Unsaturated Zone Hydrology for Scientists and Engineers

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Introduction and Brief History

INTRODUCTION

Unsaturated zone hydrology is the study and investigation of the physical state of the soil; specifically, the transport of all forms of matter and energy within the unsaturated zone of soil. Geologically, the topmost layer of the earth's crust comprises a three-phase system, which includes solid, liquid and gas. The solid phase contains mineral grains of varying types and organic matter, which represents the remains of animals and plants in varying stages of decay. The liquid phase is composed of water that may contain a wide variety of solutes. The gas phase includes air, water vapor, and other gases, all of which may be in different stages of equilibrium. The earth layer that contains all three phases of matter has been termed the unsaturated zone. Other common names given to this zone are the *zone of aeration* and the *vadose zone.*

The unsaturated zone is typically defined to extend from land surface to the underlying water table or saturated zone within porous media. In some areas, such as parts of the eastern United States, the unsaturated zone can be very shallow, ranging from a few centimeters to several meters. More typically, in the western United States, the unsaturated zone can be more than a hundred meters thick. In wetlands, the unsaturated zone may fluctuate seasonally or not exist at all. By definition, the unsaturated zone also includes the root zone of the overlying vegetation, usually about one meter thick. Roots can play a major role in chemical transport within agricultural and undeveloped settings.

The unsaturated zone has a significant influence on the movement and transport of both water and chemicals. Variables of state that affect the unsaturated zone include pressure, volume, and temperature. Soil phenomena such as capillary flow, adsorption, chemical interactions, and matric potential could be said to be dependent on variables of state. A soil system is governed by thermodynamic principles and, in most instances, follows the laws of physical chemistry. A thermodynamic system is a specific part of the physical universe under investigation. A system is defined to be separated from the rest of the universe by an imposed boundary; that part of the universe outside the boundary is referred to as the surroundings. With regard to soil, the surroundings would include the atmosphere and aquifers. Though a system is enclosed by a boundary, in unsaturated zone hydrology matter is usually transferred between the system and its surroundings, and the surroundings may do work on the system, or vice versa. If the boundary around a system prevents matter interchange, or mechanical or thermal contact, the system is called an isolated or closed system.

Most investigations in unsaturated zone hydrology verify the fact that the soil system is not an isolated system. Chemicals in the form of liquid, solids, and gases escape into the atmosphere and leach into ground-water boundaries surrounding the soil system, causing contamination from agricultural, industrial, residential, and recreational uses of land and water. Through the application of the principles of kinetics, in conjunction with thermodynamics, we are able to interpret certain thermodynamic soil properties in molecular terms that make it possible to explain physical processes, and to determine the rates of these various processes.

Soil is highly heterogeneous in both space and time, and is the basis for all terrestrial life. It exchanges water with the atmosphere in the hydrological cycle and influences the atmospheric content of greenhouse gases. It also serves as a medium for microbial activity, plant growth and, unfortunately, storage of various contaminants including radioactive wastes. The soil consists of fragmented components of varying shapes and sizes, which are arranged in complex patterns. Depending upon its mineralogical, chemical, and physical properties, a soil can freeze and thaw, shrink and swell, disperse and flocculate, precipitate and dissolve salts, crack, compact, and exchange ions during alternate wetting and drying processes. Consequently, it can be said that a soil system is never in a state of equilibrium. Due to the nature and complexity of porous media, unsaturated zone hydrology is an inherently complex science that requires a knowledge of chemistry, physics, mathematics, mineralogy, engineering, computer science, soil chemistry, hydrology, and soil–plant–water relations to ascertain answers to contemporary environmental issues. This is especially true in the areas of water quality and treatment, agricultural and waste management, and the recreational and industrial use of water.

1.1 A BRIEF HISTORY OF UNSATURATED ZONE HYDROLOGY

The origins of soil science are inextricably linked to the development of agriculture, irrigation, chemistry, and physics. The earliest writings that mention agriculture include many accounts concerning the physical aspect of soils. Examples of these include Sumerian cuneiform writings dating from circa 1700 B.C. that give instructions on the preparation of land and planting of grain crops in the Euphrates River valley (Kramer 1958, 1963), and other writings from circa 1000 B.C. that mention erosion by wind and water and its effect on crop culture (Bennett 1939). Some of the greatest philosophers, scientists, and educators have written about soil; Buol, Hole, and McCracken (1973) mention writings that involve the soil by Aristotle (384–322 B.C.), Theophrastus (ca. 372–ca. 286 B.C.), Cato the Elder (234–149 B.C.), and Varro (116–27 B.C.).

Democritus (ca. 460–ca. 370 B.C.) wrote that plant growth involved the cycling of indestructible elements. Aristotle taught that plants absorbed their nutrients from humus through the root system (Salmon and Hanson 1964). Sir E. John Russell (1957), in his discussion of the physical properties of the soil and how they are affected by biological activity, quotes from Pliny the Younger (61–ca. 113 A.D.) on the use of marl for land application. The *USDA Yearbook of Agriculture: Soils and Men* (1960, quoting Kellog 1938) refers to the Bible (1 Sam. 13:20) directing the Israelites to sharpen what would be considered their agricultural implements; also, to Homer (ca. 800 B.C.) describing Odysseus the wanderer returning to find his dog lying on a pile of refuse that was to be used to manure the land. However, when Moses says to the Israelites (Deut. 11:10–11), "For the land . . . wateredst it with thy foot . . . and drinketh water of the rain of heaven," he is referring to the irrigation practices of Egypt. Was Moses the first vadose zone hydrologist? In fact, the first Biblical reference to tilling is Gen. 4:2, which refers to Cain as a "tiller of the ground."

Unsaturated zone hydrology also went through a period of stagnation, with little literature to be found between the end of the first century A.D. and the early 1200s. It was in the mid-thirteenth century that Petrus de Crescentiis published a book on agriculture, *Opus ruralium commodum,* in Rome. Keen (1931) states that Fitzherbert's "Book of Husbandry" (1523) was the earliest work in English dealing with practical agriculture. Keen also provides an extensive bibliography of contributions to unsaturated zone hydrology.

LaRocque (1957) notes that the Frenchman Bernard Palissy (1510–1589), in his *Discours Admirables* (1580), described what was probably the first "soil auger," including a description of its construction and the mention of detachable handles. He constructed this device to aid in his exploration of soil. In his *Recepte Veritable* (1563), Palissy challenged the view of Plato (428–348 B.C.), Aristotle, and other important natural philosophers that water moved from the oceans, beneath the land, and into rivers and streams. Palissy said that "for this to happen, it would require an enclosed pipe flowing from the oceans to the mountains," since the mountains are higher than the oceans. Palissy's theory was that ground water and natural springs originated from rainfall that had infiltrated the soil; he was correct and ahead of his time in his theories. Palissy believed strongly in what he could "dig out of the bowels of the earth," and amassed entire experimental collections of various items that he used to challenge famous philosophers of his day. Palissy was a self-made scientist, and quite possibly the earliest to observe and record data from his experiments and explorations.

Sir Francis Bacon (1561–1626) believed that water was the source of nourishment for plants (Daumas 1958). This was later confirmed by Jan Baptiste van Helmont (1577–1644). According to Tisdale and Nelson (1975), in 1629, about seventy years after Palissy's book, Jan Baptiste van Helmont performed a famous experiment in which he grew a willow tree in an earthen container of soil that originally weighed 91 kg. After five years he removed the soil from the pot and weighed the soil and tree separately. The tree that had originally weighed 3 kg was found to weigh about 77 kg, and all but 57 g of the original soil was accounted for. Since the pot had been shielded from the atmosphere and only rain or distilled water had been added, van Helmont concluded that water was the sole nutrient of the plant, for he attributed the 57 g soil loss to experimental error. This idea was followed in 1673 by John Evelyn (1620–1706), a secretary of the Royal Society of London, and appeared to be supported with experimental evidence a few years later by Robert Boyle (1627–1691), also of England. Boyle confirmed the findings of van Helmont, but went one step further, stating that plants contained salts and other materials that were formed from water.

Johann Rudolf Glauber (1604–1668), a German chemist, suggested that potassium nitrate and not water was the "principle of vegetation"; John Mayow (1641–1679), an English chemist, supported the views of Glauber. About 1700, however, the Englishman John Woodward grew spearmint in samples of water he had obtained from various sources, and concluded that earth rather than water was the principle of vegetation. Jethro Tull (1674–1741), an Oxford-educated lawyer and author of *The New Horse Houghing Husbandry* (1731), concluded that plants derived their nourishment from "highly pulverized soil," or humus (Keen 1931). Arthur Young (1741–1820), one of the better known agriculturists of his time, and a prolific writer, edited a fourty-six-volume work entitled *Annals of Agriculture.* That work was supported by many experimental trials utilizing potted containers exposed to various influencing parameters, such as temperature, air, and water. Previous work by Young and others led Francis Home, in about 1775, to conclude that not just one parameter, but many, are required to describe the principles of plant growth.

At roughly the same time, Joseph Priestley (1733–1804) discovered that sprigs of mint "purified" the air, which led him to suggest that plants reversed the effect of breathing (i.e., taking in carbon dioxide and giving off oxygen). At this time he had not yet discovered what we now call oxygen, and when he did a few years later, he failed to recognize its relation to plants. However, the discovery of oxygen was a milestone, and helped unlock a great deal of mystery concerning plant life and the physical properties governing plant growth and soil interactions. This was a great help to Jean Senebier (1742–1809), a Swiss natural philosopher and historian who discovered the basics of photosynthesis in 1782 (Russell 1912). These early discoveries stimulated Nicolas-Theodore de Saussure (1767–1845) to experiment with the effect of air on plants and on the origin of salts in plants. De Saussure demonstrated that plants absorb oxygen and liberate carbon dioxide, but wrongly concluded that the soil furnishes only a small fraction of the nutrients needed by plants.

Sir Humphrey Davy (1778–1829), an English chemist, published *The Elements of Agricultural Chemistry* in 1813. Highly respected, Davy's book represented the best accepted knowledge of the time. He insisted on the importance of the physical properties of soils and their relations with heat, water, and other parameters, and was the first to apply the sciences of chemistry and physics to soil research—which marks the beginning of unsaturated zone hydrology (Wild 1988). As a result, Davy could properly be called its father. Building on the work of Davy and others, Gustav Schubler (1787–1834) greatly furthered the development of the field. Keen (1931) credits Schubler with the first technical investigations in unsaturated zone hydrology that involved systematic studies of the influence of soil physical properties on productivity of soils. Schubler also ascribed the crumbling of calcareous clay soils to the difference in the contraction of the calcareous sand and the clay substance, and has since been referred to as the father of agricultural hydrology (Hilgard 1906).

Contributions to unsaturated zone hydrology have come—and continue to come—from other fields, especially chemistry, mathematics, and physics. Many renowned scientists have made contributions to this area that are still in use today, including Ohm (1789–1854), Faraday (1791–1867), Fourier (1768–1830), Laplace (1749–1827), Helmholtz (1821–1894), Lord Kelvin (1824–1907), Boltzmann (1844–1906), Planck (1858–1947), Joule (1818–1889), and many others.

Wilhelm Schumacher used Schubler's original data to develop theories on the movement of water and air in soil, and introduced the principle of porosity. A contemporary of Schumacher and perhaps the most famous of the European scientists was Henry Darcy (1803–1858). His research in Dijon, France, in which water flux through sand filter beds was indicated to be proportional to the gradient of the hydraulic head, has become a cornerstone in water-flow principles under saturated and unsaturated conditions. This principle of water movement is known as Darcy's law, which will be discussed in detail in chapter 7.

Two other great scientists developed theories of water flow. These were Gotthilf Heinrich Ludwig Hagen (1797–1884) and Jean-Léonard-Marie Poiseuille (1797–1869), who in 1839 and 1840 started with Newton's law of viscosity and independently derived an equation for water flux in capillary tubes in terms of tube radius, pressure gradient, and fluid viscosity. That equation is currently known as the Hagen–Poiseuille equation. It expresses the same relation as Darcy's law, but with a conductivity term used for the measurable quantities of pore radius and viscosity, which adds further meaning to the equation. This relation will be discussed in detail in chapter 6.

Sir George Gabriel Stokes (1819–1903) developed an equation, known as Stoke's law, that is the relation of resistance to flow around a spherical particle. It is the basic equation used in both the hydrometer and pipette methods for particle size analysis.

Martin Edward Wollney (1846–1901) was probably the first soil scientist to be called a soil physicist. He published many articles and abstracts on the principles of unsaturated zone hydrology and agricultural meteorology (see, for example, Wollney 1878). During the late 1800s, Alphonse Theophile Schloesing and Jakob Maarten van Bemmelen (1830–1911) became interested in clays and their colloidal properties. During work with these properties it was discovered that there was a definite microbial role in soils (Russell 1912).

Due to progress in unsaturated zone hydrology as a result of advances in chemistry and physics during this time, scientists became interested in research in other areas within the field. In 1901, Eilhard Alfred Mitscherlich (1874–1956) concluded that the amount of water vapor absorbed by the soil would be proportional to the total surface area, and attempted to calculate this area based on the fact that any water present would be in the form of a monomolecular layer (Atanasiu 1956). Subsequently, the role of hygroscopic moisture was investigated by Lyman J. Briggs and Homer L. Shantz in Akron, Colorado (1912), among others.

Eugene Woldemar Hilgard (1833–1916) in California, Franklin Hyrum King (1848–1911) in Wisconsin, Thomas Burr Osborne (1859–1929) in Connecticut, and Milton Whitney (1860–1927) with the U.S. Department of Agriculture in Washington, D.C., were the best known soil physicists (i.e., unsaturated zone hydrologists) in the United States during this era. King's interest in quantitative aspects of water flow led to his collaboration with a colleague, Charles S. Slichter (1864–1946); Slichter published the results in 1898 as "Theoretical investigation of the motion of ground waters," a valuable paper describing soil water potential, in which he was able to derive the velocity, flow direction, and pressure at various points within porous media. Later, Slichter applied these principles to water flow in horizontal planes and water wells.

Edgar Buckingham (1867–1940) was a prominent scientist who worked closely with principles regarding soil moisture. In 1907, he published a significant paper dealing with capillary potential that was far ahead of its time, but which received little recognition for more than a decade. During this time two well-known Australian scientists, W. Heber Green (1868–1932) and G. A. Ampt (1887–1953), made significant contributions to unsaturated zone hydrology on the topic of infiltration. With the help of R. J. A. Barnard (1865–1945) and T. R. Lyle, they derived equations for vertical and horizontal flow of water in soils based on the Hagen–Poiseuille equation (Green and Ampt 1911).

John A. Widtsoe (1872–1952), a prominent educator in Utah and the intermountain west, made contributions to the field in the form of texts on irrigation (1914). He undoubtedly had a great influence on the progress of irrigation throughout the intermountain west. Widtsoe excelled at the application of science to logical, well-considered problems (Widtsoe and McLaughlin 1920; Gardner and Widtsoe 1921). At about this time, Willard Gardner and his colleagues expanded on Buckingham's ideas regarding capillary potential and moisture flow, and developed the tensiometer (Gardner et al. 1922). This was one of the great advances in the measurement of soil water potential. Thomas L. Martin, a contemporary of Gardner and a chemist, also contributed to soil science and its professional organizations (Martin 1921, 1925). These two men were influenced to some degree by Widtsoe.

George J. Bouyoucos (1890–1981) made major contributions to the field through the development of the hydrometer method for particle size analysis (1927a,b) and gypsum moisture blocks (1947). Bouyoucos immigrated with his family from Greece, and earned his Ph.D. in 1911, at the age of 21. It was in this same period of time that Lorenzo Adolph Richards (b. 1904), also from Utah and a student for B.S. and M.S. degrees under Willard Gardner, began making significant contributions to unsaturated zone hydrology. Richards is best known for the development of the Richards equation (1931) and its use in unsaturated flow. He is also well known for extending the idea of the tensiometer to the porous plate and pressure membrane apparatus (1941), commonly referred to as the "pressure plate apparatus." The development of the tensiometer by Gardner and the extension of this idea to pressure plates by Richards constitute two of the most significant developments in unsaturated zone hydrology.

Another prominent scientist who came under Gardner's influence is Don Kirkham (b. 1908). Kirkham taught physics until World War II, when he began naval research. Kirkham is perhaps best known for his text on soil physics (Kirkham and Powers 1972), extensive work in saturated flow and drainage, and the number of prominent students he has graduated in unsaturated zone hydrology.

Contributions to unsaturated zone hydrology by prominent European soil physicists include *Physical Properties of Soils* (1931) by Sir Bernard Keen (1890–1981). Ernest C. Childs (1907–1973) was known for his work in electric analogs applied to drainage studies, and H. L. Penman (1909–1984) worked extensively in the study of evaporation and evapotranspiration at the Rothamsted Laboratory. Another Englishman who worked at Rothamsted as a contemporary of Penman was R. K. Schofield (1901–1960), known for his introduction of pF of soil moisture. Since 1950, the field of unsaturated zone hydrology has steadily progressed, with significant work in the area of soil moisture diffusivity by Arnold Klute and one of his students, R. R. Bruce.

Eshel Bresler (1930–1991), director of the Soils and Water Institute of the Agricultural Research Organization at Bet Dagan, Israel, made significant contributions in the area of salt movement and irrigation in soils. He worked extensively in the simultaneous transport of energy and water in soils, anion exclusion, and infiltration. Bresler also published numerous texts and scientific articles, including *Saline and Sodic Soils: Principles—Dynamics—Modeling* (1982), coauthored with B. L. McNeal and D. L. Carter. Bresler's work was characterized by his direct approach to research (a result of practical experience gained in cooperative extension work in agriculture), and the interconnecting of water and soil-science disciplines to solve problems.

Limitations of space preclude a more thorough and complete listing of the many other scientists who have made contributions to unsaturated zone hydrology, and the other topics currently under study in the field. It is safe to say, however, that exciting developments to come will further enrich the fascinating history of this most terrestrial of sciences.