Porosity and Permeability

Adapted from: "Is It Full Now?" and "How Much Water Can Different Soils Hold?" in Earth: The Water Planet. Gartell, J.E. et. al. Arlington, VA: National Science Teachers Association, 1992.

Grade Level: basic, intermediate

Duration: 60 minutes

Setting: laboratory, classroom

Summary: Students learn about porosity and permeability of various soil materials by conducting simple classroom demonstrations and experiments.

Objectives: Students will learn the difference between porosity and permeability, that these are important characteristics of soil/rock material, and that these vary depending on the type of soil/rock material.

Vocabulary: unconsolidated material, consolidated material, infiltration, unsaturated zone, vadose zone, hygroscopic water, gravitational water, gravity drainage, saturated zone, unsaturated zone, water table, aquifer, porosity, permeability, hydraulic conductivity.

Related Module Resources:
- "Infiltrating the Soil" Activity
- Porosity and Permeability Visual Aids

Materials (Included in Module):
- Clear plastic cups with holes in bottom
- Clear plastic cups without holes
- Containers of sand
- Containers of gravel
- Containers of sediments / clays
- Eyedroppers
- Limited # of graduated cylinders (25mL)

Additional Materials (NOT Included in Module):
- Beakers to determine soil volumes
- extra soil / sediment samples
- water, sink, catch containers

ACADEMIC STANDARDS (ENVIRONMENT AND ECOLOGY)

7th Grade

4.4.7.B. Investigate how agricultural science has recognized the various soil types found in Pennsylvania.
- Explain the importance of particle sizes in different soil types.
- Determine how water has influenced the development of Pennsylvania soil types.

ACADEMIC STANDARDS (SCIENCE AND TECHNOLOGY)

7th Grade

3.2.7.B Apply process knowledge to make and interpret observations
- All subsections apply

BACKGROUND:

Beneath us, groundwater can be found in both soils, sediments, and solid rock. Soils and sediments are considered to be **unconsolidated material**, which is comprised of loose sediments and particles like sand and silts that are not cemented together by minerals. Rocks and bedrock are **consolidated materials**, which have grains of sediment cemented and bound together in a more compact manner. Whether or not groundwater gets into unconsolidated and consolidated materials depends on some of the characteristics of those materials.

The flow of water downward from the land surface into and through the upper soil layers is called **infiltration,** or sometimes percolation. This water can be from precipitation, melting snow, human sources, and in some cases, small streams or ponds. Gravity and water properties are natural forces encouraging infiltration. There is an attraction between soil particles and water that exerts a tension and attraction that draws moisture readily downward into the soil.

Once water infiltrates into the soil, it will move downward through an **unsaturated zone** or **vadose zone**. In this layer of soil, some of the spaces between soil particles are filled with water, and some are filled with air. While the pull of gravity tends to draw water downward, some water does remain between soil particles because of some properties of water – cohesion and adhesion. There is an attraction of water molecules to one another and an attraction of water molecules to soil particles. Often there is a film of water that exists around soil particles called **hygroscopic water**, which can be absorbed by plant roots.

If gravity exerts a force sufficient enough to overcome cohesion and adhesion, the excess water (that is not hygroscopic water) will flow further downward. This water is called **gravitational water** or **free water** and the process is called **gravity drainage**.

Gravitational water that travels downward will eventually reach a soil/rock layer that is completely full of water. This is the **saturated zone**. In this zone, all the pore spaces and voids in the soil and rock are filled with water. The upper boundary of the saturated zone is called groundwater table or simply **water table.** If a hole was drilled below the water table into the saturated zone, water from the surrounding saturated zone would flow into the hole and fill it to the level of the water table.

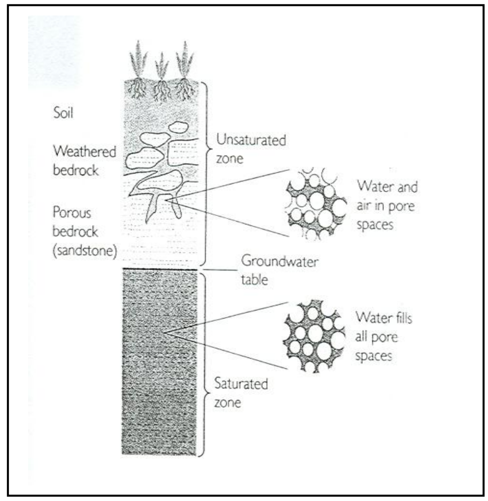
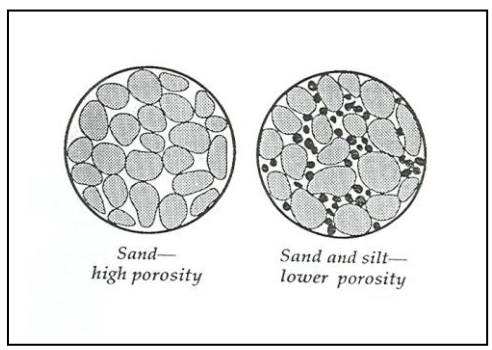


Fig. 1: Water travels downward through the unsaturated zone thanks to gravity drainage. The water table is the top of the saturated zone. The saturated zone can either be composed of soil layers or all bedrock or both.

The saturated zones and beds of material underground that can carry and store water are called **aquifers**. Aquifers can act as storage units able to supply sufficient quantities of water for municipal or household wells. Aquifers can have many different names and characteristics, usually relating to the types of soil and rock that compose them.



As expected, water in saturated zones and aquifers does not stay still. It can move further downward or it can flow horizontally through the saturated zone. There are many factors that influence this water movement underground and the quantity of water stored in these various zones. Some of these factors that influence groundwater movement are discussed below.

The main factor is the amount of space available between particles, sediments, and rocks in the soil layers and spaces between particles in rocks and rock layers. The amount of pore space in soil, sediments, and rock is called **porosity**, which can also be defined as the percentage of a material's total volume that is taken up by pores. This "empty" space has a fantastic ability to hold water that seeps down from the land surface. Material with good porosity can be called "porous". Mathematically, porosity can be expressed as the ratio of the volume of pore space to the total volume of the material as given by the following formula:

$$\%\ \text{porosity} = \frac{\text{Volume of pore space}}{\text{Total volume of sediment}} \times 100$$

Porosity depends on the size, shape, and mixture of grains and particles that compose soil and rock. For instance, small particles such as clays are able to compact more closely together, reducing the amount of porosity. However, larger particles such as sand and gravel will have more spaces available between them. Round particles compacted together will have more spaces than elongated grains that stack more tightly. Particles of uniform size (well sorted) will also have more pore space available than grains of varying sizes (poorly sorted) because small particles can fill in the spaces between the larger grains. Porosity can change between various layers of soil and types of solid rock as you go deeper into the ground.

Porosity and Permeability Ranges for Sediments

	Porosity	Permeability
Well-sorted sand or gravel	25-50%	High
Sand and gravel, mixed, poor sort	20-35%	Medium
Glacial till	10-20%	Medium
Silt	35-50%	Low
Clay	33-60%	Low

From C.W. Fetter, 1994. Applied Hydrogeology, 3rd edition.

In addition to porosity (the amount of pore space), permeability is another important factor needed for groundwater movement to occur. **Permeability** is the measure of how easily water flows through soil or rocks, so it depends on the size of the pore space and how well connected they are to one another. It is often defined as pore interconnectedness and the unit of measurement is usually distance (cm, m, or ft.) per time (second, minute, day). Permeability can also be referred to as **hydraulic conductivity**. Like porosity, permeability can also change between various soil layers and types of solid rocks.

Permeability depends on several factors – grains size of particles and the amount of cracks and fractures. If the sediments or rock particles are composed of very small grains, such as in clays and silts, the space through which water can flow is limited. In addition, clay particles have a lot of surface area to which hygroscopic water attaches, creating a further resistance to fluid movement. If sediments are comprised of coarser grains like sand and gravel, pore space is more available. These coarser grains also have less surface area, so less water can attach to them, allowing better fluid movement. With grains of many sizes, the permeability will be at medium rates. Fine sediments fill in spaces between larger particles, reducing poor space and increasing surface areas to which water can adhere.

For rocks composed of poorly sorted material or fine grains, water movement can be slow unless there are fractures and cracks in the rock. Along roadside rock cuts, it is common to observe groundwater seeping from cracks or forming icicles. Some rocks such as limestone and dolomite can form more than just cracks; water can actually dissolve them causing openings within the rocks to widen, possibly wide enough to become caves.

Keep in mind, sediments that have high porosity and permeability tend to form rocks with the same characteristics; for instance, sands form sandstones and clays form shales. Generally, the greater the porosity, the greater the permeability. Both of these factors are important to consider when determining how much groundwater is stored in our underground layers. If you needed to drill a well to find groundwater to drink, you would hope to find a good groundwater aquifer. It would probably be rock and sediment with high porosity so that it can hold large amounts of water, and high permeability, so the water can be pumped and sucked through the layers easily.

In Pennsylvania, the permeability of rocks and sediments changes over short distances. Therefore, most aquifers in Pennsylvania are considered to be local – the same rock layer may serve as an aquifer in one location but maybe not a few miles away. In Pennsylvania, some of the best aquifers are composed of unconsolidated material (sediments that are loose and uncemented) that have good porosity and permeability. These aquifers can be found in stream valleys, especially in regions that were once covered by glaciers or drain out of these regions. Sand and gravel are deposited by water of melting glaciers, which pushed through the land and left loads of unconsolidated materials. Western Pennsylvania, especially the northwest corner, is lucky enough to have some of these great aquifers that supply vast amounts of groundwater. Many communities along major rivers and creeks use sand and gravel aquifers for their water supplies.

OVERVIEW: Students learn about porosity and permeability of various soil/rock materials by conducting simple classroom demonstrations and experiments. The experiments involve filling containers with various types of soil/rock material and determining the amount of pore space and the permeability for each.

PROCEDURE:

Teachers should note that there is one interactive demonstration and two experiments that can be completed. The demonstration can be done prior to the experiments or afterward as a review. *Experiment #1 – Determining the Porosity of Soil Materials* should be performed before Experiment #2.

Demonstration – People Soil Particles.

1. To teach students about how different sizes of soil/rock particles influence groundwater movement and permeability, select 3-4 students to become water molecules. The remainder of students will represent varying soil/rock materials.
2. The students representing water molecules attempt to pass through 3 different types of soil/rock material: gravel/coarse sand, fine sands, and clay.

3. Gravel / coarse material: To represent this soil/rock material, have "non-water" students cluster in a group, distancing each other an <u>arm-length</u> apart. The water molecule students' goal is to <u>walk</u> through the soil students to the other side of the room.
4. Fine sand material: To represent this soil/rock material, have students place their hands on their hips with their elbows sticking out. Position students so the elbows almost touch their neighbors. Tell students to keep their arms as stiff as possible. Now have the water molecule students <u>walk</u> through the soil students to the other side of the room.
5. Clay material: To represent this soil/rock material, have students place their hands flat against their sides, and then huddle them together in a tight circle with only 6-12 inches separating each students. Warning the water molecule students to <u>walk</u>, they should have a difficult time in traveling through the clay material.

Experiment #1 - Determining the Porosity of Soil Materials

1. Clear plastic cups (with no holes) are needed for this experiment. Gather additional clear cups, containers, or small soda pop bottles as needed. They should be clear so students can view the soil from the side.
2. You may need to have additional soil materials depending on how many cups you want to create for the experiment. Please note, for this experiment, the soil/sand/gravel must be dry.
3. You may want to decide the contents of the various cups prior to the experiment and have this information available to the students. You will also need to determine the consistent volume of cup materials (150-200mL will work). The greater the volume, the better the disparity between the result for the various cup materials. Students can still be responsible for filling the cups with the materials though.
4. You may also need to obtain additional graduated cylinders (small volume) for the experiment.
5. Hand out *Student Worksheet* and have students follow directions on it.
6. At the conclusion of the experiment, you may want students to continue with Experiment #2.

Experiment #2 - Determining the Permeability of Soil Materials

1. Clear plastic cups with lots of holes in the bottom are needed for this experiment. If additional cups with holes in the bottom are needed, teachers may elect to poke holes in the bottom prior to the experiment by using a thumbtack or metal dissecting probe. Keep the approximate number of holes equal between all cups.
2. The soil materials do not need to be dry for this experiment. You can use the cups of soil from *Experiment #1 – Determining the Porosity of Soil Materials,* just dump the soil samples into the cups with the holes in the bottom. However, to be consistent with results, either use all damp soils/sediments or all dry soils/sediments.
3. Hand out *Student Worksheet* and have students follow directions on it.
4. At the conclusion of the experiment, you may elect to keep the soil/sand/gravel for additional future. Have students wash out the cups. Please reuse cups – do not discard.

DISCUSSION:

What is the difference between porosity and permeability? *Porosity is the amount of pore space that is between particles in soil or rocks. Permeability takes this pore space and connects the voids together so that water can pass through. Porosity is more associated with storage of water, while permeability is more associated with groundwater movement and flow.*

What type of soil /rock materials have the best porosity? What type of soil /rock materials have the best permeability? *Usually the larger the consolidated (well sorted) grain size, the better the porosity and permeability (aquarium gravel). If the materials are poorly sorted (lots of different sizes) then it reduces porosity and permeability because smaller grains fall between larger grains, reducing space and flow paths (gravel and sand; sand and clay mixture). Surprisingly, clay can have high porosity too because clay has a greater surface area than sand, therefore, more water can remain in the soil. However, clay has bad permeability. The connectedness between clay particles is low and clay tends to retain water (because of the greater surface area again), slowing gravitational flow downward.*

If you could only dig a <u>shallow</u> well to obtain groundwater, why might digging into a soil/rock type that has high porosity and high permeability be a poor choice for obtaining a sufficient water supply? *Since the soil/rock type has high porosity and permeability, water may move downward from gravity through the rock layer into lower layers. A shallow well may not pull up a sufficient supply as compared to a deeper well. A shallow well may be better suited in a layer with high/medium porosity and medium permeability.*

Gardeners in Western Pennsylvania may add sand to their garden soil. Why do they do this? *Some surface soils in the area have a high clay content (very small particles), so they have high porosity but low permeability. Adding sand helps increase the average soil particle size, increasing the permeability. More water can be retained in the clay/sandy soil for plants to use and water will drain better through the soil if it has more sand. High clay content retains water much longer, which might end up being too much water for your plants. Also, wet clay soil does not let water drain into it (infiltrate) as quickly, so instead of soaking into the ground, water may just wash away at the surface or worse yet, puddle at the surface. Adding sand helps alleviate this from occurring.*

Questions from the worksheet could also be used for discussion.

EVALUATION:

- Students will correctly calculate the porosity of various soil materials.
- Students will compare the porosity and permeability of soil materials.
- Students will understand why certain factors in the experiments are kept constant (ie. same volume of water used, same volume of soil materials, using all wet sediments vs. some wet, some dry).
- Worksheet questions

EXTENSIONS AND MODIFICATIONS:

- Instead of using the cups for the experiments, you can use the 1.5 ft. long plastic tubes that have one hole in the bottom instead. Cover the hole with tape for the porosity experiment. For the permeability experiment, uncover the hole, tilt the tubes at a consistent angle, and have the hole at the bottom face upward as to not lose any of the sediment sample inside.
- Test various types of soil collected around the school or from student's homes.
- Test different volumes of soil material to see how the porosity changes at different volumes and to see if the difference between various soil materials is more apparent at greater volumes.
- In the permeability experiment, have students test dry soil material vs. wet soil material.
- You may elect to conduct the "Infiltrating the Soil" experiment also because it uses the same materials.
- Have students use geologic maps or soil survey books to research the types of soils that they have in their area. Have them predict if these different soils would have low, medium, or high porosity and permeability. Relate this information to the experimentation completed.

NOTES (PLEASE WRITE ANY SUGGESTIONS YOU HAVE FOR TEACHERS USING THIS ACTIVITY IN THE FUTURE):

Activity edition / update: March 2003