Soil Water - Potential, Constants and Movement

Ketan F. Satashiya, Krutika S. Patel, Sweta A. Patel, T.C. Poonia

Water in soil plays a crucial role in the soil-plant-atmosphere system and it has an effect on processes which determine crop yield and the stability of the ecosystem. The chapter gives a clear-cut review of the soil water, beginning with the physical characteristics of water in regard to soil behaviour. It branches into discussing the soil water potential, the description of which includes explanation of the role of matric, gravitational, osmotic and pressure potentials in the retention, movement and availability of water to plants. The major processes, including infiltration, percolation, permeability, drainage, and hysteresis, are looked into and the importance of the processes in relation to the soil texture, structure, pore-size distribution, and management practices are brought to light. The water flow in the soil profile is investigated both in a saturated and unsaturated state and the importance of Darcy law and hydraulic conductivity are emphasized. The retention curves of soil moisture and constants, which include saturation, field capacity, permanent wilting point, and available water capacity are explained and the means of determining the soil moisture content. The soil plant atmosphere continuum (SPAC) framework illustrates water flow from soil to atmosphere. Lastly, the principles of plant–water relations, including root uptake and transpiration, are explored, connecting soil processes with plant physiological responses for effective soil and water management in agricultural systems.

Keywords: *Soil water constants, potential, movement, retention, soil-plant-atmosphere continuum*

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Introduction

World water resources are undergoing a profound and accelerating change. This shift is driven not only by rapid economic development and expanding human activity, but also by growing urbanization, agricultural intensification, and population increase, climate-driven changes in rainfall patterns, groundwater depletion, and pollution of freshwater sources. Worldwide, the water status remains under grim situation. According to the UNESCO-2023 report, about 2.2 billion people (roughly 1 in 4 people) still lack access to safely managed drinking water. Meanwhile, nearly 3.5–3.6 billion people lack access to safely managed sanitation. Freshwater withdrawals have risen globally in between 2000 and 2021, global freshwater withdrawals climbed by around 14%**,** with agriculture alone accounting for approximately 72% of total water use. As a result, many regions now face 'high to critical' water stress-in fact; dozens of countries (representing a quarter of the world's population) are under extremely high water-stress conditions annually. Given these trends, many parts of the world (especially in Asia, Africa, the Middle East, and parts of Latin America) are likely to experience serious water crises in coming decades, unless sustainable water management practices are adopted. Soil water is depleted due to evaporation from soil surface, transpiration through the plant and deep percolation into the soil beyond the rhizosphere. Water availability to plants is reduced gradually and plants are subjected to moisture stress. Plants cannot grow in a dry soil as roots proliferation is reduced due to high mechanical resistance of dry soil. Application of water provides favorable environment to the plants. The movement of water in soil is governed by its physical state and energy status (soil water potential). Soil water exists in different forms among which capillary water is the most important for plants growth as it is readily available for root absorption. The limits of plant available water are defined by soil moisture constants particularly in between field capacity and permanent wilting point. Its movement in soil and in plant largely depends on hydraulic conductivity and transpiration pull, respectively. Soil water movement occurs through infiltration (at soil surface) and percolation (at deeper layers). The water is also retained in the soil colloids like clay or humus particles. These soil colloids absorb water and as result of it get swollen. The water thus retained in the soil is called as imbibitional moisture. Soil moisture is expressed as percentage on oven dried basis either on weight basis or on volume basis. For instance, when a soil is stated to contain 12% moisture on oven dried basis, it means 100g of dried soil holds 12g of water. As soils are normally moistened with water, the term soil moisture and soil water are used generally as synonymous or interchangeable. Soil moisture is expressed in depth (cm/m). Availability of soil moisture, its movement in soil, retention, its uptake by plants and its translocation are the various steps to understand soil-plant-atmosphere continuum processes. Knowledge on water potential, soil moisture retention and its movement is essential for its efficient management, groundwater recharge, water conservation and sustainable agricultural practices in changing climatic scenarios.

India's Water Challenges: A Microcosm

The water stress situation in India is especially acute due to poor management. The country has only about 4% of the earth's freshwater resources**,** making it extremely susceptible and it is only at around 1,486 m^3 /head/year. For example, estimates suggest that up to 600 million people in India experience high to extreme water crisis (Amarasinghe, 2004). To depend totally on ground water, heighten susceptibility as rural India drinking water and agricultural irrigation depends on groundwater. Water quality is reduced day-by-day due to heavy pollution vital issues for human health. Given India's large population, growing urbanization, expanding agriculture, and climate variability (erratic and uneven rainfall, droughts, floods, etc.), the demand for freshwater is rising faster than availability.

Why This Matters and What It Implies?

The Indian water budget shows a high-water stress which is a present-day truth. Demographic regions populated very dense, adopting intensive agricultural practices, speedy urbanization over alarming water resources (like Punjab, Uttar Pradesh) are among the most susceptible today. India is the largest agricultural exports of rice, cotton, sugar and buffalo meat require thousands of liters of water for every kilogram of product. India's urban population, which was 377 million in 2011, is expected to rise to nearly 600 million by the end of 2031 (Amarasinghe, 2004) and may cross 820 million by 2050. Hence, effective water management demands foresight and integrated policies. Naturally, India has been endowed with extensive surface water resources. Water is one of the most critical resources necessary for nourishment of life and central to socio-economic welfare. India, with 2.4% of the world's total geographical area and 18% of the world's population, has only 4% of the world's total fresh water resources (Gulati et al., 2019). Irrigation sector constitute 78% of the country's freshwater demand which demands newer dimensions of management. In Indian agriculture, irrigation through canals and groundwater accounts for about 87% and 63% of the net irrigated area, respectively. Further, per capita availability of water in India has declined drastically (nearly 75%) up to 2050 (Table-1)**.** National reports emphasize that by 2050**,** the country's water demand may be thrice the available supply**,** leading to conditions of acute scarcity (NITI Aayog, 2019). The fast urbanization and soil pollution may reduce the land capacity to absorb and recharge groundwater resulting in declining aquifer levels, increased land surface runoff and a heightened risk of flooding in large and densely populated urban regions (Howard and Gelo, 2002). Globally, water budget is largely depending on rainfall and its distribution (Figure 1). The average rainfall of India is 1194 mm. When considered over the geographical area of 328 m ha, this rainfall amounts to 392 million-hectare-meters (m ha m). Out of this, 75% is received from the south-west monsoon period (June to September) and rest in the remaining eight months. A major portion of the rain water (215 m ha m) soaks into the soil while 70 m ha m is lost as evapotranspiration. Evapotranspiration constitutes nearly 99 per cent of total water uptake.

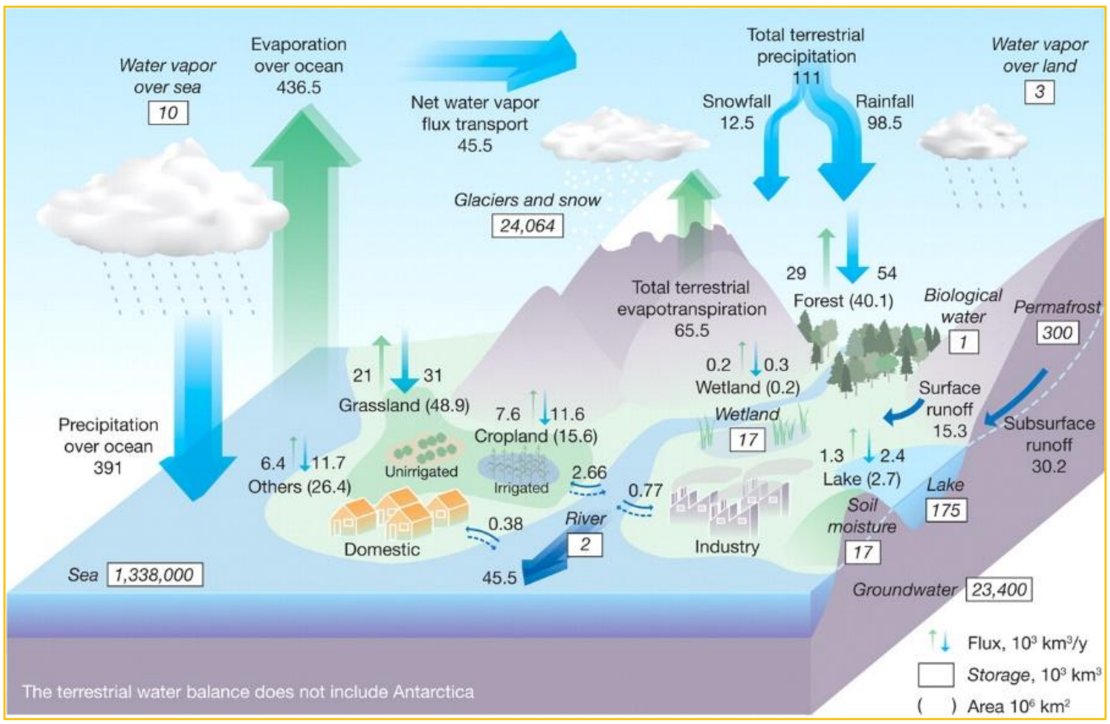

Figure 1. Global water budget

Water Availability in India

India receives an average annual precipitation of about 3,880 billion cubic meters (BCM) and is endowed with an extensive river network as well as snow-fed Himalayan systems. However, due to the highly uneven spatial and temporal distribution of rainfall and significant evaporation losses, the net utilizable water resources are estimated at only 1,123 BCM**.**

Table 1. Estimated global water distribution in present day

Source: Peter H. Gleick (1993)

Water source	Volume (m^3 miles)	Volume (m^3 km)	% of freshwater	% of total water
Oceans, seas, and bays	321,000,000	1,338,000,000	-	96.54
Ice caps, glaciers, and permanent snow	5,773,000	24,064,000	68.7	1.74
Ground water	5,614,000	23,400,000	-	1.69
Fresh	2,526,000	10,530,000	30.1	0.76
Saline	3,088,000	12,870,000	--	0.94
Soil moisture	3,959	16,500	0.05	0.001
Ground ice and permafrost	71,970	300,000	0.86	0.022
Lakes	42,320	176,400	-	0.013
Fresh	21,830	91,000	0.26	0.007
Saline	20,490	85,400	-	0.006
Atmosphere	3,095	12,900	0.04	0.001
Swamp water	2,752	11,470	0.03	0.0008
Rivers	509	2,120	0.006	0.0002
Biological water	269	1,120	0.003	0.0001

This includes contributions from precipitation (rainfall and snow), surface water stored in rivers, lakes, and reservoirs, and replenish type groundwater. Of the total utilizable water resources, nearly 690 BCM is derived from surface water**,** while about 436 BCM comes from groundwater. According to the most recent estimates by the Central Ground Water Board (2022) the India's annual groundwater recharge is 437.60 BCM.

Table 2. Current water availability in India

Parameter	Unit (BCM /year)
Annual water availability	1,869
Usable water	1,126
Surface water	690
Ground water	436

Projected Water Demand of India

Recent report by the Indian government cautions by 2030, the country's water demand is projected to be twice the available supply and the deficit shall cause 6% loss in the country's GDP. India is facing a nationwide groundwater crisis with 54% of wells declining in water level due to exploitative groundwater use, 600 million people face heightened water stress, 75% of Indian households do not have drinking water on premises and 84% of rural households do not have piped water access (NITI, 2019).

Table 3. Projected water demand (BCM) in India (by different usage)

Demand sector	Up to 2010	% share in demand	Up to 2050	% share in demand	% increase 2010-2050
Irrigation (Agriculture)	557	78.4	807	68.4	44.9
Drinking water (Industry)	43	6.0	111	9.4	158.1
Industry sector	37	5.2	81	6.9	118.0
Energy sector	19	2.7	70	5.9	288.9
Others	54	7.7	111	9.4	105.6

Physical properties of water

Water is a odorless, colorless and tasteless (when pure) liquid, exists in three states of solid, liquid, gas (Figure 2). The molecules of water have extensive hydrogen bonds (H_2O) resulting in unusual properties in the condensed form. This also leads to high melting (0.00 °C) and boiling points (99.98 °C). As compared to other liquids, water has a higher specific heat (75.375 ± 0.05 J/mol·K), thermal conductivity (0.6065 W/m·K), surface tension (0.072 N/m) at room temperature and dipole moment. These properties form the reason for its significance in the biosphere. Water is an excellent solvent and therefore it helps in the transportation of ions and molecules required for metabolism. It has a high latent heat of vaporization which helps in the regulation of body temperature.

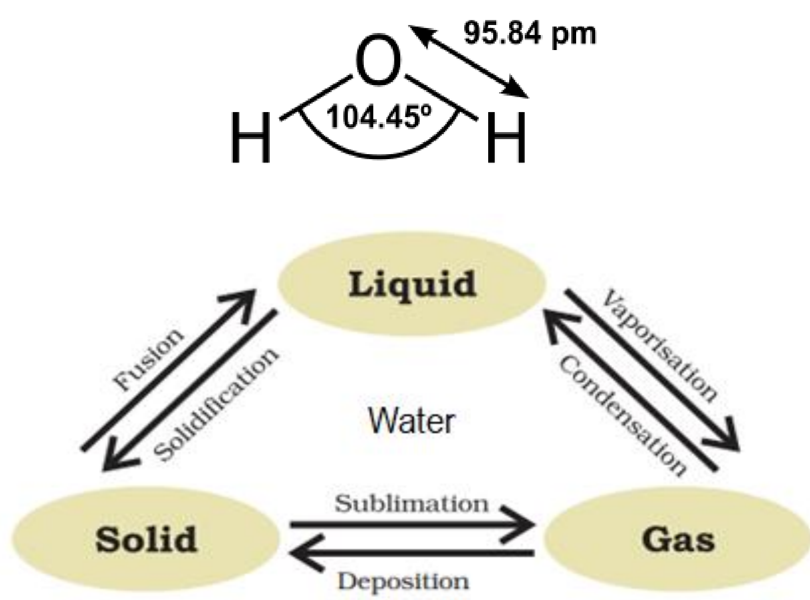

Figure 2. Water molecule and its inter-conversion in three states of matter

Transport Mechanism of Water

Particles of matter are continuously moving, that is, they possess what we call the kinetic energy. Heat energy and electric current always moves from regions of high to low**.** Particles of matter intermix on their own with each other by getting into the spaces between the particles. This intermixing of particles of two different types of matter on their own is called diffusion. For instance, water dissolved in a gas or liquid move from regions of high concentration to low concentration. The rate of diffusion of liquids is higher compared to solids. In soil, water movement occurs through pressure and gravitational forces.

Soil water potential and its energy state

Water potential (Ψ) is the free energy of water, determining its movement from higher potential (pure water, zero value) to lower potential (solutions, negative values) through osmosis/diffusion and articulated in Pascals (Pa). Soil water potential is more complex property surrounding multiple factors that influence water movement in soil. Soil water is affected by several forces that cause its potential to differ from that of pure free water. These forces occur from:

$$\Psi t = \psi g + \psi o + \psi m + \psi ep + \ldots$$

Where; ψt = Total soil water potential

ψg = Gravitational potential

ψo = Osmotic potential

ψm = Matric potential

ψep = External gas pressure potential (=additional terms are theoretically possible)

Gravitational potential (ψg)

Every object on the Earth's surface is attracted toward the center of the earth by a gravitational force equal to its weight, which is the product of its mass and the gravitational acceleration. To move a body against this attraction, work must be done, and this work is stored in the body as gravitational potential energy**.** The amount of this energy depends on the body's position within the gravitational field. Similarly, the gravitational potential of soil water (ψg\psi gψg) at a given point is determined by the elevation of that point relative to an arbitrary reference level.

- If the point is above the reference level, ψg\psi_gψg is positive.
- If the point is below the reference level, ψg\psi_gψg is negative.

Thus, gravitational potential depends only on the vertical distance between the reference level and the point in question, and it is independent of soil properties**.**

Osmotic/solute potential (ψo/Ψs)

Osmotic potential (solute) is the amount by which the presence of a solute in pure water reduces the water potential. The free mobility of the water molecules decreases when solutes are mixed to pure water. Pure water has zero solute potential; the potential of solute is either negative or less than zero.

Soil matrix potential (ψm)

Matrix represents things that are on the surface, such as soil particles, cell wall and protoplasm. Matrix potential results from the inter-molecular interactions and H-bonds assisting in the bonding of water to the matrix (capillary or adsorption). Capillary is the results of surface tension of water and its contact angle with soil grains. In an unsaturated soil**,** curved water menisci form between soil particles, following the capillary movement. Adsorption is the attraction of water molecules to the surfaces of soil grains like a thin layer.

External gas pressure potential (ψep)

In plants, the main factors which control the water potential are pressure, concentration and gravity. The factor of gravity causes water to move downward side till the gravitational force is meets by an equal antagonistic force. In the laboratory, applying excess air pressure to alter the pressure of soil water is a common practice. This creates what is known as the pneumatic potential **or** external gas pressure, which is considered a component of the soil water potential.

Movement of Soil Water from Soil Surface

The movement of water through soil is influenced by soil properties, water potential, and external forces such as gravity. The main processes are:

1. Infiltration

- Definition**:** The downward entry of water from the soil surface into the soil profile.
- Factors affecting infiltration:
    - Soil texture and structure
    - Soil moisture and soil organic matter content
    - Soil compaction
    - Surface cover (like vegetation, mulching)
- Measurement**:** It can be measured using an infiltrometer (for instance ring infiltrometer) which determines the rate at which water enters the soil.

2. Percolation

- Definition**:** The movement of water downward through the soil profile, beyond the root zone, under the influence of gravity.
- Importance**:** Recharges groundwater but may carry soluble nutrients and contaminants below the root zone.

3. Permeability

- Definition**:** The ability of soil to transmit water under a unit hydraulic gradient.
- Factors affecting permeability**:**
    - Soil texture (sandy soils have high permeability, clayey soils have low)
    - Soil structure and aggregation
    - Degree of saturation
- Measurement**:** Laboratory or field methods using permeameters or constant/head and falling-head tests**.**

4. Drainage

- Definition**:** The removal of excess water from soil, naturally or artificially, to improve aeration and prevent waterlogging.

- Types**:**
    - Natural drainage: By gravitational flow through soil layers to streams or groundwater
    - Artificial drainage: Through ditches, tiles, or subsurface drains
- Importance**:** Prevents crop damage, reduces salinity, and improves soil aeration.

5. Hysteresis

- Definition**:** Hysteresis is the difference in soil moisture content at the same tension during wetting versus drying (Figure 3). The main causes are:
    - Presence of capillary and non-capillary pores
    - Shrinking and swelling of soil minerals affecting pore size
    - Pore shape, size, and interconnection
    - Nature of soil colloids, bulk density and entrapped air

Key Points:

- Moisture content is lower during wetting (sorption) and higher during drying (desorption).
- The most important factor affecting hysteresis is air entrapment, which blocks some pores and prevents effective water contact.

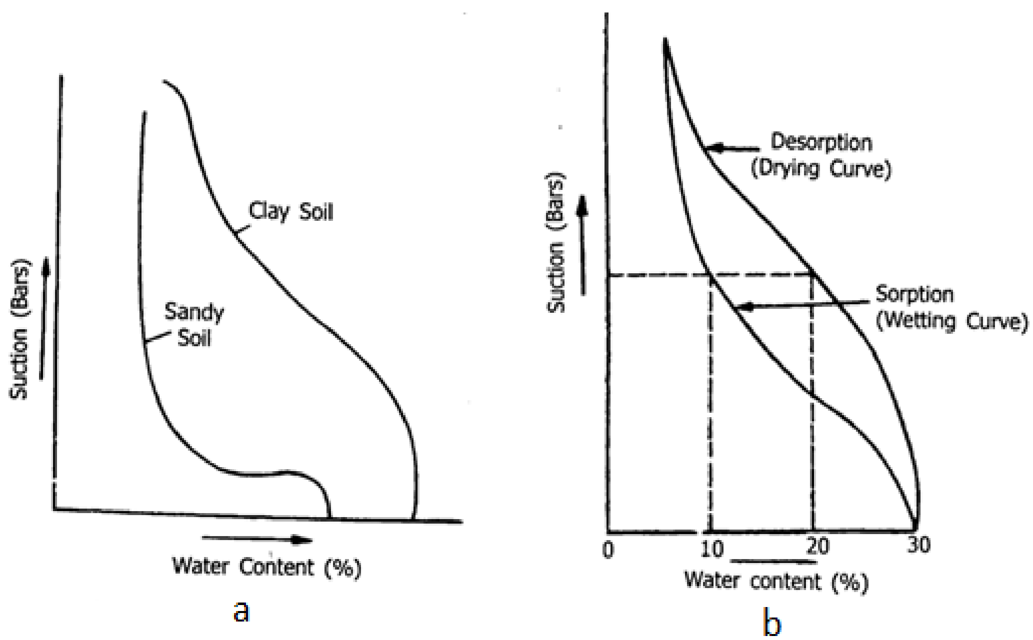

Figure 3. Soil moisture characteristic (a) and sorption and desorption curve (b)

Movement of Water in the Soil

Water is added at soil surface either as irrigation or rain enters in to soil and moves down to lower layers. It continuous to move down even after water supply is stopped at soil surface. The movement of water in the soil is caused by water potentials and it moves from a place of higher potential to that of lower potential. Water is move in the soil by three phases *viz*., liquid, gases and solids. Liquid water moves under saturated and unsaturated flow. When most of the pore spaces are filled with water, the flow occurs in the zone of ground water or sometimes in the soil after heavy rains or during irrigation. Saturated flow is a temporary phase and water under this condition is tension free and flows under the gravity force. Under unsaturated flow, soil pore spaces are filled with water and air, the water is under tension and moves under the influence of surface tension. Water vapour moves by diffusion as results of vapour pressure (partial pressure) difference and as a mass with other gases in response to differences in total pressure. Water movement as solid (ice) does not occur in ordinary conditions but occurs as a part of movement of entire soil body. Generally, it is not important.

Water movement in the soil comprises three phases-infiltration, redistribution and withdrawal. Mainly it occurs in three main ways

i) Saturated flow,

ii) Unsaturated flow and

iii) Water vapour movement.

1. Saturated Flow

Saturated flow occurs when soil pores are completely filled with water. In this condition, water moves at water potentials greater than -33 kPa.

Characteristics

- Determined primarily by gravity like movement of rainwater into the soil.
- Begins with infiltration, which is the downward movement of water into the soil when rain or irrigation water is present on the soil surface.
- Once the soil profile is wetted, further movement of water through the saturated soil is called percolation.

Hydraulic Conductivity (K)

As per Darcy's Law, hydraulic conductivity is defined as the velocity of flow of water through a soil under a unit hydraulic gradient. Intrinsic soil permeability, fluid properties, extent of saturation and soil texture and structure are the factors affecting hydraulic conductivity.

Factors Affecting Movement of Water in Soil

1. Soil Texture and structure: Soil texture determines pore size and its distribution. Sandy soils allow faster movement than clayey soils. Well-structured soils with stable aggregates facilitate easier water flow in the soil. Higher the pore size, more rapid is the saturated flow.
2. Amount of Organic Matter: Increases porosity and water-holding capacity, improving water movement.
3. Depth of Soil to Hard Pan: Shallow soils over hard pans restrict vertical flow.
4. Amount of Water in Soil: Saturated soils transmit water faster than dry soils.
5. Temperature: Higher temperatures reduce water viscosity hence increasing flow rate.
6. Pressure: External pressure (e.g., irrigation or applied pneumatic pressure) can influence water movement.

2. Unsaturated Flow

Unsaturated flow is the movement of water in soil held at water potentials lower than –1/3 bar (–33 kPa). Water moves from areas of higher potential (wetter regions) to areas of lower potential (drier regions), following the greater “pulling” force.

Characteristics

- The direction of flow may be any, not necessarily vertical.
- The rate of flow increases with:
    - A greater water potential gradient (difference between wet and dry regions)
    - Larger water-filled pores

The two main forces responsible for unsaturated flow *viz.*,
i) adhesion- attraction of soil solids for water and
ii) capillarity- movement of water through small pores due to surface tension.

Under field conditions it occurs when macro-pores (non-capillary pores) are mostly filled with air and micro-pores (capillary pores) contain water and are partially filled with air.

Water Vapour Movement (soil)

The movement of water vapour from soils occurs in two ways:

1. Internal movement

- Water changes from the liquid to vapour state within the soil pores.
- This process occurs entirely inside the soil matrix.

2. External movement

- Water vapour moves from the soil surface to the atmosphere.
- This involves processes like diffusion and convection.

Mechanism of diffusion

- Water vapour moves from areas of higher vapour pressure to areas of lower vapour pressure.
- The vapour pressure gradient is the driving force, defined as the difference in vapour pressure between two points per unit distance. Temperature influences water vapour movement.
- A greater gradient results in:
    - Faster diffusion
    - Greater transfer of water vapour in a given period

Water retention in the soil

Water that enters into the soil is retained by means of three forces *viz.*, adhesion, cohesion and due to soil colloids (clay and humus). The capacity of soil to hold water against the force of gravity is called soil water retention. This retained water in soil is available to plants use which directly influences plant growth, nutrient availability, soil biological activity and energy transfer. Water molecules do not exist individually. Hydrogen in the water molecule serves as a connecting link from one molecule called as hydrogen bonding. Water sticks to itself with great energy and this property is called cohesion. When water attaches itself to surface of many substances and this property is called adhesion. By adhesion water is held tightly at the soil-water interface. The amount of water present in the soil between field capacity and permanent wilting point is called as available water (Figure 4).

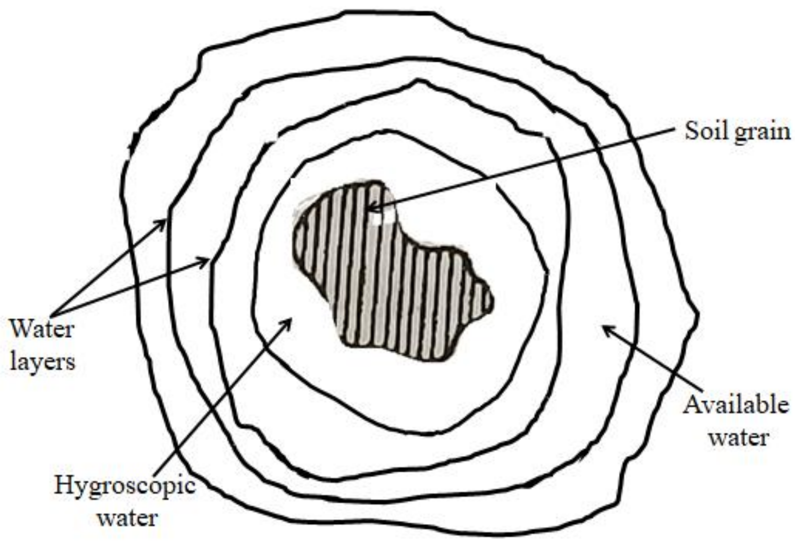

Figure 4. Water retention by soil particles

In between two stages, water is available to the plants with equal ease throughout the available range. After irrigation or rain, both micro and macro pores filled with water and soil is said to be at saturated condition. At saturation the energy status of water is zero. As the soil dries, the thickness of water around soil particles decreases, more and more energy is required to remove the water. The extent of water retention by soil is depends on soil texture, structure, organic matter content and pore size. Clay soils (fine textured) retain more water (23 cm/m depth) due to higher proportion of micro-pores than course textured sandy soil (8 cm/m depth). Addition of organic matter improves water retention capacity by increasing soil aggregation and surface area. Well-aggregated soils have a balanced distribution of macro and micro pores, enhancing both better water retention and aeration.

Soils with crumbly and granular clods are considered as soils with good structure. When the soil is subjected to tillage at optimum moisture level, crumb structure is developed so that loss of soil by erosion is greatly reduced. Rain water is held in the large pores, between the aggregates and also in the micro pores of the aggregates. It is considered that soil aggregates of 1 to 5 mm in size are favorable for growth of plants. Smaller aggregates may clog the soil pores and larger ones may have large pore space between them and affects the proliferation of rootlets of young seedlings. Soil structure is destroyed when tillage is carried out at inappropriate soil moisture content. The relative proportion of different sized soil aggregates is known as size distribution of soil aggregates. For irrigated agriculture higher amount of larger aggregates (> 5 mm in diameter) are necessary, while under dry land agriculture higher amount of smaller aggregates (1 to 2 mm in diameter) are necessary.

Soil Moisture Constants

Soil moisture is always being subjected to pressure gradients and vapour pressure differences that cause it to move. Thus, soil moisture cannot be said to be constant at any pressure. However, it has been found experimentally that certain moisture contents described below are of particular significance in agriculture and these are often called soil moisture ‘constants’. To know the availability soil moisture to crops, the knowledge of following soil moisture constants is essential. Soil moisture constants represent definite soil-water relationships under certain standard conditions. They serve as reference points for irrigation management (Table 4).

Table 4. Soil moisture constants and their values

Moisture constants	Definition	Typical values
Maximum Water Holding Capacity (MWHC)	Water when soil is fully saturated	Sum of gravitational, capillary, and hygroscopic water
Moisture Equivalent (ME)	Water retained against centrifugal force 1000× gravity	ME ≈ FC; varies with soil type
Field Capacity (FC)	Moisture after free drainage ceases (~48–72 hrs after saturation)	Sandy: 5–10%, Loam: 18–25%, Clay: 32–40%
Permanent Wilting Point (PWP)	Moisture where plants wilt permanently	Sandy: 2–6%, Loam: 8–12%, Clay: 15–19%
Hygroscopic Coefficient (HC)	Water tightly bound to soil colloids	Only vapour movement is possible

1. Maximum Water Holding Capacity (MWHC)

Definition: Water held in the soil when all pores are filled (100% saturation).
Components: Sum of gravitational, capillary, and hygroscopic water.

2. Moisture Equivalent (ME)

Definition: Percentage of water a soil can retain against centrifugal force 1000× gravity (Briggs & McLane, 1907).

- Relation to Field Capacity (FC):
  - Sandy soil → ME < FC
  - Clay soil → ME > FC
  - Medium soil → ME = FC

3. Field Capacity (FC)

Definition: Moisture content of a well-drained soil a few days after saturation, when downward movement of excess water ceases (48–72 hours).

- Influencing factors to FC:
  - Sandy soils reach FC faster than clayey soils.
  - Organic matter and fine texture increase FC.
- Other terms: Field carrying capacity (FCC), moisture capacity (MC), capillary capacity (CC), water holding capacity (WHC), moisture retention capacity (MRC).
- Force at FC: 0.1–0.3 atm.
- Typical FC values by soil type:
  - Sandy: 5–10%
  - Sandy loam: 10–18%
  - Loam: 18–25%
  - Clay loam: 24–32%
  - Clay: 32–40%

4. Permanent Wilting Point (PWP)

Definition**:** Soil moisture content at which plants wilt permanently and do not regain turgidity even after watering. At this stage plants wilt but do not die.

- Significance**:** Lower limit of available water for plant growth**.**
- Force at PWP: ~15 atm.
- Typical PWP values by soil type:
  - Sandy: 2–6%
  - Sandy loam: 4–8%
  - Loam: 8–12%
  - Clay loam: 11–15%
  - Clay: 15–19%

5. Hygroscopic Coefficient (HC)

Definition**:** Water remaining in an air dry soil and watr retain at -60 bars.
Characteristics**:** Water is tightly adsorbed to soil colloids. Only vapour movement is possible. At this stage plants die permanently.

Methods of Determining Soil Moisture

1. Gravimetric Method

- Soil samples are collected, weighed, dried in an oven, and weighed again.
- Soil moisture content (θ) = (Weight of water / Weight of dry soil) ×100%
- Simple and accurate but destructive.

2. Tensiometers (Irrometers)

- Measures soil water tension (matric potential) in the field.
- Suitable for sandy to loamy soils with moderate moisture content.

3. Electrical Methods

- Electrical resistance blocks: Soil moisture affects the resistance between electrodes.
- Time-domain reflectometry (TDR): Measures the dielectric constant of soil to estimate water content.

4. Neutron Scattering Method

- Measures hydrogen atom content in soil using neutron probes; highly accurate for field monitoring.

Soil-Plant-Atmosphere Continuum (SPAC)
Concept

The Soil-Plant-Atmosphere Continuum (SPAC) is a unified, dynamic system that integrates the soil, plants, and atmosphere to describe water extraction and utilization by plants**.** In this system, all components are physically interconnected, and water flow occurs interdependently**,** like links in a chain. The *universal principle* of SPAC is that "Water always flows spontaneously from regions of higher potential energy to regions of lower potential energy"**.**

Water Potential in SPAC

- Different terms used to describe the state of water in soil, plant, and atmosphere are essentially expressions of water potential or energy level**.**
- Gradients of water potential between locations in the system act as the driving force for water movement**.**
- Different components of the overall potential gradient may be effective to varying degrees in different parts of the soil-plant-atmosphere system.

Flow Path of Water in SPAC

Water moves through the SPAC along a continuous path:

1. Liquid water movement in soil toward plant roots.
2. Water movement at the root-soil interface, which may include both liquid and vapour phases.
3. Absorption into roots and across root cell membranes into the xylem vascular system.
4. Ascent through the xylem from roots to leaves.
5. Evaporation in the intercellular spaces within leaves.
6. Vapour diffusion through stomata cavities and out of stomata to the boundary air layer at the leaf surface.
7. Transfer into the turbulent atmosphere**,** which carries water away from the soil-plant system.

Key Principle

SPAC is continuous, passive movement of water from areas of higher water potential (soil) to lower water potential (atmosphere), driven by a gradient and facilitated by the cohesive properties of water and resistances within soil, plant (xylem), and atmosphere. Any interruption in one part of the continuum (e.g., soil drying, high atmospheric water demand, or dead roots) affects the entire system.

Plant Function and Water Relations

Water in plant life plays a vital role in plant life. Its absorption via root hairs, movement through xylem (transpiration pull), and loss through transpiration, maintains turgidity, facilities photosynthesis, transports nutrients, and drives growth. Unlike animals, which minimize external surface area to conserve water and heat, plants maximize surface exposure, both above and below ground.

- Aerial parts: Plant canopies often exceed the area of ground cover several times over, allowing plants to intercept sunlight and absorb CO_2, both of which are diffused rather than concentrated.
- Underground parts: Root systems are highly proliferative, absorb maximize water and nutrients from a soil solution. For instance, a single annual plant may develop a root system several hundred kilometers long with hundreds of square meters of surface area. Roots forage through soil continuously, moving towards water and nutrients, because soil solution moves very slowly compared to the atmosphere.

Factors influencing root growth include

- Soil moisture and nutrient availability
- Temperature and aeration
- Mechanical resistance

- Presence of toxic substances
- Geotropism (primary roots growing vertically downward)

Plant Adaptation to Water Availability

Different plants have evolved adaptations to cope with varying water availability:

- Hydrophytes: Aquatic plants inhabiting water-saturated environments.
- Phreatophytes: Plants accessing shallow water tables.
- Mesophytes: Plants growing in aerated soils under semi-humid to semi-arid climates; most crop plants are mesophytes.

  Mesophytes optimize water economy by:
  - Developing extensive root systems
  - Maintaining an efficient root: shoot ratio
  - Regulating stomatal aperture
- Xerophytes**:** Desert-adapted plants with xeromorphic features to minimize water loss, like-
  - Thickened epidermis and waxy cuticle in desert plants
  - Recessed stomata and reduced leaf area
  - Specialized water storage tissues (succulence)

Transpiration and Water Use

- Water use efficiency: Only a small fraction (<1%) of water absorbed by plants is used for photosynthesis**;** the majority (often >98%) is lost as vapour through transpiration.
- Necessity of transpiration: Large moist cell surfaces exposed to the atmosphere facilitate gas exchange for photosynthesis and respiration. Transpiration also prevents overheating of leaves by dissipating excess solar energy.
- Water deficits**:** Plants, especially mesophytes, are highly sensitive to water shortages. Insufficient water replacement during transpiration can impair growth and may be fatal.
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Nutrient uptake and transpiration

- Previously believed to be linked, nutrient absorption and transport are now understood to be largely independent of transpiration (The main force for tall plants).
- Nutrient uptake involves metabolically active processes, not just passive water flow.
- Transpiration's primary benefit is likely thermal regulation rather than enhanced nutrient uptake. Reduced transpiration under water deficit conditions raises canopy temperatures.

Water Uptake by Roots and Transpiration
Factors Affecting Water Uptake

The rate of water uptake from a given soil volume depends on:

- Rooting density**:** Effective root length per unit soil volume.
- Soil hydraulic conductivity**:** Ability of soil to transmit water.
- Water potential gradient: Difference between average soil-water suction and root suction.
- If soil-water suction is uniform but roots are unevenly distributed, water uptake is highest where root density is greatest**.**

- Rapid uptake in dense root zones leads to faster local depletion of soil moisture**,** so the uptake rate does not remain constant for long.

Root Layer Dynamics
The rooting system can be conceptually divided into two layers:

1. Upper layer**:**
    - Root density is highest and fairly uniform.
    - Water depletion occurs uniformly.
2. Lower layer Dynamics**:**
    - Roots are sparse.
    - Water depletion is slower and occurs via:
        - Direct uptake by roots in the layer
        - Upward flow of water from deeper layers driven by suction gradients

Mature vs. Young Plants
- Mature plants:
    - Roots occupy a relatively fixed soil volume**.**
    - Water uptake depends mainly on:
        - Size of soil volume
        - Soil water content and hydraulic properties
        - Root density
- Young plants:
    - Root extension into deeper and wetter soil layers can significantly contribute to meeting water requirements.

Pot grown vs. Field grown Plants
- Pot-grown plants:
    - Roots often have fairly uniform distribution throughout the soil.
- Field-grown plants:
    - Root density generally varies with depth**.**
    - Roots at different depths may differ in water uptake and hydraulic resistance**.**
    - Deeper roots may offer greater resistance to water movement within the plant than shallow roots.
    - Moist sub-layers below the rooting zone can contribute significantly, especially where a high water table exists.

Conclusion

The soil water is the most important component of the soil, which plays a vital role in crop growth and production. Water is retained as a thin film around soil particles and in capillary pores by the forces of adhesion, cohesion, and surface tension. The size of individual pores is highly important for the movement of water in soil. Knowledge of soil properties, including water retention, hydraulic conductivity, and moisture constants, is essential for efficient water management. Hence, understanding the water movement from the surface to deeper layers in soil forms the basis for efficient water use in agriculture and allied sectors, as well as aquifer recharge for sustainable agricultural production.

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