Abstract
Darcy’s Law is one of the most essential concepts in hydrogeology. Before moving on to more complex problems, students must first thoroughly understand the basic principles of one-dimensional fluid flow through saturated porous media that are embodied in Darcy’s Law. We believe that the best way for students to learn these principles is through experimentation. In this paper, we introduce an experimental apparatus and laboratory exercises designed to facilitate student exploration of Darcy’s Law. Our permeameter design is simple and inexpensive to construct from readily available materials; it is also nearly indestructible and easy to use. The exercises we present are flexible, and suitable for high school or university students. Students performing the exercises will gain an understanding of the relationships between hydraulic gradient, pore size, porosity, fluid viscosity, particle size (mean and distribution), and volumetric flow rate.

Introduction
Darcy’s Law, which describes one-dimensional laminar flow through saturated porous media (i.e., rocks, soil) is perhaps the most essential concept in the study of hydrogeology. Providing students with hands on laboratory experience helps them to develop an intuitive understanding of the relationship between hydraulic head and fluid flow in porous media that is embodied in Darcy’s Law. Once the basic concepts are thoroughly understood, students have a firm foundation from which to move on to more complex and realistic problems. Here we begin by providing an introduction to Darcy’s Law. We then identify a set of fundamental principles regarding flow in porous media that we believe are best learned through laboratory experimentation. After introducing a simple experimental apparatus capable of performing the relevant tests, we conclude by suggesting a series of student exercises with sample results.

Darcy’s Law and Groundwater Motion
Darcy (1856) performed his original experiments in the context of municipal water filtration for the city of Dijon, France. Unable to find an existing relation between flow rate and filter size, Darcy performed a series of experiments to aid in his design calculations (Hubbert, 1957). Pressurized water entered the top of a sealed vertical column filled with filtration sand and exited through a tap at the base of the column. Potential energy within the fluid was measured at the inlet and outlet using manometers, and reported in meters of water above datum (base of the sand column). Darcy found that for a given sand,
Fluid flows in response to decreasing hydraulic head; hence the hydraulic gradient is inherently negative. The negative sign in (1) is therefore required to make volumetric flow rate (Q) a positive quantity. For steady, one-dimensional flow through a sample of length L and cross-sectional area A, (1) can be integrated to yield

\[ Q = KA \frac{\Delta h}{L} \]  

where:

\[ \Delta h = h_{\text{inlet}} - h_{\text{outlet}} \]  

Subsequent to Darcy’s original experiments, it was discovered that for a given porous media, measured K increases with fluid density (\( \rho \)) and is inversely proportional to fluid viscosity (\( \mu \)). Hubbert (1940) suggested the existence of an innate material property (k) that related hydraulic conductivity to \( \rho \), \( \mu \), and the gravitational constant (g):

\[ K = \frac{k \rho g}{\mu} \]  

As Hubbert suggested, k, which is now known as intrinsic permeability must be determined by experimental means.

Based on classroom experience, we have identified the following principles as crucial to full understanding of Darcy’s Law and its implications with respect to flow in porous media:

1. The linear relationship between hydraulic gradient and volumetric flow rate.

2. The influence of fluid properties (particularly viscosity) on K.

3. The influence of particle size (and distribution) on k.

4. Flow is driven solely by the hydraulic gradient; therefore, orientation of the sample (gravity, datum) has no effect on flow rate.

5. Where flow must pass across a material boundary, the material with smaller k dominates system response.

6. Darcy’s law breaks down at high fluid velocities (large Reynolds number).

In the remainder of this paper we describe apparatus and laboratory exercises designed to enhance student understanding of these principles.

**Demonstration Apparatus**

Quantitative laboratory measurements of hydraulic conductivity are typically made with an apparatus known as a permeameter. Such devices are commonly designed for batch operation rather than student experimentation. As a result, educators have developed demonstration permeameters to help students understand subsurface flow. Many such devices (e.g., Werner and Roof, 1994) are made of a transparent material so that introduction of a visible tracer (e.g., food coloring) to the flowing water allows students to directly observe flow paths and tracer dispersion.

After reviewing commercially available designs, and those presented in the literature, none were found to be fully suitable for our specific needs. In addition to demonstrating principles 1-6 (above), we required that the apparatus be inexpensive, virtually indestructible, simple to construct, and easy to use. By forgoing the use of a transparent sample tube, we were able to design a simple permeameter that met our needs and could be constructed from hardware store materials for around $10.

**Design and Construction**

The basic design of apparatus for measuring hydraulic conductivity has not changed significantly since Darcy’s original experiments; a typical permeameter consists of a sample tube, end caps, manometers to measure hydraulic head, and inflow/outflow plumbing. The end caps allow water to enter and exit the sample tube, while preventing the sample from eroding. We employ commonly available plumbing items for the end caps and sample tubes; all other materials are standard laboratory supplies. A 1.27 cm (1/2 inch) diameter, pre-threaded plastic pipe (sprinkler riser) is used as a sample tube. Sprinkler risers are available in a variety of lengths; through trial and error we have found the 20.3 and 25.4 cm (8 and 10 inch) lengths to be most convenient. Brass adapters that attach 1.27 cm (1/2 inch) pipe thread to 0.635 cm (1/4 inch) tubing (compression fitting or barbed) are used as end caps (see Figure 1). In order to prevent the sample from eroding, a piece of stainless steel screen is inserted into the end cap. Fortuitously, we discovered that a common faucet aerator (Plum...
Pak part # PP28002) contained two properly sized round screens and a slotted piece of plastic that can be used to support the screen. In order to avoid restricting flow, we drill out the center of the slotted plastic. While other arrangements could be easily developed, these end caps perform exceptionally well for materials down to the size of fine sand. It is important to note that this instrument is strictly intended for instructional purposes, as the small diameter of the sample tube is expected to result in relatively large edge effects.

**Figure 1:** Diagram showing permeameter design. The sample tube consists of a length of pre-threaded plastic pipe (sprinkler riser). The sample is constrained between end caps (only one is shown) fastened onto each end of the sample tube. Plumbers thread sealing tape (PTFE) is used to obtain a watertight seal between end caps and sample tube.

Measurement of K using (3) requires that Δh (and hence Q) be held constant. On the inlet side, a Mariotte bottle (see below) is used to supply fluid to the permeameter at constant head, while the outlet tube is simply vented to atmospheric pressure. The constant head boundaries (Mariotte bottle and drip point) are supported on common lab stands, as is the permeameter (Figure 2). Note that head loss is required to induce flow through the 0.635 cm (1/4 inch) flexible plastic tubing that connects the constant head boundaries to the sample. Therefore, it is necessary to measure head loss (Δh) across the sample using manometers (open ended tubes) attached to T fittings adjacent to the permeameter (Figures 1 and 2). The T fittings should be located as close to the permeameter as is physically possible. A meter stick is used to measure hydraulic head in the inlet and outlet manometers.

**Figure 2:** Apparatus for measuring hydraulic conductivity. Fluid levels are shown in black. Numbered components and additional details are as follows: (1) Fluid source (e.g., Mariotte bottle, constant head reservoir, pump). (2) Manometers - open ended tubes of 0.95 cm (3/8") diameter clear plastic are attached to a vertical meter stick with clear tape or rubber bands. Note that capillary effects in small diameter tubes will complicate reading the fluid levels. (3) Permeameter (see Figure 1 for details). (4) Drip point - vents flow to atmospheric pressure. (5) Outflow container - plastic cups are used to collect outflow for gravimetric measurement of flow rate (Q). (6) Standard laboratory stands and clamps are used to support the apparatus. (7) Clear flexible tubing is used for all lines to facilitate locating and purging air bubbles.

Various methods (e.g., pump, reservoir) may be used to supply fluid to the permeameter at constant head; however, we find a device known as a Mariotte bottle (e.g., McCarthey, 1934) to be the most convenient. A sealed reservoir is equipped with an outlet (siphon) and air inlet, both of which are submerged (Figure 3). When flow is initiated, air enters through the inlet tube to replace fluid leaving the reservoir; provided that fluid level in the reservoir does not drop below the bottom of the inlet or outlet tubes, fluid pressure at the bottom of the air inlet remains at atmospheric pressure. This effect produces flow at constant head, even though fluid level within the reservoir is declining. While one could construct such a device
from standard glassware, for safety reasons we employ plastic wherever possible. The device illustrated in Figure 3 was constructed from a one-liter flat-sided plastic laboratory bottle. We found that larger plastic bottles tended to flex, which in turn led to small fluctuations in head at slow flow rates. We chose a flat sided bottle so that we could tap the inlet/outlet lines through the sides rather than the cap. Running the lines through the cap is easier to construct, but significantly complicates adding fluid during the course of an experiment. An alternative design, and straightforward discussion of the physics are provided by Cutler (1959).

![Diagram of Mariotte bottle](image)

**Figure 3:** Mariotte bottle constructed for laboratory usage. Note that the cap must be tightly sealed in order for this device to function. Steady bubbling from the air inlet tube is a good indicator that the device is working properly.

**Porous Media**

Sand is a convenient material for studying the properties of flow in porous media. Sand is easy to work with, and the relatively large hydraulic conductivity allows visible amounts of flow to occur in a short time span. In addition to providing students with visual evidence of the relationship between $\Delta h$ and $Q$, high flow rates allow a number of experiments to be performed within a single laboratory session. We selected a standard washed play sand at the local building center. Although this material can be used as is, we chose to separate the sand based on grain size by passing it through a sieve stack consisting of #’s 10, 20, 30, and 40 US Standard sieves. The fraction retained on the #20 sieve after passing through the #10 sieve (10-20 sand) has a grain size that ranges between 0.85 and 2 mm. Likewise, the 20-30 sand has grain size between 0.6 and 0.85 mm, and the 30-40 sand has a grain size between 0.425 and 0.6 mm. The difference in grain size between these three sand fractions is readily apparent to the naked eye, and helps students to understand the influence of pore size on hydraulic conductivity.

**Sample Preparation**

Sample preparation begins by fixing one end cap onto the sample tube, using plumbers thread sealing tape (PTFE) to attain a watertight seal. The sample can then be poured in through the open end. Tapping the sample tube against a hard surface will facilitate packing of the particles, and minimize subsequent settlement. After filling, the second end cap is attached. An advantage to using narrow distribution sands, as described above, is that materials with a wide distribution of particle sizes will tend to segregate by size during filling. Students are encouraged to experiment with different filling methods using a clear graduated cylinder. If the dry sample mass ($m$) is measured during the filling process, sample porosity ($n$) can be obtained from the sample volume ($V_s$) and material density (e.g., $\rho = 2.65 \text{ g/cm}^3$ for quartz). Porosity is defined as the ratio of void volume ($V_v$) to sample volume. For a dry sample, total volume is the sum of void volume and volume of solids ($V_s$), which in turn may be obtained from the sample mass and material density ($V_s = m/\rho$).

$$n = \frac{V_v}{V_s} = \frac{V_t - V_s}{V_t} = 1 - \frac{V_s}{V_t} = 1 - \frac{m}{V_t\rho} \quad (5)$$

After filling the sample tube with sand, it is connected to the inflow, outflow, and manometers as shown in Figure 2. While saturating the sample with water, it is important to minimize air entrapment within the sample. Trapped air lowers measured hydraulic conductivity by obstructing fluid flow; furthermore, the compressibility of air implies that the degree of obstruction will change with pressure (head). It is best to avoid these effects by saturating the sample from the bottom; tapping the sample tube after adding water will release any large trapped air bubbles. Air entrapment can also be reduced by adding a softening agent to the water (Werner and Roof, 1994) or employing coarse grained samples. In order to prevent outgassing within the sample, tap water must be allowed to equilibrate to ambient pressure before use. Allowing the water to equilibrate to ambient conditions also minimizes temperature effects on viscosity.
Example Exercises
Here we present several sample exercises that students can perform during a laboratory session. Typically we break the class up into arbitrarily assigned groups of three for laboratory sessions. Each group works on a given sample until they have completed the appropriate measurements, and then moves to another station. In order to eliminate waiting time, we prepare more stations than there are groups.

Exercise 1 - Effects of pore size, hydraulic gradient, and a material boundary
In this exercise, students explore the linear relationship between Q and ∆h, the influence of pore size on K, and the effect of a material boundary within the sample. Two homogenous samples are prepared, one containing 10-20 sand, and the second 30-40 sand. A third sample is prepared by partially filling the sample tube with 10-20 sand, and then topping it off with 30-40 sand to create a layered sample. Students measure ∆h, Q, and outflow temperature for each sample at 5-10 different values of ∆h. Students are cautioned to allow the manometers to stabilize each time that ∆h is changed. The time required for ∆h to equilibrate will decrease with increasing mean grain size. Flow rate (Q) may be determined either volumetrically or gravimetrically. In the volumetric method, the outflow is captured in a graduated cylinder for a measured amount of time. The gravimetric method is similar, except that volume is estimated by weighing the outflow and dividing by the fluid density. Data are entered into a spreadsheet program as it is collected. We then rewrite (3) as

\[
\frac{Q}{A} = K \frac{\Delta h}{L} \tag{6}
\]

The left hand side of (6) gives a quantity known as the Darcy flux (q), which is plotted as a function of the second term on the right hand side (∆h/L). The slope of a best fit line through the data gives K. As Q is expected to be 0 when ∆h = 0, the best fit line must pass through the origin. Sample data (Figure 4) show the linear increase in Q with ∆h as predicted by Darcy’s Law, and the clear difference in K between the three samples. Standard tables for density and viscosity of water as a function of temperature (e.g., Fetter, 1994) provide the data necessary to calculate k using (4).

After calculating K for the three samples, students use their data from the homogeneous samples (10-20 sand and 30-40 sand) to calculate the average hydraulic conductivity (Kave) for a layered system and compare the result to their experimental measurement. Theoretical Kave for one-dimensional flow perpendicular to the layering is given by (c.f., McWhorter and Sunada, 1977):

\[
K_{ave} = \frac{L_1 K_1}{L_1 K_1 + L_2 K_2} \tag{7}
\]

where L1 and L2 are the lengths of materials K1 and K2, respectively. The layered sample measured in the example (Figure 4) was filled 80% full with the 10-20 sand, and the 30-40 sand used to fill the remaining 20%; (7) gives Kave = 0.21 cm/s, which compares well with our experimental result of 0.22 cm/s.

Exercise 2 - Indifference of flow to sample orientation
In this exercise, students learn that flow is driven solely by the difference in head across the sample, and therefore, is indifferent to orientation and location of the sample with respect to gravity. In our system, the permeameter is mounted on a lab stand with a standard test-tube clamp (Figure 2). This design allows orientation and elevation of the permeameter to be easily changed. Each group of students works with a single sample, and measures K (as per exercise 1) with the sample in three different physical locations. First the sample is oriented vertically, then...
it is rotated to horizontal, and finally, the sample is raised or lowered with respect to datum. Care must be taken not to introduce air into the sample or manometer tubes while the sample is being moved. Students observe that because flow is driven by $\Delta h$ rather than $h$, it is insensitive to the orientation of the sample. We suggest concluding the exercise by asking students to describe natural systems where the principles demonstrated in this exercise would be relevant.

**Exercise 3 - Effect of fluid viscosity**

In this exercise, students explore the effect of fluid viscosity on hydraulic conductivity by using ice water as the flowing fluid. After measuring $K$ (as per exercise 1) using water at ambient temperature, ice cubes are added to the Mariotte bottle and the sample is submerged in ice water. We also submerge a length of the inlet tubing in the ice chest. The system is then allowed time to equilibrate to the new environment, and $K$ is remeasured. In order to obtain a representative value, fluid temperature is measured at the outlet manometer connection. In our laboratory, this methodology lowers temperature of the flowing water to ~4˚ C from an ambient temperature of ~23˚ C. The viscosity of pure water increases by ~65% over this temperature range (Fetter, 1994), while the increase in density is negligible (~0.2%). Therefore, it is unnecessary to correct measured $h$ for changes in fluid density as implied by (2). Example results (Figure 5) show the significant change in $K$ that occurs when water temperature is reduced. Results are within 5% of predictions based on the measured temperature change.

Another approach to exploring the effects of fluid properties on hydraulic conductivity would be to measure $K$ with water, and then repeat the measurement on that sample using a different fluid. However, for classroom experimentation, ice water has a number of advantages over alternative fluids (e.g., dish soap, cooking oil, sucrose solution, brine). Chilling the water changes viscosity significantly, while having a negligible effect on fluid density; therefore, measured $h$ can be used directly. As can be seen from (2), changes in fluid density will require that $h$ be corrected to equivalent units (e.g., Fetter, 1994). The density and viscosity of water as a function of temperature are also well known and readily available, hence calculation of $k$ from (4) is straightforward. Changing water temperature is a relatively fast process that results in minimal down time while the system equilibrates. Adding a solute (e.g., salt, sucrose) to change fluid properties requires that the system be thoroughly flushed with the new fluid before taking measurements. Changing from water to an immiscible fluid (e.g., cooking oil) cannot be done in a single laboratory session. In order to assure that the sample is fully saturated with the second fluid, the sample must be completely dried out before changing fluid; this is at best an overnight process. From a practical standpoint, chilled water is easy to work with; alternative fluids may be messy and difficult to clean up. Finally, using chilled water in this exercise serves to remind students that hydraulic conductivity measured at ambient laboratory temperature will differ significantly from field conditions, where shallow groundwater is expected to be close to the mean annual temperature.

**Figure 5:** Effects of fluid viscosity on hydraulic conductivity. Water is considerably more fluid at 23˚ C (black circles) than at 4˚ C (black squares). As a result, measured hydraulic conductivity (slope of the best fit lines) increases with increasing water temperature.

**Additional Possibilities**

In addition to the activities described in exercises 1-3, there are a number of other possible classroom exercises that could be performed with our apparatus.

1. The amount of water that empties from a unit volume of saturated porous media by gravity drainage is known as the specific yield ($S_y$). This quantity is important in evaluating water production from unconfined aquifers. Gravity will not provide sufficient force to drain 100% of the water from the pore space, some water will be held in place by capillary attraction. The amount of water retained in a
unit volume of saturated porous media following gravity drainage is known as the specific retention (S_r). The sum of these two quantities is equal to porosity (n = S_y + S_r). If porosity is measured when filling the sample, our apparatus can be used to estimate S_r and S_y.

2. In describing our permeameter, we stated that hydraulic conductivity was measured under steady state conditions; that is, all parameters in (3) are held constant during a given experimental trial. This approach works well for relatively high permeability materials such as sand. An alternative approach, known as the falling-head test, is commonly used to measure K in low permeability materials such as silt or clay (e.g., Fetter, 1994). Our apparatus can be reconfigured as a falling-head permeameter by eliminating the outlet tubing and manometer. Performing this exercise also provides students with insight on the basic principles of field slug tests. In our experience, the 30-40 sand is the most permeable material than can be used, coarser grained sand results in an experiment that is too rapid to measure reliably.

3. Darcy’s Law is only valid for laminar flow, which in turn implies that viscous forces dominate inertial forces. The upper limits on the validity of Darcy’s Law can be explored by gradually increasing fluid velocity within the sample until inertial effects become significant. In order to do so, it is necessary to maximize fluid velocity (large K and Δh/L) by employing a short sample tube (e.g., 10.2 cm) and coarse sand. As the gradient is increased, the graph of Q/A vs. Δh/L is expected to become non-linear when inertial forces become significant.

4. The linear relationship between L and Q and can be explored by preparing 2-4 samples of different length, each with the same material. Theory suggests that a well sorted fine sand will probably show the least sample-to-sample variance in K.

5. In exercise 1, the dominance of the lower K material for flow in series was considered by using a layered sample. One could also arrange 2 or more permeameters in parallel to show the dominance of the higher K material for flow through separate layered aquifers.

Summary
After providing an overview of Darcy’s Law, we have outlined several concepts that we believe are crucial to student comprehension of groundwater flow. We then introduced an inexpensive and durable apparatus designed for hands-on student experimentation. Finally, we have presented a series of laboratory exercises designed to help students develop an intuitive understanding of the fundamental mechanics of groundwater flow that are embodied in Darcy’s Law.

Acknowledgments
Partial support for this work was provided by the U.S. Department of Energy, Basic Energy Sciences Geoscience Research Program under contract number DE-FG03-99ER14944. We would like to thank Kay McQueen and two anonymous reviewers for their thorough and constructive comments on the draft manuscript. We would also like to thank Jacob Elder for laboratory assistance.

References