# Dam Fun: A Scale-model Classroom Experiment for Teaching Basic Concepts in Hydrology and Sedimentary Geology

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## ABSTRACT

This paper describes a scale-model classroom experiment that illustrates several fundamental concepts in sedimentary geology and hydrology, speaks to relevant societal issues, and provides an inexpensive and straightforward demonstration for single to multiple classroom period(s). The model simulates the cross-section of an earthen dam and reservoir system using a flat acrylic tank (ant farm dimensions). The dam is constructed by pouring sand into the middle of the tank. During this process, visible grain-size sorting occurs, and the concepts of gravitational settling, superposition, and angle of repose are illustrated. Water is poured into the reservoir side of the dam, and the concepts of porosity and permeability are illustrated as water seeps into the dam. The initial water movement is dominated by capillary flow in the fine-grained layers, whereas flow in the saturated state is dictated by differences in permeability and hydraulic head. Water is observed to move uphill, and then downhill, following bedding orientation. The possibility of toxic waste storage in dams is evaluated by injecting water with brightly colored dye into the dam. The dye illustrates the movement and ultimate fate of the 'toxic waste', and forms a coherent pool on the downstream side of the dam. The grand finale occurs when the dam is overtopped by water and catastrophically fails. The experiment is suited for teaching K-12 and college undergraduate audiences, has been universally well received by students and teachers, and leaves lasting visual impressions of processes in sedimentology, hydrology, and environmentally relevant water issues.

## INTRODUCTION

An important goal of education in the geosciences is to instill in students an understanding of process. Geologic phenomena are time-transgressive events that take place in four dimensions, but are typically described using dimensionless devices such as words and mathematics. Students are variously adept at transforming ideas taught through these devices into visualized understandings of the concepts. Knowing the facts, nomenclature, and consensus conclusions surrounding a particular concept does not guarantee real understanding, and real understanding does not require knowledge of academic descriptions. The disconnect between real-world processes and descriptions of these processes is well recognized by geoscience educators, and has prompted the use of model experiments in the classroom that enable direct visualization of processes in four dimensions. Visual-based learning has been shown to be effective at enhancing the understanding of difficult concepts (Thornton and Sokoloff, 1998).

This paper describes a scale-model classroom experiment that depicts an earthen dam and reservoir system in cross-section. The basic experiment involves constructing a dam by pouring various sands into the center of an ant-farm dimension tank, adding water to the 'reservoir' side of the dam, and evaluating the movement and ultimate fate of this water. The experiment clearly illustrates fundamental concepts in sedimentology and hydrology, including superposition, grain-size sorting, angle of repose, hydraulic head, capillary versus saturated flow, plume movement, and catastrophic failure. It is inexpensive to construct (~$50), requires about 30 min. to assemble, and is easy to execute within a single 50-minute classroom period. The experiment was originally devised for a non-major undergraduate course, 'The Water Planet', focusing on the role of water in Earth system processes, but can also be used successfully in K-12 settings, where the focus of the experiment is adjusted according to the level of the students.

This experiment is superficially similar to the widely used groundwater flow models (e.g. larger tanks featuring piezometric wells, reservoirs, and aquitards, see Hannula, 2003), but differs in that the focus is on both sedimentary processes and groundwater movement, whereas typical groundwater flow models are specialized for teaching more advanced concepts in hydrology. The present experiment is also smaller and more portable, easier to use, and less expensive than the groundwater flow models.

The outline of this paper is as follows. First, we list the materials necessary for constructing the model and performing the experiment. Next, we outline the basic experimental procedure (variations on this are expected and encouraged) and highlight the geologic concepts that are illustrated at each step. Following this, we suggest possible exercises and calculations to compliment the learning experience, and we conclude with a discussion of concepts learned and broader implications in the context of water issues as a major challenge facing future generations.

## MATERIALS

**'Ant Farm' Tank** - The 'Ant Farm' is constructed out of clear sheet acrylic-a material with an ideal combination of rigidity, transparency, and ease of assembly. Dimensions for the six pieces needed to construct a 40 x 15 x 3 cm tank similar to ours (Figure 1) are given below in both metric and English units (acrylic thicknesses available in the United States are usually specified in English units):

| | | |
|---|---|---|
| 2 @ | 40 x 15 x 0.5 cm | (16 x 6 x 0.25 in.) |
| 2 @ | 15 x 2.5 x 0.5 cm | (6 x 0.75 x 0.25 in.) |
| 1 @ | 40 x 3.5 x 0.5 cm | (16 x 1.25 x 0.25 in.) |
| 1 @ | 40 x 8 x 0.5 cm | (16 x 3 x 0.25 in.) |

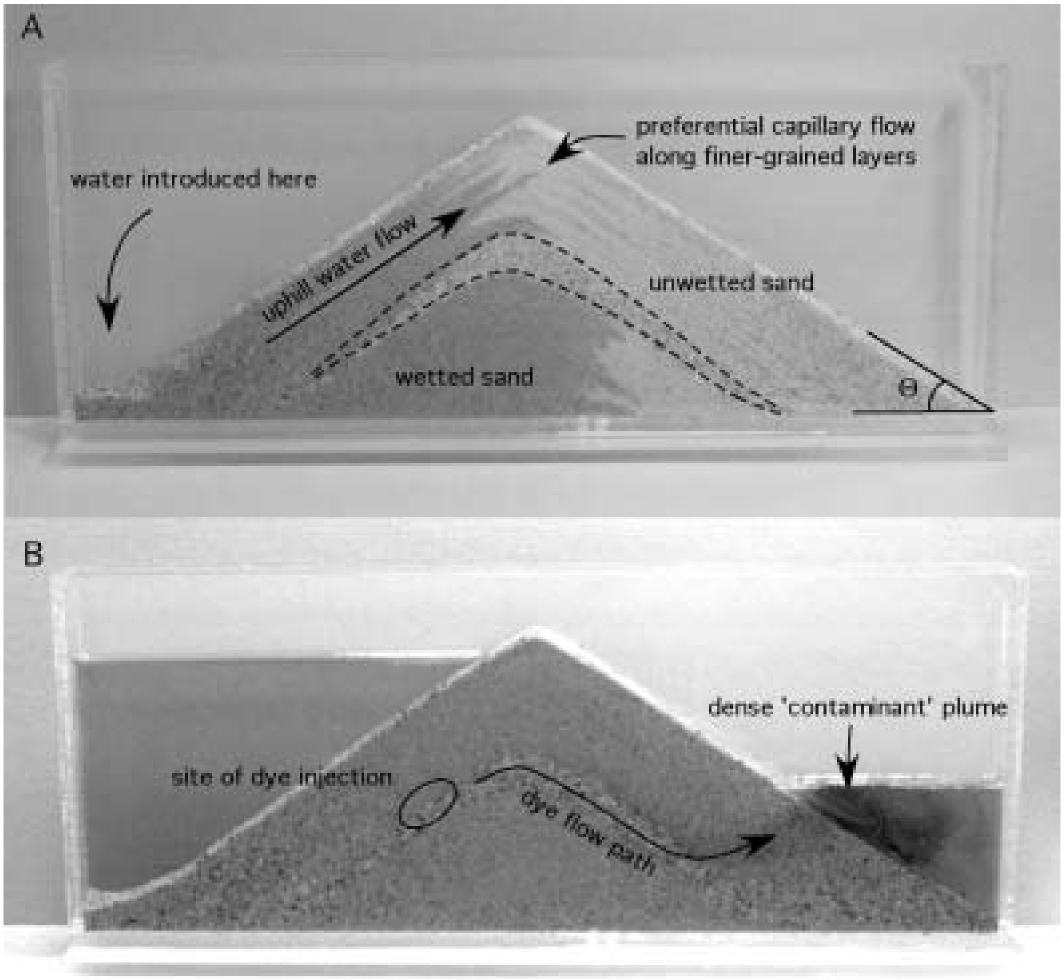

**Figure 1. Photos showing the 'Dam Fun' scale-model experiment at two different stages during the exercise. Dam is approximately 12 cm high at apex. A. Water is added to the reservoir side of the model, and seeps into the dam under unsaturated conditions. Water flows uphill and preferentially follows fine-grained layers. Dashed line shows the coarse-sand layer, which resists capillary flow. B. Injected dye preferentially moves through the coarse-sand layer under saturated conditions, and forms a semi-coherent plume at the zone of groundwater discharge. Elapsed time between the two photographs is approximately 10 minutes.**

The pieces are welded together using an acrylic solvent and the 'capillary method': two pieces are held together in the proper orientation, and acrylic solvent is introduced along the junction through a hollow needle. Capillary action wicks the solvent between the two pieces, with the solvent dissolving the plastic and evaporating within a few minutes to leave a strong weld. For this method to work, it is important that all pieces are precision-cut to exact specifications and have smooth edges. Most acrylic suppliers will provide custom pre-cut sheets that meet these requirements. Assembly of the tank can be accomplished in less than one-half hour when pre-cut sheets are supplied. This tank is useful for a variety of additional experiments, including demonstration of thermohaline circulation (see Dudley, 1984, and O'Connell, 2000), and as a flat version of the 'Aquifer in a Jug' experiment described by Dowse (2000).

**Sand and Other Materials** - Sand should be washed and free of clays and silts that impede water flow and cloud the water that pools on the 'downstream' side of the reservoir (unless these phenomena are intended to be illustrated). Fine-grained sand is needed in order to observe capillary water movement, and sand containing a distribution of grain sizes is needed in order to observe grain-size sorting during construction of the dam. We typically use two different sands: a poorly sorted, sub-angular, very fine- to medium-grained quartzofeldspathic sand, and a well-sorted, sub-angular, coarse-grained quartzofeldspathic sand. The former is used for building up the bulk of the dam, and the latter is used as a thin interbed that resists capillary flow, is highly conductive when saturated, and has a steeper angle of repose.

Other materials needed to carry out the experiment are water, food coloring, assorted bottles to contain the various colored water solutions and waste water, a syringe with a 4+ cm needle for injecting food coloring tracers, a rubber hose and large syringe (~60 cc) for siphoning pooled water from the downstream side of the dam, and a protractor for measuring angle of repose. A funnel is convenient for avoiding sand spillage during the construction of the dam.

## THE EXPERIMENT

**Earthen Dam Construction** - The dam is constructed by slowly pouring sand into the middle of the tank. We typically begin the dam with the very fine- to medium-grained-sand. The triangular cross-section of the dam develops according to the angle of repose of the sediment being used (Boggs 2000). Oversteepening frequently occurs and is alleviated by sand avalanches running down the sides of the dam. These events may leave sedimentary traces similar to grain-flow 'sand toes' common in ancient eolian sandstones (Hunter 1977). Sedimentary sorting occurs as sand moves downward from the apex of the dam, and visualization of this process is enhanced by using poorly sorted sand. After the dam is about one-third of its final height, we typically switch to coarse sand and construct an interbed that is 1-2 cm thick. This results in a visible increase in the angle of repose, and forms a hydraulic heterogeneity that is important later in the experiment. The dam is finished with the very fine- to medium-grained sand, with the apex of the dam placed about 1/2" below the top of the tank. During the construction of the dam, the concepts of relative age and superposition are illustrated, and it is clear to students why underlying sediments layers are older than overlying sediment layers.

**Filling the Reservoir** - The reservoir is filled by gently adding water to one side of the tank, taking care to avoid erosive damage to the dam. Food coloring added to the water beforehand enhances the visualization of water movement, and the adds to the overall aesthetic appeal of the experiment. As water is initially introduced into the system, the water quickly seeps into the pore volume of the dam, and its movement is dominated by unsaturated capillary flow. The capillary flow preferentially follows the fine-grained sand layers with higher capillary potential (Stephens 1995), including the very thin layers that formed by natural sorting during construction of the dam, and flows uphill along the bedding orientation. At this stage, water movement is severely retarded in the coarse interbeds, where inter-grain pore space provides an effective barrier to capillary wetting.

As more water is added, the dam approaches the point of saturation, and water begins to pool on the 'downstream' side of the dam. At this point, water movement becomes dominated by saturated flow and preferentially follows the coarse sand layers where hydraulic conductivity is greatest. This phenomenon is visualized by injecting concentrated food coloring/water solutions (~ 25:75) into different grain-size layers of the dam using a syringe. The dye may or may not be immediately visible depending on where the injection is made relative to the narrow dimension of the tank. Dye in the coarse layers moves significantly faster than dye in the fine layers. The phenomenon of 'sapping' frequently occurs at this point in the experiment: the zone in the downstream side of the dam where there is concentrated groundwater discharge becomes eroded by the combination of water flow and high pore-fluid pressure. The amount of sapping increases as the coarse grained, high-conductivity interbed is made thicker.

The injected tracer dyes, if concentrated enough, will have very different density and chemistry compared to the bulk water. This leads to a partial immiscibility between the dyes and bulk water, and the dyes pool coherently on the downstream side of the dam. This phenomenon illustrates the plume behavior of groundwater contaminants, and approximates the behavior of the well-studied DNAPL (dense non-aqueous phase liquid) class of groundwater contaminants (Huling and Weaver 1991). Students can attempt to 'remediate' the water by carefully siphoning away the plume using a syringe. This illustrates the fact that, because of dilution, the volume of contaminated water that must be removed or processed is several orders of magnitude larger than the original volume of the contaminant.

**Overtopping** - The final part of the experiment is the overtopping and catastrophic failure of the dam. Prior to overtopping the dam, the water on the downstream side of the dam should be drained so as to maximize the vertical distance between the top of the dam and base-level. Following this, water should be slowly added to the reservoir side of the dam, such that the actual overtopping begins with the slightest trickle of water over the top of the dam, which inevitably leads to further erosion and a run-away feedback ending in failure of the dam.

**Suggested Exercises and Advanced Experiments** - The basic experiment outlined above may lead to a variety of questions, calculations, and auxillary experiments geared toward specific groups of students. Obvious calculations are dam volume, bulk porosity of the dam, and water storage in the pore-space of the dam. Measurements of angle of repose can be made during construction of the dam, or a lab period can be devoted to studying angle of repose as a function of grain size and morphology (food items such as rice, beans, etc., are possibilities: see Weight, 1998). Other possibilities include measuring steady-state flow rate through the dam as a function of lithology or reservoir level, or a project focusing on optimal dam design, where each group of students is given identical starting materials (e.g. x amount of clay, y amount of fine sand, a flexible plastic straw, etc.), and the resulting designs are evaluated in terms of lowest conductivity or greatest resistance to over-topping.

## EVALUATION

Scientific evaluation of the effectiveness of one teaching strategy versus another is an involved process, requiring segregation of demographically indistinguishable experimental and control groups, subjecting each to different teaching strategies, and giving identical tests for evaluating what has been learned. Although such a rigorous evaluation was beyond the scope or intention of the present study, we did perform a qualitative evaluation to gauge students' knowledge before and after the experiment.

Students in the University of Utah's 'The Water Planet' class are primarily non-majors at the freshman through senior levels, although there are a minority of geoscience majors in the class. Prior to and following the experiment, students are given five graphical questions about topics illustrated by the experiment. The topics include angle of repose, superposition, direction of water flow through groundwater, water-storage capacity of sediment, and recovery potential of water from saturated sediment. The results show that prior to the experiment, students are familiar with the concepts of superposition and angle of repose, do not generally anticipate the possibility that groundwater can move uphill, and overestimate the amount of water that will naturally drain from saturated sediment. Following the experiment, the percentage of correct answers increases for all questions, and most notably students acknowledge the possibility of groundwater moving uphill, and realize that only a very small fraction of water added to dry sediment can be effectively recovered via natural draining of the sediment.

Perhaps more meaningful than the qualitative evaluation outlined above are the results of the end-semester, university-administered course evaluations. Year after year, a majority of students mention the in-class demonstrations when they are asked to describe their favorite aspect of the class. This suggests to us that students enjoy learning through hands-on experiences, and importantly that they remember these experiences. These results are consistent with generally positive comments that we receive from students about the experiments, and the high level of enthusiasm exhibited by the students during the experiments.

## DISCUSSION AND CONCLUSIONS

In this experiment, students are able to witness first-hand a variety of basic processes in sedimentology and hydrology. Students leave with lasting visual impressions of diverse phenomena such as sedimentary stratification and capillary wetting of dry sediments. The experiment is efficient in the sense that many processes are illustrated within a short period of time. Many of the behaviors of the system are contrary to expectations, including the uphill movement of water, and the coherence of the contaminant plume. Students are more apt to believe that these phenomena really do occur if they are able to see them happen for themselves.

A major goal of geoscience education is to inform and educate the public about socially and environmentally relevant issues. This experiment naturally brings up a discussion of water issues. What is the ultimate fate of groundwater contaminants? What happens to water that enters a reservoir? How much water might be lost to seepage into bedrock? Under what circumstances does water "flow uphill"? Water availability is a major issue confronting humanity, and it is important for students to think about water in the context of real geologic processes. Students in geoscience classes are voters and future policy makers, and learning experiences such as the one described here are a contribution towards wise decision-making.

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