03. SOIL WATER MOVEMENT - SATURATED AND UNSATURATED FLOW AND VAPOUR MOVEMENT - SOIL MOISTURE CONSTANTS AND THEIR IMPORTANCE IN IRRIGATION

Soil Moisture Tension

Soil moisture tension is a measure of the tenacity with which water is retained in the soil and shows the force per unit area that must be exerted to remove water from a soil. The tenacity is measured in terms of the potential energy of water in the soil measured, usually with respect to free water. It is usually expressed in atmospheres, the average air pressure at sea level. Other pressure units like cm of water or cm or mm of mercury are also often used (1 atmosphere = 1036 cm of water or 76.39 cm of mercury). It is also sometimes expressed in bars (1 bar = 10^6 dynes / cm^2 = 1023 cm of water column.

$$1 \text{ millibar} = \frac{1}{1000} \text{ bar}).$$

Soil moisture tension is brought about at the smaller dimensions by surface tension (capillarity), and at the higher dimensions by adhesion. Buckingham (1907) introduced the concept of 'capillary potential' to define the energy with which water is held by soil. This term, however, does not apply over the entire moisture range. In a wet soil, as long as there is a continuous column of water, it might be called 'hydrostatic potential', in the intermediate range the term 'capillary potential' is appropriate. In the dry range the term 'hygroscopic potential' would be suitable. However, the term 'soil moisture potential', 'soil moisture suction' and 'soil moisture tension' are often used synonymously to cover the entire range of moisture (Khonke, 1968).

pF of soils: Scholfield (1935) suggested the use of the logarithm of soil moisture tension and gave the symbol pF of this logarithm which is an exponential expression of a free-energy difference (based on the height of a. water column above free-water level in cm). The pF function, analogous to the acidity-alkalinity scale pH, is defined as the logarithm to the base 10 of the numerical value of the negative pressure of the soil moisture expressed in cm of water.

$pF = \log_{10}{}^{h}$ in which

h = soil moisture tension in cm of water

If the osmotic tension is negligible, *i.e.,* at low salt concentration, the pF of the soil moisture may nearly equal the logarithm of the capillary tension expressed in cm of water.

Soil Moisture Characteristics

Soil moisture tension is not necessarily an indication of the moisture content of neither the soil nor the amount of water available for plant use at any particular tension. These are dependent on the texture, structure and other characteristics of the soil and must be determined separately for each soil. Generally sandy soils drain almost completely at low tension, but fine textured clays still hold a considerable amount of moisture even at such high tensions that plant growing in the soil may wilt. Moisture extraction curves, also called moisture characteristic curves, which are plots of moisture content versus moisture tension, show the amount of moisture a given soil holds at various tensions. Knowledge of the amount of water held by the soil at various tensions is required, in order to understand the amount of water that is available to plants, the water that can be taken up by the soil before percolation starts, and the amount of water that must be used for irrigation.

Soil moisture stress

Soil-moisture tension as discussed in the preceding paragraphs is based on pure water. Salts in soil water increase the force that must be exerted to extract water and thus affect the amount of water available to plants. The increase in tension caused by salts is from *osmotic pressure*. If two solutions differing in concentration are separated by a membrane impermeable to the dissolved substance, such as a cell membrane in a plant root, water moves from the solution of lower concentration to the one of higher concentration. The force with which water moves across such a membrane is called osmotic pressure and is measured in atmospheres.

Plant growth is a function of the soil moisture stress which is the sum of the soil moisture tension and osmotic pressure of soil solution. In many irrigated soils, the soil solution contains an appreciable amount of salts. The osmotic pressure developed by the soil solution retards the uptake of water by plants. Plants growing in a soil in which the soil-moisture tension is, say, I atmosphere apparently can extract enough moisture for good growth. But if the osmotic pressure of the soil solution is, say, 10 atmospheres, the total stress is 11 atmospheres and the plants cannot extract enough water for good growth. Thus, for successful crop production in soils having appreciable salts, the osmotic pressure of the soil solution must be maintained as low as possible by controlled leaching and the soil moisture tension in the root zone is maintained in a range that will provide adequate moisture to the crop.

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’.

Saturation capacity. When all the pores of the soil are filled with water, the soil is said to be under saturation capacity of *maximum water holding capacity.* The tension of water at saturation capacity is almost zero and it is equal to free water surface.

Field capacity. The field capacity of soil is the moisture content after drainage of gravitational water has become very slow and the moisture content has become relatively stable. This situation usually exists one to three days after the soil has been thoroughly wetted by rain or irrigation. The terms field capacity, field-carrying capacity, normal moisture capacity and capillary capacity are often used synonymously. At field capacity, the large soil pores are field with air, the micro pores are filled with water and any further drainage is slow. The field capacity is the upper limit of available moisture range in soil moisture and plant relations. The soil moisture tension at field capacity varies from soil to soil, but it generally ranges from 1/10 to 1/3 atmospheres.

Filed capacity is determined by ponding water on the soil surface in an area of about 2 to 5 sq m and permitting it to drain for one to three days, with surface evaporation prevented. Evaporation may be prevented by spreading a polythene sheet or a thick straw mulch on the ground surface. One to three days after the soil is thoroughly wetted, soil samples are collected with an auger from different soil depths at uniform intervals throughout the wetted zone. The moisture content is determined by the gravimetric method.

Moisture equivalent. Moisture equivalent is defined as the amount of water retained by a sample of initially saturated soil material after being subjected to a centrifugal force of 1000 times that of gravity for a definite period of time, usually half an hour. To determine the moisture equivalent, a small sample of soil is whirled in a centrifuge with a centrifugal force of 1000 times that of gravity. The moisture remaining in the sample is determined. This moisture content when expressed as moisture percentage on over dry basis, gives the value of the moisture equivalent. In medium textured soils, the values of field capacity and moisture equivalent are nearly equal. In sandy soils, the field capacity exceeds the moisture equivalent. In very clayey soils, the field capacity is generally lower than the moisture equivalent.

Permanent wilting percentage: The permanent wilting percentage, also known as permanent wilting point or wilting co-efficient, is the soil moisture content at which plants can no longer obtain enough moisture to meet transpiration requirements; and remain wilted unless water is added to the soil. At the permanent wilting point the films of water around the soil particles are held so tightly that roots in contact with the soil cannot remove the water at a sufficiently rapid rate to prevent wilting of the plant leaves. It is a soil characteristic, as all plants whose root systems thoroughly permeates the soil will wilt at nearly the same soil moisture content when grown in a particular soil in a humid atmosphere.

The moisture tension of a soil at the permanent wilting point ranges from 7 to 32 atmospheres, depending on soil texture, on the kind and condition of the plants, on the amount of soluble salts in the soil solution, and to some extent on the climatic environment. Since this point is reached when a change in tension produces little change in moisture content, there is little difference in moisture percentage regardless of the tension taken as the permanent wilting point. Therefore, 15 atmospheres is the pressure commonly used for this point.

The ***wilting range*** is the range in soil-moisture content through which plants undergo progressive degrees of permanent or irreversible wilting, from wilting of the oldest leaves to complete wilting of all leaves. At the permanent wilting point, which is the top of this range, plant growth ceases. Small amounts of water can be removed from the soil by plants after growth ceases, but apparently the water is absorbed only slowly and is enough only to maintain life until more water is available. The moisture content at which the wilting is complete and the plants die is called the *ultimate wilting*. Although the difference in the amount of water in the soil between the two points may be small, there may be a big difference in tension. At the ultimate wilting point soil-moisture tension may be as high as 60 atmospheres.

The most common method of determining the permanent wilting percentage is to grow indicator plants in containers, usually in small cans, holding about 600 grams of soil. Sunflower plant is commonly used as the indicator plant. The plants are allowed to wilt and are then placed in a chamber with an approximately saturated atmosphere to test them for permanent wilting. The residual soil moisture content in the container is then calculated which is the permanent wilting percentage. The determination of moisture content at 15 atmosphere tension which is the usually assumed value of permanent wilting point can be done by the pressure membrane apparatus (Richard, 1947).

Available water. Soil moisture between field capacity and permanent wilting point is referred to as readily available moisture. It is the moisture available for plant use. In general, fine-textured soils have a wide range of water between field capacity and permanent wilting point than coarse textured soils. In contrast, sandy soils with their larger proportion of non-capillary pore space release most of their water within a narrow range of potential because of the predominance of large pores. Illustrates the three kinds of soil water and the difference in available water between typical sandy loam and silt loam soils. Tablebelow present the range of available water holding capacities of different soil textural groups. For irrigation system design, the total available water is calculated for a soil depth based on the root system of a mature plant of the crop to be grown.

Range of available water holding capacity of soils

Soil type	**Per cent moisture, based on dry weight of soil**		**Depth of available water per until of soil**
	Field capacity	**Permanent wilting percentage**	**cm per meter depth of soil**
Find sane	3-5	1-3	2-4
Sandy loam	5-15	3-8	4-11
Silt loam	12-18	6-10	6-13
Clay loam	15-30	7-16	10-18
Clay	25-40	12-20	16-30

Movement of water within soils

The movement of water within the soil controls not only the rate of infiltration but also the rate of supply of moisture to plant roots and the rate of underground flow to springs and streams and recharge of ground water. Water in the liquid phase flows through the water filled pore space under the influence of gravity. In the films surrounding soil particles (under unsaturated conditions), it moves under the influence of surface tension forces. Water also diffuses as vapour through the air-filled pore spaces along gradients of decreasing vapour pressure. In all cases, the movement is along gradients of decreasing water potential.

Terminology

Water intake. The movement of irrigation water from the soil surface into and through the soil is called water intake. It is the expression of several factors, including infiltration and percolation.

Percolation. Percolation is the downward movement of water through saturated or nearly saturated soil in response to the force of gravity. Percolation occurs when water is under pressure or when the tension is smaller than about ½ atmosphere. *Percolation rate* is synonymous with infiltration rate with the qualitative provision of saturated or near saturated conditions.

Interflow. Interflow is the lateral seepage of water in a relatively pervious soil above a less pervious layer. Such water usually reappears on the surface of the soil at a lower elevation.

Seepage. Seepage is the infiltration (vertically) downward and lateral movements of water into soil or substrata from a source of supply such as a reservoir or irrigation canal. Such water may reappear at the surface as wet spots or seeps or may percolate to join the ground water or may join the subsurface flow to springs or streams. Seepage rate depends on the wetted perimeter of the reservoir or the canal and the capacity of the soil to conduct water both vertically and laterally.

Permeability (1) *Qualitative*. It is the characteristic of a pervious medium relating to the readiness with which it transmits fluids.

(2) *Quantitative*. The specific property governing the rate or readiness with which a porous medium transmits fluids under standard conditions. According to this definition, equations used for expressing flow, which take into account the properties of the fluid, should give the same soil permeability value for all fluids which do not alter the medium.

The term *intrinsic permeability* is used as a permeability factor independent of the fluid. It must, however, be remembered that the factors which tend to change the permeability of the soil matrix to water will influence this value and prevent its use unless they can be measured or evaluated separately.

Hydraulic conductivity. Hydraulic conductivity is the proportionality factor k in Darcy's law ($v=ki$, in which v is the effective flow velocity and i is the hydraulic gradient). It is, therefore, the effective flow velocity at unit hydraulic gradient and has the dimensions of velocity (LT^{-1}). The values of k depend on the properties of the fluid with the porous medium, such as swelling of a soil. A soil that has high porosity and coarse open texture has a high hydraulic conductivity value. For two soils of the same 'total' porosity, the soil with small pores has lower conductivity than the soil with large pores because of the resistance to flow in small pores. A soil with pores of many sizes conducts water faster if the large pores form a continuous path through the profile. In fine-textured soils, hydraulic conductivity depends almost entirely on structural pores. In some soils, particles are cemented together to form nearly impermeable layers commonly called *hardpans.* In other soils, very finely divided or colloidal material expands on absorbing water to form an impervious gelatinous mass that restricts the movement of water.

Hydraulic head. Hydraulic head is the elevation with respect to a standard datum at which water stands in a riser pipe or manometer connected to the point in question in the soil. This will include elevation head, pressure head, and also the velocity head, if the terminal opening of the sensing element is pointed upstream. For non-turbulent flow of water in soil the velocity head is negligible. In unsaturated soil a porous cup must be used for establishing hydraulic contact between the soil water and water in a manometer. Hydraulic head has the dimensions of length (L).

Hydraulic gradient Hydraulic gradient is the rate of change of piezometric or hydraulic head with distance. Hydraulic gradient of ground water records the head consumed by friction in the flow in unit distance since in ground water flow the velocity heads are generally negligible.

Hydraulic equilibrium of water in soil It is the condition for zero flow rate of liquid or film water in the soil. This condition is satisfied when the pressure gradient force is just equal and opposite to the gravity force.

Movement of water under saturated conditions

Poiseuille's law forms the basis for a number of different equations which have been developed for determining the hydraulic conductivity of the soil for knowledge of its pore-size distribution. Pore size is of outstanding significance, as its fourth power is proportional to the rate of saturated flow. This indicates that saturated flow under otherwise identical conditions decreases as the pore size decreases. Generally the rate of flow in soils of various textures is in the following sequence.

Sand > loam > clay

Moisture movement under unsaturated conditions

As drainage proceeds in a soil and the larger pores are emptied of water the contribution of the hydraulic head or the gravitational component to total potential becomes progressively less important and the contribution of the matric potential ψ_m becomes more important. The effect of pressure is generally negligible because of the continuous nature of the air space. The solute potential (osmotic potential) ψ_s does not affect the potential gradient unless there is unusual concentration of slat at some point in the soil. The negligible effect of solute potential is due to the fact that both solutes and water are moving. Thus, in moisture moment under unsaturated conditions, the potential ψ (Equation 7.28) is the sum of the matric potential ψ_m and, to some extent the gravitational potential ψ_g. In horizontal movement, only ψ_m applies. Under conditions of downward movement, capillary and gravitational potentials act together. In upward capillary movement ψ_m and ψ_g oppose one another. For unsaturated flow (Equation 7.28) may be rewritten as:

$$v = -k \frac{\Delta (\psi_m + \psi_g)}{\Delta^I}$$

The direction of *I* is the path of greatest change in ($\psi_m + \psi_g$).

Under unsaturated conditions Darcy's law (Equation 7.28) is still applied but with some modifications and qualifications. It is applicable to unsaturated flow if *k* is regarded as a function of water content, i.e. *k* (0) in which 0 is the soil moisture content. As the soil moisture content and soil moisture potential decreases, the hydraulic conductivity decreases very rapidly, so that ψ_{soil} is – 15 bars, *k* is only 10^{-3} of the value at saturation. According to Philip (1957 a), the rapid decrease in conductivity occurs because the larger pores are emptied first, which greatly decreases the cross-section available for liquid flow. When the continuity of the films is broken, liquid flow no longer occurs.

In unsaturated soil moisture movement, also called capillary movement, *k* (Equation 7.28) is often termed as *capillary conductivity,* though the term hydraulic conductivity is also frequently used. The unsaturated conductivity is a function of soil moisture content as well as number, size and continuity of soil pores. At moisture contents below field capacity, the capillary conductivity is so low that capillary movement is of little or no significance in relation to plant growth. Many investigations have shown that capillary rise from a free water table can be an important source of moisture for plants only when free water is within 60 or 90 cm of the root zone.

Movement of unsaturated flow ceases in sand at a lower tension than in finer textured soils, as the water films lose continuity sooner between the larger particles. The wetter the soil, the greater is the conductivity for water. In the 'moist range', the range of unsaturated flow in soils of various textures is in the following order:

Sand < loam < clay

It may be noticed that this is the reverse of the order encountered in saturated flow. However, in the 'wet range' the unsaturated conductivity occurs in the same or similar order as saturated conductivity.

Water vapour movement

Movement of soil water in unsaturated soils involves both liquid and vapour phases. Although vapour transfer is insignificant in high soil water contents, it increases as void space increases. At a soil moisture potential of about-15 pars, the continuity of the liquid films is broken and water moves only in the form of vapour. Diffusion of water vapour is caused by a vapour pressure gradient as the driving force. The vapour pressure of soil moisture increases with the increase in soil moisture content and temperature, it decreases with the increase in soluble salt content.

Water vapour movement is significant only in the 'moist range'. In the 'wet range' vapour movement is negligible because there are few continuous open pores. In the 'dry range' water movement exists, but there is so little water in the soil that the rate of movement is very small.

Water vapour movement goes on within the soil and also between soil and atmosphere, for example, evaporation, condensation and adsorption. The rate of diffusion of water vapour through the soil is proportional to the square of the effective porosity, regardless of pore sizes. The finger the soil pores, the higher is the moisture tension under which maximum water vapour movement occurs. In a coarse textured soil pores become free of liquid water at relatively low tensions and when the soil dries out there is little moisture left for vapour transfer. But a fine textured soil retains substantial amounts of moisture even at high tensions, thus permitting vapour transfer. It is interesting to note that maximum water vapour movement in soils vapour movement is of greatest importance for the growth and survival of plants.