Teaching Groundwater Flow and Contaminant Transport Modeling via a Sand-Tank Model

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Abstract In this study, a sand-tank model as a physical analog of a real-world aquifer is presented for groundwater instruction. The sand tank is used for introducing flow nets and quantifying groundwater flow, for groundwater modeling and calibration via a spreadsheet, and for dye-transport modeling. Students learn from the sand tank through interaction and visualization, and by collecting and interpreting data. This integrates the theories from lectures into the sand-tank laboratories, enhancing students’ skills and understanding.

Keywords Sand tank · Groundwater · Dye transport · Flow nets

1 Introduction

Over recent decades, groundwater, and fundamentally hydrogeology, has emerged as a core course for students with diverse backgrounds in a wide spectrum of institutions and disciplines. This course is required in the geological engineering curriculum at South Dakota School of Mines and Technology (SDSMT). It is also an elective course for students from programs in geology, environmental science, atmospheric science, civil engineering, mining engineering, and chemical engineering. The instruction provides fundamental training for geoscientists and engineers. There is a high demand for groundwater instruction because of strong employment prospects for trained hydrogeologists and the growing recognition of groundwater in other fields such as water resources and biology. For example, an article published in Science (Coontz 2008)
indicates the strong demand for hydrogeologists. Also, according to the U.S. Department of Labor and the American Geological Institute (now the American Geosciences Institute), the job market for groundwater specialists is growing (Santi and Higgins 2005).

A variety of pedagogical approaches have been successfully developed for groundwater instruction, depending on learning outcomes and the background of students. Classroom and field pedagogies are the main teaching activities in groundwater instruction, as is the case at SDSMT. Classroom lectures are used to teach fundamental knowledge of groundwater such as Darcy’s law and water balance, as well as to tackle multidisciplinary topics that might be raised from students with potentially diverse backgrounds. For example, Siegel and McKenzie (2004) presented a real-world contamination project that divides students into three groups and culminates in a day-long mock trial. Neupauer (2008) described a semester-long project that integrates classroom theories into weekly assignments. Singha (2008) used a cardboard juice box to mimic a confined aquifer for introducing the concepts of total stress, effective stress, and fluid pressure during groundwater extraction. Mays (2010) presented a 1-week module on stochastic groundwater modeling. Rodhe (2012) used physical models for classroom teaching. Gómez-Hernández (2022) employed spreadsheets to teach numerical groundwater flow modeling. All the approaches above are aimed at emphasizing fundamental knowledge and stimulating student engagement.

Teaching hands-on groundwater techniques such as well hydraulic tests in the field is essential because it provides experience and first-hand data that can be used to understand aquifers and to quantitatively gauge their capability for water supply or contaminant migration. For example, Rahn and Davis (1996) developed an on-campus operational well field consisting of a main pumping well and 14 observation wells for well hydraulic tests at SDSMT. Trop et al. (2000) introduced a short field trip for observing outcrops and extent of aquifer rocks, which gives students a greater understanding of an entire aquifer. Fryar et al. (2010) presented a watershed-based summary field exercise in a hydrogeology course. Through field teaching, students collected data and felt ownership over their learning. These field-based exercises also strengthened independent research skills and vocational skills. Classroom pedagogy enhances the theories, while field exercises help students collect data first-hand and be engaged in their learning. Many groundwater instructors agree that classroom and field pedagogies are critical components in a hydrogeology curriculum. Students in geoscience and geological engineering programs often tend to be strongly oriented toward visual learning, so laboratory exercises that involve physical analog models can be especially effective for instruction on basic principles of groundwater flow.

In this work, we present a sand-tank model for groundwater instruction. In particular, the sand tank can be used for constructing flow nets, which are commonly required in undergraduate groundwater courses, and for groundwater flow and solute transport modeling exercises in courses at the graduate level. By mimicking a real-world aquifer with the sand tank, students can develop vocational skills through data collection, analysis, and a deeper understanding of theories discussed in the lecture. The sand-tank model, as a physical analog of an aquifer, leads to greater student motivation and advancement of theoretical and vocational knowledge. This will support effective geoscience and engineering education to help tackle a number of natural
resource and environmental concerns such as groundwater contamination and future water supplies, which have been framed by the National Academy of Engineering as some of the greatest technological challenges for the professionals of the future (Clough 2004).

2 Sand Tank

The sand tank is located in the groundwater laboratory at SDSMT (see Fig. 1). It has dimensions of 2.5 ft length, 1.5 ft height, and 0.5 ft width. A Styrofoam dam is located at the center of the tank, extending partway down into the sand and separating the sand tank into upstream and downstream parts. The height of the sand is 0.7 ft. Water from a faucet enters through a plastic tube into the left side of the sand tank, in an upstream reservoir with a water level of 1.4 ft above the base of the sand tank, which is used as the datum for head values. Groundwater then flows through the sand beneath the dam to the downstream reservoir, with a water level at 0.7 ft. The water finally discharges from the downstream reservoir through a plastic outlet tube to a sink drain. When the inflow upstream equals the discharge downstream, the groundwater flow reaches steady-state conditions.

The sand is used from the St. Peter Sandstone. This can be obtained commercially from sources including a quarry near Le Sueur, Minnesota. The St. Peter Sandstone is Ordovician in age and is a well-sorted sand with frosted, rounded grains about 0.5 to 1 mm in diameter. It is more than 99% silica. Because of its frosted grains and relatively narrow size range, it appears to have been a dune sand during at least one

![Fig. 1 Configuration of sand tank. Water enters the tank on the left-hand side through a tube from a faucet. The water level is about 1.4 ft above the tank on the left (upgradient) side. Water exits the tank on the right (downgradient) side through an outflow tube to a drain. Note that the water level in the glass tube piezometer on the upgradient side of the sand tank is below the reservoir level, and the water level in the piezometer on the downgradient side is above the outflow reservoir level, as shown by red dye in the glass tubes](image-url)
time in its sedimentary history. Although it is a Paleozoic sandstone, it is friable and not well cemented. The uniform nature of the sand makes it suitable for the sand-tank model. Figure 2 is a photomicrograph of sand grains from the St. Peter Sandstone (from Davis 2012). Part of the sand-tank laboratory can involve a binocular microscope that is set up for students to observe the sand grains and make inferences about the environment of deposition. In an earlier laboratory exercise, the same sand can be used in a permeameter for determination of hydraulic conductivity, which can be compared to the value determined in the sand-tank and flow-net laboratory exercise.

3 Projects

3.1 Project 1: Flow Nets

Flow nets are an essential component for teaching groundwater principles. Box 1 is a sample assignment for a groundwater course at the undergraduate level. In using the sand tank, students can understand the concepts of (i) steady-state conditions by adjusting the inflow and discharge of the sand tank, (ii) hydraulic head by reading piezometers, (iii) hydraulic gradient by observing the velocity of dye, and (iv) hydraulic conductivity by constructing flow nets. By visualizing the dye movement in the sand tank and therefore understanding flow paths, students can be engaged in active learning rather than using limited, simplistic paper-and-pencil solutions.

Uniform sand can be used in the sand tank for undergraduate laboratories, so that the material is isotropic. In this case, flow lines and potentiometric contours meet each other at right angles. Normally a flow net is drawn with squares that are defined by the intersections of flow lines and potentiometric contours.

Dye is used as a tracer in the sand tank. For the dye tracer, dry tablets of water-soluble dye such as fluorescein is recommended, which can be obtained commercially. The tablets can be crushed gently with a mortar and pestle, and tweezers can be used to insert into the sand a very small piece of crushed dye about 2 mm diameter or less.
Box 1 Assignment: sand-tank model and design of flow nets

Design a flow-net solution to calculate the hydraulic conductivity of the sand used in the sand-tank model for this exercise

1. Adjust the inflow and discharge of the sand tank so that steady-state conditions are maintained
2. Introduce a tracer into the sand to show the flow paths that the water follows beneath the dam. Flow lines can be delineated clearly by inserting pieces of water-soluble, fluorescent dye tablets about ¼ inch below the surface of the sand, next to the plate glass, in the upstream (reservoir) side of the tank
3. Accurately record the results of the sand-tank experiment. Photographs are helpful. Determine relative velocities within the sand. Where does the dye move faster: near the dam, or farther to the left, near the glass?
4. Measure the volumetric discharge ($Q$) from the downstream side of the sand tank
5. Measure the hydraulic gradient for two of the flow paths of the dye. Explain why the dye travels faster in the sand near the dam, compared to its velocity in the sand farther from the dam, near the left side of the tank. Show sample calculations of velocity for both cases
6. Explain why the water levels in the two piezometers (the two glass tubes) are different from the water levels in the sand tank
7. With the use of a form of Darcy’s law and the volumetric discharge determination, design a flow net and develop a solution to calculate the hydraulic conductivity of the sand. Use the potentiometric map provided by the instructor to help draw your flow net
8. Observe GMS (Groundwater Modeling System 10.2) computer simulations of flow and dye transport in the sand tank. The instructor will assist you with the modeling software

If too large a piece is used, it can take a long time for it to be flushed from the sand, making it difficult to get the sand-tank model ready for other uses or later classes. In most cases it is better for an experienced instructor to insert the dye into the sand, rather than taking the risk of allowing students (or sometimes other professors) to do this—the dye is extremely concentrated and can stain clothing or skin quickly.

Flow nets are composed of flow lines that trace the path of particles of groundwater and equipotential lines that describe hydraulic heads. A flow net can help students understand and quantify a flow system, including flow directions and potentiometric contours. Flow nets can also be used to determine the hydraulic conductivity of aquifers with the following equation,

$$Q = \frac{(n_f K H_t b)}{n_d},$$

where $Q$ is the volumetric discharge [L$^3$T$^{-1}$], $n_f$ is the number of flow tubes bounded by adjacent pairs of flow lines or an impermeable boundary, $n_d$ is the number of head drops, $H_t$ is the total head loss [L], $K$ is hydraulic conductivity [LT$^{-1}$], and $b$ is the thickness of the aquifer [L]. (In this case, where a flow net is applied to a cross section, $b$ is the width of the sand tank.) Equation (1) can then be rearranged to solve for hydraulic conductivity. Box 2 shows how Eq. (1) can be derived from Darcy’s law, as a demonstration for students or as an assignment.

In drawing flow nets for the sand-tank model, potentiometric contours must meet impermeable boundaries at right angles, such as along the glass or the Styrofoam dam, because flow is parallel to an impermeable boundary. On the upstream side of the sand tank, the interface of the sand and water forms the upgradient potentiometric contour...
Box 2 Assignment or demonstration: flow-net equation

It is helpful for students to realize that the flow-net solution in Eq. (1) is simply a form of Darcy’s law, as shown by Freeze and Cherry (1979) and other groundwater textbook authors. Note that the discharge through one flow tube can be expressed with Darcy’s law as

\[ q = K \frac{\Delta h}{\Delta s} A, \]  

where \( q \), in this case, is the volumetric flow rate through an individual flow tube, \( \Delta h/\Delta s \) is hydraulic gradient (dimensionless), and \( A \) is cross-sectional area \([L^2]\) through which flow occurs. The cross-sectional area, \( A \), can be expressed as \( \Delta l \cdot b \) (see Fig. 3), where \( \Delta l \) is the width of the flow tube. Equation (2) then becomes

\[ q = K \frac{\Delta h}{\Delta s} b \Delta l. \]  

In the term for hydraulic gradient, \( \Delta h \) can be defined as the head change from one potentiometric contour to the next (Fig. 3), so that \( \Delta s \) is the distance between the contours. If the flow net is constructed with squares (Fig. 3), then \( \Delta l = \Delta s \) and Eq. (3) becomes

\[ q = K \Delta h b. \]  

With a flow net, especially in a field situation where upstream head and downstream head are known (as with a dam and reservoir), the potentiometric contours might not be well defined initially. Thus, it is easier to determine the total head loss (upstream reservoir head minus downstream head at the toe of the dam). From Fig. 3, \( \Delta h \) can be shown as the total head loss (\( H_t \)), divided by the number of head drops (\( n_d \)) in the flow net

\[ \Delta h = H_t/n_d. \]  

This can be substituted into Eq. (4) to give

\[ q = (K H_t b)/n_d. \]  

Then, note that the total volumetric discharge for the flow net, \( Q \), is equal to the flow through an individual flow tube, \( q \), multiplied by the number of flow tubes (\( n_f \)) in the flow net

\[ Q = q n_f. \]  

This can be inserted into Eq. (6) to give the flow-net solution in Eq. (1). This short exercise shows students the fundamental importance and power of Darcy’s law, and that many of our groundwater applications spring directly from it and is a constant-head boundary with a head of 1.4 ft, which is the water level in the upstream reservoir. Similarly, the downstream interface of sand and open water is a constant-head boundary at 0.7 ft.

As students observe dye movement through the sand tank, they can visualize the concept of flow lines, which helps in the construction of their flow nets. Time-lapse photographs in Fig. 4 show the progress of dye in the sand tank as groundwater seeps through the sand. A potentiometric map of the sand tank in cross section is provided in the class (Fig. 5), as a base for their flow-net construction. This increases the students’ confidence at the beginning of flow-net construction, so that they have fewer unknown parameters with which to contend. In constructing flow nets, students are encouraged to draw lightly and use an eraser frequently at the beginning of their work. We also encourage them to continue to refine their flow-net drawings until they show a reasonable representation of the flow conditions in the sand tank. Common early mistakes of students include terminating a flow line at an impermeable boundary, but when students see that the dye streaks don’t do this, they are challenged to improve their work. A completed flow net has curvilinear squares, especially near corners, but \( \Delta s = \Delta l \) for each cell (Fig. 6). This flow net has 9 flow tubes and 15 head drops. \( H_t \) is
0.7 ft (1.4 – 0.7 ft). A typical discharge through this sand tank, under these conditions, is 15 ml/sec. Equation (1) then can be rearranged to solve for hydraulic conductivity (K), yielding a value, in this case, of 250 ft/day. Students then can compare this value to the typical range of hydraulic conductivity for a clean sand, as shown in standard textbooks by authors such as Freeze and Cherry (1979).

Students often are surprised when they learn that the discharge through each flow tube is equal in the flow net. However, this concept is easier for them to understand when they see that the narrower flow tubes, near the Styrofoam dam, have a steeper hydraulic gradient and faster velocity, while the wider flow tubes, farther from the dam, have a weaker gradient and slower velocity. In this way, students gain a deeper understanding of Darcy’s law. The sand-tank model also provides an opportunity to show students that potentiometric contour lines are a two-dimensional representation of a three-dimensional potentiometric surface.

Note that even though dye was first injected at the far left of the sand tank (Fig. 4a), the dye injected later near the dam is moving faster (Fig. 4c–f). Part of this exercise involves groundwater velocity. Earlier in the semester, the students are asked to become familiar with various forms of Darcy’s law, including this expression for velocity,

\[ v = \frac{(K/\theta)}{\Delta h/\Delta s}. \]  

(8)

In Eq. (8), \( v \) is groundwater velocity and \( \theta \) is effective porosity. When students can visually observe that the velocity is faster in the flow lines near the dam, they are challenged to understand and explain why. Note that the flow lines farthest from the dam are the longest (Figs. 4 and 6). For example, a dye streak that starts at the far left side of the sand tank and terminates at the far right will have a total length

![Fig. 3 Simplified flow net](image-url)
Fig. 4 Time-lapse photographs of dye transport through the sand tank. Note that although dye was first placed near the left side of the tank (top left photo, a), it moves very slowly along that flow path. Dye placed near the Styrofoam dam (middle left photo, c) moves much faster. Photos by Darrel D. Sipe. Note that the background of the white box is not part of the sand-tank experiments.

Fig. 5 Potentiometric map of sand-tank model, drawn with Visual MODFLOW
of about 3 ft or more. This length is the value of the term for $\Delta s$ in Eq. (8). Because $\Delta s$ is in the denominator, this makes the groundwater velocity relatively slower. In comparison, a dye streak closer to the dam (Figs. 4 and 6) has a length ($\Delta s$) of 1 ft or less, which gives a faster velocity when inserted into Eq. (8). In both cases, the head difference ($\Delta h$) is the same, but the hydraulic gradient is greater for the flow paths near the dam. This part of the exercise shows students that hydraulic gradient is one of the main driving forces for groundwater flow—not just the head difference, but rather the head difference divided by the length of the flow path. Figure 7 shows velocity vectors, as illustrated with Visual MODFLOW. For undergraduate classes, a numerical simulation of dye transport (Fig. 8) with MT3DMS is also shown to students (Zheng and Wang 1999).

The glass tubes (Fig. 1) act as wells that are open at their bottom, as the simplest form of a piezometer. The well on the upgradient side shows a water level that is lower than the reservoir level on the left side of the tank, which helps students visualize the head in the sand at that point where it is measured. A small amount of liquid dye added to the glass tube can make this water level easier to see. The well on the downgradient side shows a water level that is higher than the reservoir level on the right side of the tank (Fig. 1), which helps students understand an upward gradient. In some field situations similar to this, a flowing artesian well can be obtained with a sand-point well near a stream where the hydraulic gradient is upward.
In using the sand tank and flow net, students learn that graphical methods are among the most accurate and useful tools in groundwater hydrology, even though more sophisticated numerical models are available.

3.2 Project 2: Groundwater Flow Modeling and Calibration Using a Spreadsheet

A numerical groundwater model is a data integrator that can be used to understand flow processes and factors that control flow and transport in the aquifer. This is useful for developing vocational skills of students. Groundwater flow modeling usually is offered for courses at the graduate level, as is the case at SDSMT.

According to Olsthoorn (1985), the groundwater flow model can be solved by using a spreadsheet without a special program. Specifically, the mass-balance equation can be built using five-point finite difference (see Fig. 9)

\[ q_1 + q_2 + q_3 + q_4 = 0, \]  

where \( q_1 \) denotes the specific flow. Assume that an aquifer is homogeneous and isotropic, and that the grid cells have an equal size; by combining with Darcy’s law, Eq. (9) can be rewritten as

\[ h_0 = \frac{h_1 + h_2 + h_3 + h_4}{4}, \]  

where \( h_0 \) is the head to be calculated. If there is a no-flow boundary condition along the edge of the sand tank, as shown in Fig. 9b, Eq. 10 can be rewritten as (Freeze and Cherry 1979)

\[ h_0 = \frac{h_2 + 2h_3 + h_4}{4}. \]  

At a corner with two impermeable boundaries, Eq. (10) can be shown as

\[ h_0 = \frac{2h_2 + 2h_3}{4} = \frac{h_2 + h_3}{2}. \]  

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Given the maximum number of iterations and the maximum change, hydraulic heads can be solved automatically in a spreadsheet. Students have the opportunity to understand how to handle inactive cells (dam), no-flow boundaries, and constant-head boundaries using the finite-difference method in this exercise.

With the solved hydraulic head, the total discharge \( Q \) can be calculated with Eq. (2) in modified form as

\[
Q = K \frac{\Delta h}{\Delta s} A. \tag{13}
\]

Students can use the measured discharge, which is the total discharge from the reservoir downstream, to inversely calibrate the initial guess of hydraulic conductivity. This can be conducted either with an iterative manual trial-and-error approach to get a match for the discharge, or with a mathematically rigorous automated solver to calculate the best hydraulic conductivity that results in a match in the spreadsheet. The manual trial-and-error approach not only improves the match but also provides key insights into how the groundwater system behaves. Figure 10 is an example from a student who conducted the groundwater modeling exercise for the sand tank using the finite-difference method and automatic calibration of hydraulic conductivity with the measured discharge. The reader could check the latest work on groundwater modeling via spreadsheets by Gómez-Hernández (2022). Box 3 is a sample assignment for a groundwater modeling class at the graduate level.

With a spreadsheet and the sand-tank model, students can build a simple finite-difference model without working on special numerical modeling software. Also, the water balance can be better understood in a spreadsheet with the measured data in the lab. The groundwater model can be calibrated with the data from both piezometers and the discharge value collected by students. In this way, students feel a greater sense of investment in their learning after calibrating the model and using their own data. Students can also use software such as Visual MODFLOW or GMS.
Fig. 10 Example of student-generated results from finite-difference modeling with a spreadsheet. The numbers in the black are the dimensions of the sand tank, while the numbers in the blue and gray are the simulated hydraulic head (unit: ft). The measured discharge is 15 ml/sec, and the calibrated hydraulic conductivity is about 350 ft/day.

Box 3 Assignment: simulation of sand-tank model using finite difference with a spreadsheet

Use a spreadsheet to simulate groundwater flow in the sand-tank model shown during the class demonstration

1. Determine the dimensions and boundary conditions of the model
2. After steady-state conditions are reached, measure the discharge through the sand
3. Make a rough estimate of the sand’s hydraulic conductivity
4. Design a model grid for simulation of flow through the sand-tank model using a spreadsheet
5. Calibrate the hydraulic conductivity by using the measured discharge
6. Describe your results in a brief report

3.3 Project 3: Dye-Transport Modeling

One of the core parts in contaminant hydrogeology instruction is a detailed understanding of contaminant migration in aquifers. Often, most instructors employ a lecture format using published data from groundwater contamination sites in their courses. Without a visualization environment, however, students might develop a very limited view of what constitutes meaningful learning, because they only build lower-level skills such as memorizing facts and terms.
Box 4 Assignment: simulation of dye transport in sand-tank model

1. Use GMS to simulate the movement of dye in the sand-tank model shown during the class demonstration
2. Use your previous sand-tank modeling work to show velocity vectors
3. Use an appropriate method for introduction of dye concentrations in the modeling simulations, such as the “Point Source” option. Introduce dye concentrations in at least three locations
4. Use the MT3DMS model for simulating dye transport. Compare your modeled output concentrations to the actual paths of dye in the sand tank. Do the modeling simulations show wider streaks of dye or other variations from the sand tank photographs? If so, consider changes that could be made in input values for the model and simulation options. One such input value is dispersivity

Describe your results in a brief report

The three-dimensional advection–dispersion equation for solute transport is often written as (Freeze and Cherry 1979)

\[ \theta \frac{\partial C(x, t)}{\partial t} = -\nabla[q(x)C(x, t)] + \nabla[\theta D \nabla C(x, t)], \tag{14} \]

where \( \theta \) is the effective porosity, \( C \) is the dissolved concentration of solute in the liquid phase, \( q \) is the Darcy velocity, and \( D \) is the local hydrodynamic dispersion coefficient. For graduate students, this equation will be briefly introduced with emphasis on the mass conservation and the physical meaning of each variable.

A groundwater flow model can be built with Visual MODFLOW or GMS, as a prerequisite for contaminant transport simulations with software such as MT3DMS. Grids of 70 rows by 250 columns with cell sizes of 0.01 ft \( \times \) 0.01 ft were used, although somewhat coarser grid spacings can be used. We use dye to mimic a contaminant in the sand tank. Students can visualize the dye’s migration in response to the hydraulic gradient, which leads to a greater understanding of advective-dispersion transport processes in the aquifer (see Fig. 4). Also, the dye migration with time can be used to calibrate the groundwater model (Zheng and Wang 1999). Groundwater velocity depends on effective porosity and hydraulic conductivity (see Eq. 8). After the students choose a representative porosity value, they can adjust the hydraulic conductivity in the numerical model until the calculated dye transport matches their timed observations from the sand-tank model. Other model parameters such as dispersivity need adjustment as well. Figure 8 shows an example of a dye-transport simulation. Box 4 is a sample assignment for students working on modeling of dye migration in the sand tank. Numerical modeling of the sand-tank model increases students’ confidence for simulating more complicated field situations later in the semester, while also giving them an appreciation of the difficulties with which they must contend.

3.4 Other Potential Applications of the Sand Tank

The sand-tank model can also be used in undergraduate classes to demonstrate the importance of minimizing seepage under a dam, in order to ensure the integrity of its foundation. A proper foundation is of utmost importance (Rahn 1996), and dams
sometimes have failed spectacularly because of excessive leakage through an inadequate foundation. As a class demonstration, the instructor can reach in and loosen the sand beneath the Styrofoam dam from the downstream side, dramatically illustrating what happens when an acceptably small amount of seepage becomes a disastrously large amount of leakage that undermines the dam’s foundation. In this case, the water in the upstream reservoir, with an initial head of 1.4 ft, causes a sand boil that quickly erodes beneath the dam and equalizes the water levels on both sides of the dam. A real-world example of failure because of leakage through an inadequate foundation is the Teton Dam (see, e.g., Rahn 1996).

Another use of the sand tank is for demonstrations to visiting middle-school and high-school students during events at SDSMT such as Girls’ Day, Engineers’ Week, or water festivals. The visual nature of the dye streaks and their observable progress through the sand are fascinating to younger students, who often have simple but practical questions about why the dye moves in this way. This is also an opportunity to show students that groundwater contamination can move unseen beneath the land surface from one place to another, possibly ending up in someone’s well. Young visitors are receptive to the concept that prevention of pollution is much better than trying to clean it up after it occurs.

Other types of sand-tank models can be used in undergraduate and graduate groundwater classes, including a cross-sectional setup that mimics an earth-fill dam (Fig. 11), and a sand tank with coarse-grained, permeable channels embedded within less permeable material (Fig. 12). The earth-fill dam (Fig. 11) can illustrate the parabolic shape of a water table in cross section, giving an opportunity to introduce students to the Dupuit-Forchheimer equation (Freeze and Cherry 1979) as an approximation for the

Fig. 11 Sand-tank model for illustrating seepage through an earth-fill dam. Note that there is no water filled in this sand tank
Fig. 12 Sand-tank model with permeable channels embedded in finer-grained material. The total length of this sand tank is 10 ft. Note that there is no water filled in this sand tank.

water table in an unconfined situation in which transmissivity is not constant because saturated thickness is decreasing downgradient. The sand tank with permeable channels (Fig. 12) can demonstrate how quickly a contaminant (e.g., dye tracer) can move downgradient, compared to the slower velocities in less permeable material. It also illustrates the refraction of flow lines that occurs at the boundary between materials with different hydraulic conductivities. This is especially helpful for showing students how contaminants can spread in alluvial or fluvial environments of deposition.

4 Summary

A visualized aquifer using a sand tank was presented to allow students to better understand groundwater flow nets, groundwater modeling via finite difference, and contaminant transportation via a dye test. Following a brief introduction of the sand tank, sample assignments for the sand tank are provided. Specifically, flow nets, groundwater modeling and calibration with a spreadsheet and with software, and simulation of dye transport are implemented with the sand tank. This provides a useful analog because students can measure hydraulic heads using piezometers, understand the roles of boundaries in numerical modeling, and simulate dye migration. Three course projects were designed and showed that the sand tank is a valuable tool for teaching hydrogeology.

A final piece of advice: When using the sand-tank model, don’t leave the water running unattended and risk letting the tank be overtopped. (One of the authors knows this from hard experience.) An overflow tube near the top of the sand tank on the upgradient side is helpful.
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