TRANSPORT PHENOMENA AND VULNERABILITY OF THE UNSATURATED ZONE

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Summary

This article provides a detailed overview of transport phenomena in the unsaturated geologic media above the regional groundwater table. We generally refer to this portion of the subsurface environment as “the unsaturated zone” or “the vadose zone.” When considering these transport phenomena, we pay particular attention to how they relate to the vulnerability of the unsaturated zone to natural and anthropogenic perturbations. The reader will find that the transport phenomena identified and discussed are actually relevant to many if not all of the topics and technical articles compiled for the Groundwater theme area of the EOLSS. In fact, such connections are implicitly woven into the organization of the EOLSS Groundwater theme. Following this topic-level summary a number of technical areas related to this topic are considered in detail by experts in these fields, including:

- physical properties of solid and fluid matrices
- saturation-capillary pressure relationships
- water and solute transport in the vadose zone
- biodegradation in the vadose zone
- processes causing attenuation in the unsaturated and saturated zone
- groundwater vulnerability in different climatic zones
- organic compounds in the vadose zone
- heavy metals and radioactive nuclides in the unsaturated and saturated zone
- modeling flow and transport in the unsaturated zone.

In this article, each of these technical areas is alluded to within the broader context of their relationship to their roles in the hydrologic processes that affect the earth’s natural life-support systems. Those hydrologic processes include: infiltration and redistribution, rainfall–runoff relationships, seepage and drainage, groundwater recharge, nutrient cycling, and groundwater contamination. This article concludes with reflections on ways to protect the unsaturated zone so that it can continue to provide a vital role in the hydrologic cycle and nutrient cycling to help sustain healthy human and nonhuman communities.

1. Introduction

The vadose zone refers to the geologic media above the water table of the shallowest year-round aquifer. At the water table, the water is at atmospheric pressure (zero gage pressure); therefore in the vadose zone the pressure of water is typically less than zero (it is under tension, or suction). The term vadose zone has not been strictly defined, and some people use it to refer to the “unsaturated zone” above an aquifer. This differs from our definition by excluding the capillary fringe, which is typically saturated but above the water table, as well as regions that are only seasonally saturated or localized perched water tables atop low permeability layers. In this article, we interchangeably use “the unsaturated zone” and “the vadose zone.”

The thickness of the vadose zone ranges from zero (for example, in swamps and wetlands) to up to hundreds of meters (for example, the US desert south-west). In general, thickness greater than 5 m indicates that either there is drainage in the area (for instance, gully, escarpment, valley, or canyon) or that people have been pumping groundwater. Without the help of plant roots, water cannot evaporate from depths greater than a few meters below the soil surface, leaving vast supplies of groundwater under many areas that have been deserts for millennia (for example, central Somalia, where the water table can be reached easily with hand-dug wells).

The importance of the unsaturated zone to human existence cannot be overstated. The vast majority of plants depend on the nutrients and water stored in the vadose zone; almost all of the available groundwater (which accounts for more than half of all potable water) is generated by percolation through the vadose zone. The vadose zone is composed of highly reactive compounds (clays, organic acids, oxygen, and water), which serve to purify water passing through and provide nutrients for plants that root in it.

The study of processes in the vadose zone is included in many disciplines, most notably soil science and geology. It is also of significant interest to a wide range of professions, including civil, petroleum, and geotechnical engineering, forest science and engineering, and microbiology. It is, therefore, evident that no single text can adequately treat this topic in complete detail. In the EOLSS we focus on the fundamental physical and chemical properties of the vadose zone and attempt to provide a quantitative framework for understanding the basic processes. Any of the topics covered here can be explored in greater depth by availing oneself of texts from an appropriate related discipline. There are several quality textbooks related to this topic (see the Bibliography).

If one had to identify a single common feature of hydrogeologic environments, including the unsaturated zone, it would be the heterogeneous nature of the materials. The vadose zone is typically composed of a structured weathered mineral surface soil overlying lithified geologic materials. Soil properties typically vary spatially in a log-normal fashion, with layering resulting from both sequential deposition and weathering, with varying mineralogy, structure, and chemistry. The complexity posed by such amalgams of materials presents great challenges to the prediction of transport processes. Although we primarily employ deterministic approaches to quantifying transport processes, the nature of the vadose zone lends itself to stochastic analysis methods. The underlying message is that when addressing problems related to unsaturated zone hydrology, it is often more useful and reasonable to predict the range of possible outcomes rather than a single, unlikely value.

1.1. Technical Foundations of Unsaturated Zone Hydrology Science

It is worthwhile to understand the historical context of the study of unsaturated flow and transport, as it is quite a young field of study with some areas still early in their conceptual development. Here, we will provide a cursory overview of the development of this field.

Quantitative understanding of the movement of water below the soil surface was established by the work of Darcy, who in 1856 published his landmark study of the hydraulic properties of porous media. Darcy introduced the concept of potential flow, whereby water was observed to move in direct proportion to the gradient of potential energy, as well as the permeability of the media. Darcy obtained the governing equation for saturated water flow through porous media, which provides the basis for much of the transport analysis presented in the Groundwater theme materials of the EOLSS.

In the mid-1870s Bousinesq extended Darcy's law to include the possibility that water might drain and fill media, and widened Darcy's law to include problems where there was a "free water surface" (that is, the aquifer was not confined between impermeable boundaries). Bousinesq provided several very useful solutions to this equation of interest to designers of irrigation ditches, as well as to farmers who wish to drain their fields. Unlike Darcy's equation, which is linear in all parameters, the Bousinesq equation is strongly nonlinear. Solutions are far harder to come by, and it continues to provide fertile ground for research in mathematical hydrology to this day.

In 1899, Slichter published his *Theoretical Investigation of the Motion of Groundwater*, which provided the first encyclopedic source of solutions to Darcy's governing equation. Aside from providing a rigorous conceptual basis for Darcy's findings, Slichter generated exact solutions for the flow and pressure fields around pumped wells, and other useful boundary conditions for problems of groundwater supply.

Until the end of the nineteenth century, the study of flow through porous media considered only the case of flow through saturated media. In 1907, Buckingham extended Darcy's law to flow in unsaturated systems. Buckingham proposed that the same governing equation could be applied, but that the conductivity term must be made a function of the degree of saturation of the media and the term for hydraulic potential must be expanded to include capillary-induced pressures which are less than zero. When applied to the unsaturated zone, the governing equation is often referred to as the Buckingham–Darcy equation to credit this contribution.

The next major contribution came in 1911 from Australian pair Green and Ampt who decided to attack the key problem of how quickly water infiltrates into soil. They modeled the soil as a collection of capillary tubes that fill in parallel, considering only infiltration that started from dry conditions and filled to saturation. Their approach is so powerful and accurate that it remains the most widely used alternative to the full rigor of the true governing equation for these problems, with new applications of this approach still being published today.

In the early 1920s, researchers in Gardner's laboratory developed the tensiometer, which allows direct measurement of the negative capillary pressures in soils via a porous ceramic cup. L.A. Richards extended this idea in the development of the tension plate, which allows laboratory measurement of the moisture content as a function of capillary pressure as well as establishing controlled unsaturated flow experiments. In 1931, Richards combine the Darcy–Buckingham unsaturated flux law with mass balance principles to derive the governing equation for unsaturated flow, which came to be known as the Richards equation.

In 1930, Haines pointed out that unsaturated porous media could have a variety of moisture contents at a given capillary pressure depending on the history of wetting. This process is known as hysteresis. Haines remarked that even in an idealized media the advancement (or retreat) of fluid into porous media was a highly nonlinear process, proceeding in a sequence of “jumps” as the fluid proceeds (or recedes) from pore to pore. Although still frequently ignored in practice, accounting for hysteretic behavior is often essential to understanding unsaturated flow processes.

Solutions to the Richards equation have been slow in arriving for a variety of reasons. First, the equation includes terms for pressure and moisture content, which are clearly interrelated. Although Buckingham in 1907 had introduced the soil–water diffusivity, which allowed the writing of the Richards equation in terms of moisture content alone, only in 1956 was this method exploited by Bruce and Klute to estimate soil water diffusivity from laboratory infiltration experiments. When cast in terms of moisture content only, the Richards equation takes the form of a diffusion equation, which is more conducive to solution than the pressure-based formulation. Since that time, a number of additional analytical solutions have been presented, although the strong nonlinearity of the equation has limited these to quite specialized boundary and initial conditions, and highly constrained descriptions of the soil moisture retention curve. The advent of the high-speed computer has at last allowed us to make wide use of Richards' important result through implementation of numerical solutions. Technical Article *Modeling Flow and Transport in the Unsaturated Zone of* the EOLSS provides an introduction to numerical methods for solving the Richards equation.

Since the 1950s, research in the area of unsaturated transport processes has grown dramatically, making a concise comprehensive summary for this later period more difficult. A few key contributions, however, deserve special note. For decades, a topic of focus for unsaturated zone science has been the search for a simple method to determine the permeability of material as a function of degree of saturation without having to actually measure this directly (which is very difficult). Among the first efforts were Slichter in 1899, and later work by Kozeny (in 1927) and Carmen (in 1937) who provided theories for the permeability of saturated materials based on their particle size distribution. These results were then extended to unsaturated media in a series of significant contributions through the 1950s, and later by Mualem in 1976. These papers provide models that predict the permeability as a function of fluid content, which can be fitted parametrically through the fluid content versus pressure relationship. This “trick” has been extended in recent years by inserting a parameterized form of the water retention function into the results of Burdine and Mualem to generate a very simply parameterized set of relationships for water retention and permeability.

In 1956, Miller and Miller presented a generally applicable framework for understanding the relationship of the grain size of porous media to all of the capillary properties, now known as the Miller scaling theory. In 1962, Poulovassilis introduced the concept of the independent domain model of hysteresis to describe fluid retention in natural porous media. This made it possible to include quantitatively the observations of Haines (from three decades earlier!) in flow modeling. Another three decades later, these ideas at last began to be included in numerical models of vadose flow.

The 1970s began a period of coming to grips with the limitations of many of the assumptions that had been adopted in order to obtain solutions to the governing equations of flow. In 1973 Nielsen, Biggar, and Erh were the first to document quantitatively the magnitude and importance of heterogeneity at the field scale in vadose materials. They showed that properties were not only variable, but varied in a lognormal fashion, such that the mean value of a property was of relatively little use in predicting the range of values that would be observed. Contemporaneously, other researchers were showing that infiltration in homogeneous and layered soils was far more complex than earlier thought. They experimentally demonstrated that advancing wetting fronts could be hydrodynamically unstable, breaking into vertical fingers of flow rather than advancing uniformly as assumed until this time. These developments were quickly followed by the observation of the importance of “macropores” (the few very largest apertures in a media) in the rapid movement of water and contaminants. Phenomena, such as macropore and finger flow, which give rise to rapid advance of solutes, are referred to generically as preferential flow. Each of these areas of research remains very active to this time, with literally hundreds of publications in the literature related to the effect of heterogeneity on transport, unstable wetting processes, and preferential flow.

Finally, in 1985 the work of Yeh, Gelhar, and Gutjahr employed a spectral stochastic approach (developed by Gelhar and his colleagues in the late 1970s and early 1980s) to the meld, together geostatistical descriptions of geologic heterogeneity with the Richards equation for unsaturated flow. Using this approach, Yeh, Gelhar, and Gutjahr derived formulae for the head variance, the moisture content variance, and the expected effective unsaturated hydraulic conductivity for flow through heterogeneous media. These equations provided new insights into what types of state-variable variability one might expect to see at a field site in response to observed media variability. They also showed that the effective hydraulic conductivity tensor should exhibit an anisotropy that varies with the degree of saturation, consistent with numerous field observations before and since that time. The work of Yeh and colleagues provided the foundation for physically based stochastic unsaturated flow and transport, which has been the subject of literally scores of publications since the early 1980s.

1.2. Relationship to Saturated Media

Much of the theory and conceptual framework for understanding processes in the vadose zone has its origins in the study of flow in saturated systems. For instance, the geologic media are similar, and Darcy’s potential flow law holds for both saturated and unsaturated conditions. While the great similarity has been very useful, it is also the source of many errors resulting from using groundwater-hydraulics intuition to explain or predict processes in the vadose zone.

The distinctions between processes in saturated and unsaturated media are most pronounced in three areas:

- Capillarity, which gives rise to situations where flow occurs in isolated regions (for example, fingered flow) and where flow will not cross between zones of differing texture (for example, the capillary barrier effect). This also leads to situations in which silt may be more “permeable” than coarse sand under unsaturated conditions.

- Partially saturated conditions extend the heterogeneity of hydraulic properties from the spatial domain, as observed in saturated media, into the temporal domain, with transport properties being direct functions of the presence of the transported fluid.
- There is the tremendous biochemical activity of a region that has quasi-continuous gas phase present. Transport via diffusion is two orders of magnitude faster in gas than liquid, and there is a generous supply of oxygen, which can support an abundance of microbial life.

These distinctions dictate that one must be very careful in applying principles developed for application to saturated conditions to the vadose zone.

1.3. Contemporary Concerns with the Unsaturated Zone

Almost all research related to vadose zone transport carried out prior to 1980 was directly related to agricultural applications. However, in the last two decades of the twentieth century, a much broader range of disciplines became interested in the unsaturated zone. Within the agricultural sector, the ever-increasing population pressures on freshwater supplies and water conservation have driven a more careful analysis of crop water requirements and salinity management. The ability to reliably project nutrient/solute storage and transport are critical to maintaining aquifer quality for agricultural and waste-disposal applications. The increasing awareness of global warming has pointed to the critical role of soil water in the atmospheric energy budget. A major area of activity in vadose zone research has been directed to the understanding of the migration and remediation of non-aqueous-phase liquids (NAPLs), which have been introduced to the subsurface via leaking underground storage tanks and other unmonitored releases. The study of NAPLs has led to greater awareness of the similarity of the problems addressed by petroleum reservoir engineers and those working on problems related to the unsaturated zone.

To illustrate a typical problem that might arise in the context of industrial contamination, consider this example. Suppose that a large volume of some nasty NAPL is spilled on the soil over an aquifer that has a depth of 10 m. How much of the NAPL makes it to the aquifer? How long does it take? How much will stay in the material above the aquifer after a month? A year? During these periods, how much will be transformed to other chemicals?

A typical agricultural application might focus on design and operation of a drip irrigation system for a particular crop. Given the soil properties, the crop water needs, depths to the water table and drainage conditions, and the irrigation water quality, what is the optimal irrigation rate? How frequently, if ever, do you need to apply higher rates to flush accumulated salts? What should be the emitter spacing?

The only way to prepare for the wide range of possible vadose zone problems is to understand the basic processes of infiltration into, flow through, and geochemical reactions in, unsaturated porous media. With this basis you should be able to reason your way through many of the complexities of the real world vadose zone.

2. Transport Processes

To fully appreciate how the unsaturated zone behaves as a distinct component of the Earth's life-support systems, one needs to develop an understanding of the transport processes that mediate the flow of materials (dissolved solids, liquids, and gases) and energy through the geologic media that comprise it. The operative processes to consider include:

- liquid (principally water) transport,
- gas transport,
- heat transport, and
- solute transport, in which solid, liquid, or gaseous compounds are transported through the unsaturated zone when dissolved as solutes.

After discussing each process independently, we consider the potential for coupling any or all of the processes as may be required depending on the unsaturated zone situation. The depth of coverage in this topic-level manuscript is quite shallow; more detailed treatments can be found in EOLSS technical articles *Physical Properties of Solid and Fluid Matrices*; *Volumetric Water Content–Matric Potential Relationships*; *Water and Solute Transport in the Vadose Zone*; *Biodegradation in the Vadose Zone*; and *Processes Causing Attenuation in the Unsaturated and Saturated Zone*.

Following a summary of each of these transport processes, we present a brief overview of biogeochemical and geologic heterogeneity issues that can affect transport. However, before the overview, it is germane to briefly consider the properties of soils and geologic media.

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Biographical Sketches

James (Jim) T. McCord was born in 1959 in Ventura, California (USA). He completed a Bachelor of Science degree in Civil Engineering (with a minor in Geology) from Virginia Tech in 1981. He was a consulting engineer from 1981 through 1983, and returned to graduate school at New Mexico Tech (USA), where he earned a Master of Science and Ph.D. in Hydrology. Since completing his doctoral studies, Dr. McCord has been an assistant professor at Washington State University (Pullman, Washington, USA; 1989–1990), a senior staff member at Sandia National Laboratories (Albuquerque, New Mexico, USA. 1990–1997), and a hydrology consultant (1997–present). At Sandia Labs, he worked on high-level and low-level radioactive waste disposal programs, and on environmental restoration projects. As a consultant, Dr. McCord has been involved as a hydrology expert on environmental litigation projects, and as a hydrologist and project manager on regional water resource supply and allocation studies. He is currently the Principal Hydrologist for Hydrosphere Resource Consultants' New Mexico office. He co-authored the textbook *Vadose Zone Processes* with Prof. John Selker of Oregon State University and Prof. Kent Keller of Washington State University. In addition to his professional activities, Dr. McCord owns and operates with his wife Cecilia an organic farm in the Rio Grande Valley of central New Mexico, USA.

John Selker was born in 1960 in Seattle, Washington (USA). He completed his Bachelor of Arts degree in Physics in 1981 (with a minor in sculpture) from Reed College in Portland Oregon (USA). He worked as a consulting engineer in the USA, Kenya, Somalia, Sri Lanka, and England from 1981–1987, when he went to graduate school at Cornell University, receiving his M.S. in 1989 and Ph.D. in 1991. Since completing his doctoral studies Dr. Selker has been a professor in the department of Bioengineering at Oregon State University studying vadose zone processes. He has published a book (see above), as well as more than 50 peer reviewed publications. Current research projects include waste migration at the Hanford Site, microbial effects on vadose hydrology, regional hydrologic modeling of the Chilean Secano Interior, the effect of off season cover cropping on groundwater quality, and a range of projects developing improved instrumentation for vadose investigations.