**Crop Water Relations**

**(PPS502)**



**Submitted to: Dr. Ali Abdullah Alderfasi**

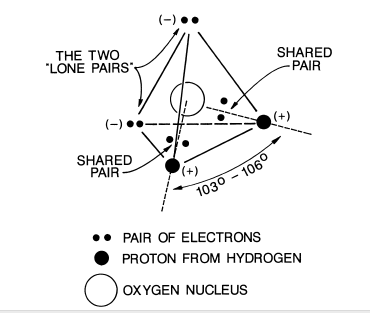
**Compiled by: Awais Ahmad (432108560)**

**Muhammad Afzal (432108561)**

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**Water Properties and Functions**

To understand the nature of water in soil and plants, we need a mental picture of the water molecule. The water molecule is composed of two **hydrogen** atoms and one **oxygen** atom. The water molecule is positively charged on one side and negatively charged on the other and is, thus, a **dipole**. Two hydrogen atoms each share a pair of electrons with a single oxygen atom. The two hydrogen atoms of the water molecule are separated at an angle of **103 to 106** degrees, measured with the oxygen atom as the apex of the angle and with the two hydrogen protons as points on the angle sides. The electron pairs shared between the oxygen nucleus and the two hydrogen protons only partially screen (neutralize) the positive charge of the protons. The result is that the proton side of the molecule becomes the positive side of the water molecule. They are called the **lone-pair electrons**. One pair is above the plane and one pair is below. These two lone pairs of electrons do not take part directly in bond formation, as do the electrons shared between the hydrogen and oxygen atoms of the water molecule. The electric charge structure of the water molecule resembles a **tetrahedron** with the oxygen near the center, two of its corners positively charged due to the partially screened protons of the hydrogen, and the remaining two corners of the tetrahedron negatively charged due to the two pairs of lone-pair electrons. Dipole is a term used in physics and physical chemistry and is anything having two equal but opposite electric charges or magnetic poles, as in a hydrogen atom with its positive nucleus and negative electron.

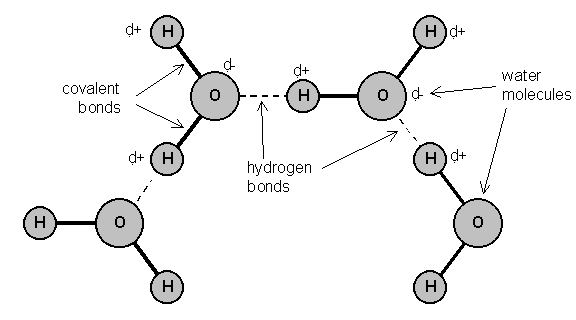


Tetrahedral charge structure of a water molecule

1. **Water binding forces of water:**

There are two attractive forces between water molecules: hydrogen bonding and the van der Waals-London force.

1. **Hydrogen Bonding:** Hydrogen bonding results from the electrical structure of water molecules that makes them group together in a special way. The negative **lone-pair** electrons of one water molecule are attracted to a positive partially screened **proton** of another water molecule. Thus each corner of the four corners of the water tetrahedron can be attached, by electrostatic attraction, to four other water tetrahedron molecules in solution. This type of bonding is called **hydrogen bonding**.



Hydrogen bonding is important in binding water molecules together. Hydrogen bonds have a binding force of about **1.3 to 4.5** kilocalories per mole in water. Only part of the structure of water due to hydrogen bonding is destroyed by heating, and about 70% of the hydrogen bonds found in ice remain intact in liquid water at 100°C. It was found that at 400°C almost all hydrogen bonding is broken down.

1. **van der Waals-London Force:** A van der Waals-London force is one that exists between neutral **nonpolar** molecules, and, therefore, does not depend on a net electrical charge. This attractive force occurs because the electrons of one atom **oscillate** in such a way as to make it a rapidly fluctuating (about 1015 or 1016 Hertz) dipolar atom, which in turn **polarizes** an adjacent atom, making it, too, a rapidly fluctuating dipole atom such that the two atoms attract each other. It is generally felt that this force contributes little to the attraction of water to itself.
2. **Specific Heat:**

Water has the highest specific heat of any known substance except liquid ammonia, which is about 13 percent higher. If a quantity of heat **H** calories is necessary to raise the temperature of **m** grams of a substance from **t1 to t2** °C, the specific heat, s, is….

**s = H/[m(t2 - t1)]**

The units of specific heat are **cal gram-1C-1**. The specific heat of water decreases with an increase of temperature up to **35°C**, and then the specific heat increases with further increase in temperature. Specific heat of water is 4.2 Jg-1C-1.

1. **Heat of Vaporization:**

The heat of vaporization of water is the **highest** known. The heat of vaporization is “defined as the amount of heat needed to turn one gram of a liquid into a vapor, without a rise in the temperature of the liquid.” The units are **cal/gram** and values for the heat of vaporization of water at different temperatures (597.3 cal g-1 at 0C). The heat of vaporization is a **latent heat**. Latent heat is the additional heat required to change the state of a substance from solid to liquid at its melting point, or from liquid to gas at its boiling point, after the temperature of the substance has reached either of these points. Note that a latent heat is associated with **no change in temperature**, but a change of state. It causes the cooling effect of water very much important for arid and dry land plants.

1. **Heat of Fusion:**

The heat of fusion of water is unusually high. The heat of fusion “is the quantity of heat necessary to change one gram of a solid to a liquid with no temperature change.” It is also a latent heat and is sometimes called the latent **heat of fusion**. It has only one value for water, because water freezes at one value (0°C), and it is **79.71 cal/gram** or the rounded number **80 cal/gram.** The high heat of fusion of water is used in frost control. Irrigation water drawn from the ground is often at a uniform temperature above freezing.

1. **Heat Conduction:**

Water is a good conductor of heat compared with other liquids and nonmetallic solids, although it is poor compared to metals. Heat conductivity is “the quantity of heat in calories which is transmitted per second through a plate one centimeter thick across an area of one square centimeter when the temperature difference is one degree Centigrade.” The units, therefore, are **cal s-1 cm-2** (°C/cm)-1 or cal cm-1 s-1°C-1. Values of thermal conductivity of water differ at different temperatures. Water has a thermal conductivity of **0.00144 cal s-1 cm-1°C-1**at 20°C much higher than metals. Survival of crops in the spring can depend on **thermal conductivity**.

1. **Transparency to Visible Radiation:**

Water is transparent to visible radiation. This allows light to penetrate bodies of water and makes it possible for algae to photosynthesize at considerable depths.

1. **Opaqueness to Infrared Radiation:**

Water is nearly opaque to longer wavelengths in the infrared range. Thus, water filters are good heat absorbers.

1. **Surface Tension:**

Water has a much higher surface tension than most other liquids because of the high **internal cohesive forces** between molecules. The high surface tension of water provides the tensile strength required for the **cohesion theory** for the **ascent of sap** (water in the xylem). The cohesion theory is only a theory, but appears to be the best explanation for the rise of water in plants. Unit for surface tension is **g s−2** equivalent to **dyne/cm.**

1. **Density:**

Water has a high density and is remarkable in having its maximum density at **4°C** instead of at the freezing point. Average 1000g/dm3

1. **Expansion Upon Freezing:**

Water expands on freezing, so that ice has a volume about **9%** greater than the liquid water from which it was formed. This explains why ice floats and pipes and radiators burst when the water in them freezes. If ice sank, bodies of water in the cooler parts of the world would be filled permanently with ice, and aquatic organisms could not survive.

1. **Ionization:**

Water is very slightly ionized. Only one molecule in **55.5 × 107** is dissociated when pure.

1. **Dielectric Constant:**

Water has a high dielectric constant [dia= through, across + electric: so called because it permits the passage of the lines of force of an electrostatic field, but does not conduct the current] Water, therefore, is a good insulator.

1. **Solvent for Electrolytes:**

Water is a good solvent for electrolytes, because the attraction of ions to the partially positive and negative charge on water molecules results in each ion being surrounded by a shell of water molecules, which keeps ions of opposite charge separated.

1. **Solvent for Nonelectrolytes:**

Water is a good solvent for many nonelectrolytes, because it can form hydrogen bonds with amino and carbonyl groups.

1. **Adsorption:**

Water tends to be adsorbed, or bound strongly, to the surfaces of clay micelles, cellulose, protein molecules, and many other substances. This characteristic is of great importance in soil and plant water relations.

1. **Viscosity:**

Water has a high viscosity. “All fluids possess a definite resistance to change of form and many solids show a gradual yielding to forces tending to change their form. This property, a sort of internal friction, is called viscosity; it is expressed in **dyne-seconds per cm2** or poises.” It differ with temperature changes.

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**Aqueous Solutions and Measuring Concentrations**

The air we breath is a huge gaseous solution, the oceans are solutions of about fifty different salts in water, and many of the rocks and minerals of the earth are solid solutions. And we ourselves are largely **aqueous solutions**, most of it within our cells. So in order to understand the world in which we live and the organisms that inhabit it, we need to know something about solutions, and this is where we begin. Solutions are **homogeneous** (single-phase) mixtures of two or more components. For convenience, we often refer to the majority component as the solvent; minority components are solutes. But there is really no fundamental distinction between them.

We usually think of a solution as a liquid made by adding a gas, a solid or another liquid solute in a liquid solvent. Actually, solutions can exist as gases and solids as well. Gaseous mixtures don't require any special consideration beyond what you learned about Dalton’s Law earlier in the course. Solid solutions are very common; most natural minerals and many metallic alloys are solid solutions. Still, it is liquid solutions that we most frequently encounter and must deal with. Experience has taught us that sugar and salt dissolve readily in water, but that “oil and water don’t mix”. Actually, this is not strictly correct, since all substances have at least a slight tendency to dissolve in each other. This raises two important and related questions: why do solutions tend to form in the first place, and what factors limit their mutual solubilities?

**Understanding and Measuring Concentrations:** Concentration is a general term that expresses the quantity of solute contained in a given amount of solution. Various ways of expressing concentration are in use; the choice is usually a matter of convenience in a particular application. You should become familiar with all of them.

1. **Parts-per concentration:**

In the consumer and industrial world, the most common method of expressing the concentration is based on the quantity of solute in a fixed quantity of solution. The “quantities” referred to here can be expressed in weight, in volume, or both (i.e., the weight of solute in a given volume of solution.) In order to distinguish among these possibilities, the abbreviations **(w/w), (v/v) and (w/v)** are used.

In most applied fields of Chemistry, (w/w) measure is often used, and is commonly expressed as weight-percent concentration, or simply "**percent concentration**". For example, a solution made by dissolving 10 g of salt with 200 g of water contains "1 part of salt per 20 g of water". It is usually more convenient to express such concentrations as "parts per 100", which we all know as "percent". So the solution described above is a "5% (w/w) solution" of NaCl in water.

**Problem Example:** The Normal Saline solution used in medicine for nasal irrigation, wound cleaning and intravenous drips is a 0.91% (w/v) solution of sodium chloride in water. How would you prepare 1.5 L of this solution?

Solution: The solution will contain 0.91 g of NaCl in 100 mL of water, or 9.1 g in 1 L. Thus you will add (1.5 × 9.1g) = 13.6 g of NaCl to 1.5 L of water.

Percent means parts per 100; we can also use parts per thousand **(ppt)** for expressing concentrations in grams of solute per kilogram of solution. For more dilute solutions, parts per million **(ppm)** and parts per billion (109; **ppb)** are used. These terms are widely employed to express the amounts of trace pollutants in the environment.

**Problem Example:** Describe how you would prepare 30 g of a 20 percent (w/w) solution of KCl in water.

Solution: The weight of potassium chloride required is 20% of the total weight of the solution, or 0.2 × (3 0 g) = 6.0 g of KCl. The remainder of the solution

(30 – 6 = 24) g consists of water. Thus you would dissolve 6.0 g of KCl in 24 g of water.

1. **Molarity: mole/volume basis:**

This is the method most used by chemists to express concentration, and it is the one most important for you to master. Molar concentration **(molarity)** is the number of moles of solute per liter of solution. The important point to remember is that the volume of the solution is different from the volume of the solvent; the latter quantity can be found from the molarity only if the densities of both the solution and of the pure solvent are known. Similarly, calculation of the weight-percentage concentration from the molarity requires density information; you are expected to be able to carry out these kinds of calculations, which are covered in most texts.

**Problem Example:** How would you make 120 mL of a 0.10 M solution of potassium hydroxide in water?

Solution: The amount of KOH required is (0.120 L) × (0.10 mol L–1) = 0.012 mol. The molar mass of KOH is 56.1 g, so the weight of KOH required is

(.012 mol) × (56.1 g mol–1) = 0.67 g. We would dissolve this weight of KOH in a volume of water that is less than 120 mL, and then add sufficient water to bring the volume of the solution up to 120 mL.

**Problem Example:** Calculate the molarity of a 60-% (w/w) solution of ethanol (C2H5OH) in water whose density is 0.8937 g mL–1.

Solution: One liter of this solution has a mass of 893.7 g, of which

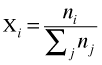
0.60 × (893.7 g) = 536.2 g consists of ethanol. The molecular weight of C2H5OH is 46.0, so the number of moles of ethanol present in one liter (that is, the molarity) will be.

1. **Normality and equivalents:**

Normality is a now-obsolete concentration measure based on the number of **equivalents** per liter of solution. The equivalent weight of an acid is its molecular weight divided by the number of titratable hydrogens it carries. Thus for sulfuric acid H2SO4, one mole has a mass of 98 g, but because both hydrogens can be neutralized by strong base, its equivalent weight is 98/2 = 49 g. A solution of 49 g of H2SO4 per liter of water is 0.5 molar, but also "1 normal" (1N = 1 eq/L). Such a solution is "equivalent" to a 1M solution of HCl in the sense that each can be neutralized by 1 mol of strong base. The concept of equivalents is extended to salts of polyvalent ions; thus a 1Msolution of FeCl3 is said to be "3 normal" (3 N) because it dissociates into three moles/L of chloride ions.

1. **Mole fraction: mole/mole basis:**

This is the most fundamental of all methods of concentration measure, since it makes no assumptions at all about volumes. The mole fraction of substance i in a mixture is defined as



In which nj is the number of moles of substance j, and the summation is over all substances in the solution. Mole fractions run from zero (substance not present) to unity (the pure substance).

**Problem Example:** What fraction of the molecules in a 60-% (w/w) solution of ethanol in water consist of H2O?

Solution: From the previous problem, we know that one liter of this solution contains 536.2 g (11.6 mol) of C2H5OH. The number of moles of H2O is

( (893.7 – 536.2) g) / (18.0 g mol–1) = 19.9 mol. The mole fraction of water is thus

Thus 63% of the molecules in this solution consist of water, and 37% are ethanol.

In the case of ionic solutions, each kind of ion acts as a separate component.

**Problem Example:** Find the mole fraction of water in a solution prepared by dissolving 4.5 g of CaBr2 in 84.0 mL of water.

Solution: The molar mass of CaBr2 is 200 g, and 84.0 mL of H2O has a mass of very close to 84.0 g at its assumed density of 1.00 g mL–1. Thus the number of moles of CaBr2 in the solution is (4.50 g) / (200 g/mol) = .0225 mol.

Because this salt is completely dissociated in solution, the solution will contain 0.268 mol of Ca2+ and (2 × .268) = .536 of Br–. The number of moles of water is (84 g) / (18 g mol–1) = 4.67 mol.

The mole fraction of water is then

(.467 mol) / (.268 + .536 + 4.67)mol = .467 / 5.47 = 0.854.

Thus H2O constitutes 85 out of every 100 molecules in the solution.

1. **Molality: mole/weight basis:**

A 1-molal solution contains one mole of solute per 1 kg of solvent. Molality is a hybrid concentration unit, retaining the convenience of mole measure for the solute, but expressing it in relation to a temperature-independent mass rather than a volume. Molality, like mole fraction, is used in applications dealing with certain physical properties of solutions.

**Problem Example:** Calculate the molality of a 60-% (w/w) solution of ethanol in water.

Solution: From the above problems, we know that one liter of this solution contains 11.6 mol of ethanol in (893.7 – 536.2) = 357.5 g of water. The molarity of ethanol in the solution is therefore (11.6 mol) / (0.3575 kg) = 32.4 mol kg–1.

**Conversion between concentration measures:**

Anyone doing practical must be able to convert one kind of concentration measure into another. The important point to remember is that any conversion involving molarity requires a knowledge of the densityof the solution.

**Problem Example:** A solution prepared by dissolving 66.0 g of urea (NH2)2CO in 950 g of water had a density of 1.018 g mL–1.

Express the concentration of urea in a) weight-percent; b) mole fraction;

c) molarity; d) molality.

Solution:

a) The weight-percent of solute is (100%) –1 (66.0 g) / (950 g) = 6.9%

The molar mass of urea is 60, so the number of moles is

(66 g) /(60 g mol–1) = 1.1 mol. The number of moles of H2O is

(950 g) / (18 g mol–1) = 52.8 mol.

b) Mole fraction of urea: (1.1 mol) / (1.1 + 52.8 mol) = 0.020

c) molarity of urea: the volume of 1 L of solution is (66 + 950)g / (1018 g L–1)

= 998 mL. The number of moles of urea (from a) is 1.1 mol.

Its molarity is then (1.1 mol) / (0.998 L) = 1.1 mol L–1.

d) The molality of urea is (1.1 mol) / (.066 + .950) kg = 1.08 mol kg–1.

**Problem Example:** Ordinary dry air contains 21% (v/v) oxygen. About many moles of O2 can be inhaled into the lungs of a typical adult woman with a lung capacity of 4.0 L?

Solution: The number of molecules (and thus the number of moles) in a gas is directly proportional to its volume (Avogadro's law), so the mole fraction of O2is 0.21. The molar volume of a gas at 25° C is

(298/271) × 22.4 L mol–1 = 24.4 L mol–1

so the moles of O2 in 4 L of air will be

(4 / 24.4) × (0.21 mol) × (24.4 L mol–1) = 0.84 mol O2.

**Dilution calculations:**

These kinds of calculations arise frequently in both laboratory and practical applications. If you have a thorough understanding of concentration definitions, they are easily tackled. The most important things to bear in mind are

* + Concentration is inversely proportional to volume;
  + Molarity is expressed in mol L–1, so it is usually more convenient to express volumes in liters rather than in mL;
  + Use the principles of unit cancellations to determine what to divide by what.

**Problem Example:** Commercial hydrochloric acid is available as a 10.17 molar solution. How would you use this to prepare 500 mL of a 4.00 molar solution?

Solution: The desired solution requires (0.50 L) × (4.00 M L–1) = 2.0 mol of HCl. This quantity of HCl is contained in (2.0 mol) / (10.17 M L–1) = 0.197 L of the concentrated acid. So one would measure out 197 mL of the concentrated acid, and then add water to make the total volume of 500 mL.

**Problem Example:** Calculate the molarity of the solution produced by adding 120 mL of 6.0 M HCl to 150 mL of 0.15 M HCl. What important assumption must be made here?

Solution: The assumption, of course, is that the density of HCl within this concentration range is constant, meaning that their volumes will be additive.

Moles of HCl in first solution: (0.120 L) × (6.0 mol L–1) = 0.72 mol HCl

Moles of HCl in second solution: (0.150 L) × (0.15 mol L–1) = 0.02 mol HCl

Molarity of mixture: (0.72 + 0.02) mol / (.120 + .150) L = 4.3 mol L–1.

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**Plant Cell Water Relations**

Water is the most abundant constituent of all physiologically active plant cells. Leaves, for example, have water contents which lie mostly within a range of 55–85% of their fresh weight. Other relatively succulent parts of plants contain approximately the same proportion of water, and even such largely nonliving tissues as wood may be 30–60% water on a fresh-weight basis. The smallest water contents in living parts of plants occur mostly in dormant structures, such as mature seeds and spores. The great bulk of the water in any plant constitutes a unit system. This water is not in a static condition. Rather it is part of a hydrodynamic system, which in terrestrial plants involves absorption of water from the soil, its translocation throughout the plant, and its loss to the environment, principally in the process known as transpiration.

* Cell is the structural and functional unit of life.
* The direction in which water flows from one cell to another cell depends on the water potential.
* Two factors which affect the water potential are the amount of solutes and the external pressure.
* Due to endosmosis protoplasm expands and exerts pressure on elastic cell wall - Turgor pressure.
* Plants perform best when they are turgid, that is when the water within their cells has a positive hydrostatic pressure.
* Leaves often transpire several times their own volume of water each day, but the net loss is usually small owing to the inflow of water drawn up the plant from the soil, this flow being known as the ‘transpiration stream’.
* The water status of a plant is expressed as ‘water potential’, the chemical potential of water divided by the volume of 1 mole of water to give units of pressure.
* Water potential (ψ) comprises two main components, hydrostatic pressure (P) and osmotic pressure (π), such that ψ=P–π.
* The flows of water through plant and soil are driven by gradients in hydrostatic pressure over macroscopic distances, by differences in water potential across semipermeable membranes or by diffusion as water vapour from the leaves to the atmosphere.
* Resistance to these flows, and the factors influencing them, vary markedly as the transpiration stream moves from soil, across the roots, longitudinally in the xylem and eventually through the tissue of the leaves to the evaporating surfaces within the leaf.
* In the smaller pores of the soil, water is held against the force of gravity by capillary forces is called capillary water.
* Movement of water from the soil into root hairs and from there to the cells of the xylem with lower water potential results in root pressure which pushes the water up in the xylem vessels.
* When root pressure is high and transpiration is low, plants may lose small quantities of liquid water in the form of drops from the margins of tips of leaves. This process is called guttation.
* The adhesion of water molecules to the xylem vessels and cohesion of water molecules, both by hydrogen bonds, together help to form thin, unbroken columns of water in the capillaries of xylem vessel elements.
* When the transpiration pull is exerted, a negative pressure or tension is generated in the xylem.
* About 98% water absorbed by land plants evaporates from aerial plants parts and diffuses into atmosphere.
* The opening and closing of stomata is controlled by the size and shape of guard cells resulting from the change in their turgor pressure.
* The stomata open when guard cells take up K+ ions from the surrounding cells.
* The uptake of K+ ions is balanced by one of the factors as:
* uptake of Cl-
* Transportation of H+ ions released from organic acids
* by the negative charges of organic acids when they lose H+ ions (hydrogen ions).
* Wilting occurs when loss of water by transpiration exceeds the rate of water uptake by roots.
* Transpiration is influenced by environmental factors like light, temperature, wind, atmospheric humidity and availability of soil water.
* Cultivation of agro-climatic zones is determined by water requirement of crops.
* The scope of the chapter in real life applications:
* Turgidity plays an important role in plants. So wilting can be remedied by watering.
* Anti-transpirant spray reduces the rate of transpiration.
* The use of anti-transpirants is still under study and in an experimental stage due to certain limitations in their application on plants

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**Water Potential and its Components**

Water potential is “the **potential energy** of water per unit volume relative to pure water in reference conditions.” Water potential quantifies the **tendency** of water to move from one area to another due to osmosis, gravity, mechanical pressure, or matrix effects such as surface tension. Water potential has proved especially useful in understanding water movement within plants, animals, and soil. Water potential is typically expressed in potential energy per unit volume and very often is represented by the Greek letter; **Psi (Ѱ).**

Water potential integrates a variety of different potential drivers of water movement, which may operate in the same or different directions. Within complex biological systems, it is common for many potential factors to be important. For example, the addition of solutes to water lowers the water's potential (makes it more negative), just as the increase in pressure increases its potential (makes it more positive). If possible, water will move from an area of higher water potential to an area that has a lower water potential. One very common example is water that contains a dissolved salt, like sea water or the solution within living cells. These solutions typically have negative water potentials, relative to the pure water reference. If there is no restriction on flow, water molecules will proceed from the locus of pure water to the more negative water potential of the solution; flow proceeds until the difference in solute potential is balanced by another force, for example, pressure potential.

Many different factors may affect the total water potential, and the sum of these potentials determines the overall water potential and the direction of water flow:

**Ѱ = Ѱ 0 + Ѱ π + Ѱ p + Ѱ s + Ѱ v + Ѱ m**

where:

Ѱ 0 is the reference correction,

Ѱ π is the solute potential,

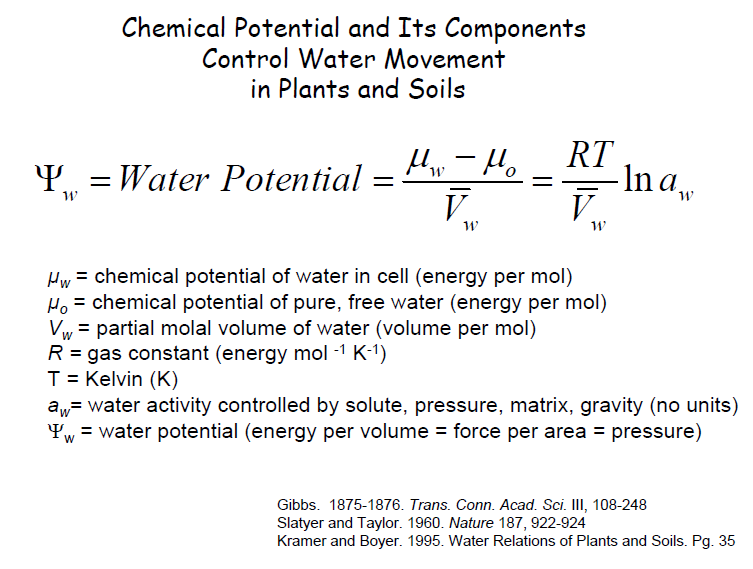
Ѱ p is the pressure component,

Ѱ s is the gravimetric component,

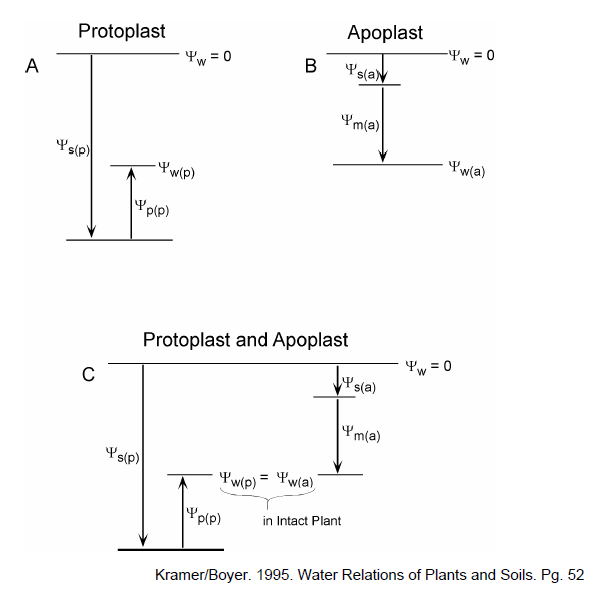
Ѱ v is the potential due to humidity, and

Ѱ m is the potential due to matrix effects (e.g., fluid cohesion and surface tension.)

All of these factors are quantified as potential energies per unit volume, and different subsets of these terms may be used for particular applications (e.g., plants or soils). Different conditions are also defined as reference depending on the application: for example, in soils, the reference condition is typically defined as pure water at the soil surface.



Component Potentials in a Cell



**Pressure Potential:**

Pressure potential is based on mechanical pressure, and is an important component of the total water potential within plant cells. Pressure potential increases as water enters a cell. As water passes through the cell wall and cell membrane, it increases the total amount of water present inside the cell, which exerts an **outward pressure** that is retained by the structural rigidity of the cell wall. By creating this pressure, the plant can maintain turgor, which allows the plant to keep its rigidity. Without turgor, plants lose structure and wilt.

The pressure potential in a living plant cell is usually **positive**. In **plasmolysed** cells, pressure potential is almost **zero**. Negative pressure potentials occur when water is pulled through an open system such as a plant xylem vessel. Withstanding negative pressure potentials (frequently called tension) is an important adaptation of xylem vessels.

**Osmotic potential:**

Pure water is usually defined as having an osmotic potential **(Ѱ π)** of zero, and in this case, solute potential can never be positive. The relationship of solute concentration (in molarity) to solute potential is given by the **van 't Hoff equation**:

**Ѱ π = - MiRT**

Where **M** is the concentration in molarity of the solute, **i** is the **van 't Hoff factor**, the ratio of amount of particles in solution to amount of formula units dissolved, R is the ideal gas constant, and **T** is the absolute temperature.

For example, when a solute is dissolved in water, water molecules are less likely to diffuse away via osmosis than when there is no solute. A solution will have a lower and hence more negative water potential than that of pure water. Furthermore, the more solute molecules present, the more negative the solute potential is.

Osmotic potential has important implication for many living organisms. If a living cell with a smaller solute concentration is surrounded by a more concentrated solution, the cell will tend to lose water to the more negative **water potential** **(Ѱw)** of the surrounding environment. This is often the case for marine organisms living in sea water and halophytic plants growing in **saline** environments. In the case of a plant cell, the flow of water out of the cell may eventually cause the plasma membrane to pull away from the cell wall, leading to plasmolysis. It can be measured in plant cells using the **Pressure bomb**. Most plants, however, have the ability to increase solute inside the cell to drive the flow of water into the cell and maintain turgor. This effect can be used to power an osmotic power plant.

**Matrix potential (Matric potential):**

When water is in contact with solid particles, **adhesive** intermolecular forces between the water and the solid can be large and important. The forces between the water molecules and the solid particles in combination with attraction among water molecules promote **surface tension** and the formation of **menisci** within the solid matrix. Force is then required to break these menisci. The magnitude of matrix potential depends on the distances between solid particles; the width of the menisci and the chemical composition of the solid matrix. In many cases, matrix potential can be quite large and comparable to the other components of water potential discussed above.

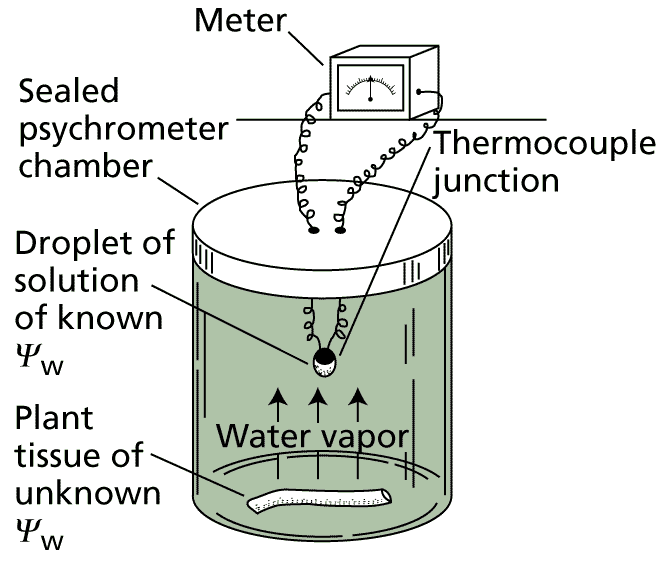
It is worth noting that matrix potentials are very important for plant water relations. Strong (very negative) matrix potentials bind water to soil particles within very dry soils. Plants then create even more negative matrix potentials within tiny pores in the cell walls of their leaves to extract water from the soil and allow physiological activity to continue through dry periods. **Germinating seeds** have a very negative matric potential. This causes water uptake in even somewhat dry soils and hydrates the dry seed. In terms of negative water potential, creosote bushes can tolerate extreme drought stress by operating fully at **-50 bars** of water potential and have been found living down to **-120 bars**.

**Measuring Water Potential**

Plant scientists have expended considerable effort in devising accurate and reliable methods for evaluating the water status of a plant. Four instruments that have been used extensively to measure Ψw , Ψs , and Ψp are described here: psychrometer, pressure chamber, cryoscopic osmometer, and pressure probe.

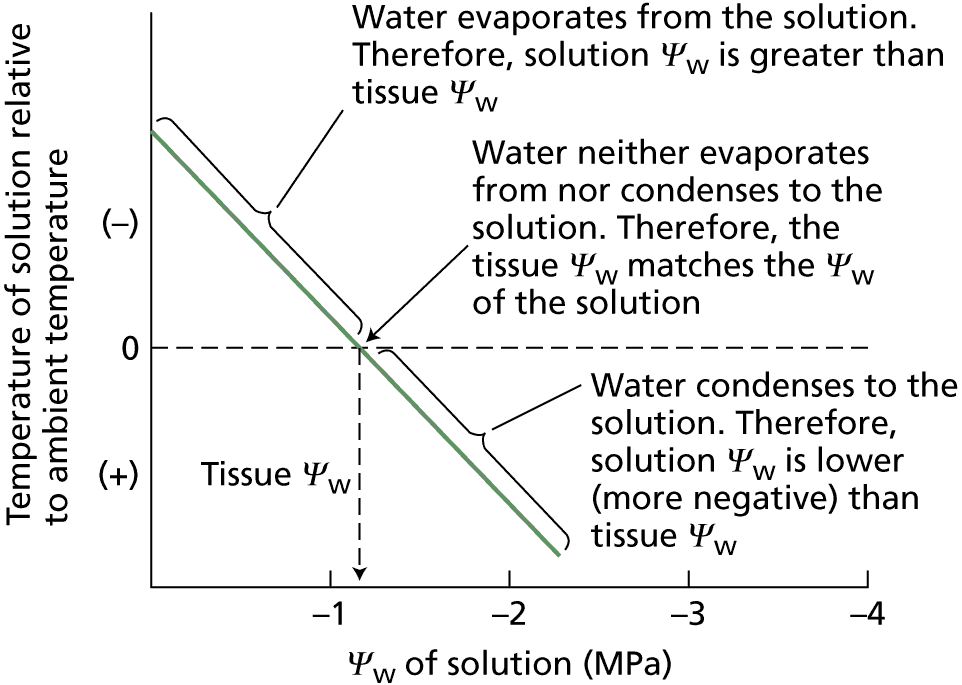
1. **Psychrometer (Ψw measurement):**

Psychrometry (the prefix "psychro-" comes from the Greek word psychein, "to cool") is based on the fact that the vapor pressure of water is lowered as its water potential is reduced. Psychrometers measure the water vapor pressure of a solution or plant sample, on the basis of the principle that evaporation of water from a surface cools the surface.



**Figure:** Diagram illustrating the use of isopiestic psychrometry to measure the water potential of a plant tissue.

Investigators make a measurement by placing a piece of tissue sealed inside a small chamber that contains a temperature sensor (in this case, a thermocouple) in contact with a small droplet of a standard solution of known solute concentration (known Ψs and thus known Ψw). If the tissue has a lower water potential than that of the droplet, water evaporates from the droplet, diffuses through the air, and is absorbed by the tissue. This slight evaporation of water cools the drop. The larger the difference in water potential between the tissue and the droplet, the higher the rate of water transfer and hence the cooler the droplet. If the standard solution has a lower water potential than that of the sample to be measured, water will diffuse from the tissue to the droplet, causing warming of the droplet. Measuring the change in temperature of the droplet for several s olutions of known Ψw makes it possible to calculate the water potential of a solution for which the net movement of water between the droplet and the tissue would be zero signifying that the droplet and the tissue have the same water potential.

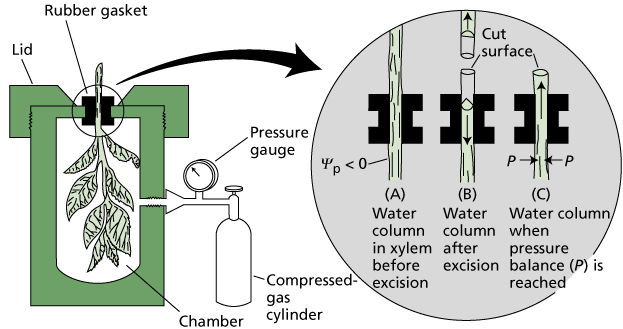


Psychrometers can be used to measure the water potentials of both excised and intact plant tissue. Moreover, the method can be used to measure the Ψs of solutions. This can be particularly useful with plant tissues. For example, the Ψw of a tissue is measured with a psychrometer, and then the tissue is crushed and the Ψs value of the expressed cell sap is measured with the same instrument. By combining the two measurements, researchers can estimate the turgor pressure that existed in the cells before the tissue was crushed (Ψp = Ψw – Ψs).

A major difficulty with this approach is the extreme sensitivity of the measurement to temperature fluctuations. For example, a change in temperature of 0.01°C corresponds to a change in water potential of about 0.1 MPa. Thus, psychrometers must be operated under constant temperature conditions. For this reason, the method is used primarily in laboratory settings.

1. **Pressure chamber (Ψw measurement):**

A relatively quick method for estimating the water potential of large pieces of tissues, such as leaves and small shoots, is by use of the pressure chamber. In this technique, the organ to be measured is excised from the plant and is partly sealed in a pressure chamber. Before excision, the water column in the xylem is under tension. When the water column is broken by excision of the organ (i.e., its tension is relieved allowing its Ψp to rise to zero), water is pulled rapidly from the xylem into the surrounding living cells by osmosis. The cut surface consequently appears dull and dry. To make a measurement, the investigator pressurizes the chamber with compressed gas until the distribution of water between the living cells and the xylem conduits is returned to its initial, pre-excision, state. This can be detected visually by observing when the water returns to the open ends of the xylem conduits that can be seen in the cut surface. The pressure needed to bring the water back to its initial distribution is called the balance pressure and is readily detected by the change in the appearance of the cut surface, which becomes wet and shiny when this pressure is attained.



**Figure:** The pressure chamber method for measuring plant water potential. The diagram at left shows a shoot sealed into a chamber, which may be pressurized with compressed gas. The diagrams at right show the state of the water columns within the xylem at three points in time: (A) The xylem is uncut and under a negative pressure, or tension. (B) The shoot is cut, causing the water to pull back into the tissue, away from the cut surface, in response to the tension in the xylem. (C) The chamber is pressurized, bringing the xylem sap back to the cut surface. (Click image to enlarge.)

The pressure chamber is often described as a tool to measure the tension in the xylem. However, this is only strictly true for measurements made on a non-transpiring leaf or shoot (for example, one that has been previously enclosed in a plastic bag). When there is no transpiration, the water potential of the leaf cells and the water potential in the xylem will come into equilibrium. The balancing pressure measured on such a non-transpiring shoot is equal in magnitude but opposite in sign to the pressure in the xylem (Ψp). Because the water potential of our non-transpiring leaf is equal to the water potential of the xylem, one can calculate the water potential of the leaf by adding together Ψp and Ψs of the xylem, provided one collects a sample of xylem sap for determination of Ψs. Luckily Ψs of the xylem is usually small (> –0.1 MPa) compared to typical midday tensions in the xylem (Ψp of –1 to –2 MPa). Thus, correction for the Ψs of the xylem sap is frequently omitted.

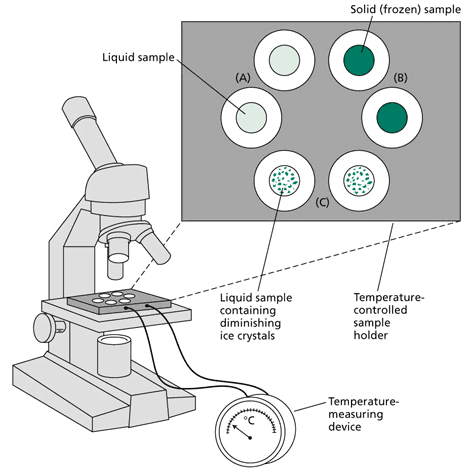
Balancing pressure measurements of transpiring leaves are more difficult to interpret. The fact that water is flowing from the xylem to the leaf means that differences in water potential must exist. When the transpiring leaf or shoot is cut off, the tension in the xylem is instantly relieved and water is drawn into the leaf cells until the water potentials of the xylem and the leaf cells come into equilibrium. Because the total volume of the leaf cells is much larger than the volume of sap in the xylem, this equilibrium water potential will be heavily weighted towards that of the leaf. Thus, any measurement of the balancing pressure on such a leaf or shoot will result in a value that is approximately the water potential of the leaf, rather than the tension of the xylem. (To be exact, one would have to add the Ψs of the xylem sap to the negative of the balancing pressure to get the leaf water potential.) One can explore the differences between the water potential of the xylem and the water potential of a transpiring leaf by comparing balancing pressures measured on covered (i.e., non-transpiring) versus uncovered (transpiring) leaves.

Pressure chamber measurements provide a quick and accurate way of measuring leaf water potential. Because the pressure chamber method does not require delicate instrumentation or temperature control, it has been used extensively under field conditions.

1. **Cryoscopic osmometer (Ψs measurement):**

The cryoscopic osmometer measures the osmotic potential of a solution by measuring its freezing point. Solutions have colligative properties that collectively depend on the number of dissolved particles and not on the nature of the solute. For example, solutes reduce the vapor pressure of a solution, raise its boiling point, and lower its freezing point. The specific nature of the solute does not matter. One of the colligative properties of solutions is the decrease in the freezing point as the solute concentration increases. For example, a solution containing 1 mol of solutes per kilogram of water has a freezing point of –1.86°C, compared with 0°C for pure water.

Various instruments can be used to measure the freezing-point depression of solutions (for two examples, see Prager and Bowman 1963, and Bearce and Kohl 1970). With a cryoscopic osmometer, solution samples as small as 1 nanoliter (10–9 L) are placed in an oil medium located on the temperature-controlled stage of a microscope. The very small sample size allows sap from single cells to be measured and permits rapid thermal equilibration with the stage. To prevent evaporation, the investigator suspends the samples in oil-filled wells in a silver plate (silver has high thermal conductivity). The temperature of the stage is rapidly decreased to about –30° C, which causes the sample to freeze. The temperature is then raised very slowly, and the melting process in the sample is observed through the microscope. When the last ice crystal in the sample melts, the temperature of the stage is recorded (note that the melting and freezing points are the same). It is straightforward to calculate the solute concentration from the freezing-point depression; and from the solute concentration (cs), Ψs is calculated as –RTcs .

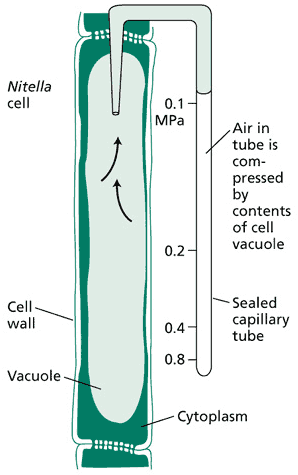
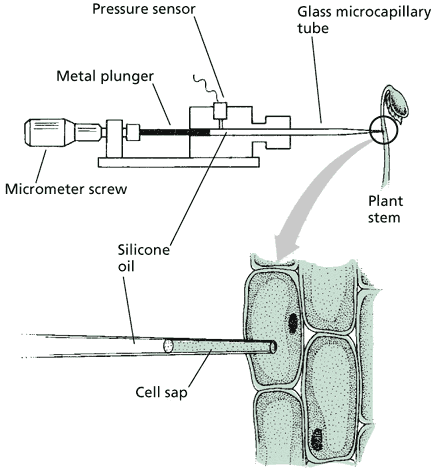


**Figure:** A cryoscopic osmometer measures the concentration of total dissolved solutes by measuring the freezing-point depression of a solution. (A) Very small liquid samples are loaded onto the temperature-controlled stage of a microscope. (B) When the temperature is quickly reduced, the samples supercool and freeze. (C) Slowly warming the stage causes the samples to thaw. The temperature at which the last ice crystal melts provides a measure of the melting point of the sample. (Click image to enlarge.)

1. **Pressure probe (Ψp measurement):**

If a cell were as large as a watermelon or even a grape, measuring its hydrostatic pressure would be a relatively easy task. Because of the small size of plant cells, however, the development of methods for direct measurement of turgor pressure has been slow. In this technique, an air-filled glass tube sealed at one end is inserted into a cell. The high pressure in the cell compresses the trapped gas, and from the change in volume one can readily calculate the pressure of the cell from the ideal gas law (pressure × volume = constant). This method works only for cells of relatively large volume, such as the giant cell of the filamentous green alga Nitella. For smaller cells, the loss of cell sap into the glass tube is sufficient to deflate the cell and this yields artifactually low pressures.

This instrument is similar to a miniature syringe. A glass microcapillary tube is pulled to a fine point and is inserted into a cell. The microcapillary is filled with silicone oil, a relatively incompressible fluid that can be readily distinguished from cell sap under a microscope. When the tip of the microcapillary is first inserted into the cell, cell sap begins to flow into the capillary because of the initial low pressure of that region. Investigators can observe such movement of sap under the microscope and counteract it by pushing on the plunger of the device, thus building up a pressure. In such fashion the boundary between the oil and the cell sap can be pushed back to the tip of the microcapillary. When the boundary is returned to the tip and is held in a constant position, the initial volume of the cell is restored and the pressure inside the cell is exactly balanced by the pressure in the capillary. This pressure is measured by a pressure sensor in the device. Thus the hydrostatic pressure of individual cells may be measured directly.

**a)**  **b)** 

**Figure a:** Use of the micromanometer, a pressure probe, to measure cell turgor pressure. Nitella cells (which are particularly large—about 100 mm in diameter and many centimeters long) were used for these measurements.

**Figure b:** Diagram of the simplest pressure probe (not to scale). The primary advantage of this method over the one shown in Web Figure 3.6.E is that cell volume is minimally disturbed. Minimal disturbance is of great importance for the tiny cells that are typical of higher plants, in which loss of even a few picoliters (10–12 L) of fluid can substantially reduce turgor pressure.

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**The importance of Water in Plants**

Plants need large quantities of water for growth. The most important factor driving water movement in plants is a process known as **transpiration**. Transpiration is the loss of water from plants in the form of vapor (evaporation). Plants utilize most of the water absorbed from the soil for **transpiration (95%),** but a small portion of the water absorbed is used during photosynthesis for producing the **carbohydrates** necessary for **plant growth (5%).** The rate of transpiration is dependent on water availability within the plant (and soil) and on sufficient energy to vaporize water. Most energy supporting transpiration is derived directly from the sun (solar radiation). Sunny, hot weather increases the rate of transpiration and thus the risk for **wilting** if adequate water is not available.

Water typically makes up **80 – 95%** of the mass of growing plant tissues. Mature woody plant tissue water content ranges from **45 – 50%** while **herbaceous** plant water content ranges from **70 – 95%.** Plants have cell walls that allow the buildup of **turgor pressure** within each cell. Turgor pressure contributes to **rigidity** and mechanical stability of non-woody plant tissue and is essential for many physiological processes including cell **enlargement** (plant growth), gas exchange in the leaves, transport of water and **sugars**, and many other processes.

Plants have adapted over time to tolerate extremes in water availability. Plant water availability is influenced by soil moisture. The texture and structure of soils and container substrates influence their relative capacities to retain water. Plant water uptake does not always keep up with transpirational water loss rates, even if soil moisture is adequate. Temporary midday **wilting** is common during hot, sunny afternoons, but plants can rehydrate over night when lower temperatures result in decreased transpirational water losses. If the soil/substrate dries without addition of water from precipitation or irrigation, **permanent wilting** may occur, resulting in plant death. It is critical to manage the water status of nursery crops and to irrigate based on soil moisture and plant needs.

**Growth** is dramatically affected by the timing and amount of water applied during production. Certain stages of plant growth are more sensitive to water stress than others. Plant **vigor** and overall resistance to stress from insects and/or disease are influenced by water status. Water management is the most important cultural practice of nursery growers whether growing field or container crops. Therefore, optimum growth and quality of nursery plants can only be achieved if water is properly managed. In the nursery industry the goal is not simply plant survival but ultimately the production of quality plants in the shortest amount of time, using minimal production space, with least impact on the environment, and with the most efficient and effective use of other resources so that bottom line costs are reduced.

Water performs the following important functions in plants summarized below:

1. Water is essential for the germination of seeds and growth of plants.

2. During the process of photosynthesis, plants synthesize carbohydrates from carbon dioxide and water. Therefore, water is one of the essential components for the plant.

3. Water acts as a solvent for fertilizers and other minerals, which are taken up by the plant roots in the form of solution. Thus, water serves as the medium in which plants absorb soluble nutrients from the soil.

4. Water serves as medium for transport of chemicals to and from cells.

5. Water pressure in plant cells provides the firmness to the plants.

6. Aquatic life is possible in water only.

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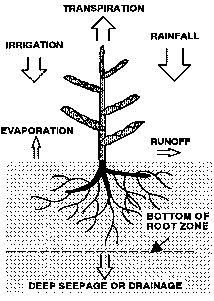
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**Water in Soil and Plants**

The soil is composed of three major parts: air, water, and solids. The solid component forms the framework of the soil and consists of **mineral** and **organic matter**. The mineral fraction is made up of sand, silt, and clay particles. The proportion of the soil occupied by water and air is referred to as the **pore volume**. The pore volume is generally constant for a given soil layer but may be altered by tillage and compaction. The ratio of air to water stored in the pores changes as water is added to or lost from the soil. Water is added by rainfall or irrigation, as shown. Water is lost through surface runoff, evaporation (direct loss from the soil to the atmosphere), transpiration (losses from plant tissue), and either percolation (seepage into lower layers) or drainage.



**Fig:** Source and fate of water added to a soil system.

The pore volume is actually a reservoir for holding water. Not all of the water in the reservoir is available for plant use. Figure below represents a "wet" (saturated) soil immediately after a large rainfall. Note that all of the pores are filled with water. Gravity will pull some of this water down through the soil below the crop's root zone. The water that is redistributed below the root zone due to the force of gravity is **gravitational water**. In general, gravitational water is not **available** to plants, especially in sandy soils, because the redistribution process occurs quickly (in two days or less).

After the redistribution process is complete, the soil is at **field capacity**. Under this condition it contains the greatest amount of water that is potentially available to plants. The actual volume of water present when the soil is at field capacity depends on the **soil texture**.

|  |
| --- |
| **Important Water Terminology** |
| * **Gravitational Water:**   When the water enters the soil and passes through the spaces between the soils particles and reaches the water table, the type of soil water is called gravitational water. This water lies far below and is generally not available to the plant roots.   * **Capillary Water:**   In smaller pores of the soil, water is held against the force of gravity by capillary forces and is called capillary water. This form of water is most important to plants and constitutes the only available source of water to plants.   * **Hygroscopic Water:**   This is the form of water which is held by soil particles on soil surface. The water is held tightly around the soil particles due to cohesive and adhesive forces. These forces greatly reduce the water potential and thus this type of water in soil is not available to plants.   * **Run Away Water:**   All the rain water falling on the soil is not retained by it. Run away water does not enter the soil and gets drained away from soil surface.   * **Combined water:**   Some water is present in the form of hydrated oxides of aluminium, iron, silicon inside the soil. This is also a non-available form of water for plant roots.  Different forms of soil water and relationship with soil and plant water status   * **Saturation:**   Refers to a soil's water content when practically all pore spaces are filled with water. This is a temporary state for well-drained soils, as the excess water quickly drains out of the larger pores under the influence of gravity, to be replaced by air.   * **Permanent Wilting Point (PWP):**   Refers to the water content of a soil that has been exhausted of its available water by a crop, such that only non-available water remains. The crop then becomes permanently wilted and cannot be revived when placed in a water-saturated atmosphere. At this point the soil feels nearly dry or only very slightly moist.   * **Available Water Capacity (AWC):**   Is the water available for plant growth held between Field Capacity and Permanent Wilting Point.   * **Permanent Wilting Point:**   The point at which the amount of water in the soil has dropped to such a level that the plants begin to wilt and will not recover, even if moved to a cool and dark place, unless more water is added to the soil. It occurs when the water potential of the soil is the same as, or lower (more negative) than, the water potential of the plant. The amount of water retained in the soil when the permanent wilting point is reached varies depending on the plant species and the type of soil. |



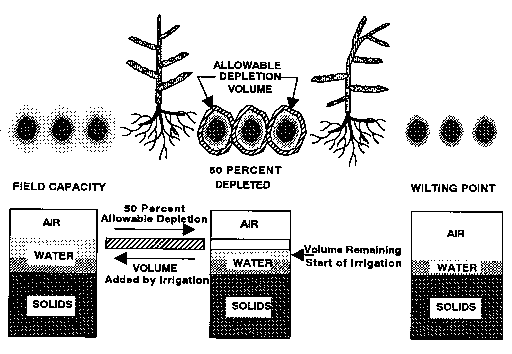
Plants get most of their water from **capillary water**. This is the water retained in soil pores after gravitational water has **drained**. Surface tension (suction) holds capillary water around the soil particles. As water is removed by plants or by evaporation from the soil surface, the films of water remaining around the soil particles become thinner and are held by the soil particles more tightly. When the surface tension becomes high, the plant is unable to take up any of the remaining water and permanent **wilting** results. When the plant has removed all available water, the soil's water content has reached the **permanent wilting point** (PWP).

**Soil-Water and Plant Stress:**

As a plant extracts water from the soil, the amount of PAW remaining in the soil decreases. The amount of PAW removed since the last irrigation or rainfall is the **depletion** volume. Irrigation scheduling decisions are often based on the assumption that crop yield or quality will not be reduced as long as the amount of water used by the crop does not exceed the allowable depletion volume.

The allowable depletion of PAW depends on the soil and the crop. For example, consider corn growing in a sandy loam soil three days after a soaking rain. Even though enough **PAW** may be avai1able for good plant growth, the plant may wilt during the day when potential **evapotranspiration (PET)** is high. Evapotranspiration is the process by which water is lost from the soil to the atmosphere by evaporation from the soil surface and by the transpiration process of plants growing in the soil. Potential evapotranspiration is the maximum amount of water that could be lost through this process under a given set of atmospheric conditions, assuming that the crop covers the entire soil surface and that the amount of water present in the soil does not limit the process. **Potential evapotranspiration** is controlled by atmospheric conditions and is higher during the day. Plants must extract water from the soil that is next to the roots. As the zone around the root begins to dry, water must move through the soil toward the root. Daytime wilting occurs because PET is high and the plant takes up water faster than the water can be replaced. At night when PET decreases to near zero, water steadily moves from the wetter soil to the drier zone around the roots. The plant recovers turgor and wilting ceases. This process of wilting during the day and recovering at night is referred to as **temporary wilting**. Proper irrigation scheduling reduces the length of time a crop is temporarily wilted.

Most crops will recover overnight from temporary wilting if less than 50 percent of the PAW has been depleted. Therefore, the allowable depletion volume generally recommended in North Carolina is 50 percent (Figure). However, the recommended volume may range from 40 percent or less in sandy soils to greater than 60 percent in clayey soils. The allowable depletion is also dependent on the type of crop, its stage of development, and its sensitivity to drought stress. For example, the allowable depletion recommended for some drought-sensitive crops (vegetable crops in particular) is only 20 percent during critical stages of development. The allowable depletion may approach 70 percent during noncritical periods for drought-tolerant crops such as soybeans or cotton.



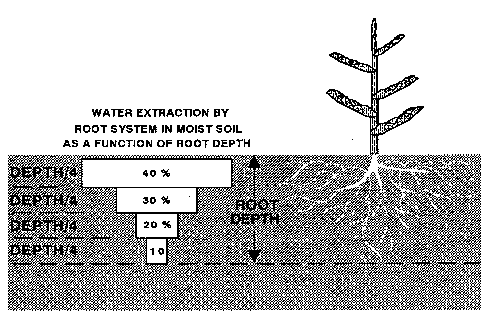
**Plant Factors:**

Three plant factors must be considered in developing a sound irrigation schedule: the crop's effective root depth, its moisture use rate, and its sensitivity to drought stress (that is, the amount that crop yield or quality is reduced by drought stress).

* **Effective Root Depth:**

Rooting depth is the depth of the soil reservoir that the plant can reach to get **PAW**. Crop roots do not extract water uniformly from the entire root zone. Thus, the effective root depth is that portion of the root zone where the crop extracts the majority of its water. Effective root depth is determined by both crop and soil properties.

**Plant Influence on** **Effective Root Depth**: Different species of plants have different **potential rooting depths**. The potential rooting depth is the maximum rooting depth of a crop when grown in a moist soil with no barriers or restrictions that inhibit root elongation. Potential rooting depths of most agricultural crops important in North Carolina range from about **2 to 5 feet**. For example, the potential rooting depth of corn is about 4 feet. Water uptake by a specific crop is closely related to its root distribution in the soil. About 70 percent of a plant's roots are found in the upper half of the crop's maximum rooting depth. Deeper roots can extract moisture to keep the plant alive, but they do not extract **suffficient** water to maintain optimum growth. When adequate moisture is present, water uptake by the crop is about the same as its root distribution. Thus, about 70 percent of the water used by the crop comes from the upper half of the root zone (Figure 10). This zone is the effective root depth.



**Soil Influence on Effective Root Depth.** The maximum rooting depth of crops in North Carolina is usually less than their potential rooting depth and is restricted by soil chemical or physical barriers.

* Crop Water Use Rate:

Often, irrigation scheduling requires an estimate of the rate at which PAW is being extracted. A "**checkbook**" approach is often used to keep a daily accounting of water additions and removal. Traveling irrigation systems usually require several days to complete one irrigation cycle. Soil-water measurements should be used to **schedule irrigation** for these systems, but continued **PAW** extraction during the irrigation cycle must also be estimated so that the last part of the field does not get too dry.

**Crop Sensitivity to Drought Stress:**

The reduction in crop yield or quality resulting from drought stress depends on the stage of crop development. For example, corn is most susceptible to stresses caused by dry conditions at the slicing stage. For a given level of stress, the yield reduction for corn would be four times greater at the silking stage than at the knee-high stage. From the yield standpoint, applying irrigation water at silking would be worth four times more than if the same amount of water was applied during the knee-high stage. Knowledge of this relationship is most useful when the irrigation capacity or water supply is limited. When water is in short supply, irrigation should be delayed or cancelled during the least susceptible crop growth stages. This water can then be reserved for use during more sensitive growth stages.

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**Root Growth and Functions**

In vascular plants, the root is the organ of a plant that typically lies below the surface of the soil. However, this is not always the case, a root can also be aerial (growing above the ground) or aerating (growing up above the ground or especially above water). Furthermore, a stem normally occurring below ground is not exceptional either (see rhizome). So, it is better to define root as **“**a part of a plant body that bears no leaves, and therefore also lacks nodes. There are also important internal structural differences between stems and roots.**”**

**Primary Root Tissues and Structure:**

The organization of tissues in the primary root is simpler than in the primary stem because no leaves are produced on the roots and, consequently, there is no need to connect the vascular system laterally to offshoots. The primary body, produced by the three primary meristems, consists of a central cylinder of vascular tissue, the **stele**, surrounded by large storage **parenchyma cells**, the **cortex**, on the outside of which lies a protective layer of cells, **the epidermis**.

* **Epidermis:**

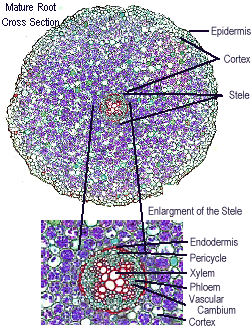
The root hairs of the young epidermal cells vastly increase the surface area through which movement of materials can occur. The thread-like hairs are simply enlargements of the protoplast that extend outward into the soil. They have little wall material and are extremely fragile and easily broken. The root epidermis of some plants is covered by a thin, waxy cuticle, which apparently isn't thick enough to impede movement of substances through the epidermis.

* **Cortex:**

The cortex, composed primarily of parenchyma cells, is the largest part of the primary root, but in most dicots (eudicots) and in gymnosperms that undergo extensive secondary growth, it is soon crushed, and its storage function assumed by other tissues. Three layers of cortex are recognized: the hypodermis (also called exodermis), the endodermis and, between them, the storage parenchyma. The outer and inner layers of the cortex, the hypodermis and endodermis, are cylinders of tightly packed cells with heavily suberized walls and no intercellular spaces. (Suberin is the fatty substance that gives cork its distinctive attributes.) In contrast, the storage parenchyma cells are thin-walled and loosely packed with many intercellular spaces among them.

* **Hypodermis (exodermis):**

Just under the epidermis forming the outermost layer of the cortex is a layer one or two cells in width called the hypodermis. Since its cell walls are heavily suberized and impermeable to water its apparent function is to keep the water and nutrients (which are absorbed in the root zone further down the root) from leaking out through the cortex. The hypodermis is especially well developed in plants of arid regions and in those with shallow root systems. It also deters the entrance of soil microorganisms.



* **Endodermis:**

The innermost layer of the cortex is the endodermis, which is readily identifiable by the presence of Casparian strips, bands of suberin present on transverse and radial walls of its cells—the walls perpendicular to the surface of the root. The endodermis regulates the passage of water and dissolved substances by forcing them to move through living plasma membranes and plasmodesmata and not simply diffuse through the porous cell walls. The absorption and translocation of materials is thus selective; not everything in the surrounding soil gets through and into the plant body. An endodermis almost always is present in roots and generally never in stems.

* **Storage parenchyma:**

The bulk of the cortex consists of thin-walled, living parenchyma cells, which store starch and other substances. The cells expand or shrink as materials move in and out of their protoplasts. The large volume of air present in the intercellular spaces of this tissue provides important aeration for roots.

* **Stele (vascular cylinder):**

The stele includes all of the tissues inside of the cortex: the pericycle, the vascular tissues—xylem and phloem—and, in some plants, a pith. Most dicot (eudicot) roots have a solid core of xylem in their center whereas most monocots have a pith composed of parenchyma.

* **Pericycle:**

The pericycle is a cylinder of parenchym, one or at most a few cells in width, which lies in the stele immediately inside the endodermis. The cells retain their ability to divide throughout their lives, and localized divisions in the pericycle give rise to lateral (branch) roots. When secondary growth occurs in roots, the vascular cambium and usually the first cork cambium originate in the pericycle. Other cell divisions in the pericycle produce additional pericycle cells.

* **Vascular tissues:**

Most dicot (eudicot) roots differ from eudicot stems in having a lobed column of primary xylem as their core with phloem tissue occurring as strings of cells between the lobes. This arrangement is called a protostele. The primary xylem of monocots, on the other hand, forms a cylinder around a central mass of pith parenchyma, a siphonostele. The way in which the vascular tissues develop is useful in tracing ancestral relationships in the plant kingdom.

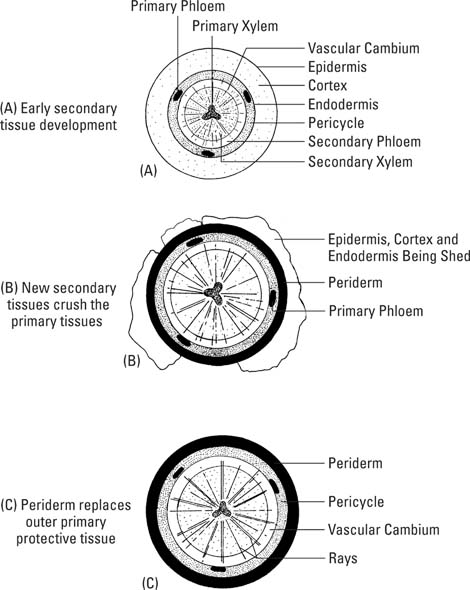
**Secondary Growth of Roots:**

Secondary tissues comprise the greatest volume of the root mass of woody perennial plants. Primary tissues continue to form in the feeder roots, but the supporting root structure consists of secondary tissues produced by the lateral meristems, the vascular cambium, and one or more cork cambia. The usually unobserved underground root systems of most trees are as massive as the huge aerial bodies and counterbalance the aboveground weight thus keeping the tree upright and stable. Roots produce branch roots and secondary tissues at the expense of the primary tissues. Cells in the primary tissue are broken and discarded as secondary growth proceeds. New lateral roots form endogenously (from within the root) and push outward from the pericycle, destroying cortex and epidermal tissues on their way to the soil.

Initiation of secondary growth takes place in the zone of maturation soon after the cells stop elongating there. The vascular cambium differentiates between the primary xylem and phloem in this zone and pericycle cells divide simultaneously with the procambium initials. The result is a cylinder of cambium encircling the primary xylem.

The vascular cambium almost immediately begins producing xylem cells inward and phloem cells toward the outside of the root, in the process flattening the primary phloem against the more resistant endodermis. Concomitant differentiation of cork cambia in the pericycle adds other areas of cell division in the stele. The combination of periderm and vascular tissue production not only physically breaks the remaining cells of the cortex and epidermis, but the lignified and suberized new cell walls laid down by the cambia effectively isolate the outer tissues as well from their source of supplies in the interior of the root. Their death is inevitable.

By the end of the first year, secondary growth has obliterated all but the central core of primary xylem cells and a few fibers of primary xylem pushed against the periderm. The zones at this time, therefore, from outside to inside are: periderm, pericycle, primary phloem, secondary phloem, vascular cambium, secondary xylem, and primary xylem.



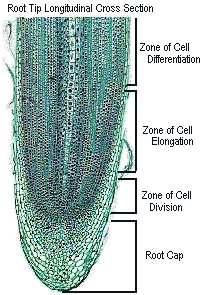
**Root Structures and Their Functions:**

* **Root Tip:**

The end 1 cm of a root contains young tissues that are divided into the root cap, quiescent center, and the subapical region.

* **Root Cap:**

Root tips are covered and protected by the root cap. The root cap cells are derived from the rootcap meristem that pushes cells forward into the cap region. Root cap cells differentiate first into columella cells. Columella cells contain amylopasts that are responsible for gravity detection. These cells can also respond to light and pressure from soil particles. Once columella cells are pushed to the periphery of the root cap, they differentiate into peripheral cells. These cells secrete mucigel, a hydrated polysaccharide formed in the dictyosomes that contains sugars, organic acids, vitamins, enzymes, and amino acids. Mucigel aids in protection of the root by preventing desiccation. In some plants the mucigel contains inhibitors that prevent the growth of roots from competing plants. Mucigel also lubricates the root so that it can easily penetrate the soil. Mucigel also aids in water and nutrient absorption by increasing soil:root contact. Mucigel can act as a chelator, freeing up ions to be absorbed by the root. Nutrients in mucigel can aid in the establishment of mycorrhizae and symbiotic bacteria.



* **Quiescent Center:**

Behind the root cap is the quiescent center, a region of inactive cells. They function to replace the meristematic cells of the rootcap meristem. The quiescent center is also important in organizing the patterns of primary growth in the root.

* **Subapical Region:**

This region, behind the quiescent center is divided into three zones. Zone of Cell Division - this is the location of the apical meristem (~0.5 -1.5 mm behind the root tip). Cells derived from the apical meristem add to the primary growth of the root. Zone of Cellular Elongation - the cells derived from the apical meristem increase in length in this region. Elongation occurs through water uptake into the vacuoles. This elongation process shoves the root tip into the soil. Zone of Cellular Maturation - the cells begin differentiation. In this region one finds root hairs which function to increase water and nutrient absorption. In this region the xylem cells are the first of the vascular tissues to differentiate.

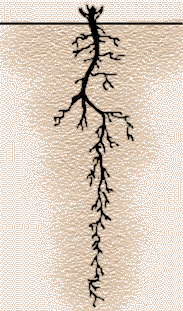
**Types of Roots Systems:**

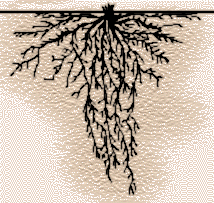
* **Tap root system:**

The first root produced from a seed is called the radicle. In many dicotyledonous plants this root greatly enlarges to become the most prominent root of the plant and is known as a tap root. Many smaller branch roots may grow from the tap root.

* **Fibrous root system:**

In monocotyledonous plants, the radicle is short lived and is replaced by numerous roots of more or less equal size. These roots are adventitious which means they can grow from plant organs other than roots e.g. stems.

a) Tap root system  b) Fibrous root system



* **Adventitious Root System:**

The primary root usually dies at an early stage and is replaced by numerous roots that develop from the stem. These roots, which develop from the stem, are equal in size. They are known as a adventitious roots, which give rise to branch or lateral roots and form an adventitious root system, e.g. the mealie.

**Role of Enzymes to Regulate Root Growth:**

In plants, each developmental process integrates a network of signaling events that are regulated by different phytohormones, and interactions among hormonal pathways are essential to modulate their effect. Continuous growth of roots results from the postembryonic activity of cells within the root meristem that is controlled by the coordinated action of several **phytohormones**, including **auxin** and **ethylene**. Although their interaction has been studied intensively, the molecular and cellular mechanisms underlying this interplay are unknown. We show that the effect of ethylene on root growth is largely mediated by the regulation of the auxin biosynthesis and transport-dependent local auxin distribution. Ethylene stimulates auxin biosynthesis and basipetal auxin transport toward the elongation zone, where it activates a local auxin response leading to inhibition of cell elongation. Consistently, in mutants affected in auxin perception or basipetal auxin transport, ethylene cannot activate the auxin response nor regulate the root growth. In addition, ethylene modulates the transcription of several components of the auxin transport machinery. Thus, ethylene achieves a local activation of the auxin signaling pathway and regulates root growth by both stimulating the auxin biosynthesis and by modulating the auxin transport machinery.

**Functions of Roots in Plants:**

1. **Anchorage and support:** The plant root system anchors the plant in the soil and provides physical support. Redwood trees (a gymnosperm) about 100 meters tall have stood erect for thousand years only because millions of individual fibrous roots dig into the ground, even though the depth of penetration is only up to about 5 meters. In general, however, taproot system provides more effective anchorage such that they are more resistant to toppling during storms.

**2.** **Absorption and conduction:** The plant root system absorbs water, oxygen and nutrients from the soil in mineral solution, mainly through the root hairs. They are capable of absorbing inorganic nutrients in solution even against concentration gradient. From the root, these are moved upward. Plants with a fibrous root system are more efficient in absorption from shallow sources. In the desert plants called phreatophytes like the mesquite, the roots seek permanent underground water reserves. These plants are water indicators and knowledge of such plants has been put to use by digging wells where they grow.

**3. Storage:** The root serves as storage organ for water and carbohydrates as in the modified, swollen roots of carrot, sweet potato (camote) and yam bean (sinkamas). Fibrous roots generally store less starch than taproots. Some roots are capable of storing large amounts of water; the taproots of some desert plants store more than 70 kg of water.

**4. Photosynthesis:** Some roots are capable of performing photosynthesis, as in the epiphytic orchids and aerial roots of mangrove.

**5. Aeration:** Plants that grow in stagnant water or other watery places have modified roots called pneumatophores to which oxygen from the air diffuses.

**6. Movement:** In many bulb- and corm-forming plants, contractile roots pull the plant downward into the soil where the environment is more stable.

**7. Reproduction:** The plant root system also serves as a natural means of perpetuating a species. In mature Norfolk Island pine and certain plants, suckers are commonly seen growing profusely around the trunk from horizontally growing roots. Likewise, new plants emerge from left-over tuberous roots after harvest in fields grown to sweet potato and yam bean (Pachyrhizus erosus). As a rule, plants with a fibrous root system are easier to transplant than those with tap roots.

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**Absorption Mechanisms and Water Movement through Plants**

Water is highly essential for plants for various metabolic activities. Land plants get their water supply from soil which serves as the source of water and minerals to them. The way in which water from soil enters roots, particularly to the root xylem, is called "mechanism of water absorption". Both Active and Passive absorption have been proposed for mechanism of water absorption.

**Active Absorption:**

It is absorption of water by roots with the help of metabolic energy generated by the root respiration. The force for water absorption originates from the cells of root due to root respiration. As the root cells actively take part in the process so it is called Active absorption. According to Renner, active absorption takes place in **low transpiring** and well-watered plants and **4%** of total water absorption is carried out in this process. The active absorption is carried out by two theories which are, Active osmotic water absorption and Active non-osmotic water absorption.

* **Active osmotic water absorption:**

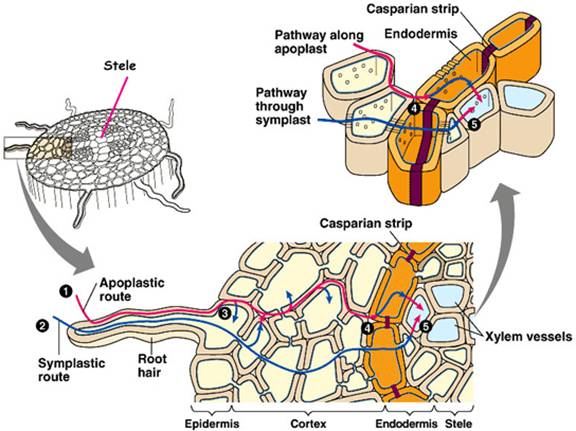
This theory was given by Atkins (1916) and Priestley (1921). According to this theory, the root cells behave as ideal osmotic pressure system through which water moves up from soil solution to root xylem along an increasing gradient of D.P.D. (suction pressure, which is the real force for water absorption). If solute concentration is high and water potential is low in the root cells, water can enter from soil to root cells through endosmosis. Mineral nutrients are absorbed actively by the root cells due to utilization of **adenosine triphosphate** (ATP). As a result, the concentration of ions (osmotica) in the xylem vessels is more in comparison to the soil water. A **concentration gradient** is established between the root and the soil water. Hence, the solute potential of **xylem** water is more in comparison to that of soil and correspondingly water potential is low than the soil water. Otherwise stated, water potential is comparatively positive in the soil water. This gradient of water potential causes endosmosis. The **endosmosis** of water continues till the water potential both in the root and soil becomes equal. It is the absorption of minerals that utilize metabolic energy, but not water absorption. Hence, absorption of water is indirectly an active process in a plant's life.

* **Active non-osmotic water absorption:**

This theory was given by Thimann (1951) and Kramer (1959). According to the theory, sometimes water is absorbed against **concentration gradient**. This requires expenditure of metabolic energy released from respiration of root cells. There is no direct evidence, but some scientists suggest involvement of energy from respiration. In conclusion it is said that, the evidences supporting active absorption of water are themselves poor.

**Passive absorption:**

This mechanism is carried out without utilization of metabolic energy. Here only the root act as an organ of absorption or passage. Hence, sometimes it is called water absorption 'through roots', rather 'by' roots. It occurs in rapidly transpiring plants during daytime, because of opening of stomata and the atmospheric conditions. The force for absorption of water is created at the leaf end i.i. the **transpiration pull**. The main cause behind this transpiration pull, water is lifted up in the plant axis like a bucket of water is lifted by a person from a well. Transpiration pull is responsible for **dragging water** at the leaf end, the pull or force is transmitted down to the root through water column in the xylem elements. The continuity of **water column** remains intact due to the **cohesion** between the molecules and it act as a rope. Roots simply act as a passive organ of absorption. As transpiration proceeds, simultaneously water absorption also takes place to compensate the water loss from leaf end. Most volume of water entering plants is by means of passive absorption.



**Water Movement in Roots:**

Water in the roots move by two pathways. They can be classified as

1) Apoplast pathway

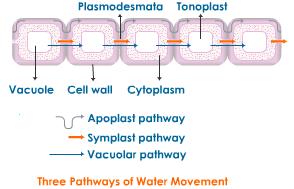
2) Symplast pathway

* **Apoplast Pathway:**

In this pathway the movement of water occurs exclusively through cell wall without the involvement of any membranes. Majority of the amount of water goes through the apoplast pathway. The cortex of the root does not oppose such movement of the water.

* **Symplast Pathway:**

Here the movement of water molecules is from cell to cell through the plasmodesmata. The plasmodesmata forms a network of cytoplasm of all cells



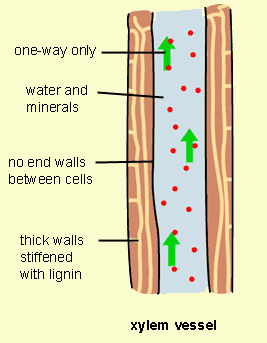
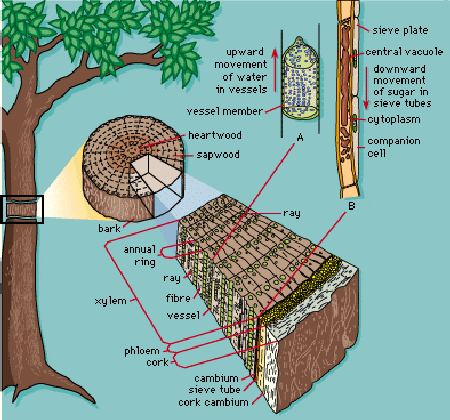
**Water Movement in Plants:**

Long-distance water movement is crucial to the survival of land plants. Although plants vary considerably in their tolerance of water deficits, they all have their limits, beyond which survival is no longer possible. About **85** percent of the fresh weight of leaves can be water. On a dry, warm, sunny day, a leaf can evaporate **100** percent of its water weight in just an hour. Water loss from the leaves must be compensated for by the uptake of water from the soil. Water transport is also important for the uptake of essential mineral nutrients from the soil.

Water that is absorbed by roots has to be transported to the terminal regions of plants. This movement of water is called **Ascent of Sap** or **Translocation of Water**.

**Structures involved in Ascent of Sap:** Various experiments like girdling, staining and plugging, indicate that the xylem tissue is mainly responsible for the movement of water. As xylem consists of tracheae otherwise called vessels, they form a system of fine channels running from roots to all other regions of the plant body and form a beautifully branched supply system, which is almost similar to that of arteries in animals.

**Rate of direction of transportation**: The rate with which the water is transported along the length of the stem varies from plant of plant. External conditions also play a significant role in controlling the rate of ascent of sap. But, under normal conditions the rate is **75-100 cm/hr**. This is quite a rapid process. Generally most of the water is translocated upwards i.e. in longitudinal direction, but some of the water is also translocated horizontally to reach the peripheral tissues.



**Theories Involved in Water Movement:**

Following theories are commonly known to involve in water movement through plant.

* **The Cohesion-Tension Theory:**

The major mechanism for long-distance water transport is described by the cohesion-tension theory, whereby the driving force of transport is transpiration, that is, and the evaporation of water from the leaf surfaces. Water molecules cohere (stick together), and are pulled up the plant by the tension, or pulling force, exerted by evaporation at the leaf surface.

Water will always move toward a site with lower water potential, which is a measure of the chemical free energy of water. By definition, pure water has a water potential of **0 Mega Pascals** (MPa). In contrast, at 20 percent relative humidity, the water potential of the atmosphere is **-500** MPa. This difference signifies that water will tend to evaporate into the atmosphere. The water within plants also has a negative potential, indicating water will tend to evaporate into the air from the leaf. The leaves of crop plants often function at **-1 MPa**, and some desert plants can tolerate leaf water potentials as low as **-10 MPa**. The water in plants can exist at such low water potentials due to the cohesive forces of water molecules. The chemical structure of water molecules is such that they cohere very strongly. By the cohesion-tension theory, when sunlight strikes a leaf, the resultant evaporation first causes a drop in **leaf water potential**. This causes water to move from stem to leaf, lowering the **water potential** in the stem, which in turn causes water to move from root to stem, and soil to root. This serves to **pull** water up through the xylem tissue of the plant.

* **Root pressure theory:**

Absorption of water by roots has been mainly a passive process. However, the involvement of an active process is not ruled out totally. On a rainy day, when the atmospheric humidity is at its maximum, and transpiration is at its minimum, root system absorbs excess of water than it can normally absorb. As a result of it hydrostatic pressure is built up within the roots, and this is called **root pressure**. This is believed to act as the motive force to force the water into the **xylem columns** upwards. Under the above said environmental conditions, water is forced out of the water-stomata as guttated water. Hence root pressure has been considered as an important phenomenon in ascent of sap. However, it has been noted that, some of the tallest trees found on this planet do not show any root pressure. Thus this theory fails to explain the transportation of water especially in tall trees.

* **Passive or Physical Force Theories:**

Physical forces like capillary force, collision force, atmospheric pressure, imbibitions, diffusion pressure, are found to operate in plants in one way or the other. Along with the development of science of plant physiology, people from time to time have come out with various theories involving one or to time have come out with various theories involving one or the other physical force as an explanation for ascent of sap.

* **Atmospheric pressure theory:**

The protagonists of this theory have assumed that plants are closed systems. When water escapes by transpiration from the surface of the leaves, it is believed that vacuum will be created within the plant body. As the root system is submerged in soil water, with the atmospheric action on the soil water, in order to fill up the vacuum created in the xylem vessels, water just enters passively; thus the water is translocated upwards. Unfortunately plants are not closed systems but they exhibit openness, for, the gases can diffuse into and out of the plant system with ease and facility. Added to this, atmospheric pressure can support and facility. Added to this, atmospheric pressure can support the water to be lifted only to a height of **34 feet**; but there are plants which are taller than this and still there is transport of water. Hence it can be concluded that atmospheric pressure could not be the force for ascent of sap.

* **Capillary Force Theory:**

When one end of the blotting paper or a chalk piece is dipped into ink, the ink slowly moves up. This movement through the paper is called capillary movement. Blotting paper is made up of innumerable cellulose fibres interwoven into a close network. Between such fibres, extremely narrow spaces are found, which are connected with each other and form a fine net work of capillary canals. If water is provided to such capillary system at one end, water is sucked in and it moves along the channels of capillary network by a force called capillary force. According to capillary network by a force theory, such capillary system exists within the plant body. Tracheids and tracheae which are found longitudinally oriented in the vasculature have lumen as empty space, roots to terminal regions of the stem as continuous capillary system. When water is absorbed by the root system, the capillary system of xylem elements take up the water by capillary force and the water is supported to move upwards slowly but steadily.

**Factors Affecting the Absorption of Water**

Living root system is very essential for the survival of plants, for it is involved in the absorption of water and minerals which is a must. The factors that regulate the health of the roots also control the process of absorption of water. But the most important of them are soil temperature, soil water, soil aeration and the root structure.

* **Root System:**

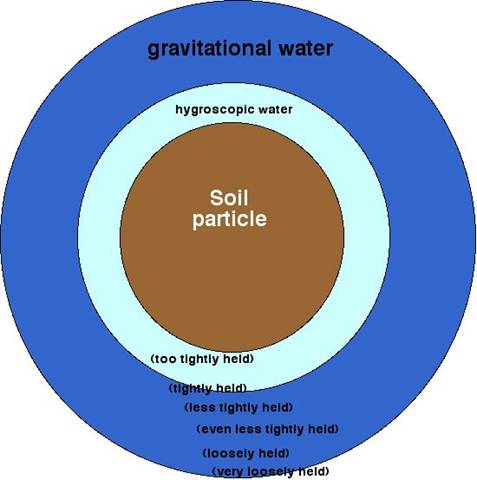
The efficiency of absorption of water depends upon the extent of root branching and the total surface area of the absorptive structures of root hairs. Though most of the water is absorbed by the root hair zone, other regions also contribute in absorption to some extent. Still the efficiency of absorption varies from one root system to the other.

* **Soil Temperature:**

In most of the cases, the soil temperature is little lower than that found in aerial regions. As temperature influences the viscosity mobility of water and also the metabolic activity of the plant cells, it affects the ability and the efficiency of absorption of water. The rate of absorption of water is lower, if the temperature is lowered this is because the mobility of water is decreases and the viscosity of liquid water increases. Thus low temperature resists the free movement of water which in turn affects the rate of absorption. However very high temperatures have adverse effect on the root’s efficiency.

* **Soil Water:**

Soil water is not pure water but it consists of a large number of minerals ad organic compounds in dissolved state, so it is a solution. The osmotic concentration of soil solution under full field capacity is always many fold lower the osmotic concentration of cell sap. This provides a kind of osmotic gradient between the soil solution and root cells. When conditions are favorable for rapid transpiration and shortage of water in the soil, plants exhibit wilting features. If the water is not replaced within a particular period of time, plants experience permanent wilting stress and they may die. In fact, under normal conditions, the rate of absorption of water shows diurnal rhythm i.e. higher rate of absorption during day and low rate at nights. Thus soil water and its constituents determine not only the rate of absorption but also the amount of water absorbed.



* **Aeration of Soil:**

Soil being made up of fine rock particles of different dimensions, clay particles and other components, possess plenty of lung space within which air is present. If the soil is water logged, most of the air is expelled from the capillary spaces and roots experience anaerobic conditions and their metabolism suffers. This affects the growth of the roots. Sometimes, excess of clay particles also clog the spaces and soil is rendered unsuitable for the normal growth of the root. Some plants are adapted to grow in water logged areas. In such situations the rate of absorption of water and mineral salts is greatly affected. Even greater accumulation of CO2 within the soil causes change in the pH of the soil solution. Such changes will be detrimental to the root system. But normally the soil CO2 is replaced by the atmospheric air.

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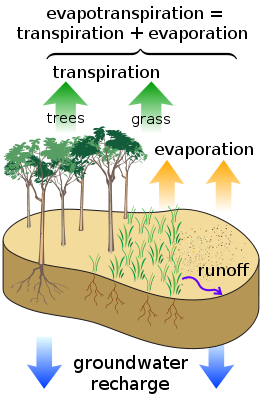
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**Evapotranspiration and Crop Water Consumption**

**Introduction:**

Evapotranspiration **(ET)** is a term describing the transport of water into the atmosphere from surfaces, including soil (soil evaporation), and from vegetation (transpiration). The latter two are often the most important contributors to evapotranspiration. The process of evapotranspiration is one of the main consumers of solar energy at the Earth's surface. Energy used for evapotranspiration is generally referred to as **latent heat flux**; however, the term latent heat flux is broad, and includes other related processes unrelated to transpiration including condensation (e.g., fog, dew), and snow and ice sublimation. Apart from precipitation, evapotranspiration is one of the most significant components of the water cycle.

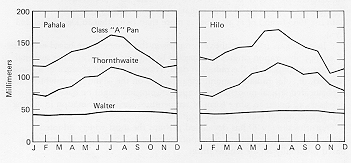
The **evaporation** component of ET is comprised of the return of water back to the atmosphere through direct evaporative loss from the soil surface, standing water (depression storage), and water on surfaces (intercepted water) such as leaves and/or roofs. **Transpired** water is that which is used by vegetation and subsequently lost to the atmosphere as vapor. The water generally enters the plant through the root zone, is used for various **biophysiological functions** including photosynthesis, and then passes back to the atmosphere through the leaf stomates. Transpiration will stop if the vegetation becomes stressed to the wilting point, which is the point in which there is insufficient water left in the soil for a plant to transpire, or if the plant to atmosphere vapor concentration gradient becomes prohibitive to plant physiological processes (e.g. photosynthesis).



**Potential Evapotranspiration (PET):**

Potential evapotranspiration (PET) is the amount of water that would be evaporated and transpired if there were **sufficient water** available. This demand incorporates the energy available for evaporation and the ability of the lower atmosphere to transport evaporated moisture away from the land surface. **PET** is higher in the summer, on less cloudy days, and closer to the equator, because of the higher levels of solar radiation that provides the energy for evaporation. PET is also higher on windy days because the evaporated moisture can be quickly moved from the ground or plant surface, allowing more evaporation to fill its place.

PET is expressed in terms of a depth of water, and can be graphed during the year (see figure).



Monthly estimated potential evapotranspiration and measured pan evaporation for two locations in Hawaii, Hilo and Pahala.

Potential evapotranspiration is usually measured indirectly, from other climatic factors, but also depends on the surface type, such as free water (for lakes and oceans), the soil type for bare soil, and the vegetation. Often a value for the potential evapotranspiration is calculated at a nearby climate station on a reference surface, conventionally short grass. This value is called the reference evapotranspiration, and can be converted to a potential evapotranspiration by multiplying with a surface coefficient. In agriculture, this is called a crop coefficient. The difference between potential evapotranspiration and precipitation is used in irrigation scheduling.

Average annual PET is often compared to average annual precipitation, P. The ratio of the two, P/PET, is the aridity index.

**Evapotranspiration and the Water Cycle:**

Evapotranspiration is a significant water loss from drainage basins. Types of vegetation and land use significantly affect evapotranspiration, and therefore the amount of water leaving a drainage basin. Because water transpired through leaves comes from the roots, plants with deep reaching roots can more constantly transpire water. Herbaceous plants generally transpire less than woody plants because they usually have less extensive foliage. Conifer forests tend to have higher rates of evapotranspiration than deciduous forests, particularly in the dormant and early spring seasons. This is primarily due to the enhanced amount of precipitation intercepted and evaporated by conifer foliage during these periods. Factors that affect evapotranspiration include the plant's growth stage or level of maturity, percentage of soil cover, solar radiation, humidity, temperature, and wind.

Through evapotranspiration, forests reduce water yield, except in unique ecosystems called cloud forests. Trees in cloud forests collect the liquid water in fog or low clouds onto their surface, which drips down to the ground. These trees still contribute to evapotranspiration, but often collect more water than they evaporate or transpire. In areas that are not irrigated, actual evapotranspiration is usually no greater than precipitation, with some buffer in time depending on the soil's ability to hold water. It will usually be less because some water will be lost due to percolation or surface runoff. An exception is areas with high water tables, where capillary action can cause water from the groundwater to rise through the soil matrix to the surface. If potential evapotranspiration is greater than actual precipitation, then soil will dry out, unless irrigation is used. Evapotranspiration can never be greater than PET, but can be lower if there is not enough water to be evaporated or plants are unable to transpire readily.

**Estimating Evapotranspiration:**

Evapotranspiration can be measured or estimated using several methods.

**Indirect methods:**

**Pan evaporation** data can be used to estimate lake evaporation, but transpiration and evaporation of intercepted rain on vegetation are unknown. There are three general approaches to estimate evapotranspiration indirectly.

**Catchment water balance:** Evapotranspiration may be estimated by creating an equation of the water balance of a drainage basin. The equation balances the change in water stored within the basin (S) with inputs and exports:

**ΔS = P - ET - Q - D**

The input is precipitation **(P),** and the exports are evapotranspiration (which is to be estimated), streamflow (**Q**), and groundwater recharge (**D**). If the change in storage, precipitation, streamflow, and groundwater recharge are all estimated, the missing flux, **ET**, can be estimated by rearranging the above equation as follows:

**ET = P -Δ S - Q - D**

**Hydrometeorological equations:** The most general and widely used equation for calculating reference ET is the Penman equation. The Penman-Monteith variation is recommended by the Food and Agriculture Organization.The simpler Blaney-Criddle equation was popular in the Western United States for many years but it is not as accurate in regions with higher humidities. Other solutions used includes Makkink, which is simple but must be calibrated to a specific location, and Hargreaves. To convert the reference evapotranspiration to actual crop evapotranspiration, a crop coefficient and a stress coefficient must be used. Crop coefficients referred to in many hydrological models are themselves the result of equations that describe predictable variation in coefficient values depending upon plant conditions that change during periods for which the model is used. This is because crops are seasonal, perennial plants mature over multiple seasons, and stress responses can significantly depend upon many aspects of plant condition.

**Energy balance:** A third methodology to estimate the actual evapotranspiration is the use of the energy balance.

**ƛ E = Rn + G - H**

Where **λE** is the energy needed to change the phase of water from liquid to gas, **Rn** is the net radiation, **G** is the soil heat flux and H is the sensible heat flux. Using instruments like a scintillometer, soil heat flux plates or radiation meters, the components of the energy balance can be calculated and the energy available for actual evapotranspiration can be solved.

The SEBAL algorithm solves the energy balance at the earth surface using satellite imagery. This allows for both actual and potential evapotranspiration to be calculated on a pixel-by-pixel basis. Evapotranspiration is a key indicator for water management and irrigation performance. SEBAL can map these key indicators in time and space, for days, weeks or years.

**Experimental Method for measuring ET:**

One method for measuring ET is with a weighing **lysimeter**. The weight of a soil column is measured continuously and the change in storage of water in the soil is modeled by the change in weight. The change in weight is converted to units of length based on the surface area of the weighing lysimeter and the unit weight of water. ET is computed as the change in weight plus rainfall minus percolation.

**Factors Affecting Evapotranspiration:**

The rate of evapotranspiration at any location on the Earth's surface is controlled by several factors:

* **Energy availability.** The more energy available, the greater the rate of Evapotranspiration. It takes about 600 calories of heat energy to change 1 gram of liquid water into a gas.
* **The humidity gradient** away from the surface. The rate and quantity of water vapor entering into the atmosphere both become higher in drier air.
* **The wind speed** immediately above the surface. The process of evapotranspiration moves water vapor from ground or water surfaces to an adjacent shallow layer that is only a few centimeters thick. When this layer becomes saturated evapotranspiration stops. However, wind can remove this layer replacing it with drier air which increases the potential for Evapotranspiration. Winds also affect evapotranspiration by bringing heat energy into an area. A 5-mile-per-hour wind will increase still-air evapotranspiration by 20 percent; a 15-mile-per-hour wind will increase still-air evapotranspiration by 50 percent
* **Water availability.** Evapotranspiration cannot occur if water is not available.
* **Physical attributes of the vegetation**. Such factors as vegetative cover,plant height, leaf area index and leaf shape and the reflectivity of plant surfaces can affect rates of evapotranspiration. For example coniferous forests and alfalfa fields reflect only about 25 percent of solar energy, thus retaining substantial thermal energy to promote transpiration; in contrast, deserts reflect as much as 50 percent of the solar energy, depending on the density of vegetation.
* **Stomatal resistance**. Plants regulate transpiration through adjustment of small openings in the leaves called stomata. As stomata close, the resistance of the leaf to loss of water vapor increases, decreasing to the diffusion of water vapor from plant to the atmosphere.
* **Soil characteristics**. Soil characteristics that can affect evapotranspiration include its heat capacity, and soil chemistry and albedo.

Seasonal trends of evapotranspiration within a given climatic region follow the seasonal declination of solar radiation and the resulting air temperatures. Minimum evapotranspiration rates generally occur during the coldest months of the year. Maximum rates generally coincide with the summer season. However since evapotranspiration depends on both solar energy and the availability of soil moisture and plant maturity the seasonal maximum evapotranspiration actually may precede or follow the seasonal maximum solar radiation and air temperature by several weeks.

**Geographical Pattern of Evapotranspiration:**

Assuming that moisture is available, evapotranspiration is dependent primarily on the availability of solar energy to vaporize water. Evapotranspiration therefore varies with latitude, season of year, time of day, and cloud cover. Most of the evapotranspiration of water on the Earth's surface occurs in the subtropical oceans (Figure 1). In these areas, high quantities of solar radiation provide the energy required to convert liquid water into a gas. Evapotranspiration generally exceeds precipitation on middle and high latitude landmass areas during the summer season. Once again, the greater availability of solar radiation during this time enhances the evapotranspiration process.

Estimates of average nationwide evapotranspiration for the conterminous United States range from about 40 percent of the average annual precipitation in the Northwest and Northeast to close to 100 percent in the Southwest. During a drought, the significance of evapotranspiration is magnified, because evapotranspiration continues to deplete the limited remaining water supplies in lakes and streams and the soil. The lower 5 miles of the atmosphere transports an average of about 40,000 billion gallons of water vapor over the conterminous United States each day. Slightly more than 10 percent of this moisture, however, is precipitated as rain, sleet, hail, or snow. The greatest proportion, about 67 percent, is returned to the atmosphere through evapotranspiration. About 29 percent is discharged from the conterminous United States as surface-water flowing into the Pacific and Atlantic Oceans and across the borders into Canada and Mexico, about 2 percent is discharged as groundwater outflow, and about 2 percent is consumed by people, animals, plants, and used for industrial and commercial processes. For most of the United States, evaporation returns less moisture to the atmosphere than does transpiration. Globally, evaporation processes are resposible for an overwhelming majority of the water returned to the atmosphere.

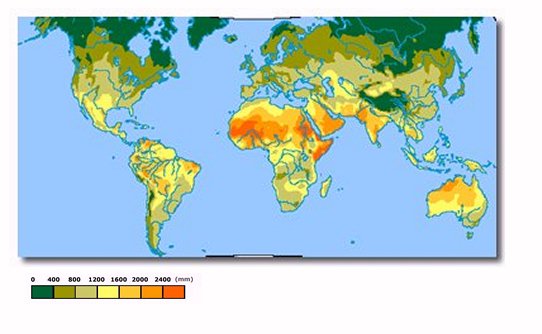


Figure. Mean Annual Potential Evapotranspiration. Source: UNEP World Atlas of Desertification Figure 1. Mean Annual Potential Evapotranspiration. Source: UNEP World Atlas of Desertification.

**Crop Water Consumption and ET:**

Prevailing weather conditions, available water in the soil, crop species, and growth stage influence crop water use. At full cover, a crop is at the maximum ET rate (reference ET or potential ET [PET]) if soil water is not limited, namely, if the soil root zone is at field capacity. Different crops reach full cover at different growth stages and times after planting. To standardize ET measurements and calculations, a PET or reference crop ET (ETr) is used to estimate actual ET (ETa) for other crops. In humid and semihumid areas where water usually is not a limiting factor, grass is used as a reference ET crop. In arid or semiarid areas, alfalfa is more suitable as a reference ET crop because it has a deeper root system, which reduces its susceptibility to water stress resulting from dry weather. Also, the pan evaporation is used to estimate PET. The standard is a large pan of water in or near a field. Figures 1 and 2 show corn and soybean ET factors, respectively, over a growing season. The ETa is the water use of a particular crop at a given time. ETa of an annual crop reaches its maximum at full canopy and can be higher or lower than PET, depending on the crop. Actual ET can be calculated by multiplying PET by crop coefficient (KC). A crop coefficient is the ratio between ETa of a particular crop at a certain growth stage and PET. If the crop coefficient is less than one, the crop uses less water than PET.

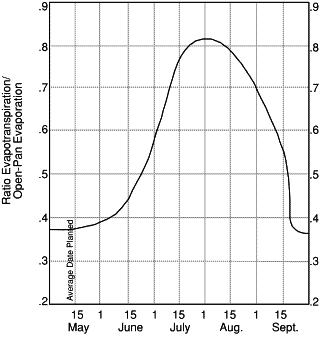


Fig. 1. Variation of corn ET factor over the growing season. For example, on June 7 ET from a cornfield would be 40 percent of measured pan evaporation. On August 1 it would be 82 percent.

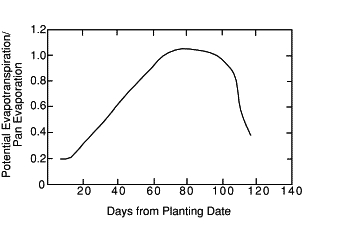
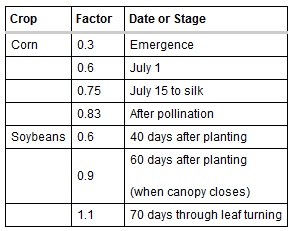


Fig. 2. Variation of soybean ET factor over the growing season.

The actual soil water content also influences crop water use. As soil dries, it becomes more difficult for the plant to extract water from the soil. At field capacity (maximum water content), plants use water at the maximum rate. When the soil water content drops below field capacity, plants use less water. Crops differ in their response to water stress at a given growth stage. Different crops have different water requirements and respond differently to water stress. The range of water use for crops varies from one area to another. However, we can use some guidelines to determine crop water use. If we assume that corn uses approximately 0.3 (Table 1) of the pan evaporation at emergence, crop water use will increase as the crop reaches pollination, then water use will drop gradually. For soybeans, the factor would be 0.6 at 40 days after planting. When the canopy closes on the soybean field, a maximum value of 1.1 (110 percent of the water from the pan) is used 70 days after planting until leaves turn yellow. Then water use drops off. The total amount of water used by a corn and a soybean crop would normally be the same (22.3, 21.5, and 22.1 inches in north central, southwestern, and southeastern Iowa, respectively). However, the soybeans tend to use water a little later in the season than does corn. The critical growth stages of corn for water use will be at tassel until grain is fully formed. The highest water use by corn will be during July and August. For soybeans, critical growth stages for water availability are during bloom and fruit set. Shortage in moisture supply during these growth stages will cause yield reduction.



Crop stage and relative water use as a portion of pan evaporation.

**Water Use for Vegetative Growth:**

For annual crops such as wheat, barley or canola, a certain amount of moisture is needed to not only initiate germination, but to take the crop through the vegetative growth stages to the stage where seed can be produced.

For wheat, barley and canola, at least 100 mm (4 inches) and often closer to 125 mm (5 inches) of water are needed to get a crop from germination to the reproductive growth stage where it can produce grain. The amount of moisture needed during vegetative growth varies because crops do not need as much moisture for transpiration in a cool spring compared to a warm, dry spring.

All crops shown in Figure 1 are cool season crops, with the exception of corn (Figure 1d). For cool season crops, daytime high temperatures in the range of 20° C are ideal for growth as crops are able to use more of the available soil moisture for vegetative crop growth than for transpiration to keep cool.

Cereal crops at the tillering stage use approximately 2 to 3 mm/day of water, and at the stem elongation stage, they need about 3 to 5 mm/day of water. When temperatures are above 25° C, the moisture needed is about 5 mm/day.

On warm days at the stem elongation growth stage, a cereal crop will use about 20 to 35 mm of water in one week, depending on environmental conditions such as solar radiation, temperature, humidity and wind.

When cereal crops are at the heading stage, often by early July, water use is 7 to 8 mm/day under ideal conditions. This situation means that peak water use is substantial from mid-June to late July or early August for cereal crops grown in Alberta. If moisture is lacking during this period, significant yield reduction can occur.

**Water Use for Reproductive Growth:**

Once a crop shifts from vegetative to reproductive growth, water use remains high. Cereal crops after heading and canola at the flowering growth stage will continue to use 7 to 8 mm/day of water from heading to flowering and to grain filling, under optimum growth conditions. As grain filling nears completion, crop water use declines and drops off rapidly as plants approach maturity.

Alberta research has shown that under good environmental conditions, for each 25 mm (1 inch) of water used, wheat produces 5 to 7 bushels/acre, barley produces 7 to 9 bushels/acre and canola produces 3.5 to 4 bushels/acre.

**Effects of Moisture Stress on Crops:**

When a crop is in a moisture deficit condition during vegetative growth, the first effect is a reduction in the growth rate of leaves and stems. When soil moisture availability is limited, cell expansion and division within the plant slow down. The effect is that plants reduce the production of enzymes and proteins needed for growth.

As the soil moisture deficiency increases, plant roots cannot take up enough water to meet transpiration needs. Crops respond by closing their stomata. Plant leaves become less rigid, and leaves exhibit wilting in mid-day heat. As air temperatures cool and solar radiation decreases later in the day and into the evening, plants recover from wilting as stomata open to meet transpiration needs.

When cereal crops begin wilting, older leaves and tillers are aborted, and stem elongation is reduced. When oilseed crops wilt, plants respond by abortion of older leaves, reduced stem elongation and reduced branching, which will reduce crop yield potential.

If the moisture deficit becomes more advanced, wilting becomes more prolonged each day until plants reach a condition where recovery overnight does not occur, and plants completely senesce and die.

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**Agricultural Crop Water Requirements**

It is defined as, "The quantity of water required by a crop in a given period of time for normal growth under field conditions." It includes evaporation and other unavoidable wastes. Usually water requirement for crop is expressed in water depth per unit area.

**IRRIGATION WATER NEED = Crop water need — available rain fall**

The first thing you need to consider when planning your garden is what growing zone you live in. This is based on both the temperature range of your climate and the amount of precipitation. Take a close look at the area in which you are going to plant your garden. If the ground tends to be very moist, choose plants that can tolerate constantly wet soil, and even standing water. If you live in an area that suffers from frequent droughts, however, select plants that can tolerate going long periods without water, especially in light of the frequent watering restrictions imposed on such areas. If you are lucky enough to live in an area that has a balanced climate, you have a wider range of choices for your plants.

* **Low Water Requirement Plants:**

Water Requirements of Crops Plants that require low levels of water are often called drought tolerant. Drought-tolerant plants can thrive in hot, dry conditions with very little water. They include both perennials and annuals. Most drought-tolerant plants only have to be hand-watered when they are planted and while they are establishing themselves. After that, they can be left to the natural cycle of the elements. Popular drought tolerant trees include the red cedar. live oak, crape myrtle, and the windmill and saw palmetto palm trees. All citrus trees are also drought tolerant. Many homeowners in areas prone to drought, such as parts of the southern United States, use shrubs and ground covering vines as part of their landscaping. These include Texas sage, orange jasmine and Chinese fountain grass. There are not many perennial drought-tolerant plants, but amaryllis is one that is very popular, along with the African iris. Popular drought-olerant annuals include marigold, cosmos and the Dahlberg daisy.

* **Mid-Level Water Requirement Crops:**

Most plants land in this range when it comes to water requirements. These plants do not need to be watered every day, but they need to be watered when the soil has been dry for over a week or two. Sometimes these plants are classified as plants lying in the "occasional water zone". These include popular plants such as geraniums, most roses, wisteria, clematis and other vine plants, sunflowers, spring flowering bulbs, and most flowering perennial shrubs. Note that flowering annuals planted in containers will need watering at least once or twice a week, while annuals planted in the ground will need watering less often.

* **High Water Requirement Plants:**

Some plants require large amounts of water. These plants typically grow in marshy areas or bogs, or along the banks of rivers, streams and lakes. The soil for these plants should always be kept moist. Standing water is not a concern for these plants, so you don't have to worry about root rot. Perennials are especially good for wet areas because they don't have to be replanted year after year, which can be difficult in marshy areas. Popular perennials for wet soil include iris plants, cannas, bee balms, ferns, and bog salvia. Aquatic mint is a pleasant ground cover that likes wet soil. The red osier dogwood does very well in wet conditions. Most annual flowering plants also do well in constantly moist soil.

**Water Requirement of Crop:**

Water requirement of crop is the quantity of water regardless of source, needed for normal crop growth and yield in a period of time at a place and may be supplied by precipitation or by irrigation or by both.

Water is needed mainly to meet the demands of evaporation (E), transpiration (T) and metabolic needs of the plants, all together is known as consumptive use (CU). Since water used in the metabolic activities of plant is negligible, being only less than one percent of quantity of water passing through the plant, evaporation (E) and transpiration (T), i.e. ET is directly considered as equal to consumptive use (CU). In addition to ET, water requirement (WR) includes losses during the application of irrigation water to field (percolation, seepage, and run off) and water required for special operation such as land preparation, transplanting, leaching etc.

WR = CU + application losses + water needed for special operations.

Water requirement (WR) is therefore, demand and the supply would consist of contribution from irrigation, effective rainfall and soil profile contribution including that from shallow water tables (S)

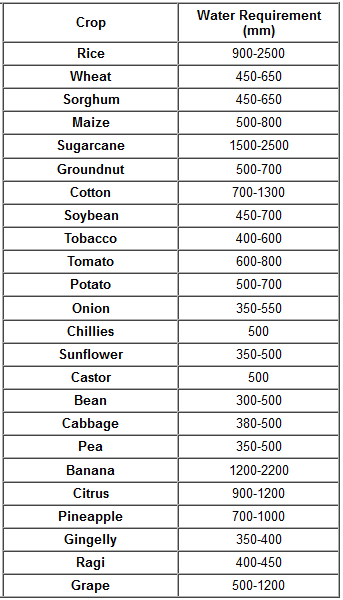
**WR = IR + ER + S**

Under field conditions, it is difficult to determine evaporation and transpiration separately. They are estimated together as evaportranspiration (ET). IR is the irrigation requirement.

Water requirement of any crop depends on crop factors such as variety, growth stage, and duration of plant, plant population and growing season. Soil factors such as temperature, relative humidity, wind velocity and crop management practices such as tillage, fertilization, weeding, etc. Water requirement of crops vary from area to area and even field to field in a farm depending on the above-mentioned factors.

**Water Requirement of Different Crops:**

Amount of water required by a crop in its whole production period is called water requiremrnt. The amount of water taken by crops vary considerably. What crops use more water and which ones less.......



**Factors Influencing Crop Water Requirement:**

**A) Atmospheric factors:**

1) Precipitation

2) Sunshine

3) Wind velocity

4) Temperature

5) Relative humidity

**B) Soil factors:**

1) Depth of water table

2) Available soil moisture

3) Amount of vegetative cover on soil surface.

**C) Plant factors:**

1) Plant morphology

2) Crop geometry

3) Plant cover

4) Stomatal destiny

5) Root depth

**D) Water factors:**

1) Frequency of irrigation

2) Quality of water ET.

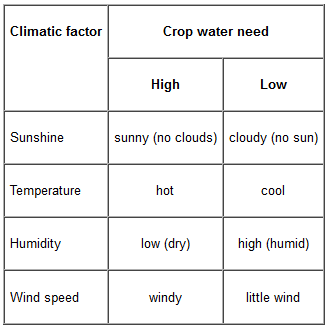
The following are the factors which effect on the water requirements of the crops, detail description.

* **Influence of climate**

In hot climate the evaporation loss is more and hence the water requirement will be more and vice versa. A certain crop grown in a sunny and hot climate needs more water per day than the same crop grown in a cloudy and cooler climate. There are, however, apart from sunshine and temperature, other climatic factors which influence the crop water need. These factors are humidity and wind speed. When it is dry, the crop water needs are higher than when it is humid. In windy climates, the crops will use more water than in calm climates.

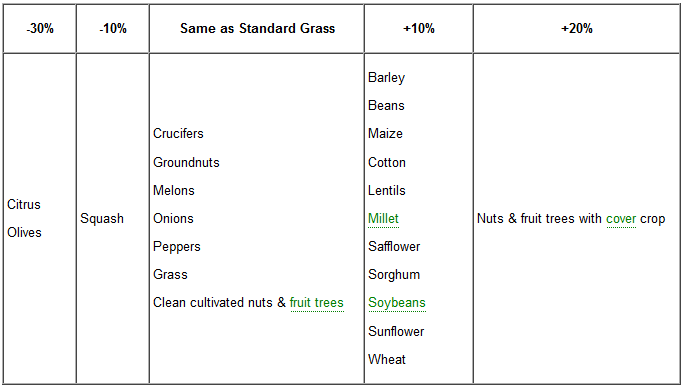
The highest crop water needs are thus found in areas which are hot, dry, windy and sunny. The lowest values are found when it is cool, humid and cloudy with little or no wind. From the above, it is clear that the crop grown in different climatic zones will have different water needs. For example, a certain maize variety grown in a cool climate will need less water per day than the same maize variety grown in a hotter climate.

Effect of major Climatic Factors on Crop Water Needs



For the various field crops it is possible to determine how much water they need compared to the standard grass. A number of crops need less water than grass, a number of crops need more water than grass and other crops need more or less the same amount of water as grass. Understanding of this relationship is extremely important for the selection of crops to be grown in a water harvesting scheme.

Crop water needs in peak period of various crops compared to the standard grass crop



* **Influence of crop type on crop water needs:**

As different crops require different amount of water for maturity, duties are also required. The duty would vary inversely as the water requirement of crop. The influence of the crop type on the crop water need is important in two ways.

**a.** The crop type has an influence on the daily water needs of a fully grown crop; i.e. the peak daily water needs of a fully developed maize crop will need more water per day than a fully developed crop of onions.

**b.** The crop type has an influence on the duration of the total growing season of the crop. There are short duration crops, e.g. peas, with a duration of the total growing season of 90-100 days and longer duration crops, e.g. melons, with a duration of the total growing season of 120-160 days. There are, of course, also perennial crops that are in the field for many years, such as fruit trees.

While, for example, the daily water need of melons may be less than the daily water need of beans, the seasonal water need of melons will be higher than that of beans because the duration of the total growing season of melons is much longer.

* **Water Table:**

If the water table is nearer to the ground surface, the water requirement will be less & vice versa.

* **Ground Slope:**

If the slope of the ground is steep the water requirement will be more due to less absorption time for the soil.

* **Intensity of Irrigation:**

It is directly related to water requirement, the more the intensity greater will be the water required for a particular crop.

* **Type of Soil:**

In sandy soil water percolates easily so water required is more. While in clayey soils water requirement is less.

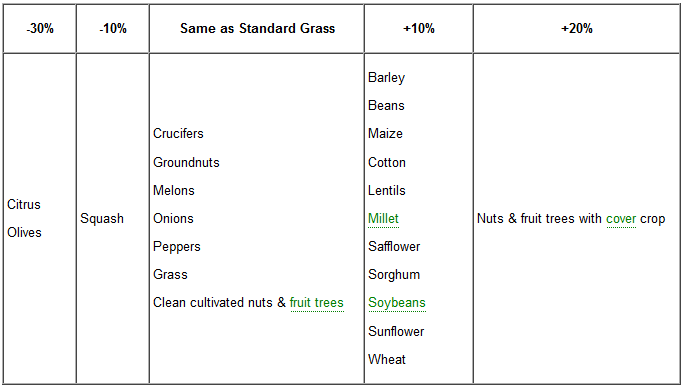
* **Method of Application of water:**

In sprinkler method less water is required as it just moist the soil like rainwater whereas in flood more water is required.

* **Method of Ploughing:**

In deep ploughing less water is required and vice versa.

Irrigation requirement of some common crops grown in India



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**Water Use Conservation**

As population continues to increase around the world, there is a growing demand for safe, reliable sources of water to meet the needs of the expanding population. Farmers, ranchers, and rural communities are particularly susceptible to the mounting pressures to provide more water to urban and urbanizing areas at the expense of water supplies in rural and agricultural communities. The term “agricultural water security” describes the need to maintain adequate water supplies to meet the food and fiber needs of the expanding population maximizing the efficiency of water use by farmers, ranchers, and rural communities.

Agriculture uses **70%** of all freshwater resources and **40%** of the food produced is irrigated. The demand for water resulting from rapidly population growth, urbanization and from industrialization means that pressure for reallocating water from agriculture to other uses is mounting. Recent food and water demand projections show that in order to meet the global food demands by 2050 a major shift has to occur in the way we manage water. Water use in agriculture has to become much more efficient, particularly in irrigated agriculture. Better use has to be made of the blue and green **water cycle**, and water conservation is the most important short term option in order to adapt to the challenges associated with increased climatic variability.

**Definitions & Terms used in Irrigation:**

* **Hydroscopic Water:** That water is adsorbed from an atmosphere of water vapour because of attractive forces in the surface of particles.
* **Hysteresis:** It is the log of in one of the two associated process or phenomena during reversion.
* **Indicator Plant:** It is the plant, which reflects specific growing condition by its presence or character of growth.
* **Infiltration Rate**: It is the maximum rate at which a soil under given condition and at given time can absorb water when there is no divergent flow at borders
* **Intake Rate or Infiltration Velocity:** It is the rate of water entry into the soil expressed as a depth of water per unit area applicable or divergence of flow in the soil.
* **Irrigation Requirement:** It refers to the quantity of water, exclusive of precipitation, required for crop production. This amounts to net irrigation requirement plus other economically avoidable losses. It is usually expressed in depth for given time.
* **Leaching:** It is removal of soluble material by the passage of water through the soil.
* **Leaching Requirement:** It is the fraction of water entering the soil that must pass through the root zone in order to prevent soil salinity from exceeding a specific value.
* **Oasis effect:** It is the exchange of heat whereby air over crop is cooled to supply heat for evaporation.
* **Percolation:** It is the down word movement of water through the soil.
* **Permanent Wilting Point (PWP):** Permanent wilting point is the moisture content in percentage of soil at which nearly all plants wilt and do not recover in a humid dark chamber unless water is added from an outside source. This is lower limit of available moisture range for plant growth ceases completely. The force with which moisture is held by dry soil this point corresponds to 15 atmospheres.
* **Permeability:** Permeability is the property of a porous medium to transmit fluids It is a broad term and can be further specified as hydraulic conductivity and intrinsic permeability.
* **PF:** It is the logarithm of height in cm of column of water which represents the total stress with which water is held by soil.
* **PH:** It is the negative logarithm of hydrogen ion concentration.
* **Potential Evaporation:** It represents evaporation from a large body of free water surface. It is assumed that, there is no effect of addictive energy .It is primarily a function of evaporative demand of climate.
* **Potential Evapo-transpiration:** It is the amount of water evaporated in a unit time from short uniform green crop growing actively and covering an extended surface and never short of water. Penman prefers the term potential transpiration.
* **Seepage:** It is the water escaped through the soil under gravitational forces.
* **Agricultural Drainage:** It is removal of excess water known as free or ravitational water from the surface or below the surface of farm land to create favorable condition for proper growth and development of the plot.
* **Surface Drainage:** when the excess water saturates the pores spaces removal of water of water by downward flow through the soil is called subsurface drainage.

**Irrigation Efficiency:**

Irrigation water is an expansive input and has to be used very efficiently. The main losses that occur during irrigation of fields as conveyance, run off, seepage and deep percolation. Irrigation efficiency can be increased by reducing these losses. Uneven spreading and inadequate filling of root zone are the other causes for low irrigation efficiency. Irrigation efficiency at the field level can be increased by selecting suitable method of irrigation, adequate land preparation and engaging an efficient irrigator. At the project level, it can be increased by proper conveyance and distribution system. Irrigation efficiency is the ratio usually expressed as percent of the volume of irrigation water transpired by plants, plus that evaporate from the soil, plus that necessary to regulate the salt concentration in the soil solution and that used by plants in building plant tissue to total volume of water diverted, stored or pumped for irrigation.

Wt + Ws - Rs

Ei = -------------------- X 100

Wi

Where,

**Ei** = Irrigation efficiency (percent)

**Wt** = the volume of irrigation water / unit area of land transpired by plants, evaporation from the soil during the crop period.

**Ws** = the volume of irrigation water per unit area of land to regulate the salt Content of soil solution.

**Re**  = Effective rainfall

**Wi** = the volume of water per unit area of land that is stored in reservoirs or diverted for irrigation. Irrigation efficiency indicates how efficiency the available water supply is being used. The efficiency of irrigation projects in India is as low as 20 to 40%.

**For maximization of the water use conservation, irrigation scheduling and application of limited amount or water at critical time is necessary. Following data includes to increase the efficiency of applied water and practices.**

**Criteria for Scheduling Irrigation or Approaches for Irrigation Scheduling**

An ideal irrigation schedule must indicate when to apply irrigation water and how much quantity of water to be applied; several approaches for scheduling irrigation have been used by scientist and farmers. These are as under

**1) Soil moisture depletion approach:**

The available soil moisture in the root is a good criterion for scheduling irrigation. When the soil moisture in a specified root zone depth is depended to a particular level (which is different for different crops) it is too replenished by irrigation.

**2) Plant basis or plant indices:**

As the plant is the user of water, it can be taken as a guide for scheduling irrigation. The deficit of water will be reflected by plants itself such as dropping, curling or rolling of leaves and change in foliage colour as indication for irrigation scheduling. However, these symptoms indicate the need for water. They do not permit quantitative estimation of moisture deficit.

**3) Climatological approach:**

Evapotranspiration mainly depends up on climate. The amount of water lost by evapotranspiration is estimated from Climatological data and when ET reaches a particular level, irrigation is scheduled. The amount of irrigation given is either equal to ET or fraction of ET. Different methods in Climatological approach are IW/CPE ratio method and pan evaporimeter method.

**4) Critical growth approach:**

In each crop, there are some growth stages at which moisture stress leads to irrevocable yield loss. These stages are known as critical periods or moisture sensitive periods. If irrigation water is available in sufficient quantities, irrigation is scheduled whenever soil moisture is depleted to critical moisture level. Say 25 or 50 percent of available soil moisture. Under limited water supply conditions, irrigation is scheduled at moisture sensitive stages and irrigation is skipped at non-sensitive stages. In cereals, panicle initiation, flowering, and pod development are the most important moisture sensitive stages.

**5) Plant water status itself:**

This is the latest approach for scheduling of irrigation. Plant is a good indicator of a soil moisture and climate factors. The water content in the plant itself is considered for scheduling irrigation. It is however, not yet common use for want of standard and low cost technique to measure the plant water status or potential.

**Simple Technique for Scheduling Irrigation:**

* **Soil cum sand mini plot technique:**

In this method, one cubic meter pit is dug in the middle of field. About five percent of sand by volume is added to the dug soil, mix well and pit is filled in the natural order. Crops are grown as usual in the entire area of the field including the pit area. The plants in the pit show wilting symptoms earlier than the other plants in the remaining area. Irrigation is scheduled as soon as wilting symptoms appear on the plants in the pit.

* **Sowing high seed rate:**

In an elevated area, one square meter plot is selected and crop is grown with four times thicker than natural seed rate. Because of high plant density, plants show wilting symptoms earlier than in the area indicating the need for scheduling irrigation.

* **Feel and appearance method:**

Moisture content can be roughly estimated by taking the soil from root zone in to hand and making in to small ball. It requires lot of experience to estimate the soil moisture by this method.

* **Irrometers or tensiometer:**

Tensiometer is also called irrometers since they are used in irrigation scheduling. Tensionmeters provide a direct measure of tenacity (tension) with which water is held by soil. It consist of 7.5 cm porous ceramic or clay cup, a .0protective metallic tube, a vacuum gauge and a hollow metallic tube holding all parts together. At the time of installation, the system is filled with water from the opening at the top and rubber corked when set up in the soil. Moisture from cup moves out with drying of soil, creating a vacuum in the tube which is measured with the gauge. Care should be taken to install tensiometer in the active root zone of the crop. When desired tension is reached, the soil is irrigated. The vacuum gauge is graduated to indicate tension values up to inch atmosphere and is divided in to fifty divisions each of 0.2 atmosphere value.

**Merits of tensiometer:**

1. It is very simple and easy to read soil moisture in situ.

2. It is very useful instrument for scheduling irrigation to crops which require frequent irrigations at low tension.

**Limitations:** Sensitivity of a tensiometer is only up to 0.85 atmospheres while available soil moisture range is up to atmosphere and hence is useful more on sandy soils wherein about 80% of available water is held within 0.85 ranges.

* **Plant indices:**

As the plant is the user of water, it can be taken as a guide for scheduling irrigation. The deficit of water will be reflected by plants itself such as dropping, curling or rolling of leaves and change in foliage colour as indication for irrigation scheduling. However, these symptoms indicate the need for water. They do not permit quantitative estimation of moisture deficit. Growth indicators such as cell elongation rates, plant water content and leaf water potential, plant temperature leaf diffusion resistance etc. are also used for deciding when to irrigate. Some indicator plants are also a basis for scheduling irrigation e.g. sunflower plant which is used for estimation of PWP of soil is used in Hawaii as an indicator plant for irrigation sugar cane.

* **Infra red thermometer:**

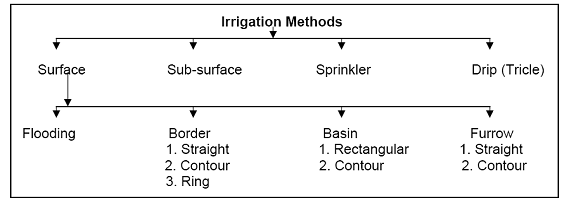
Canopy temperature is measured with infrared thermometer. It also simultaneously measures canopy temperature (Tc) and air temperature (Tq) and displays Tc-Tq value. Tc-Tq values can be used for scheduling irrigation. When transpiration is normal, due to its cooling effect canopy temperature is less than air temperature. The negative values of Tc-Tq indicate the plants have sufficient amount of water. When Tc-Tq values are zero or positive, which indicates stress irrigation is scheduled. Stress degree days (SDD), useful for scheduling irrigation are summed in a manner that is analogous to growing degree days SDD = (Tc-Tq) canopy temperature is measured during midday when air temperature is maximum. Yield reduction is maximum, when total number of cumulative SDD’s exceeds 10 to 15 between irrigations.

* **Remote sensing:**

In projects areas, where a single crop is grown on large area, irrigation scheduling can be done with the help of remote sensing data. Reflectance of solar radiation by the plants with sufficient amount of water is different from that of stressed plants. This principle can be used for scheduling irrigation. The following methods can be recommended to farmers for scheduling irrigation.

* Soil -Cum-Sand Mini Plot Technique
* Increased Plant Population
* Pan Evaporimeter

**Methods of Irrigation:**



There are three principle methods of irrigation viz. surface, sub surface and aerial, overhead or sprinkler irrigation.

1. **Surface irrigation:**

There are four variations under this method viz.

(1) Flooding,

(2) Bed or border method (Saras and flat beds),

(3) Basin method (ring and basin) and

(4) Furrow method (rides and furrows, broad ridges or raised beds)

**Flooding:** It consist of opening a water channel in a plot or field so that water can flow freely in all directions and cover the surface of the land in a continuous sheet. It is the most inefficient method of irrigation as only about 20 percent of the water is actually used by plants. The rest being lost as a runoff, seepage and evaporation. Water distribution is very uneven and crop growth is not uniform. It is suitable for uneven land where the cost of leveling is high and where a cheap and abundant supply of water is available. It is unsuitable for crops that are sensitive to water logging the method suitable where broadcast crops, particularly pastures, alfalfa, peas and small grains are produced.

**Adaptations:**

(1) An abundant supply of water

(2) Close growing crops

(3) Soils that do not erode easily

(4) Soils that is permeable

(5) Irregular topography

(6) Areas where water is cheap.

**Advantages:**

(1) Can be used on shallow soils

(2) Can be employed where expense of leveling is great

(3) Installation and operation costs are low

(4) System is not damaged by livestock and does not interfere with use of farm implements.

**Disadvantages:**

(1) Excessive loss of water by run of and deep percolation

(2) Excessive soil erosion on step land.

(3) Fertilizer and FYM are eroded from the soil.

**Bed or border method** (Sara and Flat beds or check basin): In this method the field is leveled and divided into small beds surrounded by bunds of 15 to 30 cm high. Small irrigation channels are provided between two adjacent rows of beds. The length of the bed varies from 30 meters for loamy soils to 90 meters for clayey soils. The width is so adjusted as to permit the water to flow evenly and wet the land uniformly. For high value crops, the beds may be still smaller especially where water is costly and not very abundant. This method is adaptable to most soil textures except sandy soils and is suitable for high value crops. It requires leveled land. It is more efficient in the use of water and ensures its uniform application. It is suitable for crops plant in lines or sown by broadcast. Through the initial cost is high requires less labour and low maintenance cost. This may also be called a sort of sara method followed locally in Maharashtra but the saras to be formed in this method are much longer than broader.

**Adaptations:**

(1) A large supply of water

(2) Most soil textures including sandy Loam, loams and clays

(3) Soil at least 90 cm deep

(4) Suitable for close growing crops.

**Advantages:**

(1) Fairly large supply of water is needed.

(2) Land must be leveled

(3) Suited only to soils that do not readily disperse.

(4) Drainage must be provided

**Basin irrigation:** This method is suitable for orchids and other high value crops where the size of the plot to be irrigated is very small. The basin may be square, rectangular or circular shape. A variation in this method viz. ring and basin is commonly used for irrigating fruit trees. A small bund of 15 to 22 cm high is formed around the stump of the tree at a distance of about 30 to 60 cm to keep soil dry. The height of the outer bund varies depending upon the depth of water proposed to retain. Basin irrigation also requires leveled land and not suitable for all types of soil. It is also efficient in the use of water but its initial cost is high.

There are many variations in its use, but all involve dividing the field into smaller unit areas so that each has a nearly level surface. Bunds or ridges are constructed around the areas forming basins within which the irrigation water can be controlled. Check basin types may be rectangular, contour and ring basin.

**Adaptations:**

1) Most soil texture

2) High value crops

3) Smooth topography.

4) High water value/ha

**Advantages:**

1) Varying supply of water

2) No water loss by run off

3) Rapid irrigation possible

4) No loss of fertilizers and organic manures

5) Satisfactory

**Disadvantages:**

1) If land is not leveled initial cost may be high

2) Suitable mainly for orchids, rice, jute, etc.

3) Except rice, not suitable for soils that disperse easily and readily from a crust.

**Furrow method** (rides and furrow, broad ridges, counter furrow etc.): Row crops such as potatoes, cotton, sugarcane, vegetable etc. can be irrigated by furrow method. Water is allowed to flow in furrow opened in crop rows. It is suitable for sloppy lands where the furrows are made along contours. The length of furrow is determined mostly by soil permeability. It varies from 3 to 6 meters. In sandy and clay loams, the length is shorter than in clay and clay loams. Water does not come in contact with the plant stems. There is a great economy in use of water. Some times, even in furrow irrigation the field is divided into beds having alternate rides and furrows. On slopes of 1 to 3 percent, furrow irrigation with straight furrows is quite successful. But on steeper slopes contour furrows, not only check erosion but ensure uniform water penetration.

**Adaptations:**

1) Medium and fine textured soils.

2) Variable water supply

3) Farms with only small amount of equipment.

**Advantages:**

1) High water efficiency

2) Can be used in any row crop

3) Relatively easy in stall

4) Not expensive to maintain

5) Adapted to most soils.

**Disadvantages:**

1) Requirement of skilled labour is more

2) A hazard to operation of machinery

3) Drainage must be provided.

**B. Subsurface method:**

Subsurface irrigation or sub-irrigation may be natural or artificial. Natural sub surface irrigation is possible where an impervious layer exists below the root zone. Water is allowed in to series of ditches dug up to the impervious layer, which then moves laterally and wets root zone.

In artificial sub surface irrigation, perforated or porous pipes are laid out underground below the root zone and water is led into the pipes by suitable means. In either case, the idea is to raise the water by capillary movement. The method involves initial high cost, but maintaince is very cheap. There is a risk of soil getting saline or alkaline and neighboring land damaged due to heavy seepage.

It is very efficient in the use of water as evaporation is cut off almost completely. The plant roots do not suffer from logging, there is no loss of agricultural land in laying out irrigation system and implements can be worked out freely. This method is however rarely noticed in our country but followed in other countries like Israel.

**C. Drip or trickle irrigation:**

It involves slow application of water to the root zone. The drip irrigation system consist of

1) Head

2) Main line and sub line

3) Lateral lines

4) Drip nozzles.

The head consists of a pump to lift water and produce the desired pressure (about 2.5 tmosphere) and to distribute water through nozzles. A fertilizer tank for applying fertilizer solution directly to the field along with the irrigation water and filter which cleans the suspended impurities in irrigation water to prevent the blockage of holes and passage of drip and nozzles

Mains and sub mains are normally of flexible material such as black PVC pipes. Laterals or drip lines are small diameter flexible lines (usually 1 to 1.25 cm diameter black PVC tubes) taking off from the mains or sub mains. Laterals are normally laid parallel to each other. Lateral lines can be up to about 50 meters long and are usually 1.2 cm diameter black plastic tubing. There is usually one lateral line for each crop row. By laying the main line along the center line of the field, it is possible to irrigate either side of the field alternately by shifting the laterals. A pressure drop of 10 percent is permitted between the ends of lateral. Drip nozzles are also known as emitters or values and are fixed at regular intervals in the laterals. These PVC values allow water to flow at the extremely slow rates, ranging from 2 to 11 liters per hour and they are of different shapes and design. The spacing between laterals is controlled by the row-to-row spacing of the crop to be irrigated. Drip laterals laid on soil surface are buried underground at the depth of 5 to 10 cm.

**Advantages:**

1) The losses by drip irrigation and evaporation are minimized

2) Precise amount of water is applied to replenish the depleted soil moisture at frequent intervals for optimum plant growth.

3) The system enables the application of water fertilizers at an optimum rate to the plant root system.

4) The amount of water supplied to the soil is almost equal to the daily consumptive use, thus maintaining a low moisture tension in soil.

**Disadvantages:**

The initial cost of the drip irrigation for large-scale irrigation is its main limitation. The cost of the unit per hectare depends mainly on the spacing of the crop. For widely spaced crops like fruit trees, the system may be even more economical than sprinkler.

**D. Sprinkler or overhead irrigation:**

This method consists of application of water to soil in the form of spray, somewhat as rain. It is particularly useful for sandy soils because they absorb water too fast. Soils that are too shallow, too steep or rolling can be irrigated efficiently with sprinklers.

This method is suitable for areas having uneven topography and where erosion hazards are great.

In sprinkler irrigation, water is conveyed under pressure through pipes to the area to be irrigated where it is passed out through or sprinklers the system comprises four main parts

i. Power generator

ii. Pump

iii. Pipeline and

iv. Sprinkler

The power generator may be electrical or mechanical. A centrifugal pump may be used for suction lift up to 37 to 50 cm. A piston type pump is preferable where water is very deep. The pipe consists of two sections, the main line and the laterals.

The main line may be permanently buried underground or may be laid above ground, if it is to be used on a number of fields. The main pipes are usually made of steel or iron. The laterals are lightweight aluminum pipes and are usually portable. The sprinkler nozzles may be single or double, revolving or stationery and mounted or riser pipes attached to riser. Each sprinkler head applies water to circular area whose diameter depends up on the size of water, which varies from ¼ to ¾ inch per hour is determined by selecting the proper combination of nozzles.

**Adaptations:**

1) A dependable supply of water

2) Uneven topography

3) Shallow soils.

4) Close growing crops.

**Advantages:**

1) It ensures uniform distribution of water

2) It is adaptable to most kinds of soil.

3) It offers no hindrance to the use of farm implements

4) Fertilizers material may be evenly applied through sprinklers. This is done by drawing liquid fertilizer solution slowly in to the pipes on the suction side of the pump so that the time of application varies from 10 to 30 minutes.

5) Water losses are reduced to a minimum extent

6) More land can be irrigated

7) Costly land leveling operations are not necessary and

8) The amount of water can be controlled to meet the needs of young seedling or mature crops.

**Disadvantage:**

1) The initial cost is rather very high.

2) Any cost of power to provide pressure must be added to the irrigation charges.

3) Wind interferes with the distribution pattern, reducing spread or increasing application rate near lateral pipe.

4) There is often trouble from clogged nozzle or the failure of sprinklers to revolve.

5) The cost of operations and maintaince is very high. Labour requirement for moving a pipe and related work approximately nearly one hour per irrigation.

6) It requires a dependable constant supply of water free slit and suspended matter and 7) It is suitable for high value crops.

**Water Conyenance Efficiency & Water Use Efficiency**

* **Water Conyenance Efficiency:**

It indicates the efficiency with which water is conveyed from source of supply to the field. It estimates the conveyance losses. It is expressed as

**Wf**

**Ec = --------- X 100**

**Ws**

Where,

Ec = Water conveyance efficiency (percent)

Wf= Water delivered at the field

Ws= Water delivered at the source

* **Water Application Efficiency:**

Irrigation water applied to the field is lost due o surface run off and deep percolation. Surface run off occurs due in long furrow or long border strips if ridges are weak. The water moves from one plot to another due to weak bunds giving way to water which may collect in large quantities even to break strong bunds. In furrows, water is allowed most of the time at the beginning of furrow till the flow reaches the other end of the furrow. It results in deep percolation of water in the first quarter of furrow. Water application efficiency is the measure of efficiency with which delivered to the field is stored in the root zone.

**Water stored in the root zone**

**Water application efficiency = ------------------------------------ X 100**

**Water delivered to the field**

* **Water Storage Efficiency:**

This parameter estimates whether the amount of water necessary for the crop is stored in the root zone or not. It is expressed as the percentage of water needed in the root zone prior to irrigation to that stored in the root zone during irrigation.

**Water stored in the root zone**

**Water storage efficiency = ------------------------------------- X 100**

**Water needed in the root zone**

* **Water Distribution Efficiency:**

Water distribution efficiency is defined as the percentage of difference from unity of the ratio between the average numerical deviations from the average depth stored during the irrigation.

**Water distribution efficiency = {1-Y/d} X 100**

Where,

d = Average depth of precipitation along the run off during irrigation

Y = Average numerical deviation from –d

Water distribution efficiency indicates uniformity in distribution of water over the entire root zone.

* **Water Use Efficiency (WUE):**

Water use efficiency is defined as yield of marketable crop produced per unit of water used in evapotranspiration.

**WUE = Y / ET**

Where,

WUE = Water use efficiency (kg/ha/mm of water)

Y = marketable yield (kg/ha)

ET= Evapotranspiration (mm)

If yield is proportional to ET, water use efficiency has to be constant but it is not so. Actually, Y and ET are influenced independently by crop management and environment. Yield is more influenced by crop management practices, while ET is mainly dependent on climate and soil moisture. Fertilization and other cultural practices for high yield usually increase in water use accompanying fertilization is often negligible. Crop production can be increased by judicious irrigation without markedly increasing ET. Under optimum water supply, ET is not dependent on kind of plant canopy provided the soil is adequately covered with crop.

Increasing the amount of plant canopy has therefore little or no effect on ET. Obviously, any practice that promotes plant growth and more efficient use of sunlight in photosynthesis without causing a corresponding increase in ET will increase WUE.

* **Factors affecting WUE:**

**1. Nature of the plant:** There are considerable between plant species to produce a unit dry matter per unit amount of water used resulting in widely varying values of WUE. There is also difference in WUE between varieties of the same crop. Selection of properly adopted crop, with good rooting habit, low transpiration rates increase.

**2. Climatic Conditions:** Weather affects both Y and ET. Manipulation of climate to any extent is possible at present. However, ET can be reduced by mulching, use of antitranspirant etc. To limited extent, but may not be economical or practical. Weed control is the most effective means of reducing ET losses and increasing the amount of water available to the crop thereby increasing WUE.

**3. Soil Moisture Content:** In adequate supply of soil moisture as well as excess moisture supply to the crop have an adverse effect on plant growth and production and therefore conductive to low WUE. For each crop combination of environment conditions, there is a narrow range of soils moisture level at which WUE is higher than with lesser or greater supply of water, proper scheduling of irrigation will increase WUE.

**4. Fertilizers:** Irrigation improves a greater demand for plant nutrients. Nutrient availability is highest for most of the crops when water tension is low. All available evidences indicate that under adequate irrigation suitable fertilization generally increase yield considerably, with a relatively small increase in ET and therefore, markedly improve WUF.

**5. Plant population:** Higher yield potential made possible by the favorable water regime provided by irrigation, the high soil fertility level resulting from heavy application of fertilizers and genetic potential of new varieties and hybrids, could be achieved only with appropriate adjustments of the population. The highest yields and WUE are possible only through optimum levels of soil moisture regime, plant population and fertilization.

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**Water Deficit and Plant Growth**

**What is plant water stress?**

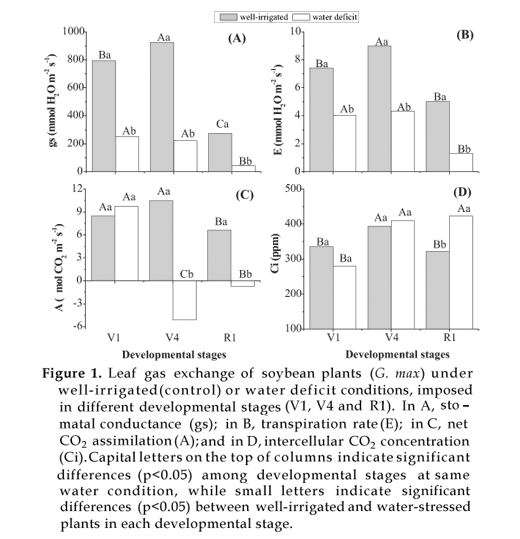
Plant water stress, often times caused by drought, can have major impacts on plant growth and development. When it comes to crops, plant water stress can be the cause of lower yields and possible crop failure. The effects of plant water stress vary between plant species. Early recognition of water stress symptoms can be critical to maintaining the growth of a crop. The most common symptom of plant water stress is wilt. As the plant undergoes water stress, the water pressure inside the leaves decreases and the plant wilts. Drying to a condition of wilt will reduce growth on nearly any plant. From an irrigator's perspective, managing water to minimize stress means knowing plant water availability, recognizing symptoms of water stress, and planning ahead. This article outlines how water stress impacts plant growth and development and how to anticipate plant water stress to minimize negative consequences.

**How does water stress impact plant growth and development?**

Plants take in water through their roots. The amount of force needed for a plant to remove water from the soil is known as the matric potential. When soil moisture is low, plants have to use more energy to remove water from the soil, thus the matric potential is greater. When the soil is dry and the matric potential is strong, plants show symptoms of stress. This is known as the matric effect. Plants can also have difficulties extracting water from the soil if salts are present in the root zone. Generally, when the soil solution is more saline than the plant, more energy is needed to uptake water than if the soil solution is not saline. Plant water stress caused by saline conditions is known as the osmotic effect. Stress from the osmotic effect will cause the same symptoms as stress from the matric effect.

The main consequence of moisture stress is decreased growth and development caused by reduced photosynthesis. Photosynthesis is the process in which plants combine water, carbon dioxide and light to make carbohydrates for energy. Chemical limitations due to reductions in critical photosynthetic components such as water can negatively impact plant growth. Low water availability can also cause physical limitations in plants. Stomates are plant cells that control movement of water, carbon dioxide, and oxygen into and out of the plant. During moisture stress, stomates close to conserve water. This also closes the pathway for the exchange of water, carbon dioxide, and oxygen resulting in decreases in photosynthesis. Leaf growth will be affected by moisture stress more than root growth because roots are more able to compensate for moisture stress.

Water deficiency is a common environmental factor that constrains plants to express their ecophysiological potential, causing short and long term effects in different hierarchical levels, from biochemical to morphological ones, and affecting crop yield. Water deficiency leads invariably to a decrease in photosynthetic rate, although levels of tolerance may vary in different plant species. Among the factors that contribute to this photosynthesis reduction stomatal closure can be considered as a direct response to leaf water potential reduction induced by drought. Stomatal conductance reduction limits CO2 supplying, lowering intercellular CO2 concentration (Ci) consequently constraining net CO2 which decreases plant growth and productivity.



Water deficit induced significant (p<0.05) decreases in leaf gas exchange in all plants at the different developmental stage (Figure 1). Stomatal conductance (gs) was significantly reduced in all developmental stages, mostly R1 which showed gs values lower than in V1 and V4 even in control plants (Figure 1A), indicating a developmental effect on stomatal aperture probably caused by plant growth regulators balance (INCOLL and JEWER, 1987; DAVIES and MANSFIELD, 1987). Similarly, transpiration (E) showed the same response pattern of gs, i.e., water deficit induced significant E reductions in the three developmental stages evaluated. Moreover, plants in R1 stage showed lower E values than plants in V1 or V4 developmental stages regardless water supplying (Figure 1B).

**How can plant water stress be managed?**

Crop selection can be a key component when dealing with or anticipating moisture stress. Generalizations about plant groups and how they behave under moisture stress can be used to guide decisions about crop selection for drought and saline conditions.

**Determinate crops:** Resistant to moisture stress during vegetative stages, determinate crops are grown for harvest of mature seed and include small grains, cereal crops, peas, beans, and oil seed crops. Determinate crops show a linear relationship between water stress and seed production. These crops are most sensitive to stress during seed formation including heading, flowering, and pollination. Each has a minimum threshold growth and water requirement for seed production. This process can be interrupted by stress and generally can't be recovered with removal of the stress.

**Indeterminate crops:** Indeterminate crops include tubers and root crops such as potatoes, carrots, and sugar beets. These crops are relatively insensitive to moisture stress in short intervals (4-5 days) throughout the growing season and have no specific critical periods. If and indeterminate crop is subject to moisture stress, quality will be affected rather than yield. Harvestable yield increases as water use increases. Indeterminate crops are more directly related to climatic demand and cumulative water use during the season than to stress during any particular growth stage.

**Forages:** Forage crops are grown for hay, pasture, and biomass production. In comparison to determinate and indeterminate crops, perennial forages are impacted least by moisture stress. Perennials usually have deep well established roots systems. Forage yields are typically in response to climatic conditions. Forages that have undergone moisture stress will have lower yields than those that have not. Annual forages are an effective way to take advantage of early season moisture and cooler temperatures. In general, as water stress is increased, forage nutritional value is increased, yet overall yield and harvestable protein is decreased.

**How can the consequences of plant water stress be minimized?**

Producers can minimize the consequences of plant water stress by learning how to manage it ahead of time. Water stress timing and crop selection choices can be very important details. If one had to prioritize to deal with moisture stress, the list might look a lot like this:

**Water stress timing**

1st choice - Early in the crop growth cycle

2nd choice - Close to harvest

**Crop selection choices**

1st choice - Perennial forages

2nd choice - Annual forages

3rd choice - Short season indeterminate crops

4th choice - Short season determinate crops

5th choice - Long season determinate crops

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**Drought and Tolerance Mechanisms**

Drought stress is the most common adverse environmental condition that can seriously reduce crop productivity. Increasing crop resistance to drought stress would be the most economical approach to improve agricultural productivity and to reduce agricultural use of fresh water resources. As a result, understanding the mechanisms of drought tolerance and breeding for drought-resistant crop plants has been the major goal of plant biologists and crop breeders. However, drought tolerance is recalcitrant to molecular genetics study mainly due to our limited awareness of specific traits linked to drought tolerance. Furthermore, it is difficult to conduct drought stress treatments in a quantitative and reproducible way. These difficulties have significantly impeded research on plant drought tolerance. Consequently, the biological basis for drought tolerance is still largely unknown and few drought tolerance determinants have been identified.The slow pace in revealing drought tolerance mechanisms has hampered both traditional breeding efforts and use of modern genetics approaches in the improvement of drought tolerance of crop plants.

Despite the lack of understanding of drought tolerance mechanisms, physiological and molecular biological studies have documented several plant responses to drought stress. In particular, drought can result in the closure of stomata and increased biosynthesis of the stress hormone abscisic acid (ABA), as well as the induction of drought- and ABA-responsive genes. In the last decade, molecular and biochemical studies have identified many of these ABA- and stress-responsive genes and a few of the transcription factors responsible for their induction in model plants as well as crop plants. The products of certain stress-responsive genes could function in alleviating stress damage through still unclear mechanisms. Many laboratory studies, as well as a couple of field trials, have shown that transgenic expression of some of these stress-regulated genes, either by overexpressing these target genes directly or by regulating their transcription factors, results in increased tolerance to drought and other stresses. These transgenic approaches are currently the mainstream method to bioengineer drought tolerance in crop plants. Nonetheless, enhanced expression of these genes is frequently associated with retarded growth and thus may limit its practical applications. Clearly, breeding or bioengineering the next generation of drought-tolerant crop plants requires better understanding of the molecular and genetic basis of drought tolerance.

Scarcity of water is a severe environmental constraint to plant productivity. Drought-induced loss in crop yield probably exceeds losses from all other causes, since both the severity and duration of the stress are critical. Here, we have reviewed the effects of drought stress on the growth, phenology, water and nutrient relations, photosynthesis, assimilate partitioning, and respiration in plants. This article also describes the mechanism of drought resistance in plants on a morphological, physiological and molecular basis. Various management strategies have been proposed to cope with drought stress. Drought stress reduces leaf size, stem extension and root proliferation, disturbs plant water relations and reduces water-use efficiency. Plants display a variety of physiological and biochemical responses at cellular and whole-organism levels towards prevailing drought stress, thus making it a complex phenomenon. CO2 assimilation by leaves is reduced mainly by stomatal closure, membrane damage and disturbed activity of various enzymes, especially those of CO2 fixation and adenosine triphosphate synthesis. Enhanced metabolite flux through the photorespiratory pathway increases the oxidative load on the tissues as both processes generate reactive oxygen species. Injury caused by reactive oxygen species to biological macromolecules under drought stress is among the major deterrents to growth. Plants display a range of mechanisms to withstand drought stress. The major mechanisms include curtailed water loss by increased diffusive resistance, enhanced water uptake with prolific and deep root systems and its efficient use, and smaller and succulent leaves to reduce the transpirational loss. Among the nutrients, potassium ions help in osmotic adjustment; silicon increases root endodermal silicification and improves the cell water balance. Low-molecular-weight osmolytes, including glycinebetaine, proline and other amino acids, organic acids, and polyols, are crucial to sustain cellular functions under drought. Plant growth substances such as salicylic acid, auxins, gibberrellins, cytokinin and abscisic acid modulate the plant responses towards drought. Polyamines, citrulline and several enzymes act as antioxidants and reduce the adverse effects of water deficit. At molecular levels several drought-responsive genes and transcription factors have been identified, such as the dehydration-responsive element-binding gene, aquaporin, late embryogenesis abundant proteins and dehydrins. Plant drought tolerance can be managed by adopting strategies such as mass screening and breeding, marker-assisted selection and exogenous application of hormones and osmoprotectants to seed or growing plants, as well as engineering for drought resistance.

**Response of Plants to Drought Stress**

Plants growing in drought stress may have the ability to control / avoid stress by escaping (Enduring Drought) or tolerating stress (by developing succulent or Non-succulent habit). These two capabilities are collectively termed as Drought Tolerance.

**i. Drought Evading Plants:**

These plants remain under dormant / perennation to avoid stress period by seeds and shoots. Such plants complete their life-cycle in few weeks within the rainy season (eg. CO 16 variety of sorghum). They are called as Ephemerals. These plants also prolong their life cycle for some time based on the necessity. They reduce water loss by certain mechanism.



**ii. Succulents:**

These (CAM) plants store enough water in their tissues. Their stomata open at night. They have thick leaves and possess modifications (such as phyllodes and phylloclades) under water stress conditions. They fix carbon during day time with the help of malic acid and CO2, which is released internally during respiration.Succulents-Pineapple.

**iii. Non-succulents:**

These plants endure drought with the following adaptive features:

* Smaller leaves with thick cuticle
* Sunken stomata with hair (pubescence) eg. Nerium
* Shedding their leaves during summer to avoid excess water loss
* Dehydration of protoplasm
* Reducing enzyme activity
* Favouring the syntheses of ABA (stress hormone) and Ethylene (senescence hormone)
* Closing stomata due to increase ABA concentration, thereby reducing water lossNerium

Thus, because of these special features, succulents and non-succulents grow well under drought conditions. They are not or least affected by stress. Similarly, the arid zone plants also develop mechanisms to tolerate water stress, hence they are not adversely affected in terms of growth and yield. But, the non-arid zone plants suffer heavy loss in growth and yield because they do not have above said mechanisms to tolerate the stress.

**iv. Drought Resistant Plants:**

These plants resist the water stress situations due to the following adaptive features / mechanisms. Therefore, these plants can be grown in drought facing / arid-zone areas. Higher rate of photosynthesis because of efficient carboxylating systems (increased activities of RuBPCase, PEPCase, Malic Enzyme etc.)

Store much water for proper hydration of protoplasm

Fix carbon by C4 pathway rather than usual C3

Producing “Aquaporins” – an intrinsic membrane protein in water-stressed plants, which enhance the water flow by 10 – 20 folds (Chrispeels and Maurel, 1994).

**Drought Resistance Mechanism:**

The ability of a crop species or variety to grow and yield satisfactorily in areas subjected to periodic water deficits is termed as drought resistance

Types of drought resistance

**Drought escape:** The ability of a plant to complete the lifecycle before serious soil and plant water deficits develop.

**Drought tolerance with high tissue water potential**: The ability of the plant to endure periods of drought whilst maintaining a high plant water stress. This is also referred to as drought avoidance (Levitt, 1972).

**Drought tolerance with low tissue water potential**: The ability of the plant to endure periods without significant rainfall and to endure low tissue water potential.

**I. Drought Escape:**

Two features of desert ephemerals that are important in drought resistance are

Rapid phonological development

Developmental plasticity.

**1. Rapid phonological developmentearly flowering:** Ability to produce flowers with a minimum of vegetative structure enables them to produce seeds on a limited water supply.

**2. Developmental plasticity:** This feature enable the plants to produce an abundance of vegetative growth, flowers and seeds in seasons of abundant rain, enables the desert ephemerals to both escape drought and survive long periods without rain.

In crop plants, the greatest advance in breeding for water limited environment is achieved by a shortening of life cycle, thereby allowing the crops to escape drought. Therefore, there is a strong consistent negative correlation between grain yield and days to first ear emergence and 40-90% variation in wheat yield under drought condition was accounted for by earliness. In wheat it was observed that drought resistance is greater in early lines than late ones even at the same intensity of drought. However, under adequate water supply, yield is often positively correlated with maturity date in determinate annual crops such as maize, sorghum and sunflower.

An important aspect of developmental plasticity is the ability of plants to transfer assimilates accumulated prior to seed-filling to the grain during the seed filling stage. It was also suggested that when water supply is adequate only a small proportion of grain dry weight comes from the store of prior assimilate in the stems and roots, but when stress occurs in the seed filling stage, an increased proportion of the prior assimilate is transferred to the seed.

To achieve the developmental plasticity, plants frequently have an indeterminate habit. This is an important survival mechanism in that it enables the large amounts of seed produced in wet years to carry the species through prolonged drought periods.

Selection of rapid phonological development is the most rewarding approach in breeding for drought resistance in crops. In cereals, drought resistance varieties of wheat and barley flowered early than the others. However earliness is often negatively correlated with yield in year of adequate rainfall.

**II. Drought Tolerance at High Tissue Water Potential:**

Ability of the plant to endure periods of drought by maintaining high tissue water potential. This mechanism is also called as drought avoidance.

To maintain a high water status during a period of high evaporative demand / or increasing soil water deficit, the plant has two options. It must either reduce the water loss or maintain its supply of water.

**A. Reducing Water Loss:**

1. Increased pubescence and
2. Increased leaf waxiness



**B. Maintenance of water uptake:**

i) Deeper root system

ii) Hydraulic conductance of plants (increasing either the diameter of xylem vessels or their numbers).

**III. Drought Tolerance at low tissue water potential:**

It is the ability of the plant to endure periods of drought and endure low tissue water potentials. This tolerance can be achieved by

1. Maintenance of Turgor
2. Desiccation Tolerance

**Desiccation Tolerance:** Based on the desiccation tolerance of the protoplasm, plants can be classified as poikilohydric or homohydric plants.

**1) Poikilohydric (resurrection plants):** The protoplasm of poikilohydric plants can withstand almost complete dehydration and can also withstand dehydration and rehydration in concert with available water without damage.

**2) Homoiohydric plants:** Majority of the plants are homoiohydric plants. During growth and development, the protoplasm of homoiohydric plants cannot withstand low water potential without injury. Dehydration caused mechanical injury to the protoplast by physical tearing and destruction during water extraction and shrinkage. Small cells with no vacuoles and also the cells that lose their vacuoles and also the cells that lose their vacuoles during dehydration can withstand the most severe desiccation without mechanical injury. The changes in viscosity o the protoplasm and permeability of the membrane play a role in desiccation tolerance. It was also observed that cytoplasmic proteins are more stable to denaturation, coagulation or hydrolysis in desiccation resistant plants and that enzymes are less susceptible to inactivation by stress. RNA-DNA complex through which enzymes are manufactured is generally susceptible to desiccation and sugars play a role in protecting this mechanism in desiccation resistant species and varieties. Sugars may also provide protection against desiccation.

**Biochemical effect of drought tolerance:**

1) Accumulation of Proline, Glycinebetaines etc.

2) Synthisis of Abscisic acid (ABA) etc.

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**Salt and Crop Water Status**

Irrigation water quality can have a profound impact on crop production. All irrigation water contains dissolved mineral salts, but the concentration and composition of the dissolved salts vary depending on the source of the irrigation water. For example, snow melt or water supplies from the Sierra Nevada contain very small amounts of salt whereas groundwater or wastewater typically has higher salt levels. Too much salt can reduce or even prohibit crop production while too little salt can reduce water infiltration, which indirectly affects the crop. An understanding of the quality of water used for irrigation and its potential negative impacts on crop growth is essential to avoid problems and to optimize production.

**Dissolved salts:**

Dissolved salts in irrigation water form ions. The most common salts in irrigation water are table salt (sodium chloride, NaCl), gypsum (calcium sulfate, CaSO4), Epsom salts (magnesium sulfate, MgSO4), and baking soda (sodium bicarbonate, NaHCO3). Salts dissolve in water and form positive ions (cations) and negative ions (anions). The most common cations are calcium (Ca2+), magnesium (Mg2+), and sodium (Na+) while the most common anions are chloride (Cl-), sulfate (SO42-), and bicarbonate (HCO3-). The ratios of these ions, however, vary from one watern supply to another. Potassium (K+), carbonate (CO32-), and nitrate (NO3-) also exist in water supplies, but concentrations of these constituents are comparatively low. In addition, some irrigation waters, particularly from groundwater sources, contain boron at levels that may be detrimental to certain crops. It should be noted that substantial salinization potential is realized through nat- ural weathering and dissolution of soil parent materials, and these salt contributions will attenuate or augment irrigation water ionic constituents.

**The Effect of Salinity on Plant Available Water:**

Salinity has a dual effect on plant growth via an osmotic effect on plant water uptake, and specific ion toxicities. By decreasing the osmotic potential of the soil solution, plant access to soil water is decreased, because of the decrease in total soil water potential. As the soil dries, the concentration of salt in the soil solution increases, further decreasing the osmotic potential. In order to maintain water uptake from a saline soil, plants must osmotically adjust. This is done either by taking up salts and compartmentalizing them within plant tissue, or synthesizing organic solutes. Plants which take up salts generally have a higher salt tolerance and greater ability to store high salt concentrations in plant tissue without affecting cell processes, and are known as halophytes. Plants which synthesize organic solutes are known as glycophytes, and they try to prevent excess salt uptake because they can tolerate much lower concentrations of salt in plant tissues before cell processes are adversely affected. In most cases glycophytes tend to be salt sensitive, although this is not always the case. While these are the two extremes, most plants utilize a combination of these strategies, and differences exist between varieties. Even with complete osmotic adjustment, a reduction in growth may occur due to the metabolic demands of maintaining osmotic adjustment.

While increased uptake of salts may contribute to osmotic adjustment, Na+ and Cl- toxicity may result. A range of symptoms have been described, with chlorosis on the tips of older leaves, developing to necrosis, followed by death of leaves, common across many species.

Accumulation of excess Na+ may cause metabolic disturbances in processes where low Na+ and high K+ or Ca2+ are required for optimum function. A decrease in nitrate reductase activity, inhibition of photosystem II, and chlorophyll breakdown are all associated with increased Na+ concentrations. Cell membrane function may be compromised as a result of Na+ replacing Ca2+, resulting in increased cell leakiness.

**Hazards Associated With Water Quality:**

There are three principal problems that can arise from the quality of irrigation water delivered to the agricultural fields.

* **Salinity hazard:**

This is directly related to the quantity of salts dissolved in the irrigation water. All irrigation water contains potentially injurious salts and nearly all the dissolved salts are left in the soil after the applied water is lost by evaporation from the soil or through transpiration by the plants. Unless the salts are leached from the root zone, sooner or later they will accumulate in quantities which will partially or entirely prevent growth of most crops.

* **Sodicity (alkali) hazard:**

This is another problem often confronting long-term use of certain water for irrigation and relates to the maintenance of adequate soil permeability so that the water can infiltrate and move freely through the soil. The problem develops when irrigation water contains relatively more sodium ions than divalent calcium and magnesium ions while the total concentration of salts is generally not very high. Accumulation of sodium ions on to the exchange complex results in a breakdown of soil aggregates responsible for good soil structure needed for free movement of water and air through the soils. As in the case of sodic soils, accumulation of sodium on the exchange complex can be reduced by applying appropriate quantities of amendments, e.g. gypsum.

* **Toxicity hazard:**

A third problem results from the existence, in some water, of such toxic substances as boron or heavy metals. Boron, though an essential element for plant growth and nutrition, is required only in very small amounts. A high concentration of boron in the irrigation water can have a toxic effect on the growth of many plants. Similarly, certain other ions, e.g. chloride, sodium, etc., could prove toxic to specific crops if present in excessive quantities.There are other factors which could influence the suitability of water for irrigation but one or more of the above factors are of concern in most situations and are discussed below.

* **Salinity problems:**

A salinity problem related to water quality occurs if the total quantity of salts in the irrigation water is such that the salts accumulate in the root zone to the extent that crop yields are adversely affected. The salinity level of an irrigation water can be determined directly by evaporation of a known quantity of water and measuring the residue of dissolved salts that remain. The results are often expressed in parts of salt per million parts of water (mg/l). An indirect and a more common method of determining the salt content of an irrigation water is to measure its electrical conductivity (EC). The greater the conductivity, the greater is its salt content. EC of irrigation water is expressed in deci Siemens per metre at 25 °C (dS/m), superseding the old millimhos per centimetre (mmho/cm). Irrigation water has a wide range of total salinity. Most surface irrigation water, whose source is snow-fed rivers, has a total salinity of less than about 0.5 to 0.6 dS/m. Groundwater in the semi-arid and arid regions has generally higher salinity and may vary from less than one dS/m to more than 12 to 15 dS/m. Sea water is highly saline with an average total soluble salts content of about 35 g/l corresponding to an electrical conductivity of about 50 dS/m. The higher the total salinity of an irrigation water, the higher is its salinity hazard for the crops if the soil and climatic conditions and the cultural practices remain the same. Soil, crop, climatic and cultural factors which promote accumulation of soluble salts in the root zone are inimical to the utilization of high salinity water for irrigation. Similarly, factors that promote leaching of salts from the root zone through periodic leaching favour the utilization of high salinity water for irrigation. Under favourable conditions groundwater with salinity of more than 10 dS/m has been used for the production of semi-tolerant crops like wheat in coarse textured soils (Paliwal, 1972; Manchanda, 1976) with only slight yield reductions. On the other hand unfavourable soil and climatic conditions and/or poor management have resulted in serious salinity problems even with the use of water of as low salinity as 0.4 to 0.5 dS/m. Ayers and Westcot (1985) reviewed the existing information on the subject and developed practical guidelines for evaluating water quality for irrigation. These guidelines, reproduced in Table 43, are intended to be of help for preliminary evaluation of the suitability of a water supply for irrigation. In arriving at these guidelines the authors made certain basic assumptions which must be kept in view while evaluating any irrigation water for its suitability. These assumptions are:

**Yield Potential**: Full production capability of all crops, without the use of special practices, is assumed when the guidelines indicate no restrictions on use. A ‘restriction on use’ indicates that there may be a limitation in choice of crop, or special management may be needed to maintain full production capability. A ‘restriction on use’ does not indicate that the water is unsuitable for use.

**Site Conditions:** Soil texture ranges from sandy loam to clay loam with good internal drainage. There is no uncontrolled shallow water table present within 2 metres of the surface. The climate is semi-arid to arid and rainfall is low. Rainfall does not play a significant role in meeting crop water demand or leaching requirement. (However, in a monsoon climate or in areas where precipitation is high for part or all of the year, infiltrated water from rainfall is effective in meeting all or part of the leaching requirement; in these cases, the restrictions are less severe.)

**Methods and Timing of Irrigations:** Normal surface or sprinkler irrigation methods are used. Water is applied infrequently, as needed, and the crop utilizes a considerable portion of the available stored soil-water (50 percent or more) before the next irrigation. At least 15 percent of the applied water percolates below the root zone (leaching fraction [LF] ³15 percent). The guidelines are too restrictive for specialized irrigation methods, such as localized drip irrigation, which results in near daily or frequent irrigations, but are applicable for subsurface irrigation if surface applied leaching satisfies the leaching requirements.

**Water Uptake by Crops**: Different crops have different water uptake patterns, but all take water from wherever it is most readily available within the rooting depth. On average about 40 percent is assumed to be taken from the upper quarter of the rooting depth, 30 percent from the second quarter, 20 percent from the third quarter, and 10 percent from the lowest quarter. Each irrigation leaches the upper root zone and maintains it at a relatively low salinity. Salinity increases with depth and is greatest in the lower part of the root zone. The average salinity of the soil-water is three times that of the applied water and is representative of the average root zone salinity to which the crop responds. These conditions result from a leaching fraction of 15-20 percent and irrigations that are timed to keep the crop adequately watered at all times.

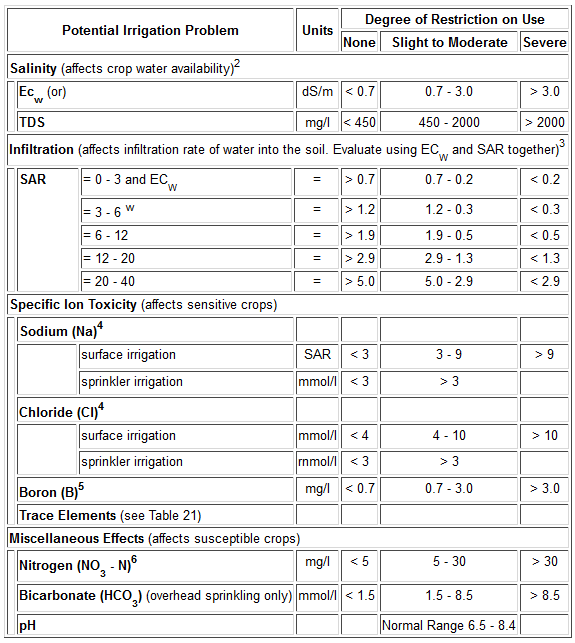
Salts leached from the upper root zone accumulate to some extent in the lower part but a salt balance is achieved as salts are moved below the root zone by sufficient leaching. The higher salinity in the lower root zone becomes less important if adequate moisture is maintained in the upper, ‘more active’ part of the root zone and long-term leaching is accomplished.

**Restriction on Use:** The ‘Restriction on Use’ shown in Table is divided into three degrees of severity: none, slight to moderate, and severe. The divisions are somewhat arbitrary since change occurs gradually and there is no clear-cut breaking point. A change of 10 to 20 percent above or below a guideline value has little significance if considered in proper perspective with other factors affecting yield. Field studies, research trials and observations have led to these divisions, but management skill of the water user can alter them. Values shown are applicable under normal field conditions prevailing in most irrigated areas in the arid and semi-arid regions of the world.

Ordinarily no soil or cropping problem due to water quality would be experienced or recognized when using water containing less than the values shown for no restriction on use in Table. On the other hand, if water is used which exceeds the values shown for the ‘severe’ restriction on use, the user will probably experience soil or cropping problems. With water quality values between these guides, a gradually increasing restriction on use is likely to be experienced as the water quality deteriorates. Specific conditions that may warrant a modification in the suggested values include the leaching fraction, the conditions of drainage, method of irrigation, the climate including rainfall, physical soil conditions, tolerance of crops shown to salinity and the chemical soil characteristics.

Several workers have proposed classifications in respect of water quality to suit local soil and environmental conditions. It was suggested guidelines for Indian conditions where invariably a rainfall of 300 to 400 mm or more is received in the monsoon season which leaches down the salts accumulated in the preceding cropping season.

Table: Guidelines for interpretation of mater quality for irrigation



2. ECW means electrical conductivity, a measure of the water salinity, reported in deci Siemens per metre at 25°C (dS/m) formerly millimhos per centimetre (mmho/cm).

3. SAR means sodium adsorption ratio. SAR is sometimes reported by the symbol RNa. At a given SAR, infiltration rate increases as water salinity increases.

4. For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride, while most annual crops are not sensitive.

5. For boron tolerances.

6. NO3 -N means nitrate nitrogen reported in terms of elemental nitrogen (NH4 -N and Organic-N should be included when wastewater is being tested).

**Management practices for efficient use of high salinity water:**

It would thus seem that there can be very wide variations in the permissible limits of salinity levels of water for irrigation. For this reason any rigid generalizations may prove disadvantageous for field level workers and there is need to develop guidelines for each major area having similar soil, climatic and agricultural conditions. More important however is our ability to use a water of a particular salinity level under a given set of conditions. Management practices can often be modified to obtain a more favorable distribution of salts in the profile and therefore better crop yields, water quality remaining the same. Management practices that can help to overcome a high salinity problem of the irrigation water are discussed below. Desalinization of water to remove soluble salts has often been referred to as a technical possibility but at the present stage of available technologies it is doubtful if this method can have any large-scale application in the utilization of saline water for irrigation of most agricultural crops, at least in the near future.

* **More frequent irrigation:**

The adverse effects of the high salinity of irrigation water on the crops can be minimized by irrigating them frequently. More frequent irrigations maintain higher soil water contents in the upper parts of the root zone while reducing the concentration of soluble salts. Both these factors result in reduced effect of high salts on the availability of water to plants and therefore promote better crop growth. The sprinkler method of irrigation is generally more amenable to increased frequency of water applications. In surface irrigation methods however, more frequent irrigations almost invariably result in an appreciable increase in water use.

* **Selection of salt tolerant crops and varieties:**

As indicated in previous sections, there is a wide range in the relative tolerance of agricultural crops to soil salinity. Proper choice of crops can result in good returns even when using high salinity water, whereas use of such water for growing a relatively salt-sensitive crop may be questionable. Similarly, selection and breeding of salt-resistant crop varieties offer tremendous possibilities of utilizing saline water resources for crop production. Some workers have suggested induction of salt tolerance by soaking seeds for a certain period in salt solutions as a method for obtaining increased yields in saline water irrigated soils, while others suggest that growing seeds obtained from parents that have been irrigated with saline water helps in obtaining higher crop yields. These suggestions, however, have not been tested extensively on a field scale.

* **Use of extra water for leaching:**

To prevent excessive salt accumulation in the soil, it is necessary to remove salts periodically by application of water in excess of the consumptive use. The excess water applied will remove salts from the root zone provided the soil has adequate internal drainage. This concept (Richards, 1954) is quantified in the term ‘leaching requirement’ often referred to by the abbreviation, LR. By definition, leaching requirement (LR) is the fraction of total water applied that must drain below the root zone to restrict salinity to a specified level according to the level of tolerance of the crop.

* **Conjunctive use of fresh and saline waters:**

There are situations where good quality water is available for irrigation but not in adequate quantities to meet the evapotranspirational needs of crops. Under these conditions, the strategies for obtaining maximum crop production could include mixing of high salinity water with good quality water to obtain irrigation water of medium salinity for use throughout the cropping season. Alternatively, good quality water could be used for irrigation at the more critical stages of growth, e.g. germination, and the saline water at the stages where the crop has relatively more tolerance. Further research is needed to define the best options considering the tolerance of crops at different growth stages, critical stages of growth vis-a-vis soil salinity, etc.

* **Cultural practices:**

Cultural practices can often be modified to reduce the hazard of high salts in the irrigation water. Similarly a modification in the method of irrigation can result in improved use of water for some crops. These aspects have been discussed earlier.

**The sodicity (alkali) problem:**

1. Role of magnesium
2. Management practices for efficient use of water with sodicity hazard

Prolonged use of certain irrigation water results in reduced crop yields due to deterioration in the soil physical properties. The adverse effect of irrigation water quality on soil physical properties is associated with the accumulation of sodium ion on the soil exchange complex which imparts instability to the soil aggregates and whose disruption followed by dispersion of clay particles results in clogging of soil pores.

* **Role of magnesium:**

In recent years research efforts have been made to define precisely the relative role of magnesium ions vis-a-vis monovalent sodium and divalent calcium ions in influencing soil properties and therefore in developing appropriate modifications in the criteria for quality rating of water with a high proportion of magnesium ions.

* **Management practices for efficient use of water with sodicity hazard:**

As in the case of irrigation water with a salinity hazard, appropriate management practices can often help in better and more efficient use of water with a high sodicity hazard. These practices include:

**i.** Application of amendments Since accumulation of the sodium ion on the exchange complex is mainly responsible for poor soil physical properties, irrigation water having a sodicity hazard could be improved by increasing the soluble calcium status of the water, thereby decreasing the proportion of sodium to the divalent cations and therefore its adsorption on the soil exchange complex. Applied soluble calcium salts will also neutralize the bicarbonate and carbonate ions thereby reducing the sodicity hazard of the water.

**ii.** Mixing with an alternate source of water If an alternate source of irrigation water is available, mixing the two sources may be helpful in obtaining water which is acceptable for irrigation considering its sodicity hazard. Detailed chemical analysis and the quantities in which the water is available from the two sources can help in deciding the proportions in which they need to be mixed.

**iii.** Irrigating more frequently Irrigating frequently with small quantities of water is an effective way to manage water with a sodicity hazard. Reduced permeability of the soils restricts water supply to the roots. Also applying large amounts at a time can result in surface stagnation which affects most crops adversely. Frequent irrigations could also reduce the precipitation of calcium by reaction with bicarbonates in water by keeping the soils wet. Using sprinkler irrigation with the ability to supply controlled amounts of water at a time should be considered where feasible.

**iv.** Growing crops with low water requirements When the irrigation water tends to create a sodicity problem, it is advisable to use small quantities of water, waters with significant quantities of residual sodium carbonate (RSC) will cause a continuous increase in the exchangeable sodium status of soils and therefore the need to limit water use. Unlike saline water, where application over and above the evapotranspiration requirements is recommended, extra application of water with a sodicity hazard will further aggravate the problem. If feasible, growing crops and irrigating during periods of high evapotranspiration demands should be avoided.

**v.** Growing tolerant crops Growing crops tolerant of excess exchangeable sodium and poor soil physical conditions will help obtain better returns than if sensitive crops are grown.

**vi.** Organic matter applications Heavy dressings of organic manures, regular incorporation of crop residues, application of such organic materials as rice hulls, sawdust, sugar factory wastes, etc., have all been found useful in maintaining and improving soil physical properties and in counteracting the adverse effect of high levels of exchangeable sodium. Wherever feasible therefore, organic matter applications are especially recommended if irrigation water has a sodicity hazard.

**The toxicity problem:**

Apart from the salinity or the sodicity hazard, the constituents of much irrigation water may cause toxicity problems when taken up by the plants in excess amounts. The toxic constituents of major concern are sodium, chloride and boron. Fruit trees, vines and woody ornamentals are especially sensitive to sodium and chloride ions. Most annual crops are not so sensitive but may be affected by higher concentrations. Sodium and chloride ions are freely taken up by the plants and become concentrated as water is lost through transpiration. Toxicity results when the concentration of these elements exceeds the tolerance limits of the plants. ‘Leaf burn’ scorch, and dead tissue along the outside edges of leaves are typical symptoms of sodium toxicity which first occur in the oldest leaves, usually appearing as a burn or drying of tissue at the outer edges of the leaf. As the severity increases, the drying progresses towards the leaf centre until the entire tissue is dead. Injury due to chloride toxicity however, typically, starts at the extreme leaf tip of older leaves and progresses from the tip back as the severity increases.

Other constituents of some irrigation water, such as lithium, selenium, molybdenum, fluoride and chromium may have deleterious effects on plants or animals even at very low concentration; however their occurrence in irrigation water has only very occasionally been reported.

**Management practices:**

Field practices that can eliminate or reduce the hazard due to presence of toxic elements include irrigating the crops more frequently. Frequent irrigations reduce the effective concentration of toxic constituents and therefore their adverse effect. Occasional application of excess water to leach the salts will further reduce the amounts of toxic elements in the root zone. Accumulation of sodium in plant parts can usually be reduced by maintaining a favourable concentration of calcium ions in the soil solution. Adequate quantities of calcium in the irrigation water and soil solution prevent excessive uptake of sodium by plants. Application of amendments, such as soluble calcium salts or sulphuric acid, can therefore greatly reduce the toxicity hazard due to excess sodium. Blending of water supplies, planting less sensitive crops, improving drainage conditions through profile modification, use of fertilizers in optimum doses to obtain otherwise vigorously growing plants etc. are some of the other practices that will help overcome toxicity problems.

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**Measurement of Water Status in Soil and Plant**

A variety of methods and devices can be used to measure soil-water. These include the feel method, gravitational method, tensiometer, electrical resistance blocks, neutron probe, Phene cells, and time domain reflectometer. Most of these methods and devices do not measure soil-water directly; they measure a property of the soil that can be related to soil-water status and are therefore called indirect methods. These methods differ in their ease of use, reliability, cost, and amount of labor required.

* **Feel Method:**

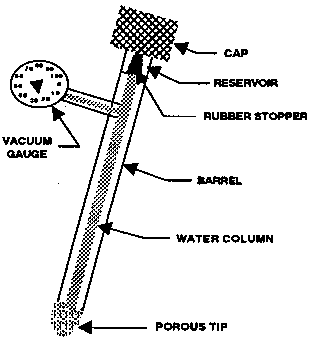
As its name implies, the feel method involves estimating soil-water by feeling the soil. This method is easy to use, and many growers schedule irrigation in this way. However, this method is entirely subjective; the results depend on the experience of the individual making the measurement. The reliability of this method is usually poor unless the operator is very experienced. The feel method is not generally recommended and should be used only as a last resort.

* **Gravimetric Method:**

With the gravimetric method, soil moisture is determined by taking a soil sample from the desired soil depth, weighing it, drying it in an oven (for 24 hours at 220 degrees F), and then reweighing the dry sample to determine how much water was lost. This method is simple and reliable. Unfortunately, it is not practical for scheduling irrigation because it takes a full day to dry the sample. In a sandy soil that dries quickly, irrigation may be needed before the results of the measurement are obtained. The gravimetric method is most useful for calibrating other devices for measuring soil-water.

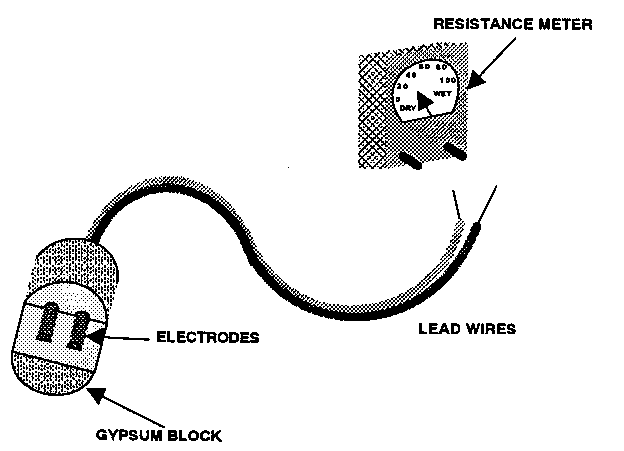
* **Tensiometer:**

A tensiometer is a sealed, airtight, water-filled tube (barrel) with a porous tip on one end and a vacuum gauge on the other, as shown in Figure 1. A tensiometer measures soil water suction (negative pressure), which is usually expressed as tension. This suction is equivalent to the force or energy that a plant must exert to extract water from the soil. The instrument must be installed properly so that the porous tip is in good contact with the soil, ensuring that the soil-water suction is in equilibrium with the water suction in the tip. The suction force in the porous tip is transmitted through the water column inside the tube and displayed as a tension reading on the vacuum gauge. Soil-water tension is commonly expressed in units of bars or centibars. One bar is equal to 100 centibars (cb).

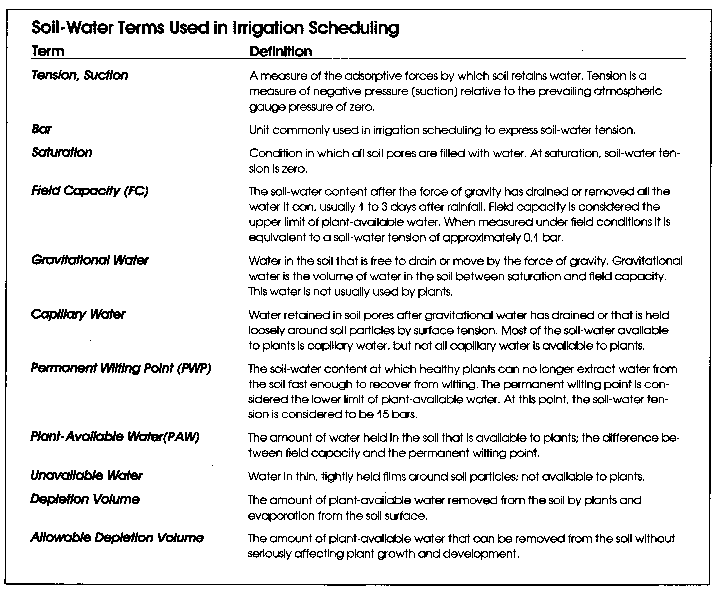


Electrical Resistance Blocks:

Electrical resistance blocks consist of two electrodes enclosed in a block of porous material, as shown in Figure 2. The block is often made of gypsum, although fiberglass or nylon is sometimes used. Electrical resistance blocks are often referred to as gypsum blocks and sometimes just moisture blocks. The electrodes are connected to insulated lead wires that extend upward to the soil surface. Resistance blocks work on the principle that water conducts electricity. When properly installed, the water suction of the porous block is in equilibrium with the soil-water suction of the surrounding soil. As the soil moisture changes, the water content of the porous block also changes. The electrical resistance between the two electrodes increases as the water content of the porous block decreases. The block's resistance can be related to the water content of the soil by a calibration curve. To make a soil-water reading, the lead wires are connected to a resistance meter containing a voltage source. The meter normally reads from 0 to 100 or 0 to 200. High readings on the scale (corresponding to low electrical resistance) indicate high levels of soil-water, whereas low meter readings indicate low levels. Because of the pore size of the material used in most electrical resistance blocks, particularly those made of gypsum, the water content and thus the electrical resistance of the block does not change dramatically at suctions less than 0.5 bar (50 cb). Therefore, resistance blocks are best suited for use in fine-textured soils such as silts and clays that retain at least 50 percent of their plant-available water at suctions greater than 0.5 bar. Electrical resistance blocks are not reliable for determining when to irrigate sandy soils where over 50 percent of the plant-available water is usually depleted at suctions less than 0.5 bar. Methods for preparing and installing electrical resistance blocks are discussed in a later section



Schematic of an electrical resistance block and meter. The block is buried in the soil at one-half the effective root depth. With the proper calibration curve, the meter reading can be related to soil moisture



* **Neutron Probe:**

The neutron probe uses a radiation source to measure soil-water. An empty tube (access tube) with a 2-inch inside diameter must be installed vertically in the soil at each field location where the soil-water is to be measured. When properly calibrated, the neutron probe is easy to use, reliable, and accurate, but it is expensive ($3,000 to $4,000 per unit). One of its advantages is that soil-water measurements can be made easily at different depths in the soil profile. Because of its cost, a neutron probe is not as practical as other methods for on-farm use. It may be a viable option for operators with large acreages of irrigated land. At present, it is used by some irrigation consultants to perform the technical tasks required to schedule irrigation.

* **Phene Cell:**

The Phene cell works on the principle that a soil conducts heat in relation to its water content. By measuring the heat conducted from a heat source and calibrating the conductance versus water content for a specific soil, the Phene cell can be used reliably to determine soil-water content. Because the Phene cell is placed at the desired soil depth, a separate cell is needed for each depth at each location to be monitored. A cell costs about $100, and the instrument required to measure the heat dissipation costs an additional $1,000. For irrigating small acreages, the total cost of using the Phene cell is less than that of the neutron probe. For large acreages, the neutron probe may be more cost effective.

* **Time Domain Reflectometer:**

The time domain reflectometer (TDR) is a new device developed to measure soil-water content. Two parallel rods or stiff wires are inserted into the soil to the depth at which the average water content is desired. The rods are connected to an instrument that sends an electromagnetic pulse (or wave) of energy along the rods. The rate at which the wave of energy is conducted into the soil and reflected back to the soil surface is directly related to the average water content of the soil. One instrument can be used for hundreds of pairs of rods. This device, just becoming commercially available, is easy to use and reliable.

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