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Turbidity Currents

Comparing Theory and Observation in the Lab

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PURPOSE OF ACTIVITY

The goal of this exercise is to enable students to explore some of the controls on fluid flow by having them simulate turbidity currents using lock-gate exchange tanks while varying the bed slope and the turbidity. Observational data are compared with theoretical relationships known from the scientific literature. The exercise promotes collaborative/peer learning and critical thinking while using a physical model and analyzing results.

AUDIENCE

This activity has been used four times since 2012 in a combined upper-level undergraduate/graduate class in the annually offered Sedimentology & Stratigraphy course at Kent State University. The majority of the students were undergraduates working toward BS degrees in geology or environmental geology. The remainder of the class was composed of BA students in geology or Earth science, or first-year graduate students who had not completed a similar course as undergraduates. Graduate students were asked to cooperate in one group, and the undergraduates were divided into multiple groups of about four to five students each. Prior to this activity during class periods, students were introduced to background theory and observation regarding turbidity currents, the **Reynolds**, **Froude**, **Rouse**, and **Richardson numbers**, and settling velocity relationships (**Stokes Law** and the **Impact Law**) using the course textbook (Boggs, 2006) and supplemental materials.

Students should have a solid basis in algebra and knowledge of how to enter formulas in Microsoft Excel or a similar spreadsheet program to be successful in comprehending and completing this exercise.

WHAT THE ACTIVITY ENTAILS

During two lab periods of two and half hours duration, students use a physical model to simulate turbidity currents flowing over differing bottom slopes. They are given a Plexiglas tank and gate, a wooden stand to change the bottom slope, a drill with a paint stirring attachment to generate turbulence, sediment, rulers, and other equipment as described below. They determine how much sediment to add to vary the density of the flow. The tank is filled with water of a known temperature (and thus known density and viscosity). The gate is inserted into the tank to provide a known volume of water in the lock behind the gate. While the drill is used to generate turbulence in the lock, a known mass of sand is poured into the lock. The lock gate and drill are then removed, allowing the simulated turbidity current to flow down the tank. Students use smart phones or cameras to videotape and record the duration of the flow during the simulation. They record data needed to characterize the flows using sediment transport and basic fluid dynamics equations, and they write group reports of their findings. The simulations are conducted during the first lab period. The group analyzes the data during the second lab period and outside of class. The instructor and the teaching assistant are available to support the group learning experience during the lab periods, providing assistance with the calculations and background on dimensional scaling.

DIMENSIONAL SCALING AS A MEANS OF COMPARING FLUID FLOWS

We can employ dimensional scaling to compare the properties of various fluid flows. When the assumptions underlying these simple theories are met, the results match empirical observations. A current can pick up sediment off the bottom when the boundary shear stress (the force acting on the particle in the direction of the current) exceeds the drag on the particle. How the particle is transported depends on its density, size, and the properties of the fluid flow. Larger particles are transported as bed load, rolling or scraping along the bottom. Smaller, less dense particles saltate (bounce along the bottom), and finer grains are transported by suspension. The finest particles remain in suspension the longest and are referred to as the wash load. The **Rouse number** relates the settling velocity of the particle to the boundary shear stress to estimate the manner of transport. The **Reynolds number**, the **Froude number**, and the **Richardson number** define the characteristics of the fluid flow. The Reynolds number can be used to determine the relative importance of turbulence and laminar flow. The Froude number is used to determine if the flow is rapid or tranquil, and the Richardson number provides an estimate of the stability of the flow, which in this context relates to how effectively the turbulence can be damped by the flow.

BACKGROUND

Turbidity currents form one class of sediment gravity flows (e.g., Middleton, 1993). They are an important mechanism of sediment transport in fluid environments (lakes and the ocean) as they move coarse-grained material from the margins to the interiors of basins. The ocean's broad, flat abyssal plains are formed in part by the action of turbidity currents. Submarine canyons are carved by their repeated flow into the deep sea (Figure 1a).

Turbidity currents can be triggered by submarine failures such as a slumps and slides or by earthquakes or other disturbances such as storm-induced waves (e.g., Meiburg and Kneller, 2009). The supporting mechanism for the flow is turbulence. The current consists of sediment-laden, turbid water that travels downslope. As the sediment gravity flow accelerates downslope, it scours the bottom, entraining fluid from above and sediment from below. The flow consists of a well-defined head, body, and tail.

A turbidite deposit forms as the sediment drops out of suspension or bedload transport ceases. Turbidites are composite graded beds that include a variety of sedimentary structures related to differences in the flow regime (Pickering et al., 1986). Turbidites are capped by thin drapes of silt or clay. Coarse, proximal turbidites, which are deposited near the initiation points of turbidity currents, consist of thick beds of coarse-grained material over scoured bases. Intermediate-grained, medial turbidites are often expressed in the classic Bouma sequence (Figure 1b), consisting of scoured bases and several graded crossbeds sandwiched between thick basal sand and thinner silt or clay caps (Bouma, 1964; Bouma and Brouwer, 1964). Fine-grained, distal turbidite deposits exhibit smaller grain sizes and may lack high energy, cross-bedded features, making them difficult to differentiate from hemipelagic or pelagic sedimentation.

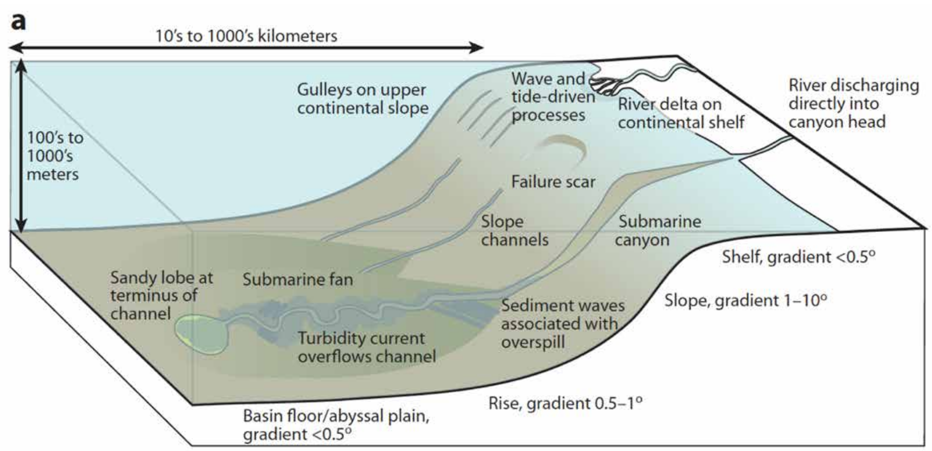
This laboratory exercise allows students to generate turbidity currents under controlled conditions using fine-grained sediment to create the turbidity that drives the transport (Figure 2). This activity provides a more concrete connection to the actual sediment transport and deposition of the flows observed in nature than simulations using water of differing densities or colored with dye, or fluids of different densities or viscosities (such as milk) to generate the turbid flow.

We can measure the velocity of the flow empirically if we know the distance traveled per unit time:

$$U_{obs} = {}^{d}\!/_{t} \tag{1}$$

Considerable theoretical work has evaluated the factors that contribute to flow velocity (e.g., Middleton, 1993; Meiburg and Kneller, 2009; An, 2010). As the mass of sediment suspended in the flow increases, so does the density of the turbid flow relative to that of the ambient low-density water above it, and thus its velocity increases. We can estimate the flow velocity of the head using the theoretical relationship

$$U_{head} = F_r \sqrt{\left(\frac{\rho_t}{\rho} - 1\right) gh} \tag{2}$$



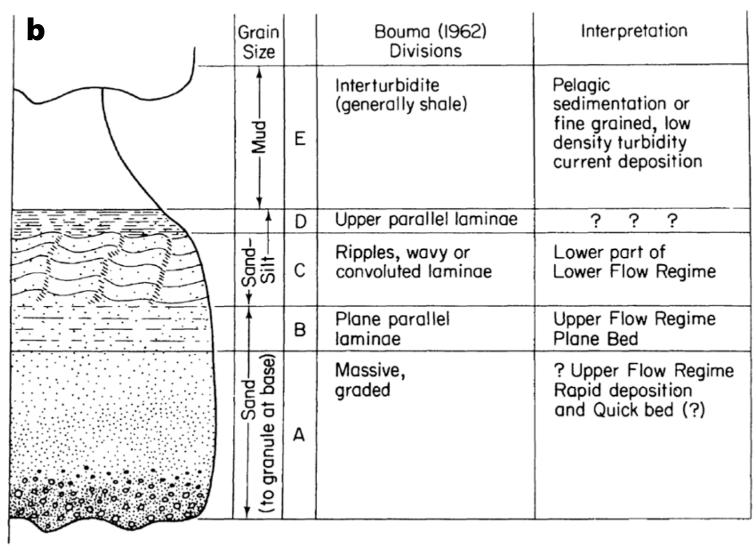


FIGURE 1. (a) Schematic of the marginal environment in marine and lacustrine settings where turbidity currents arise and turbidites are deposited (Source: Meiburg and Kneller, 2009). (b) Definition of the classic Bouma sequence, one of several classification schemes that have been proposed for turbidite deposits. Note that proximal turbidites will exhibit coarser beds than distal turbidites, and not all beds in the Bouma sequence are present in all turbidite deposits (Source: Middleton, 1993).

Notice that the flow velocity of the head is proportional to the density difference between the higher density, turbid, sediment-laden water in the flow (ρ_t in kg m^{-3}) and the lower density, ambient water (ρ) multiplied by the acceleration of gravity (g in m s^{-2}) and the height of the turbidity current (h in m). Prior research indicates the Froude number for the flow (F_r)—the ratio of inertial to gravitational forces acting on the flow—yields the proper coefficient of proportionality to relate the flow velocity to the density contrast (e.g., Kneller and Buckee, 2000).

The Froude number for a turbidity current is defined as

$$F_r = U_{head} \Big/ \sqrt{\left(\frac{\rho_t}{\rho} - 1\right) gh} \quad (3)$$

where U_{head} is the mean velocity of the turbid flow (in m s^{-1}). When F_r is greater than 1, the flow is rapid, while for values less than 1, the flow is tranquil. Studies suggest that appropriate Froude numbers for turbidity currents range between $F_r = 2^{-1/2}$ to 1 for turbulent flow in deep water, while flows in finite water depth follow a relationship in which $F_r \propto h/H$, where h is the height of the turbulent flow, and H is the water depth (e.g., Middleton, 1993; Meiburg and Kneller, 2009). In addition to the Froude number, the properties of turbidity currents can be described using three additional dimensionless numbers, the Reynolds number, the Rouse number, and the Richardson number.

The Reynolds number (R_e) is dimensionless. It relates the turbulent forces driving the flow (numerator term) to the dissipative, frictional forces that diminish it (denominator term). For R_e greater than 2000, the flow is turbulent. For values less than 2000, the flow is laminar. The R_e number is defined as

$$R_e = \frac{\rho_t U_{head} h}{\mu} \quad (4)$$

where ρ_t is the density of the turbid fluid (in kg m^{-3}), U_{head} is the mean velocity of the head of the turbidity current (in m s^{-1}), h is the height of the turbidity current head, and μ is the dynamic (or molecular) viscosity of the water (in kg m^{-1}s^{-1}), which depends on the temperature of the water. The viscosity and density of freshwater based on its temperature can be taken from a plot (Figure 3) or calculated from an online form (http://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html). Given a measure of the water temperature, the form can be used to look up the density and viscosity of the freshwater in the tank. To calculate the density of the turbid, sediment-laden water, students need to account for the mass and volume of sediment added to the freshwater, which increases the density of the turbid mixture.

The Richardson number, which determines the stability of the flow, is defined as

$$R_i = \frac{\left(\frac{\rho_t}{\rho} - 1\right) gCh}{2u_*^2} \quad (5)$$

where C is the volume concentration of sediment in the flow (the ratio of the sediment volume to the volume of water in the lock),

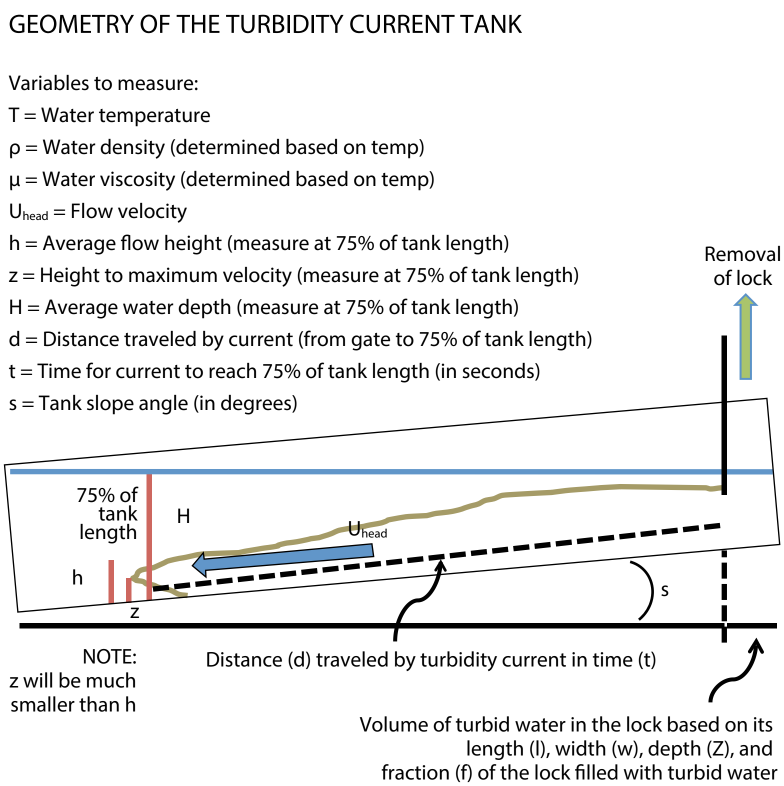


FIGURE 2. Lab handout documenting tank geometry and variables to measure.

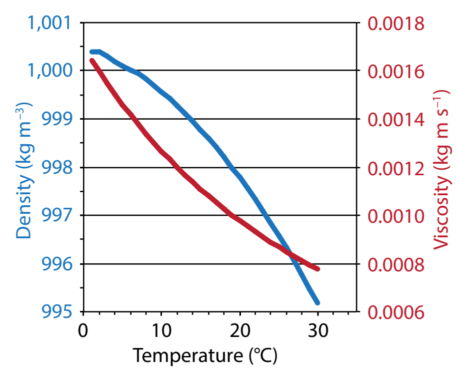


FIGURE 3. The temperature dependence of density and dynamic viscosity for freshwater. Values obtained from: http://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html.

u_* is the shear velocity of the flow (in m s^{-1}), and the other variables are as defined above. The shear velocity in this context is a measure of the rate of change of the velocity of the flow with distance from the bottom boundary, where friction causes the velocity to go to zero. This is the so-called "no slip" constraint. The shear velocity (u_*) is defined as

$$u_* = \sqrt{\frac{\tau}{\rho_t}} \text{ and } \tau = \mu\frac{\partial u}{\partial z} \text{ thus,} \qquad \text{by substitution: } u_* = \sqrt{\frac{\mu}{\rho_t}\frac{\partial u}{\partial z}} \tag{6}$$

in which τ is the bottom boundary shear stress, a measure of the force acting on the sediment particles; ρ_t is the fluid density of the turbulent flow (in kg m^{-3}); μ is the dynamic viscosity of water (in kg m^{-1}s^{-1}); and $\partial u/\partial z$ is the vertical velocity gradient, the rate of change of velocity with depth (in s^{-1}). Without sophisticated equipment, measurements of $\partial u/\partial z$ and u_* are difficult to quantify, but they can be measured with acceptable error. We can use the "no slip" assumption—which states that the velocity must be zero at the bottom boundary of the flow—in conjunction with the observed estimate of U to approximate ∂u. This will provide a crude, two-point estimate of the vertical velocity gradient from zero at the base of the flow to U, the observed mean velocity of the head. That provides the numerator, ∂u, for the vertical velocity gradient. We will have to make an estimate of the depth where the velocity profile reaches the mean flow value. We will assume that it is equal to the flow height as it rides up over the clear water in front of the turbidity current to estimate ∂z based on our observation of the height of the leading edge of the head of the turbidity current, which we define as z. Thus, we can estimate R_i and plot R_i vs. slope to see how they are related.

With a description of the these flow characteristics, we also can determine the manner in which sediment is transported by the turbid flow using the Rouse number, which relates the settling velocity of a grain to the shear boundary stress acting on it. The Rouse number P is defined as

$$P = \frac{w_s}{\kappa u_*} \tag{7}$$

where w_s is the settling velocity of particles, κ is the von Kármán constant (generally taken as 0.41, see Gaudio et al., 2010), and u_* is the shear velocity (in m s^{-1}), as described above. With a von Kármán constant of 0.41, a Rouse number <0.8 indicates "wash load" transport of very fine sediment. Values in the range of 0.8 to 1.2 indicate "suspended load" transport, values of 1.2 to 2.5 indicate that 50% of the transport is by suspension, and values >2.5 indicate bedload transport (Dade and Friend, 1998; Udo and Mano, 2011).

For the settling velocity (w_s in m s^{-1}), we will use the Impact Law, defined as

$$w_s = \sqrt{\frac{4}{3C_d}\left(\frac{\rho_t}{\rho} - 1\right) gd} \tag{8}$$

where C_d, is a drag coefficient, ρ_t is the density of the turbulent flow (in kg m^{-3}), ρ is the density of the fluid (in kg m^{-3}), g is the acceleration of gravity (in m s^{-2}), and d is the diameter of an average spherical sediment particle (in m). To estimate C_d, we need to calculate a particle Reynolds number (Re_p) in which the density and length scale are based on the properties of the grain:

$$Re_p = \frac{\rho_t w_s d}{\mu} \tag{9}$$

We can then determine the drag coefficient C_d for particles of specific shape from an empirical curve of Re_p vs. C_d. This poses an immediate problem, however, because we see from Equation 9 that the Re_p itself depends on w_s, but we need to know C_d to determine w_s using Equation 8. One solution to this problem is to iteratively solve for Re_p by using initial estimates of C_d and w_s and then to replace values of C_d and w_s iteratively until the relationship converges on a solution with minimal errors in C_d. For operational purposes, we will define the convergence as a $<10^{-4}$ difference in the initial and revised estimates of C_d. Once students know C_d and w_s, they can determine the Rouse number using Equation 7 (see also Figures 4 and 5). We provide online supplemental materials that include a worksheet detailing what variables to measure and a Microsoft Excel spreadsheet that can be used to solve Equations 8 and 9. Figure 2 includes a sketch of the tank and list of variables to measure during the lab.

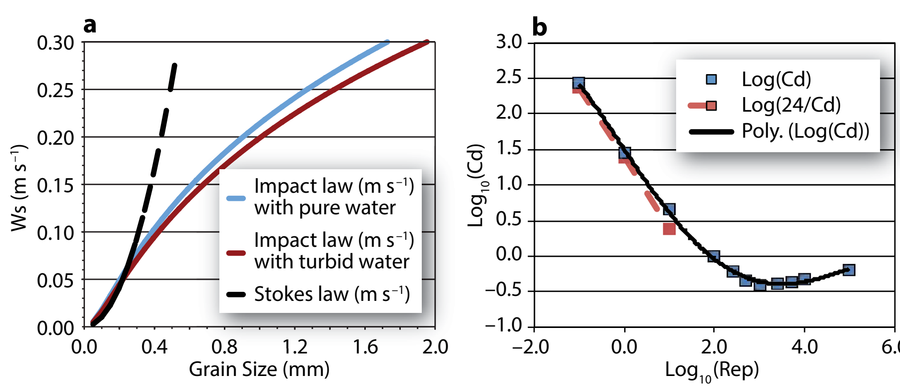


FIGURE 4. (a) The relationship between w_s and grain size under the Impact law with pure and turbid water and under Stokes law. (b) The relationship between the $\log_{10}$-transformed drag coefficient (C_d) and the $\log_{10}$-transformed particle Reynolds number (Re_p) plotted as blue-filled squares. The red-filled squares depict an approximation for the drag coefficient applicable for Stokes settling law, $Re_p \sim 24/C_d$. The black curve provides a fourth-order, least-squares polynomial fit between the log-transformed C_d and Re_p data: $y = -4.56 \times 10^{-3}(x^4) + 4.24 \times 10^{-2}(x^3) + 2.59 \times 10^{-2}(x^2) - 9.54 \times 10^{-1}(x) + 1.49$.

CRITICAL THINKING QUESTIONS

The students should consider the following questions as they analyze their results. They should read the paper by Cantero et al. (2012) to help answer some of the research questions.

All Students (Equations 1–6)

How closely does the observed velocity of the turbidity current follow the theoretical relationships based on the Froude number? If the results are different, how can this be explained?

The data the students collect will allow them to calculate U_{head} and F_r in different ways for comparison. Some differences between theory and observations will arise from the simplifying assumptions on which the theory is based. Others will arise from observational error. Students should calculate residuals between the observed and theoretical velocity given by Equations 1 and 2 (i.e., $U_{res} = U_{obs} - U_{head}$). They can compare the observed F_r value with the range of expected values or the scaling law for turbidity currents in finite depth.

How might the results change if saltwater were used instead of freshwater?

Use of saltwater will decrease the density contrast between the turbid water and the ambient water, which would result in slower flow rate for the same sediment concentration. However, the denser salt water may support a higher sediment concentration prior to turbulent damping.

How will the results vary as grain size is increased?

Increasing the sediment grain size will make it harder to keep the sediment in suspension. This will result in a greater disparity between the observational and theoretical calculations as much of the sediment will drop out of suspension sooner, resulting in flow that is much less dense than anticipated by the initial conditions.

Which variables are likely to introduce the greatest error into each equation?

One of the most important factors determining the flow velocity is whether the sediment remains in suspension, maintaining the density contrast of the flow. Measurement of z, the height of the trailing edge, is difficult because this height is often a few millimeters off the bottom. The best way to capture that height is with a camera zoomed in on a ruler taped to the side of the tank.

Do the turbidity currents generated follow the R_i scaling function of 1/S described in Cantero et al. (2012)? If the results are different, how can this be explained?

This result can be measured using this equipment, but the results are tank dependent. Each group should make measurements at multiple slopes with their tank. The students need to be consistent with their procedures, make sure to measure the temperature in their tank, and hold the sediment concentration of the turbidity currents constant between runs.

Graduate Students (Equations 7–9)

What is the settling velocity of the average-sized grain in the turbidity current and what is the mode of sediment transport by the turbidity current using the Rouse number?

These calculations require use of the supplemental Excel spreadsheet provided online. We use sediment of a known grain size (#110 sand; ~130 μm) obtained from a local gravel supply yard. The grain size can also be measured in the lab using a particle size analyzer or sieve set. Students could also determine the grain size from settling experiments (e.g., see Spalding et al. [2009] and associated references).

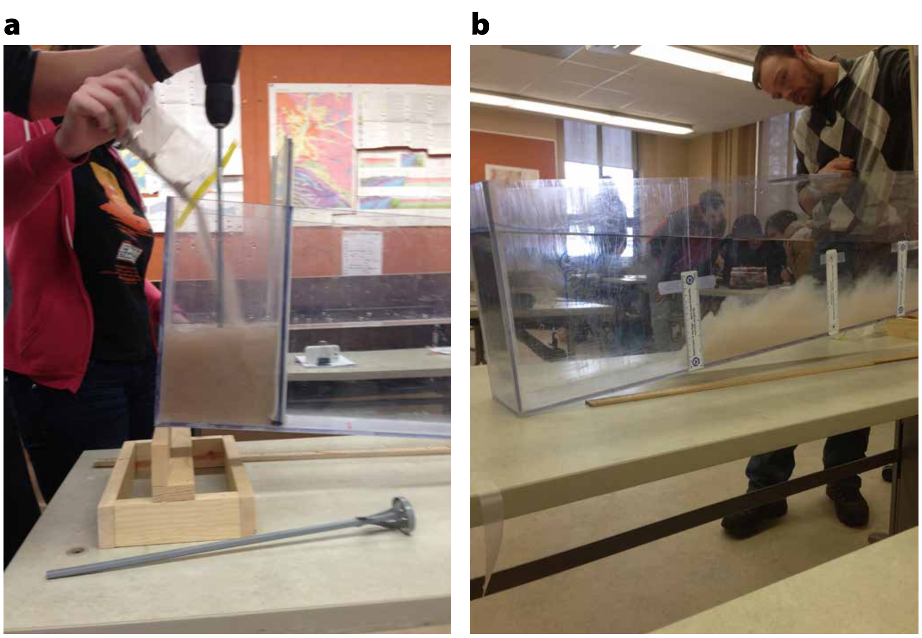


FIGURE 5. (a) Adding sediment to the tank while stirring with a drill to generate turbulence in the flow. The maximum slope of 6° is used here. (b) Example of a turbidity current generated in the lab.

SOME GENERAL COMMENTS ON THE LAB

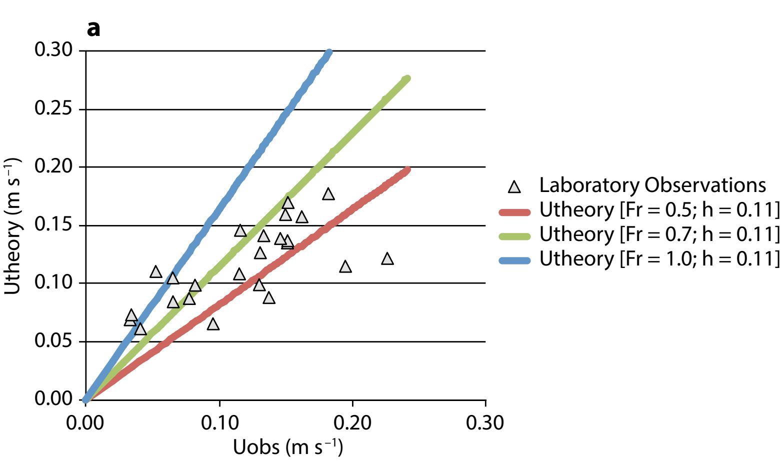
The tanks used in this lab were each constructed from single sheets of 3/8" thick Plexiglas, cut on a table saw to size. The edges of the Plexiglas should be wrapped in painter's tape along the cutline to prevent splintering. Use safety precautions (hold downs, push sticks, eye and hearing protection) while cutting the material. The seams were welded with acrylic cement, and then sealed with silicone caulk. Cement a piece of Plexiglas across part of the top of the tank at the center to give the tank rigidity. Apply weather stripping along the edges of the Plexiglas gate to prevent leakage between the lock and the main tank before the start of each simulation.

Given a tank with dimensions of 1.20 m long, 0.30 m tall, and 0.12 m wide and a lock positioned 0.1 to 0.2 m from the upslope end of the tank, we have conducted simulations using sand masses in the range of 100–600 g. In a lock that is half full with water, this works out to concentrations that range from ~25 g L^{-1} on the low end up to ~350 g L^{-1} on the high end. The precise sediment concentration varies with each simulation depending on where the lock is placed in the tank, the slope of the tank, how much water is added, and the amount of sediment employed. It is difficult to keep all of the sand in suspension at the upper limit of this range. Students should start their source of turbulence (a drill equipped with a stirring paddle) prior to adding the sediment to the tank (Figure 5a), and then remove the gate and the drill at the same time to start each simulation. Adding the sediment first, and then applying turbulence, results in lower mean velocities for the turbidity currents because it is difficult to re-suspend all of the sediment in the tank. Furthermore, the gate should be removed quickly (and perpendicularly) to avoid formation of surface waves at the water-air interface, which then interact with the turbidity current, causing it to surge and slow as the waves reflect in the tank (Figure 5b).

Cantero et al. (2012) discussed differences in the nature of turbulence in continuously flowing fluvial streams and surge-like turbidity currents. They argue that the principal difference between these two systems is the nature of the forcing: turbidity currents are generated by a single event (such as an earthquake or individual storm). The energy available to a turbidity current decays rapidly (in comparison to the more continuous forcing of the seasonal hydrograph) due to friction, entrainment of surrounding low-density water, and decreasing slope.

Plotting the observed velocity of the turbidity currents (Equation 1) against the theoretical velocity (Equation 2) provides an estimate of how closely the flows follow the theoretical relationship (Figure 6a). The students can plot the data vs. a range of F_r numbers, selecting the average observed F_r and flow height (h) to determine which criteria best fit the data. In general, the results indicate that $R_i \propto 1/S$, although there is considerable uncertainty due to changes in density contrast between runs and observational error (Figure 6b).

The principal sources of error are associated with measuring z (height to maximum velocity of turbidity current) accurately and keeping the sediment in suspension prior to the removal of the gate. As described above in the section on estimating shear stress, z is typically on the order of a few millimeters and thus should be estimated from video observations. At low sediment concentration (~25 g L^{-1}, in our case), h may also be difficult to measure because it can be hard to define the boundary between the turbid flow and the ambient water above. Attaching white paper to the far side of the tank helps to make the flow more visible; food coloring could also be added to help the turbidity current stand out from the background flow. It is important that the gates fit the tank snugly and be watertight. If the gate leaks sediment or water into the tank before it is removed, then the initial apparent density contrast used will cause overestimation of the actual density contrast if sediment is lost, or underestimation if water is gained. In such cases, the observed flow will not match the theoretical velocity used for comparison. If the initial sediment concentration is too high (>350 g L^{-1}, in our case), the volume concentration of the flow may be above the limit that can be sustained by the turbulence supplied by the drill. When this happens, the flow becomes self-damping (see Cantero et al., 2012), and much of the sediment drops out of suspension once the gate and source of turbulence are removed. The observed flow velocity in these cases will be too slow relative to the apparent density contrast based on the amount of sediment initially supplied because the turbidity current flowing down the tank is actually much less turbid than the initial conditions. Finally, if the changes in density



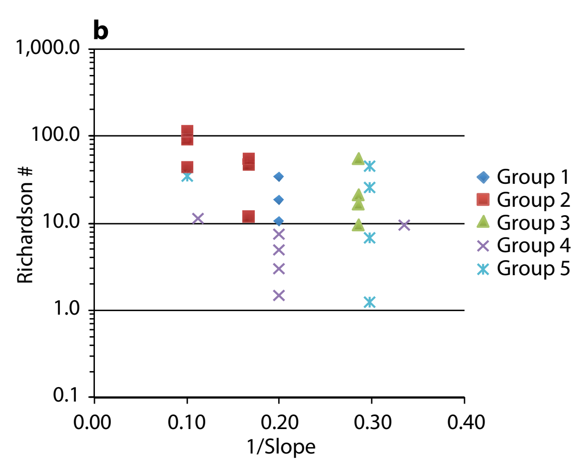


FIGURE 6. (a) Observed versus theoretical velocity of turbidity currents for different Froude numbers. (b) Relationship between R_i (log-scale) and $1/S$ for typical simulations.

contrast and slope are correlated, then the theoretical value for F_r for the flow approaches or exceeds 1, and the inverse relationship between R_i and S may be obscured by the change in density contrast. In these cases, R_i will not follow an inverse relationship with S. However, the observed F_r value in these flows may underestimate the true value because the density contrast is overestimated if sediment drops out of suspension too soon.

To get the most out of the exercise, students should have strong quantitative backgrounds and adequate preparation. The data analysis portion of the lab can be challenging to students because they must understand that results from the various tanks may differ due to the interaction of various sources of error (e.g., variable sediment additions, differences in water temperature and thus density and viscosity, slope angle, and amount of leakage—if any—prior to flow initiation). The students sometimes have difficulty calculating the density of the turbid flow, which is a weighted average of the density of the water and the sediment in the flow. This type of assignment, however, helps them to make the transition from concrete thinkers to abstract thinkers by improving their critical thinking skills and helping them to grasp how to deal with uncertainty.

MATERIALS

- Turbidity current tank (1.20 m long, 0.30 m tall, and 0.12 m wide)
- Gate (0.35 m tall by 0.12 m wide)
- Grease pens or erasable whiteboard markers to mark the sides of the tanks
- Stand to change the slope of the tank from 0° to 2°, 4°, and 6°
- Sediment with a known size distribution (i.e., determined using sieve analysis or an automated tool, such as a Malvern Mastersizer 2000)
- Scoop
- Plastic bag to hold sediment while measuring mass
- Drill equipped with a stirring apparatus to power the current
- Rulers, protractors, and meter sticks
- Scale
- Buckets for sand and water
- Thermometer
- Stopwatch (or phone with timer function)
- Still and video cameras or smart phone

ACTIVITY

1. During the first lab period, provide a short description of the project tasks and then form the student groups (~30 minutes).
2. Students develop their procedural designs to measure the parameters needed and to determine the constants needed to answer the research questions (~20 minutes).
3. Students discuss their plans with the professor and the TA (~10–15 minutes).
4. Provide materials needed to perform the simulation so that students can fill the tanks with water and do test runs to become familiar with the method. Tasks should be divided among the members of each team (~15 minutes).
5. Students carry out simulations, making sure to collect the data listed below (2–3 hours). The tanks should be emptied and cleaned between simulations, with the sand saved in a bucket and dried for future use. Groups generally complete between two and four runs during a lab period of 2½ hours.
6. Before the second lab period, students should read the article by Cantero et al. (2012), and there should be a class discussion of it (~30 minutes).
7. During the second lab period, the groups can work on calculations and report writing. Reports should include an introduction, a methods section, results, discussion, conclusion, and what could be changed if there were an opportunity to do the simulation again. Videos can be uploaded to an ftp space or dropbox (one to two weeks following the lab).

Each group will need to measure or estimate and record the following for each simulation:

Prior to Simulation

1. Slope of tank measured in degrees (°) with a protractor or determined trigonometrically: slope % = 100*(rise/run), then convert to slope (°) = atan*(slope %/100).
2. Mass of sediment added (determine the sediment volume based on assumed density of quartz). Remember to convert units. Use a sediment mass concentration (mass of sediment divided by mass of water in the lock) in the range between 25 and 350 g L^{-1}.
3. Water temperature. To get water density [ρ], molecular viscosity [μ], and the mass of water in the lock based on its density and volume, see Equation 4.
4. Dimensions of the lock behind the gate to determine the initial volume of turbid water in order to estimate the density of turbid water: ρ_t = (sediment mass + water mass)/(sediment volume + water volume).
5. Water depth, H.

During Simulation

1. Height of turbidity current, h.
2. Time s in seconds to reach a specific constant distance, d (from this, we get: $U_{obs} = d/s$).
3. Height above the bottom of the leading edge of the turbidity current, z.

After Simulation

1. Calculate U empirically as: $U_{obs} = d/s$.
2. Use U_{obs}, μ, ρ_t, and z to estimate u_* from Equation 6.
3. Compare U_{obs} with the theoretical relationships for U_{head} from Equation 2 and calculate values for each of the other equations. Calculate residuals ($U_{res} = U_{obs} - U_{head}$) to estimate the difference between theory and observation.

ALTERNATIVE APPROACHES

The more complicated, graduate student portion of the lab (Equations 7–9), exploring the Rouse Number and settling velocity, can be omitted to shorten the lab or if it is not possible to measure the grain size due to logistical constraints.

An (2010) provides an alternative formulation for Equation 2, which deals with the bottom slope explicitly:

$$U = F_r \sqrt{\left(\frac{\rho_t}{\rho} - 1\right) gh * \cos(S)} \qquad (2b)$$

In the physical model that we employ, the slope is generally less than 6°, yielding cosine values close to 1, and thus can be neglected, which yields Equation 2 above.

An alternative approach models the flow using a modified version of the Chézy Equation for steady uniform flow (see Middleton, 1993; Kneller and Buckee, 2000, for further details):

$$U = \sqrt{\frac{8\left(\frac{\rho_t}{\rho} - 1\right) gh * \sin(S)}{f_b + f_i}} \qquad (2b)$$

The terms in the denominator of Equation 2b are the Darcy-Weisbach friction coefficients for the lower and upper boundaries of the flow, respectively, with $f_i > f_b$. These friction coefficients depend on the shear boundary stresses at the lower and upper bounds of the flow, as well as the Froude number of the flow. As a result of this interdependence, they are difficult to measure directly. Cantero et al. (2012) argued that $(f_i + f_b)$ is on the order of ~0.01 for large turbidity currents, but a value two orders of magnitude greater (~1.0) is required to fit the data from our tank configuration, which differs from their design in that our tank has an open top.

The viscosity of the water also depends on the sediment concentration (see Equation 1 in Kneller and Buckee, 2000) and can account for differences in viscosity by as much as an order of magnitude, but we will neglect this effect for simplicity, given the errors in estimating sediment concentration (as discussed above).

SUPPLEMENTARY MATERIALS

Supplemental materials for this activity, including the laboratory instructions, worksheet, and accompanying spreadsheet, are available online at http://dx.doi.org/10.5670/oceanog.2015.73.

REFERENCES

An, R.-D., and J. Li. 2010. Characteristic analysis of the plunging of turbidity currents. *Journal of Hydrodynamics* 22:274–282, http://dx.doi.org/10.1016/S1001-6058(09)60055-X.

Boggs, S. Jr. 2006. *Principles of Sedimentology and Stratigraphy*, 4th ed. Pearson Prentice Hall, Upper Saddle River, NJ, 662 pp.

Bouma, A.H. 1964. Ancient and recent turbidites. *Geologie en Mijnbouw* 43:375–379.

Bouma, A.H., and A. Brouwer, eds. 1964. *Developments in Sedimentology 3: Turbidites*. Elsevier, Amsterdam, 264 pp.

Cantero, M.I., A. Cantelli, C. Pirmez, S. Balachandar, D. Mohrig, T.A. Hickson, T.-H. Yeh, H. Naruse, and G. Parker. 2012. Emplacement of massive turbidites linked to extinction of turbulence in turbidity currents. *Nature Geoscience* 5:42–45, http://dx.doi.org/10.1038/ngeo1320.

Dade, W.B., and P.F. Friend. 1998. Grain-size, sediment-transport regime, and channel slope in alluvial rivers. *The Journal of Geology* 106:661–676, http://dx.doi.org/10.1086/516052.

Gaudio, R., A. Miglio, and S. Dey. 2010. Non-universality of von Kármán's κ in fluvial streams. *Journal of Hydraulic Research* 48:658–663, http://dx.doi.org/10.1080/00221686.2010.507338.

Kneller, B., and C. Buckee. 2000. The structure and fluid mechanics of turbidity currents: A review of some recent studies and their geological implications. *Sedimentology* 47:62–94, http://dx.doi.org/10.1046/j.1365-3091.2000.047s1062.x.

Meiburg, E., and B. Kneller. 2010. Turbidity currents and their deposits. *Annual Review of Fluid Mechanics* 42:135–156, http://dx.doi.org/10.1146/annurev-fluid-121108-145618.

Middleton, G.V. 1993. Sediment deposition from turbidity currents. *Annual Review of Earth and Planetary Sciences* 21:89–114, http://dx.doi.org/10.1146/annurev.ea.21.050193.000513.

Pickering, K., D. Stow, M. Watson, and R. Hiscott. 1986. Deep-water facies, processes and models: A review and classification scheme for modern and ancient sediments. *Earth-Science Reviews* 23:75–174, http://dx.doi.org/10.1016/0012-8252(86)90001-2.

Spalding, H.L., K.M. Duncan, and Z. Norcross-Nu'u. 2009. Hands-on oceanography: Sorting out sediment grain size and plastic pollution. *Oceanography* 22(4):244–250, http://dx.doi.org/10.5670/oceanog.2009.117.

Udo, K., and A. Mano. 2011. Application of Rouse's sediment concentration profile to aeolian transport: Is the suspension system for sand transport in air the same as that in water? *The Journal of Coastal Research* 64 (Proceedings of the 11th International Coastal Symposium):2,079–2,083, http://www.cerf-jcr.org/images/stories/2011_ICS_Proceedings/SP64_2079-2083_K._Udo.pdf.

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