Groundwater Principles: A Hands-On 3-Dimensional Classroom Activity to Determine Groundwater Flow Direction & Gradient

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Abstract

A groundwater hydrology course provides insight into fundamental theories and properties of groundwater flow through aquifers. Determining direction of groundwater flow as well as gradient is an important aspect within the course. A widely used technique to determine flow direction and gradient is known as the “three-point problem”. Solving a three-point problem requires knowing the groundwater elevation of three points that are not in a straight line, and the distances between the three points. The three-point problem utilizes simple geometry principles to determine both the direction of flow and gradient. In geometry, three points define a plane; knowing the groundwater elevations defines the plane in hydrogeologic space, allowing the inclination/gradient to be determined. Basic groundwater principles state that groundwater flows down-slope in aquifers, allowing direction of flow in a homogeneous, isotropic aquifer to be determined using this method.

This paper shows how utilizing a 3-dimensional hands-on activity can be more engaging than a traditional lecture. To better visualize the three-point problem, a hydrogeologic system is simulated in a classroom setting using low-cost materials which can be commonly found at hardware stores. Required materials consist primarily of PVC pipes and fittings, string/yarn, and a measuring device. The low-cost and simple technology requirements of the activity can be easily re-created at other educational institutions. The activity allows students the opportunity to apply what they’ve learned and visually see what is occurring in a 3-dimensional space, as opposed to simply solving the problem graphically in 2-dimensions on paper. Pipes are placed from floor to ceiling in a classroom, and string is used to mark the groundwater depth on each pipe. The ceiling acts as ground surface and everything in the room is considered to be below-ground. String is also used to mark the isocline line as well as the sloped groundwater flow line.

Keywords

hydrogeology, hydrology, water resources, geoscience, wells

Introduction and Background

Mercer University’s Environmental Engineering and Engineering for Development programs have been incorporating low-cost field testing and exploration methods for the past several years, including manual drilling techniques[1] and inexpensive geophysical testing techniques. Other course activities have also included a focus on well-testing laboratories using manual pumps.[2]

The purpose of developing the teaching activity presented in this paper is to help students in visualizing and understanding groundwater flow direction and gradient, using a 3-dimensional (3-

D) version of a ‘three-point problem’ that can be set up in any classroom using basic materials. The activity is designed so that various problems can be solved, by moving pipes to different locations within the room and/or altering well water-level elevations.

The current method commonly used to solve three-point problems is done graphically, on paper.[3,4] This method requires students to solve a 3-D problem in 2-dimensions by drawing and connecting points, using a ruler to measure distances and a protractor to measure flow direction. The 2-D method does not provide students the ability to fully visualize how it is applied to wells and groundwater, which are already challenging to visualize and teach since they occur below ground surface.

Mercer University’s Groundwater Hydrology course presents students with fundamental theories and properties of porous media, groundwater movement, and geological factors. The course emphasizes development of fundamental governing equations and the determination of aquifer formation constants. The design of production and monitoring wells and the development of aquifer testing plans are introduced. The three-point problem is taught in the groundwater movement module of the course.

The objective of three-point problems is to determine the direction and gradient of groundwater flow using three separate piezometric head measurements. This method is valid when the 3-D space within the three points is isotropic and homogeneous, that is, when the hydraulic conductivity is the same in all directions and aquifer parameters are constant throughout the medium. The only data required is the water level in three wells and the well locations relative to each other. Through mathematical interpolation, the isocline, or the line along which all points have an equal piezometric head, that passes through the well with the medium-well-water-depth can be estimated. The isocline is an essential component because it is used to find the direction of flow. The flow direction line is perpendicular to the isocline and passes through the point with the lowest piezometric head (i.e., the well with the deepest water level). It is a vector that points towards the point (well) of lowest elevation, and has a magnitude and a slope (referred to as gradient).

In determining the direction of groundwater flow, it is understood that groundwater flows down-gradient. Knowing the magnitude and direction of this groundwater flow line can help with characterization of groundwater contamination (fate and transport) and is a consideration for determining the placement of monitoring wells.

Methods

Materials

The materials required for this hands-on activity are low-cost and can be found in any hardware store. The length of PVC pipes needed is variable, depending on the classroom ceiling height. The following materials were primarily used to complete this activity:

- 40 feet of ¾” PVC pipe
- PVC connectors
- String (thick yarn)
- Scissors
- Tape

- Chalk
- Marker (ideally one that is not permanent, but that will stay on the pipe surface until it is washed off)
- Measuring tape
- Protractor
- Stepping stool

Procedures

The three-point problem activity can be set up in any classroom and manipulated to create numerous different scenarios. The following steps were used to set up and solve a given problem/assignment.

1. Once all materials are collected the system can be set up as follows:
    a. Use chalk to make marks on the ceiling representing the locations of the three wells; these can vary between problems/assignments.
    b. Connect two 5' PVC pipe sections together with a PVC connector (Figure 1 shows a modified t-fitting that held the two sections in-place). Another option is to connect two threaded PVC pipe sections with a threaded connector.
    c. Wedge the connected PVC pipes in between the floor and the chalk-marked-point on the ceiling. To ensure a tight fit, use another connector at the top that can be manipulated. Alternatively, if using threaded PVC pipes and a threaded connector, the minute height adjustment can be achieved by slightly/gradually (un)threading the two pipes at the mid-point.
    d. Repeat this process for the other two wells (as shown in Figure 1).

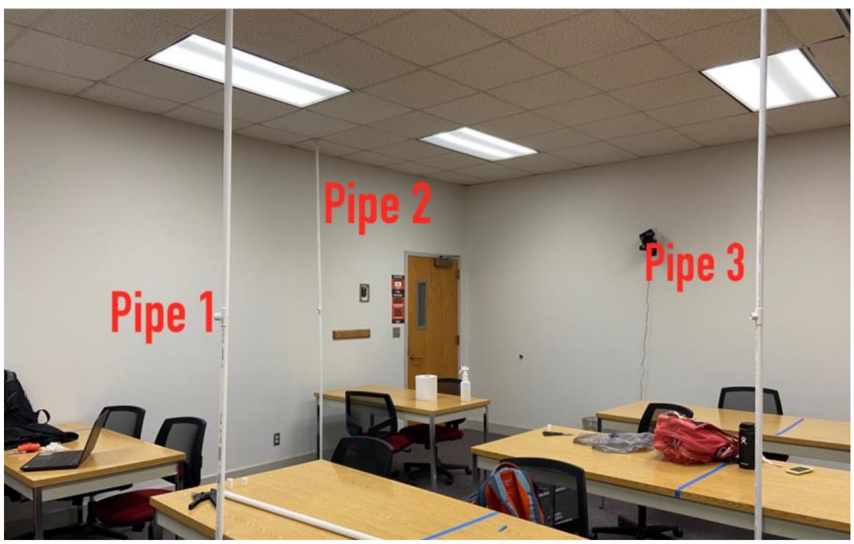

Figure 1: Pipes 1, 2, and 3 in the classroom represent the below-ground-extent of three wells in a groundwater system. The ceiling represents ground surface. This setup allows students to clearly visualize each well, and the corresponding depth to water level, in 3-dimensional space.

2. The piezometric head of each well (measured from the floor) is provided in a problem statement, and marked on the respective pipe.

With the three points set up, the following steps should be followed to solve the problem and determine groundwater flow gradient and direction:

3. Determine the gradient from the well with the lowest water level to the well with the highest water level.
    a. Identify the well with the lowest water level and the well with the highest water level by identifying the smallest and largest elevations, respectively, written on the PVC pipes.
    b. Fix one end of string to the marked elevation on the well with the lowest water level.
    c. Extend the other end of the string until it is fixed at the marked elevation of the well with the highest water level. Attach the string to both PVC pipes by using a knot and/or tape to hold each end in place (Figure 2). This is *Yarn 1*.

Figure 2: The gradient from the shallowest to the deepest wells is represented by Yarn 1, which connects their respective piezometric head values (marks on the PVC pipes).

    d. Measure the **horizontal distance** between the well with the lowest water level and the well with the highest water level, using a measuring tape. This value is the ΔL term for the first interpolation. (Note: this horizontal distance may be most easily measured along the ground – it is *not* the same distance as the sloped distance of *Yarn 1*. Another length of string, *Yarn 2*, can represent this horizontal distance.)
    e. Use the ΔL value and the change in height, ΔH, between the two wells to determine the initial flow gradient using the following equation:

$$i_1 = \frac{\Delta H_1}{\Delta L_1}$$

Where,

i_1 = gradient between wells with lowest and highest water levels

ΔH_1 = change in elevation between wells with lowest and highest water levels

ΔL_1 = horizontal length between the wells with the lowest and the highest water levels

4. Identify the isocline of the well with the intermediate water level.
   a. Using gradient i_1, calculated in Step 3, use mathematical interpolation to find the point between the well with the lowest water level and the well with the highest water level (represented by *Yarn 1*) that has a piezometric head equal to that of the well with the intermediate water level. The following equation can be used:

$$\Delta L_2 = \frac{\Delta H_2}{i_1}$$

Where,

ΔL_2= distance from the well with the lowest level and the isocline elevation, along the horizontal line (represented by *Yarn 2*)

ΔH_2= change in elevation between well with the lowest water level and the well with the intermediate water level

   b. Measure this calculated value, ΔL_2, starting from the well with the lowest water level, and mark it on *Yarn 2* using a marker. Install a 4th pipe vertically (floor to ceiling) at this mark on the string, attaching *Yarn 1* to it (Note: this pipe is not shown in the figures, and is used to stabilize the strings, allowing them to be taut.)
   c. Using another length of string, connect the marked point on *Yarn 1* (at the 4th pipe) to the marked elevation of the median well. This length of string, *Yarn 3*, should be **horizontal** since it represents the isocline for the water level of the intermediate (median) well. (Figure 3)

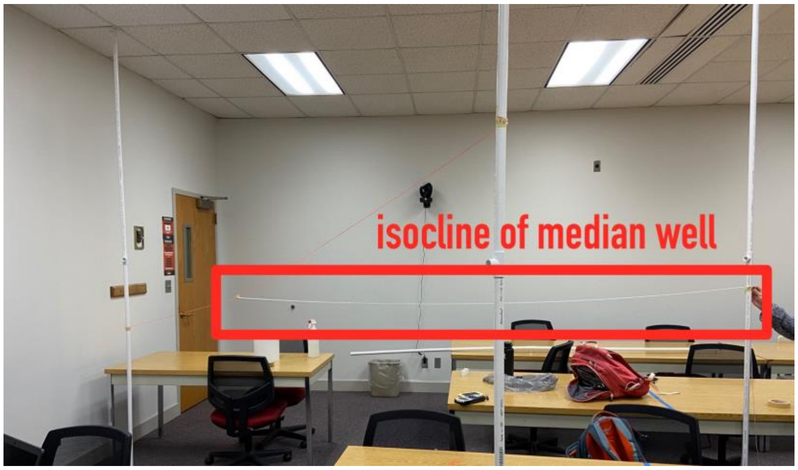

Figure 3: The isocline for the median well (Yarn 3) is represented by a horizontal string which connects the intermediate well's piezometric head value to the same head value on the gradient line (Yarn 1, which connects the deepest to shallowest wells).

5. Connect a fourth length of string, *Yarn 4*, that is perpendicular to the isocline and passes through either the well with the lowest water level or the well with the highest water level. This is the groundwater flow vector.

   Note: Convention dictates that a positive flow value should point towards the direction of the well with the lowest water level (i.e., with the lowest piezometric head).
6. Install a fifth length of string, *Yarn 5*, that measures the horizontal distance from the isocline to either the well with the lowest water level or the well with the highest water level.
7. Calculate the system's overall **flow gradient**, i_{FLOW}, using the equation below. To find this value, measure the length of *Yarn 5* (from Step 6), which is denoted as L_{FINAL}. Now, calculate ΔH between the two pipes attached to *Yarn 5*. This is your ΔH along your flow vector, denoted here as ΔH_{FINAL}. If a scale is provided in the problem statement, then multiply your gradient by the scale value to calculate the final flow gradient, i_2.

$$i_{FLOW} = \frac{\Delta H_{FINAL}}{\Delta L_{FINAL}} * scale(optional, provided\ in\ problem\ statement)$$

   Where,

   i_{FLOW} = overall flow gradient of the system

   ΔH_{FINAL} = change in head along measured flow vector

   ΔL_{FINAL} = horizontal distance along measured flow vector

8. Determine the system's **direction of flow**. The problem statement should note a point in the classroom to use as North. Using a protractor, measure the degrees clockwise from North for the direction of flow.

Teaching Activity Results

This hands-on activity proved to be an effective way of helping students learn about groundwater flow – helping them better visualize the 3-dimensional underground context. One group of students built the setup and completed the 3-point problems for themselves, while two other student groups completed example problems developed by the first group. A narrated introduction video was produced by the first group, since the number of students in the room carrying out and/or observing the activity was extremely limited due to the ongoing COVID-19 pandemic. Students reported finding the 3-dimensional hands-on activity to be engaging, thought-provoking, and memorable. This activity can be replicated in or adapted to any room, and all materials are low-cost and commonly available at local hardware stores.

References

1 Resto, M. C., MacCarthy, M. F., and K. E. Trout (2017) Low-Cost Groundwater Development: Manual Drilling in Academic Research and Training, *2017 American Society for Engineering Education Zone 2 Conference*, San Juan, Puerto Rico, March 2017. http://zone2.asee.org/sessions/program/3/111.pdf

2 MacCarthy, M. F., Bowers, C. E., Graham, M. E., Conlon, A. M., and M. C. Resto-Fernández (2021) Groundwater Hydrology: Using Manual Water-Lifting Devices in Groundwater Pumping Labs, *2021 American Society for Engineering Education Southeast Conference*, March 2021.

3 Heath, R. C. (1983) Basic Ground-Water Hydrology, U.S. Geological Survey Water Supply Paper 2220. http://pubs.er.usgs.gov/publication/wsp2220

4 Beljin, M., Ross, R. R., & S. D. Acree (2013). 3PE: a tool for estimating groundwater flow vectors. EPA.

Biographical Information

Michael F. MacCarthy, PhD, is an Associate Professor of Environmental and Civil Engineering at Mercer University, where he directs the Cecil Day Center for International Groundwater Innovation and the Engineering for Development program (e4d.mercer.edu). His research and teaching interests include: low-cost environmental health technologies; sustainable groundwater development; self-supply in energy and water; mobility and accessibility; energy poverty; technology design and introduction/transfer; green engineering; and effecting behavior change.

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