ground water

Technical Commentary/

The Water Table

by Thomas L. Holzer

The water table is a fundamental concept in hydrogeology, yet it is frequently incorrectly defined. For example, both the NGWA (2003) and AGI (Neuendorf et al. 2005) glossaries define the water table as the atmospheric pressure surface that is coincident with the top of the zone of saturation. This definition is also found occasionally in groundwater textbooks as well as in primers, where it is simply defined as the top of the zone of saturation. This incorrect definition of the water table perpetuates an important conceptual misunderstanding in hydrogeology that the top of the zone of saturation is uniquely related to the water table. This commentary reviews the correct definition of the water table and addresses evidence for unsaturation beneath the water table.

To avoid confusion about terminology in this commentary, I adopt the term saturation to refer to the fraction of pore space that is filled with water. This physical definition implies that the pore space in saturated sediment is filled with water. Saturation is a parameter that can be directly measured. For discussion purposes, I am also only considering regional, not perched, water tables. A perched water table by definition must overlie a regional water table and presumably an unsaturated zone in most cases.

The persistence of this incorrect definition of the water table is impressive because we have known for almost 70 years that it is wrong. Hubbert (1940) demonstrated in his classic paper, "The theory of ground-water motion," that the water table is a pressure surface where pore-water pressure is at local atmospheric pressure. Hubbert argued that this is the condition required for pore-water to flow into an open uncased well in an unconfined aquifer that just penetrates this surface. If the pore-water pressure is less than atmospheric, water will not flow into the well. If the pore-water pressure is greater than atmospheric, pore water will flow into the well until the free surface of the water standing in the well is at the level of the local atmospheric pressure surface. Hubbert's analysis implies nothing about saturation.

Ironically, the potential for saturated conditions above the water table in violation of the definition is generally accepted and frequently described in groundwater textbooks. Acknowledgment of this exception dates back to Meinzer (1923) who described the capillary fringe and the possibility of saturation above the water table. Pore-water pressure is subatmospheric in the capillary fringe, and pore water cannot flow into open holes in this zone. Gillham (1984) provides a particularly instructive description of the capillary fringe.

But what about unsaturation below the water table? Other than unsaturation beneath perched water tables, groundwater textbooks are silent. Yet there are published hydrogeological and geophysical investigations that document unsaturation beneath regional water tables. Ronen et al. (1989, 2000) conducted a comprehensive investigation to measure the variation in saturation in both the capillary fringe and beneath the water table. Unsaturated conditions prevailed in the shallow region below the water table in their field area. At least two geophysical investigations document unsaturation beneath the water table as well (Bonnet and Meyer 1988; Holzer and Bennett 2003).

My first exposure to unsaturation beneath the water table was when my ignorance of this possible condition led me to misinterpret a series of seismic refraction surveys in an alluvial valley in central California (Holzer and Bennett 2003). I initially interpreted refraction from the top of the zone of saturation, which ranged from 1.7 to 5.2 m below the water table, to be from a stratigraphic contrast. When subsequent cone penetration testing failed to detect the stratigraphic contrast, it was the P-wave velocity and the velocity structure as revealed in a crosshole seismic survey that provided evidence that the refractor was the top of the zone of saturation (Holzer and Bennett 2003). Seismic velocity is a powerful parameter for detecting unsaturated sediment. The P-wave velocity of saturated unconsolidated sediment ranges

Engineering Geologist, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025; (650) 329-5637; fax (650) 329-5163; tholzer@usgs.gov

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approximately from 1500 to 1800 m/s, varying inversely with porosity; it decreases precipitously as sediment desaturates (Allen et al. 1980). This sensitivity is so widely accepted in geotechnical engineering that the P-wave velocity of a soil specimen is sometimes used in laboratory experiments to determine if the specimen is saturated.

The absence of comprehensive field explorations for unsaturated zones beneath regional water tables leaves open the question of how common they are. It also would be interesting where they occur to know their magnitude and how such conditions can be created and maintained. A few potential causes of unsaturation appear plausible (Ronen et al. 2000). First, air may be entrapped either during the recovery of a water table after a decline or from surface recharge. I suspect that natural water-table fluctuations caused the unsaturation observed in the alluvial valley in California, in which case unsaturation beneath water tables may be fairly common. The study area had been subjected to severe droughts that presumably caused large water-table declines comparable to the differences that I observed between the water table and top of the zone of saturation. The result of such a fluctuation can be anticipated from wetting curves of porous media, which predict entrapment of air during rewetting or imbibition (e.g., Gillham 1984). And second, gases generated by bacterial decomposition of either dissolved or buried organic matter may displace water from the pore space. This is commonly observed in the shallow marine environment (Claypool and Kvenvolden 1983).

My main point is that the water table should be defined only as the pressure surface where pore-water pressure is at local atmospheric pressure. Its definition should not refer to saturation. The top of the zone of saturation may be above, at, or below this surface. If a definition for a nontechnical audience is required, the surface connecting water levels in dug or shallow open wells will suffice in most cases. In fact, it is instructive to note that the definition of the water table as a pressure surface logically follows from how it is measured.

The proposed correct definition of the water table highlights a related semantics problem regarding the word saturation. If an unsaturated zone is present beneath the water table, it is inappropriate to refer to equations for flow in this zone as the saturated flow equations. Hydrogeology may be stuck with a dichotomy unless nonsaturation-specific terminology is adopted to describe the flow below the water table. It may be reassuring to know that geotechnical engineering lives with a similar dichotomy. Engineers apply the phrase "unsaturated soil mechanics" to the capillary fringe with full awareness that the capillary fringe is essentially saturated (Fredlund 2006). Regardless, I recommend that hydrogeology be rigorous in defining the water table as only a pressure surface because the presence of a gas phase below the water table has important practical implications. Ronen et al. (1989) point out how bubbles can reduce hydraulic conductivity and cause an essentially stagnant water layer below the water table. My seismic refraction surveys demonstrate the importance of being aware of the possibility of unsaturation beneath the water table in geophysical interpretations.

In closing, I acknowledge the complication introduced when the gas phase above the water table is not in equilibrium with local atmospheric pressure. This can be caused by wetting fronts (Weeks 2002), atmospheric pressure fluctuations (Elberling et al. 1998), and tidal loading (Jiao and Li 2004). However, I do not think any of these field conditions invalidate the definition of the water table as a pressure surface. They simply highlight natural complexities associated with the deceptively simple concept of the water table.

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