3.1 General

Water entering the soil at the surface of ground is termed as infiltration. It replaces the soil moisture deficit and the excess water moves downward by the force of gravity, which builds up the ground water. Different approaches are being used to determine the soil infiltration rate. Many simple analytical equations are available for determination of infiltration by double ring infiltrometer. Some of the well-known infiltration equations are:

1. Green and Ampt 1911
2. Kostiakov Equation 1932
3. Modified Kostiakov Equation 1978
4. Horton Equation 1940
5. Philip Equation 1954

The infiltration rate of a soil determines the maximum rate at which irrigation should be applied. When irrigation water is applied at a higher rate it results in ponding of water and surface runoff. Infiltration plays very important role in the process of hydrological cycle. Detailed study of infiltration process meets the following purposes:

- Estimation of peak flow rates and volumes of runoff for planning of dams, culverts, and bridges etc.
- Estimation of surface runoff and overland flow.
- Watershed planning and management.
- Estimation of groundwater recharge.
- Assessment of soil moisture deficit and planning for irrigation and drainage system etc.

3.2 Definitions and Terminologies

a) **Infiltration**: The entry of water into the soil, generally by downward flow.

b) **Infiltration Rate** (i): The amount of water entering the soil per unit time.

c) **Basic Infiltration Rate**: The rate at which infiltration becomes constant is called as basic infiltration rate. It is also called as constant infiltration rate and upon type of soil.

d) **Infiltration Capacity (Infiltrability)**: The amount of water per unit time which a given soil profile takes in through its surface when it is continued in contact with water at the atmospheric pressure.
e) **Average Infiltration Rate** ($i_{av}$): Average infiltration rate is the cumulative infiltration divided by the total time of infiltration measured from the beginning of infiltration ($I/t$).

f) **Sorptivity ($S$)**: It is a function of initial and as well as saturated water contents, and may be obtained by determining the slope of $I/t$ versus $t$. Sorptivity is mainly required in Philip’s two-term model of infiltration.

g) **Saturated Hydraulic Conductivity ($K$)**: It measures the soil’s ability to conduct water when saturated. The type of soil affects the value of the saturated hydraulic conductivity and it is site-specific.

h) **Permanent Wilting Point (PWP)**: The permanent wilting point is the water content of a soil when most plants growing in that soil wilts and fail to recover their turgidity even after rewetting.

i) **Field Capacity (FC)**: The field capacity is the amount of water remaining in the soil a few days after having been wetted and after free drainage has stopped. The larger pores drain first so gravity drainage, if not restricted, may only take hours, whereas in clay soils (without microspores); gravity drainage may take two to three days. The volumetric soil moisture content remaining at field capacity is about 15 to 25% for sandy soils, 35 to 45% for loam soils, and 45 to 55% for clayey soils.

j) **Water Holding Capacity**: The ability of soil to hold water depends upon types of soils, and capacity of plant roots to extract water easily from soil. Readily available water (RAW) is defined as the millimeters of water that tree roots can utilize per centimeter of soil depth. The amount of readily available water in the root zone of a tree crop (millimeters) is the cumulative total of the depth in centimeters of each soil layer multiplied by the appropriate RAW value for the soil texture of that layer.

The number calculated denotes the water holding capacity of soil in the tree crops root zone, that is, the amount of irrigation water applied in millimeters that which it takes in to fill the soil profile (Fig. 3.1). This is indicative of the amount of water that a soil loses when it dries from its field capacity (-8kPa) to the refill point (approximately -60kPa). The amount of water required to be applied for a single watering should not exceed this value; otherwise water would lost below the root zone.
Fig. 3.1 Water Holding Capacity of a Soil in the Tree Crops Root Zone

3.3 Factors Affecting Infiltration

The infiltration process appears to be very simple. However it is influenced by various factors. Following are some of the factors influencing the soil infiltration:

a) **Organic Matter:** A dead bodies of the animals, plant materials, dead or alive is called as organic matter. This material commonly assists the infiltration process. Organic matter raises the entry of water by protecting the soil masses from getting broken down during the impact of raindrops. Particles broken from masses can clog the pores and will seal the surface, decreasing infiltration throughout a rainfall event.

b) **Compaction:** A compacted layer of soil or an impervious zone adjacent to the surface checks the entry of water into the soil and it tends ponding of water on the soil surface.

c) **Permeability:** The ability of a material to allow fluids such as water to pass through it. Larger particles will increase permeability, because pore space is larger. Impermeability may be due to tight packing or cementing of particles, which seals off the pores from one another.

d) **Capillarity:** The process by which water is drawn into openings due to the attractive force between water molecules and the surrounding earth materials. As the particle size decrease, capillarity increases. When water moves upward against gravity, it is called as capillary action.

e) **Porosity:** Porosity is the percentage of open space (pores and cracks) in a material compared to its total volume. Generally, greater the porosity, greater would be the amount of the infiltration that can occur (Fig. 3.2).
It is dependent upon shape of particles as:

i) Well rounded particles have a greater porosity,  
   ii) Angular particles.

(a) Round particles = more pore space, higher porosity and more infiltration  
(b) Angular particles = less pore space, less porosity and less infiltration

Fig. 3.2 Particle Shape and Infiltration Relation

f) Vegetation: The foliage of Grasses and plants capture the falling precipitation, keeping that water away from being absorbed into the earth. The water flowing through the vegetation reduces the velocity of the flowing and this will provide time to the ground to absorb the water. The ground without vegetation, have usually high runoff and less infiltration rates.

g) Initial Moisture Content: The initial moisture content affects the preliminary infiltration rate though the basic rate of infiltration is not substantially affected. A dry soil reaches the basic infiltration rate later than the wet soil (Fig. 3.4). This has very important aspect from irrigation point of view. The quantity of water infiltrated in dry and wet soils in the time ‘T’ at the same rate of application is different. It is higher in dry soils than in the wet soils.

Fig. 3.3 Effect of Land Cover and Evaporation
h) Sorting: If all the particles in a material are about the same size, they are said to be sorted while if the particles are of mixed sizes, they are said to be unsorted (Fig. 3.5). In case of sorted particles higher porosity and unsorted lower porosity as the smaller particles fill in the pore space.

![Sorted and Unsorted Material Arrangement](image)

Fig. 3.5 Sorted and Unsorted Material Arrangement

i) Surface Sealing and Crusting: Changes in the hydraulic conductivity of the surface soil has a stronger influence on the infiltration rate than most of the other factors. A crust on the soil surface can seal the pores and restrict the entry of water into the soil. The formation of a seal 5 mm thick lead to a 75% decrease in infiltration rate.

j) Rainfall Rates: A high rainfall rates may cause destruction of the soil surface leading to surface sealing or the formation of soil crusts and reduction in infiltration rate.

k) Soil Texture and Structure

In general, fine textured soils have lower infiltration rates than the course textured soils (Fig. 3.6). The structure of soil also influences the infiltration process and rates. Clay soils for example, swell because of their structure and after an initial period, show a definite sharp decrease in the infiltration rate.
Fig. 3.6 Typical Infiltration Rates for Various Soils

3.4 Zones of Infiltration

The distribution of water during the process of infiltration under the ponded conditions is categorized into five zones as illustrated in Figure 3.7.

a) Saturated zone: The pore space in the saturated zone is filled with water, or is saturated and is just below the surface. Depending on the length of time elapsed from the initial application of the water; it extends generally only to a depth of a few millimeters.

b) Transition zone: This zone is characterized by a rapid decrease in water content with depth, and will extend approximately a few centimeters.

c) Transmission zone: The transmission zone is characterized by a small change in water content with depth. In general, the transmission zone is a lengthening unsaturated zone
with uniform higher water content. The hydraulic gradient in this zone is primarily driven by gravitational forces.

d) **Wetting zone:** In this zone, the water content sharply declines with depth from the water content of the transmission zone to near the initial soil water content.

e) **Wetting front:** This zone is characterized by a steep hydraulic gradient and forms a severe boundary among the wet and dry soil. The hydraulic gradient is primarily driven by matrix potentials. Beyond the wetting front, there is no noticeable water penetration.

### 3.5 Methods of Infiltration Measurement

Numerous methods have been developed for measuring infiltration rates of soils in the field. These methods may be classified into three groups.

- a) **Instrumental Methods**
- b) **Hydrograph Methods**
- c) **Other Methods**

#### 3.5.1 Instrumental method

In instrumental method, cylindrical infiltrometer also called as flooding infiltrometer are used for the determination of infiltration by the constant head method or by the variable head method. For this method single ring or double ring infiltrometer may be used. In flooding infiltrometer the infiltration rate is calculated from the drop in water level per unit time or the amount of water required maintaining the specified depth or head of water per unit time and the maximum rate of entry of water into the soil is measured.

#### 3.5.1.1 Single Ring Infiltrometer

Single ring infiltrometer in its simplest form consists of only one cylinder (Fig. 3.8) with which infiltration is measured by pouring the water into the cylinder and measuring the quantity of water added for the particular time interval by maintaining the constant head. As the name suggests single ring infiltrometer consists of single ring having diameter 30 cm and depth about 25 cm. In this infiltrometer lateral movement of water is not restricted therefore it shows large variations in infiltration rates. To account for this drawback in measurement of infiltration rate, double ring infiltrometer is used.
Fig. 3.8 Single Ring Infiltrometer

3.5.1.2 Double Ring Infiltrometer

In double ring infiltrometer there are two concentric cylinders as shown in Fig. 2.1 in previous chapter. During measurement of infiltration, observations are taken with respect to inner cylinder and water is filled in the outer cylinder to the same height as that of water in inner cylinder to avoid lateral movement of water. Though it has some advantages, it also have some disadvantages such as; the soil gets disturbed while inserting the cylinder into the ground. The interference between the soil and the side of the metal ring may also cause unnatural seepage and high infiltration rates. It requires relatively little water compared with the basin infiltrometer, and only one person can set up and run several tests simultaneously. The double ring infiltrometer system provides the most accurate results while taking care of lateral flow.

3.5.1.3 Limitations of infiltrometer

The ring infiltrometer are having certain limitations such as infiltration rate decreases with increase in depth and diameter of infiltration rings. The rate of infiltrometer increases as the head of water increases in constant head and cannot be used on a sloping soil surface.

3.5.2 Hydrograph method

Infiltration rate curves can be obtained for field plots and watersheds through the analysis of runoff hydrograph. In the hydrograph methods the infiltration rate is determined from the record of the rainfall and runoff from the catchments area, neglecting evaporation for each period of intense rainfall in a given storm will produce a peak on the runoff hydrograph, the infiltration rate is obtained by subtracting the amount of surface runoff under each peak from the amount of the rainfall. Also total volumes of infiltration and various other losses from a
given recorded rainfall can be obtained from a discharge hydrograph. From the total discharge hydrograph the base flow is separated by using any method of base flow separation. When base flow is separated the discharge hydrograph results into direct runoff hydrograph (DRH) and this will account for the direct surface runoff. Direct surface runoff also called as excess rainfall in terms of inches uniformly distributed over a watershed can readily be calculated by picking values of direct runoff hydrograph discharge ordinates at equal time intervals from the hydrograph and using the following relationship.

\[ Pe = \frac{(0.03719) \left( \sum qi \right)}{An_d} \]  

(3.1)

Where, \( Pe \) = Precipitation excess in inches, \( qi \) = DRH ordinates at equal time intervals in cubic feets, \( A \) = Drainage area in million inches square, \( n_d \) = number of time intervals in a 24- hour period.

### 3.5.3 Other methods

There are other methods that can be used for measurement of infiltration such as rainfall simulator, basin ponding method, inflow outflow method, block furrow method, recycling furrow method, and sprinkler infiltration method.

#### 3.5.3.1 Rainfall Simulator

Rainfall simulators are used to a close to hundred years in various forms and differing degrees of refinement. The development of rainfall simulator has reflected advances in both technology, and in our knowledge of rainfall and its interaction with soil. Currently, there are many designs of rainfall simulators. In this a small plot of land, of about 2 m × 4 m size, is provided with a series of nozzles on the longer size with arrangements to collect and measure the surface runoff rate. The specially designed nozzles produce raindrops falling from a height of 2m and are capable of producing various intensities of rainfall.

Experiments are conducted under controlled conditions with various combinations of intensities and durations and the surface runoff is measured in each case. Using the water budget equations involving the volume of rainfall, infiltration and runoff, the infiltration rate and its variation with time are calculated. Fig. 3.9 (a) show the fabrication work of dripper type rainfall simulator in progress and Fig. 3.9 (b) completed rainfall simulator at S.R.E.S., College of Engineering; Kopargaon.
Advantages and limitations of rainfall Simulator
Like other methods the rainfall simulator are having some advantages and also disadvantages.

The advantages are:
i) The ability to take many measurements quickly without having to wait for natural rain and, 
ii) It is quicker and simpler to set up over existing plots.

The Limitations are:
i) It is cheap for few square meters but expensive and cumbersome for big plots and, 
ii) Simulators are likely to be affected by heavy wind.

Fig. 3.9 (a) Fig.3.9 (b)
Fig. 3.9 Dripper Type Rainfall Simulator Installed by Prof. Jejurkar at Kopargaon

1.5.3.2 Sprinkler infiltrometer

As the name implies, it is a test where the irrigation is practiced by sprinkler irrigation. In the test for the border, basin or furrow, the rate of application is always more or equal to the rate of infiltration of soil at that moment.

Fig. 3.10 Sprinkler Infiltrometer Layout (Source: WALMI- Part-II)
3.5.3.3 Basin ponding method

The basin ponding method is very similar in principle to the cylinder method except that a circular or rectangular basin is used instead of a cylinder. This method is particularly useful in Vertisols where the infiltration rate is low and where basin or border irrigation is practiced. The basin is prepared on a level ground by constructing levees on the sides of the basin. The levees are 0.2m high and well compacted, cracks are sealed and a plastic sheet is laid in the basin. A hook gauge is fixed to record the water level in the basin. Water is then introduced in basin to a depth of 12cm. The plastic sheet is instantaneously removed. The water level is noted at zero time.

Also drop in level is noted at different time intervals as in the cylinder test. Usually the size of the basin is 1m diameter in case of the circular basin and 1sq.m in case of the square basin. The infiltration curves and equations can be developed similar to cylinder test.

3.6 Commonly used Infiltration Equations

a) Kostiakov Equation – A simple form of the Infiltration equation which is in general use was developed by Kostiakov (1932) and is expressed as:

\[ Y = at^b \]  

(3.2)

Where: \( Y \) - cumulative infiltration, \( t \) - time from start of infiltration, ‘a’ and ‘b’ are soil constants to be determined experimentally. The Kostiakov parameters ‘a’ and ‘b’ must be evaluated from the field measured infiltration data, since they have no physical interpretation. The Kostiakov equation describes the measured infiltration curve and the soil under consideration and with the same initial moisture condition, allows speculation of an infiltration curve using the same constants developed for existing conditions. Criddle et al., (1956) used the logarithmic form of the equation to determine the parameter values for ‘a’ and ‘b’ by plotting log(Y) against log(t), which results in a straight line provided the Kostiakov equation is applicable to the given data.

The intercept of the equation (infiltration rate at time \( t = 1 \)) is log (a), and the slope is b. For the higher value of ‘b’; the slope is steeper and the rate of decline of infiltration would be greater. The greater the value of ‘a’ the greater the initial infiltration value (Naeth et al., 1991). The Kostiakov equation is commonly and widely used because of its simplicity, ease
of determining the equation constants from measured infiltration data and reasonably fit to infiltration data for various soils over the short time periods.

b) Modified Kostiakov Equation

The SCS (USA) modified the form of the above equation by introducing a term ‘c’.

\[ Y = at^b + c \]  

Where, \( c \) - soil decay constants.

c) Horton Infiltration Model

The infiltration process was thoroughly studied by Horton in the early 1939. The infiltration capacity of the soil is given by the following relation:

\[ f_t = f_c + (f_0 - f_c)e^{-kt} \]  

Where: \( f_t \) - infiltration capacity at some time \( t \), \( k \) - constant representing the rate of decrease in capacity, \( f_c \) - final capacity, \( f_0 \) - initial infiltration capacity. It shows that if the rainfall supply exceeds the infiltration capacity, infiltration tends to decline in an exponential manner (Fig. 3.11). Although simple in form, difficulties in determining useful values for \( f_0 \) and \( k \) restrict the use of this equation.

Fig. 3.11 Horton’s Infiltration Curve and Hyetograph
The area under the curve for any time interval represents the depth of water infiltrated during the interval. By observing the variation in infiltration with time and developing plots of $f$ versus $t$, we can estimate $f_0$ and $k$. Two sets of $f_p$ and $t$ are selected from the curve and entered in equation. Two equations having two unknowns are thus obtained; they can be solved by successive approximations for $f_0$ and $k$.

d) Green-Ampt Equation

The Green-Ampt model of infiltration, firstly projected in 1911, has had a renaissance of interest. This methodology is based on Darcy’s law. In 1973, Mein and Larson conceived a approach for applying the Green-Ampt infiltration model to a stable rainfall input. They also established a technique for determining the capillary suction which is used in the model. The original formulation by Green-Ampt in their original formulation made assumption that the soil surface was covered by negligible ponded depth of water and that the infiltrated water has constant initial water content and infiltrate s through homogenous soil. If the conductivity in the saturated zone is $K$, then Darcy’s law is given by the equation.

$$f_p = \frac{K_s(L+S)}{L} \quad (3.5)$$

Where, $L =$ distance between the ground surface and wetting front, $S =$ capillary suction, $K_s =$ saturated hydraulic conductivity.

e) Philip’s Two- Term Model

The Philip’s two- term model is based on the Taylor power series solution which is presented by Philip (1957). It states that at early stage of infiltration when time duration ($t$) is very small, the equation is dominated by the first term. At this phase, the vertical infiltration progresses almost at the same rate of horizontal infiltration due to the gravity component which is denoted by the second term of equation being negligible. As infiltration progresses, the second term becomes more important until it leads the infiltration process. Philip recommended the use of this two- term model in practical hydrology very time $t$. The Philip two- term model is denoted by the following relationship:

$$q(t) = \frac{1}{2}St^{-1/2} + A \quad (3.6)$$
\[ I(t) = St^{1/2} + At \]  

where, \( q \) is infiltration rate in cm/h, \( t \) is time for infiltration in hours, \( S \) is the sorptivity in cm/h\(^{1/2} \), \( A \) is a constant having unit cm/h which depends on the soil properties as well as initial and saturated water contents, and \( I(t) \) is the cumulative infiltration in cm at any interval of time \( t \).

**Assumptions and limitations**

The primary assumptions for this model are:

i) Homogeneous soil conditions and properties,

ii) Water content distribution is uniform as well as constant.

The limitations for this model are: Field soils are seldom homogeneous, and this model is not designed for layered system.

In chapter 3 emphases is given on basics which is a stepping stone for this study. After this chapter 4 is dealing with the details of study area and the methodology for the present study applied. It highlights about the details of field observation points and soil infiltration measurement methodology adopted. Also gives details of various field tests and methods of collection of samples during the tests. The ANN methodology employed and development of ANN models is described in detail.