COURSE CODE: *SOS 513*

COURSE TITLE: *Soil Physics*

NUMBER OF UNITS: *3 Units*

COURSE DURATION: *Three hours per week*

COURSE DETAILS:

Course Coordinator: **Dr. J. K. Adesodun.** *BSc., MSc., PhD*
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Other Lecturers: Prof. F. K. Salako; Dr (Mrs.) S. J. Akinsete

COURSE CONTENT:

Soil physics as a basic and an applied science. Soil phases: solid, liquid and air; volume-mass relationship. Soil solid: texture; colloids and surface area of soil particles; bulk density and porosity; soil consistency; soil strength; stress-strain relationships. Soil compaction, hardsetting and surface crusts. Soil water; water content; soil water potential; principles of saturated and unsaturated water flow. Available soil water; Soil hydrology, solute transport and water quality; Soil heat; energy balance of the earth's surface; soil temperature; modification of soil temperature; Soil air; soil atmosphere composition; gaseous exchange in soil; soil air and plant growth. Relevance of soil physics to soil management: tillage; soil productivity; soil erosion; irrigation; drainage.

Practical: Soil core sampling for bulk density and water content determinations; Penetrometer resistance measurement; Water retention determination at various potentials; Measurement of saturated hydraulic conductivity, soil temperature etc.

COURSE REQUIREMENTS:

This is a compulsory course for all final year students in the Department of Soil Science, College of Plant Science and Crop Production (COLPLANT). In view of this, students are expected to participate in all course activities and have a minimum of 75 % attendance to be able to write the final examination.

READING LIST:

1. Brady, N. C. and R. R. Weil. *The Nature and Properties of Soils*. 12th ed. Prentice-Hall, New Jersey: Prentice-Hall Incorporated, 1999.

2. Lal, R., Shukla, M. J. 2004. Principles of soil physics. Marcel Dekker, Inc. New York, USA.

3. Obi, M. E., 1991. Physical properties of soils: basic principles. Department of Soil Science, University of Nigeria, Nsukka

4. Daniel Hillel. (1980). Fundamental of Soil physics. Academic Press, New York

LECTURE NOTES

1.0 Introduction

What is soil?

Soil is the upper most layer of earth crust, and it supports all terrestrial life. It is the interface between the lithosphere and atmosphere, and strongly interacts with biosphere and the hydrosphere. It is a major component of all terrestrial ecosystems, and is the most basic of all natural resources. Most living things on earth are directly or indirectly derived from soil.

Soil is the unconsolidated material at the earth's surface that serves as a medium for plant growth, regulator of water regime, environmental filter and functions as supporting medium. It is a dynamic 3-phase system comprised of solids, liquids and gases.

What is Soil Physics?

Soil physics is the application of principle of physics to the characterization of soil properties and the understanding of soil processes involving the transport of matter and energy.

Soil physicists are generally concerned with heat and mass transport in soil. Subject they considered frequently include: soil aeration, soil temperature and soil water. These are described in both static and dynamic terms.

Static parameters:

- Soil porosity
- Water content
- Degree of saturation
- Void ratio
- Bulk density
- Particle density
- Soil water potential, i.e. the potential energy of water

Dynamic parameters:

Mass and energy transport in soil are described using:

- Darcy's law for water
- Fourier law for heat
- Fick's law for gas

Each of these laws states that a flux density of heat or substance is proportional to a driving force. The driving are:

- Water potential gradient for water flow
- Temperature gradient for heat flow
- Concentration gradient for gas diffusion

What are the major roles of Soil physicist?

Although soil physicists still must remain concerned about the physical environment of plants, conservation of resources against degradation and pollution problems by agricultural and non-agricultural agents have become the responsibilities of soil physicist too. Soil physicist must be concerned with flow and transport processes in the zone between the soil surface and groundwater table, i.e. the VADOSE ZONE. So, soil physicist are increasingly becoming participants in global-scale hydrologic research cooperating with hydrologists, climatologists, geologists and other scientists who study soil from non-agricultural point.

1.1 Soil Components

The four major components or constituents of soil are:

a). Mineral matter, b). Organic matter, c). Water and, d). Air

1.2 Soil Phase

Phase is portion of a system with definite geometrical boundaries and uniform properties.

Soil has three major phases:

- Solid phase
- Liquid phase
- Gaseous phase

Solid phase: Solid phase is the most dominant with great influence over the behaviour of other two phases. The solid phase is the soil matrix or skeleton of the soil. It is the product of weathering of parent rocks/materials and materials which they contain. The solid phase consists of mineral matter and decomposed or decomposing organic matter of all shapes, sizes and arrangement.

Liquid phase: This is primarily water, i.e. soil solution containing various ions such as Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3, SO_4^{2-}, etc.

Gaseous phase: This is the soil air. It composed of N_2, O_2, CO_2 and H_2O (vapour) mainly. Other gases in the atmosphere are also present in the soil. Others also like CH_4, H_2S which are by-products of impeded drainage condition could be found in the soil.

2.0 SOLID PHASE

2.1 Surface Relationship

Soil specific surface is used to describe the extent of the surface of the dispersed soil system. It is defined as the sum of the surfaces of constituent dispersed soil particles referred to unit mass or unit volume of the soil. Specific surface is a geometrical concept which is strongly dependent on the degree of dispersion of the soil, i.e. soil texture. Thus,

Specific surface of soil (A_m) or (A_v):

$$= \frac{total\ surface\ area\ of\ soil}{Mass\ or\ Volume\ of\ soil} \qquad = \frac{A_S}{M_S\ or\ V_S}$$

Units: $A_m = A_s/M_s$ (cm^2/g) or (L^2/M)

$A_v = A_s/V_s$ (cm^2/cm^3)

The relationship between A_m and A_v:

From $\rho_s = M_s/V_s$

$M_s = \rho_s V_s$

$\therefore A_m = A_s/\rho_s V_s$

$= A_s/V_s \times 1/\rho_s$

$= A_v/\rho_s$

where ρ_s = average density of soil particle i.e. 2.65 g cm^{-3}

NOTE: Most soil physical and chemical reactions occur at the surface, and the amount of these reactions is directly proportional to the specific surface.

Factors influencing specific surface:

- Size
- Shape
- Mineralogy of the soil or material

(a) Particle Size:

Side of cube (cm)	**NO. of Particles in $1cm^3$**	**Surface of single particle (cm^2)**	**Total (cm^2)**	**Specific surface of 1 g particle where** $\rho_s = 2.65$ g cm^{-3}
1	1	6	6	$A_m = 6cm^2/2.65$ g $= 2.26$ cm^2/g
10^{-1}	10^3	6×10^{-2}	60	2.26×10 cm^2/g
10^{-5}	10^{15}	6×10^{-10}	6×10^5	2.26×10^5 cm^2/g

(b) Particle Shape:

(i) Sphere with diameter d:

$$A_v = A_s/V_s$$

Area of sphere = $4\Pi r^2 = \Pi d^2$ Note: $r^2 = (d/2)^2 = d^2/4$

Volume of sphere = $4/3\Pi r^3 = \Pi d^3/6$

$$A_v = \Pi d^2/(\Pi d^3/6)$$

$$=6/d$$

$A_m = A_v/\rho_s$, and assume $\rho_s = 2.60$ g cm^{-3}

$A_m = 2.3/d$

(ii) Cube of edge L:

$A_v = 6L^2/L^3 = 6/L$

$\therefore A_m = 2.3/L$

2.2 Soil Texture

Definition: Soil texture is relative proportion of different sized groups in the soil on percentage basis. It describes the sand, silt and clay composition of a soil.

Soil Textural Class: Grouping based on relative proportion and specifically on % sand, silt and clay in given soil sample. The class name essentially describes the separate which most influence the sample physical/chemical/biological properties.

2.3 Soil Structure

The term structure relates to the arrangement of primary soil particles into groupings called AGGREGATES or PEDS. The pattern of pores and peds defined by soil structure greatly influence water movements, heat transfer, aeration and porosity in soils.

Types of Soil Structure:

Different types of structural peds in soils occur within horizons of soil profile. Soil structure is characterized in terms of shape (type or form), size and distinctiveness (grade) of the peds.

GRADE: Describes the distinctiveness of the peds (differential between cohesion within peds and adhesion between peds). It relates to the degree of aggregation or the development of soil structure. In the field a classification of grade is based on a finger test (durability of peds) or a crushing of a soil sample.

FORM: Is classified on the basis of the shape of peds, such as spheroidal, platy, blocky, or prismatic. A granular or crumb structure is often found in A horizons, a platy structure in E horizons, and a blocky, prismatic or columnar structure in Bt horizons. Massive or single-grain structure occurs in very young soils, which are in an initial stage of soil development. There may two or more structural arrangements occurring in a given profile. This may be in the form of progressive change in size/type of structural units with depth (e.g. A horizons that exhibit a progressive increase in size of granular peds that grade into subangular blocks with increasing depth) or occurrence of larger structural entities (e.g. prisms) that are internally composed of smaller structural units (e.g. blocky peds).

The four principal shape of soil structure are: (i) Spheroidal; (ii) Blocklike; (iii) Prismlike; and (iv) Platy.

(i) Spheroidal: We have (a) Granular structure and (b) crumb structure. The granular structure consists of spheroidal peds or granules that are usually separated from each other in loosely packed arrangement. When the spheroidal peds are porous, they are classified as **crumbs.**

(ii) Blocklike: Blocky peds are irregular, roughly cubelike in shape and range from about 5 to 50 mm across. When the edges of the blocks are sharp and the rectangular faces are distinct, the subtype is referred to as **angular blocky.** When the corners are round and the edges are sharp, then it is called **subangular blocky.**

(iii) Prismlike: This has two sub-types namely (a) Columnar and (b) Prismatic.. Columnar structure has pillars with distinct, rounded top and this is especially common in subsoils high in Na^+. When the tops are of the prisms are relatively angular and flat horizontally, the structure is designated as Prismatic.

(iv) Platelike: Platy structure is characterized by relatively horizontal peds or plates and may be found in both surface and subsurface horizons. The horizontal axes are longer than vertical, i.e. horizontal cleavage planes predominate.

3.0 Soil Consistency

Definition: Soil consistency describes the state of the soil, i.e. solid, plastic and liquid states.

OR:

- Ability of soil to keep its place or maintain its form when stress is applied.
- Soil consistence (or consistency) refers to the manifestations of the physical forces of cohesion and adhesion acting within the soil at a range of soil moisture contents.

Adhesion refers to the attraction between dissimilar objects, i.e. to the attraction of water to the soil solids. While cohesion is attraction between similar objects, i.e. bonding between soil particles. Cohesive forces in soil are due to attractive forces between the particles.

These forces are due to physicochemical mechanisms including:

- van der Waals forces

- Electrostatic attraction between negatively charged clay surfaces and positively charged clay edges
- Cationic bridges,
- Cementing effects of humic substances and salts, and
- Surface tension of water

Soil consistence encompasses several attributes including friability, tilth, plasticity, stickiness, and resistance to compression.

4.0 **Soil Strength and Compaction**

Soil strength is an important soil physical property, with numerous applications to agronomy and engineering. Important agronomic applications are those related to impacts of crusting and compaction on plant growth and agronomic yield.

Surface crust / seal

Soil crust or surface seal, refers to the thin dense layer on the soil surface characterized by low porosity, high density, and low permeability to air and water. Crusting is a soil surface phenomena caused by susceptibility of aggregates at the soil-air interface to disruptive forces of climatic elements (the impact of raindrops) and perturbations caused by agricultural practices (e.g., tillage, traffic and trampling action of livestock or humans). Slaking, deflocculation, or dispersion of aggregates on rapid wetting or submersion in water, is attributed to numerous factors including the effect of entrapped air, predominance of Na^+ on the exchange complex, and weak aggregate strength caused by low level of soil organic matter content and weak ionic bonds.

Crusting has adverse impacts on seedling emergence and growth. Preventative measures are based on strategies of enhancing aggregation, improving soil structure, and minimizing the disruptive effects of raindrop impact.

Hardsetting

"Hardsetting" refers to a process in which soils set hard into a structureless mass following drying. When dry and set hard, these soils have a high bulk density, high penetration resistance, high strength, and are difficult to plow or dig. Hard setting soils have a narrow range of workable soil moisture content.

Hardsetting soils have a weakly developed structure characterized by: (i) low aggregation, (ii) aggregates prone to slaking and dispersion, (iii) low infiltration rate, and (iv) high runoff and erosion.

There are some soil attributes that make it susceptible to hardsetting. Hardsetting soils have textural properties ranging from loamy sand to sandy clay, low swell-shrink capacity, low soil organic matter content, and predominantly low activity clays.

Hardsetting behavior has numerous limitations with regards to timings of cultivation, restricted root growth, and poor yield. Management of hardsetting soils involve techniques that improve aggregation and aggregate strength. These techniques include use of residue mulch, no-till or conservation tillage, cover crops, etc.

Stress-strain relationship

Soil strength is the soil's ability to bear or withstand stress without collapsing or deforming excessively. Soil strength is attributed to forces of cohesion and adhesion and varies with soil moisture content. When subjected to external force or stress (i.e., force per unit area), soil undergoes different types of deformation or strain.

Soil Porosity

Soil porosity refers to the relative volume of voids or pores, and is therefore expressed as a fraction or percent of the total volume or of the volume of solids. Soil porosity can be expressed as, *Total porosity; Air-filled porosity*

SOIL AIR AND AERATION

Soil Air

Soil is a three-phase, porous media, composed of solids, liquids, and gases.

Soil air can be defined as the air that fills the soil pore spaces not occupied by water. That is the gaseous phase of the soil not occupied by solid or liquid.

Soil Air Composition

Air Composition	*Atmosphere*	*Soil*
Oxygen	21%	< 20% (10.35 – 20.03)
Carbon Dioxide	0.035%	> 0.035% (0.10 – 20.0)
Nitrogen	78%	78%
Argon	0.94	
Hydrogen	0.01	

Gaseous Composition of Soil Air

Oxygen

- Soil air is consistently lower in oxygen
- The oxygen content may be only slightly below 20% in the upper layers of a soil
- Wet soils typically have low oxygen contents.
- Once the supply of oxygen is virtually exhausted, the soil environment becomes anaerobic

- Drastic reductions in the oxygen content of soil air may occur following a heavy rain.

Carbon dioxide

- Carbon dioxide typically increases in soil air.
- Carbon dioxide may become toxic to plants when it is as high as 10% in soil air.

Other Gases

- Soil air is usually higher in water vapour than in the atmosphere.
- Under waterlogged conditions, the concentrations of methane (CH_4), and hydrogen sulphide (H_2S) are particularly higher in soil air.
- Ethylene (C_2H_4) gas, a product of anaerobic microbial metabolism is toxic to plant roots, even in very small concentrations.

Soil Aeration

Definition: Soil aeration is the ability of soil to exchange gases with the atmosphere. This involves the rate of ventilation, composition of soil air, proportion of pore space filled with air, and redox reaction potential.

Poor Soil Aeration

1. This refers to a condition in which the availability of oxygen in the root zone is insufficient to support optimal growth of most plants and aerobic microorganisms.
2. Poor aeration becomes a serious impediment to plant growth when more than 80 to 90% of the soil pore space is filled with water, leaving less than 10 to 20 % of the pore space filled with air.
3. The high soil water content not only leaves little pore space for air storage but, more important the water blocks the pathways by which gases could exchange with the atmosphere.

Water Saturated (Waterlogged) Conditions

- The soil is said to be ***water saturated*** or ***waterlogged*** when all or nearly all of the soil pores are filled with water. Such conditions occur naturally in wetlands.
- Plants adapted to grow in waterlogged soils are known as ***hydrophytes*** (water-loving plants), e.g., grasses and rice. Respiration is via hollow structures in their stems and roots known as ***aerenchyma tissues.***
- When oxygen becomes depleted, soil conditions are said to be ***anaerobic***. Methane, hydrogen sulphide, and ethylene are often evolved under these conditions.

Adverse Effects of Suboptimal Aeration on Plants and Soils

1. Morphologic structure (e.g., Thin cell walls in root; Suppression of root hair formation)
2. Physiologic function (e.g., Decline in pH of plant sap; Reduction in transpiration rate)

3. Induced chemical/biochemical reactions (Denitrification; Manganese reduction; Iron reduction; Organic matter reduction).

Factors Affecting Soil Aeration
- Texture
- Bulk density
- Aggregate stability
- Organic matter content
- Biopore formation
- Soil heterogeneity –(tillage)
- Seasonal differences
- Vegetation

Mechanisms for soil aeration

Mass flow: This mechanism is dependent upon overall pressure gradients and is thus affected by soil water content, wind, and changes in barometric pressure.

Diffusion: Gases moves in the direction determined by its partial pressure. Consequently, the higher concentration of oxygen in the atmosphere will result in a net movement of this particular gas into the soil. Carbon dioxide and water vapour normally move in the opposite direction, since the partial pressure of these two gases are generally higher in the soil air than in the atmosphere.

Soil Temperature and thermal properties

Temperature is a measure of the thermal state of a body with respect to its ability to transfer heat.

Soil temperature affects:
- Soil (physical, biological and chemical processes occurring in the soil)
- Growing plants

Soil Processes Affected by Variation in Soil Temperature

a. In cold soil, rate of chemical and biological reactions are slow.

b. Microbial activities are slowed down at low temperatures, which bring biological decomposition to near standstill.

c. Absorption and transport of water and nutrients ions by higher plants are inhibited by low temperatures.

d. Plants and microbial processes are also inhibited by too high temperature.

e. Seed germination is most sensitive to soil temperature.

Solar Radiation

The primary source of energy to heat soils is the solar radiation from the sun.

Factors influencing the amount of solar radiation

- **Albedo –** This is the fraction of incident radiation that is reflected by the land surface.
- **Aspect –** The angle at which the sun's rays strike the soil
- **Rain/Irrigation water –** affect the soil temperature.
- **Soil Cover –** depends on whether the soil is bare, or is covered with vegetation or mulch.

Soil Thermal Properties

- Specific heat (heat capacity) **:** This is the amount of energy required to raise the temperature of a substance by 1^oC.

  Unit - (cal/g) or joules per gram (J/g)
- Thermal Conductivity: The amount of heat transferred through a unit cross-sectional area of unit thickness in unit time and unit temperature gradient.
- Thermal Diffusivity: Temperature change that takes place in a portion of a given soil as heat flows into it from adjacent layer.

Mode of Heat Transfer

- Conduction – Flow of heat through matter unaccompanied by any motion
- Convection – The transfer of heat by moving matter.
- Radiation – The transfer of heat through vacuum / space

Modification of soil thermal regime Most of the methods are aimed at modifying the surface intake / loss of heat.

- Mulch
- Tillage
- Irrigation
- Drainage
- Weed control
- Plants/trees.

Energy balance of soil

Net radiation is the sum of all incoming minus all outgoing radiation on Earth's surface.

Steady state one-dimensional heat energy balance at the soil surface or crop canopy can be written as:

Net heat energy arriving at surface − net heat energy leaving surface = 0

The net radiation received by the soil surface is transformed into heat, which warms soil and air and vaporizes water.

Calculating the Specific Heat of Moist Soils

$$c_{moist\ soil} = \frac{c_1 m_1 + c_2 m_2}{m_1 + m_2}$$

Where c_1 and c_2 are specific heat of the two substances and m_1 and m_2 are mass of the substances.

Specific heat: Water = 1.0 cal/g; dry mineral soil = 0.2 cal/g

SOIL WATER

Properties of Water Which Are Relevant to its Behavior in Porous Media

Water is the most common of all liquids, and it is indispensable for life. It accounts for 60-95% of the material in all organisms and it is a means of transporting nutrients dissolved or suspended in it to all parts of plants and other biological and porous bodies like soil. Water is thus a solvent to make solutions or suspension.

In a solution, a chemical species (the solute) breaks up into its molecules or into portions of its molecules when it is added to a pure liquid (the solvent) and the result is a homogenous solution in which it is impossible to detect the physical presence of the solute**.** *In a suspension*, one substance made up of the very small particles is present in a pure liquid, but the particles are a size that makes them physically distinguishable from the liquid. As the size of the particles in a suspension is reduced, we reach a state referred to as *the colloidal state*, which is half way between the true solution and a true suspension.

Soil Water Content and Potential

Quantity of water in soil is expressed by gravimetric or volumetric water content. However, water can also be characterized by describing its free energy per unit mass, which is termed potential. The tenacity with which water is held in soil solid is characterized by matric or pressure potential. When volumetric water content and matric potential are plotted graphically, the relationship is termed *Soil Moisture Characteristic Curve.*

When all soil pores are filled with water, the soil is at its maximum retentive capacity called saturation. In the field, the lowest wetness you can observe is called air-dryness and in the laboratory it is called oven-dry condition.

$$w = M_w/M_s$$

$$\theta = V_w/V_t = V_w/(V_s + V_w + V_a)$$

$$\theta = w(\rho_b/\rho_w) = w\Gamma_b$$

where Γ (capital letter of gamma) is the bulk specific gravity of the soil. The conversion of w to θ is easily done in son-swelling soil where soil bulk density does not change with wetness.

Application of soil water by irrigation or rainfall is reported as the depth of water if it were accumulated in a layer. This indicates the equivalent depth, d_w, soil water would have if it were ponded over the surface

$$d_w = \theta d_t = w\Gamma_b d_t$$

d_t is depth of soil per unit area

Usually dw is given in mm, as rainfall and evaporation

To obtain the volume of water applied to a given area would require multiplication of the depth by the area, measured in the same length units.

Water Potential

The International Soil Science Society defines total potential of soil water as “the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water(at the point under consideration”. Soil water is subject to a number of force fields, which cause its potential to differ from that of pure, free water. Each of these forces is a component of the total soil water potential and they result from the attraction of the solid matrix for water, as well as from the presences of solutes and the action of external gas pressure and gravitation. Thus, the total potential $\Phi = \phi_g + \phi_w + \phi_o + \phi_a + \phi_e$

is the summation of the component potentials:

where - ϕ_g = gravitational potential

ϕ_w = is the soil water potential

ϕ_o = Osmotic potential owing to the difference in chemical composition of the soil solutiom related to free, pure, bulk water at the same elevation.

ϕ_a = pneumatic potential which accounts for air pressure inside the soil pores being different from the outside atmospheric air pressure acting upon the reference water

ϕ_e =envelope potential. When an external mechanical pressure such as the overburden pressure of the topsoil layers acts upon the soil, the magnitude of change of the total potential is expressed by the envelope potential, which is usuall negligible for sandy soils and becomes more important for soils having greater clay contents.

In the majority of situations, the simplest definition of the total potentasl is

$\Phi = \phi_w + \phi_g$

and with the potential expressed as energy per unit weight of water

$H = h + z$

Thus, the total potential head of soil water (H) is the sum of the pressure potential head (h) and gravitational potential head (z). H is commonly called hydraulic head.

Hysteresis

The relationship between soil water content and potential, determined as soil dries out, will differ somewhat from the relationship measured as the soil is rewetted. This phenomenon describing the dependence of the equilibrium content and state of soil water upon the direction of the process leading up to it is called hysteresis.

Available soil water

Soil Water is classified according to how "tightly" it is being held in the Soil.

Free water or gravitational water will drain from a soil until the soil water potential reaches **-1/3 bar**. This is called **field capacity**. Gravitational water is not considered available to plants because it is in the soil only a short time and reduces oxygen levels to the point where the plant will not be absorbing water anyway.

As the soil continues to dry--or water is used by plants--more and more energy is needed by the plants to remove the water. Eventually a point is reached where the plant can no longer remove water. This is called the **wilt point** and occurs at -15 bars water potential for most plants. From **-1/3 to -15** bars is the zone of **available water.**

If the soil dries to an **air dry** state, the potential is **-31** bars. (This assumes that the air has 100% relative humidity.) Plants cannot exert enough tension to pull water away from the soil. Tension is used to express water potential with positive numbers. So a tension of +15 bars equals a potential of -15 bars.

Additional drying requires putting the soil in an oven to drive off the tightly held water. Water is held in the soil like a series of beads, the farther the beads are from the soil particle, the weaker they are held by cohesion

Water flow in saturated soil

Soil pores are highly irregular, tortuous and intricate with the consequence that the geometry of the pores restrict flow of water compared to what it would have been in straight tubes. However, the detailed flow pattern of water in soil is ignored, and it is treated as if it were a uniform medium, with flow spread over the entire cross section. The movement of water through a porous system occurs whenever there is a difference in potential energy of water within the porous matrix. The water content in a saturated soil system does not change during flow and only positive potentials are the driving force during the water transport.

Water flow in unsaturated soil

Unsaturated flow of water is a more commonly prevailing condition in the field than saturated flow. An unsaturated soil zone, or vadose zone, provides a continuum of water unsaturated subsurface porous media connecting the soil/atmospheric interface and underlying saturated groundwater zone. It has several functions including:

(i) storage of water and nutrients, and

(ii) transmission of water and other substances.

The storage of water and nutrients is vital to the biosphere, and the water transmission is important for replenishing the aquifers. Unsaturated flow conditions are more complex and very often do not have direct solutions. Instead indirect methods, approximations, and numerical methods are more commonly used in the solution of unsaturated flow problems.

The fundamental driving forces in both saturated and unsaturated flow are the potential gradient and hydraulic conductivity. As a stream of water is passed through the unsaturated soil matrix, the incoming water replaces the air present in the soil pores; it increases the total volume of water inside the soil, thus increasing the moisture content (θ) of soil. This agrees with the fundamentals of continuity equation, which states that the difference in the inflow and outflow rate is equal to the change of water storage in soil. The gradient causing flow in unsaturated soils is of negative pressure potential. The flow paths in unsaturated flow are more tortuous as several pores are filled with air

.

Table 1. Some differences between saturated and unsaturated flow

Parameter	Saturated flow	Unsaturated flow
Water content	Constant	Variable over space and time
Air content	Zero (close to zero)	Variable over space and time

Potential gradient	Positive and constant	Negative and variable
Hydraulic conductivity	Maximum, constant	Low and variable
Water flow	Steady	Steady as well as unsteady
Flow paths	Continuous	Tortuous

Source – Lal and Shukla, 2004

Solute transport and water quality

When water flows on soil surface as overland flow and/or through the soil matrix, it also dissolves solutes (e.g., salts, fertilizers, pesticides). These solutes not only move with soil water but also within the soil matrix mainly due to the concentration gradients. Sometimes, solutes react among themselves and/or with soil material according to a range of physical and chemical processes. In agricultural ecosystems, solutes may be categorized on the basis of their function (e.g., nutrients, pesticides, waste compounds, salts, organic chemicals, and heavy metals). Understanding transport of solutes in soil is important to many management problems in agriculture. It can help when developing procedures for maximizing the effective use of fertilizers or pesticides and other chemicals within the root zone while minimizing their movement into groundwater, so as to safeguard water quality. Knowledge of these processes is important to understanding the problems of contamination of natural water through leaching or redistribution within a vadose zone to groundwater.