Sediment transport - Most sediment transport is due to gravity. Things fall down hill in slumps, debris flows, and mudflows, and are transported downhill by fluids, like water, ice, and air. In some cases, processes like waves, currents, and wind transport sediment up a slope such as a beach or up mountain slopes. This transport goes against gravity and is driven by the processes of fluid dynamics. Fluid dynamics is the main topic of today’s and Wednesday’s lectures. We will come back to mass wasting processes in a couple of lectures when we talk about erosion. Mass wasting is important for transporting large volumes of sediment short distances, but fluid transport is required to move sediments long distances and is responsible for most sediment transport. To understand sediment transport, it is essential to understand the mechanics of fluid flow.

Fluid Flow

There are two end member ways fluids flow: 1) laminar flow and 2) turbulent flow. There is a wide gradation between these two end members, specifically flows that are called transitional flows.

Laminar Flow - In laminar flow, water molecules move in straight, parallel lines down current. If you add a dye to a fluid that is in the laminar flow regime, the dye would not mix into the water; it would streak out in an approximately straight line. Laminar flow is characteristic of very slow moving, shallow water, which is uncommon in nature, and flows where the fluid is very viscous, like glacial ice or mud flows that have little water.

Turbulent Flow - In contrast, turbulent flow is characterized by complex motion of water (or other fluid) molecules. Molecules move in all directions in bursts of upward, downward, and forward motion, and even some backward movement. There is abundant mixing in the flow, and an added dye would mix into the water very quickly. Most water and air flows are turbulent, at least to some degree. Turbulence is important for sediment transport because it makes grains easier to transport and tends to keep them moving longer.

Transitional Flow – Transitional flows have some characteristics of laminar flow and some of turbulent flow. For example, dye may take some time to mix into the flow, but it does mix.

Reynolds Number - Reynolds number predicts the extent of turbulence in a fluid based on how fast the fluid is flowing, the geometry of the flow (how deep and wide it is, etc.), and the density and viscosity of the fluid.

Viscosity is a measure of the resistance of a material to flow, i.e. how “thick” and easily deformed it is. Viscosity is sort-of like the amount of friction within a substance. Walking through air is easy, because there is not much friction between air molecules. Air has a low viscosity. Swimming is more difficult because the water drags on your body. This is due to the “friction” between adjacent water molecules, i.e. higher viscosity. Ice is more viscous and impossible to move through because of the crystal bonds between the water molecules. It flows, but it does so slowly.
Back to the Reynolds number. The variables for the Reynolds number (Re) are: flow velocity (u), characteristic length (l) which represents flow geometry, say river depth, fluid density (ρ), and fluid viscosity (µ). The book uses μ/ρ = v (kinematic viscosity). Re = (fluid inertial forces)/(fluid viscous forces) = l*u*ρ/µ. The units for this equation are typically (length)*(length/time)*(mass/length³)/(mass/(length*time)). These all cancel out to form a unitless number, if you choose the same set of units for each variable, which you should do.

Re can be viewed as inertial forces divided by viscous forces. Inertia is the resistance to change in motion, and inertial forces tend to make a bit of the fluid keep flowing in its own direction if it is misdirected from the main flow direction. Thus, high inertial forces tend to cause more turbulence. In contrast, viscous forces tend to suppress turbulence by damping out variations in motion through friction. Thus, a flow with a high viscosity (ice) tends to have less turbulence than a low viscosity flow (air).

The magnitude of Re gives an idea of whether the flow is turbulent or laminar. Turbulent flow has Re>2000 and laminar flow has Re<500. Flow with Re between 500 and 2000 is transitional and has some characteristics of laminar flow, but some turbulence as well. In most cases, water and air flows have high Re because l is large, u is high and µ is low. Rivers and wind storms are good examples of turbulent flow. In contrast, ice has a large µ and flows slowly (u is low), so it is laminar flow. Also, very slow, thin flows of water, such as water flowing off a smooth cement parking lot, has a low Re because l and u are small. Thus, it can be laminar. Laminar flow also occurs locally in turbulent flows right at the contact between the fluid and a smooth surface it is flowing over because u becomes very slow. This is really important for sediment transport.

Side note: For air, both the density and viscosity are low, so does Re tend to be high or low? The density of dry air at 1 atm at 15°C is 1.225 kg/m³, and its viscosity is 1.8x10⁻⁵ kg/(m*s), giving p/µ=68056 s/m² for air versus 1 s/m² for water. In a sense, the low viscosity of the air overcomes its low density to create turbulent flow.

Boundary Layer - There is boundary layer at the edge of every flow. Flows have an average speed in the middle, but friction with immobile surfaces slows down the speed of the flow right at the surface. This creates a boundary layer that has different flow characteristics than the rest of the flow. Right at the surface, the water does not move, but as you go higher into the flow it starts to move more like the average flow. The area of the flow that has a reduced speed is called the boundary layer. The thickness of the boundary layer depends on Re (i.e. the amount of turbulence) and the roughness of the surface the flow is moving past. If the main water flow is turbulent, it changes the velocity distribution because more of the high speed water is mixed down into the lower speed areas. Thus, the boundary layer tends to be thin. In laminar flow, there is very little mixing of high speed water into the boundary layer, so the boundary layer tends to be thicker.

Bed roughness or the characteristics of the surface also affect the boundary layer by affecting the amount of water that has to interact with the surface. A very smooth bed, say one made of mud, does not deflect the water at all, so there is less mixing and less turbulence. In contrast, a bed with pebbles or boulders disrupts the direction of water flow in the boundary layer. The water gets deflected around the pebbles. Water from above tends to take its place. Since it is moving faster, the average water speed in the boundary layer increases. Thus, a rough bed reduces the thickness of the boundary layer much like a more turbulent flow does.
**Viscous/Laminar Sublayer** - Within the boundary layer, right next to the surface, the viscous sublayer is present. \( Re = \frac{u \cdot l \cdot \rho}{\mu} \) - remember this defines the difference between laminar and turbulent flow. Because \( u \) (water speed) is very low at the base of the boundary layer, the \( Re \) is low there and the flow is laminar. The laminar flow part of the boundary layer is called the viscous sublayer, “viscous” because the viscous effects are more important than the inertial effects. (The fluid is NOT more viscous here.) Farther up in the flow, \( u \) is higher, so the flow is typically turbulent. If grains do not extend above the top of this layer, they do not “see” much turbulence, and they are less likely to be transported. If they do stick up beyond the viscous sublayer because the viscous sublayer is thin or the grains are large, the grains feel the force of the turbulent flow.

**Sediments and Flow**

**Key Concept:** The boundary layer determines the amount of “Bed Shear Stress” which corresponds to the forces that tend to roll particles along the bed and the pressure differences above and below the grain.

**Bed Shear Stress** - Sediments are affected by the difference in flow speeds from the bottom to the top of the boundary layer, gravity, and friction with the ground. Bed shear stress is a measure of these differences; it is the differential force that a grain feels from top to bottom. In a thick boundary layer, the speed of water flow at the top of the grains is not much different from the bottom, so bed shear stress is lower, and sediment is less likely to move. In a thin boundary layer, bed shear stress is much higher, and grains are likely to roll down flow. Thus, more turbulent flow (with a thinner boundary layer) results in more sediment transport. Bed shear stress increases with increasing fluid density, slope, and turbulence (water depth and flow speed). For example, water is better at moving sediment than air because it has a higher density and exerts a larger bed shear stress than air can. Steep rivers are more efficient at moving sediment because the bed shear stress is greater because gravity helps increase it more than in gently sloping rivers. Also, deep, fast rivers move more sediment than shallow, slow rivers because of more turbulence and higher flow speeds in the boundary layer in fast rivers.

**Bernoulli Effect**

Bed shear stress tends to push grains along a bed, but grains also get picked up into the flow. How?

**Key Concept:** Pressure difference “pulls” grains off the bed (Bernoulli Effect). Pressure difference comes from a difference in water (or air) speed above and below the grain.

**Pressure and Water Speed:** Pressure is due to the collision of molecules with an object and the force the collisions exert on the object. In a still fluid, the force is equal in all directions. You do not notice the pressure that the air in this room is exerting on you at 1 atm or 14.7 lb/in² (which is actually a lot!) because you are used to it, and it is uniform. However, in a moving fluid, the force an object feels is not uniform because there are more collisions on one side than the other. For example, a strong wind is “strong” because the air molecules are colliding with you and exerting a significant force. The same is true for grains, and it is that pressure that pushes them along the bed. What about the sides? Because the water molecules are moving quickly downstream, there are few collisions with the grain, so there is less pressure. It may not be as low as the pressure downstream, but it is less. We do not notice this effect in the wind, but it is there. In fact, it is so important that airplanes can fly - it is the same effect. Airplane wings are designed to provide “lift” by having the air move faster across the top of the wing than across the bottom creating a big enough pressure difference that the weight of the plane can be supported. The necessary speed difference is why we need runways: the plane has to be going fast enough relative to
the air that the pressure difference is huge. Water flow speeds are much lower, so boulders
do not tend to be picked up in rivers, but the pressure difference is there. The 12/26/04
tsunami had sufficient pressure differences from its rapid flow speed and high turbulence to
move boulders, cars, etc. when it hit many of the beaches along the Indian Ocean.

The Bernoulli Effect is the pressure difference between the top and bottom of a grain. The
book does the derivation mathematically with energy, but it is saying essentially the same
thing: If a grain is sitting on the bottom, water is moving faster over the top of the grain
than the bottom because of the increase in water speed away from the bed in the boundary
layer. Thus, the pressure is lower above the grain. If this pressure difference is big enough
to overcome gravity, the grain will lift off the bed (like an airplane). Once it is off the bed, it
moves downstream with the flow, falling back to the bed as the pressure difference above
the grain becomes no longer large enough to support the weight of the grain.

**Concept Summary**
Laminar vs. Turbulent flow
Boundary Layers and Bed Shear Stress (sediment transport by rolling)
Bernoulli Effect and “Lift” (sediment transport by entrainment)