Evapotranspiration

Evaporation (E) of water is a diffusive process by which liquid water in the form of vapour is lost to the atmosphere. Two essential requirements for evaporation are: (i) A source of heat to transform liquid water into water vapour. Solar radiation is the principal source of energy (590 cal g⁻¹ of water at 20°C).

(ii) Concentration gradient between evaporating surface and surrounding air.

The climatological parameters for assessing evaporation are- solar radiation, air temperature, air humidity and wind speed.

Datton’s law of evaporation

Evaporation (E) = (es - ea) f (u)

Where es = Saturation vapour pressure of water

Ea = Actual vapour pressure of air above

f (u) = function of wind velocity

Evaporation measurements are usually made by piche evaporimeter, atmometer and pan evaporimeter. The standard US Weather Bureau (USWB) class A Pan is the most widely used evaporation pan. It is 122 cm in dia and 25 cm in depth, made up of 22 gauge galvanized iron. Painted white and installed on a wooden frame. Water is filled to a depth of 20 cm, water level is daily measured with a hook gauge in a stilling well. Evaporation is computed as the differences between observed levels, adjusted for any precipitation measured in a rain gauge. Water is added daily to bring the level to a fixed point in the stilling well. The pans have higher rate of evaporation than a large free water surface. Thus a factor of 0.7 is, usually used for converting the observed evaporation to those of large water surface area. This factor is called Pan Coefficient.
Evaporation from land surface is affected by degree of soil saturation, temperature of soil and air, humidity and wind velocity.

**Transpiration (T):** Loss of water in the form of vapour from the plant canopy to the atmosphere is termed as transpiration.

**Evapotranspiration:** The total loss of water from soil surface through evaporation and that as water vapour from plant surface through transpiration, in together refers to evapotranspiration. It has direct correlation with crop yield. Evaporation rate is normally expressed in millimeters (mm) per unit time.

As one hectare = 10000 m$^2$

One mm = 0.001 m

Loss of 1 mm of water = 10 m$^3$ water ha$^{-1}$

Thus 1 mm ET/day = 10 m$^3$ ha$^{-1}$ day$^{-1}$

Energy or heat required to vapourise free water, known as latent heat of vapourisation ($\lambda$), is a function of the water temperature. At 20°C, $\lambda$ is about 2.45 MJ kg$^{-1}$; means 2.45 MJ are needed to vapourise 1 kg or 0.001 m$^3$ of water. Hence, an energy input of 2.45 MJ per m$^2$ is able to vapourise 0.001 m or 1 mm of water. Therefore, 1 mm water = 2.45 MJ m$^{-2}$ Evapotranspiration rate expressed in units of MJ m$^{-2}$ day$^{-1}$ is represented by ET, the latent heat flux.

**Conversion factors for ET**

<table>
<thead>
<tr>
<th>Expression</th>
<th>Depth mm day$^{-1}$</th>
<th>Volume per unit area m$^3$ ha$^{-1}$ day$^{-1}$</th>
<th>1 s$^{-1}$ ha$^{-1}$</th>
<th>Energy per unit area MJ m$^{-2}$ day$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm day$^{-1}$</td>
<td>1</td>
<td>10</td>
<td>0.116</td>
<td>2.45</td>
</tr>
<tr>
<td>1 m$^3$ ha$^{-1}$ day</td>
<td>0.1</td>
<td>1</td>
<td>0.012</td>
<td>0.245</td>
</tr>
<tr>
<td>1 l s$^{-1}$ ha$^{-1}$</td>
<td>8.640</td>
<td>86.40</td>
<td>1</td>
<td>21.17</td>
</tr>
<tr>
<td>1 MJ m$^{-2}$ day$^{-1}$</td>
<td>0.408</td>
<td>4.082</td>
<td>0.047</td>
<td>1</td>
</tr>
</tbody>
</table>
Factors affecting evapotranspiration

A. weather/climatic parameters
1. Air temperature
2. Solar radiation
3. Relative humidity
4. Wind velocity
5. Precipitation

B. Crop characteristics
1. Stomata number and size
2. Stomatal opening and closing
3. Canopy cover
4. Adaptive mechanism
5. Rooting characteristics
6. Length of crop growing season

C. Management and environment factors
1. Tillage
2. Irrigation schedule
3. Fertilizers
4. Plant protection
5. Weed management
6. Wind breaks
7. Salinity
8. Antitranspirants
9. Ground water level.

Evapotranspiration and crop yield relationship
Water use-yield relationship – Under adequate water supply the ET is expected to be maximum for realizing potential crop yield, provided other management practices are optimal. Relative yield is the proportion of actual yield (Ya) to the
maximum yield \((Y_m)\), can be expressed as percentage or as a function by subtracting by one. \((1 - \frac{Y_a}{Y_m})\). Similarly, relative ET can be expressed as \(1 - \frac{E_{ta}}{E_{Tm}}\). Thus, the relationship equation can be as-

\[
1 - \frac{E_{Ta}}{E_{Tm}} = K_y \left(1 - \frac{Y_a}{Y_m}\right)
\]

Where \(K_y\) is a constant which is the yield response factor and can be estimated if the ET and yield data are available.

**Evapotranspiration and consumptive use:**

Evapotranspiration (ET) = Evaporation from crop field \((E)\) + Transpiration \((T)\) + intercepted precipitation by crop and lost as evaporation \((IP)\)

Consumptive use \((CU)\) = E.T. + water used by crop plants for metabolic activities \((W_w)\). It is nearly 1%

**Evapotranspiration concepts**

Potential Evapotranspiration \((PET)\) is the highest rate of evapotranspiration by a short and actively growing crop with abundant foliages completely shading the ground surface with abundant soil water supply under a given climate. This refers to the maximum water loss from the crop field.

Reference crop evapotranspiration \((E_{T0})\)- Evapotransiration rate from a reference surface, not short of water is called the reference crop evapo-transpiration. Reference surface is a hypothetical grass reference crop with specific characteristics. The redefined (FAO Penman-Monteith ) crop evapotranspiration (Allen et al. 1998) is: ‘Evapotranspiration from a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 sm\(^{-1}\) and the albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered.
Actual crop evapotranspiration (ET crop) refers to the rate of evapotranspiration by a particular crop in a given period under prevailing soil water and atmospheric conditions. Crop evapotranspiration under standard condition is the evapotranspiration from a well maintained crop, grown in large fields, under optimum soil moisture condition and able to give maximum production under given climatic condition.

To find the ET crop the following relationship is used

$$ETc = ETo \times Kc$$

$Kc = \text{Crop coefficient}$

$$Kc = \frac{ETc}{ETo}$$

Crop evaporation under non-standard condition ($ETc_{adj}$) is the evapotranspiration from crops grown under management and environmental condition that differ from standard condition.

$ETc_{adj}$ is calculated by using a water stress coefficient $Ks$ and /or by adjusting crop coefficient $Kc$ for other stresses and environmental constraints.

The effects of soil water stress are described by multiplying the basal crop coefficient $Kcb$ by the water stress coefficient $Ks$:

$$ETc_{adj} = (Ks \ Kcb + Kc) \ ETo$$

**Measurement of Evapotranspiration**

1. Energy balance and microclimatological methods.
2. Soil water balance
3. Lysimeters
4. Empirical methods (from meteorological data).
1. **Energy balance and microclimatological methods**

Evaparation of water requires energy in the form of sensible heat or radiant energy. Therefore, the evapotranspiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available.

\[
Rn - G - \lambda Et - H = 0
\]

Where \( Rn \) = net radiation, \( H \) = Sensible heat, 
\( G \) = Soil heat flux, \( \lambda ET \) = Latent heat flux,

Latent heat flux (\( \lambda ET \)) representing the evapotranspiration fraction can be derived from the ‘energy balance equation’ if all other components are known.‘Rn’ and ‘G’ can be estimated from climatic parameters. Measurement of ‘H’ is complex and requires accurate temperature gradients above the surface.

2. **Soil water balance**: It is an account of all quantities of water added, removed or stored in soil during a given period of time.

Change in soil water = Inputs of water – Losses of water

**Water Inputs** = \( P + I + C \)

Where, \( P \) = Precipitation, \( I \) = irrigation
\( C \) = Contribution from ground water.

**Losses of water** = \( ET + D + RO \)

Where \( ET \) = Evapotranspiration, \( D \) = Deep drainage \( RO \) = Surface runoff.

Thus, **Change in soil water** = \( (P + I + C) - (ET + D + RO) \). Suppose, the amount of water in root zone at the beginning is \( M_1 \) and at the end of period is \( M_2 \).

Then, \( M_1 - M_2 = P + I + C - ET - D - RO \)

Or \( M_1 + P + I + C = ET + D + RO + M_2 \)

Using this equation any unknown parameter can be computed, if all others are known. This is useful for selecting appropriate water management strategies.

3. **Lysimeters**: Lysimeters provide the direct measurement of water flux from vegetative surface. Lysimeter is a large tank filled with soil. Rectangular units of 4.0
m² are satisfactory for most crops. Total depth ranges between 100-150 cm as per root depth of crops. In general, 50% available soil moisture depletion in root zone should not be exceeded. The crop grown in lysimeter is the same as in surrounding area.

There are two types of lysimeters, weighing and drainage type. In the drainage type, the inflows and drainage are measured, but changes in storage within soil are not measured. In weighing type lysimeters each element i.e. rainfall, irrigation, runoff and ET can be determined by using water balance equation.

\[
\text{ET} = \text{Weight change} + \text{water added} - \text{percolation}
\]

4. **Empirical methods:** Empirical methods to predict the water requirements are primarily based on climatological data and crop factors. There are four methods of predicting ET under different climatic conditions, recommended by FAO group of Scientists (Doorenbos and Pruitt, 1975)

1. Blaney-Criddle method
2. Radiation method
3. Modified penman method
4. Pan evaporation method

Three major steps involved in estimation of ET by empirical methods are

1. Estimation of reference evapotranspiration (ET₀)
2. Determination of crop coefficients (Kc)
3. Making adjustments to location specific environments

Modified Penman and radiation methods offer best results for periods as short as 10 days followed by pan evaporation method. Blaney-criddle method is ideal for periods of one month or more in many climates.
**Blaney-criddle Formula:** Blaney- Criddle (1950) formula is based on mean monthly temperature, daylight hours and locally developed crop coefficients

\[ U (CU) = u = KF = kf = \frac{ktp}{100} \]

Where,

- **U or CU** = Seasonal consumptive use
- **u** = monthly consumptive use
- **t** = Mean monthly temperature (°F)
- **p** = Monthly daylight hours expressed as percentage of daylight hours of the year.
- **f** = \( t \times p/100 \), monthly consumptive use factor
- **k** = empirical consumptive use crop coefficient, for the month (= \( u/f \))

Doorenbos and Pruitt (1975) recommended following relationships for ‘f’ in this formula

\[ f = p \times (0.46 \times t + 8.13) \text{, using } t \text{ in } ^\circ \text{C} \]

Or

\[ f = 25.4 \times (p \times t) / 100 \text{, using } t \text{ in } ^\circ \text{F} \]

Thus, finally it become

\[ ET_0 = C [p \times (0.46 \times t + 8.13)] \]

Where, \( ET_0 = \) reference ET (mm day\(^{-1}\)) for the month

- **C** = adjustment factor depending on RHmin, daytime wind velocity and ratio of actual sunshine h to maximum possible sunshine hour.
- **T** = mean daily temperature for the month.
- **P** = mean daily percentage of total annual daytime.
**Radiation method**: This method requires direct measurement of bright sunshine hours, general levels of humidity and wind velocity.

\[ ET_0 = C \times (W \times \text{Rs}) \]

Where, \( \text{Rs} = \) Measured mean incoming shortwave radiation (mm day\(^{-1}\)) – (by pyrenometer) or obtained from \( \text{Rs} = (0.25+0.50 \times \frac{n}{N}) \times \text{Ra} \). Where \( \text{Ra} \) is extraterrestrial radiation (mm day\(^{-1}\)), \( N \) = maximum possible sunshine duration (h day\(^{-1}\)), \( n \) = measured mean actual sunshine duration (h day\(^{-1}\)), \( W \) = Temperature and altitude dependent weighing factor

\( C \) = Adjustment factor made graphically on \( W \). \( \text{Rs} \) using estimated values of R H mean and U daytime.

**Pan evaporation method**: Evaporation from pans provides measurement of integrated effect of radiation, wind, temperature and humidity on evaporation from open water surface. To relate pan evaporation to \( ET_0 \), empirically derived Pan coefficients are suggested to account for climate, type of Pan and Pan environments

\[ ET_0 = K_{\text{pan}} \times E_{\text{pan}} \]

Where, \( E_{\text{pan}} \) = evaporation (mm day) from class A Pan

\( K_{\text{pan}} \) = Pan coefficient.

**Modified Penman method**: It gives fairly satisfactory results for predicting the effect of climate on \( ET_0 \) as it utilises almost all the meteorological Parameters associated with ET.

\[ ET_0 = C \times [W \times R_n + (1- W) \times f(u) \times (e_a - e_d)] \]

\( R_n \) = Net radiation (mm day\(^{-1}\))

or \( R_n = 7.5 \times \text{Rs} - \text{Rnl} \)

\( \text{Rs} \) = Short wave radiation (given earlier)
Rn1 = net long wave radiation (mm day\(^{-1}\)) a function of temperature f (T), of actual vapour pressure f (ed) and sunshine duration f (n/N) or Rnl= f (T) x f (ed).

\(e_{a} - ed\) = Vapour pressure deficit, the difference between saturation vapour pressure (ea) at T mean (mb) and actual vapour pressure (ed)

\(f(U)\) = wind function or \(f(U) = 0.27 (1 - U/100)\) with U in Km day\(^{-1}\) at 2 m ht.

W = Temperature and altitude dependent weighting factor.

C = Adjustment factor for the ratio U day/U night for RH max and for Rs.

**Crop coefficients for estimating ET crop**

The conditions that affect crop water loss (ET\(_C\)) will also affect evaporation from free water surface in a similar manner. It is then necessary to obtain a crop coefficient (Kc) to estimate ETc.

\[ETc = ETo \times Kc\]

Actual crop water requirements, in addition to climate, include the effect of crop characteristics and management practices. Crop coefficient is used to account for all these variations. The climatic data required for selection of crop coefficients are wind speed and humidity. The FAO kc curve is constructed by dividing crop growing period into four growing periods and placing straight line segments through initial and mid season periods being horizontal. The four growth periods are initial period, crop development, mid season and late season. However, FAO coefficients (kc) for major crops (Doorenbas and kassam, 1979) are available for use.
CROPWAT : FAO IDP 46 and 49

CROPWAT is a water balance based computer programme to calculate crop water requirements and irrigation water requirements from climatic and crop data. The programme also allows the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying cropping patterns. Water balance procedures also allow an assessment of effective rainfall and an evaluation of rainfed production through calculated yield decreases through water balance procedures. This also allows yield reduction predictions to be made and taken into account in making irrigation management decisions to optimize crop water productivity and return to investment.

Soil Plant and Meteorological factors determining Water needs of crops
**Water requirement (WR):** Water requirement of crop is the quantity of water, required by a crop or diversified pattern in a given period of time for their normal growth under field conditions. It includes ET and other economically unavoidable losses.

**Consumptive use (CU):** It is the sum of the volumes of water used by crop over a given area in producing plant tissue, in transpiration (T), and that evaporated (E) form adjacent soil or plant foliage. Since the volume used in producing plant tissue is negligible (≤ 1%), CU can be approximately equal to ET.

\[
WR = CU = ET
\]

Since water requirement also include the unavoidable application losses eg. Percolation, seepage, runoff etc. (AL) and water used for special operations (WSO) like land preparation, presowing irrigation etc, it is expressed as -

\[
WR = ET + AL + WSO
\]

In terms of source of water it is expressed as -

\[
WR = IR + EP + S
\]

Where, \( IR \) = Irrigation requirement

\[
EP = \text{Effective precipitation}
\]

\[
S = \text{Soil profile moisture contribution}
\]

**Irrigation requirement (IR):** The total amount of water required to supplement precipitation (EP) and soil moisture contribution (S) to meet crop water needs for optimum growth and yield.

\[
IR = WR - (EP + S)
\]
**Net irrigation requirement**: It is the depth of irrigation water exclusive of precipitation and ground water contribution or other gains in soil moisture, that is required for plant growth; the amount of irrigation water required to bring the soil moisture level in the effective root zone to the field capacity.

\[ \text{NIR} = (\text{CU} - \text{EP}) + \text{AL} \]

**Gross Irrigation requirement**: It is the net irrigation requirement and losses in conveyance, distribution and application of water in operating system.

\[ \text{GIR} = \frac{\text{NIR}}{\text{Irrigation Efficiency}} \]

**Optimum water requirement (OWR)**: It is the amount of water required during the growing season to produce highest crop yield.

**Irrigation frequency**: It refers to the number of days between two successive irrigation during the periods without precipitation.

**Determination of crop water requirements**

**A. Direct measurements**

1. Transpiration ratio method
2. Depth-interval – yield approach
3. Lysimeter experiments
4. Soil moisture depletion studies
5. Field experimentation
6. Water balance method
B – From climatic data

1. Pan evaporation data 2. Estimation by climatic parameters.

Factors affecting irrigation water needs

1. Climate and crop growing season 2. Crop characteristics 3. Soil factors
4. Crop management practices

1. **Climate**: Principal climatic factors influencing crop water requirement are precipitation, solar radiation, temperature, wind velocity and relative humidity.
   - Well distributed rainfall during the crop season minimises the irrigation need of crops.
   - Crop in sunny and hot climate need more water per day than that under cloudy and cool climate.
   - Crop water needs are higher under dry weather than the humid.
   - High wind velocity increase crop water requirement

2. **Crop characteristics**: Crop water requirements vary according to growth habit, canopy development, leaf area, sensitivity to drought and duration of crops.
   - Tall crops and varieties intercept more solar radiation and have more daily water requirement than shorter crops & varieties.
   - Crops with deep root system, have higher water requirement than shallow rooted crops.
   - High leaf area increases crop water needs.
   - Longer the duration, higher crop water need.
   - Crop with higher water sensitivity suffer greater reduction in yield.
General sensitivity of crops to drought

Group I - Low sensitive: Safflower, ground nut, pearlmillet.

Group II - Moderate Low: Sorghum, finger millet cotton, sunflower, castor sugarcane

Group III – Moderate high: Wheat, Pulses, upland rice

Group IV – Highly Sensitive: Lowland rice, Maize

3. Soil factors: Coarse textured and well aggregated soil retain less water and have low hydraulic conductivity; hence they support less E.T.
   - Ridgees and furrows minimize evaporation loss.
   - Dark coloured soils absorb more heat which lead to higher E.T.

4. Crop management Practices
   - Frequent irrigations increases crop water requirements.
   - Water requirements with border and check basin irrigation are higher.
   - Harrowing or hoeing minimizes water loss.
   - Weed management reduce water loss.
   - Fertilizer application increases water needs.
   - Plant population and row spacing influence E.T.
SCHEDULING IRRIGATION

**Irrigation Scheduling**: Supply of water in optimum quantity at right time with appropriate application method is called irrigation scheduling.

It enables irrigator to apply exact amount of water; increases irrigation efficiency. There is accurate measurement of the volume of water applied or depth of application.

**Advantages**

1. It enables the farmers to schedule water rotation among different fields to minimise water stress and maximise yields.
2. It reduces cost of water and labour through fewer irrigations, thereby making maximum use of soil moisture.
3. Save fertilizer costs by reducing run off and leaching losses.
4. Increases net returns by increasing yield and crop quality.
5. It minimises water logging problems.
6. It assist in controlling root zone salinity problems through controlled leaching.
7. Additional returns by using saved water.

**Factors influencing irrigation schedules**

1. Soil  
2. Plant  
3. Climate  
4. Managements

**When to irrigate**

1. Maintenance of soil moisture around field capacity is ideal for many crops.
2. As the soil moisture tension increases crops can’t extract needed moisture for optimum growth.
3. Crop starts wilting leading to retard growth and permanent wilting.
4. Crop should not experience moisture stress between two irrigations.

5. By knowing ASM in crop root zone and ET demand, irrigation need can be determined.

**Approaches for scheduling irrigation**

1. **Soil moisture monitoring**
   
   (i) Measurement of soil water potential by tensiometer or gypsum blocks etc.
   
   (ii) Soil moisture content by direct methods (gravimetric)
   
   (iii) Feel and appearance method.

2. **Atmospheric measurements and water balance technique**
   
   (i) Measurement of crop evapotranspiration (ETc)
   
   (ii) IW/CPE approach
   
   (iii) Lysimeter studies
   
   (iv) Field water balance

3. **Plant based monitoring**
   
   (i) **Contact methods**

   a. Measuring plant-water status by pressure chamber, Dew point hygrometer, osmometer, tissue water content.

   b. Measurement of plant response by sap flow sensors, stomatal conductance (porometers) and plant growth rate.

   (ii) **Non contact method**

   a. Site specific crop management and irrigation

   b. Plant spectral responses

   c. Radiometric sensors
- Multispectral sensors
- Hyperspectral sensors
- Thermal sensing

**Plant Indices**

1. Visual symptoms
2. Soil cum sand miniplot
3. Plant population
4. Growth rate
5. Indicator plants

**Delta** is the total depth of irrigation to a crop in centimeters. It can be calculated by dividing the volume of irrigation water by the area irrigated.

**Duty** is the ratio between irrigated area and quantity of water used. It is expressed in litres per second per ha and indicates the flow requirement per hectare of cropped area.
**Water Resources**

**World:** Ocean cover 3/4th of earth surface. UN estimated total amount of water 1400 million cubic kilometer on earth.

Fresh Water: Only 2.7% of total water on earth, of which 68.7% lies frozen in polar region & 30.1% as ground water and rest in lakes, rivers, atmosphere, moisture, soil and vegetation.

India: India occupies only 3.29 M km2 geographical area which is 2.4% of the world’s land area and 17% population.

India supports about 1/6th of world population, 1/50th worlds land and 1/25th of water resources (Institution of Engineers 2003).

The total utilizable water flows of India are estimated as 668 BCM by Garg and Hassan (2007) as against 1110 BCM by CWC (1988), 1209-1255 BCM by NCIWRDP (1999) and 1122 BCM by national water Policy of India.

It is estimated that 1.952 x 1011 m3 of water is available out of total precipitation of 4 x 1011 m3. The CWC estimate that ultimate irrigation Potential that can be created through major, medium and minor projects would be around 75.9 M ha. Irrigation Potential with ground water has been assessed as 64 M ha. Thus, the total irrigation potential would be about 139.9 M ha (MOWR 2006).

Water budget in its elementary form can be represented by the equation-

Total rainfall input = Surface water flows+Ground water recharge + evapotraspiration.

**Principal annual components of India’s water budget:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume(Km³)</th>
<th>Precipitation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>3838</td>
<td>100</td>
</tr>
<tr>
<td>Potetial flows in river</td>
<td>1869</td>
<td>48.7</td>
</tr>
<tr>
<td>Natural recharge</td>
<td>432</td>
<td>11.3</td>
</tr>
<tr>
<td>Available water</td>
<td>1869+432=2301</td>
<td>60.0</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>3838-(1869+432)=1537</td>
<td>100-(48.7+11.3)=40</td>
</tr>
</tbody>
</table>
Water resources scenario in India

<table>
<thead>
<tr>
<th>S.No</th>
<th>Resource</th>
<th>Quantity (BCM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Annual Precipitation including Snow fall</td>
<td>4000 (3000 during monsoon)</td>
</tr>
<tr>
<td>2</td>
<td>Evaporation + ground water</td>
<td>2131</td>
</tr>
<tr>
<td>3</td>
<td>Av. Annual Potential flow in rivers</td>
<td>1869</td>
</tr>
<tr>
<td>4</td>
<td>Utilisable surface water resources</td>
<td>1122</td>
</tr>
<tr>
<td>a</td>
<td>Conventional means</td>
<td>690</td>
</tr>
<tr>
<td>b</td>
<td>Replenishable ground water</td>
<td>432</td>
</tr>
<tr>
<td>5</td>
<td>Present Utilization</td>
<td>605</td>
</tr>
<tr>
<td>6</td>
<td>Future demand by</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2025 AD</td>
<td>1093</td>
</tr>
<tr>
<td></td>
<td>2050 AD</td>
<td>1447</td>
</tr>
<tr>
<td>7</td>
<td>Possible additional water Utilization through inter - basin water transfer</td>
<td>170-200</td>
</tr>
</tbody>
</table>

1Km$^3$ = $10^9$m$^3$ = 1 Billion cubic meter (BCM) = 0.10 million ha-m

**Ground water resources:** Annual Potential G.W. recharge from rainfall in India is about 342.43 Km$^3$ which is 8.56% of total annual rainfall.

**Ground water Resources of India (CGWB, 2002)**

<table>
<thead>
<tr>
<th>S.No</th>
<th>Particular</th>
<th>Quantity Km$^3$ yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total replenishable ground water resource</td>
<td>432</td>
</tr>
<tr>
<td>2</td>
<td>Provision for domestic industrial &amp; other uses</td>
<td>71</td>
</tr>
<tr>
<td>3</td>
<td>Available G.W. resources for irrigation</td>
<td>361</td>
</tr>
<tr>
<td>4</td>
<td>Utilizable G.W. resource for irri. (90% of S.3)</td>
<td>325</td>
</tr>
<tr>
<td>5</td>
<td>Total Utilizable GW resources (2+4)</td>
<td>396</td>
</tr>
</tbody>
</table>

**Problems of water resources**

1. Spatial & Temporal distribution-Rainfall
   - Mousinram, cherrapunji, Meghalaya-11690 mm
   - Jaisalmer, Rajasthan - 150mm
2. Conflicting objectives of water Resource Development

Major & Medium irrigation Projects are multipurpose with hydropower generation, flood control and irrigation. The operational aspects of multipurpose Projects need to be optimized.

3. Increasing Sectorial competition:

With increasing Population, change in food habits, life style changes, increasing emphasis on travel/tourism the demand scenario is expected to change.

4. Pollution of surface & G.W. resources:

- Effluents form municipal and industries into rivers.
- Indiscriminate use of fertilizers, insecticides, & fungicides
- Disposal of domestic & industrial sewage
- G.W. Pollution is more serious.

5. Rising & Falling water table:

- 60-65% water lost in conveyance in field leading to rise in water table and ultimately water logging & soil salinity.
- Over exploitation of ground water causing decline in water table.

**Irrigation Development in India:**

At the time of Independence 19.4 Mha

Net irrigated Area

**During 2014-15 (Area M ha):**

Net Irrigated area- 68.38, Gross Irrigated Area - 96.46.

Net sown area- 140.13., Gross sown Area – 198.36

Cropping Intensity 141.6

<table>
<thead>
<tr>
<th>State</th>
<th>Net irrigated area (000ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uttar Pradesh</td>
<td>14389</td>
</tr>
<tr>
<td>Madhya Pradesh</td>
<td>9584</td>
</tr>
<tr>
<td>Rajasthan</td>
<td>7882</td>
</tr>
</tbody>
</table>

**Crop-wise gross irrigated area (mha) in India**

<table>
<thead>
<tr>
<th></th>
<th>Rice</th>
<th>Wheat</th>
<th>Total food grains</th>
<th>Total pulses</th>
<th>Fruits &amp; Veg.</th>
<th>Total oilseeds</th>
<th>Sugar-cane</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigated area</td>
<td>26.58</td>
<td>30.21</td>
<td>65.53</td>
<td>4.31</td>
<td>6.55</td>
<td>7.78</td>
<td>5.02</td>
<td>96.46</td>
</tr>
<tr>
<td>% of total area under the crop</td>
<td>60.1</td>
<td>94.2</td>
<td>53.1</td>
<td>19.9</td>
<td>65.6</td>
<td>27.4</td>
<td>90.2</td>
<td>48.6</td>
</tr>
</tbody>
</table>

## Important Irrigation Projects (44)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Name</th>
<th>Distt &amp; River</th>
<th>Capacity at Full Res. Level (M m$^3$)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Andra Pradesh</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>I</td>
<td>Nagarjun Sagar</td>
<td>Nalgonda -Krishna</td>
<td>11561</td>
<td>Biggest in Asia</td>
</tr>
<tr>
<td>II</td>
<td>Sriram Sagar (Telangana)</td>
<td>Nizamabad- Godavari</td>
<td>3454</td>
<td>Multipurpose</td>
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<tr>
<td>III</td>
<td>Sri Sailam (Telangana)</td>
<td>Kurnaoil-AP-Krishna mehboobnagar</td>
<td>8722</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>Gujrat</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Sardar Sarovar</td>
<td>Bharuch-Narmada</td>
<td>(9.5km$^3$)</td>
<td>2$^{nd}$ largest dam in world</td>
</tr>
<tr>
<td>II</td>
<td>Ukai</td>
<td>Tapi- Tapi</td>
<td>8511</td>
<td></td>
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<tr>
<td>III</td>
<td>Sabarmati(Dharoi) dam</td>
<td>Mehsana-Sabarmati</td>
<td>908</td>
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<tr>
<td>IV</td>
<td>Kadana</td>
<td>Mahi sagar-Mahi</td>
<td>1542</td>
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</tr>
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<td>3</td>
<td><strong>Karnataka</strong></td>
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<tr>
<td>I</td>
<td>Krishnaraja Sagar(KRS)</td>
<td>Mandya –Kaveri</td>
<td>1400</td>
<td>India’s first irri-dam</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>vridavan garden</td>
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<tr>
<td>II</td>
<td>Linganamakki</td>
<td>Lingammakki,Sagara-Sharavathi</td>
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<td>Multipurpose</td>
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<tr>
<td>III</td>
<td>Tungbhadra</td>
<td>Chikmanglur-Tunghadra</td>
<td>3429</td>
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<tr>
<td>IV</td>
<td>Ghataprabha</td>
<td>Belgaum &amp; Bijapur-Ghatprabha</td>
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<tr>
<td>V</td>
<td>Malprabha</td>
<td>Belgaum-Malprabha</td>
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<tr>
<td>VI</td>
<td>Kabini</td>
<td>Mysore-Kabini</td>
<td>553</td>
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<td>VII</td>
<td>Bhadra</td>
<td>Chickmanglur-Bhadra</td>
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<tr>
<td>S.No</td>
<td>Name</td>
<td>Distt &amp; River</td>
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<td>Remarks</td>
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<td>4</td>
<td>Kerala</td>
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<tr>
<td>I</td>
<td>Idukki</td>
<td>Idukki-Periyar</td>
<td>997</td>
<td>Arch dam, Hydroelectric</td>
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<td>5</td>
<td>Madhya Pradesh</td>
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<tr>
<td>I</td>
<td>Ban Sagar</td>
<td>Shahdol -Son</td>
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<td>II</td>
<td>Bargi</td>
<td>Jabalpur -Narmada</td>
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<td>III</td>
<td>Indira Sagar</td>
<td>Khandwa –Narmada</td>
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<td>Largest resovior</td>
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<td>Gandhi Sagar</td>
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<td>Hoshangabad-Tawa</td>
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<td>VI</td>
<td>IndiraSagar Medikheda dam</td>
<td>Shivpuri-Sindh</td>
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<td>I</td>
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<td>Godavari</td>
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<td>Khadakvasla</td>
<td>Pune-Mutha</td>
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<td>S.No</td>
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<td>Distt &amp;River</td>
<td>Capacity at</td>
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<td>Balimela</td>
<td>Malkangiri-Sileru</td>
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<td>IV</td>
<td>Salandi/Hadagarh</td>
<td>Kendujhar-Salandi</td>
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<td>8</td>
<td>H.P</td>
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<tr>
<td>I</td>
<td>Gobind Sagar</td>
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<td>Beas- Sutlej link</td>
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<td>II</td>
<td>Pongdam/Maharana Pratap Sagar</td>
<td>Kangra-Beas</td>
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<td>9</td>
<td>Rajasthan</td>
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<td>Ranapratap Sagar</td>
<td>Rawatabhata-chambal</td>
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<td>10</td>
<td>Tamil Nadu</td>
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<td>I</td>
<td>Lower Bhavani/Bhavani sagar</td>
<td>Erode-Bhavani</td>
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<td>II</td>
<td>Mettur</td>
<td>Salem-Cauvery</td>
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<td>III</td>
<td>Vaigai</td>
<td>Theni- Vaigai</td>
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<td>IV</td>
<td>Parambikulam</td>
<td>Palakkad-Parambikulam</td>
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<td>V</td>
<td>Adiyar</td>
<td>Chennai-Adyar</td>
<td>109</td>
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<tr>
<td>S.No</td>
<td>Name</td>
<td>Distt &amp; River</td>
<td>Capacity at</td>
<td>Remarks</td>
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<td>------</td>
<td>---------------</td>
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<tr>
<td>11</td>
<td>Uttar Pradesh</td>
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<td></td>
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<td>I</td>
<td>Matatila</td>
<td>Lalitpur-Betwa</td>
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<td>Garhwal-Ramganga</td>
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<td>III</td>
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<td>Mayurakshi (Jharkhand)</td>
<td>Deoghr-Mayurakshi</td>
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<td>II</td>
<td>Kangsabati Kumari</td>
<td>Bankura-Kangswnti Kumari</td>
<td>52</td>
<td>Irrigation, flood control</td>
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<td>13</td>
<td>DVC</td>
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<td>Dhanbad</td>
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<td>III</td>
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<td>IV</td>
<td>Tilaiya-Jharkhand</td>
<td>Koderna</td>
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</table>
Soil water movement in soil and plants

Soil: The soil is a dynamic natural body developed as a result of pedogenic process during and after weathering of rocks, consisting of mineral and organic constituents, possessing definite chemical, physical, mineralogical and biological properties, having a variable depth over the earth surface and provide a medium for plant growth.

Soil is heterogeneous mixture of silicate particles, humus and a variety of insoluble salt and oxides of metals called solid phase, a liquid phase and a gaseous phase. Inside of the soil particles, the empty space constitutes the pore spaces that may be filled by air and water.

Soil texture: Soil texture refers to the relative proportion of the primary particles (sand, silt and clay) in the soil. According to the International soil science society (ISSS) the particles are classified as under

<table>
<thead>
<tr>
<th>Clay</th>
<th>Silt</th>
<th>Fine Sand</th>
<th>Coarse Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.002 mm</td>
<td>0.002-0.02 mm</td>
<td>0.02-0.2 mm</td>
<td>0.2-2.0 mm</td>
</tr>
</tbody>
</table>

Classification according to united states Department of Agriculture (USDA)

<table>
<thead>
<tr>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very fine</td>
<td>fine</td>
</tr>
<tr>
<td>0.002mm</td>
<td>0.05mm</td>
<td>0.1mm</td>
</tr>
</tbody>
</table>

Particles larger than 2.0-75mm in diameter termed as gravel, are ignored while considering texture. Sand and gravels are non sticky, have no plasticity, and possess low water holding capacity because of large pore space. Sandy soils are well drained.

Silt particles are intermediary in size and have properties between sand and clay. Silt cause soil surface compact and crusty.

Clay particles vary in shape from plate like to round. When it is wet, tends to be sticky and plastic. Water and air movement is restricted. Water holding capacity is high. It becomes hard and cloddy when dry. Clay fraction controls most of the important properties of the soils. They are chiefly composed of secondary minerals-crystalline alumino silicate.
There are six types of clay minerals.

1. **Kaolinite** - 1:1 type, in which one silica tetrahedral layer is joined with one aluminum octahedral layer. \( \text{Si}_4 \text{Al}_4 \text{O}_{10} (\text{OH})_8 \), CEC 3 to 15 me/100g soil. Total surface area = 37-45 m\(^2\)/g.

2. **Smectite** - One central layer of aluminum octahedron is attached with two layers of silica tetrahedral, one at top and another at bottom. Montmorillonite- \( \text{Si}_8 (\text{Al}_3\text{Mg}) \text{O}_{20}(\text{OH})_4 \text{nH}_2\text{O} \). In montmorillonite the major replacement is Mg\(^{++}\) for Al\(^{+++}\) in octahedral layer. There is considerable interlayer space between the units. CEC ranges between 80-150 me/100g. Total surface area is 580-750 m\(^2\)/g.

3. **Illite** - Structure of illite is the same as that of mica. One octahedral layer occurs between two tetrahedral layers of silica. Illite –K2 (\( \text{Si}_6\text{Al}_2 \) (\( \text{Al}_4 \))O\(_{20}\)(OH)\(_4\)\). 1/6\(^{th}\) of the silicon ions Si\(^{+++}\) have been replaced from tetrahedral positions by Al\(^{+++}\). Hence the K\(^+\) occur in the hexagonal cavity between two units of illite and bind it tightly. Thus they become non-expanding. CEC is 15-40 me/100gm. Total surface 120-170 sqm/g

4. **Vermiculite** - It consists of two silica tetrahedral layer and one octahedral layer, joined together. Some silicon ions are isomorphously substituted by Al ions and therefore magnesium ions occur between the sheets of vermiculite to balance the structure electrically. Magnesium ions hold the units together, therefore the expansion is somewhat limited. CEC-100 to 150 m.e./100g. Total surface area 780 to 900 sqm/g

   \( \text{Mg}_2 (\text{Si}_6\text{Al}_2) (\text{Mg}_2 \text{Fe}_2) \text{O}_{20}(\text{OH})_4 \text{nH}_2\text{O}. \)

5. **Chlorite** - It consists of one unit of a vermiculite layer and one unit of a magnesium octahedral layer called Brucite. Chlorite is also called 2:2 type clay. CEC is 15 to 40 m.e./100g and total surface area is 130-180 sqm/g.

6. **Allophanes** - Allophanes are amorphous hydrated aluminosilicates which are random asymmetrical arrangement of silica tetrahedral and aluminum octahedral.

   \( \text{Al}_2 \text{O}_3.2(\text{SiO}_2. \text{H}_2\text{O}. \) It has high CEC.

**Soil Structure**: Soil structure refers to the arrangement of soil particles. The combination of primary soil separates into secondary
groupings is called aggregates or peds. Water movement, aeration and porosity are influenced by structure. It is classified into seven principal types.

1. **Platy** - Aggregates are arranged in relatively thin horizontal plates.
2. **Prismatic** - This unit has the appearance of a prism with the particles arranged in a vertical line; the other two dimensions are much less, tops of the structural units have angular vertices.
3. **Columnar** - The characteristics are same as those of prismatic except that the tops (vertices) have rounded and smooth caps, frequently observed in alkali soils.
4. **Angular blocky or blocky** - The Structural units have the appearance of blocks of polyhedrons, having plane or curved surface that are casts of the molds formed by the faces of surrounding peds; faces are flat and most vertices are angular; these break into small angular blocky peds; observed in sub-surface horizons of the black soils.
5. **Sub-angular blocky** - Same as blocky but have mixed rounded and plane vertices.
6. **Granular** - The units are small and spheroid, not fitted to adjoining peds; relatively non porous.
7. **Crumb** - Peds are small, spherical, not fitted to adjoining ped; Peds are soft and porous.

**Particle density**: The Particle density (ps) also called density of soil solids, is the ratio of mass of soil solids (Ms) to the volume of soil solids (Vs) and is expressed in g cm$^{-3}$ or Mg m$^{-3}$. In most mineral soils the mean density of Particles varies from 2.6 to 2.7 g cm$^{-3}$.

$$Ps = \frac{Ms}{Vs}$$

**Dry bulk density**: Dry bulk density or bulk density(Pb) is the ratio of mass of oven dry soil solid particles(Ms) to the total volume of the soil (Vt). This volume includes the volume of soil solids (Vs), Soil water (Vw) and soil air (Va). It is expressed as gcm$^{-3}$.

$$Pb = \frac{Ms}{Vt} = \frac{Ms}{Vs} + Vw + Va$$
Soil in which pores constitute half of the volume bulk density is half of Particles density i.e. 1.3 to 1.5 g cm\(^{-3}\). In sandy soils bulk density can be as high as 1.6g cm\(^{-3}\). Ideal bulk density for optimum crop growth varies from 1.2 g cm\(^{-3}\) for a clay soil to about 1.4 g cm\(^{-3}\) for a sandy soil.

**Total or wet bulk density** - It is the ratio of total mass of soil (Mt) to the total volume of soil (Vt). The bulk density depends more on the moisture content of the soil.

\[
pt = \frac{Mt}{Vt} = Ms + \frac{MW}{Vs} + Vw + Va
\]

**Porosity** : Porosity (f) is the ratio of total volume of pore spaces (vf) to the total volume of the soil (Vt) and is expressed as a fraction or percentage.

\[
\text{Porosity (f)} = \frac{vf}{vt} = \frac{Vw}{Vs} + Vs + Vw + Va
\]

It is related to the bulk density as under -

\[
\text{Porosity}(f) = 100 - \frac{\text{Bulk density}}{\text{Particle density}} \times 100
\]

Or f=(ps–pb)/ps or 1-(pb/ps) or pb=(1-f) ps

Porosity is an index of relative pore volume in the soil. Its value, generally lies between 0.3 to 0.6 (or 30 to 60%).

**Pore Space** - The pores larger than 0.06 mm in dia are considered as macropores and those smaller than this are micropores.

**Void ratio (e)** - It is an index of fractional volume of soil pores to the volume of solids.

\[
e = \frac{\text{Vol.of Pore space}}{\text{Vol.of Soil Solids}} \quad \text{or} \quad (Va+Vw)/Vs
\]

Generally e varies between 0.3 to 2.0.

**Gravimetric water content or mass wetness (w)**: It is the mass (weight) of water (Mw) relative to mass of oven dry soil particles (Ms) and expressed as a fraction or percentage.

\[
W = \frac{Mw}{Ms}
\]

**Volumetric water content or volume wetness (vwc)**: It is the ratio of
total volume of water occupied in the pore spaces at a specific time to the total volume of soil and is expressed as a fraction or percentage. 

\[ V_{wc} = \frac{V_w}{V_t} = \frac{V_w}{(V_s+V_f)} \]. It can be computed from gravimetric water content by multiplying with bulk density.

\[ V_{wc} = w \times p_b. \]

Degree of saturation (DoS): It is the ratio of volume of water present in the soil at a particular time to the volume of pores.

\[ DoS = \frac{V_w}{V_f}. \]

**How soil holds water:**

Soil holds water in two ways (1) as a thin film on individual soil particle i.e. by adsorption. (2) Water stored in the pores of the soil, said to be in capillary storage.

**Cohesion and adhesion** - The attraction of like molecules (water) is known as cohesion, and the attraction of unlike-molecules (soil & water) is known as adhesion.

**Soil water retention:** When water is added to a dry soil it is distributed around soil particles, displaces air and fills the pores. When all the pores are filled with water, the soil is said to be saturated and it is at its maximum retentive capacity. This water is classified in three forms.

1. **Gravitational water** - Water in the macro-pores that moves downward freely under the influence of gravity beyond the root zone; held in soil at 1/3rd or less atm is termed as gravitational water. It is not available for plants.
2. **Capillary water** - Water retained by soil in the micro-pores (capillary), against gravity by the forces of surface tension, as a continuous film around soil particles is called capillary water. It is held between tensions of 1/3rd to 31 atm.
3. **Hygroscopic water** - The water held tightly around soil particles by adsorption forces and no longer movement in capillary pores is called hygroscopic water. Water remains at a tension of 31 bars.

**Soil moisture constants**

1. **Maximum water holding capacity**: The amount of moisture in a soil when total pore space is filled with water is called maximum water holding capacity or saturation percentage or maximum retentive capacity.
MWHC (%) = \( \frac{\text{Max. amount of water absorbed by soil}}{\text{Oven dry weight of soil}} \times 100 \)

Saturation Percentage is approximately 4 times of wilting point and two times of field capacity. MWHC can be determined with Keen’s box.

2. **Field capacity**: In the saturated soils, water continues to drain from large pores for a day or two and become negligible thereafter. The macro-pores are again filled with air. The micro-pores are still filled with water. When all the micro-pores are filled with water the soil is said to be at field capacity. The field capacity is considered as upper limit of water availability to plants. The soil water potential at FC ranges from -0.1 to -0.3 bars. Soil water content at FC always move in the direction of increasing tension.

3. **Moisture equivalent**: The amount of water retained by initially saturated soil after being centrifuged for 1000 times that of gravitational force for about half an hour is called moisture equivalent. Moisture remaining in the soil after this process is determined gravimetrically. This moisture content when expressed as percentage moisture on oven dry basis give the value of moisture equivalent. The values of FC and ME are nearly equal in medium textured soil. In sandy soils FC exceeds Me. In very clayey soils FC is generally lower.

4. **Permanent wilting point**: Also known as the wilting coefficient, is the moisture content of the soil at which plant can no longer obtain enough moisture to meet the transpiration requirements and remain wilted unless the water is added to the soil. The plant is not dead but remain in wilted condition. Soil moisture tension at PWP ranges between 7-32 atm. Commonly used average value is 15 atm. Soil water potential at this point is -15 bars or -1.5 MPa.

At soil water potential of -30 bars water can move only in vapour phase. Moisture content of soil at this point is termed hygroscopic coefficient. At -60 bars plants can not absorb moisture and die eventually. Soil moisture content at which plants die is called **ultimate wilting point**.
Available soil moisture: Moisture available for plant growth is the capillary water between FC and PWP, Hence, ASM = FC - PWP. Sandy soils have the lower amount of ASM and clay soils the highest. Soil texture, Soil structure, organic matter and concentrations of CaCO$_3$ and iron oxide (Fe$_2$O$_3$) affects moisture holding capacity of soil.

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<tr>
<th>Soil texture</th>
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<th>PWP%</th>
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<td>1.5-1.8</td>
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Concept of soil water availability:
1. Equal availability from FC to PWP: water availability and consequently the crop growth is equal and uniform over the entire range from field capacity to permanent wilting point. This holds good for orchard & tree crops.
2. Equal availability from FC to critical moisture beyond which it decreases: water availability and crop growth proceed uniformly from the field capacity to certain critical point beyond which crop growth decreases rapidly till the permanent wilting point is reached. This view holds good for most of the seasonal crops.
3. Availability decreases continuously: the availability of water and rate of crop growth decrease gradually as the soil water content decreases from FC to PWP. Holds good for most of the forage crops.
Water: Water is a bipolar liquid. It has a symmetrical structure in which hydrogen (H+) atoms are attached to the oxygen in sort of 'V' arrangement. The H+ atoms side holds a net positive charge and oxygen atom side holds a net negative charge.

Properties of water: The Properties of water arise from the hydrogen bonding and tetrahedral arrangement of electron pairs around the oxygen (4 faces) atom. The size of water molecule is $2.75 \, \text{Å}^0$ ($1\, \text{Å}^0 = 10^{-10}\, \text{m}$).

Polarity: Water molecules are dipolar in nature for which they cling to each other through H+ bonding rather than acting individually.

Hydrogen bounding: The Phenomenon by which hydrogen atoms act as connecting linkages between water molecules.

Surface tension: Phenomenon occurring typically at the interface of liquid and gas and results from the greater attraction of water molecules for each other the for the gas above.

$$\text{Surface Tension(T)} = \frac{F(\text{Force-Dynes})}{L(\text{Length-cm})}$$

S. T. of water $= 72\, \text{dynes/cm}$ at 25 degree C

Capillary rise: The rise of water in a capillary tube to a level higher than that in the container is called capillary rise. This rise is due to combined action of cohesion, adhesion and surface tension.

$$H = \frac{2T}{Pgr}$$

Where ,$T=$ Surface tension(dynes/cm)
$P=$ Density of water (gm/cm$^3$)
$g =$ acceleration due to gravity (981cm/sec$^2$)
$r =$ radius of capillary tube (cm)

Viscosity: When a fluid is moved in shear, the force required is proportional to the velocity of the shear. The Proportionality factor is called viscosity. For water viscosity decreases about 3% Per 1°C rise in temperature.
**Role of water:** Water is essential for human, animal & Plant life. Water plays a key role in photosynthesis. It is a medium for transport of nutrient and photosynthesis. Crop production depends on availability of water. Importance of water is classified as ecological and physiological values.

**Ecological:** The distribution of vegetation over the each surface is controlled more by the availability of water than any other factor. Temperature is correlated in this process.

**Physiological:**

1. Water is structural constituent of plants cells and maintains turgor pressure/Turgidity. In young plants 85-90% and in matured plants 20-50% is water, by weight.


3. Serves as a solvent of substances and a medium in plants allowing metabolic reactions to occur.

4. Acts as a solvent of plant nutrients and help in uptake of nutrients from soil. Plants also absorb nutrients through leaves from nutrient sprays.

5. Carrier of photosynthates to be distributed to different plant parts.

6. Transpiration occurs at a potential rate as long as water is available in adequate amount. It otherwise seriously affect plant growth & yield.

7. Regulates opening & closing of stomata by maintaining turgor pressure of guard cells.

8. Cells and tissues are formed and plant growth occurs when an adequate amount of soil water is available.

9. Water acts as a buffer against high or low temperature injury as it has high heat of vaporization and high specific heat.

As a whole, water encourages good growth, development and yield of plants and quality of produce when available in sufficient quantities. plants cannot survive without water.
### Categorization of water and their role in agriculture

<table>
<thead>
<tr>
<th>S.No</th>
<th>Category</th>
<th>Sources</th>
<th>Potential use in agriculture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Blue Water</td>
<td>Sea, lakes, river canal etc</td>
<td>Extensively used in irrigation, Availability decrease with increasing competition from other sources.</td>
</tr>
<tr>
<td>2</td>
<td>Green Water</td>
<td>Soil moisture and water in plants</td>
<td>Mostly used by plants /crops, Particularly forest, grass lands, &amp; dry land agriculture.</td>
</tr>
<tr>
<td>3</td>
<td>Fossil Water</td>
<td>Ground water</td>
<td>Mostly agricultural and domestic use, availability decreases with increasing competition from other sources.</td>
</tr>
<tr>
<td>4</td>
<td>Grey Water</td>
<td>Waste water from bathrooms, kitchens and wash basins</td>
<td>Potential for use in crop production, Irrigation in kitchen garden &amp; lawns</td>
</tr>
<tr>
<td>5</td>
<td>Black Water</td>
<td>Domestic sewage/ industrial waste</td>
<td>Potential for use in crop production, provided the technology to avoid heavy metal and Pathogen is available.</td>
</tr>
<tr>
<td>6</td>
<td>Virtual Water</td>
<td>Water used in Producing grains/ animals products</td>
<td>Export import of food grains/animal products indirectly results in export-import of water. will be important in future.</td>
</tr>
</tbody>
</table>
Soil water movement in soil and plants

Soil: The soil is a dynamic natural body developed as a result of pedogenic process during and after weathering of rocks, consisting of mineral and organic constituents, possessing definite chemical, physical, mineralogical and biological properties, having a variable depth over the earth surface and provide a medium for plant growth.

Soil is heterogeneous mixture of silicate particles, humus and a variety of insoluble salt and oxides of metals called solid phase, a liquid phase and a gaseous phase. Inside of the soil particles, the empty space constitutes the pore spaces that may be filled by air and water.

Soil texture: Soil texture refers to the relative proportion of the primary particles (sand, silt and clay) in the soil. According to the International soil science society (ISSS) the particles are classified as under

<table>
<thead>
<tr>
<th>Clay</th>
<th>Silt</th>
<th>Fine Sand</th>
<th>Coarse Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.002 mm</td>
<td>0.002-0.02mm</td>
<td>0.02-0.2mm</td>
<td>0.2-2.0mm</td>
</tr>
</tbody>
</table>

Classification according to united states Department of Agriculture (USDA)

<table>
<thead>
<tr>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Very fine</td>
<td>fine</td>
<td>Med</td>
<td>Coarse</td>
</tr>
<tr>
<td>0.002mm</td>
<td>0.05mm</td>
<td>0.1mm</td>
<td>0.25mm</td>
<td>0.5mm</td>
<td>1.0mm</td>
</tr>
</tbody>
</table>

Particles larger than 2.0-75mm in diameter termed as gravel, are ignored while considering texture. Sand and gravels are non sticky, have no plasticity, and possess low water holding capacity because of large pore space. Sandy soils are well drained.

Silt particles are intermediary in size and have properties between sand and clay. Silt cause soil surface compact and crusty.

Clay particles vary in shape from plate like to round. When it is wet, tends to be sticky and plastic. Water and air movement is restricted. Water holding capacity is high. It becomes hard and cloddy when dry. Clay fraction controls most of the important properties of
the soils. They are chiefly composed of secondary minerals-crystalline alumino silicate.

There are six types of clay minerals.

1. **Kaolinite** - 1:1 type, in which one silica tetrahedral layer is joined with one aluminum octahedral layer. Si$_4$ Al$_4$ O$_{10}$ (OH)$_8$, CEC 3 to 15 me/100g soil. Total surface area = 37 - 45 m$^2$/g.

2. **Smectite** - One Central layer of aluminium octahedron is attached with two layer of silica tetrahedral, one at top and another at bottom. Montmorillonite- Si$_8$ (Al$_3$Mg) O$_{20}$(OH)$_4$ nH$_2$O. In montmorillonite the major replacement is Mg$^{++}$ for Al$^{+++}$ in octahedral layer. There is considerable interlayer space between the units. CEC ranges between 80-150 me/100g. Total surface area is 580-750 m$^2$/g.

3. **Illite** - Structure of illite is the same as that of mica. One octahedral layer occurs between two tetrahedral layers of silica. Illite –K2 (Si$_6$ Al$_2$) (Al$_4$)O$_{20}$(OH)$_4$. 1/6th of the silicon ions Si$^{+++}$have been replace from tetrahedral Positions by Al$^{+++}$. Hence the K$^+$ occur in the hexagonal cavity between two units of illite and bind it tightly. Thus they become non-expanding. CEC is 15-40 m e/100gm. Total surface 120-170sqm/g

4. **Vermiculite** - It consists of two silica tetrahedral layer and one octahedral layer, joined together. Some silicon Ions are isomorphously substituted by Al ions and therefore magnesium ions occur between the sheets of vermiculite to balance the structure electrically. Magnesium ions hold the units together, therefore the expansion is some what limited. CEC-100 to150 m.e./100g. Total surface area 780 to 900 sqm/g

   Mg$_2$ (Si$_6$ Al$_2$) (Mg$_2$ Fe$_2$) O$_{20}$(OH)$_4$ nH$_2$O.

5. **Chlorite** - It consist of one unit of a vermiculite layer and one unit of a magnesium octahedral layer called Brucite. Chlorite is also called 2:2 type clay. CEC is 15 to 40 m.e./100g and total surface area is 130 -180 sqm/g.

6. **Allophanes** - Allophanes are amorphous hydrated aluminosilicates which are random asymmetrical arrangement of silica tetrahedral and aluminium octahedral.

   Al$_2$ O$_3$.2(SiO$_2$. H$_2$O. It has high CEC.

**Soil Structure**: Soil structure refers to the arrangement of soil particles. The combination of primary soil separates into secondary
groupings is called aggregates or peds. Water movement, aeration and porosity are influenced by structure. It is classified into seven principal types.

1. **Platy** - Aggregates are arranged in relatively thin horizontal plates.

2. **Prismatic** - This unit has the appearance of a prism with the particles arranged in a vertical line; the other two dimensions are much less, tops of the structural units have angular vertices.

3. **Columnar** - The characteristics are same as those of prismatic except that the tops (vertices) have rounded and smooth caps, frequently observed in alkali soils.

4. **Angular blocky or blocky** - The Structural units have the appearance of blocks of polyhedrons, having plane or curved surface that are casts of the molds formed by the faces of surrounding peds; faces are flat and most vertices are angular; these break into small angular blocky peds; observed in sub-surface horizons of the black soils.

5. **Sub-angular blocky** - Same as blocky but have mixed rounded and plane vertices.

6. **Granular** - The units are small and spheroid, not fitted to adjoining peds; relatively non porous.

7. **Crumb** - Peds are small, spherical, not fitted to adjoining ped; Peds are soft and porous.

**Particle density**: The Particle density (PS) also called density of soil solids, is the ratio of mass of soil solids (MS) to the volume of soil solids (Vs) and is expressed in g cm^{-3} of Mg m^{-3}. In most mineral soils the mean density of Particle varies from 2.6 to 2.7 g cm^{-3}.

\[ PS = \frac{Ms}{Vs} \]

**Dry bulk density**: Dry bulk density or bulk density (Pb) is the ratio of mass of oven dry soil solid particles (Ms) to the total volume of the soil (Vt). This volume includes the volume of soil solids (Vs), Soil water (Vw) and soil air (Va). It is expressed as gcm^{-3}.

\[ Pb = \frac{Ms}{Vt} = \frac{Ms}{Vs + Vw + Va} \]

Soil in which pores constitute half of the volume bulk density is half of Particle density i.e. 1.3 to 1.5 g cm^{-3}. In sandy soils bulk density can be as high as 1.6g cm^{-3}. Ideal bulk density for optimum
crop growth varies from 1.2 g cm\(^{-3}\) for a clay soil to about 1.4 g cm\(^{-3}\) for a sandy soil.

**Total or wet bulk density** - It is the ratio of total mass of soil (Mt) to the total volume of soil (Vt). The bulk density depends more on the moisture content of the soil.

\[
Pt = \frac{Mt}{Vt} = \frac{Ms + Mw}{Vs + Vw + Va}
\]

**Poracity**: Poracity (f) is the ratio of total volume of pore spaces (vf) to the total volume of the soil (Vt) and is expressed as a fraction or percentage.

\[
Poracity (f) = \frac{vf}{Vt} = \frac{Vw + Va}{Vs + Vw + Va}
\]

It can be determined by the following formulae

\[
Porocity = 100 - \frac{Bulk\ density}{Particle\ density} \times 100
\]

Porocity is an index of relative pore volume in the soil. Its value, generally lies between 0.3 to 0.6 (or 30 to 60%).

**Pore Space** - The Pores larger than 0.06 mm in dia are considered as macropores and those smaller than this are micropores.

**Void ratio (e)** - It is an index of fractional volume of soil pores to the volume of solids.

\[
e = \frac{Vol.\ of\ Pore\ space}{Vol.\ of\ Soil\ Solids}
\]

Generally e varies between 0.3 to 2.0.

**How soil holds water**: Soil holds water in two ways (1) as a thin film on individual soil particle i.e. by adsorption. (2) Water stored in the pores of the soil, said to be in capillary storage.

**Cohesion and adhesion** - The attraction of like molecules (water) is known as cohesion, and the attraction of unlike molecules (soil & water) is known as adhesion.

**Soil water retention**: When water is added to a dry soil it is distributed around soil particles, displaces air and fills the pores. When all the pores are filled with water, the soil is said to be saturated and it
is at its maximum retentive capacity. This water is classified in three forms.

1. **Gravitational water** - Water in the macropores that moves downward freely under the influence of gravity beyond the root zone; held in soil at 1/3rd or less atm is termed as gravitational water. It is not available for plants.

2. **Capillary water** - Water retained by soil in the micropores (capillary), against gravity by the forces of surface tension, as a continuous film around soil particles is called capillary water. It is held between tensions of 1/3rd to 31 atm.

3. **Hygroscopic water** - The water held tightly around soil particles by adsorption forces and no longer movement in capillary pores is called hygroscopic water. Water remains at a tension of 31 bars.

**Soil moisture constants**

1. **Maximum water holding capacity** : The amount of moisture in a soil when total pore space is filled with water is called maximum water holding capacity or saturation percentage or maximum retentive capacity.

   \[
   \text{MWHC (\%)} = \frac{\text{Max. amount of water absorbed by soil}}{\text{Oven dry weight of soil}} \times 100
   \]

   Saturation Percentage is approximately 4 times of wilting point and two times of field capacity. MWHC can be determined with Keen’s box.

2. **Field capacity** : In the saturated soils, water continues to drain from large pores for a day or two and become negligible thereafter. The macropores are again filled with air. The micropores are still filled with water. When all the micropores are filled with water the soil is said to be at field capacity. The field capacity is considered as upper limit of water availability to plants. The soil water potential at FC ranges from -0.1 to -0.3 bars. Soil water content at FC always move in the direction of increasing tension.

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**Factors affecting available soil moisture**

1. Soil texture  
2. Soil structure  
3. Conc. of CaCo3 & Fe2O3
**Water Intake**: The movement of water from the soil surface into and through the soil is called water intake. It includes infiltration and Percolation.

**Infiltration**: Infiltration is the Process of water entry into the soil. The water flux into the soil is called infiltration rate (mm/h) or the rate at which water is passing through the surface to the soil.

It is grouped in four categories-
1. Very slow < 0.25cm h\(^{-1}\) – very clay soil
2. Slow 0.25 to 1.25 cm h\(^{-1}\) – high clay
3. Moderate 1.25 to 2.50 cm h\(^{-1}\) – sandy loam / silt loam
4. Rapid > 2.50cm h\(^{-1}\) – deep / sandy silt loam

**Typical values of final infiltration rate (FIR)**

<table>
<thead>
<tr>
<th>Soil type</th>
<th>FIR mm h(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sands</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Sandy &amp; Silty soils</td>
<td>10-20</td>
</tr>
<tr>
<td>Loams</td>
<td>5-10</td>
</tr>
<tr>
<td>Clayey soils</td>
<td>1-5</td>
</tr>
<tr>
<td>Sodicclay soils</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

**Factors affecting infiltration rate;**
1. Compactness of soil surface
2. Impact of raindrop
3. Soil cover
4. Soil wetness
5. Soil temperature
6. Soil texture
7. Soil depth

**Measurement**: by cylinder infiltrometer.

**Permeability**: Qualitatively it is the characteristic of a porous medium relating to the readiness with which it transmits fluids.

Quantitatively, it is the specific property governing the rate of readiness with which a porous medium transmits fluids under standard conditions.
Factors
1. Macro & Micropores
2. Depth of soil
3. Soil texture
4. Soil moisture status
5. Salt concentration
6. Organic matter content

Slow- < 2.5 cm h^{-1}
Moderate-around 5.0 cm h^{-1}

**Percolation:** Percolation is the downward movement of water through saturated or nearly saturated soil in response to the force of gravity. It occurs when tension is smaller than 1/2 atm. It depends on soil and climate.

**Inter flow:** Interflow is the lateral flow of water in a relatively pervious soil above a less pervious layer.

**Seepage:** Seepage is the downward and lateral movement of water in the soil.

**Measurement of soil moisture:**
The soil moisture is determined by direct and indirect methods.

**Direct measurement (Gravimetric methods):** Involve removing water from a soil sample by evaporation, leaching or chemical reaction. Soil moisture content is calculated from the mass of water removed and the mass of dry soil. They are simple and inexpensive, hence widely used.

7. **Oven Drying:** This is a standard method to which all other methods are referred. Soil samples are collected from the desired depth with a auger. They are placed in aluminium boxes and weighed. These samples are dried in oven at 105-110 °C atleast for 24 hrs. Then weight of dried samples is taken. The moisture content is calculated as under –

Moisture content (%) = \( \frac{\text{Wt. of wet soil}(W_1)-\text{wt. of dry soil}(W_2)}{\text{Wt. of dry soil}(W_2)} \times 100 \)

Volumetric water content (%) = \( \frac{W_1-W_2}{W_2} \times 100 \times \text{Bulk density} \)

Depth of water per unit Soil depth (cm) = Vol. water content x Soil depth

8. **Alcohol Burning method:** Soil moisture from the sample is evaporated by adding alcohol and igniting. 1.0 ml of alcohol per g of
soil at FC and 0.5 ml at PWP is adequate for evaporating soil moisture. This method is not recommended for soil with high organic matter.

9. **Hot air drying**: Hot air around 110°C is passed on a screen with weighed samples of moist soil. Samples must be pulverized.

10. **Gypsum sorption plugs**: Gypsum plugs placed in soil comes into equilibrium with surrounding soil moisture. They are removed and weighed to determine soil moisture content. It is necessary to calibrate the wt. of porous cup with soil moisture content for different soils.

11. **Infrared balance**: It gives fairly reliable moisture estimate in about 5 minutes. It consists of a 250 watt infrared lamp, sensitive torsion and autotransformers, all housed in an aluminium cabinet. The radiation emitted by infrared lamp quickly vaporize the soil moisture. The instrument is directly calibrated in % moisture.

12. **Feel and appearance method**: A rough guide for scheduling irrigation. Soil moistures are judged by manipulating soil with hand and fingers. The soil samples from root zone are observed for colour, plasticity and cohesiveness.

**Indirect methods**: Usually measures the volumetric soil moisture content. Relatively quick and accurate.

8. **Tensiometric method**: Tensiometer is also called irrometer, used in irrigation scheduling. It provide a direct measure of tenacity (tension) with which water is held by soil. It estimate the soil-water matric potential which includes adsorption and capillary effects.

The working Principle of tensiometer is that when a sealed water-filled tube is placed in contact with the soil through a permeable and saturated porous material, the water (inside the tube) comes into equilibrium with the soil solution. Hence, the soil water matric potential is equivalent to the vaccume or suction created inside the tube.

Tensiometer consists of a sealed water filled plastic tube with a ceramic cup at one end and a negative pressure gauge at the other. Typically measurement range is 0 to 0.80 bars. The vaccume gauge is graduated to indicate tension values upto one atm and is divided into 50 divisions each of 0.2 atm. It is calibrated in centibars or 1/100 of one bar. (Bar is an international unit of pressure in metric
system= 14.5 Psi or 0.987 atm.). One centibar is equal to 1 kilopaskal (kPa).

Tensiometer is installed at a depth of 30 cm and 60 cm below the ground surface with the help of a probe or screw auger. Depth of hole should be ¼ to 1 inch less than actual depth for the porous tip. Pour ¼ cup of water into the hole. Insert the tensiometer and gently push it down to the desired depth. Instrument is ready to use 24 hrs after installation. Readings should be taken early in the morning.

A reading of zero corresponds to a completely saturated condition. A reading of 85 indicates a very dry condition.

### Meaning of tensiometer reading

<table>
<thead>
<tr>
<th>Reading Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5 cb</td>
<td>Saturated soil</td>
</tr>
<tr>
<td>10 cb</td>
<td>Field capacity</td>
</tr>
<tr>
<td>10-25 cb</td>
<td>Ideal soil water and aeration</td>
</tr>
<tr>
<td>25-85 cb</td>
<td>Decreased soil water availability</td>
</tr>
</tbody>
</table>

### Irrigation scheduling for different soils

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Reading Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay &amp; Clay loam textured</td>
<td>50 cb</td>
</tr>
<tr>
<td>Fine sand textured and sandy duplex</td>
<td>30-40 cb</td>
</tr>
<tr>
<td>Corse sand textured</td>
<td>20-30 cb</td>
</tr>
</tbody>
</table>

**Pressure plate technique**: This is a laboratory method. The Pressure plate and Pressure membrane apparatus measures the uptake and release from soil samples over a wide range of suction values.

**9. Electrical Resistance method**: It works on the Principal based on the linear relationship between the electrical resistance and moisture content of soil. Electrical resistance increases with decrease in moisture content.

The resistance blocks are made of gypsum. The electrodes in the blocks are connected to a conductance-meter for measuring the electrical resistance or conductance.

The blocks are buried at an appropriate depth at a certain distance. After sometime equilibrium is reached. As the soil moisture increases or decreases, the water content of block also increases or decreases. Higher the water content, higher is the conductivity.
Resistance blocks read low resistance (400 to 600 ohms) at FC and high resistance (50,000 to 75,000 ohms) at PWP. Associated soil water content must be obtained from a calibration curve.

Granular matrix sensors and dielectric soil moisture sensors are also used in this method.

10. **Radiation methods**: Neutron scattering and gamma ray attenuation methods are used to determine soil moisture content.
11. **Thermal methods**: Heat dissipation sensors, heat capacity sensors and soil psychrometers are used to determine soil moisture.
5. **Remote sensing**: Based on infrared or electromagnetic Properties of soil.
**Water Resources**

**World:** Ocean cover 3/4<sup>th</sup> of earth surface. UN estimated total amount of water 1400 million cubic kilometer on earth.

**Fresh Water:** Only 2.7% of total water on earth, of which 68.7% lies frozen in polar region &30.1% as ground water and rest in lakes, rivers, atmosphere, moisture, soil and vegetation.

**India:** India occupies only 3.29 M km<sup>2</sup> geographical area which is 2.4% of the world’s land area &15% population.

India supports about 1/6<sup>th</sup> of world population, 1/50<sup>th</sup> worlds land and 1/25<sup>th</sup> of water resources (Institution of Engineers 2003).

The total utilizable water flows of India are estimated as 668 BCM by Garg and Hassan (2007) as against 1110 BCM by CWC (1988), 1209-1255 BCM by NCIWRDP (1999) and 1122 BCM by national water Policy of India.

It is estimated that 1.952 x 10<sup>11</sup> m<sup>3</sup> of water is available out of total precipitation of 4 x 10<sup>11</sup> m<sup>3</sup>. The CWC estimate that ultimate irrigation Potential that can be created through major, medium and minor projects would be around 75.9 M ha. Irrigation Potential with ground water has been assessed as 64 M ha. Thus, the total irrigation potential would be about 139.9 M ha (MOWR 2006). Water budget in its elementary form can be represented by the equation:

Total rainfall input = Surface water flows+Ground water recharge + evapotranspiration.

National commision for Integrated water resource Development plant, Mowr

Principal annual componenets of Indias wate buget

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume(Km&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Precipitation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>3838</td>
<td>100</td>
</tr>
<tr>
<td>Potential flows in river</td>
<td>1869</td>
<td>48.7</td>
</tr>
<tr>
<td>Natural recharge</td>
<td>432</td>
<td>11.3</td>
</tr>
<tr>
<td>Available water</td>
<td>1869+432=2301</td>
<td>60.0</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>3838-(1869+432) =1537</td>
<td>100-(48.7+11.3)=40</td>
</tr>
</tbody>
</table>

Where Indias Av. Annual Raifall=1170 mm

Land area 3.29m Km<sup>2</sup>

Total Rainfall input 3838 Km<sup>3</sup>
### Water resources scenario in India

<table>
<thead>
<tr>
<th>S.No</th>
<th>Resource</th>
<th>Quantity (BCM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Annual Precipitation including Snow fall</td>
<td>4000 (3000 dry Months)</td>
</tr>
<tr>
<td>2</td>
<td>Evaporation+ground water</td>
<td>2131</td>
</tr>
<tr>
<td>3</td>
<td>Av. Annual Potential flow in rivers</td>
<td>1869</td>
</tr>
<tr>
<td>4</td>
<td>Utilisable surface water resources</td>
<td>1122</td>
</tr>
<tr>
<td></td>
<td>a Conventional means</td>
<td>690</td>
</tr>
<tr>
<td></td>
<td>b Replenishable ground water</td>
<td>432</td>
</tr>
<tr>
<td>5</td>
<td>Present Utilization</td>
<td>605</td>
</tr>
<tr>
<td>6</td>
<td>Future demand by 2025 AD</td>
<td>1093</td>
</tr>
<tr>
<td></td>
<td>2050 AD</td>
<td>1447</td>
</tr>
<tr>
<td>7</td>
<td>Possible additional water Utilization</td>
<td>170-200</td>
</tr>
</tbody>
</table>

1Km$^3$ = $10^9$m$^3$ = 1 Billion cubic meter (BCM)=0.10 million ha-m

### Ground water resources

Annual Potential G.W. recharge from rainfall in India is about 342.43 Km$^3$ which is 8.56% of total annual rainfall.

Ground water Resources of India (CGWB, 2002)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Particular</th>
<th>Quantity Km$^3$ yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total replenishable ground water resource</td>
<td>432</td>
</tr>
<tr>
<td>2</td>
<td>Provision for domestic industrial &amp; other uses</td>
<td>71</td>
</tr>
<tr>
<td>3</td>
<td>Available G.W. resources for irrigation</td>
<td>361</td>
</tr>
<tr>
<td>4</td>
<td>Utilizable G.W. resource for irri. (90% of sr.3)</td>
<td>325</td>
</tr>
<tr>
<td>5</td>
<td>Total Utilizable GW resources (2+4)</td>
<td>396</td>
</tr>
</tbody>
</table>

### Problems of water resources:

1. Spatial & Temporal distribution - Rainfall
   - Mousinram, Cherrapunji, Meghalaya - 11690 mm
   - Jaisalmer, Rajasthan - 150 mm

2. Conflicting objectives of water Resource Development
   Major & Medium irrigation Projects are multipurpose with hydropower generation, flood control and irrigation. The operational aspects of multipurpose Projects need to be optimized.
Increasing Sectorial competition:
With increasing Population, change in food habits, life style changes, increasing emphasis on travel/tourism the demand scenario is expected to change.

Pollution of surface & G.W. resources:
- Effluents form municipal and industries into rivers.
- Indiscriminate use of fertilizers, insecticides, & fungicides
- Disposal of domestic & industrial sewage
- G.W. Pollution is more serious.

Rising & Falling water table:
60-65% water lost in conveyance in field leading to rise in water table and ultimately water logging & soil salinity.
Over exploitation of ground water causing decline in water table.

Irrigation Development:

<table>
<thead>
<tr>
<th>At the time of Independence</th>
<th>India</th>
<th>19.4 Mha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pak</td>
<td>8.8 Mha</td>
<td></td>
</tr>
</tbody>
</table>

During 2011-12 (Area M ha):
Net Irrigated area - 65.26, Gross Irri. Area - 91.53.
Net Un irri. area - 75.54, Gross Un Irri. Area – 103.72.
Percent of G.I to total cropped area 46.9, Cropping Intensity 138.7
## Important Irrigation Projects (44)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Distt &amp;River</th>
<th>Capacity at Full Res. Level (M m³)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Andra Pradesh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Nagarjun Sagar</td>
<td>Nalgonda-Krishna</td>
<td>11561</td>
</tr>
<tr>
<td>II</td>
<td>Sriram Sagar (Telangana)</td>
<td>Nizamabad- Godavari</td>
<td>3454</td>
</tr>
<tr>
<td>III</td>
<td>Sri Sailam (Telangana)</td>
<td>Kurnaol-AP-Krishna mehboobnagar</td>
<td>8722</td>
</tr>
<tr>
<td>2</td>
<td>Gujrat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Sardar Sarovar</td>
<td>Bharuch-Narmada</td>
<td>(9.5km³)</td>
</tr>
<tr>
<td>II</td>
<td>Ukai</td>
<td>Tapi- Tapi</td>
<td>8511</td>
</tr>
<tr>
<td>III</td>
<td>Sabarmati(Dharoi) dam</td>
<td>Mehsana-Sabarmati</td>
<td>908</td>
</tr>
<tr>
<td>IV</td>
<td>Kadana</td>
<td>Mahi sagar-Mahi</td>
<td>1542</td>
</tr>
<tr>
<td>3</td>
<td>Karnataka</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Krishnaraja Sagar(KRS)</td>
<td>Mandya –Kaveri</td>
<td>1400</td>
</tr>
<tr>
<td>II</td>
<td>Linganamakki</td>
<td>Linganamakki,Sagara-Sharavathi</td>
<td>4497</td>
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<tr>
<td>III</td>
<td>Tungbhadra</td>
<td>Chikmanaglur-Tunghadra</td>
<td>3429</td>
</tr>
<tr>
<td>IV</td>
<td>Ghataprabha</td>
<td>Belgaum &amp; Bijapur-Ghatprabha</td>
<td>1440</td>
</tr>
<tr>
<td>V</td>
<td>Malprabha</td>
<td>Belgaum-Malprabha</td>
<td>1068</td>
</tr>
<tr>
<td>VI</td>
<td>Kabini</td>
<td>Mysore-Kabini</td>
<td>553</td>
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<tr>
<td>VII</td>
<td>Bhadra</td>
<td>Chickmanaglur-Bhadra</td>
<td>26</td>
</tr>
<tr>
<td>S.No</td>
<td>Name</td>
<td>Distt &amp;River</td>
<td>Capacity at Full Res. Level (M $m^3$)</td>
</tr>
<tr>
<td>------</td>
<td>------------------------</td>
<td>---------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>4</td>
<td>Kerala</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Idukki</td>
<td>Idukki-Periyar</td>
<td>997</td>
</tr>
<tr>
<td>5 Madhya Pradesh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Ban Sagar</td>
<td>Shahdol -Son</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Bargi</td>
<td>Jabalpur -Narmada</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Indira Sagar</td>
<td>Khandwa -Narmada</td>
<td>Largest resovior</td>
</tr>
<tr>
<td>IV</td>
<td>Gandhi Sagar</td>
<td>Mandsour-Chambal</td>
<td>7413</td>
</tr>
<tr>
<td>V</td>
<td>Tawa</td>
<td>Hoshangabad-Tawa</td>
<td>2312</td>
</tr>
<tr>
<td>VI</td>
<td>Indira Sagar</td>
<td>Medikheda dam</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shivpuri-Sindh</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Maharashtra</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Jayakwadi</td>
<td>Godavari</td>
<td>2909</td>
</tr>
<tr>
<td>II</td>
<td>Khadakvasla</td>
<td>Pune-Mutha</td>
<td>86</td>
</tr>
<tr>
<td>III</td>
<td>Koyna</td>
<td>Sangli-Koyna</td>
<td>2797</td>
</tr>
</tbody>
</table>
## Important Irrigation Projects (44)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Name</th>
<th>Distt &amp; River</th>
<th>Capacity at</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Orissa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Hira Kund</td>
<td>Sambalpur-Mahanadi</td>
<td>8146</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Mach Kund</td>
<td>Koraput-Machkund</td>
<td>971</td>
<td></td>
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<tr>
<td>III</td>
<td>Balimela</td>
<td>Malkangiri-Sileru</td>
<td>3610</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Salandi/Hadagarh</td>
<td>Kendujhar-Salandi</td>
<td>566</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>H.P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Gobind Sagar</td>
<td>Bilaspur-Sutlej</td>
<td>9351</td>
<td>Beas- Sutlej link</td>
</tr>
<tr>
<td>II</td>
<td>Pongdam/Maharana Pratap Sagar</td>
<td>Kangra-Beas</td>
<td>8579</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Rajasthan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Ranapratap Sagar</td>
<td>Rawatabhata-chambal</td>
<td>2905</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Tamil Nadu</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Lower Bhavani/Bhavani sagar</td>
<td>Erode-Bhavani</td>
<td>929</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Mettur</td>
<td>Salem-Cauvery</td>
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<tr>
<td>III</td>
<td>Vaigai</td>
<td>Theni- Vaigai</td>
<td>193</td>
<td></td>
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<tr>
<td>IV</td>
<td>Parambikulam</td>
<td>Palakkad-Parambikulam</td>
<td>505</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Adiyar</td>
<td>Chennai-Adyar</td>
<td>109</td>
<td></td>
</tr>
<tr>
<td>S.No</td>
<td>Name</td>
<td>Distt &amp; River</td>
<td>Capacity</td>
<td>Remarks</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>----------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>11</td>
<td><strong>Uttar Pradesh</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Matatila</td>
<td>Lalitpur-Betwa</td>
<td>883</td>
<td>Multipurpose</td>
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<tr>
<td>II</td>
<td>Ramganga/Kewlagarh(U.Khand)</td>
<td>Garhwal-Ramganga</td>
<td>2448</td>
<td></td>
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<tr>
<td>III</td>
<td>Rihand/Gobind Ballabh Pant Sagar</td>
<td>Sonbhadra-Rihand</td>
<td>10607</td>
<td></td>
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<tr>
<td>12</td>
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<td></td>
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<tr>
<td>I</td>
<td>Mayurakshi (Jharkhand)</td>
<td>Deoghr-Mayurakshi</td>
<td>617</td>
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<td>II</td>
<td>Kangsabati Kumari</td>
<td>Bankura-Kangswnti Kumari</td>
<td>52</td>
<td>Irrigation, flood control</td>
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<tr>
<td>13</td>
<td><strong>DVC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Maithon-Jharkhand</td>
<td>Dhanbad</td>
<td>1275</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Panchethill dam- Jharkhand</td>
<td>Dhanbad- Damodar</td>
<td>1475</td>
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<tr>
<td>III</td>
<td>Konar –Jharkhand</td>
<td>Hazaribagh</td>
<td>336</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Tilaiya-Jharkhand</td>
<td>Koderna</td>
<td>394</td>
<td></td>
</tr>
</tbody>
</table>
**Water Intake:** The movement of water from the soil surface into and through the soil is called water intake. It includes infiltration and Percolation.

**Infiltration:** Infiltration is the Process of water entry into the soil. The water flux into the soil is called infiltration rate (mm/h) or the rate at which water is passing through the surface to the soil.

It is grouped in four categories-

1. Very slow : < 0.25 cm h\(^{-1}\) – very clay soil
2. Slow : 0.25 to 1.25 cm h\(^{-1}\) – high clay
3. Moderate : 1.25 to 2.50 cm h\(^{-1}\) – sandy loam/ silt loam
4. Rapid : > 2.50 cm h\(^{-1}\) – deep / sandy silt loam

**Typical values of infiltration rate (FIR) final**

<table>
<thead>
<tr>
<th>Soil type</th>
<th>F I R mm h(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sands</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Sandy &amp; Silty soils</td>
<td>10-20</td>
</tr>
<tr>
<td>Loams</td>
<td>5-10</td>
</tr>
<tr>
<td>Clayey soils</td>
<td>1-5</td>
</tr>
<tr>
<td>Sodicclay soils</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

**Factors affecting infiltration rate:**

1. Compactness of soil surface
2. Impact of raindrop
3. Soil cover
4. Soil wetness
5. Soil temperature
6. Soil texture
7. Soil depth

**Measurement** - by cylinder infiltrometer.

**Permeability:** Qualitatively it is the characteristic of a porous medium relating to the readiness with which it transmits fluids.

Quantitatively, it is the specific property governing the rate of readiness with which a porous medium transmits fluids under standard conditions.

**Factors**

1. Macro & Micropores
2. Depth of soil  
3. Soil texture  
4. Soil moisture status  
5. Salt concentration  
6. Organic matter content  
7. Soil aggregates.

- **Slow** - < 2.5 cm h\(^{-1}\)  
- **Moderate** - around 5.0 cm h\(^{-1}\)

**Percolation**: Percolation is the downward movement of water through saturated or nearly saturated soil in response to the force of gravity. It occurs when tension is smaller than 1/2 atm. It depends on soil and climate.

**Interflow**: Interflow is the lateral flow of water in a relatively pervious soil above a less pervious layer.

**Seepage**: Seepage is the downward and lateral movement of water in the soil.

**Measurement of soil moisture**:

The soil moisture is determined by direct and indirect methods.

**Direct measurement (Gravimetric methods)**: Involve removing water from a soil sample by evaporation, leaching or chemical reaction. Soil moisture content is calculated from the mass of water removed and the mass of dry soil. They are simple and inexpensive, hence widely used.

1. **Oven Drying**: This is a standard method to which all other methods are referred. Soil samples are collected from the desired depth with a auger. They are placed in aluminium boxes and weighed. These samples are dried in oven at 105-110 °C at least for 24 hrs. Then weight of dried samples is taken. The moisture content is calculated as under –

\[
\text{Moisture content(%) = } \frac{\text{Wt.of wet soil}(W_1) - \text{wt.of dry soil}(W_2)}{\text{Wt. of dry soil}(W_2)} \times 100
\]

\[
\text{Volumetric water content } (\%) = \frac{W_1 - W_2}{W_2} \times 100 \times \text{Bulk density}
\]

\[
\text{Depth of water per unit Soil depth (cm) = Vol. water content x Soil depth}
\]
2. **Alcohol Burning method**: Soil moisture from the sample is evaporated by adding alcohol and igniting. 1.0 ml of alcohol per g of soil at FC and 0.5 ml at PWP is adequate for evaporating soil moisture. This method is not recommended for soil with high organic matter.

3. **Hot air drying**: Hot air around 110°C is passed on a screen with weighed samples of moist soil. Samples must be pulverized.

4. **Gypsum sorption plugs**: Gypsum plugs placed in soil comes into equilibrium with surrounding soil moisture. They are removed and weighed to determine soil moisture content. It is necessary to calibrate the wt. of porous cup with soil moisture content for different soils.

5. **Infrared balance**: It gives fairly reliable moisture estimate in about 5 minutes. It consists of a 250 watt infrared lamp, sensitive torsion and autotransformers, all housed in an aluminium cabinet. The radiation emitted by infrared lamp quickly vaporize the soil moisture. The instrument is directly calibrated in % moisture.

6. **Feel and appearance method**: A rough guide for scheduling irrigation. Soil moistures are judged by manipulating soil with hand and fingers. The soil samples from root zone are observed for colour, plasticity and cohesiveness.

**Indirect methods**: Usually measures the volumetric soil moisture content. Relatively quick and accurate.

1. **Tensiometric method**: Tensiometer is also called irrometer, used in irrigation scheduling. It provide a direct measure of tenacity (tension) with which water is held by soil. It estimate the soil -water matric potential which includes adsorption and capillary effects.

   The working Principle of tensiometer is that when a sealed water-filled tube is placed in contact with the soil through a permeable and saturated porous material, the water (inside the tube ) comes into equilibrium with the soil solution. Hence, the soil water matric potential is equivalent to the vacuum or suction created inside the tube.
Tensiometer consists of a sealed water filled plastic tube with a ceramic cup at one end and a negative pressure gauge at the other. Typically measurement range is 0 to 0.80 bars. The vacuum gauge is graduated to indicate tension values up to one atm and is divided into 50 divisions each of 0.2 atm. It is calibrated in centibars or 1/100 of one bar. (Bar is an international unit of pressure in metric system= 14.5 Psi or 0.987 atm.). One centibar is equal to 1 kilopascal (kPa).

Tensiometer is installed at a depth of 30 cm and 60 cm below the ground surface with the help of a probe or screw auger. Depth of hole should be ¼ to 1 inch less than actual depth for the porous tip. Pour ¼ cup of water into the hole. Insert the tensiometer and gently push it down to the desired depth. Instrument is ready to use 24 hrs after installation. Readings should be taken early in the morning.

A reading of zero corresponds to a completely saturated condition. A reading of 85 indicates a very dry condition.

**Meaning of tensiometer reading**

| i  | 0-5 cb | Saturated soil |
| ii | 10 cb  | Field capacity |
| iii| 10-25 cb | Ideal soil water and aeration |
| iv | 25-85 cb | Decreased soil water availability |

**Irrigation scheduling for different soils**

| i  | Clay & Clay loam textured | 50 cb |
| ii | Fine sand textured and sandy duplex | 30-40 cb |
| iii| Corse sand textured | 20-30 cb |

**Pressure plate technique**: This is a laboratory method. The Pressure plate and Pressure membrane apparatus measures the uptake and release from soil samples over a wide range of suction values.

2. **Electrical Resistance method**: It works on the Principal based on the linear relationship between the electrical resistance and
moisture content of soil. Electrical resistance increases with decrease in moisture content.

The resistance blocks are made of gypsum. The electrodes in the blocks are connected to a conductance-meter for measuring the electrical resistance or conductance.

The blocks are buried at an appropriate depth at a certain distance. After sometime equilibrium is reached. As the soil moisture increases or decreases, the water content of block also increases or decreases. Higher the water content, higher is the conductivity. Resistance blocks read low resistance (400 to 600 ohms) at FC and high resistance (50,000 to 75,000 ohms) at PWP. Associated soil water content must be obtained from a calibration curve.

Granular matrix sensors and dielectric soil moisture sensors are also used in this method.

3. **Radiation methods**: Neutron scattering and gamma ray attenuation methods are used to determine soil moisture content.

4. **Thermal methods**: Heat dissipation sensors, heat capacity sensors and soil psychrometers are used to determine soil moisture.

5. **Remote sensing**: Based on infrared or electromagnetic Properties of soil.
ENERGY STATE OF SOIL WATER:
Since the movement of water in soil is quite slow, its kinetic energy (Proportional to the velocity squared) is considered negligible.
The potential energy which is due to its position or internal conditions determines the state and movement of water in soil.
Water potential refers to the ability of water to move in the soil.
More water in soil= more water potential. At saturation potential is near zero. As soil dries values become more negative.

Total potential of soil water is the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water (at the point under consideration) –ISSS (1963)

Soil-water potential (Soil-water tension) is a measure of tenacity with which water is retained in the soil and shows the force per unit area that must be exerted to remove water from soil. It is measured in terms of potential energy of water in soil measured ,with respect to free water .It is expressed in atmosphere, the average air pressure at sea level. Other pressure units i.e. cm or mm of water or mercury are also used.

1 atm= 1036 cm of water = 76.39 mm of mercury.
1 bar= 10⁶ dynes cm⁻² = 1036 cm of water.
1 milli bar= 1/1000 bar

The term capillary potential or pF is also used to define the energy with which water is held by soil. The pF function is defined as the numerical value of the negative pressure of the soil moisture expressed in cm of water.
The total water potential (Ψt) is the sum of gravitational potential (Ψg), the matric potential (Ψm), the pressure potential (Ψp), and the osmotic/solute potential (Ψo) and any other potential.
Ψᵣ = Ψg + Ψm + Ψp + Ψo

The gravitational potential is due to the gravitational force field of the earth and is dependent on the vertical location of the water relative to the reference level.
Gravitational potential may be expressed as \( \Psi_g = gZ \) (mass) or \( P_w g z \) (vol.)

Where \( g = \) Acceleration due to gravity, cm s\(^{-2}\)

\( Z = \) height above reference level

\( P_w = \) Density of water, g cm\(^{-3}\)

When water is above reference level, its \( \Psi_g \) is positive,

**The matric potential** (\( \Psi_m \)) is associated with the more or less solid colloidal matrix of the system (Defined as negative pressure/positive suction head). It includes the forces of adsorption and surface tension. Free water has zero \( \Psi_m \) and will move into a dry soil. The \( \Psi_m \) is negative in unsaturated soil and zero in saturated soil. Thus, removal of water from a soil water system decreases \( \Psi_m \) of remaining water.

\( \Psi_m \) per unit mass \( = gh \)

\( \Psi_m \) per unit volume \( = P_w gh \)

\( \Psi_m \) per unit weight \( = h \) (submergence depth)

**The pressure potential** (\( \Psi_p \)) results from the external pressure on the soil-water i.e. overlying water or submergence depth (h) and atmospheric pressure is the reference. \( \Psi_p \) will be positive in a saturated soil and zero in unsaturated soil.

\( \Psi_p \) per unit mass \( = gh \)

\( \Psi_p \) per unit vol \( = p \) (pressure of water)

**The osmotic potential** (\( \Psi_o \)) / **solute potential** (\( \Psi_s \)) results from the solutes dissolved in soil water.

\( \Psi_o = \pi \) (Osmotic pressure due to dissolved salts or solutes)

**Units of potential** – Pascal (\( P_a \)), Kilopascal (\( Kpa \)) or megapascal (\( MPa \))

1 Bar = 0.1 MPa or 100 \( Kpa \).

Soil water potential is usually negative because of negative matrix potential.

The soil-water potential can be measured in the field with-

1. Tensiometers- 0 to -80 KPa (-0.8 to -800 cm)
2. Thermocouple psychrometers- -98 to -3000 KPa (-1 to -30 bars)
3. Heat dissipation sensors- -9.8 to -100,000 Kpa (-0.1 to -1000 bars)
4. Electrical resistance blocks – 0 to -890 or – 1500 Kpa (0 to -10 or -15 bars)

**Pressure potential in different units** (Marshall et al 1996 & Hillel 1982)
Soil moisture characteristics: Soil moisture tension does not indicate the moisture content of the soil and the amount of moisture that can be withdrawn for plant use at any particular tension. Knowledge of the amount of moisture is essential to know amount of water available to plants, water that can be absorbed by plants and the amount of water required for irrigation.

Soil-moisture or water characteristic curve: Soil-water retention curve are plot of moisture content versus moisture tension which show the amount of moisture in the given soil at various tensions. SWCC:

- Describes relationship between soil-water potential and volumetric water content.
- Can be determined by simultaneous measurement of water content and pressure potential.
- Soil-water retention is a function of pore size distribution.
- At zero pressure potential, the soils volumetric content is said to be saturated water content.
- As soils drains, the larger pores empty first since they have smallest capillary forces.
- Maximum pressure potential at which soil begins to de-saturate is defined as the air entry value of the soil and is determined by largest pores in soil.

SMCC is strongly affected by soil texture. Greater the clay content, greater the water content at any particular suction and more gradual the slope of the curve. In sandy soils, most of the pores are relatively large and once these pores are emptied only a small amount of water remains.
Soil structure also affects the shape of SMCC particularly at low suction range. Soil compaction decreases total porosity, specially the volume of large interaggregate pores, Hence ‘Saturation water content’ and ‘initial decrease of water content’ at low suction are reduced. Volume of intermediate pores is greater in compacted soil, while interaggregate pores remain unaffected. Hence the curves for compact and uncompacted soil may be identical at high suction. At very high suction water is held by adsorption and retention is textural than a structural attribute.

Soil water characteristic relationship may be obtained by

1. Desorption: Taking an initially saturated sample and applying suction or pressure to de-saturate.
2. Sorption: Gradually wetting an initially dry soil.
These two pathways produce curbs that in most cases are not identical. The water content in the ‘drying’ curve is higher for given metric potential than that in the wetting branch. This is called hysteresis, defined as the phenomenon exhibited by a system in which the reaction of the system to change is dependent upon its past reactions to change.

**Capillary movement** - Water moves in the form of thin film from wet to dry region, through micropores, until the thickness of film is equal in both regions.

**Flow of water in the soil**
Flow of water in soil is complex because of
- Various states and direction in which it flows
- The forces that cause it to flow. Water flows downwards due to gravity. It moves in small pores due to capillarity. Because of heat it vapourises and diffuses through soil air. However, rate of flow is greatly affected by soil texture, structure, porosity, soil temperature and soil water content.
**Darcy’s Law:** As per Darcy’s law, the discharge rate $Q$, being the volume $V$, flowing through the column per unit time $(t)$ is directly proportional to the cross-sectional area $A$ and to the hydraulic head drop $\Delta H$, and inversely proportional to the length of the column $L$,

$$Q = \frac{V}{t} = \frac{A\Delta H}{L}.$$ 

Hydraulic head drop across the systems $\Delta H = H_{i} - H_{o}$ at the inflow boundary $(H_i)$ – head at outflow boundary $(H_o)$

The head drop per unit distance in the direction of flow ($\Delta h / L$) is the hydraulic gradient which in fact is the driving force.

The specific discharge rate, $Q/A$ (i.e. the volume of water flowing through a cross sectional area $A$ per unit time $t$) is called flux density (or flux) and indicated by $q$.

Thus the flux is proportional to the hydraulic gradient

$$q = \frac{Q}{A} = \frac{V}{A} \frac{\Delta H}{L}.$$ 

The proportionality factor $K$ is designated as hydraulic conductivity

$$q = k \frac{\Delta H}{L}.$$ 

This equation is known as Darcy’s law.

The hydraulic conductivity determines the ability of soil fluid to flow through the soil matrix system under a specified hydraulic gradient; the soil fluid retention characteristics determine the ability of soil system to retain the soil fluid under a specified pressure condition.

H.C. depends on soil texture, structure and saturation.

**Limitations** of Darcy’s law

1. It applies only when flow is laminar and where soil water interactions do not result in a change of permeability with a change in gradient.
2. Management practices like tillage may affect the flow and H.C.
3. Pore spaces may be entrapped by gases under submerged condition.
4. In coarse sands & gravels, hydraulic gradients in excess of unity may result in non laminar flow.
**Movement of water in the soil:** Water tends to move from an area of higher potential energy to one of lower potential energy.

**MoW under saturated condition** – Saturated flow occurs when the soil pores are completely filled with water. This water moves at water potentials larger than -33 KPa. It is caused by gravity pull. It begin with infiltration. In wetted soil percolation occurs. This movement is affected by texture, structure, organic matter content, depth of soil to hard pan, amount of water in soil, temperature and pressure. Rate of flow follow the sequence sand> silt> clay.

**Moisture movement under unsaturated condition**- In unsaturated soil, moisture movement is also called capillary movement. It is the flow of water held with water potential lower than -33 Kpa. Water will move towards the lower potential. Water moves from wetter to drier areas. It occurs when soil is at field capacity. Sequence-Sand<Loam<clay.

**Water vapour movement**

1. **Internal movement** – The change from liquid to the vapour within the soil, that is in the soil pores.
2. **External movement** - The phenomenon occurs at the land surface and the resulting vapour is lost to atmosphere by diffusion & convection. Movement of water vapour through diffusion depends on vapour pressure gradient i.e. the difference in vapour pressure of two points, a unit distance apart.

Vapour transfer is insignificant in high soil water contents, it increases as void space increases. At soil moisture potential of about-15 bars, the continuity of liquid films is broken and water moves only in vapour form. The vapour pressure of soil moisture increases with increase in soil moisture content and temperature, it decreases with increase in soluble salt content. Water vapour movement is significant only in moist range. In wet and dry range it is negligible or very small.

It is notable that maximum vapour movement in soils is of greatest importance for the growth and survival of plants.
**Capillary rise** The rise of water in a capillary tube to a level higher that in the container is called capillary rise. This rise is due to combined effect of cohesion, adhesion and surface tension.

\[ H = \frac{2T}{pgr} \]

Where 
- \( T \) = Surface tension (dynes/cm)
- \( p \) = density of water (gm/cm\(^3\))
- \( g \) = acceleration due to gravity 981cm/sec\(^2\)
- \( r \) = radius of capillary tube (cm)

**Plant-water relationships**

Plant-water relations deal with the absorption of water by the plant and its loss to the atmosphere through evapotranspiration. The chemical free energy of water in its purest form is also called water potential (\( \Psi_s \)). Its value is given as ‘0’ bars. Plants use water potential to transport water to the leaves. Water always move from the system with a higher water potential to that with lower. For transpiration the condition must as-\( \Psi_{soil} > \Psi_{root} > \Psi_{stem} > \Psi_{leaf} > \Psi_{atm} \).
The water potential is represented by the equation.

$$\Psi_w = \Psi_s + \Psi_p + \Psi_g + \Psi_m$$

1. **$\Psi_s$: Solute Potential** (-$V_e$): when sugar is added to water, the solute potential or energy drops as water molecules bond to sugar. Thus sugar or other molecules accumulated in leaf (relative to root) drop its potential - 1 to -2 MPa.’

2. **$\Psi_p$: Pressure/turgor potential** (+ ve or -ve): As the water is transpired from leaves it creates a negative pressure or tension, Thus is generally less than -2MPa.

3. **$\Psi_m$: Matric potential** (-$V_e$): As water adheres to cell walls it lowers its potential. The walls of xylem, made up of carbohydrates, attract water molecules.

4. **$\Psi_g$: Gravity potential**: This force is not critical at a cellular level but important in tall treas.

New and old terminology

$$\Psi = (-) \text{DPD} - \text{Diffusion pressure deficit}$$

$$\Psi_s = (-) \text{OP} - \text{Osmotic pressure}$$

$$\Psi_p = \text{TP} - \text{Turgor Pressure}$$

$$\Psi_m = \text{MP} - \text{Metric Pressure}$$

**Magnitude of water potentials in SPAC (Soil plant atmosphere continuum)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Water potential (bars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soils</td>
<td>- 0.1 to -20</td>
</tr>
<tr>
<td>Leaf</td>
<td>- 5.0 to -50</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>- 100 to -2000</td>
</tr>
</tbody>
</table>

**Relative water content** (RWC) is the ratio of actual water content to water content at saturation (fully turgid), expressed as percentage.

Actual water content (%) = \( \frac{FW-\overline{DW}}{FW} \times 100 \)
Water content at saturation (%) = \frac{TW - FW}{TW - DW} \times 100

Relative water content (%) = \frac{FW - DW}{TW - DW} \times 100

FW= fresh wt
TW= Turgid wt
DW= Dry wt

For saturation tissues are to be floated on water for 3 to 24 h. for DW samples are dried in oven at 65° to 80°C.

The indirect methods of estimating plant-water status involve measuring leaf temp., canopy temp., canopy air temp. differentials, diffusive resistance, transpiration rate etc. Leaf temp. of stressed plant is high due to reduced transpiration compared with plants adequately irrigated. Thermocouples or infrared thermometers are used for measuring leaf temperature. **Porometers** are used to measure leaf temp. in addition to transpiration and stomata resistance measurements.

**Measurement of Plant water potential**

1. **Pressure chamber:** Pressure chamber measures the tension on the water conducting tissue (xylem). Tension within the xylem is believed to be equivalent to the pressure in the chamber at the first appearance of water and regarded to be measure of physiological ‘dryness’ of the plant, called the water potential.

2. Psychomotor: It measure the water vapour pressure of a solution or plant sample, on the basis of the principle that evaporation of water cools the surface.

3. Dew point hygrometer

4. Osmometer
5. Leaf temperature measurement
6. Canopy temperature measurement
7. Canopy air temperature differentials
8. Diffusive resistance
9. Transpiration rate measurement etc.

Water absorption by plants

Passive absorption- When water is drawn into the roots by negative pressure in the conducting tissues created by transpiration, the process is known as passive absorption.

Active absorption- The plant roots absorb water by spending energy, it is called active absorption, Under normal condition active absorption is negligible. Certain plant surviving in soil at permanent wilting point are able to absorb moisture from atmosphere. This is known as aerial absorption or negative transpiration.

Soil-plant-water relationship-
Water in the soil-plant-atmosphere system moves in response to the differences in energy status of water from one region of the system to the other and always from a region of higher potential to that of a lower potential.

**Soil-plant-water-relationship** deal with the physical properties of soil and water that influence the movement, retention and use of water by the plant that must be considered to plan for an efficient irrigation system.

**Soil-plant-atmosphere continuum** (SPAC) is the pathway for water moving from soil through plant to the atmosphere and back. The SPAC is defined as a concept recognising that the field with all its components (soil, plant, water, atmosphere) constitutes a physically integrated, dynamic system in which the various flow processes involving energy and matter occur simultaneously and independently like links in the chain.

**Conductance pathway**: Soil water → Epidermal cells of root → cortical cell and intercellular spaces → conductive cells of xylem → leaf cells -- intercellular spaces in leaf → stomata → atmosphere.

**Approximate magnitude of - Ψ in the soil – plant – atm system (plant and moreshet, 1973)**

<table>
<thead>
<tr>
<th>Components</th>
<th>Water potential (Bars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>-0.1 to -20</td>
</tr>
<tr>
<td>Leaf</td>
<td>-5.00 to -50</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>-100 to -2000</td>
</tr>
</tbody>
</table>

This decrease in water potential from soil to the atmosphere acts as a driving force that decides the flow of water along the direction of decreasing water potential. Under certain conditions water movement is in the reverse direction when soil is dry and atmosphere is saturated i.e. dew or fog on leaves.

**Plant characteristics influencing irrigation practices**

1. **Root characteristics** – Irrigation methodology should be suitable to the type of root system of the crop i.e. tap root (central primary root and its branches) or
adventitious and depth of roots. The depth of roots is seriously affected by soil characteristics and ground water level. The soil depth from which the crop extracts most of the water needed to meet its evapotranspiration requirement is known as **effective root zone depth**. It is also called as **design moisture extraction depth**, the depth used to determine irrigation water requirement for design.

**Rooting depth (cm) of annual field crops on deep, well drained soil.**

<table>
<thead>
<tr>
<th>Shallow</th>
<th>Medium</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop</td>
<td>Root depth (cm)</td>
<td>Crop</td>
</tr>
<tr>
<td>Rice</td>
<td>50-60</td>
<td>Barley</td>
</tr>
<tr>
<td>Onion</td>
<td>30-50</td>
<td>Wheat</td>
</tr>
<tr>
<td>Cabbage</td>
<td>40-50</td>
<td>Caster</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>30-50</td>
<td>Tobacco</td>
</tr>
<tr>
<td>Potatoes</td>
<td>40-60</td>
<td>Chilies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peas</td>
</tr>
<tr>
<td>Tomato</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**2. Moisture extraction Pattern**- For most plants, concentration of absorbing roots is in upper root zone and near the base of plants. Extraction of water is most rapid in the zone of greatest root concentration under favorable environment. Usual moisture extraction pattern shows as under:

<table>
<thead>
<tr>
<th>Moisture extraction %</th>
<th>Part of root zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>Upper quarter</td>
</tr>
<tr>
<td>30</td>
<td>Second quarter</td>
</tr>
<tr>
<td>20</td>
<td>Third quarter</td>
</tr>
<tr>
<td>10</td>
<td>Fourth bottom quarter</td>
</tr>
</tbody>
</table>

This pattern slightly vary with irrigation frequency. Higher frequency- greater the extraction from upper quarter.
3. Moisture sensitive (critical) periods of crops

Certain periods during the crop growth and development are most sensitive to moisture stress compared with others. These periods are known as moisture sensitive periods.

1. Rice - Panicle initiation and flowering
2. Sorghum – Seedling, panicle initiation, booting, flowering and milk.
3. Maize - Tasseling and silking.
4. Pearl millet - Flowering and grain development.
5. Finger millet - Panicle initiation and flowering
6. Wheat - Crown root initiation and heading
7. Barley - End of shooting and heading
9. Sesame - Flowering to maturity.
10. Sunflower - Flower bud initiation, flowering and milk.
12. Soybean- Flowering and seed formation
13. Cotton - Flowering and boll development
14. Sugarcane - Formative phone and tillering
15. Tobacco - Entire growth period
16. Chilies - Flowering
17. Potato- Sprouting and tuberisation
18. Onion - Bulb formation to maturity
19. Tomato - Commencement of fruit set.
20. Peas - Flowering and pod development.
21. Cabbage - Head initiation until become firm.
22. Citrus - Flowering, fruit setting, fruit growth.
23. Banana - Early vegetative, flowering and fruit formation.

**Water stress and plant growth**

The action of excess or deficit of water on plant is known as water stress. However, in general, stress is used to imply water deficits, Hsiao (1973) classified water stress into three categories.

1. **Mild stress** - A drop of relative water content (RWC) by 8 to 10 percent compared to the value in a well-watered plant under conditions of mild evaporative demand of atmosphere. This corresponds to a drop of plant water potential by -5 to -6 bars.

2. **Moderate stress** - A drop of RWC by 10 to 20% compared to the value in a well-watered plant under low evaporative demand of atmosphere. This corresponds to a drop of water potential by -12 to -15 bars.

3. **Severe stress** - A drop of RWC by >20% compared to the value in well watered plant under conditions of low evaporative demand of atmosphere. This corresponds to a drop of water potential by >-15 bars.

Whenever transpiration exceeds the water uptake, stress (deficit) prevails in plants. **Water deficit affects** water relation in plants, Photosynthesis, respiration, metabolic reactions, hormonal reactions, nutrition, growth and development and yield.

1. **Water relations** - Water deficit alters the water status of plants by influencing absorption, translocation and transpiration, Moisture stressed plant show typical
reduction in leaf water potential and relative water content. It cause increase in leaf and canopy temperatures.

2. **Photosynthesis** - Water deficit cause reduction in photosynthesis due to reduction in photosynthetic rate, chlorophyll content, leaf area and assimilate saturation (storage of carbohydrates).

3. **Respiration** - Respiration increases with mild stress but decreases with increase in moisture stress.

4. **Metabolic reactions** - Almost all the metabolic reactions are affected by water deficit. Severe water deficit cause decrease in enzymatic activity. Accumulation of sugars and amino acids takes place due to breakdown of carbohydrates and proteins.

5. **Hormonal relationship** - Under water deficit the activity of growth promoting hormones like cytokinin, gibberellic acid, indoleacetic acid etc. decrease and growth regulation hormones like abscisic acid, ethylene etc. increases. With change in hormonal balance, growth of leaves, production of tillers or branches is reduced and stomata closure and leaf senescence are increased.

6. **Nutrition** - Water deficits cause reduction in fixation, uptake and assimilation of nitrogen in leguminous plants. The uptake of nitrogen, phosphorus and potassium is reduced by moisture stress, NPK uptake and transpiration rate are highly correlated.

7. **Growth and development** - Generally the organ growing most rapidly at the time of stress is the one most affected. The expansion of cells and cell division are reduced due to moisture stress and results in decreases in growth of leaves, stem and fruits. It affects germination, leaf area, leaf expansion and root growth.
8. Yield - Moisture regime during flowering and grain development determines the number of fruits/grains and individual grain weight, respectively.

Excess water: Excess water causes several changes in soil and plant resulting in reduced growth and in some cases death of plants. The degree of injury depends on type of crop, crop stage, period of water logging and climatic conditions.

The susceptible crops for water logging in descending order are tobacco, tomato, chilies, pulses etc, whereas, rice is the most resistant. Germination and seedling stages are highly susceptible.

Water logging causes plant injury due to low oxygen supply to the roots and accumulation of toxic substances in soil and plant. Mild toxic substances like carbondioxide, hydrocarbon gases, hydrogen sulphide etc are produced due to reduced condition. Shoot elongation, senescence, abscission and production of adventitious roots takes place because of water logging. Respiration in roots change from aerobic to anaerobic. Permeability of roots decreases which result in decreased uptake of water and nutrients.

Crop plant adaptations under moisture stress condition

A Avoidance: Ability of a plant to maintain sufficient water content and turgidity even under severe moisture stress is known as water stress avoidance. It is being achieved in two ways i.e. conserving water in plants and improving water uptake from soil.

(1) Conserving water: Changes in anatomical characters of plant for conservation of cell sap against accelerated transpiration due to higher temperature are as under:

a. Stomatal mechanism- Periodic opening of stomata i.e. stomata open only for few hours in morning and remain closed for rest of the day which result in an
efficient photosynthesis with least loss of water. The process is observed mostly in cereals, which enable the plant to survive for longer period, but limited to a certain thresh-hold level of water content in plant.

b. Increased Photosynthetic efficiency - The plant types having CO₂ assimilation capacity (C-4 group) like maize, soybean, finger millet, sudan grass etc have capacity to fix most of the CO₂ into the form of organic acids (malic acid etc.) during night and convert it into carbohydrate during day time, the so called C-4 pathway. These physiological changes use to inhibit photorespiration and thereby the net photosynthesis is enhanced.

c. Low rate of cuticular transpiration - Plants develop a waxy coating over cuticles for reducing transpiration, as observed in durum wheat, triticale and barley. Cactus have very low rate of cuticular transpiration & survive under stress for quite long period.

d. Decreasing transpiration - Under drought condition soybean plant produce lipid covering on the surface which reduce transpiration (Levitt, 1972)

e. Reduced Leaf area - The water loss through transpiration is directly proportionate to the leaf area. The Xeromorphic plant (cacti, pineapple) reduce their transpiring surface and find fit for stress condition. In some plants rolling and curling of leaves at noon time and taking normal shape in evening time is observed, which escape heat and reduce transpiration. In rice, leaf rolling and unrolling has been suggested as a crierian for scoring drought tolerance.

f. Leaf surface - Development of thick cuticle deposition of more lipids and waxy covering, development of spines are the pronounced changes in leaf surface.
g. **Stomata functioning** - The drought affected plants use to bear less number of stomata which are located in depressions and they retard the rate of transpiration by avoiding direct contact with hot air.

**Awns** - Awned varieties of wheat and rice are best adopted under drought conditions. Under drier condition awned varieties of wheat give better yield than awnless. Awns contribute about 12% to the total dry matter production of drought affected plants. These awns possess chloroplasts and stomata.

(2) **Accelerating water uptake by roots:** well developed and extensive root system can withdraw water from relatively deeper layer.

a. **Effective root system** - Vertical root growth is more helpful. Deeper roots with well developed laterals and extensive root hairs are more beneficial.

b. **High root to top ratio** - The water movement to deeper layers in soil results in more root elongation and hence the root growth exceeds considerably from that of stem.

c. **Differences in osmotic potential of plants** - Plants grown under dry conditions use to have high osmotic pressure and survive for relatively longer period when compared with the plants under irrigated condition.

d. **Development of water economy in plants** - under reduced availability of water, the rate of transpiration is reduced automatically.

B. **Inducing drought tolerance:**

1. **Mitigating moisture stress** - Some plants develop adaptations by maintaining high turgor pressure and avoid dehydration in following ways-
a. Resistance to dehydration- Plants accumulates sufficient solutes which help in maintaining a higher turgor pressure that prevents internal desiccation and the plasma become more drought tolerant. Plants keep on growing in normal way.

b. Prevention of leaf collapse- Morphological Adaptations like thick cell wall, sunken stomata, lipids, spines etc. prevent wilting by reducing transpirational loss of water.

c. Resistance to metabolic setback- The drought tolerance in the plant is tolerated by maintaining turgidity of stomatal guard cells. The plants which reduce their metabolic activity below dehydration compensation point would need lower carbohydrate and would be more drought tolerant. (The dehydration compensation point is a water potential at which the volume of CO₂ evolved during respiration and CO₂ absorbed during photosynthesis becomes equal). Protein loss is avoided by the drought resistant plants by decreasing rate of breakdown.

**Escaping drought** - The plants with shorter life span can escape the drought.

**Type of plants according to drought resistance capability**

**Ephemerals** - These are drought escaping plants. Under semiarid regions the seeds germinate with rains and plants complete their life cycle within a few weeks time.

**Succulent Plants** - These plants are able to survive dry periods on account of large reserves of water accumulated in the inner tissues of the fleshy stems or leaves. They are frequently found in locally dry habitats of semiarid regions and mostly belongs to *Cactaceae, Euphorbiaceae, Liliaceae, Aizoaceae*.

**Drought enduring plants**-Only this group of plants can resist the drought injury. Example-Creosote bush (*Lerrea tridentate*) a dominant plant in semiarid tegions.

Thus the physiological adaptations in plants can be summarised as under-
1. Deeper roots
2. Less number of leaves
3. Smaller leaves
4. Thick cuticles
5. Hypodermal sclerenchyma
6. Close stomata
7. Lower transpiration
8. Leaf modification
9. Thick wax coating over leaf and stem.


**Evapotranspiration**

Evaporation (E) of water is a diffusive process by which liquid water in the form of vapour is lost to the atmosphere. Two essential requirements for evaporation are:

(i) A source of heat to transform liquid water into water vapour. Solar radiation is the principal source of energy (590 cal g\(^{-1}\) of water at 20\(^0\)C).

(ii) Concentration gradient between evaporating surface and surrounding air.

The climatological parameters for assessing evaporation are—solar radiation, air temperature, air humidity and wind speed.

**Datton’s law of evaporation**

Evaporation (E) = (es - ea) f (u)

Where es = Saturation vapour pressure of water

Ea = Actual vapour pressure of air above

f (u) = function of wind velocity

Evaporation measurements are usually made by piche evaporimeter, atmometer and pan evaporimeter. The standard US Weather Bureau (USWB) class A Pan is the most widely used evaporation pan. It is 122 cm in dia and 25 cm in depth, made up of 22 gauge galvanized iron. Painted white and installed on a wooden frame. Water is filled to a depth of 20 cm, water level is daily measured with a
hook gauge in a stilling well, Evaporation is computed as the differences between observed levels, adjusted for any precipitation measured in a rain gauge. Water is added daily to bring the level to a fixed point in the stilling well. The pans have higher rate of evaporation than a large free water surface. Thus a factor of 0.7. is, usually used for converting the observed evaporation to those of large water surface area. This factor is called Pan Coefficient.

Evaporation from land surface is affected by degree of soil saturation, temperature of soil and air, humidity and wind velocity.

Transpiration (T) : Loss of water in the form of vapour from the plant canopy to the atmosphere is termed as transpiration.

Evapotranspiration : The total loss of water from soil surface through evaporation and that as water vapour from plant surface through transpiration, in together refers to evapotranspiration. It has direct correlation with crop yield. Evaporation rate is normally expressed in millimeters (mm) per unit time.

\[
\begin{align*}
\text{As one hectare} & = 10000 \text{ m}^2 \\
\text{One mm} & = 0.001 \text{ m} \\
\text{Loss of 1 mm of water} & = 10 \text{ m}^3 \text{ water ha}^{-1} \\
\text{Thus 1 mm ET/day} & = 10 \text{ m}^3 \text{ ha}^{-1}\text{day}^{-1}
\end{align*}
\]

Energy or heat required to vapourise free water, known as latent heat of vapourisation (\( \lambda \)), is a function of the water temperature. At 20\(^{0}\)C, \( \lambda \) is about 2.45 MJ kg\(^{-1}\); means 2.45 MJ are needed to vapourise 1 kg or 0.001 m\(^3\) of water. Hence, an energy input of 2.45 MJ per m\(^2\) is able to vapourise 0.001 m or 1 mm of water. Therefore, 1 mm water = 2.45 MJ m\(^2\) Evapotranspiration rate expressed in units of MJ m\(^2\)day\(^{-1}\) is represented by ET, the latent heat flux.
Conversion factors for ET

<table>
<thead>
<tr>
<th>Expression</th>
<th>Depth mm</th>
<th>Volume per unit area</th>
<th>Energy per unit area MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m³ ha⁻¹ day⁻¹</td>
<td>s⁻¹ ha⁻¹</td>
</tr>
<tr>
<td>1 mm day⁻¹</td>
<td>1</td>
<td>10</td>
<td>0.116</td>
</tr>
<tr>
<td>1 M³ ha⁻¹ day⁻¹</td>
<td>0.1</td>
<td>1</td>
<td>0.012</td>
</tr>
<tr>
<td>1 s⁻¹ ha⁻¹</td>
<td>8.640</td>
<td>86.40</td>
<td>1</td>
</tr>
<tr>
<td>1 MJ m⁻² day⁻¹</td>
<td>0.408</td>
<td>4.082</td>
<td>0.047</td>
</tr>
</tbody>
</table>

Factors affecting evapotranspiration

A. weather/climatic parameters

1. Air temperature
2. Solar radiation
3. Relative humidity
4. Wind velocity
5. Precipitation

B. Crop characteristics

1. Stomata number and size
2. Stomatal opening and closing
3. Canopy cover
4. Adaptive mechanism
5. Rooting characteristics
6. Length of crop growing season

C. Management and environment factors

1. Tillage
2. Irrigation schedule
3. Fertilizers
4. Plant protection
5. Weed management
6. Wind breaks
7. Salinity
Evapotranspiration and crop yield relationship

Water use-yield relationship – Under adequate water supply the ET is expected to be maximum for realizing potential crop yield, provided other management practices are optimal. Relative yield is the proportion of actual yield \((Y_a)\) to the maximum yield \((Y_m)\), can be expressed as percentage or as a function by subtracting by one. \((1 - Y_a/Y_m)\). Similarly, relative ET can be expressed as \(1 - Eta/ETm\). Thus, the relationship equation can be as-

\[
1 - \frac{ETa}{ETm} = K_y \left( 1 - \frac{Y_a}{Y_m} \right)
\]

Where \(K_y\) is a constant which is the yield response factor and can be estimated if the ET and yield data are available.

Evapotranspiration and consumptive use:

Evapotranspiration (ET) = Evaporation from crop field (E) + Transpiration (T) + intercepted precipitation by crop and lost as evaporation (IP)

Consumptive use (CU) = E.T. + water used by crop plants for metabolic activities (Ww). It is nearly 1%

Evapotranspiration concepts

Potential Evapotranspiration (PET) is the highest rate of evapotranspiration by a short and actively growing crop with abundant foliage completely shading the ground surface with abundant soil water supply under a given climate. This refers to the maximum water loss from the crop field.

Reference crop evapotranspiration \((ET_0)\)- Evapotranspiration rate from a reference surface, not short of water is called the reference crop evapo-transpiration. Reference surface is a hypothetical grass reference crop with specific
characteristics. The redefined (FAO Penman-Monteith crop evapotranspiration (Allen et al. 1998) is: ‘Evapotranspiration from a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 sm\(^{-1}\) and the albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered.

Actual crop evapotranspiration (ET crop) refers to the rate of evapotranspiration by a particular crop in a given period under prevailing soil water and atmospheric conditions. **Crop evapotranspiration under standard condition** is the evapotranspiration from a well maintained crop, grown in large fields, under optimum soil moisture condition and able to give maximum production under given climatic condition.

To find the ET crop the following relationship is used

\[
ETc = ETo \times Kc
\]

\[
Kc = \text{Crop coefficient}
\]

\[
Kc = \frac{ETc}{ETo}
\]

Crop evaporation under non-standard condition \((ETc \text{ adj})\) is the evapotranspiration from crops grown under management and environmental condition that differ from standard condition.

\(ETc \text{ adj} \) is calculated by using a water stress coefficient \(Ks\) and/or by adjusting crop coefficient \(Kc\) for other stresses and environmental constraints.

The effects of soil water stress are described by multiplying the basal crop coefficient \(Kcb\) by the water stress coefficient \(Ks\):

\[
ETc \text{ adj} = (Ks \cdot Kcb + Kc) \cdot ETo
\]
Measurement of Evapotranspiration

1. Energy balance and microclimatological methods.
2. Soil water balance
3. Lysimeters
4. Empirical methods (from meteorological data).

1. **Energy balance and microclimatological methods**

Evaporation of water requires energy in the form of sensible heat or radiant energy. Therefore, the evapotranspiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available.

\[ R_n - G - \lambda E_t - H = 0 \]

Where Rn = net radiation, H = Sensible heat

\[ G = \text{Soil heat flux}, \quad ET = \text{Latent heat flux}, \]

Latent heat flux (ET) representing the evapotranspiration fraction can be derived from the ‘energy balance equation’ if all other components are known. 'Rn' and ‘G’ can be estimated from climatic parameters. Measurement of ‘H’ is complex and requires accurate temperature gradients above the surface.

2. **Soil water balance** : It is an account of all quantities of water added, removed or stored in soil during a given period of time.

Change in soil water = Inputs of water – Losses of water

**Water Inputs** = P + I + C

Where, P = Precipitation, I = irrigation

\[ C = \text{Contribution from ground water}. \]
Losses of water = ET + D + RO

Where ET = Evapotranspiration, D = Deep drainage, RO = Surface runoff.

Thus, Change in soil water = (P + I + C) - (ET + D + RO)

Suppose, the amount of water in root zone at the beginning is M₁ and at the end of period is M₂. M₁ - M₂ = P + I + C – ET - D – RO

Or M₁ + P + I + C = ET + D + RO + M₂

Using this equation any unknown parameter can be computed, if all others are known. This is useful for selecting appropriate water management strategies.

3. **Lysimeters**: Lysimeters provide the direct measurement of water flux from vegetative surface. Lysimeter is a large tank filled with soil. Rectangular units of 4.0 m² are satisfactory for most crops. Total depth ranges between 100-150 cm as per root depth of crops. In general, 50% available soil moisture depletion in root zone should not be exceeded. The crop grown in lysimeter is the same as in surrounding area.

There are two types of lysimeters, weighing and drainage type. In the drainage type, the inflows and drainage are measured, but changes in storage within soil are not measured. In weighing type lysimeters each element i.e. rainfall, irrigation, runoff and ET can be determined by using water balance equation.

\[
ET = \text{Weight change} + \text{water added} - \text{percolation}
\]

4. **Empirical methods**: Empirical methods to predict the water requirements are primarily based on climetological data and crop factors. There are four methods of predicting ET under different climatic conditions, recommended by FAO group of Scientists (Doorenbos and Pruitt, 1975)

1. Blaney - Criddle method
2. Radiation method
3. Modified penman method
4. Pan evaporation method

Three major steps involved in estimation of ET by empirical methods are
1. Estimation of reference evapotranspiration (ET0)
2. Determination of crop coefficients (Kc)
3. Making adjustments to location specific environments

Modified Penman and radiation methods offer best results for periods as short as 10 days followed by pan evaporation method. Blaney-criddle method is ideal for periods of one month or more in many climates.

**Blaney-criddle Formula:** Blaney- Criddle (1950) formula is based on mean monthly temperature, daylight hours and locally developed crop coefficients

\[ U \ (CU) = u \ (\text{monthly consumptive use}) = KF \ (\text{consumptive use factor}) = kf \ (\text{empirical consumptive use crop coefficient, for the month}) = \frac{100}{100} \]

Where,

\[ U \ \text{or} \ CU \ = \ \text{Seasonal consumptive use} \]

\[ u \ = \ \text{monthly consumptive use} \]

\[ t \ = \ \text{Mean monthly temperature (}^{0}\text{F)} \]

\[ p \ = \ \text{Monthly daylight hours expressed as percentage of daylight hours of the year.} \]

\[ f \ = \ t \times P/100, \ \text{monthly consumptive use factor} \]

\[ k \ = \ \text{empirical consumptive use crop coefficient, for the month (= u/f)} \]

Doorenbos and Pruitt (1975) recommended following relationships for ‘f’ in this formula

\[ f = p \ (0.46 \times t + 8.13) , \ \text{using t in } ^{0}\text{C} \]
Or

\[ f = 25.4 \frac{p \times t}{100}, \text{using } t \text{ in } ^{\circ}\text{F} \]

Thus, finally it becomes

\[ ET_0 = C [p (0.46 t + 8.13)] \]

Where, \( ET_0 \) = reference ET (mm day\(^{-1}\)) for the month

\[ C = \text{adjustment factor depending on RHmin, daytime wind velocity and ratio of actual sunshine h to maximum possible sunshine hour.} \]

\[ T = \text{mean daily temperature for the month.} \]

\[ P = \text{mean daily percentage of total annual daytime.} \]

**Radiation method**: This method requires direct measurement of bright sunshine hours, general levels of humidity and wind velocity.

\[ ET_0 = C (W \times Rs) \]

Where, \( Rs = \) Measured mean incoming shortwave radiation (mm day\(^{-1}\)) – (by pyrenometer) or obtained from \( Rs = (0.25+0.50x n/N) Ra. \)  Where \( = Ra \) is extraterrestrial radiation (mm day\(^{-1}\)), \( N = \) maximum possible sunshine duration (h day\(^{-1}\)), \( n = \) measured mean actual sunshine duration (h day\(^{-1}\)), \( W = \) Temperature and attitude dependent weighing factor

\[ C = \text{Adjustment factor made graphically on w. Rs using estimated values of R H mean and U daytime.} \]

**Pan evaporation method**: Evaporation from pans provides measurement of integrated effect of radiation, wind, temperature and humidity on evaporation from open water surface. To relate pan evaporation to \( ET_0 \), empirically derived Pan coefficients are suggested to account for climate, type of Pan and Pan environments
ET\(_0\) = K\(_\text{pan}\) \times E\(_\text{pan}\)

Where,  
E\(_\text{pan}\) = evaporation (mm day\(^{-1}\)) from class A Pan  
K\(_\text{pan}\) = Pan coefficient.

**Modified Penman method**: It gives fairly satisfactory results for predicting the effect of climate on ET\(_0\) as it utilises almost all the meteorological Parameters associated with ET.

\[
ET_0 = C \left[ W \times Rn + (1 - W) \times f(u) \times (ea - ed) \right]
\]

R\(_n\) = Net radiation (mm day\(^{-1}\))

or  
R\(_n\) = 7.5 \(R_s\) – R\(_{nl}\)

\(R_s\) = Short wave radiation (given earlier)

R\(_{nl}\) = net long wave radiation (mm day\(^{-1}\)) a function of temperature \(f(T)\), of actual vapour pressure \(f(ed)\) and sunshine duration \(f(n/N)\) or \(R_{nl} = f(T) \times f(ed)\).

\(ea - ed\) = Vapour pressure deficit, the difference between saturation vapour pressure \((ea)\) at \(T\) mean (mb) and actual vapour pressure \((ed)\)

\(f(U)\) = wind function or \(f(U) = 0.27 \left(1 - \frac{U}{100}\right)\) with \(U\) in Km day\(^{-1}\) at 2 m ht.

W = Tempreature and altitude dependent weighting factor.

C = Adjustment factor for the ratio \(U\ day/U\ night\) for RH max and for \(R_s\).

**Crop coefficients for estimating ET\(_C\)**

The conditions that affect crop water loss (ET\(_C\)) will also affect evaporation from free water surface in a similar manner. It is then necessary to obtain a crop coefficient (K\(_c\)) to estimate ET\(_c\).

\[
ET_c = ETo \times Kc
\]
Actual crop water requirements, in addition to climate, include the effect of crop characteristics and management practices. Crop coefficient is used to account for all these variations. The climatic data required for selection of crop coefficients are wind speed and humidity. The FAO kc curve is constructed by dividing crop growing period into four growing periods and placing straight line segments through initial and mid season periods being horizontal. The four growth periods are initial period, crop development, mid season and late season. However, FAO coefficients (kc) for major crops (Doorenbas and kassam, 1979) are available for use.

CROPWAT : FAO IDP 46 and 49

CROPWAT is a water balance based computer programme to calculate crop water requirements and irrigation water requirements from climatic and crop data. The programme also allows the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying cropping patterns. Water balance procedures also allow an assessment of effective rainfall and an evaluation of rainfed production through calculated yield decreases through water balance procedures. This also allows yield reduction predictions to be made and taken into account in making irrigation management decisions to optimize crop water productivity and return to investment.
Soil Plant and Meteorological factors determining Water needs of crops

**Water requirement (WR):** Water requirement of crop is the quantity of water, required by a crop or diversified pattern in a given period of time for their normal growth under field conditions. It includes ET and other economically unavoidable losses.

**Consumptive use (CU):** It is the sum of the volumes of water used by crop over a given area in producing plant tissue, in transpiration (T), and that evaporated (E) form adjacent soil or plant foliage. Since the volume used in producing plant tissue is negligible (1%), CU can be approximately equal to ET.

\[ WR = CU = ET \]

Since, water requirement also include the unavoidable application losses eg. Percolation, seepage, runoff etc. (AL) and water used for special operations (WSO) like land preparation, presowing irrigation etc, it is expressed as -

\[ WR = ET + AL + WSO \]

In terms of source of water it is expressed as - \[ WR = IR + EP + S \]

Where, \[ IR = \text{Irrigation requirement} \]

\[ EP = \text{Effective precipitation} \]
S = Soil profile moisture contribution

**Irrigation requirement (IR):** The total amount of water required to supplement precipitation (EP) and soil moisture contribution (S) to meet crop water needs for optimum growth and yield.

\[
IR = WR - (EP + S)
\]

**Net irrigation requirement:** It is the depth of irrigation water exclusive of precipitation and ground water contribution or other gains in soil moisture, that is required for plant growth; the amount of irrigation water required to bring the soil moisture level in the effective root zone to the field capacity.

\[
NIR = (CU - EP) + AL
\]

**Gross Irrigation requirement:** It is the net irrigation requirement and losses in conveyance, distribution and application of water in operating system.

\[
GIR = \frac{NIR}{Irri: Efficiency}
\]

**Optimum water requirement (OWR):** It is the amount of water required during the growing season to produce highest crop yield.

**Irrigation frequency:** It refers to the number of days between two successive irrigation during the periods without precipitation.

**Determination of crop water requirements**

A. **Direct measurements**

6. Water balance method

B – From climatic data

1. Pan evaporation data 2. Estimation by climatic parameters.

Factors affecting irrigation water needs

1. Climate and crop growing season 2. Crop characteristics 3. Soil factors

4. Crop management practices

1. **Climate**: Principal climatic factors influencing crop water requirement are precipitation, solar radiation, temperature, wind velocity and relative humidity.

   - Well distributed rainfall during the crop season minimises the irrigation need of crops.
   - Crop in sunny and hot climate need more water per day than that under cloudy and cool climate.
   - Crop water needs are higher under dry weather than the humid.
   - High wind velocity increase crop water requirement

2. **Crop characteristics**: Crop water requirements vary according to growth habit, canopy development, leaf area, sensitivity to drought and duration of crops.
- Tall crops and varieties intercept more solar radiation and have more daily water requirement than shorter crops & varieties.
- Crops with deep root system, have higher water requirement than shallow rooted crops.
- High leaf area increases crop water needs.
- Longer the duration, higher crop water need.
- Crop with higher water sensitivity suffer greater reduction in yield.

**General sensitivity of crops to drought**

**Group I - Low sensitive**: Safflower, ground nut, pearl millet.

**Group II - Moderate Low**: Sorghum, finger millet cotton, sunflower, castor sugarcane

**Group III – Moderate high**: Wheat, Pulses, upland rice

**Group IV – Highly Sensitive**: Lowland rice, Maize

3. **Soil factors**: Coarse textured and well aggregated soil retain less water and have low hydraulic conductivity; hence they support less E.T.
   - Rideges and furrows minimize evaporation loss.
   - Dark coloured soils absorb more heat which lead to higher E.T.

4. **Crop management Practices**
- Frequent irrigations increases crop water requirements.
- Water requirements with border and check bason irrigation are higher.
- Harrowing or hoeing minimizes water loss.
- Weed management reduce water loss.
- Fertilizer application increases water needs.
- Plant population and row spacing influence E.T.
**SCHEDULING IRRIGATION**

**Irrigation Scheduling**: Supply of water in optimum quantity at right time with appropriate application method is called irrigation scheduling.

It enables irrigator to apply exact amount of water; increases irrigation efficiency. There is accurate measurement of the volume of water applied or depth of application.

**Advantages**

1. It enables the farmers to schedule water rotation among different fields to minimise water stress and maximise yields.
2. It reduces cost of water and labour through fewer irrigations, thereby making maximum use of soil moisture.
3. Save fertilizer costs by reducing run off and leaching losses.
4. Increases net returns by increasing yield and crop quality.
5. It minimises water logging problems.
6. It assists in controlling root zone salinity problems through controlled leaching.
7. Additional returns by using saved water.

**Factors influencing irrigation schedules**
1. Soil  
2. Plant  
3. Climate  
4. Managements

**When to irrigate**

1. Maintenance of soil moisture around field capacity is ideal for many crops.
2. As the soil moisture tension increases crops can’t extract needed moisture for optimum growth.
3. Crop starts wilting leading to retard growth and permanent wilting.
4. Crop should not experience moisture stress between two irrigations.
5. By knowing ASM in crop root zone and ET demand, irrigation need can be determined.

**Approaches for scheduling irrigation**

1. **Soil moisture monitoring**
   
   (i) Measurement of soil water potential by tensiometer or gypsum blocks etc.
   (ii) Soil moisture content by direct methods (gravimetric)
   (iii) Feel and appearance method.

2. **Atmospheric measurements and water balance technique**
   
   (i) Measurement of crop evapotranspiration (ETtc)
   (ii) IW/CPE approach
   (iii) Lysimeter studies
   (iv) Field water balance

3. **Plant based monitoring**
   
   (i) **Contact methods**
   
   a. Measuring plant-water status by pressure chamber, Dew point hygrometer, osmometer, tissue water content.
b. Measurement of plant response by sap flow sensors, stomatal conductance (porometers) and plant growth rate.

(ii) Non contact method

a. Site specific crop management and irrigation
b. Plant spectral responses
c. Radiometric sensors
   - Multispectral sensors
   - Hyperspectral sensors
   - Thermal sensing

**Plant Indices**

1. Visual symptoms
2. Soil cum sand miniplot
3. Plant population
4. Growth rate
5. Indicator plants

*Delta* is the total depth of irrigation to a crop in centimeters. It can be calculated by dividing the volume of irrigation water by the area irrigated.

*Duty* is the ratio between irrigated area and quantity of water used. It is expressed in litres per second per ha and indicates the flow requirement per hectare of cropped area.