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INFILTRATION AND GROUND WATER RECHARGE

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PREFACE

Infiltration is an important parameter in the hydrologic cycle. The growth of vegetation and evapotranspiration depends on the quantum of infiltration. The extent of recharge to groundwater also depends on the rate of infiltration in an area. The knowledge of infiltration helps in adopting proper irrigation and scheduling of water to the fields alongwith dry farming areas. Being the basic parameters, the scientific understanding of the processes take place during the infiltration and recharge to groundwater is necessary. Also the new developments in the field of instrumentation and measurement techniques have now made it possible to study these parameters precisely in a more scientific manner.

The valuable document has been prepared by Dr. S.R.Singh,Project Director, Water Technology Centre for Eastern Region,, Bhubaneshwar, Orissa and Dr. V.N. Sharda, Senior Scientist (Engineering), Central Soil and Water Conservation Research and Training Institute, Dehradun. The authors have provided valuable scientific information about infiltration and recharge to groundwater in this document.

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INFILTRATION AND GROUND WATER RECHARGE

1.0 INTRODUCTION

Out of 1.37 x 10^8 million hectare meter (M ha-m) water available on the earth surface, only 0.6% is fresh liquid water which works out to be 0.85 x 10^6 M ha-m. A major part (97.3%) is salt water which is unfit for agriculture, industrial and domestic consumption. The remaining 2.1% is in the form of snow or ice and is not readily available for practical purposes. Even the whole liquid water is not easily exploitable and 98% of it forms ground water resources, half of which lies at a depth more than 800 m below the ground surface.

Over the years, the demand for water has increased tremendously owing to pressures of urbanisation and industrialisation. Our water resources are limited and are rather insufficient to meet the long term requirements of industry, agriculture and ever increasing millions of human population in the world. Moreover, the available resources are unevenly distributed resulting in devastating floods in some areas while other areas remain chronically drought affected.

The total precipitation in the country has been estimated as 400 M ha-m. The average annual rainfall of India is about 115 cm which amounts to 370 M ha-m over the entire country. The remaining 30 M ha-m is in the form of snow melt runoff. It has been estimated that out of total 400 M ha-m precipitation, around 70 M ha-m are immediately lost through evaporation. Of the remaining 330 M ha-m or so, around 150 M ha-m enter the soil and 180 M ha-m constitute runoff mostly during monsoon season of 4-5 months. Owing to the topographic, hydrologic and other constraints, it has been assessed that only about 70 M ha-m of surface water can be utilized by conventional methods of development. Major and medium irrigation projects have so far succeeded in tapping only 17 M ha-m in their reservoirs. Another 4 to 5 M ha-m are stored in tanks and small reservoirs.

Of the 150 M ha-m which enter the soil, it is estimated that 110 M ha-m constitute soil moisture while 40 M ha-m or so percolate into the ground water aquifers. Out of the estimated total irrigation potential of 113 M ha, nearly 58 M ha would be from major and medium projects and the remaining from minor irrigation schemes including 40 M ha from ground water. The irrigation potential created by the end of the 7th plan was about 79.4 M ha.

The amount of runoff which flows over the surface can vary within wide limits, depending on the conditions encountered by the rain when it falls on the ground. Thus, a steeply sloping surface deficient in vegetation will yield more runoff as compared to mildly sloping well vegetated surface. The amount of water which joins the ground water aquifer will be much less in the former case as compared to the latter. In a country like ours where precipitation is unevenly distributed, proper land management and afforestation in watersheds are therefore the key to the storage of water within the land mass and offers the cheapest and most convenient way of conserving water. It will also help to control both floods and droughts as reduced runoff means that there would be more water to emerge as springs and to feed river flows during the lean season. In addition, it will also help to save the reservoirs of major and medium projects from premature siltation and thereby to conserve valuable irrigation, hydel and flood control potential.

2.0 HYDROLOGIC CYCLE

For efficient and judicious conservation, development, utilization and management of our water resources, it is necessary to have proper knowledge about the availability of water, its quality, location, distribution and variation in its occurrence, climatic conditions and nature of the soil. Hydrology is a branch of science which deals with origin, occurrence, distribution and properties of the water on the earth surface, in the atmosphere and underground. The hydrologic cycle is an unending flux of water in which moisture is constantly circulating between the land, the ocean and the sky. For scientific management of our water resources, it is essential to properly understand the components which constitute this cycle.

As shown in Figure 1, different components and processes involved in the hydrologic cycle may be explained through the following steps:

(i) Evaporation of water from oceans and other moist bodies into the atmosphere results in the formation of vapours through the moving air masses. This is transfer of water from the liquid to the gaseous state.

(ii) The vapours condense to form clouds through a combination of circumstances.

(iii) Under certain conditions, the clouds condense and fall back on earth in various forms of precipitation i.e. rain, hail, sleet or snow.

(iv) The precipitation reaching the earth surface is dispersed in several ways.

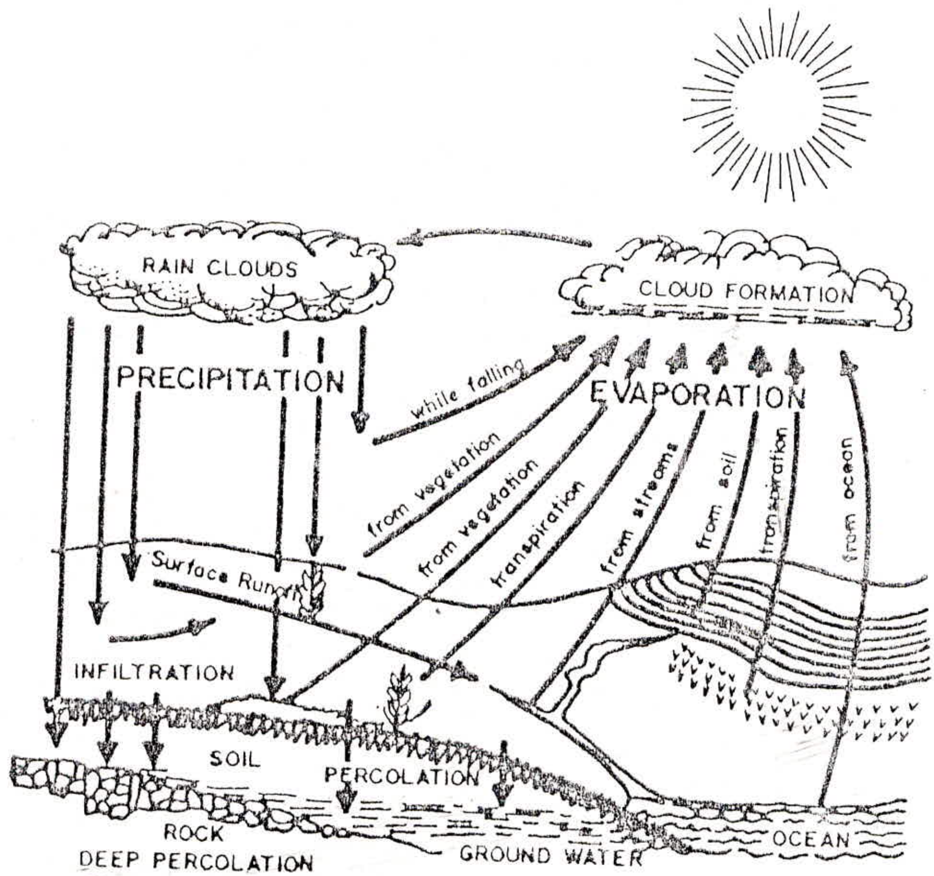

Fig. 1 The Hydrology Cycle

The basic components of the hydrologic cycle include precipitation, evaporation, evapotranspiration, infiltration, overland flow, stream flow, and ground water flow.

Precipitation refers to all forms of water derived from atmospheric vapour and deposited on the earth's surface. It may be in the form of rain, hail, mist, and snow. Some portion of precipitation is intercepted by vegetation before it reaches the ground surface. Some of the intercepted water may drip down to the soil surface through leaves as through-fall and as stem flow and the rest evaporates from leaves and other vegetated surfaces. The part of precipitation reaching the land surface that enters the surface strata is known as infiltration. Much of the water that enters the soil surface is retained in the root zone and eventually is drawn back to the surface by plants or by soil capillarity. Some of it, however, percolates below the plant root zone and under the influence of gravity continues to move downward until it enters the ground water reservoir.

The portion of liquid water which gets converted into the vapour form and released into the atmosphere is known as evaporation. It occurs from both the water surface and land surface. Transpiration is that component of the hydrologic cycle by which water in the soil is transferred to the atmosphere by plants as water vapour. Out of the total water absorbed by the plants from the soil, a substantial portion is returned to the atmosphere by transpiration and only a little part is utilized for metabolic activities.

The rainfall excess is generated only after the hydrologic losses such as interception, infiltration and depression storage are satisfied and contributes to surface flow. The portion of precipitation that makes its way towards streams, rivers, lakes or oceans as surface or as subsurface flow is known as runoff. When the flow is occurring as a shallow sheet of average depth over the land surface, it is referred to as overland flow. The portion of runoff which flows over the land surface is known as surface runoff while the part which percolates into the soil profile and appears at the surface in areas at lower elevations constitutes inter-flow.

From the foregoing discussion, it is clear that hydrologic cycle is a continuous and dynamic process and can conveniently be described through four major phases, viz; atmospheric phase (precipitation), land phase (evaporation and transpiration), surface phase (surface stream flow) and sub-surface phase (ground water). The movement of water through various phases of the hydrologic cycle is erratic in time and space giving rise to extremes of flood and drought. A temporary imbalance of the cycle in which higher volumes of water are concentrated in the streams result in flood while small or negligible amounts of water in the precipitation phase of the cycle leads to drought. The magnitude and the frequency of occurrence of these extremes are of great interest to the engineering hydrologists, and soil and water conservationist from a design and operation point of view.

In the subsequent sections, two very important components of the hydrologic cycle, namely, infiltration and ground water recharge are discussed in detail.

3.0 INFILTRATION

Infiltration may be defined as the process of water entry into the soil, generally by downward flow through all or part of the soil surface. Water may enter the soil through the entire surface uniformly as under ponding or rain, or it may enter the soil through furrows or crevices. Infiltration rate is the volume of water entering the soil profile per unit of soil surface area and time. There is a maximum rate at which a given soil in a given condition can absorb water and it is known as infiltration capacity or infiltrability of the soil. If the rainfall intensity is less than this capacity, the infiltration rate will be equal to the rainfall rate, whereas if rainfall intensity exceeds the ability of the soil to absorb moisture, infiltration occurs at the capacity rate. The excess of rainfall over infiltration depending upon amount and time distribution of rainfall determines how much water is available for surface runoff.

The water which enters the soil profile moves slowly downwards and a part of it may eventually reach the ground water reservoir. The soil, therefore, plays an important role in deciding the volume of surface runoff, its timing, its peak rate of flow, storage of moisture in the root zone and deep percolation losses.

3.1 Importance of Infiltration

The role of infiltration has been well recognised by scientists, planners and users working in different fields depending upon their requirements. A hydrologist may be more interested in the estimation of peak rates and volumes of runoff in the planning of dams, culverts and bridges etc. For a soil conservationist, the main objective is to dissipate the energy of flowing water so as to minimise the erosion hazards. He may suitably plan engineering and forestry measures to either induce infiltration over the land surface or conduct the water safely away from the affected areas.

Since, overland flow is an important agent of landscape development, geomorphologists are also interested in the magnitude, frequency and spatial characteristics of infiltration relative to rainfall intensity. Most important use of infiltration is to the agriculturists and ecologists who are concerned with the availability of soil moisture in the root zone of crops and plants. The excess of water in the root zone may cause water logging conditions whereas deficit may result in moisture stress. In either situation, the plant growth may be adversely affected. Hence optimum soil moisture levels need to be maintained in the root zone. The vegetation and crops return the water to atmosphere through evapotranspiration depending upon their foliage, density, species and stage of growth. The infiltration is, therefore, very important for assessing soil moisture deficits and planning irrigation and drainage systems.

Apart from affecting runoff generation and soil moisture supply, infiltration significantly contributes to the ground water system and augmentation of the stream flows during lean periods. In view of the ever increasing exploitation of ground water resources for irrigation proposes, greater emphasis need to be given on recharging of aquifers through induced infiltration methods.

3.2 Mechanism of Infiltration

Soil consists of primary particles of sand, silt and clay which are separated by innumerable channels of different sizes known as soil pores. These channels extend downward as well as laterally. The infiltrating water moves downward under the action of gravity through these pores. The rate of entry and movement of water depends upon the diameter of the pores. The small diameter pores, called capillary pores, have strong affinity for water than for air. The capillary force acts in all directions and water under this force may move vertically up, down or in any other direction. This force which is strongest in very fine soils frequently exceeds the force of gravity and the capillary water always moves from the wet zones towards drier zones. In large pores such as worm holes or root holes, the gravity movement is predominant and capillary forces are negligible.

Initially, when the soil is dry, the pores are empty and the water absorption is faster resulting in high infiltration rate. The reason being that the infiltration occures not only through large gravity channels but also through direct capillary action over the entire surface. The capillary potential decreases as the soil becomes wetter and wetter resulting in steady decline of the infiltration rate. Thereafter, the water moves mostly downwards through the gravity channels while the capillary channels draw water laterally through gravity pores into the finer intergranular spaces. As the capillary pores are steadily filled with water, there is progressive reduction in the infiltration rate and ultimately steady or basic rate of infiltration is reached. The value of the basic infiltration rate depends upon the type of soil.

4.0 COMPONENTS OF INFILTRATION PROCESS

The process of Infiltration consists of three interdependent sub-processes, namely, entry through the soil surface, storage within the soil, and transmission through the soil. The infiltration rate may reduce when any of these processes has a limiting effect.

4.1 Water Intake

When the soil is dry, infiltration rate is high; subsequently it decreases monotonically and eventually approaches asymptotically a constant rate which is often termed as the final infiltration capacity or basic infiltration rate or steady state infiltrability. This is invariably true for all types of soils and land uses (Fig. 2). There are mainly three processes affecting this decrease in infiltration capacity. Firstly, the filling up of finer pores with water reduces capillary forces which in turn causes reduction in the hydraulic gradients at the surface. Secondly, there is gradual deterioration of the soil structure due to break up and detachment of soil aggregates by raindrop impact and splashing or migration of finer particles over the surface and into the pores which impede the entry of water. This may partially seal the soil surface by forming a dense crust. Thirdly, bulk compression of soil air if prevented from escaping, also reduces the infiltration rate. In clayey soils, the reduction in infiltration rate is due to the swelling of particles as they become wetter.

4.2 Soil Moisture Storage

The moisture content of the soil is defined as the amount of water lost when it is oven dried and may be expressed as the volume of water per unit volume of bulk soil. The infiltrating water when stored in the soil pores raises the moisture content. The forces that keep the soil and water together are based on the attraction between the water and soil molecules (adhesion) and among water molecules themselves (cohesion). In the dry range, adsorption controls the soil moisture storage. The energy of water tension in a soil depends on the specific surface as well as the structure of the soil and on its solute content. The amount of water held in the fine capillaries depends upon the surface tension and capillary size but when held in bigger pores, gravitational forces become active. The dissolved salts tend to decrease the free energy of water and hold the water through osmotic forces.

When all the pores of the soil are filled with water, the soil is said to have achieved saturation capacity or maximum water holding capacity. The soil moisture tension at this capacity is almost zero and water is held freely in the soil. Under the gravitational force, the water in larger pores starts draining out. After one to several days, the remaining water in the soil is held under capillary and osmotic forces which are great enough to resist the force of gravity. The moisture content of the soil after the drainage of gravitational water is called field capacity of the soil. It is expressed as a percentage by volume and varies with soil texture as shown in Figure 3. The field capacity is the upper limit of available moisture range for plant growth. Depending upon the type of soil, it is generally reached between 0.1 and 0.3 atmosphere (1 atmosphere = 1036 cm of water or 76.39 cm of mercury) soil moisture tension. The field capacity can be estimated by measuring the volume of water which the soil can retain after it has been subjected to a suction of 0.1 to 0.3 atmospheres in the laboratory.

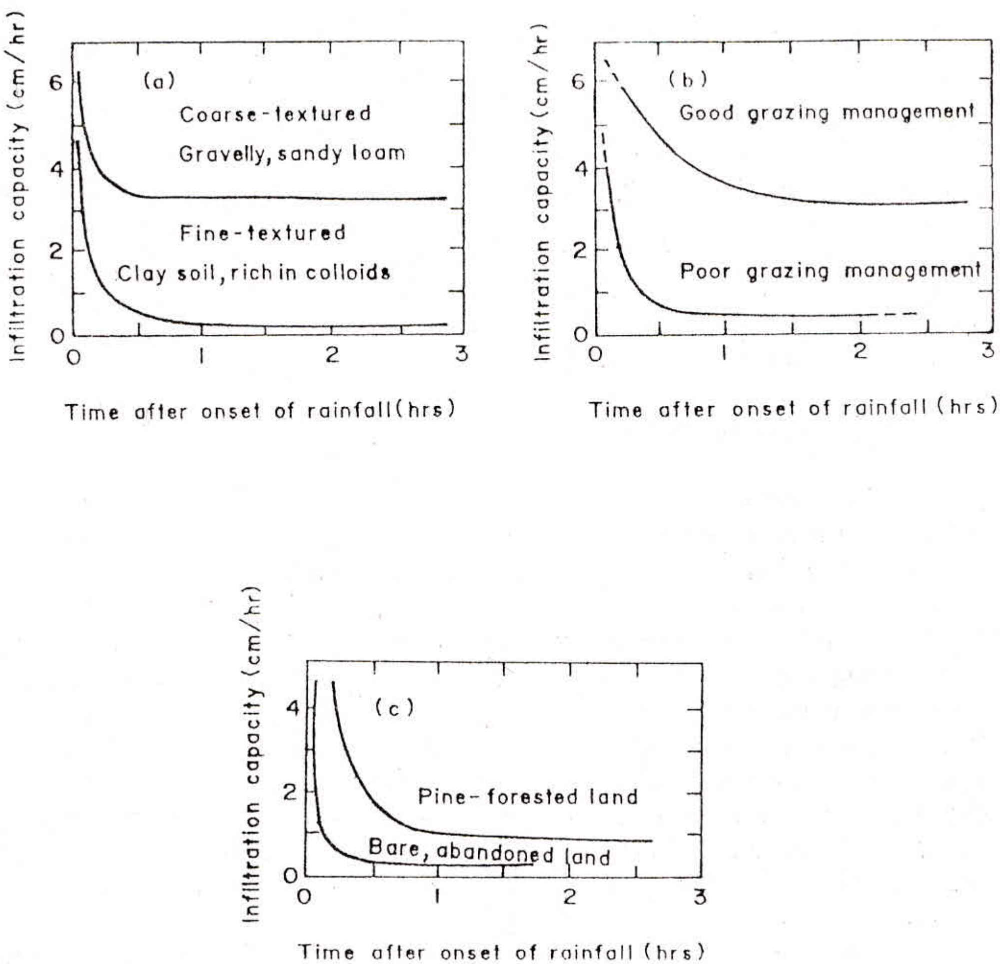

Fig.2 Infiltration capacity curves for soils of (a) different texture, (b) vegetative cover, and (c) land-use practice

The gravitational drainage, however slow it may be, does not stop at field capacity and continue to deplete the soil moisture. The major loss of water, however, is through evapotranspiration by plants. The extraction of water through roots and evaporation losses,progressively reduce the moisture content of the soil below the field capacity. The plants have to exert more and more suction to draw water from the soil as the soil becomes dry. The moisture content at which plants can no longer extract enough moisture to meet transpiration requirements and remain wilted unless water is added to the soil is known as its permanent wilting point. At this point, the water is held so tightly in thin films around soil that roots are unable to extract it at a sufficiently rapid rate to prevent wilting of the plant leaves. The moisture tension of a soil at permanent wilting point ranges from 7 to 32 atrnopsheres depending upon soil texture, type and condition of plants, amount of soluble salts and to some extent climatic environment. Most plants are able to exert a maximum suction of approximately 15 atmospheres and this pressure is commonly used for this point. As the soil moisture decreases further, the plants suffer from progressive degrees of permanent wilting. The moisture content at which the wilting is complete and the plants are unable to recover even after irrigation is called the ultimate wilting point. The soil moisture tension at this point may be as high as 60 atmospheres.

The difference between field capacity and permanent wilting point is the available moisture which can be readily utilized by plants. The fine textured soils have wide range between field capacity and permanent wilting point where as in coarse textured soils the range is narrow due to the presence of large pores. The range of available water holding capacities of different textural groups is presented in Table 1.

Table 1: Range of Available Water Holding Capacity of Soils

Soil Type	Percent moisture, based on dry weight of soil		Depth of available water per unit of soil
	Field capacity	Permanent wilting point	cm per meter depth of soil
Fine sand	3-5	1-3	2-4
Sandy loam	5-15	3-8	4-11
Silt-loam	12-18	6-10	6-13
Clay loam	15-30	7-16	10-18
Clay	25-40	12-20	16-30

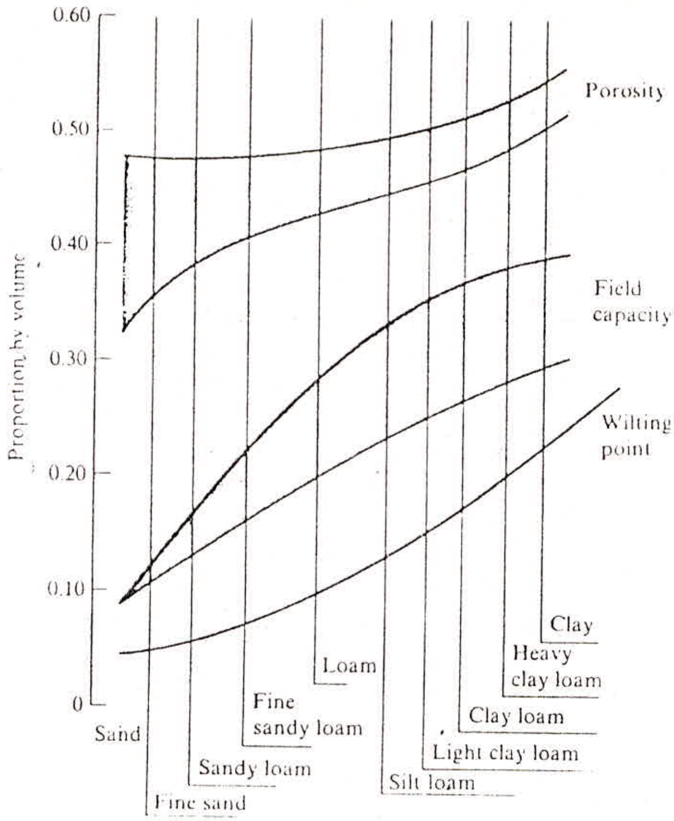

Fig. 3 Water-holding properties of various soils on the basis of their texture.

Soil with large amounts of available water are generally more favourable for plant growth. The maximum available water for plant growth is calculated upto root zone depth and varies with the type of crop and its rooting system.

Soil moisture measurements are important for estimating the quantity of irrigation water as well as for scheduling of irrigations. Gravimetric method is most commonly used for estimating soil moisture. The soil samples are collected with a soil auger or tube; weighed, ovendried and reweighed to determine the amount of soil moisture. This method, though simple and accurate, destroys the sampling site and is mainly used for experimental work.

More scientific methods or equipments have since been developed. In one such method, soil moisture can be evaluated by measuring the tension under which the water is held in the soil with the help of a tensiometer. Tension measurements by tensiometers are generally limited to metric suction values of below 1 atmosphere and as such they are best suited for sandy soils. In fine textured soils only a small part of the available moisture is held at a tension of less than 1 atmosphere. Soil moisture can also be measured electrically with the aid of nylon soil moisture blocks. The electric resistance of the nylon between wires set into the block is measured when the moisture content of the porous block is in equilibrium with the surrounding soil moisture. This method, though non-destructive, is not useful for saline soils as the resistance reading is affected by salt concentration.

Another precise and nondestructive method of measuring soil moisture is the neutron scattering method. It is based on the principle of measuring number of hydrogen nuclei that are present in a unit volume of soil, their number being a direct function of the number of water molecules contained in the same volume. The measurement is made by inserting a source of fast neutrons (probe) into a metal tube installed in the soil and counting the slow neutrons produced. It allows repeated measurements of a profile of moisture through the same undisturbed soil. The instrument is, however, expensive and its improper use can be hazardous.

4.3 Soil Drainage

The movement of water within the soil controls not only the rate of infiltration but also the flow into the rivers and streams, and ground water recharge. When the soil is saturated or nearly saturated, the water is under pressure and the tension is smaller than about 1/2 atmosphere. The excess water starts percolating or draining out of the saturated profile into the deeper layers. The poorly drained soils not only hamper ploughing, planting and harvesting operations but also place important constraints on location and construction of buildings, septic tanks and recreation activities. In India 6.0 M ha area is affected by water logging conditions. The fine textured soils are generally poorly drained soils. Various kinds of vegetation such as willows, sedges, and marshy conditions are also indicators of poor soil drainage.

The well drained soils such as sandy soils permit high infiltration rates and the percolating water may ultimately join the ground water table. This is important in regions where ground water is the only source of irrigation. The role of this component of infiltration process in augmenting the ground water resources is discussed in detail in the later section.

5.0 FACTORS AFFECTING INFILTRATION

Many factors influence the shape of the infiltration capacity curve, but the most important ones are the initial soil wetness and hence suction, the condition of surface crust, texture, structure and uniformity of the soil profile, temperature, rainfall intensity and extent of vegetative cover.

5.1 Rainfall Rates

Infiltration rate is a function of both rainfall rate and soil conditions. If the rainfall rate is less than infiltration capacity rate, infiltration may continue indefinitely at a rate equal to the rainfall rate without ponding at the surface. The water content of the soil in this case does not reach saturation at any point but approaches a limiting value which depends on rainfall intensity. However, for soils with restricting layers, infiltration will not always continue indefinitely. When the wetting front reaches the restricting layer, water contents above the layer will increase and surface ponding may result even though the rainfall rate is less than the infiltration capacity of the surface layer.

When rainfall rate is more than the infiltration capacity, the infiltration rate is limited by the capacity of the soil to absorb water. This results in surface ponding and water becomes available for runoff. Long intense storms tend to dislodge the soil and plug the soil pores with finer particles resulting in reduced infiltration rates. The clayey soils swell and may saturate the profile completely.

5.2 Soil Properties

Initially, the soil texture or pore size distribution controls the infiltration rate. But as the soil behind the wetting front approaches saturation, the hydraulic conductivity begins to control the flow rate. Coarse textured soils like sands with large pore sizes tend to have high infiltration rates while the fine textured soils such as clays have only low rates and volumes of infiltration. The depth of the soil profile and its initial moisture content determines the amount of infiltrated water which can be stored in the soil before saturation is reached. Higher the initial water content, lower will be the infiltration capacity owing to smaller suction gradients. Organic matter content also helps in promoting soil aggregation that will allow rapid infiltration and drainage.

The dynamics of infiltration process is strongly dependent upon textural and structural composition of the soil profile. The analysis has shown that for a coarse soil over a fine one, the infiltration proceeded exactly as for a coarse soil alone until the wetting front arrived at the boundary between the two layers. Thereafter, the progress of wetting front slowed and a positive pressure head developed in the top layer and the infiltration rate approached that predicted for fine soil alone. The results for fine over coarse soils were nearly the same as that predicted for a uniform fine textured soil except for a decrease in the infiltration rate when the wetting front reached the coarse layer. Normally, the least permeable layer and its depth relative to the surface layer controls the final infiltration rate. Where the least permeable layer occures at the surface, final and average infiltration rates may be nearly equal, but if it occures at a considerable depth, the average rate may be considerably higher than the final rate.

5.3 Surface Cover Conditions

Land use and surface conditions are very important controls of infiltration. A dense vegetative cover protects the soil from direct impact of the rain drops and prevents dislodging of the particles. Also, finer particles plug the pores which may result in reduced infiltration. The vegetation and litter provide organic matter for binding the soil particles together in open aggregates. This facilitates high rate of infiltration which in turn reduces the surface runoff and subsequently the soil erosion.

It has been observed that removal of vegetative and forest cover for cultivation purposes often lowers the infiltration capacity significantly. Contour ploughing and terracing in agricultural areas help in promoting infiltration and delaying runoff. In a completely bare soil, the reduction in infiltration rate is very fast due to compaction by rainfall and in washing of fine particles. The clayey soils, in particular, get puddled and a crust is formed which seals the surface and drastically reduces the infiltration rate. Most extreme reduction of infiltration capacity is experienced in urban areas where the land cover is replaced by asphalt or concrete surfaces.

Mulching greatly helps in improving the infiltration rates by absorbing the rain drop impact and preventing the formation of impervious surface layer.

5.4 Entrapment of Soil Air

It is, generally, assumed that soil air can escape through large pores that remain partially open during infiltration. But in most of the cases, the trapped air causes air pressure build up, thereby, reducing the infiltration rate. The studies have shown that a total entrapment of 10 percent can bring 80 to 90 percent reduction in hydraulic conductivity. The entrapment is found to occur primarily in the larger pores and horizontal surfaces.

Besides these factors, man's activities and climatic conditions also affect the infiltration process to a great extent. Construction of roads, buildings and play grounds etc. reduce the infiltration capacity of the soil. Over-ploughing under wet conditions destroys the soil aggregation which affects the infiltration capacity. The changes in viscosity of water results in lower infiltration capacity during winter season than during summer. The evapotranspiration requirements of the crops and vegetation also vary with season and the variations in soil moisture deficiency affect the rate of infiltration. The clayey soils swell during wet weather resulting in low infiltration rates and shrink during dry weather favouring high rates due to development of cracks.

6.0 MEASUREMENT OF INFILTRATION

The method of measuring infiltration rate depends upon purpose and type of problem in a given area. For small areas, when detailed information is required for the design of some valuable installation or land management plan, direct field measurement may be done to calculate the runoff rates. Where areas are large, infiltration capacity may be estimated from soil properties and vegetative cover. The following methods are most commonly used for measuring infiltration in the field.

6.1 Cylinder Infiltrometer

The cylinder infiltrometers are most widely used in small areas and may be of single ring type or double ring type.

a) Single Ring Type

In this type only one ring is used to flood the water and the infiltration rate is measured either by maintaining a constant head and estimating the amount of water being added or by observing the rate at which the water level is lowered in the cylinder. The inaccuracies may develop due to uncontrolled lateral movement of water below the bottom of the ring which otherwise is neglected.

b) Double Ring Type

To minimize the lateral movement of water, two concentric rings in place of one are used in this type. The outer ring acts as a buffer and ensures downwards movement only thus providing a reliable estimate of the equilibrium infiltration rate.

The infiltration rate in these infiltrometers is influenced by the cylinder diameter, thickness of cylinder bottom, the method of driving the cylinder into the soil and the installation depth. The average depth of water in the two cylinders is approximately equal and may vary from 6 mm to 12 cm. The observations are recorded at suitable locations in the field and averaged out to determine the average infiltration rate.

6.2 Tube Infiltrometer

A single tube infiltrometer is about 22.5 cm in diameter and 45 to 60 cm long and is placed at a depth at least equal to that to which water penetrates during experiment (37.5 to 52.5 cm). The rate at which water must be added to maintain a constant depth gives the infiltration rate.

The cylinder or ring infiltrometers, though cheap and simple to install, provide only relative rates of infiltration and can be used to determine the influence of land use, vegetation, slope and other physical variables. They provide only indices of variations between sites and the infiltration rate may be 2 to 10 times higher than the infiltration capacities measured during natural rainfall under the same condition.

6.3 Sprinkling Type Infiltrometers

The cylinder infiltrometers normally disturb the soil and the entrapped air may affect the infiltration rates. To eliminate these problems, sprinkler infiltrometer can be conveniently used to simulate rainfall on plots varying in size from one to more than 1000 sq. meters. The nozzles are designed to simulate closely the size and fall velocity of natural rain drops. The difference between the constant intensity rainfall and the rate of runoff from the plot gives the infiltration capacity. These devices, though accurate, are expensive and cannot be widely adopted.

6.4 Hydrograph Analysis Method

This method is applicable to small drainage basins where rainfall and runoff records are available. Complex storms consisting of several bursts are chosen and the amount of runoff in each burst is separated out from the hydrograph. The difference between the rainfall and runoff volume during each burst, gives the volume of infiltration. For each duration of the rainfall average infiltration rate is worked out and a composite infiltration curve is drawn for the entire storm period.

This method is approximate and is considered reliable for small areas of uniform soil cover, vegetation and land management.

7.0 ESTIMATION OF INFILTRATION

The methods outlined above for measuring infiltration rates normally do not hold good for large areas due to spatial variability of soil type and land use conditions. Moreover, it is very difficult to take large samples of observations in large basins. The estimation in infiltration rates in such areas is required for the calculation of runoff for design purposes and also for assessing the effect of land use changes. Many empirical and physically based models have been developed to express infiltrability as a function of time or of the total quantity of water infiltrated into the soil.

The empirical equations or models have been developed by applying the principles governing soil water movement for simplified boundary or initial conditions. They generally correlate infiltration as measured by one of the methods to some property or properties of the soil vegetative system. This involves evaluation of constants or parameters for a specific geographic location. The physically based models, on the other hand, are more complicated and apply the theory of continuity of mass and soil water movement with certain simplified assumptions. They normally employ numerical methods for the solution of governing differential equations and are extremely valuable in analysing the effects of various factors on the infiltration process.

The use of a particular equation or model depends upon the intended purpose and the accuracy desired.

8.0 RAINFALL RECHARGE

The phenomenon of rainfall recharge is very complex to study, analyse and evaluate due to erratic distribution of rainfall and unpredictable interaction between soil-vegetation-atmosphere system. Any rainfall occurring on earth's surface is presumed to disperse into interception or initial abstraction, infiltration into land surface, depression storage, surface runoff or overland flow and evapotranspiration - all components of hydrologic cycle as discussed earlier. The phenomenon of ground water recharge is mainly governed by infiltration component which has been discussed in detail in the previous sections.

9.0 FACTORS AFFECTING RAINFALL RECHARGE

The factors affecting, rainfall recharge may be broadly classified into three groups, viz; hydrological factors, meteorological factors and geological factors. The hydrological factors mostly relate to the occurrence, distribution, intensity, amount, duration, frequency and probability of dependable rainfall in particular period. The recording and non-recording gauges are generally used for computing rainfall parameters and average depth over a given area. The losses due to interception, depression storage and surface runoff are then substracted to calculate the net amount of rainfall infiltrating into the soil profile. The depressions may be small or large depending upon the nature and volume of depressions in the land surface. While small depressions are filled by initial rain, the large ones are normally filled by surface runoff or overland flow. Because of complex nature of this loss of rainfall, it is usually combined with the estimation of average evaporation/evapotranspiration or the interception itself in which case the combined loss is known as initial abstraction. This loss occures before effective infiltration of rainfall starts. The soil conservation service, USDA, has established that initial abstraction from any rainfall over any land area will be about 0.2 times the value of the potential maximum retention of rainfall or about 0.5 mm/hr of initial rainfall.

The surface runoff may be estimated by methods like water balance, stream or river gauging, watershed routing and measurement of inflow and change in storage. Though many analytical and conceptual models are also available for the purpose, direct measurement of runoff at certain standard control sections may provide reliable data for estimating direct runoff.

The meteorological factors control the moisture demand by the atmosphere and include relative humidity, vapour pressure, net radiation, evaporation, transpiration, wind speed and sunshine hours etc. They maintain dynamic energy balance between earth and atmopshere and contribute towards estimation of rain water loss by evapotranspiration through vegetal cover from the soil moisture storage.

Among the various methods used for computing evapotranspiration, formulae developed by Blaney-criddle, Christensen, Thornthwaits, Turc, Hargreaves and Penman are most widely used. The modified Penman method has been found to be more suitable for humid regions than arid zones. In arid zones where atmospheric mean temperature is the principal factor controlling evapotranspiration, Hargreaves formula can be used. The choice of a particular method, however, depends upon the specific conditions of land area, extent of availability of climatic data and the purpose of study.

The geological factors cover the type of strata and geological formulations through which rain water infiltrates to join the ground water table. The soil conservation service of Department of Agriculture, USA classified the soils into four hydrological groups depending upon their basic infiltration capacity rates. Group A consists of deep sand and aggregate silts with basic intake rate of 7.60 to 11.40 mm/hr. Group B constitutes sandy loam type soils having basic rate of 3.80 to 7.60 mm/hr. Clay loams, shallow sandy loam soils with low organic content and high clay content are classified in Group C. Their intake rate vary between 1.30 to 3.80 mm/hr. Group D covers swelling soils, heavy plastic clays and saline type soils which have basic intake rates as low as 0.0 to 1.30 mm/hr.

In the absence of adequate data on the ground water availability and developed potential, the adhoc norms given in Table 2 may be adopted depending upon the type of geological formations.

The infiltration capacity of different formations is greatly affected due to surface crusting and soil desiccation. Surface crusting results due to plugging of pores with finer particles during rainfall. The phenomenon of soil desiccation is more dominant in arid and semi-arid areas where it causes dead spaces of soil pores during dry season and makes the study on rainfall recharge more complicated.

10.0 STUDY AND ESTIMATION OF RAINFALL RECHARGE

Adoption of a specific method of study and estimation of rainfall depends primarily on the accuracy of results required, quality and quantity of data available or collected and the purpose of the study itself. Rainfall recharge is a complex function of meteorological conditions, vegetation, physiographic characteristics and properties of the geological material through which water moves. This complexity becomes more severe in semi-arid areas and areas of intermittent precipitation. Among the available methods, methods based on dynamic water balance, evaluation of infiltration process by experimental studies, rainfall/water table level relationship, analysis of seasonal/ annual rainfall and runoff have been recommended to provide reliable estimates of ground water recharge.

The dynamic water balance study deals with physical, deterministic and analytical concepts on the distributions of precipitation, soil moisture movement in liquid phase, expected value of evapotranspiration, distribution of storm surface runoff and distribution of water yield. In temperate climates where natural rainfall of high intensity (more than 25 mm/hr) and short duration occurs, rainfall recharge may be estimated by evaluating the infiltration and soil moisture deficit during individual storm events.

Table 2 : Percent rainfall infiltration to ground water body in different formations.

Sl. No.	Rock Type/Formation			Percentage rainfall infiltrating to ground water
1.	Alluvial areas			
	a.	Areas with higher clay content		10 to 20
	b.	Sandy areas		20 to 25
2.	Semi-consolidated sandstones (friable and highly porous)			10 to 15
3.	Hard rock areas			
	a)	i.	Granite terrain, weathered and fractured	10 to 15
		ii.	Unweathered	5 to 10
	b)	i.	Basaltic terrain, vesicular and jointed basalt	10 to 15
		ii.	Weathered basalt	4 to 10
	c)	Phyllites, limestones, quartzite shales etc.		3 to 10

Estimation of recharge from rainfall/water table level relationship is recommended in arid regions where ground water table level may vary widely due to high rate of depletion of aquifer storage by intermittent pumping for various purposes. This may involve solution of one dimensional differential equation under specific boundary conditions. For river basins where the annual monsoon season of water surplus is encountered with long period of deficit, both soil moisture and ground water recharge may be estimated by comparing seasonal net rainfall with their runoff. The input parameters required are rainfall, evaporation and runoff.

Though a physically based mathematical model involving deterministic, probabilistic and analytical principles may provide reliable estimation of ground water recharge, the other methods have their own utility depending upon the data availability and purpose of study.

11.0 ARTIFICIAL RECHARGE

Artificial recharge of ground water may be defined as the augmentation of the natural infiltration or precipitation or surface water into underground formations by approximate methods. In India, ground water resources are declining in certain parts of Gujarat, Tamil Nadu, Maharashtra, Andhra Pradesh, Punjab, Rajasthan and Haryana due to their over exploitation in uncontrolled manner. Studies and pilot projects on artificial recharge have been initiated in most of these states in the eighties for checking the decline in ground water table and also ensure its effective utilisation. However, there is no set pattern of planning, design, execution and maintenance of artificial projects.

Among the various methods of artificial recharge, water spreading, recharging through wells and pits and pumping have been most commonly used. The total amount of water infiltrated into the soil depends on the infiltration opportunity time which depends on the slope and the field structures which tend to hold the runoff water over long periods on the land surface.

11.1 Water Spreading

The main objective of this method is to increase the area and length of time for water to remain in contact with soil. Suitable diversion structures constructed across a stream channel cause the water level to rise on the upstream side which can be diverted to the land surface. This can be achieved either by flooding method or basin method or furrow method.

The flooding method is recommended in areas where sufficient quantity of water is available but not much monetary resources available to go for more effective techniques of artificial recharge. The water spreads evenly in a thin sheet over quite a large area without disturbing the soil. This method costs minimum as compared to other methods.

In basin method, water is diverted to the uppermost of a series of basins constructed by dikes or levees which generally run on contours. This is most practical method of artificial recharge. Recharging water laden with sediments may sometime seal the basins, which can be avoided by using the uppermost basins as settling basins or by scrapping or disking of the bottom surfaces. The basin method is particularly suitable where the ground surface is irregular and infested with a number of shallow gullies and ridges.

In the furrow or ditch method, water from a canal is distributed into a series of parallel ditches which are shallow, flat bottomed and closely spaced.

The orientation of the furrow or ditches may be contour type, lateral type or tree shaped. The width of the ditch may vary between 0.3 and 1.7 m depending upon the terrain and velocity desired. The velocity should be non-silting and non-eroding. This method has the advantages of being used in rough terrain and with recharging water have fairly high silt content. The spreading ground in direct contact with water is only 10-12% as compared to 70-80% is basin method.

11.2 Recharge Through Wells and Pits

The areas where the water bearing strata is overlain by an impervious layer and the impervious layer is at shallow depth, the recharge can be carried out by large pits. This method is also of not much practical use because of its limited area of application.

Recharge through wells is generally practical where enough land area is not available for recharge because of cultivation requirements or is unsuitable for recharge as in urban areas. The amount of water that can be recharged through wells is larger compared to other methods. The recharging wells can be of injection type or shaft type.

In injection wells, the water is injected under pressure and the diameter of the well is similar to that of a tubewell. It is practiced in localities where there are zones of low vertical permeability between the surface and the water table and infiltration is not feasible. The use of such wells is limited in areas where soil has good permeability. The high cost incurred in their construction and power requirements are the other limiting factors.

The recharge shafts are large diameter wells through which water flows under the force of gravity. No power is required in their operation to build up extra pressure. A shaft is a well like opening usually excavated by a dry excavation process and may be terminating some distance above the water table. It may be cased, uncased or back filled with gravel and may be ground or rectangular in cross-section. It has the advantages of being less costly, less surface area than surface ponding, less biological pollution and less chance of aquifer damage by sediments.

Figure 4 schematically shows different methods of ground water recharge.

11.3 Recharge Through Seepage

The seepage from canals and field channels, ponds, tanks and rivers and deep percolation from irrigated fields also contribute significantly to ground water augmentation. The complete assessment of ground water recharge through seepage from canals is possible only through systematic scientific studies. For unlined canals it may vary between 1.8-2.5 cumecs/10^6 sq.m. of wetted area in normal soils with some clay content to 3-3.5 cumecs/10^6 sq.m of wetted area in sandy soil. Studies in Punjab have indicated that canal seepage is of the order of 115 ha-m per annum per km length of main canal and 38.24 ha-m per annum per km length of distributory canals.

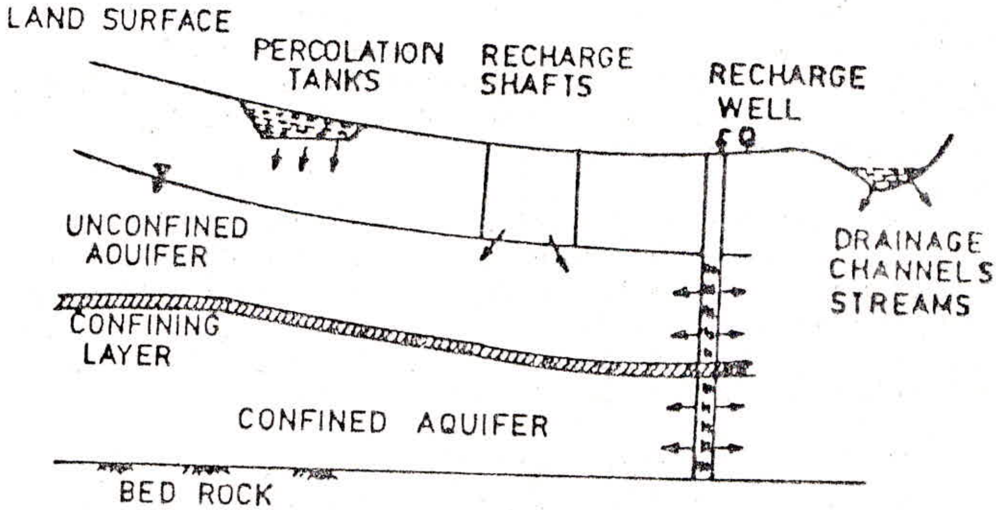

Fig. 4 Artifical Recharge Methods

In most of the canal irrigated areas, a substantial component (35-40 percent of water delivered) percolates below the root zone and contributes to ground water recharge. When irrigating with ground water sources, this contribution may lie between 30 and 35 percent. The seepage from tanks may vary from 9 to 20 percent of their live storage capacity. The seepage from percolation tanks may be as high as 50 percent of its gross storage.

11.4 Recharge Through Soil Conservation Measures

Depending upon physiographic characteristics, vegetation and landuse, the country has been divided into 10 soil conservation regions. These regions have common problems of deforestation, overgrazing and sheet and gully erosion. The biggest Centrally sponsored programme of soil conservation has been launched in 28 river valley catchments of these regions (Table 3). The size of these catchments ranges from 0.04 to 216.02 lakh ha covering a total catchment area of 69.32 m. ha. They spread over various river systems such as Ganga, Yamuna, Brahmaputra, Indus, Krishna Cauveri, Godawari and other small rivers of the country. In view of the constraints of finance and organisation, it is not feasible to treat the entire areas of these catchments. Hence, the approach has been to treat the most critically eroded areas. Since 1974-75, the soil and water conservation measures are being planned and executed on the basis of identified priority watersheds which are critical and have high silt production rate. Based upon computed silt index, 9651 watersheds having 27.5 m ha. area have been delineated out of which 3323 watersheds constituting 8.6 m ha area fall under very high (VH) and high (H) priority categories. By the end of VII Plan, about 3.0 m ha area has been treated with average unit cost varying from Rs. 1491 during 1980-81 to Rs. 4800 per ha during 1989-90.

Many major and medium irrigation projects have been taken up in the catchments of these projects. The cost of surface irrigation, however, has become prohibitively high amounting to Rs.27000/- per ha in the VII plan. The ground water, offers an incomparably cheaper and a far more efficient and manageable source of irrigation than major and medium projects. The soil and water conservation measures apart from checking runoff and soil erosion also help in augmenting the ground water storage through induced infiltration and increased opportunity time. The objective can be better achieved if for all practical purposes, the natural unit of planning in the field is taken as micro watershed with area not more than few hundred hectares.

The term watershed strictly refers to the divide separating one drainage basis from another and contributing runoff towards a single outlet. The objective of all projects planned and implemented on watershed basis is the efficient and judicious management of land and water resources in the area to maximise production on sustained basis without deterioration. For development, the size of watershed between 500-1000 ha is considered reasonable.

Table 3: River Valley Catchments of the Country

Sl. No.	Name of Reservoir catchment	Net catchment area, km²	Year of impounding	Year of observation	% area under VH & H Priority	River system
1.	Beas	12274	1974	1981	42.4	Indus
2.	Chambal (Gandhi Sagar)	21873	1960	1976	21.5	Yamuna
3.	Damanganga	1820			49.5	Damanganga
4.	Damodar Barakar					
	i. Maithon	5206	1956	1979	56.5	Ganga
	ii. Panchet	9816	1956	1974		
5.	Dhantiwada	2862	1956	1974	33.5	Banas
6.	Gumti	550		1973	78.2	Gumti
7.	Ghod	3629	1966	1970	22.3	Krishna
8.	Hirakud	82652	1956	1978	34.1	Mahanadi
9.	Kangsabati	3789	1965	1972	42.0	Ganga
10.	Kundah	114	1960	1977	7.1	Cauveri
11.	Lower Bhawani	4056	1958	1977	31.8	Cauveri
12.	Machkund	1956	1956	1978	42.2	Godavari
13.	Mahi	25330	1974	1973	56.4	Mahi
14.	Matatilla	20604	1958	1972	42.6	Yamuna
15.	Mayurakshi	1792	1955	1973	41.2	Ganga
16.	Nagarjunasagar	216020			21.6	Krishna
17.	Nizamsagar	18524	1831	1973	15.3	Godavari
18.	Pagladia	830	No.Res.		56.6	Brahmputra
19.	Pochampad	91070			30.0	Godavari
20.	Pohru	1860	No.Res.		33.9	Indus
21.	Ramganga	2997	1974	1974	33.6	Ganga
22.	Rengali Mandira	17250			12.8	Mahanadi
23.	Sukhna lake	40		1971	100.0	Suketri
24.	Sutlej	56876	1959	1979	43.8	Indus
25.	Tawa	5983	1974	1980	39.3	Narmada
26.	Tessta	12660	No.Res		42.4	Brahmputra
27.	Tungbhadra	27803	1953	1972	18.3	Krishna
28.	Ukai	6225	1971	1975	21.9	Tapi

The efficacy of soil conservation measures for conserving runoff and soil loss and augmenting ground water recharge has been well demonstrated through research by ICAR and some other organisations. In an agriculturally dominated watershed in Yamuna rivers, appropriate mechanical and biological measures reduced runoff from 8.7% of rainfall in 1962 to less than 1% in 1981 amounting to 86% reduction. Similarly, proper soil and water conservation measures in another watershed in Baroda ravines, the runoff practically reduced to zero over a period of twenty years.

Under Jhooming cultivation on 40% slope in the North Eastern Hills, the runoff which was originally 6.45% reduced to only 0.26% when good bamboo forest was restored. The bare lands when placed under natural grasses resulted in reduction of 79% in runoff in Sholapur region and 72% in the Shiwalik region near Dehradun. Against, at Dehradun, the runoff volume and peak rate reduced by 36% through field bunding alone in an agricultural watershed.

In all these studies, the reduction in soil loss was even more dramatic than reduction in runoff. This is of tremendous significance because unlike rainwater which is an annually renewable resource, the top soil is an irreplacable and non-renewable resource. It is estimated that in India, a total of 5334 million tonnes of soil is being eroded annually due to agriculture and associated activities alone which works out to be about 16.4 tonnes/ha/year, much more than the permissible value of 4.5-11.2 tonnes/ha. Of this, about 29% is lost permanently to the sea and 10% is deposited in reservoirs.

The ultimate objective of all soil conservation and afforestation programmes is to reduce runoff to the sea from the present level of 160 M ha-m to less than 100 M ha-m which apart from preventing gigantic loss of soil will also improve ground water recharge. It, therefore implies that to break the vicious circle of recurring droughts and floods, falling water tables, increasing water logging, mounting soil erosion and poor land productivity, water management and land management must go hand in hand. This will also ensure better utilization of our natural resources.

12.0 QUALITY OF RECHARGED WATER

The recharged water is generally considered bacteriologically safe for drinking and other purposes because during downward movement, the soil acts as a natural filter and removes pollutants of physical, chemical, bacterial and radioactive nature and other impurities from it. The ground water may, however, have higher salt content in areas where substrata is rich in chemicals and minerals and percolating water remains in contact for longer periods. The ground water quality may vary from place to place, stratum to stratum and season to season. The salinity of ground water increases during the summer and is significantly reduced during the monsoon due to dilution by rain water. It also depends upon the depth of water table, infiltration capacity of the soil and rainfall characteristics of the area concerned.

The quality of ground water is highly variable due to climatological and hydro-geological conditions. The quality of ground water resources of India is classified into three main groups, (i) water qualify of arid and semi-arid regions having rainfall below 45 cm per annum consisting of major parts of Rajasthan and Gujarat; Agra and Mathura districts of U.P., Ferozpur, Bhatinda and Sangrur districts of Punjab and Rohtak, Gurgaon, Mohindergarh and Hissar districts of Haryana; (ii) water quality as influenced by hydrological conditions such as high water table, consisting of some areas of Punjab, Haryana, U.P., Delhi and Rajasthan in the canal irrigated areas and river basins, and (iii) water quality of wells in some areas of the coastal regions of the country as influenced by sea water ingression and inundation. Of all these factors, aridity is the most important single factor responsible for a very high degree of salinity of well waters.

To prevent pollution of ground water, the recharged water may be chlorinated or percolated through slow sand filters. In areas where substrata is rich in salts and minerals, artificial recharge through deep wells or shafts can prevent deterioration of ground water. Where use of poor quality ground water for agriculture is inevitable, the yield potential of such areas can be increased by adopting proper management practices such as improvement of sodium and bicarbonate rich water by gypsum application, choice of salt tolerant crops and their varieties, optimum fertilization and manuring, proper irrigation management, breaking of any impervious layer by deep ploughing and adopting other management practices suitable for the area.

13.0 CONJUNCTIVE USE OF GROUND AND SURFACE WATER

The total surface water resources are capable of only meeting one-fourth to one-third of the amount needed for intensive agriculture. Moreover, the availability of total quantity of irrigation is not satisfactorily assured in time. This highlights the need for combined or conjunctive use of surface and ground water for efficient utilization of these resources.

The practice of conjunctive use is not new in India and has been in vogue in Tamil Nadu, Maharashtra, Uttar Pradesh, Haryana and Punjab. This has been planned to augment canal supplies, combat water logging and facilitate irrigation with poor quality ground water. Lot of emphasise has been placed on conjunctive use of ground and surface water resources in the 7th and 8th plans. This among other things also helps in reducing ill effects of water logging. However, the benefits of conjunctive use might be loss if the problem of water logging is tackled too seriously by irrigation departments by undertaking the lining of canals. Already in Punjab and Haryana and some other parts of country, the lining of substantial stretches of the canal system has been taken up. But it should ensure that the existing ground water exploitation is not materially affected. This implies that the recharge of ground water through seepage from canals is a good thing from the view of conjunctive use, even though it may contribute to water logging.

The planning of conjunctive use is also necessary to cut down the gestation periods for achieving the full benefits from major and medium irrigation schemes which may otherwise spill over 2 to 3 plan periods. Conjunctive use cannot. however, under any circumstances make up for the failure of surface irrigation projects. In particular, it offers no easy solutions for water logging in situations where soil strata are highly saline and where the ground water is, therefore, not fit for irrigation.

AUTHOR'S BIOGRAPHICAL SKETCH

The author joined Indian Council of Agricultural Research in 1978 through Agriculture Research Service after completing his M.Tech. in Soil and Water Engineering. He served at Agra and Ootacamund Research Centres of Central Soil & Water conservation Research and Training Institute (CS&WCR&TI), Dehradun prior to his joining at Forest Research Institute and Colleges, Dehradun as Senior Research Officer in 1984. He has published many technical reports and more than 25 research papers in journals of National and International repute. Among his major contributions are the assessment of water yield reduction under Eucalyptus plantations and the effect of management and landuse practices on the hydrology of forest and agriculture watersheds.

He completed his doctorate in Soil & Water Engineering from PAU, Ludhiana in 1990 and was instrumental in developing process based model for simulation of runoff and erosion from agricultural lands treated with soil conservation measures. He visited kenya during 1991 to review the soil conservation programmes of the country and suggest remedial measures. Presently, he is working as senior Scientist (Engg.) and Head of Division, Training at CS&WCR&TI, Dehradun. Alongwith his research persuits, he is also actively engaged in the training of gazetted and non-gazetted officers from India and abroad.