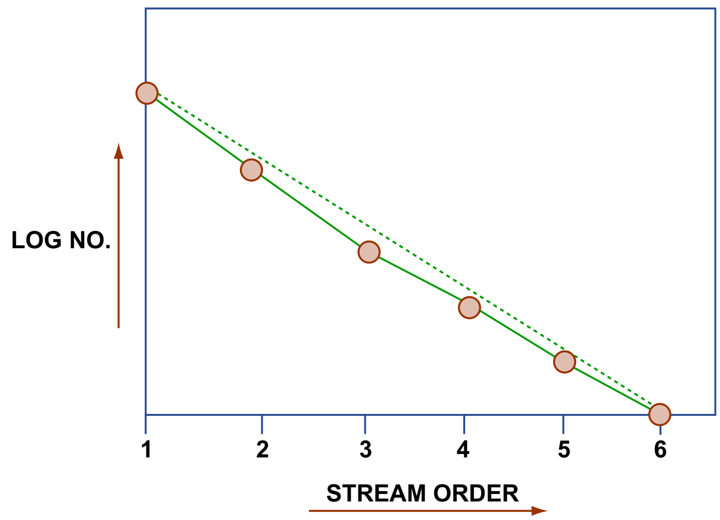


Figure by MIT OCW.

Figure 5-46. Plot of the logarithm of the number of streams of a given order against the stream order, for a given drainage basin.

6. An important observation is that Horton's law holds for almost all watersheds that have been studied, in all kinds of areas, with all kinds of climates and bedrock types. Although there seem to be some deviations caused by lack of isotropy and homogeneity of the bedrock structure and composition, the law of stream numbers on the whole is quite insensitive to such geologic controls. This suggests that there must be some very general basic cause.

8. Another interesting observation is that the bifurcation ratio also seems to be insensitive to geologic controls as well as to climate. It can be shown theoretically that the bifurcation ratio can never be less than 2; it's always between 3 and 5, and usually around 4. It shows only a small range of variation from region to region and from environment to environment, except where powerful geologic controls dominate.

9. Much effort has been expended to try to interpret the meaning of Horton's law of stream orders. Although there are dissenters, it's widely accepted that Horton's law is a manifestation of randomness in the topological development of the drainage network. In a classic paper, Shreve (1966) showed that the assumption that all topologically distinct possibilities for how streams of a given order combine to form a network are equally likely leads to the characteristically slightly concave-up curves on Horton diagrams.

---

12. FLUVIAL DEPOSITS

12.1 Fluvial deposits are an important part of the ancient sedimentary record. The reason why is not obvious; after all, rivers drain areas of the continents that are undergoing erosion. Most rivers, except the smallest, are alluvial rivers: they have a bed, and a floodplain, composed of their own sediments. But in most cases this alluvial valley sediment is not very thick. Only in certain cases does the alluvial valley fill become thicker.

12.2 Two effects are conducive to deposition in rivers: *progradation* and *crustal subsidence*.

Progradation. As a river wears down the land and delivers sediment to the sea, the mouth of the river builds seaward. Because the longitudinal profile of a river is anchored by base level at the mouth, this means that there has to be a slight upbuilding in the lowermost reach of the river (Figure 5-47). This may not seem like a big effect, but even some tens of meters is a lot of sediment.

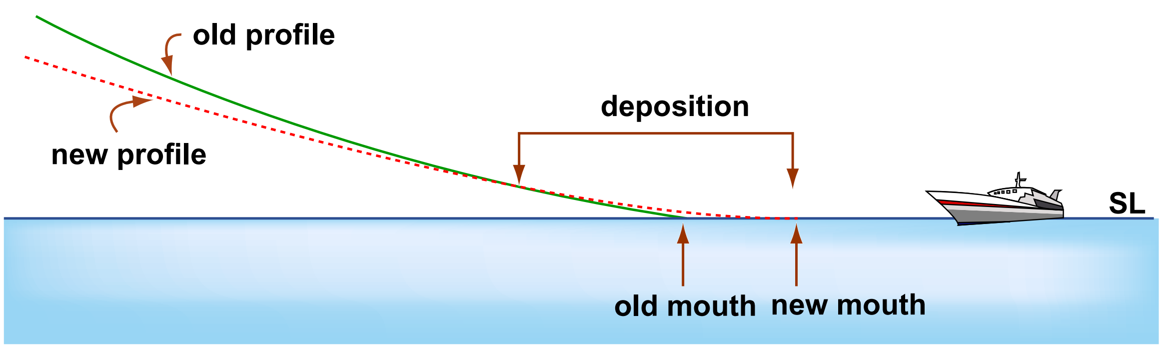


Figure by MIT OCW.

Figure 5-47. Deposition by seaward progradation in the lower reaches of a river system.

Crustal subsidence. The only way to get a really thick sequence of fluvial sediment is to *drop the continental crust beneath the river*. As this happens, slowly, along some reach of the river, there develops a very slight expansion of flow and decrease in flow velocity and therefore in sediment-moving ability. Just by simple bookkeeping, this must lead to storage of sediment along the river: if what comes into a given area of the bed is greater than what goes out, sediment is stored in that area, and the bed builds up. From an anthropomorphic standpoint, the river tries to maintain its longitudinal profile while the bottom drops out from under it, and it does so by leaving a little of the passing sediment to build up its bed (Figure 5-48).

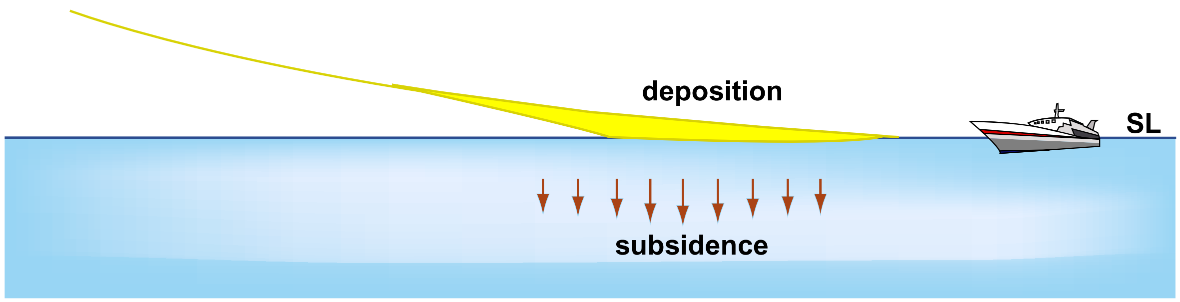


Figure by MIT OCW.

Figure 5-48. Deposition by crustal subsidence in the lower reaches of a river system.

13. FLOODS

13.1 The Definition of a Flood

13.1.1 Here's a simple definition of a river flood: *the occurrence of a flow of such magnitude that it overtops the natural or artificial banks in a reach of river channel*. If a floodplain exists, here's another way of defining a flood: *any flow that spreads out over the floodplain*.

13.1.2 The *relative* volume of flood water is not large: on average, water discharged in excess of channel capacity constitutes about 5% of the total annual discharge of the given drainage basin. But the *absolute* volume of flood water is staggering. Hypothetical example: a two-inch rainstorm over a one-square-mile catchment the soils of which can absorb 0.5 inches would supply almost 3.5 million cubic feet of water is a couple of hours! (That's a cube 150 feet on a side.)

13.1.3 A flood is a *wave*: it has a wavelike shape (although very subdued, with low amplitude relative to wavelength), and it propagates downriver at some speed, typically less than the mean velocity of flow of water in the river.

13.2 More on Floodplains

13.2.1 Here are two similar but not quite identical definitions of a floodplain, taken from the literature:

> the flat area adjacent to the river channel, constructed by the present river in the present climate and frequently subjected to overflow (Leopold, 1994)

> the flat area adjoining a river channel constructed by the river in the present climate and overflowed at times of high discharge (Dunne and Leopold, 1978)

13.2.2 As you learned in an earlier section, the existence of a floodplain is testimony to the lateral migration of the river channel. With time, the shifting channel sweeps the entire width of the floodplain, eroding the "front" bank and depositing the "rear" bank as it goes. If the climate, or the base level, changes in such a way that the river degrades (i.e., lowers its bed), the old floodplain is incised, forming a set of terraces, and a new, narrower floodplain develops. If the climate, or the base level, changes in such a way that the river aggrades, the floodplain typically (except in extreme cases) aggrades along with it.

13.2.3 What determines the height of the floodplain above the channel bed? That is, why does the river have the characteristic transverse profile we see? That has to do with the relationship between *effectiveness* and *frequency*. Low discharges are common but not effective in sediment transport and channel shaping, whereas very high discharges are very effective but very uncommon. The discharges with greatest effectiveness in maintaining channel and floodplain geometry are at some intermediate value: high but not extremely high, and common but not extremely common. For most rivers, bank-full discharges (those that spill over onto the floodplain) occur once or twice a year, on average. (It turns out that the discharge that is responsible for the maximum sediment discharge, in a given time period like a year, called the ***effective discharge*****,** is very close to being equal to the ***bank-full discharge*****.**)

13.2.4 What are floodplains like?

- They range in width from several meters, on the smallest streams, to many tens of kilometers, on the largest rivers.
- They are not flat as a board: they have minor relief, in the form of sloughs and depressions left behind by the irregular shifting of the river channel.
- They are developed in their classic sense in connection with meandering rivers. Braided rivers work irregularly across the entire valley, such that in a sense the entire valley is "river bed".
- They are typically heavily vegetated in their natural state; in fact, the bank-stabilization effect of vegetation is one of the most important, if not *the* most important, factors in the existence of the floodplain in the first place.
- They vary in their "wetness": usually they are dry and well above the local water table for most of the year, and are thus conducive to human use, but in areas with consistently high rainfall and/or strongly aggradational river regime ,there can be extensive swampy areas on the floodplain.

13.3 Important Aspects of Floods

13.3.1 There are several important aspects of floods:

discharge: discharge is important because of its close relation to flow velocity: how erosive is the flood flow in terms of banks, levees, and river structures?

stage: the height of the water determines flood damage on the floodplain (This is what the public thinks about most in connection with floods.) Also, it relates to the water-passing capacity of bridges, culverts, dam spillways, etc.

volume: this relates to how much water is available to be caught and impounded in reservoirs for water supply and flood control.

area inundated: this is determined by stage together with river-valley topography.

flow velocity: Although the flow velocity is much less over the floodplain than in the main channel, it can be great enough to cause damage.

13.3.2 Here are some important questions connected with river floods:

- governing effects?

- getting worse?
- how to control?
- how to predict?

13.3.3 What are the important effects or factors that govern the magnitude of a flood?

- **Rainfall** in the drainage basin upstream of the given point on the given river. This boils down to both rainfall *intensity* (depth per unit time) and rainfall *duration*, and also the *area* of the drainage basin covered by the rainstorm. The worst scenario is: high intensity for a long time over a large area of the drainage basin.

- Preceding condition of **soil moisture** in the area of rainfall: dry, which lessens the runoff, or saturated, which maximizes the runoff? The difference can be as much as half an inch of equivalent rainfall. That's a big effect for small floods but only a small effect for large floods.

- **Channel storage**. Think in terms of what happens when a flood discharge from an upstream river enters a large lake. The lake has a large surface area, so it takes a long time for the flood flow to raise the lake elevation and therefore increase the discharge out of the lake. This storage effect is also present to a non-negligible extent along the river channel itself: As the flood proceeds downstream, it has to fill a greater and greater volume of space in the river channel itself. This effect *attenuates* the flood in the downstream direction: in effect, it *stretches out* the hydrograph and lowers its peak (in terms of either the stage hydrograph or the discharge hydrograph).

- **Channel geometry**. The narrower the channel, for a given flood discharge, the more the stage rises. When the stage reaches bank-full, the water spreads out over the floodplain, and the stage then increases far less rapidly with increasing discharge.

- **Transition from dunes to plane bed.** As discussed in an earlier section, this tends to slow the increase in stage with increase in discharge: the channel can pass a given discharge at higher velocity and lower stage because of the reduced resistance to flow afforded by the plane bed.

13.4 Are Floods Getting Worse?

13.4.1 The answer to that question is certainly "yes", in terms of *dollar value of damage*, just because of greater human use of flood-prone areas near rivers. But the answer is yes also in terms of *higher stage*, because of the effect of more levee protection: the levees prevent the high discharges from spreading over the floodplain, so the rise in stage is confined to within the channel (Figure 5-49).

Figure 5-49. The stage of a flood flow for a given flood discharge. A) Before building of levees. B) After building of levees.

13.4.2 Is flood *discharge* increasing on average as well? There are two aspects to this question.

(1) In *urbanized* drainage basins, the percentage of area paved increases, thus decreasing the concentration time and tending to produce higher peaks in the hydrograph (stage and discharge) for a given rainfall. In rural drainage basins, bare-soil agriculture and clear cutting of forests have the same effect, although it seems not to be a really major effect. (Their effect on sediment yield is much greater, though.)

(2) Average rainfall in the drainage basin might be increasing because of *climate change* (although in much of the U.S., the prediction is that global warming will decrease precipitation rather than increase it). "Storminess" (increased incidence of major rainstorms) might increase as well.

13.5 Can Floods Be Controlled?

13.5.1 A better way of putting the question would be: how can flood damage be minimized, in the sense that a given measure affords more flood protection than it costs to institute?

(1) *Build higher and higher levees*. Yes, you can keep the floodwaters off the floodplain by building the levees higher. In a real sense, however, this is a self-defeating activity (Figure 5-50). Under natural conditions, the flood stage has built into it an inherently self-limiting effect: the floodplain area is so much greater than the channel area that, once the river goes beyond bank-full to inundate the floodplain, water-level rise is minor. (But remember that "minor" in a natural sense may be catastrophic for people living on the floodplain.) Building the levees higher restricts the river discharge to a much narrower width of the river valley, so

the flood stage is much higher than would have been the case without the higher levees. Because of the effect of eliminating the floodplain-spreading effect, effective protection would necessitate impractically high levees. Moreover, if those high levees are overtopped, the flood damage to the surrounding floodplain area is likely to be much worse than if the levees had not been there.

(2) *Flood-control dams*. Clearly, the stage and discharge hydrographs can be reduced downstream of a given point on a river by building a water-storage dam there: catch the water so as to knock down the flood peak, and release the water slowly later in times of lower discharge. The problems, aside from the great cost of building dams, is that the effect lessens downstream, so a number of dams are needed. For decades, in the mid-1900s, there was a controversy over whether to build lots of small dams in upstream areas or a few big dams in downstream areas. It was finally concluded that *for effective flood control throughout the whole basin, both sets of dams would be needed*.

(3) *Land management*. Good agricultural practices (fallow planting; terrace agriculture; contour planting) should increase infiltration and thus lower runoff, and also make the concentration time longer. Careful consideration has shown, however, that the effect is measured in tenths of an inch of equivalent rainfall, so it would be effective against minor floods but not major floods. The great benefit is greatly decreased soil erosion—which is a different (but very important) matter.

(4) *Restrictions on human use of floodplains*. Clearly the best way to prevent flood damage is not to put anything susceptible to damage on floodplains! The expense of relocation is usually too great for this to be practical (although it's happening in some places; it's a policy issue rather than a scientific issue), but intermediate measures are effective: establish floodways and spreading areas that are used for such things as agriculture (of certain kinds) and recreation, but not permanent structures. This doesn't solve the problem for already urbanized areas, though.

13.6 Can Floods Be Predicted?

13.6.1 Simple answer is just "no". Well, in a sense you *can* predict floods, but only after the rain has stopped falling! There are two aspects to this:

(1) Given the rainstorm, predict the runoff in order to create a flood hydrograph

(2) Given the flood hydrograph, watch the evolution of the hydrograph as the flood wave moves downstream. This technique is called ***flood routing***.

13.6.2 Various approximate techniques have been developed, and continue to be refined, for predicting the nature of the flood wave downstream of a rainstorm in a drainage basin. The assumptions and approximations are many: distribution of rainfall; extent of runoff vs. infiltration; time of concentration to create the hydrograph. It works okay for very small catchments but not so well for large catchments. It's a standard engineering technique for very small catchments (much less than one square mile). Once a flood is underway, however, there are good flood-routing techniques for predicting its future course down the river. Flood routing is treated at length in textbooks on fluvial hydrology.

13.6.3 The other aspect of flood prediction has to do with the *statistics or probability of floods*. One assumes that, given the climate and the nature of the drainage basin upstream of a given point on a river, there is some underlying frequency distribution of floods, in terms of either stage or discharge. Any record of floods is then a sample population (in the parlance of statistics) from that underlying frequency distribution. So if you know the frequency distribution, you can give the probability of a given flood in a given time period (that's not a prediction, but it's very useful in making a cost–benefit analysis or decision). If you are interested in learning more about how fluvial hydrologists go about figuring out the probability of a given flood in a given time period in a given river system, go to the following advanced topic.

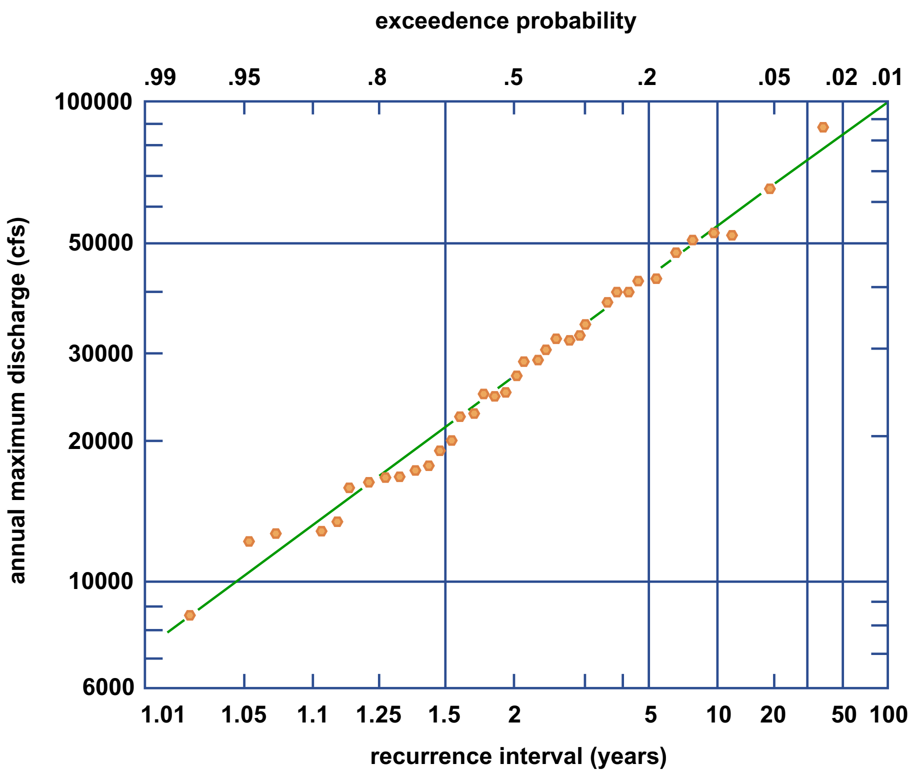
ADVANCED TOPIC: THE PROBABILITY APPROACH TO ERIVER FLOODS

1. The important question that arises is: *what can be done about establishing the probability of very large floods*? This is extremely important, but it's fraught with difficulties. Here's how it's done, given a long record of discharge at some location along the river (see Figure 5-51):

- Determine the largest momentary discharge in each year.
- Rank these in order of decreasing discharge (the highest being number one, the lowest being equal to the number of years of record).
- Compute the ***recurrence interval*** (also called the ***return period***), in years: the average number of years within which a given event (i.e., a flood of given magnitude) will be equaled or exceeded), by the formula $T =$

$(n+1)/m$, where T is the recurrence interval, n is the number of years in the record, and m is the rank of the event (or, equivalently, the probability p of a given event being equaled or exceeded in any given year; that's called the ***exceedence probability***).

- Plot the results in a graph with recurrence interval and/or exceedence probability on the horizontal axis and the annual maximum discharge on the vertical axis.
- Fit a smooth curve through the points in some way.



Flood-frequency curve plotted on logarithmic probability paper, Tana River at Garissa. Keny. 1934-1970. The scale at the top is the probability that the discharge is equaled or exceeded in any given year. The bottom scale, recurrence interval, is the average number of years in which the annual peak equals or exceeds the discharge given on the ordinate.

Figure by MIT OCW.

Figure 5-51. An example of a flood-frequency curve. (From Leopold, 1994.)

2. The results are reliable for the mid-range of the graph, but they become very uncertain near the high-discharge end because of the small numbers of very large events. Fitting such a tail of a distribution is always tricky business, but it is important if one is to try to extrapolate to much longer times, which is one of the important goals of such an exercise. Various techniques have been in use for fitting such a curve. Usually one uses a kind of graph paper with logarithmic vertical (discharge) axis and a horizontal axis rubber-sheeted so that certain theoretical frequency distributions plot as straight lines. (That makes it easier to fit the tails of the distribution.) Several such distributions have been in use. The trouble with blind curve fitting is that one or two unrepresentative or outlying points at the high-discharge end can bias the curve significantly. Some hydrologists prefer to fit the curve by eye, using judgment about whether to include such seemingly outlying points.

3. One valuable approach is to try to determine, from historical records, whether the greatest discharge in the period of record was exceeded in earlier times. If the greatest discharge in the period of record can be established to have been greater than any other for a number of years before the period of record, the period of record can be extended back in time and the ranking redone. This tends to shift the unrepresentatively large outlying point to the right and bring it more closely in line with the rest of the distribution.

13.7 Effects of Urbanization

13.7.1 Urbanization can have major effects of the magnitude and frequency of floods. Here's an example (Figure 5-52): Seneca Creek, near Rockville, Maryland, drains an area of 100 square miles. Its watershed has been subject to much urbanization in recent decades. Take the record of discharge, 61 years long, from 1931 to 1991, and divide it into two equal parts, early and late. The average annual flood in the period 1931–1960 was 3000 cfs, in the period 1961–1991 it was 6000 cfs—twice as great! Likewise, bank-full discharge occurred 1.2 times per year in first period but 2.2 times per year in second period.

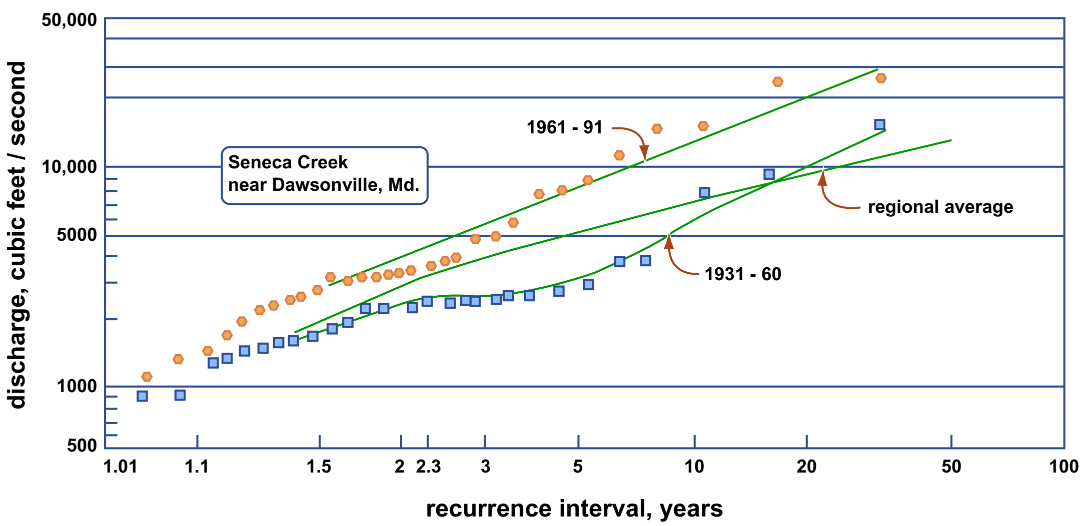


Figure by MIT OCW.

Figure 5-52. Flood-frequency curve for Seneca Creek, Maryland. (From Leopold, 1994)

13.7.2 Rainfall was almost exactly the same in the two periods, so the great differences have to be accounted for entirely by the effects of urbanization effects. The stream is not artificially leveed, so presumably the effect has been caused by a decrease in concentration time; the more pavement, the faster the runoff, and the shorter the concentration time.

13.8 Effects of Aggradation

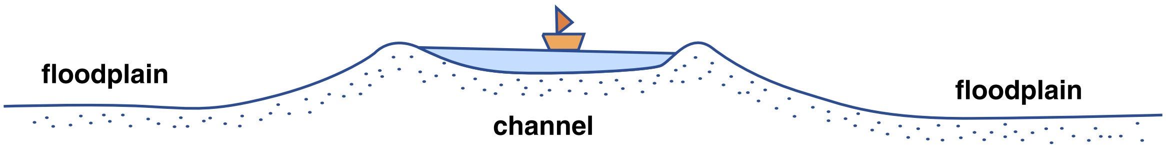
13.8.1 There's a serious long-term problem in areas, especially in the lower reaches of large rivers, where crustal subsidence is non-negligible (i.e., the substrate beneath the active channel is moving downward relative to a datum like sea level) and/or where sea level itself is rising. (The former effect is more important than the latter.) The subsidence can be a combination of two effects:

- deep crustal subsidence
- subsidence caused by compaction of the sedimentary substrate of the river

13.8.2 The river channel aggrades to keep pace with subsidence, and in consequence it finds itself higher and higher above its floodplain—because, under conditions of net aggradation, deposition can be much faster in the channel, where the river is transporting most of its sediment, than over the floodplain. At certain times the river breaks through some particularly vulnerable point along its natural levees and finds its way out onto the floodplain, which is now at a significantly lower elevation, and establishes a whole new course for long distances down the floodplain. The process is called ***avulsion***; the river is said to ***avulse***. The river then proceeds to build up its channel bed and its levees, again to be high above the floodplain, and avulse once more. Avulsions often develop over a period of time rather than happening all at once: more and more of the river discharge is diverted through the gap in the levee, flood after flood. The end result, however, is the same.

13.8.3 To prevent avulsion, humans in avulsion-prone areas tend to build higher and higher levees, in the hope of preventing such an unfortunate event. The channel bed gets higher and higher relative to the surrounding floodplain (Figure 5-53).

13.8.4 This is happening today in the lowermost reaches of the Mississippi River. Much of the city of New Orleans lies well below the river. The Mississippi has an unfortunate preference for flowing down the Atchafalaya River to Morgan City. The U.S. Army Corps of Engineers maintains a gigantic headworks on the left bank of the river upstream of New Orleans to prevent the entire discharge of the Mississippi from going down the Atchafalaya; at present, about a third of the discharge leaves the Mississippi at that point. How long such a situation can be maintained is a matter of some controversy. If you would like to read an engaging account of the problem with the lower Mississippi, see the book by John McPhee (1989).



A river valley in which the river channel and river banks have aggraded relative to the surrounding floodplain, making the river susceptible to avulsion

Figure by MIT OCW.

Figure 5-53. A river valley in which the river channel and river banks have aggraded relative to the surrounding floodplain, making the river susceptible to avulsion.

13.8.5 China has an even bigger problem with the Huang He (in English, the Yellow River), because they have been fighting the river for far longer than we have been fighting the Mississippi. I know from having been in China that the bed of the Huang He at the city of Kaifeng is almost fifteen meters above the streets of the city, only several kilometers from the river! The Chinese are working hard to come up with a way of solving this problem in the long term; for the near term (a few more decades) the levees are considered to be adequate.

14. SOME PRACTICAL ASPECTS OF RIVERS

14.1 Water Supply

14.1.1 Many large and small cities on rivers use river water for municipal water supply. The advantage is that it's there: all you have to do is pump it out of the river rather than drill and maintain deep wells or build and maintain often distant reservoirs. One big disadvantage, though, is pollution. You can chlorinate for pathogenic organisms and filter for turbidity, but you can't easily extract dissolved chemicals introduced upstream. This is especially a problem for large cities located on the lower reaches of major rivers, like New Orleans.

14.2 Irrigation

14.2.1 In many areas, rivers are important sources of irrigation water as well as groundwater. You don't have to pump: just divert some of the river into irrigation canals and let it flow by gravity into agricultural areas adjacent to the river.

14.2.2 There are problems, however:

- As with municipal water supply, this may use up a large percentage of river discharge by the time the river empties into the ocean!
- That water has to go somewhere. Where does it go? (1) It's lost by evaporation and transpiration (loss by evapotranspiration is enormous in irrigated agriculture); (2) It infiltrates, then flows as groundwater back into river downstream. Chemical pesticides used on cropland partly remain in the soil and partly are leached with return groundwater flow into the river.

14.3 Dams

14.3.1 The issue of dams is a complicated one. Humankind has been building dams since way back in prehistory. There are several kinds of dams: earth fill, rock fill, and concrete. The technology of dam construction is well advanced (but, occasionally, there still are dam failures!).

14.3.2 What are the main uses of dams? (Note: these uses are often, perhaps usually, combined.)

- water supply
- flood control
- hydropower generation
- recreation

14.3.3 Below (in no particular order) are listed some of the aspects of dams that need to be taken into consideration by urban planners and other governmental authorities as well as by environmental scientists and engineers:

- cost–benefit analysis
- safety
- displacement of humans
- land loss
- ecosystem disturbance
- evaporation loss
- siltation
- downstream degradation

14.3.4 If rivers carried no sediment, problems with dams would be far less serious. All rivers, however, carry sediment, and all but the smallest are alluvial rivers. In such rivers, sediment is in one way or another the biggest problem in reservoirs behind dams. Unless special (and very difficult and costly) engineering measures are employed, the reservoir is a sink for sediment arriving at the upstream end. *All such reservoirs therefore have a finite lifetime*. These lifetimes are usually measured in decades, and often not many decades.

14.3.5 What happens when the reservoir is mostly filled with sediment? (1) Dig it out—which is almost always impractical. (2) Let it go over the spillway with the water. The problem is most severe with respect to flood control and irrigation: the capacity of the reservoir becomes negligible. The problem is not so severe for hydropower generation, because the difference in water level between the water surface behind the dam and the turbines at the base of the dam is still there, but there are serious engineering problems connected with how to use the water without passing the sediment through the generating facility as well.

14.3.6 Degradation of the river bed below dams is another big problem. If you store the sediment in the reservoir instead of letting it pass, sediment transport rate just downstream of the dam is zero, and the river tends to entrain bed sediment to establish its equilibrium sediment load. The river then cuts down into its bed.

14.3.7 It's often not realized how much water is lost to evaporation from the water surface of the reservoir behind the dam, especially in summer and in arid climates. Various engineering schemes have been proposed for reducing such evaporation, but none has proved practical.

14.4 Cooling Water

14.4.1 Water temperature in a given river depends upon a number of natural effects: climate, season, residence time, and heating by energy dissipation. This thermal regime can be seriously disrupted by the need to supply cooling water to power plants, which are often located along rivers just for accessibility to cooling water. The main problem is the biological effect on river fauna and flora downstream.

14.5 Stabilization

14.5.1 Rivers, both meandering and braided, have an annoying tendency to shift their channels laterally. (Well, annoying for certain groups of people.) This creates obvious problems for residents along the river. In recent decades the engineering response has increasingly been to make rivers like artificial channels by lining the banks with various kinds of large heavy platy or interlocking objects, first at places of greatest vulnerability and then, increasingly, all along the river banks. Most large rivers in the United States are now partly stabilized in this way. The Mississippi is mostly stabilized. This was not always the case, as a glance at a map of the states adjacent to the Mississippi readily shows: little pieces of one state are now stranded on the other side of the river!

READINGS AND SOURCES

Allen, P.A., 1997, Earth Surface Processes. Blackwell Science, 404 p. (Chapter 3)

Bloom, A.L., Geomorphology; A Systematic Analysis of Late Cenozoic Landforms, Third Edition. Prentice Hall, 482 p. (Chapters 10–12)

Easterbrook, D.J., 1999, Surface Processes and Landforms, Second Edition: Prentice hall, 546 p. (Chapters 5–6)

Holmes, A., 1965, Principles of Physical Geology: Ronald Press, 1288 p.

McPhee, J.A., 1989, The Control of Nature: Farrar, Straus Giroux, 272 p.

Leopold, L.B., 1994, A View of the River: Harvard University Press, 298 p.

Thornbury, W.D., 1969, Geomorphology, Second Edition: Wiley, 594 p.