

## **PART II**

# **SEDIMENT TRANSPORT**

## CHAPTER 8

# SEDIMENTS, VARIABLES, FLUMES

### INTRODUCTION

**1** In the natural sciences, the word *sediment* is used for loose particulate material at the Earth's surface that has been produced by weathering of rocks and then transported by wind or water or ice. Because weathering acts everywhere to some degree, and the Earth is enveloped by moving air and water, it should not surprise you that sediment is ubiquitous. In engineering applications, the word "sediment" is used to refer not only to natural sediment but also to particulate material, of whatever origin, that is transported (or just potentially transportable) in some flow device or system.

**2** The dynamics of sediment transport is a large field, which is of interest in a wide variety of disciplines in the Earth sciences and engineering: geology, geomorphology, geography, oceanography, environmental science and engineering, civil engineering, mechanical engineering, and chemical engineering. Civil engineering has probably had more impact on the development of ideas and techniques in sediment transport mechanics than any other single discipline.

**3** In Part 2 of these notes I will deal with some of the most important phenomena and problems connected with the transport of denser solid particles by turbulent flow of a less dense fluid, which in most cases of interest is water or air. Emphasis will be on

- the *forces exerted on the sediment particles* by the flowing fluid,
- the *modes of movement of the particles* by the flow, and
- the *shaping of a loose sediment bed* by the flow.

**4** The greatest emphasis will be on flows in which the concentration of transported sediment is low enough that the turbulence structure of the flow—and the approach we can take to the dynamics of the flow itself—is not grossly different from flows without sediment. Flows with greater concentrations, sometimes approaching the limiting concentration of close packing of the sediment particles, are important in both natural sciences and engineering, but the limited scope of these notes precludes treatment here—they should be the topic of an entire additional set of notes.

## SEDIMENT

5 Before we get started on sediment movement, I will point out some useful things to know about the sediment itself. These have to do with the *size, shape, and density* of the material.

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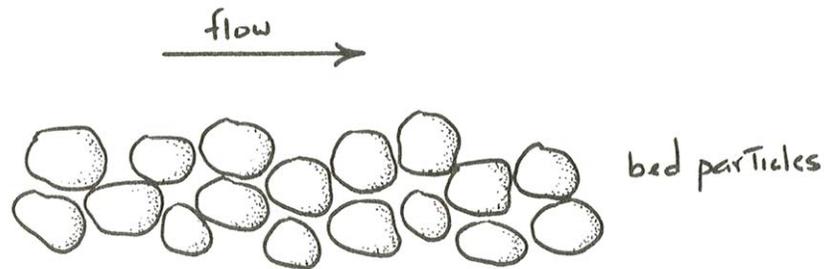


Figure 8-1. A “gravity bed” of loose sediment particles.

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6 The picture I want you to have is of what might be called a “gravity bed” of loose sediment particles: the particles are denser than the fluid, and they form a bottom boundary to the flow, below which the mass of particles rests packed together in a framework that is stable against the pull of gravity (Figure 8-1). We will be dealing with the uppermost part of this bed, where the particles are accessible to the flow—by which I mean that if not actually in motion at a given time, they are resting on the bed surface, or are located at a depth below the sediment–fluid interface small enough that the flow can (and presumably will, at some time) erode to that depth, given enough time even without any change in the overall or average flow conditions. This uppermost layer of potentially movable sediment is usually called the *active layer*.

7 Each bed particle is characterized by a size, a shape, and a density. Density is the simplest to deal with: the *mean density* of a particle is just the ratio of its mass to its volume. Size and shape are more difficult to deal with.

8 Size would be a straightforward concept only if the particle had the shape of a regular geometric solid. Some particles approach spherical shape, but most are irregular in shape. A theoretically satisfying measure of the size of an irregular particle is its *nominal diameter*: the diameter of a sphere with the same volume as the given particle. You can imagine, however, the difficulty you would have in measuring the nominal diameter of a sand grain! What is done is to define and measure size *operationally*: the meaning of size lies in how we actually measure it. The size of sediment coarser than about 0.1 mm is usually measured by passing it through a sieve with nearly square openings formed by a grid of (usually) metal wire. Approximately speaking, a sieve discriminates size

by passing all particles whose longest dimension in the smallest cross-sectional area is about that of the size of the sieve opening.

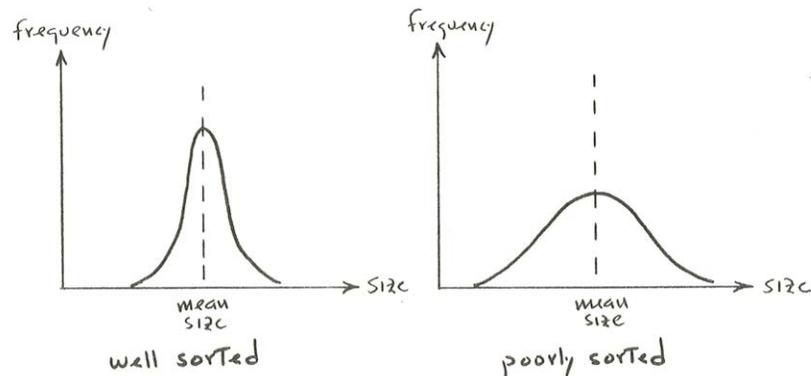


Figure 8-2. Sorting: the spread of sizes around the mean.

**9** All natural sediments have a range of particle sizes. The spread of sizes around the average size is called the *sorting*: a well sorted sediment shows a narrow spread of sizes, and a poorly sorted sediment shows a wide spread of sizes (Figure 8-2). (In civil engineering practice, the terminology is just the opposite: a well sorted sediment is poorly graded, and a poorly sorted sediment is well graded.) The effect of sorting on sediment transport is a rapidly advancing area of research nowadays.

**10** Shape is even more difficult to deal with than size. Clearly, natural sediment particles with their irregular shapes would require an enormous number of separate and independent variables to describe the shape: a hopeless situation. Fairly well-rounded sediment particles are often approximated by triaxial ellipsoids, which need only two ratios among three independent variables (longest axis, intermediate axis, and shortest axis) to characterize the shape.

**11** Even though we will not be dealing with anything but a single sediment density and an average sediment size in the following, it does not hurt to keep in mind always that a natural sediment has a three-dimensional joint distribution of size, shape, and density, which always has to be approximated in some way, and always very crudely. That joint distribution has too many axes for me to draw, but Figure 8-3 shows a simpler two-dimensional joint frequency distribution of size and density, with shape ignored. We can do better than Figure 8-3, though: most natural sediments have a dominant density fraction associated with quartz, feldspar, rock fragments, and carbonate particles, and a subordinate fraction consisting of a variety of heavy minerals with much greater density (Figure 8-4).

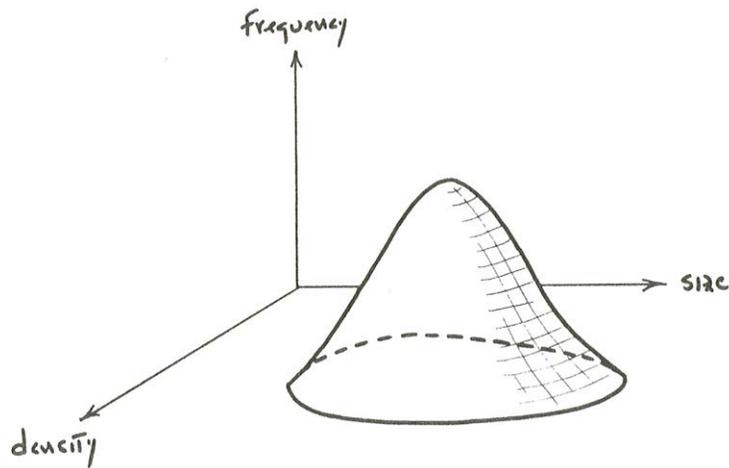


Figure 8-3. A joint frequency distribution of sediment size and sediment density.

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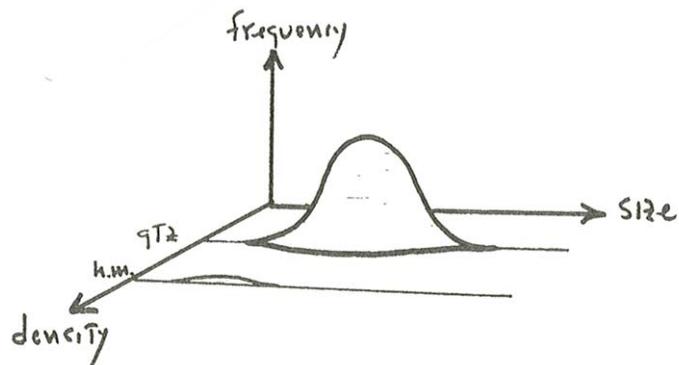


Figure 8-4. What the joint size–density frequency distribution looks like for many natural sediments.

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**12** The ratio of particle density to fluid density ranges enormously in natural sediment-transporting flows, from winds on Mars to water flows on Earth (Figure 8-5). The important points along this spectrum for us earthling sedimentologists are for quartz-density and heavy-mineral sediments in water and air. But we must not be presumptuous: think of all the places there must be in the universe where sediment is being moved, at this very moment, for which the density ratio is greatly different from these few particular cases of greatest interest

to us. It is wise for sediment dynamicists to keep a broad perspective, because otherwise, in concentrating on just a few cases some important general effects might be misinterpreted, or even missed.

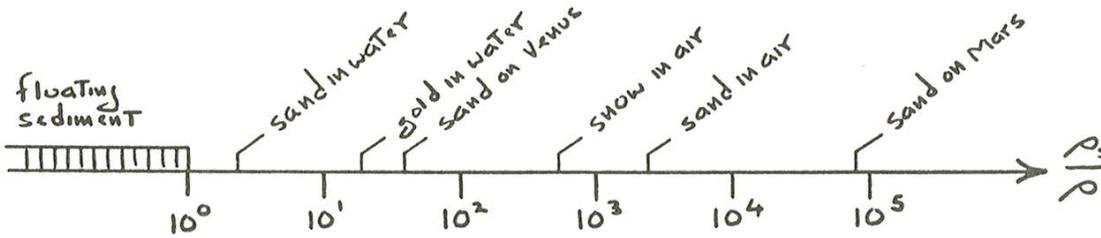


Figure 8-5. The spectrum of density ratios  $\rho$

### HYDRODYNAMIC PERSPECTIVE

**13** The dynamics of sediment transport could be viewed as part of the field of *two-phase flows*: flows of a fluid that contains within it discrete particles of some solid or even of some other immiscible fluid. Accordingly, there are liquid flows with solid particles, liquid flows with liquid particles (drops), liquid flows with gas particles (bubbles), gas flows with solid particles, and gas flows with liquid drops. (The nature of gases precludes the existence of gas flows with gas bubbles!) The included phase may be either more dense or less dense than the including phase.

**14** Turbulent sediment-transporting flows are far more important than laminar sediment-transporting flows, although some laminar flows do transport sediment. Turbulent sediment-transporting flows represent one of the most difficult problems in all of fluid mechanics, partly because the presence of the included phase alters the turbulence structure of the including phase, and partly because in many cases the flow boundary consists of the sediment particles themselves, and then the flow can shape its own boundary but is in turn affected by that shaped boundary. It is the feedback or mutual interaction between a sediment-moving flow and its deformable sediment boundary that lies at the heart of so many flows that move solid particles.

**15** Figure 8-6 may be useful in giving you some perspective on the complexity of sediment-transporting flows. Figure 8-6 shows the changes in the essential nature of the flow, starting with turbulent flow in a closed conduit and ending up in sediment-transporting flow over a loose sediment bed. The step from a circular pipe to a rectangular duct adds the presence of a weak but non-negligible secondary circulation, while the structure of the shear-flow turbulence is not greatly different. In the next step, to an open rectangular channel, the

turbulence structure is again only slightly different, as are the secondary circulations, but the deformable free surface makes for rather different effects in unsteady flows, as you have seen in Chapter 5. The next step, to a rectangular channel with a loose sediment bed, is the big one: because the flow can mold the bed, and the bed in turn has a strong effect on the flow, the turbulence structure and the free-surface geometry are significantly different in certain ranges of flow. The last step, to a channel with erodible banks, makes for greatly different bed geometry, at least in certain ranges of flow.

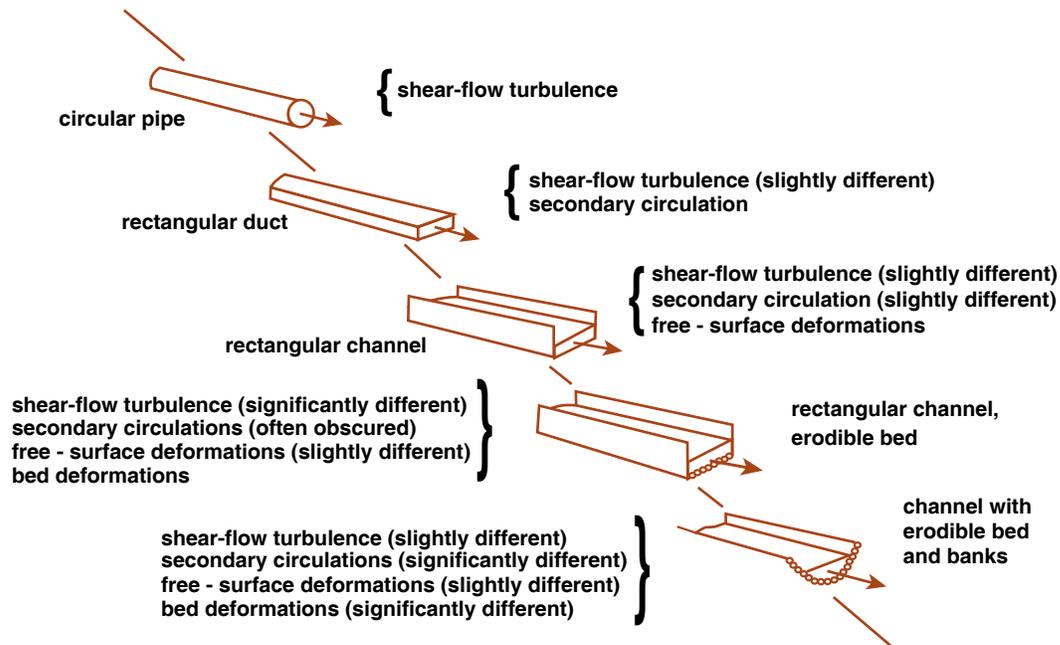


Figure by MIT OpenCourseWare.

Figure 8-6. Perspective on the complexity of sediment-transporting flows.

## PARTICLE MOTIONS VS. TURBULENCE

**16** A few qualitative observations on the effect of a turbulent flow field on the motions of suspended particles might be useful here, to set the stage for later chapters.

**17** Think about a sediment particle in a turbulent fluid. Clearly, its trajectory will be sinuous rather than straight, and its velocity will be irregular rather than constant. The particle undergoes two kinds of accelerations at the same time:

- *temporal accelerations*, because the velocity varies with time at points the particle happens to occupy; and
- *spatial accelerations*, because the particle falls through regions with different fluid velocity.

Physical effects, partly related, that we have to consider are the following. Details on some of these effects are given in later paragraphs.

- Relative inertia
- Particle size relative to eddy size
- Turbulent velocity fluctuations relative to particle velocity
- The effect of acceleration on the drag force

**18** The effect of *relative inertia* is expressed by the ratio  $\rho_s/\rho$ . For  $\rho_s/\rho \gg 1$ , the much greater inertia of the particle causes its trajectory to be relatively little affected by the turbulence (Figure 8-7A). For  $\rho_s/\rho \approx 1$ , on the other hand, the approximately equal inertia of the particle and the fluid causes the trajectory of the particle to be strongly affected by the turbulence (Figure 8-7B). This effect is independent of the weight of the particle: in an extraterrestrial place with very small  $g$ , a particle can have a small immersed specific weight  $\gamma'$  but large  $\rho_s/\rho$ , whereas in an extraterrestrial place with very large  $g$ , a particle can have a large  $\gamma'$  but small  $\rho_s/\rho$ . On the Earth, however, weight and relative inertia are unavoidably linked.

**19** If the sediment particle is much larger than the turbulent eddies, then small eddies distort the local velocity field near the surface of the particle and affect the drag force on the particle, but the motion of the particle is not much affected (Figure 8-8A). If the particle is much smaller than the surrounding eddies, however, the particle senses a nearly uniform but unsteady fluid acceleration in its vicinity; the curvature of the particle trajectory is large relative to particle size (Figure 8-8B).

**20** The effect of turbulent velocity fluctuations relative to particle velocity is especially relevant to settling particles. If the vertical turbulent velocity fluctuations are much greater than the settling velocity of the particle, then the particle has a highly sinuous trajectory, with frequent reversals of its vertical velocity component (Figure 8-9A). If the vertical turbulent velocity fluctuations are much less than the settling velocity of the particle, however, then the settling velocity is little affected by turbulence: the fall is always downward, the speed of the particle relative to the bottom varies only slightly, and the path of settling is only slightly sinuous (Figure 8-9B).

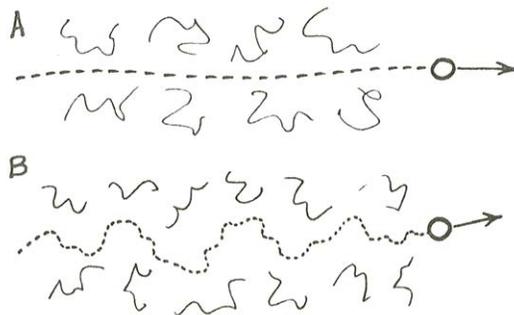


Figure 8-7. The effect of relative particle inertia when a particle moves through a turbulent fluid. **A)** Relative inertia is high; **B)** relative inertia is low.

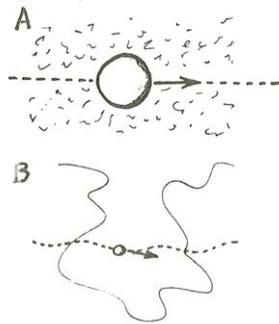


Figure 8-8. The effect of particle size relative to eddy size. **A)** The particles are much larger than the eddies. **B)** The particles are smaller than the maximum eddy size.

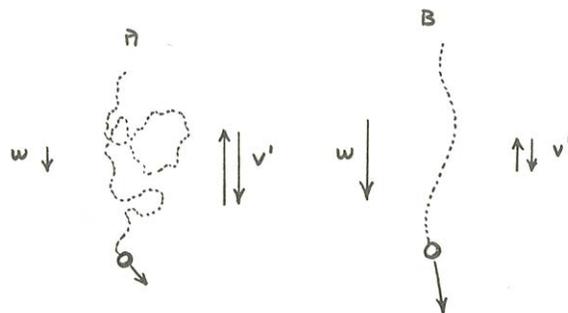


Figure 8-9. Effect of particle settling velocity relative to turbulent velocity fluctuations. **A)** The particle settles slowly relative to the vertical velocity fluctuations. **B)** The particle settles rapidly relative to the vertical velocity fluctuations.

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**21** What was done in Chapters 2 and 3 in Part 1 on the drag force on a sphere was predicated upon steady flow. When the local fluid velocity around the sphere is changing, the drag force is in general different from that predicted for a uniform relative velocity of the same value, because the local patterns of velocity and fluid pressure lag behind the changing free-stream flow velocity.

## OBSERVING SEDIMENT TRANSPORT

**22** What are the main things about sediment transport you might want to observe? Here are four of them, and some comments on the ways those observations might be carried out.

**Particle Movement.** The eye is an excellent instrument for perceiving the details of movement of sediment particles, but you need techniques like cinematography (high-speed or slow-motion) or video for a record, and also for speeding up or slowing down the process so that the eye can better perceive the nature of the movement. Various other optical methods for tracing particle movement have also been developed.

**Bed Geometry.** Visual observation and photography are the main ways of dealing with the bed configuration in still life. Time-lapse cinematography is especially useful for gaining information on the kinematics of individual bed forms: they generally move too slowly for you to see what they are doing in real time. When the bed is obscured by moving sediment, as is so often the case, you have to resort to mechanical profiling or sonic profiling.

**Sediment Load.** The sediment load can be sampled with traps or samplers of various kinds that purport to catch a representative volume sample of the sediment–water mixture. Indirect methods that involve the effect of the sediment–water mixture on a beam of light or sound are common: these can be as simple as attenuation along a line, or by focusing separate beams they can examine the sediment load in small regions that approximate points.

**Sediment Transport Rate.** It is notoriously, and frustratingly, difficult to make good measurements of the sediment transport rate without serious disruption of the flow. Local volume sampling of the load along with simultaneous measurements of local time-average velocity, integrated over the cross section of the flow, is the most common way. For bed load, traps of a great many kinds have been devised, and if they are calibrated well they can be quite reliable. I will have more to say on the intricacies of measuring the sediment load and the sediment transport rate in a later chapter.

**23** Here is a list of most of the aspects of sediment transport you might want to observe, measure, or think about, along with some brief comments.

**Entrainment.** The flow exerts sufficient force on a bed particle to set it into motion.

- Traction.** Particles are moved in contact with or close to the bed by fluid forces.
- Saltation.** Particle undergo near-bed ballistic movement, largely unaffected by turbulence.
- Suspension.** The flow lifts particles away from the bed after entrainment.
- Turbulence.** The particles distort the local fluid velocity field, alter the structure of the turbulence, and themselves undergo turbulent accelerations.
- Settling.** Particles settle toward the bed through the surrounding fluid.
- Hindered settling.** The proximity of other settling particles hinders the settling of each particle.
- Collisions.** Differing velocities plus inertia leads to collisions (or close encounters) between particles.
- Diffusion.** Suspended sediment undergoes upward turbulent diffusion against the concentration gradient.
- Distraintment.** Particles come to rest on the bed.
- Liquefaction.** Rearrangement of packing in the bed leads to reduction in particle contact, partial or total support of particles by pore fluid, then refreezing of the texture by dewatering.
- Bed configuration.** Bed-load transport plus complex dynamic bed instabilities lead to various characteristic bed geometries.

## VARIABLES

**24** It seems like a good idea at this point to think in a very general way about which variables are likely to be important in problems of sediment transport, and to organize those variables into a set of dimensionless variables that is likely to be useful as a framework from which to simplify or (complexify or specialize!) in any particular problem we deal with later. This is your chance to think about the phenomenon of sediment transport in its broadest aspects.

**25** This endeavor involves some assumptions about what might be called the *target flow*. For the sake of definiteness, we will look at the movement of cohesionless sediment by steady uniform flows in straight rectangular channels of effectively infinite width in a nonrotating system. We thereby ignore the effects of channel width, cross-section shape, channel curvature, and the Earth's rotation, and we restrict ourselves to equilibrium sediment transport. The first three restrictions are especially serious in fluvial sediment transport, but our target flow is a good start, from which these other effects can be evaluated. Ignoring the Earth's rotation is not as serious as it might seem, because most aspects of sediment transport are tied up with the local near-bottom structure of turbulent shear flows, which, as you saw in Chapter 7, are about the same in geophysical

flows as in actually or effectively nonrotating flows. Time-dependent problems in sediment transport are also of great importance, but again our target case represents a good reference. Finally, the assumption of cohesionless flows shuts us out of the complex, frustrating, and extremely important world of fine cohesive sediments—another topic that deserves its own separate set of notes.

**26** The most important sediment-transport effects we will deal with in later chapters are easy to list:

- modes of grain movement
- speeds of grain movement
- sediment load
- sediment transport rate
- bed configuration

**27** Which variables might have a role in influencing or determining these effects? The possibilities form a long list (and there probably are others I have not thought of):

**sediment:**

- joint size–shape–density distribution
- elastic properties

**fluid:**

- density  $\rho$
- viscosity  $\mu$
- specific weight (weight per unit volume)  $\gamma$
- elastic properties
- thermal properties
- surface tension

**flow:**

- mean depth  $d$
- mean velocity  $U$
- discharge (per unit width)  $q$
- boundary shear stress  $\tau_0$
- slope  $S$
- power  $P$

**system:**

- acceleration of gravity  $g$

**28** Clearly this list is too long: some items can safely be neglected, and some items are actually redundant.

**29** First, here are some comments on the variables that characterize the sediment. There are no redundancies in the items for the sediment in the above list, but they are effectively non-quantifiable because of grain shape. And even if grain shape is neglected, the size–density distribution has to be characterized by a two-variable joint frequency distribution (see Figure 8-3). As mentioned earlier, a good approximation in practice might be to assume one dominant blade-shaped spike in the distribution corresponding to crudely quartz-density sediment, and one or more subsidiary spikes for heavy minerals (Figure 8-4). It is common practice in work on sediment transport to assume that all grains have the same density, so that the sediment can be characterized by the mean or median size  $D$  and the density  $\rho_s$ . Adding the standard deviation  $\sigma$  of the size distribution makes for *three variables* describing the sediment.

**30** With regard to variables characterizing the flow, there is a serious redundancy in the foregoing list: only two variables are needed to specify the bulk flow, one of them being the flow depth and the other a flow-strength variable. The two most logical candidates for the flow-strength variable are the boundary shear stress  $\tau_0$  and the mean velocity  $U$  (or the surface velocity  $U_s$ ). (Some might take exception to that statement, however, and claim that the flow power  $P$  is the most fundamental flow-strength variable.)

**31** In choosing the flow-strength variable, we could address three considerations:

- Which variables *specify* or *characterize* the state of sediment transport, in the sense that specification of those variables unambiguously corresponds to or identifies the state of sediment movement, whether those variables are imposed upon the system or are themselves fixed by the operation of the system?
- Which variables are truly *independent*, in the sense that they are imposed on the system and are unaffected by its operation?
- Which variables *govern* the state of sediment transport, in the sense that they are dynamically most directly responsible for particle transport and bed-configuration development, whether or not they are independent?

**32** One of the important goals in studying the phenomena of sediment transport is to show as clearly and unambiguously as possible the hydraulic relationships among those phenomena. It would be good to have a one-to-one correlation between sediment-transport states and combinations of variables, because that would represent the clearest start on knowing what we have to deal with or explain.

**33** In terms of unambiguous characterization,  $U$  and  $d$  (or  $q$  and  $d$ ) are the most appropriate variables to describe the flow because, for a given fluid, for each combination of  $U$  and  $d$  in steady uniform flow there is one and only one average state of the flow, in terms of velocity structure and boundary forces. This is not the case, however, if  $\tau_0$  or  $P$  is used in place of  $U$  or  $q$ : if  $\tau_0$  or  $P$  is used, there is an element of ambiguity in that for certain variables values of  $\tau_0$  or  $P$  more than one bed state at a given flow depth is possible. Although I am getting ahead of myself in bringing up this matter before the chapter on bed configurations, I will point out here that this has to do with the substantial decrease in form resistance in the transition from ripples or dunes to plane bed with increasing  $U$  or  $q$  at constant  $d$ . You can see from the cartoon graph in Figure 8-10 that because of this effect there is a non-negligible range of  $\tau_0$  for which three different values of  $U$  are possible. But you can see from the graph that if you specify  $U$ , you thereby uniquely specify  $\tau_0$ . An alternative approach would be to use only the part of  $\tau_0$ , called the *skin friction*, that represents the local shear forces on the bed, and leave out of consideration the part of  $\tau_0$ , called the *form drag*, that arises from large-scale pressure differences on the fore and aft sides of roughness elements. The ambiguity noted above would thereby be circumvented. The problem is that although there are several published procedures for such a *drag partition*, none works remarkably well (yet).

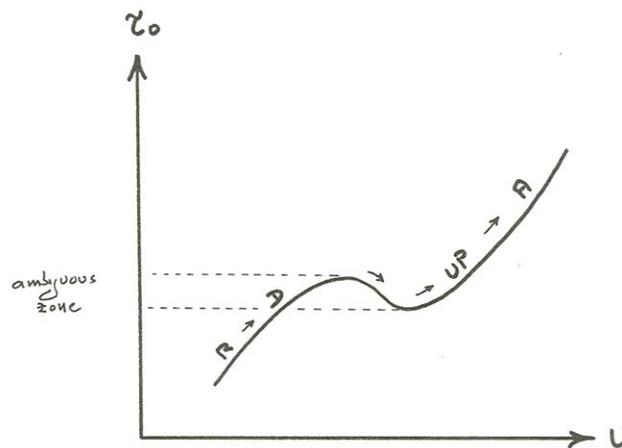


Figure 8-10. Graph of bed shear stress  $\tau_0$  vs. mean flow velocity  $U$  for a flow that is transporting sediment generating rugged bed configurations. R, ripples; D, dunes; UP, upper-regime plane bed; A, antidunes. The two horizontal dashed lines show the range of  $\tau_0$  for which a given value of  $\tau_0$  can be associated with three different values of  $U$ .

**34** *Independence* need not be a criterion in choice of variables to describe the state of sediment transport, because a given set of variables can equally well

describe the state of sediment transport whether any given variable in the set is dependent or independent: the state of sediment transport is a function of the nature of the flow but not of how the flow is arranged or established, provided that the flow is strong enough at the outset to produce general sediment movement on the bed.

**35** Independence of variables depends to a great extent upon the nature of the sediment-transporting system. For an example of this, think about an extremely long channel (tens of kilometers, say) with bottom slope  $S$ , straight vertical sidewalls, and an erodible sediment bed, into which a constant water discharge  $Q$  is introduced at the upstream end (Figure 8-11). Assume that after a transient period of flow adjustment a steady state is maintained by introducing sediment at the upstream end at a rate equal to the sediment discharge  $Q_s$  at the downstream end. The imposed variables here are  $Q$  and  $S$ ;  $Q_s$ ,  $U$ , and  $d$  are adjusted by the flow. Because of the great channel length, flow and sediment transport are virtually uniform along most of the channel except near the upstream and downstream ends. Even though the flow might prefer a different  $S$  for the given  $Q$ , adjustment in  $S$  is so slow that, on time scales that are short in terms of geologic time but long in terms of bed-form movement,  $S$  can be considered fixed. Hence  $Q$  and  $S$  are independent variables, and  $U$  and  $d$  along with all variables that express the details of flow structure and sediment transport are dependent upon  $Q$  and  $S$ .

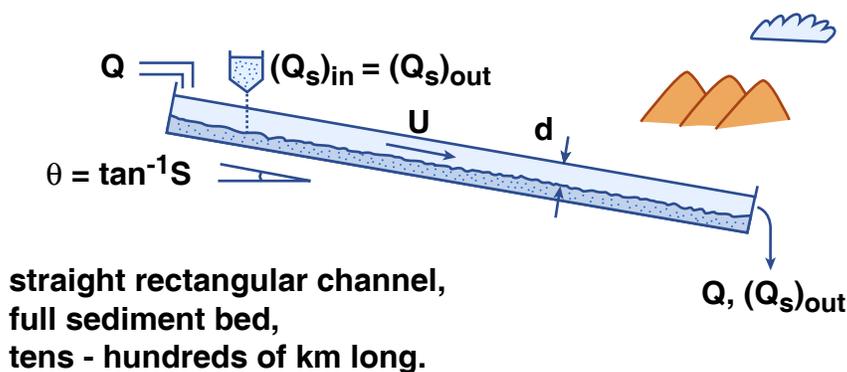
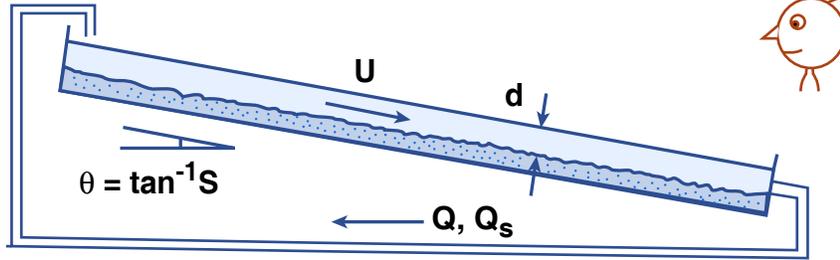


Figure by MIT OpenCourseWare.

Figure 8-11. A sediment-feed flume experiment in a very long channel.

**36** In a similar but much shorter channel, tens of meters, say (Figure 8-12),  $S$  can change so rapidly by erosion and deposition along the channel that the flow cannot be considered uniform until  $S$  has reached a state of adjustment to the imposed  $Q$ ;  $Q$  is an independent variable, but  $S$  is now dependent, in the sense that it cannot be preset except approximately by manipulation of  $d$  by means of a gate or weir at an overfall at the downstream end of the channel. And in constant-

volume recirculating channels, in which there is no overfall,  $d$  is truly independent and  $S$  is truly dependent.



**straight rectangular channel,  
full sediment bed,  
tens - hundreds of m long.**

Figure by MIT OpenCourseWare.

Figure 8-12. A sediment-feed flume experiment in a very short channel.

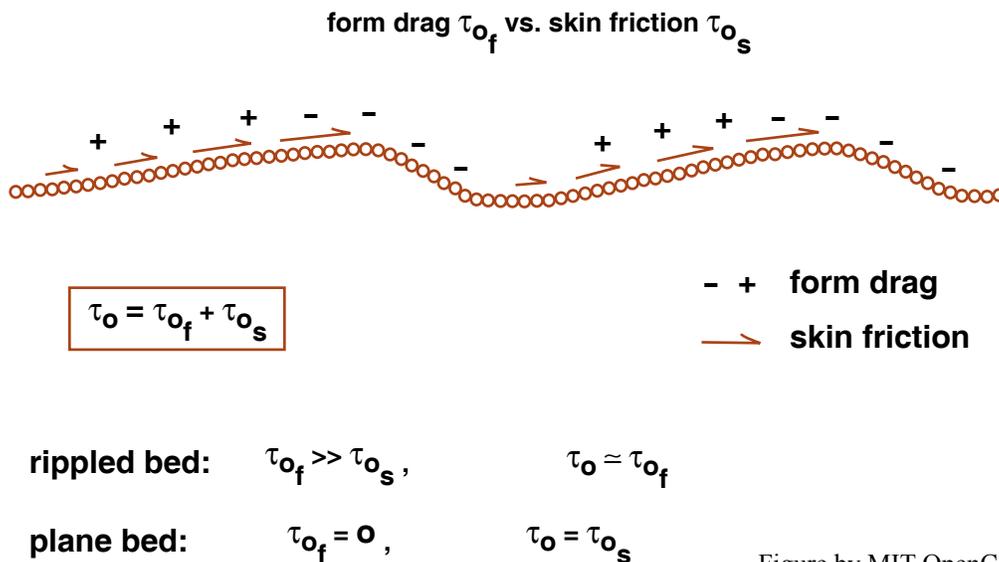


Figure by MIT OpenCourseWare.

Figure 8-13. Form drag and skin friction on a sediment bed with ripple or dune bed forms.

**37** With regard to *governing* variables, at first thought  $\tau_o$  is a more logical choice than  $U$  for characterizing the effect of the flow on the bed, because the force exerted by the flow on the bed is what causes the sediment transport in the first place. And for transport over planar bed surfaces, that is certainly true. But you will see in a later chapter that, over a wide range of flow and sediment conditions, the flow molds the bed into rugged flow-transverse ridges called bed forms. On beds covered with such bed forms, only a small part of  $\tau_o$  represents the boundary friction that is directly responsible for grain transport, the rest being

form drag on the main roughness elements (Figure 8-13). In such situations, therefore,  $\tau_0$  is as much a surrogate variable as  $U$ , in the sense that it is not directly responsible for particle transport and bed-form development, as are near-bed flow structure and distribution of boundary skin friction in space and time. These latter, however, are themselves uniquely characterized by  $U$  and  $d$ .

**38** When bed forms are present, the spatially and temporally averaged local skin friction would seem to be a better variable than  $\tau_0$  in characterizing the state of sediment transport, because it is free from the ambiguity mentioned above but at the same time is more directly responsible for the sediment movement. The trouble is that it cannot be measured, and it can be estimated only with considerable uncertainty using presently available drag-partition approaches.

**39** Several variables on the list are of minor or negligible importance in most sediment-transport problems: the elastic and thermal properties of the fluid and the sediment, and the surface tension of the fluid.

**40** So the final minimal list of variables that describe sediment transport in our target flow is as follows:

Mean flow velocity  $U$  or boundary shear stress  $\tau_0$

Mean flow depth  $d$

Fluid density  $\rho$

Fluid viscosity  $\mu$

Median sediment diameter  $D$

Sediment sorting  $\sigma$

Sediment density  $\rho_s$

Acceleration of gravity  $g$  or submerged sediment specific weight  $\gamma'$

**41** There are eight variables on the list, so we should expect to have an equivalent set of *five dimensionless variables* that describe the state of sediment transport equally well. A great many different sets are possible: you can choose a variety of sets of three repeating variables, and then you could manipulate those sets further by multiplying and dividing the various individual dimensionless variables in those sets.

**42** In general, we could move in one (or both) of two directions at this point. We could try to develop a set that has the greatest relevance to the physical effects involved in the sediment transport, or we could try to develop a set that has the sedimentologically most relevant or interesting variables segregated into different dimensionless variables.

**43** With regard to sets of dimensionless variables that are relevant to the physical effects of sediment transport, I will mention just two possibilities:

$\frac{\tau_o}{\gamma'D}$  Shields parameter, a dimensionless  $\tau_o$

$\frac{\rho u_* D}{\mu}$  roughness Reynolds number,  $Re_*$

$\frac{d}{D}$  relative roughness

$\frac{\rho_s}{\rho}$  density ratio

$\frac{\sigma}{D}$  sorting-to-size ratio

**44** You could construct this set by using  $\tau_o$ ,  $\rho$ , and  $D$  as repeaters. The physical significance of the roughness Reynolds number was discussed back in Chapter 4. The Shields parameter also has a clear physical significance. The fluid force on bed particles is approximately proportional to  $\tau_o D^2$ , whereas the weight of the bed particles is proportional to  $\gamma' D^3$ . The ratio of these two quantities is the Shields parameter, so the Shields parameter is proportional to the ratio of the fluid force on particles to the weight of the particles. For that reason it could also be called a *mobility number*.

**45** Another dynamically meaningful set of dimensionless variables can be formed using  $U$  as the flow-strength variable:

$\frac{\rho U d}{\mu}$  Reynolds number based on depth and velocity

$\frac{U}{(gd)^{1/2}}$  Froude number based on depth and velocity

$\frac{d}{D}$  relative roughness

$\frac{\rho_s}{\rho}$  density ratio

$\frac{\sigma}{D}$  sorting-to-size ratio

**46** The repeaters in this set are  $\rho$ ,  $U$ , and  $d$ . The mean-flow Reynolds number describes the structure of the mean flow, and the mean-flow Froude number is relevant to the energy state of the flow, as discussed in Chapter 5.

**47** Probably the most useful set of dimensionless variables for the purpose of unambiguous description of the state of flow and sediment transport is one in which the sedimentologically interesting variables  $U$ ,  $d$ , and  $D$  are segregated into separate dimensionless variables:

$$\begin{aligned} \left(\frac{\rho\gamma'}{\mu^2}\right)^{1/3} d & \quad \text{dimensionless flow depth } d^0 \\ \left(\frac{\rho^2}{\mu\gamma'}\right)^{1/3} U & \quad \text{dimensionless flow velocity } U^0 \\ \left(\frac{\rho\gamma'}{\mu^2}\right)^{1/3} D & \quad \text{dimensionless sediment size } D^0 \\ \frac{\rho_s}{\rho} & \quad \text{density ratio} \\ \frac{\sigma}{d} & \quad \text{sorting-to-size ratio} \end{aligned}$$

The repeaters for this set are  $\rho$ ,  $\mu$ , and  $\gamma'$ .

## FLUMES

**48** Out beyond the edge of official terminology, sedimentologists often refer to *flumology*—presumably meaning the science and art of gaining knowledge and understanding of physical sedimentary processes by passing water and sediment through laboratory open channels, called flumes. I thought that it might be useful to include this brief section on flumes before launching upon chapters dealing with sediment transport, because much of our understanding of sediment transport has been developed by watching and measuring the movement of sediment in flumes (and oscillatory-flow channels and tanks as well). I will be referring to flume experiments often in coming chapters.

**49** Dictionaries define flumes as artificial channels for transporting water. That is really not restrictive enough for our purposes, though: flumes designed for nonscientific uses are usually fairly steep and crude in structure. In the context of scientific and engineering studies, I might define a flume as *a laboratory channel through which liquid is passed in order to study hydraulic processes and phenomena under controlled conditions.*

**50** Flumes are built both indoors and outdoors. One of the most famous flumes—among geologists, at least—was G.K. Gilbert’s flume, outdoors on the campus of the University of California at Berkeley. Around the turn of the twentieth century Gilbert made a pioneering study of modes and processes of sediment transport by currents, which stands to this day as a valuable source of data and ideas. But hydraulic engineers had been using flumes for decades before that.

**51** Flumes are built of wood, metal, glass, or plastic. Each material has its advantages and disadvantages. The cross section is usually but not always rectangular. Widths usually are from several centimeters to a few meters, and lengths range from a few meters to well over a hundred meters. The largest recirculating flume in the world is at the University of Tsukuba, in Japan; it is 160 m long and 4 m wide, and it can recirculate both water and sediment. I am sure that any objective observer would consider it to be an impressive structure. (I certainly did, when I was first shown it.) I am not sure where the largest tilting flume is.

**52** The technology of construction of all but the largest flumes is straightforward, and the problems were for the most part solved long ago. In sediment-recirculating flumes, the most critical design decision revolves around the kind of pump used and/or the arrangement for extracting sediment from the flow and delivering it to the head of the channel.

**53** Flumes are only one kind of large-scale hydraulic equipment used for studying sediment movement. Flumes, carrying unidirectional gravity-driven free-surface flow, are distinct from *closed ducts and conduits*, also widely used for hydraulic studies, which have pressure-gradient-driven flow without a free surface. Closed ducts may be used for unidirectional, oscillatory, or combined flow. Also widely used are simple *tanks or basins* arranged mainly for oscillatory flows under surface gravity waves.

**54** *Advantages* of flumes:

- sediment transport is relatively easy to watch and measure
- particular processes can be isolated for study

**55** *Disadvantages* of flumes:

- flow and sedimentation can be oversimplified
- the physical scale of the flow and sediment movement is usually too small

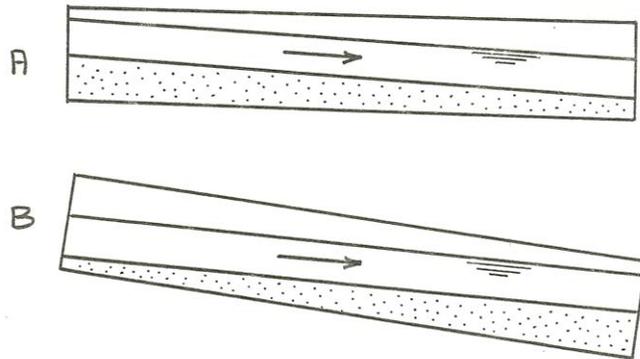


Figure 8-14. **A)** A uniform sediment-transporting flow in a flume with a floor that is less steep than the slope of the bed surface and the water surface. **B)** A uniform sediment-transporting flow in a flume with a floor steeper than the slope of the bed surface and the water surface.

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**56** The slope of the flume may be fixed or adjustable; most flumes, except the very largest, are *tilting*. But when you are working with sediment transport, your flume does not really need to be tilting, because the flow itself redistributes the sediment to produce a sediment bed with slope equal to the energy slope as uniform flow is established. If you prepare a planar and uniform bed of sediment and then set up a flow over it, if the flume slope is too steep there will be erosion near the upstream end and deposition near the downstream end until a uniform flow is attained over a sediment bed that tapers upstream (Figure 8-14A). Conversely, if you start with a flume slope that is too gentle, the result is a bed that tapers downstream (Figure 8-14B). You just have to make sure that the flume slope you start with is near enough the slope for uniform flow that you have a full bed of sediment everywhere in the flume once the flow stops adjusting to uniformity.

**57** Flumes vary in their arrangements for recirculation of water and sediment. Logically there are four possible combinations of recirculation; see Figure 8-15.

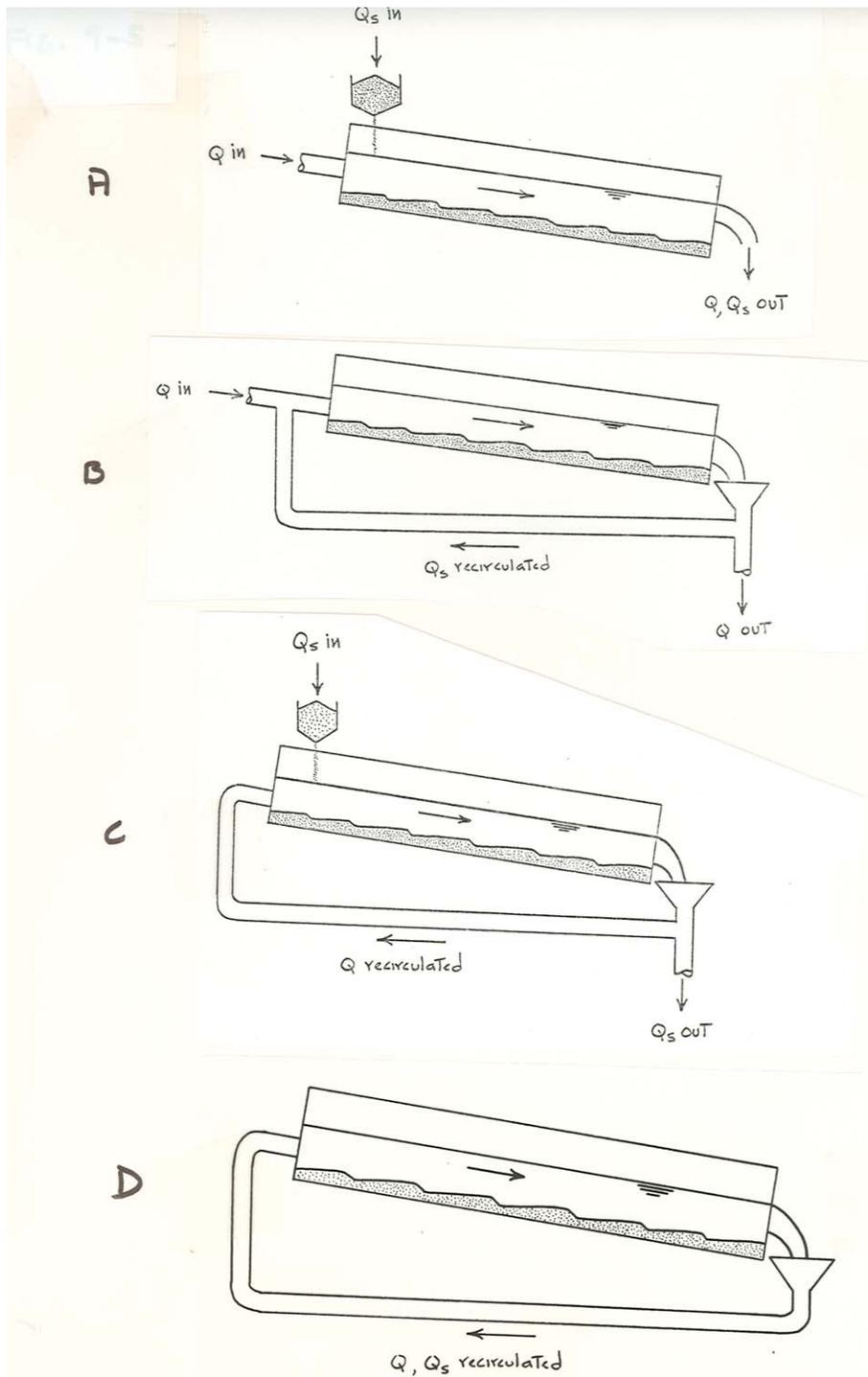


Figure 8-15. Differing arrangements for recirculation of water and sediment in flumes.

**Water no, sediment no** (Figure 1-15A). This arrangement is uncommon, because it is limited by water supply. Only laboratories located near dams on large rivers can afford to run large discharges of water through flumes without recirculation. Also, water temperature cannot be controlled independently. And if you do not catch the sediment, you lose it.

**Water no, sediment yes** (Figure 1-15B). The same comments apply as in the preceding case, except that you do not lose the sediment.

**Water yes, sediment no** (Figure 1-15C). This arrangement is more common. Its advantages are that the sediment discharge is imposed independently upon the flow. But it can be a technical challenge to separate all the sediment from the water and then feed new sediment at the upstream end.

**Water yes, sediment yes** (Figure 1-15D). This arrangement is simplest and also common. Here the flow establishes its own sediment discharge; you cannot impose sediment discharge on the system. Provided that the sediment is not too coarse, this is the easiest arrangement technologically. But it is difficult to arrange for gravels.

**58** There are two different arrangement for water-recirculating flumes:

**Overfall flumes** (Figure 1-16A). In some flumes, which I will call overfall flumes, there is a free overfall at the downstream end of the channel into a separate tailbox, from which water (and in many cases also the sediment) is pumped to the head of the channel. In such flumes, the flow depth in uniform flow is fixed by the imposed water discharge and bed roughness. You can set or adjust the slope only by fiddling with a weir or gate of some kind at the downstream end of the channel, to change the water depth and therefore the mean velocity.

**Closed-circuit flumes** (Figure 1-16B). In other flumes, which I will call closed-circuit flumes, there is no overfall at the downstream end; the flow passes continuously into the tailbox, to be pumped back to the head of the channel. In closed-circuit flumes, the flow depth is fixed by the volume of water in the system. You impose the water discharge and flow depth and thereby the mean velocity, which in turn determines all aspects of the sediment transport as well as the slope.

**59** Both overfall flumes and closed-circuit flumes are in wide use. Each has advantages and disadvantages. They are used for slightly different purposes, which I will touch upon in passing in later chapters.

**60** You will see, in Chapter 13, on mixed-size sediment, that the differences between sediment-feed flumes and sediment-recirculating flumes has significant implications (Parker and Wilcock, 1993). In a sediment-feed flume, the sediment discharge is imposed upon the flow and the flow must become adjusted to accomplish the necessary transport of all of the size fractions in the feed mix. In sediment-recirculating flumes, there is no such constraint: the flow

is free to adjust its sediment-transporting behavior without any external constraint imposed except for water discharge and bed material.

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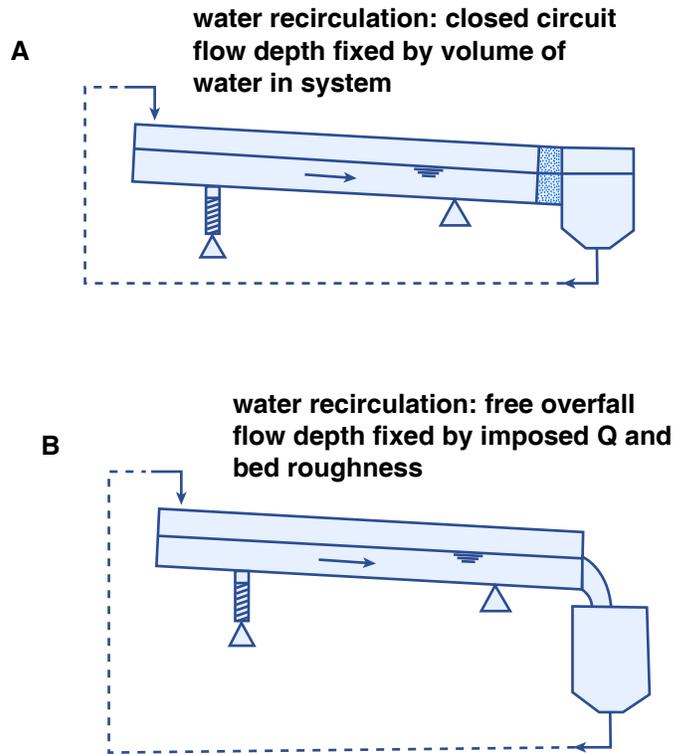


Figure by MIT OpenCourseWare.

Figure 8-16. **A)** A closed-circuit recirculating flume. **B)** A free-overfall recirculating flume.

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**References cited:**

Parker, G., and Wilcock, P.R., 1993, Sediment feed and recirculating flumes: A fundamental difference: *Journal of Hydraulic Engineering*, v. 119, p. 1192-1204.