An Active Learning Exercise for Introducing Ground-Water Extraction from Confined Aquifers

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ABSTRACT

The concepts of total stress, effective stress, and fluid pressure are important to understanding where water comes from when producing water from a confined aquifer system. However, the overall conceptual image of pumping confined aquifers is difficult for many students to grasp, because pore space is not drained, but rather water is produced as a function of the water and aquifer compressibilities. I present a simple, inexpensive demonstration, which can be used to help students visualize the interplay between stresses and fluid pressure when pumping a confined aquifer, and can be incorporated into a standard class period of an introductory hydrogeology class. This exercise uses a juice container as a simple analog for a confined pore space, and demonstrates how a decrease in fluid pressure from pumping causes an increase in effective stress assuming a constant total stress, potentially leading to subsidence.

INTRODUCTION

Macdonald et al. (2000) highlight the importance of quantitative skills in the classroom. Many students are comfortable "plugging and chugging" with equations; however, not developing an intuition for the processes described by the mathematics can prevent students from understanding their results. While the mathematics describing the extraction of water from confined aquifers is not difficult, understanding how water is extracted from confined aquifers is a challenge for many students, who find the concepts of water expansion and aquifer contraction-the controlling phenomena in removing water from confined systems-more difficult than the simple draining of pore space that occurs in unconfined aquifers. Providing students with a hands-on experience helps them to develop an intuitive understanding of the relationship between total stress, effective stress, and fluid pressure-the controlling components of confined-aquifer groundwater extraction. I describe a short demonstration that is simple, inexpensive, and memorable.

FLUID FLOW AND AQUIFER CHARACTERISTICS

Groundwater in the subsurface moves according to its total energy, which is the sum of its kinetic energy, potential energy, and elastic energy (fluid pressure). The total energy required to move a unit weight of water is defined as the hydraulic head, h [L],

$$h = \frac{v^2}{2g} + z + \frac{P}{\rho_w g} \qquad (1)$$

where v is the groundwater velocity [L/T], g is the gravitational acceleration [L/T^2], z is the elevation of the fluid above the chosen datum [L], P is the fluid pressure [M/LT^2] , and w is the density of water [M/L^3]. The velocity component in groundwater is generally so small that the first term on the right-hand side, the kinetic energy term, is ignored. Groundwater moves from locations of higher hydraulic head to areas of lower hydraulic head-not from high pressure to low pressure. I digress briefly here to note that it is worthwhile and commonly necessary to disabuse students of the misconception that water moves from areas of higher pressure to areas of lower pressure. Consider a glass of water. Although there is no movement of water inside the glass, the pressure obviously increases with depth according to $P = wgl$, where l is depth from the water surface. The increase in pressure head ($P/\ wg$) with depth is countered by the equivalent decrease in elevation head (z); hence the head is equal throughout the column and there is no movement of water.

To extract water from an aquifer for use, we can pump a well, which leads to a local decrease in the hydraulic head. The volume of water that can be removed from any aquifer is dependent on the subsurface material's ability to store water,

$$V = SA\Delta h \qquad (2)$$

where V is the volume of water removed [L^3], S is the storage coefficient of the aquifer [dimensionless], A is the surface area overlying the unconfined aquifer [L^2], and h is the decline in head.

In unconfined aquifers, which have no impermeable material overlying them, water is removed from the aquifer by a decrease in hydraulic head that occurs from draining the pore space. The storage coefficient for an unconfined aquifer is defined largely by the amount of water that is available to be drained, and is therefore somewhat less than the porosity. If an aquifer is overlain by low-permeable material and the head in the aquifer is above the top of the aquifer, it is termed a confined aquifer. Because groundwater cannot easily move out of or into many confined aquifers, the water is usually under greater pressure than in an unconfined aquifer of similar depth. When wells are drilled into confined aquifers, the water level will rise above the top of the aquifer unit due to this pressure, which is known as artesian conditions. When extracting water from a confined aquifer, pumping will lead to a decline in head, but the aquifer itself may remain saturated. Importantly, extraction of water from confined aquifers is not associated with dewatering; i.e., no pore space is drained, no rock or soil dries out. So where exactly does this water come from?

O.E. Meinzer, upon observing flowing artesian wells, where the pressure in the confined aquifer is high enough that the water level rises above land surface, was the first to predict that confined aquifers were compressible, and storage in these aquifers was described by the elasticity of the subsurface material

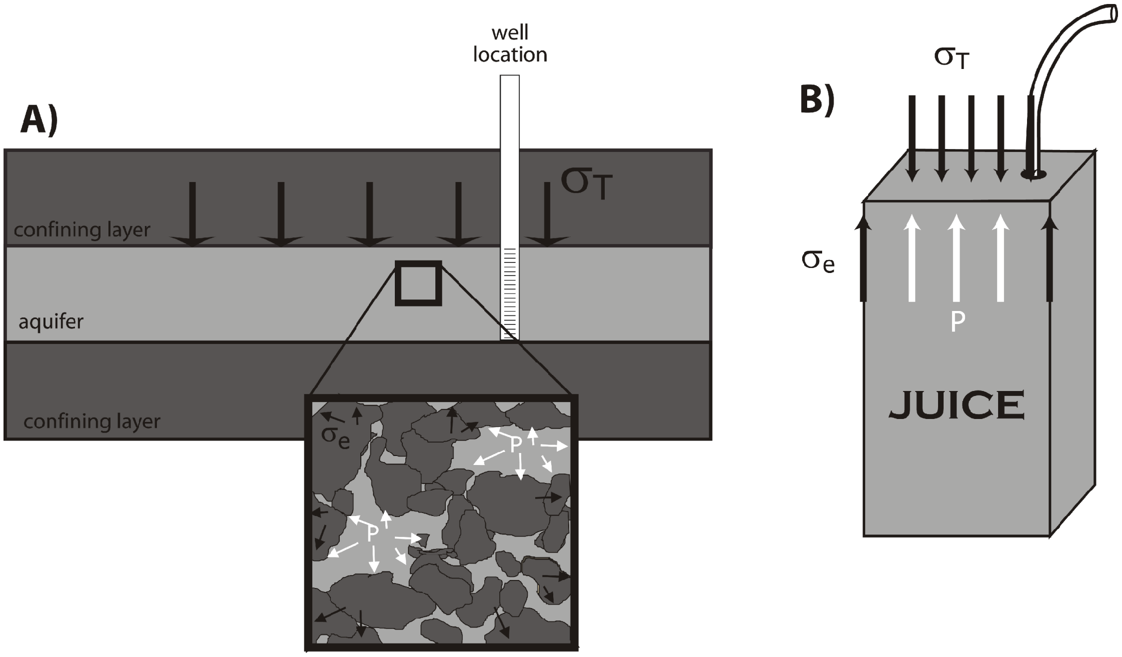

Figure 1. (A) Schematic of a confined aquifer system, with the total stress, σ_T, from the weight of rock and fluid above acting on the aquifer, which is countered by the effective stress, σ_e, of the aquifer skeleton and the fluid pressure, *P*, within the pore space; and (B) the analog confined pore.

(Narasimhan, 2006). Elasticity describes how easily a material deforms under stress and returns to shape in the absence of that stress, and is important in groundwater hydrology. When fluid pressure in the subsurface increases, the skeleton of the aquifer expands; conversely, a decrease in fluid pressure, which would occur during pumping, will lead to aquifer compression, and potentially subsidence, as described later. Meinzer proposed that the release of water in confined aquifers was a function of the elasticity and compressibility of the aquifer, especially in "aquifers that have low permeability, slow recharge, and high head" (Meinzer, 1928).

The storage coefficient in a confined aquifer is defined by the compressibility of the aquifer skeleton and the expansion of the pore fluid as defined by Jacob (1940):

$$S = \rho_w g b(\alpha + n\beta) \qquad (3)$$

where b is the aquifer thickness [L], α is the compressibility of the aquifer [LT^2/M], n is the porosity [L^3/L^3], and β is the compressibility of water [LT^2/M]. This elastic storage coefficient is much less than the storage available in an unconfined aquifer. Compressibility describes a change in volume under an applied stress. In the case of water, this stress is applied through the fluid pressure, such that

$$\beta = -\frac{\Delta V_w / V_w}{\Delta P} \qquad (4)$$

where an increase in the volume of water V_w [L^3] is a function of a decrease in fluid pressure. Similarly, an increase in the volume of an aquifer V_T [L^3] is a function of a decrease in stress carried by the soil skeleton, called the effective stress σ_e [M/LT^2], where

$$\alpha = -\frac{\Delta V_T / V_T}{\Delta \sigma_e} \qquad (5)$$

As shown in equation 3, it is the combination of these compressibilities that contributes to the aquifer storage and consequently the volume of water that can be extracted. In highly compressive aquifers, like clays, can be quite large compared to β, and most of the water comes from aquifer compression. Alternatively, β dominates in cases of very competent bedrock.

The effective stress and fluid pressure are simply related to one another in the case of a saturated porous media under equilibrium stress conditions as

$$\sigma_T = \sigma_e + P \qquad (6)$$

where the total stress on an aquifer, σ_T [M/LT^2], is defined by the weight of rock and water above the aquifer. The total stress pushing down on the aquifer is borne by both the aquifer skeleton (the effective stress) and water filling the pore space (the fluid pressure), as originally described by Terzaghi (1936). In the simplified case of a confined aquifer where the weight of the overlying rock and water is considered constant such that the total stress doesn't change, the effective stress must increase as the fluid pressure drops from pumping. A reduction in fluid pressure causes 1) the fluid to expand according to equation 4, and 2) an increase in effective stress (equation 6) because the total stress remains constant. The increase in effective stress causes the aquifer materials to compress (equation 5). The combination of these responses-the compression of the aquifer and the expansion of the fluids-leads to the production of water. Additionally, the increase in effective stress that occurs during pumping to compensate for the decrease in fluid pressure may lead to subsidence depending on the compressibility of the aquifer.

The interplay between total stress, effective stress, and fluid pressure define the extraction of water in confined aquifers. The volume of water that can be removed from these aquifers will be dependent on the material composition of the aquifer and the expansion of water. While these concepts are outlined fully in hydrogeologic textbooks (e.g., Freeze and Cherry, 1979, Domenico and Schwartz, 1990, Fetter, 1994), understanding the interplay between these stresses is difficult for many students, who may not be able to 1) visualize the removal of water from the subsurface without draining pore space, and 2) conceptualize the connection between ground-water mining and subsidence. Few hands-on exercise exist for demonstrating the concepts, and the simple hands-on demonstration described here has been found to help students new to these concepts.

CONFINED AQUIFER DEMONSTRATION

This demonstration has been used in a 40-student hydrogeology class composed of upper-level undergraduates and graduate students, and requires only a cardboard juice box or a compressible metallic juice "bag")-the kind that can be purchased at the supermarket and comes with a straw (Figure 1). Each juice container has its benefits: the box is less compressible and withstands a higher effective stress; however, one concern about the juice box is that without enough total stress applied, it has the possibility of dewatering, which would be an inappropriate analog for a confined aquifer. The collapsible juice bag may prevent such misconceptions, but is able to withstand less effective stress. Students are asked to select a partner (or two) and each student is given a juice container, which, for the purposes of this demonstration, is now considered to be a single pore in a confined aquifer. Students are asked to answer a series of prescribed questions in groups after an introduction to the concepts of total stress, effective stress, and fluid pressure as highlighted in the last section.

Before inserting the straw, students are asked to apply a downward force on the top of the juice container by pushing it against a hard surface. It is important that the students maintain this force during the experiment so that they are not misled into thinking that they are dewatering the pore space during fluid removal. They are now providing the "total stress" on their aquifer, or the weight of the overlying materials. In groups, the students are asked to discuss two concepts: 1) why the container does not collapse with the application of this total stress, and 2) what will happen with the straw is inserted, depending on the amount of force that is applied. After writing out their reasoning on a pre-made worksheet, they "drill" their confined aquifer and insert their well (the straw). After inserting the well into the aquifer, they withdraw fluids via pumping (drinking), while still providing a force from above, which leads to a decrease in the volume of the aquifer (container) as the total stress is continuously applied. Students are asked to discuss what happens to their confined aquifer during the removal of fluid.

The goal is for the students to see that the container does not collapse prior to pumping despite the application of the total stress because the effective stress (the container itself), and the fluid pressure in the pore space (the juice) push back against weight of the overburden (their hand); aquifers are similarly supported by fluid pressure and aquifer strength from the weight of overlying rock. Many note that when the straw is inserted, that fluid will spray out due to the total stress. This provides an opportunity to discuss flowing artesian wells, which are under high enough pressure that the height of fluid rises above the aquifer itself and comment that if the applied force is not that high, juice may rise in the straw above the height of the juice container, but not flow freely.

After having had the opportunity to develop the vocabulary required to describe pumping in confined aquifers, we can return to the mathematics described earlier. All of the students recognize that the juice container collapses as the fluid pressure is released, given a constant applied total stress. The relationship between the total stress applied by their hand and increase in effective stress is clear. We can return to equation 6, and note that because the total stress is remaining (approximately) constant, the change in effective stress and fluid pressure must be equal and opposite. As the effective stress borne by the skeleton increases, the fluid pressure must be decreasing, as expected.

Subsidence can also be discussed here; the aquifer compression leads to subsidence (the eventual collapse of the container) given the highly compressible aquifer material and the increase in effective stress. Students can explore equation 3, which describes the amount of water that can be released as a function of aquifer and fluid compressibility. Assuming that we're dealing only with water-filled aquifers and that fluid compressibility remains constant, the group can discuss how storage would change with a more or less compressible aquifer. Students understand that with a more compressible juice container, fluids would be easier to produce. Similarly, more water will be extracted from systems where the aquifer compressibility is higher than the water compressibility. The problem, of course, is that clays and silts compress easily, but may not easily return to their original shape. The idea of subsidence control wells may also be demonstrated by asking the students to discuss with one another what would happen if we could "re-inject" the removed fluids back into the pore space (e.g., Phien-wej et al., 1998). To re-inject fluids into the aquifer, all we need is to exceed the head in the aquifer; in the case of an artesian but non-flowing well, it would be sufficient to just drop water down a well in order to have higher head than in a deep aquifer-it is not, as mentioned earlier, a matter of exceeding in-situ pressure counter to some students' intuition. Although pressure head may be high in deep aquifers, elevation head is relatively low. The restoration of the aquifer toward its original shape will depend on the geologic conditions of the aquifer, specifically how elastic (recoverable), as opposed to inelastic (permanently deformed) the subsurface materials are. Our juice container would likely return, in part, to its original form; the juice bags are more elastic than the juice boxes and recover more easily. In reality, recharging an aquifer may not result in a notable recovery of the land-surface elevation.

Representative student feedback after the first exam about this demonstration was that "…the juice box analogy and flow through different mediums [sic, referring to Darcy tube experiments] really helped for the test", "the [juice container] analogy was helpful for a physical comparison…handling the juice box did help to remember the concept", and "Hi-C box = awesome. I used it to study, to mentally review the concept!" Other students, semesters later, have commented that they still remember how fluids are removed from confined aquifers. The most satisfying result was that almost all of the students in this class, after the demonstration, were able to explain how water produced from an unconfined aquifer differed from a confined aquifer on the exam, and could accurately describe the interplay between effective stress, total stress, and fluid pressure. This demonstration has proven effective in classrooms with both undergraduates and graduate students. It provided both a conceptual tool and "hook" to engage students, and provided a platform to which more advanced concepts could be related.

SUMMARY

I provide an inexpensive and simple hands-on exercise using juice containers to allow students to better conceptualize the relationships between fluid pressure, total and effective stress, and subsidence when pumping confined aquifers. After providing an overview of confined aquifers, stress, and storage, the students work through a short worksheet in groups of 2-3 to discuss how water is produced from an aquifer under confining pressure given a physical analog. Students work in small groups to prompt discussion, which allows them to build a vocabulary regarding stress, pressure, and confined aquifers as needed. By extracting the fluid (juice) from their confined aquifer system (juice container), students can visualize the connections between the applied total stress, the effective stress of the aquifer skeleton, and the fluid pressure. The juice container is a useful analog because students can see that the aquifer is not dewatered, but rather compressed due to the weight of the overlying material, and provides a memorable demonstration that they may think about every time they're handed a juice container.

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