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GROUNDWATER RECHARGE USING TRACER TECHNIQUES

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PREFACE

Groundwater is a dynamic and replenishable resource. The water bearing strata are recharged annually through the fraction of the rain which percolates directly or indirectly to the aquifers. In a steady state, an equivalent quantity is removed annually from the groundwater system, through effluent discharge, draft or evapotranspiration. Thus, recharge or input to the groundwater system, is an important parameter to be known for systematic planning of exploitation of groundwater reserves and for determining permissible groundwater draft from recommended and existing wells.

The National Institute of Hydrology established the Hydrological Investigation Division in 1985 with the major objectives of studying hydrological parameters using geophysical and nuclear techniques. Therefore, an attempt has been made in the division to review the present status of tracer techniques in groundwater recharge studies.

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ABSTRACT

Groundwater recharge is that amount of surface water which reaches the permanent water table either by direct contact in the riparian zone or by downward percolation through the overlying zone of aeration. It is this quantity which may in the long term be available for abstraction and which is therefore of prime importance in the assessment of any groundwater resource. Both natural and artificial tracers are being used in the country and abroad to study the soil moisture transport and estimate the direct recharge to the groundwater. The methods most commonly used are: (i) Isotopic tracer injection method and (ii) Environmental tracer method.

The injection of tritiated water below the active root zone and subsequent coring for samples in order to construct a profile of tritium concentration with depth provides one method for estimating recharge. Injections of the tracer are made at a number of locations about 10 cm apart along a line. In this way, the lateral spread of the tracer becomes of the order of a few decimeters owing to molecular diffusion. Subsequently cores are taken and cut into 10 cm sections for analysis in the laboratory. The core samples are weighed before and after extraction of the water by vacuum distillation at about 80°C, in order to obtain the soil water content of the individual cores. The accuracy of this technique is a function of the velocity of downward displacement, which in turn is dependent on the amount of recharge and

the field capacity of the soil. Many examples of this technique have been described in this report.

The second method make use of environmental tritium for the estimation of groundwater recharge. The presence of tritium in groundwater indicated that atleast some of the water has been reached during the last few decades. During the early years of environmental tritium measurements, the converse conclusion, that absence of tritium implied that recharge was not occuring, failed to take into account that the unsaturated zone might be so deep that the recharging water had not yet reached the water table. Today the presence of tritium still provides at least qualitative information on recharge. In the early 1960s the concentration of tritium in precipitation reached a maximum after the moratorium on the atmospheric testing of thermonuclear devices. This peak of tritium has been used for studying the infiltration of water through the unsaturated zone and for estimating the average recharge over the period from the peak in concentration in 1963 to the time of measurement of the tritium profile with depth.

The present status of groundwater recharge studies is reviewed in the light of techniques mentioned above.

1.0 INTRODUCTION

1.1 General

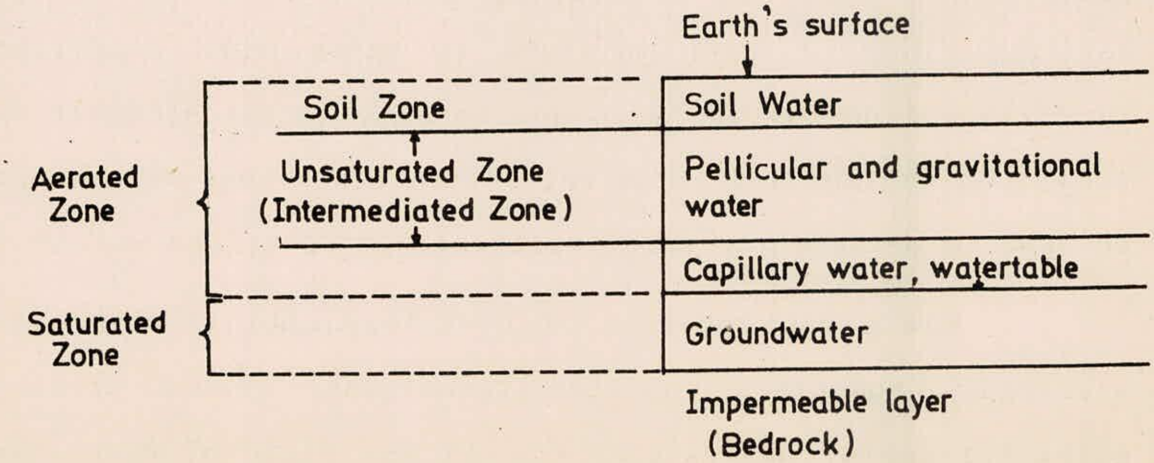
Owing to the increasing demand of ground water day to day, it is very essential to have a complete knowledge of water in the hydrological cycle. The water stored in aquifer (ground water) is important in situations where there is rainfall only for a period of three months in a year. This stored water is useful for use in other season. Therefore, the detailed knowledge of the process of flow of water to the aquifer due to rain, irrigation, seepage from canals and other sources is an important consideration. One of the important and less understood factors is the flow of water through unsaturated zone (porous medeia).

There are several methods like-Gravimetric method, Porous sorption blocks, Tensiometer, Lysimeter, Thermal conductivity method, Electrical resistivity method, Tritium tagging method, Neutron scattering probes and gamma ray scattering probes, to study the moisture profile movement. But it is clearly known that the methods given above, except neutron and gamma-ray scattering probes, are not suitable for the study of soil moisture in undisturbed conditions at different depths and time due to many technical difficulties. The neutron and gamma ray scattering probes also cannot be used to measure the soil moisture in a specified volume.

Now a days science of hydrology employs high speed electronic computers, nuclear techniques, remote sensing, satellite aerial photographs etc. In the field of hydrology, nuclear techniques are widely used for the study of recharge, moisture content, porosity, sediment movement and transport, measurement of rate of flow, snow pack studies, erosion studies etc. for the study of groundwater balance.

Nuclear techniques in hydrology (Guide Book on Nuclear Techniques in Hydrology, Tech. Reports Series No. 91, IAEA, Vienna, 1969) are of relatively recent origin and are the outcome of the ever widening multi-disciplinary approach in hydrological investigations. Physics, chemistry, geology and engineering have all enriched the filed of water resources investigation and management.

Groundwater forms part of the hydrological cycle. Water from precipitation or from surface water seeps into the ground and finally reaches layers of the earth's crust that are impermeable to its downward passage. Wherever groundwater occurs, there exists a more or less developed vertical distribution of the water in the subsoil. Above the impermeable layer is the saturated zone of the aquifer, in which all the pores and fissures in the rock are filled with water.



The layers above this zone, where pores still contain air are called the aerated zone. The aerated zone is often further divided into a soil zone near the surface, containing humue and vegetation, an under lying unsaturated zone with a vertical seepage flow, and finally a capillary fringe immediately above the saturated zone, in which the water content of the pore spaces rises in vertical profile to saturation because of the capillay forces setting there.

1.2 Infiltration

The precipitation received on the surface of soil partly infiltrates into the soil and partly it runs off over the surface. Infiltration, defined as 'the downward entry of water into soil', depends upon the physical and chemical condition of the soil and the chemical and hydraulic characteristic of the water in the soil both of which may change with time. The infiltration rate is affected by the soil structure and texture, the condition of the soil surface, the distribution of soil moisture, the chemical and physical nature of the water the head of the applied water the depth of groundwater table, the length of time of application of water, biological activities of the soil, the temperature of the water and the soil, the atmospheric pressure, the porosity of the soil, etc. (Johnson 1963).

Part of the water infiltrated gets evaporated from the top layer of the soil. Another part is lost through transpiration by the vegitation. Thus, out of the total precipitation, only a fraction is added or recharged to the groundwater.

The rate of infiltration of water through the unsaturated soil is of interest for setting up a regional water balance. The measurement enables an estimation of the fraction of rainfall that goes to recharge the groundwater reservoir.

There are a number of direct and indirect methods to measure infiltration rates. Direct methods using lysimeters or infiltrometers disturb the natural conditions of flow and are often considered non-representative. The indirect method of measuring changes in the soil moisture profiles in the unsaturated zones, using either the classical gravimetric method or the neutron probe method, need to be coupled with the computation of evapotranspiration with the attendant inaccuracies.

The tritium tracer method suggested nearly twenty years ago (Zimmermann et al., 1966) and developed to a level of easy routine application over the years provides an elegant and direct approach to infiltration studies.

The concept of the tracer method demands that the dynamic behaviour of the tracer should for all practical purposes, quantitatively represent the movement of the materal to which it is tagged in a given system. Let us first see how the soil water is supposed to be transporated in the vadose zone.

The Darcy's law for the movement of soil moisture in the vadose - zone can be written, neglecting the hysterises nature of the soil moisture characteristic curve as (Childs, 1967):

$$v = - k [1 + (\frac{\partial H}{\partial m}) (\frac{\partial m}{\partial z})] \qquad ...(1)$$

Where v is the soil moisture velocity (flow per unit area) in the z direction

H is the soil moisture suction as measured in a manometer,

k is the hydraulic conductivity, and

m is the soil moisture content.

In the above relationship k is a moisture dependent soil property as also is the specific water capacity $\frac{\partial m}{\partial H}$.

Difficulties immediately arise for a practical application of the above equation to soil moisture movement since, in most cases, we do not know the form of k (m) nor $\frac{\partial H}{\partial Z}$.

If we can assume $\frac{\partial m}{\partial z} = 0$ in a portion of the vadoze zone, equation (1) reduces to

$$v = - k \qquad ...(2)$$

Hence velocity, obviously a moisture dependent property needs to be determined for an evaluation of the rate of infiltration. The velocity measured by any tracer would be the true interstitial velocity $v_t = \frac{v}{m}$

v_t (m) x m is the moisture flux in motion. Assuming this to be the result of rainfall R during time t, the percentage of rainfall 'r' contributing to the recharge is given as:

$$r\% = \frac{100\ v(m) \times m}{R/k} = \frac{100d \times m}{R} \quad \ldots(3)$$

Where d is the tracer displacement in time t.

The above involves two implicit assumptions leading to the piston flow model.

1. The infiltrating rain water pushes the moisture ahead of it without overtaking it.
2. The movement at the zone of interest starts immediately with the onset of the rainfall and ceases immediately after the cessation of the input at the surface.

The first assumption has been reasonably well verified in many tracer experiments over the last few years, even under monsoon conditions. The second assumption, which is of particular importance to pulsed inputs in monsoon regions does not appear to have fully verified under field conditions.

2.0 SOIL MOISTURE AND GROUNDWATER RECHARGE

2.1 Soil Moisture

Water which is above the water table is called soil moisture. It is the term applied to the water held in the soil by means of molecular attraction. It forms a film around the soil particles, fills the small wedge-like spaces between soil particles and may completely fill the smaller interstitial spaces.

This moisture is held so tightly that it strongly resists any force tending to displace it. The degree of its resistance to movement is expressed by its capillary tension or potential, a measure of the force required to remove the moisture from the soil. Soil moisture can be classified as:

a. Hydroscopic moisture water - the moisture which retained about individual soil particles by molecular attraction and can be removed only by heating.

b. Capillary moisture water - the moisture which is present under the action of capillarity in small pore spaces and can be removed from soil only by applying a force sufficient to overcome the capillary forces.

c. Gravitational moisture water- Water which moves under the influence of gravity.

2.2 Methods for Measurement of Soil Moisture

2.2.1 Gravimetric method

The most simple and basic technique to determine the moisture content in a soil sample is to weigh it before and after ovendrying it at 105°C. The difference in weights divided by the oven dry weight and multiplied by 100 is the 'moisture percentage on oven-dry-weight basis'. If the volume of moisture removed by the oven dry is divided by the initial volume of the bulk soil, then the result when multiplied by 100, is the 'moisture percentage by volume'. The soil volume used in the last calculation is usually that of the soil sample as found at the field capacity. Also, the moisture percentage on an oven-dry weight basis can be multiplied by the bulk density of the oven-dry soil to obtain the moisture percentage by volume. The bulk density is ordinarily defined as the grams per c.c. of the bulk soil when it is oven-dry. The Guide-book on Nuclear Techniques in Hydrology defines-

a. Dry bulk density as the weight of oven dry soil contained in unit field volume (not the volume of soil after drying).

b. Field bulk density (or wet bulk density) as the weight of soil in its field condition (including pore water) contained in unit field volume.

This method does not give a continuous record at any location because of the necessity of removing the sample from the ground for laboratory testing. The process of sample collection distrubs the soil system, therefore, the study of the variation of moisture content with time is not possible in the same condition and at the same position.

2.2.2 Porous absorption blocks

Porous abosorption blocks are made to find the moisture in the porous materials. These blocks absorb water when they come in contact with wet soil. These porous absorption blocks are kept in close contact with the soil. These blocks may be readily removed and weighed. The moisture content of the blocks is related to the surrounding soil. This technique has another additional error due to process of transfer of moisture from soil to blocks.

2.2.3 Tensiometric measurement

Tensiometric techniques are popular to measure the soil water tensions in unsaturated soils. The tensiometer consists of a porous cup inserted in the soil and connected by a water filled tube to a manometer which is used to measure the capillary potential or tension between the water and the soil. The soil tension is related to the moisture content for any particular soil. Tensiometric measurement of soil moisture is limited to tensions in the range from zero (at saturation) to about 0.85 atmosphere. This encompasses half or more of the available water range, depending upon the soil texture. Several types of tensiometers have been designed using different types of liquids instead of water and measuring gauges using electronic devices etc. The use of this device in field is difficult and also the moisture can only be measured indirectly which requires the knowledge of moisture characteristics of the soil.

2.2.4 Thermal conductivity method

This method is based on the relation between thermal conductivity of the soil and soil moisture content. An electrical resistance constituting one leg of a wheatstone bridge, is placed in the soil. When the soil moisture is high, heat will be conducted rapidly away from this resistance, whereas for dry soil the heat conductivity of soil is low, and the resistance element will become hotter, thus increasing its resistance and throwing the bridge further out of balance.

2.2.5 Electrical resistivity method

This method is based on the relation of the electrical resistance of porous, dielectric materials(plaster of paris , nylon, fiberglass, gypsum) to their moisture content. Two electrodes are embadded in the material (one of the above mentioned) and are buried in the soil. The dielectric maintains a moisture equilibrium with the soil and the electrical resistance between the electrodes is measured by means of wheatston bridge in order to avoid polarizing the element. The block must be in intimate contact with the soil. The resistance between the electrodes varies with the moisture content of the material. The gypsum block lacks sensitivity. But other materials referred to as above give reliable calibration curves for moisture contents in the range from the wilting point to complete saturation.

Calibration is best achieved by taking periodic soil samples from the area surrounding the installation and correlating moisture content of the samples with concurrent resistivity reading.

2.2.6 Gamma transmission method

This method can be applied by sinking two parallel bore-holes with steel tubing side by side at an appropriate distance depending upon the strength of the source and the gamma-counting efficiency. The method can be applied safely for such a depth that the moisture content reaches to 30 percent to 40 percent (since in most of the natural soils in unsaturated zones with free drainage, these will not have a moisture content more than 30 percent by weight, and this method will work without any limitation in the unsaturated zone).

The attenuation of gamma rays in a medium is expressed by the following equation

$$I = I_o e^{-\mu_m x}$$

where μ_m = mass attenuation coefficient, I_o = initial intensity of gamma rays, I = intensity after transmission through the medium thickness x, if x is taken as g/cm², then μ_m is epressed as cm²/g.

By knowing the μ_m for zero moisture content it can be found from the new value of μ_m of samples with certain moisture content what is the moisture content of the sample.

2.2.7 Neutron scattering method

Slow neutrons are obtained from higher energy neutrons by allowing the latter to move through a material in which they can lose most of their energy in scattering collisions. In soil, hydrogen is present mainly in the form of moisture. Hence, fast neutrons when projected into the soil, will be scattered by the hydrogen nuclei and will be slowed down. The number of neutrons slowed down is proportional to the hydrogen concentration of the soil and hence, to the moisture content of the soil. These slowed down neutrons are detected by a thermal neutron detector and then are counted with a suitable counter. Thus the number of counts per second gives the measure of soil moisture content. A high countof slow neutrons indicates a high moisture content. Calibration between the neutron counts and moisture content percentage by value is important. Calibration of neutron probes can be done in laboratory by using a series of homogeneously packed drums of soil and known moisture content.

2.3 Groundwater Recharge

Groundwater recharge is that amount of surface water which reaches the permanent water table either by direct contact in the riparian zone or by downward percolation through the overlying zone of aeration. It is this quantity which may in the long term be available for abstraction and which is therefore of prime importance in the assessment of any groundwater resource. Recharge cannot be measured directly and so methods of estimation must be devised. The estimate must then be checked against all available evidence before confidence can be placed in the method.

Groundwater is a dynamic and replenishable resource. The water bearing strata are recharged annually through the fraction of rain which percolates directly or indirectly to the aquifers (Athavale, 1980). In a steady state, an equivalent quantity is removed annually from the groundwater system, through effluent discharge, draft or evapotranspiration. Thus, recharge or input to groundwater system is an important parameter to be known for systematic planning of exploitation of ground water reserves and for determining permissible ground water draft from recommended and existing wells.

2.4 Methods for Estimation of Recharge

For evaluation of groundwater recharge rate, several conventional methods such as storage, inventory, lysimetric, are generally employed. These in turn require the analysis of a large volume of hydrological data (precipitation, surface runoff, evapotranspiration, changes in groundwater storage etc.) accumulated over a considerable time span. However, such data is generally inadequate or lacking or unreliable in many areas where groundwater resources are yet to be fully exploited. In recent years, there has been an increasing emphasis on the use of isotopic techniques since they obviate the above mentioned difficulties to some extent. Two direct methods using environmental and artificial tritum developed by Munnich and his coworkers (Zimmermann et al., 1965, 1966, 1967; Munnich et al., 1967; Munnich, 1968) are noteworthy contributions to recharge determination methods. Since the first demonstration of such an application by Munnich and his colleagues, many researchers (Smith et al., 1970; Sukhija, 1972; Rama, 1973; IAEA, 1974; Dincer et al., 1974) have explored the utility of the methods in diverse climatic and hydrological conditions.

2.4.1 Conventional methods

The conventional methods of estimating recharge are based on the studies of Penman and Grindley (Penman, 1948, 1949, 1950; Grindley, 1967, 1969). Some of most commonly known methods may be described as:

(i) Inventory method
(ii) Lysimetric method
(iii) Storage method

2.4.1.1 Inventory method

Inventory methods are based on the following simple hydrological equation:

$$P = E + R + r$$

where,

P = Precipitation
E = Evapotranspiration
R = Surface runoff
r = vertical recharge

For this equation precipitation data are generally available but the parameters of evapotranspiration and run-off are rarely available and if it is available their accuracy is limited so this means the equation is complicated although it appears simple.

2.4.1.2 Lysimetric method

A vessel or container is placed below the ground surface to intercept and collect water moving downward through the soil. It can also be used to measure the evapotranspiration.

In this method recharge is measured by collecting the percolating water at certain depth with the help of large funnel. This method does not give accurate results because the lysimeters do not represent the actual field condition.

2.4.1.3 Storage method

Aim of this method is to determine the change in storage of water in the unsaturated and saturated zones. The changes in the unsaturated zone can be determined by periodic soil moisture measurements at several depth in a profile. But, only in some particular cases, the changes in moisture distribution when used in conjection with the measured hydraulic potentials (by tensiometers) could be useful for recharge evaluation. The recharge is the change in storage in saturation zone and that can be observed by fluctuation of spring levels and specific yield of the equifer. In order to get correct estimation of recharge, the correct value of specific yield should be choosen and allowance for horizontal flow should be taken into account.

2.4.2 Isotopic methods

The isotopic methods which are useful for evaluation of groundwater recharge may be grouped as:

(i) Groundwater dating method

(ii) Artificial tagging method

(iii) Environmental tritium method

2.4.2.1 Groundwater dating method

Reharge rate of groundwater body can be estimated by relating amount of groundwater and time that the water spends in the body.

Water sample from several points in the aquifer can be collected and age of different sample can be obtained (here it is important to avoid contamination of sample from upper zones penetrated by well at the time of sampling). The transit time (age) of groundwater can be obtained from a study based on.measurement of radio active isotopes present in ground water. The assumption that the water recharged to the aquifer is carrying with it radioactivity as a component of water molecules or as dissolved matter. By comparing the radioactivity of groundwater samples with that of fresh recharge water, the age of groundwater for each sample can be found by the equation $N = N_o e^{-\lambda t}$. Where N_o is radioactivity of fresh samples and N the activity for samples from aquifers, λ is the Decay constant, 't' age of sample.

Dating of ground water can be attempted by using radioisotopes which are present in the water like tritium (Half life 12.3 years), carbon 14 (half life 5730 years) and silicon (half life 500 years). For this method the transit times obtained by radioactive dating may be subject to errors. For example, in case of tritium the source function may not be known exactly because of introduction of tritium by nuclear explosions, and in cases of carbon-14 and silicon-32 the losses in activity due to exchange with aquifer material may also be suspected.

2.4.2.2 Artificial tagging method

This method can be used in cases of uniform and homogeneous soils without cracks and fissures. It is assumed that the soil water in the unsaturated zone moves in layers i.e. any fresh water added at the soil surface will move downward by pushing the older water further below. Thus, if the soil moisture in a given horizontal plane is tagged with a tracer like tritium, the tracer is carried along with moving water and the tagged layer acts like an impermeable sheet, so that any water added due to percolation or subtracted due to evapotranspiration, the water above and below the tagged layer cannot bypass on short cut in either direction. Although the tagged layer may spread due to diffusion effects, the layer with maximum tracer concentration can usually be located fairly accurately. Tritium (HTO) is injected at certain depth. There is a movement of tritium irrigation, from fall water etc. After certain time the position of tritium peak can be located by counting tritium in the moisture obtained from different depths of the soil. The recharge during the given period is determined by finding the amount of water contained between the tritium peak at the beginning and at the end of the period. Moisture content of soil samples which is collected from different depths by hand auger, can be estimated by gravimetric method.

2.4.2.3 Environmental tritium method

Huge amount of tritium is released from several thermonuclear bombs, tested in the atmosphere since 1952. The tritium levels measured in precipitation all over the world show that the release of tritium was in form of pulses with a peak in 1963-64. The peak concentration varied from a few hundred to a few thousand tritium units in the northern hemisphere precipitation (one tritium unit, T.U., is concentration of one tritium atom per 10^{18} hydrogen atms). There are two methods by which environmental tritium can be used for evaluation of recharge: (a) tritium integral method (b) peak tritium method.

(a) Recharge rate by the integral method:

The total amount of bomb tritium fall out for a site is calculated by adding the yearly products of the annual rainfall and its average tritium concentration.

The summation is carried out for the period 1952 (onset of thermonuclear era) to the time at which the investigation carried out. The total amount can be found by the following relation:

$$T = \Sigma(A_i \; P_i)$$

where, T = total tritium fallout (T.U)

A_i = weighted mean annual tritium concentration (T.U) of precipitation in the year i

P_i = Precipitation (cm) in the year i

The total amount of bomb tritium present in a profile is calculated by adding the differential amounts of tritium present in several segments of a profile upto a depth d, wnere tritium content becomes negligible. The total amount of tritium can be obtained by:

$$t = \sum_{g}^{d} a_j . m_j$$

where, t = total amount of tritium (T.U.) present in a profile summed from ground level g to depth d,

a_j = tritium concentration (T.U.) in soil water of segment j, and

m_j = moisture column (cm) of soil segment j.

The ratio of total tritium observed underground to the total tritium fallout in precipitation provides a measure of the fraction of precipitation that goes as recharge to the ground water.

(b) Recharge rate by the peak method:

In this method the 1963-64 tritium peak in precipitation is made use of like what is done in artificial tagged layer. By locating this peak in the soil at some depth, recharge can be calculated by finding the total amount of water present upto the tritium peak position and comparing this amount with the total rainfall from 1963 to the time of investigation. The recharge as percentage fraction of total precipitation can be found by the relation:

$$r = \frac{S}{P} \times 100$$

where, r = recharge as a percentage fraction of rainfall,

S = soil moisture (cm) in the column from the ground surface to the depth where the tritium peak is occuring, and

p = Total precipitation (cm) from 1963 to the time of investigation.

3.0 METHODOLOGY

The downward movement of soil moisture in the unsaturated zone is assumed to be layer by layer like a piston flow (Zimmermann et al., 1967). Each layer transmitting water is assumed to have a minimum moisture content corresponding to its field capacity. Any input of water to the top layer in the form of precipitation would percolate downwards by pushing an equal amount of water into the next layer beneth it and the process continues so that excess water in the last layer is transmitted to the ground water as recharge.

There are a number of direct and indirect methods to measure infiltration rates. Direct methods using lysimeters or infiltrometer disturb the natural conditions of flow and are often considered non-representative. The indirect method of measuring changes in the soil moisture profiles in the unsaturated zone, using either the classical gravimetric method or the neutron brobe method, need to be coupled with the computation of evapotranspiration with the attendant inaccuracies.

In recent times nuclear methods have been employed in the country and abroad to study the soil moisture transport and estimate the direct recharge to the ground water. The tritium tracer method suggested nearly twenty years ago (Zimmermann, 1966) and developed to a level of easy routine application over the years, provides an elegant and direct approach to infiltration studies.

In the tracer method, the soil moisture in a horizontal layer (either at the surface or at a depth) is tagged with the radiotracer. Tritiated water (HTO), being one of the isotopic species of the water molecule is often chosen as the best tracer. However, any other isotopic or chemical tracer with negligible interaction with the soil medium can be used.

Infiltration caused by rainfall or irrigation would then push the tagged layer downwards like a moving piston. The new position of the tagged layer is then located by a suitable radiation detection procedure. In the case of tritium, soil cores are taken with a hand auger, soil moisture is extracted by vacuum distillation and the tritium content of the moisture samples are determined by liquid scintillation counting. The tritium profile give the new positions of the tagged layer . Soil moisture profiles are prepared by the standard gravimetric procedure.

If the tagged layer has moved by a distance 'd' from its initial position and $\overline{m(z)}$ is the average moisture content between the initial and final positions of the tagged layer, it follows from the piston flow anology that a quantity of $\overline{m(z) \times d}$ of water infiltrated into the soil after tagging.

This piston flow concept was successfully applied to the distribution of environmental thermonuclear tritium in the unsaturated zone. The thermonuclear tritium registered a peak value in the precipitation of 1963 - 64 before the ban on atmospheric explosions. Location of this peak in the soil moisture helps in calculating the average recharge rate in the period intervening between 1963-64 and the time of detection. Many examples of successful application of this method are availale in literature. The limitations of the method, however, are the elaborate procedures needed for the determination of environmental tritium, the possibility that the 1963-64 peak might have already reached groundwaters in many areas and the evapotranspiration of the tagged precipitation.

The piston-flow mode of transport of soil moisture has also been confirmed in a number of filed experiments using injected tracers (Zimmermann, 1967; Blume, 1967).

The principal steps involved in the field application of tracer method for soil moistute movement and ground water recharge studies are as under:

1. Selection of tracer
2. Selection of injection sites
3. Plan of injection
4. Amount of tracer injected
5. Injection procedure
6. Detection of tracer position

3.1 Selection of Tracer

The isotopic tracer used for soil moisture transport studies should ideally have the following characteristics:

(a) The tracer should behave same as normal water and should not be lost or retarded due to adsorption or ion-exchange.

(b) The tracer should have a high detection sensitivity.

(c) The health and handling hazards should be minimum.

(d) The radiotracer should have sufficiently long half-life.

The most logical selection of an isotopic tracer for soil moisture movement studies would be either Deuterium or Tritium, the isotopes of hydrogen, incorporated into the water molecules. HTO molecules behave essentially same as water molecules. The high cost of HDO tracer and expensive detection method limits it for routine use. Even though HTO is an ideal tracer, it has one draw back, being a soft beta emitter it is not easily detectable in the field and hence requires laboratory support. The other commonly felt disadvantage is that the detection cannot be repeated at the same spot due to the destructive nature of soil core sampling. This has lead to the application of gamma emitting isotopes for soil moisture movement studies.

Recently gamma emitting cobalt-60 as $K_3 CO(CN)_6$ has been used (Nair, 1978) under field conditions after detailed laboratory investigations (Nair, 1981). When injected around an access tube (figure 1), Co-60 provides the advantage of in situ and non-disturbing detection. The tracer displacement can be directly followed simply by logging the access tube. The same access tube can be used for

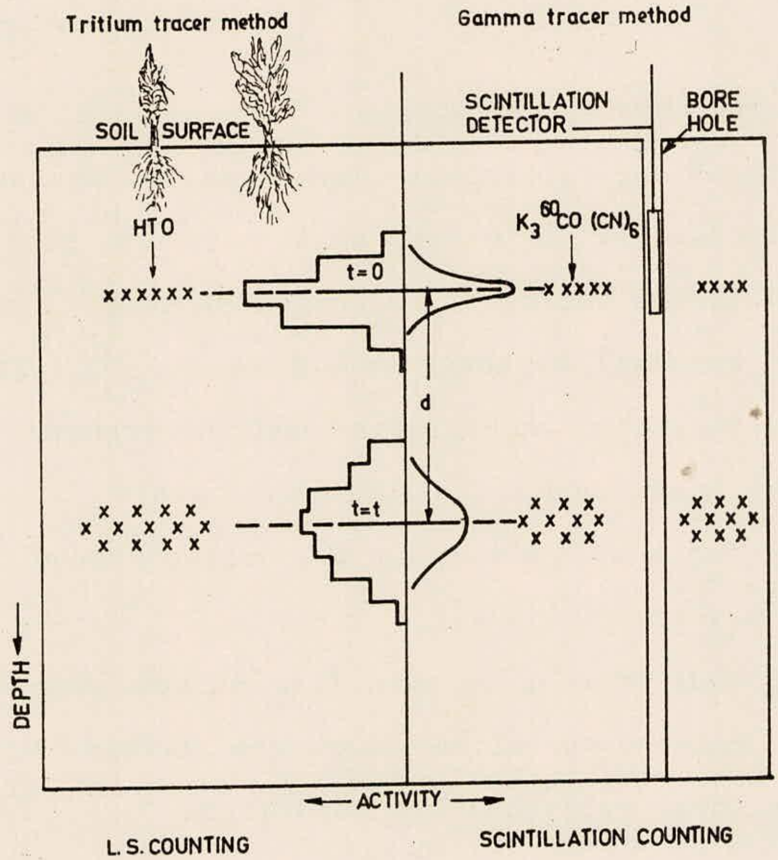


FIG.1-THE INJECTED TRACER METHOD

recording soil moisture distribution using neutron probe.

3.2 Selection of Injection Sites

This is of great importance for the success of the investigations and is probably one of the most difficult aspects of field application. The criteria normally considered are:

1. There should be adequate homogeneous soil cover without any impermeable lenses at shallow-depths. Lithological data and soil moisture profiles can aid in the choice of injection sites.
2. For rainfall recharge measurements, the site selected should be uncultivated and unirrigated.
3. The land should be flat to avoid formation of any pools or puddles in the neighbourhood of injection sites.
4. The site should be away from stream, canals, tanks or reservoirs since they are likely to disturb the local soil moisture conditions.
5. The site should also be away from big trees to avoid the effect of the roots on soil moisture transport.
6. It is necessary to have permanent markers such as electric transmission towers and buildings to enable relocation of the injeted sites for sampling.

3.3 Plan of Injection

The plan of injection in the case of tritiated water could either be a number (10 to 20) of points 10 to 15 cm apart along a horizontal line or a cluster of 5 points repeated at one meter intervals (Figure 2). The injection at each point is at a constant depth (50 to 80 cm) below the soil surface. For recharge measurements, the injections are made below the root zone.

The plan for tracer injection depends on the envisaged frequency of sampling and the ease with which the positions can be relocated for soil core sampling.

The plan for $K_3{}^{60}Co(CN)_6$ is usually on a circle of 90 cm diameter around an access hole (figure 3).

There are as such no specific guidelines as to the number of injection sites needed to arrive at a representative recharge figure. One way is to cover all types of soils (based on the mechanical analysis) encountered in the area. The second approach, more as thumb rule, is to have a network similar in size to that used for soil moisture distribution studies. There is a need for a more authoritative answer to the question.

3.4 Amount of Tracer Injected and Mode of Injection

The amount or radioactivity and the volume of the tracer solution used for injection show great variation in published studies. The activities vary from $8 \times 10^{-3} \mu Ci/dm^2$ to about to $10 \mu Ci/dm^2$ and the volume of tracer solution per point is usually of the order of 2 to 10 mL. These amount depend on the soil moisture content at the depth of injection. In all cases, it can be shown that the dilution caused

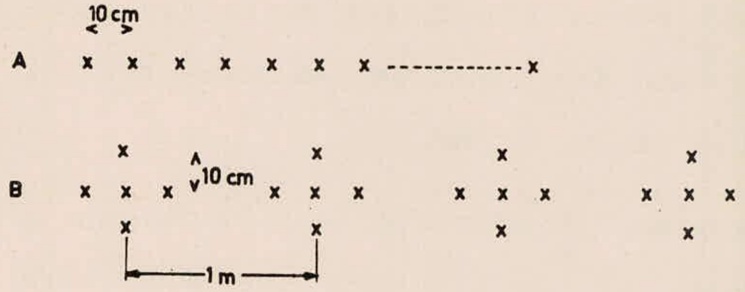


FIG. 2 PLAN OF TRITIUM INJECTIONS

A:- A SINGLE HORIZONTAL LINE OF POINT INJECTIONS.
B:- A CLUSTER OF 5 POINTS REPEATED AT INTERVALS.

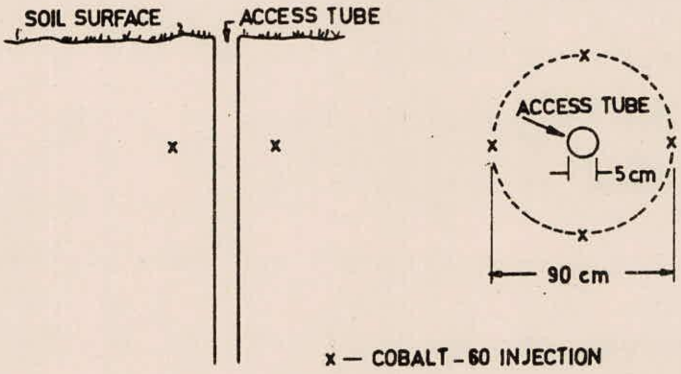


FIG. 3-PLAN OF $K_3{}^{60}Co(CN)_6$ INJECTION

by molecular diffusion will bring the concentrations below the maximum permissible levels (3 μ Ci/litre) for drinking water. Considering the fact that the injections are made in highly localised and identified areas and that the soil water is not extractable for drinking purposes, there is usually no health hazard at all. The soil moisture transport is normally low (1 m/year) and hence the tracer gets added to the ground water very slowly over period of years.

In the case of cobalt - 60, the activities injected around an access tube are of the order of 100 to 200 microcuries to obtain a peak countrate of about 10 to 20 times above background at the time of injection. Firstly, since the injections are made at a depth of over 50 cm, there is practically no external radiation at the surface. The place of injection is well marked and is always identifiable.

In the evaluation of the health physics aspects of cobalt-60 application, the following points are to be noted:

1. At no time the soil cores need be taken for analysis as in the case of tritium.
2. The activity is not accessible except by accidental digging which has only a remote possibility. Even in such a situation, the activity will get distributed in a few cubic metres of the soil bringing down the concentrations to acceptable levels.
3. The access hole is blind cased and hence no activity can enter the hole even under remote conditions

of lateral flow.

4. Water in the unsaturated zone below the root zone is not available for any use.

5. After completing the experimental programme, and before abondoning the site, the soil may be dug up, if the concentrations remained high due to low moisture transport conditions.

6. The diffusion calculations show that the concentrations near the access hole will reach a maximum of 0.09 μ Ci/litre (M P C: 0.05 μ Ci/litre for drinking water) about 300 days after injection, if there is no vertical displacement of the tracer.

3.5 Injection Procedure

The aim is to deposit a pre-determined quantity of the tracer at the desired depth and with minimum disturbance to the natural conditions. The tracer may be applied using a syringe type injector (Munich, 1968) below the root zone.

A sharp edged steel rod 1-2 cm in diameter is driven into the soil to the desired depth to make a hole. If the top soil layer is very loose and is likely to cave-in, the rod is placed in a close fitting sharp edged steel tube and both are driven down simultaneously and the rod along is withdrawn.

The tracer solution is normally injected at the bottom of the hole using a syring - type injector (Figure4)

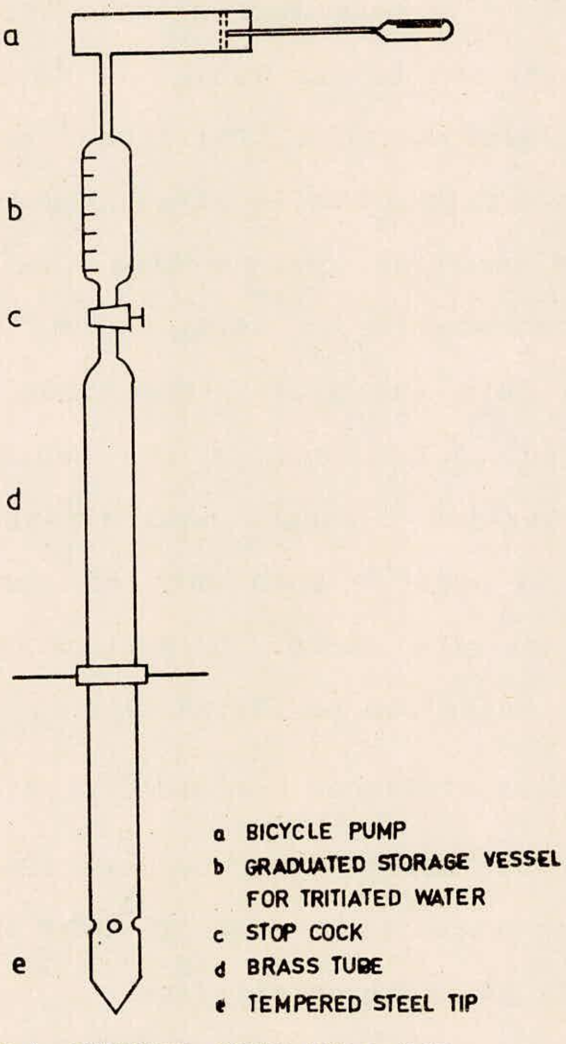


FIG. 4 - SYRINGE TYPE INJECTOR

which allows injection upto a depth of 1 metre.

A new method for tracer injection was developed by Nair and co-workers (1979). Figure 5 shows the arrangement used for the purpose. At each point a hole having a diameter of 1-2 cm is made to requisite depth using a drive rod. A thin S.S.tube having radial holes at its lower tip is introduced into the hole. The tracer solution contained in a 100 mL serum capped bottle is mounted in a stand nearby in an inverted position. By operated the peristaltic pump for a precalibrated time, a known volume (2 mL) of tracer is transferred into the S.S. tube through the hypodermic needles attached to the end of the tubing. Air inlet is provided by inserting a second needle into the bottle cap. A hand blower is used to push out all the tracer from the S.S. tube. After the tracer injections are completed in all the points, holes can be filled with dry soil.

3.6 Detection of Tracer Position

The tracer movement may be determined about 6 months or a year after injection, when it would have been displaced sufficiently due to precipitation.

In the case of tritium injection, hand augers are normally used to extract soil cores, 10 cm sections of vertical cores are collected separately with an auger (2" or 4" size). Samples generally collected to a depth of about 2 to 3 metres.

Problems are often encountered in auger sampling due to big pebbles. In clayey soils also, the operation

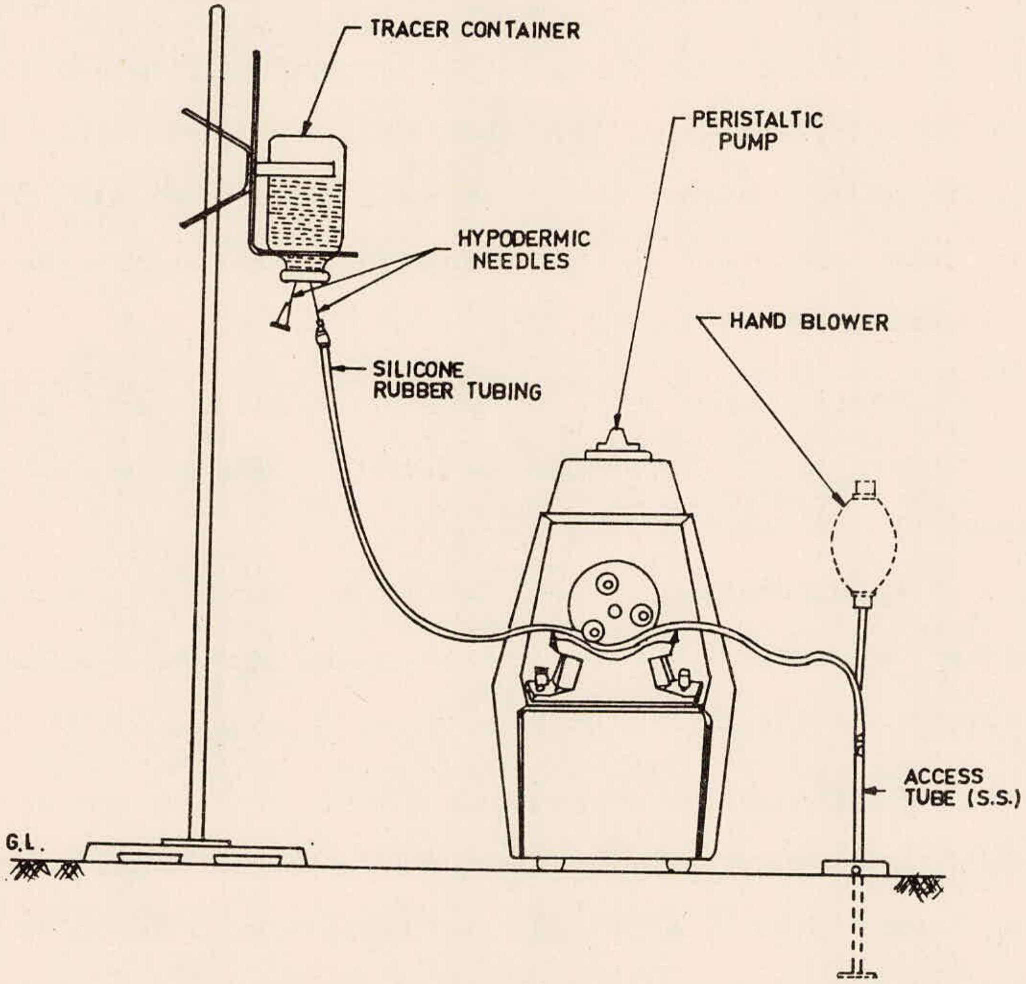


FIG. 5 - RADIOTRACER INJECTION SYSTEM

of an auger is sometimes very difficult. In such cases, it is advisable to use a hollow pipe (Athavale, 1980) with a diameter of about 40 mm and a wall thickness of 4 to 5mm. The soil cores are removed from the pipe by lightly tapping the tapered end.

Each soil core sample is weighed at site and sealed in a polyethylene bag. The toal weight of the soil cores and the total volume of loose soil needed to refill the auger hole are used to determine the average bulk density of the soil.

Where there is a large variation of soil density with depth, it is advisable to measure the volume of each section of the auger hole separately.

Measurements of soil moisture content in the core samples is carried out by the standard gravimetric method in almost all the laboratories.

Soil samples are vacuum distilled at a temperature of 80°C to extract moisture for tritium measurement (Navada, 1974). About 100 g of sample is transfered into a weighed beaker (W_1) and its weight taken (W_2). The soil moisture from the soil is extracted by vacuum distillation. The weighed soil samples in the beaker are kept in S.S. container and evacuated through capillary tubes to a pressure of few torrs with the help of vacuum pump. The sample containers are heated to a temperature of 60-70°C. The soil moisture gets distilled over and is collected in tubes colled in ice water mixture. After this the soil samples are taken out and dried in an oven at 105° C to contant weight (W_3).

Soil moisture fraction by volume is given by

$$m = \frac{\text{Volume of moisture in soil sample}}{\text{Volume of soil sample}}$$

$$= \frac{\text{Weight of soil moisture/Density of moisture}}{\text{Weight of wet soil/Density of wet soil}}$$

$$= \frac{(W_2 - W_3)/1}{(W_2 - W_1)/D} = \frac{(W_2 - W_3)\ D}{(W_2 - W_1)}$$

Where D = Bulk density.

Alternatively an infra-red moisture balance for soil moisture content determination may be employed.

A suction method for 'in situ' soil moisture sampling has also been described (Thoma, 1979). The method uses a suction probe hammered down to a desired depth. Soil moisture saturated air is pumped through the probe and the moisture is trapped in a molecular sieve. The moisture is later re-extracted quantitatively in the laboratory by heating to 400°C in a vacuum system.

1 to 4 ml soil moisture sample is normally adequate to measure the tritium content using a liquid scintillation spectrometer. Either a dioxane based scintillator or a commercially available cocktail such as Instagel is normally used for counting. No Special precautions are necessary since the information required is the relative variation of tritium concentration with depth.

For determining the position of gamma tracer the borehole can be logged using a NaI (Tl) scientillation detector. A scientillation detector (3.5 cm diameter) with 1" x 1" NaI crystal has been found to be quite suitable for this purpose. The soil moisture content and bulk density profile can be obtained using a nuclear soil moisture/density gauge using the same borehole.

3.7 Recharge Calculation

Let P be the precipitation received at the soil surface during the period of investigation. A part of this water infiltrates pushing down successive layers of moisture including the tracer labelled layer. Let d be distance by which the tracer gets displaced.

Consider a soil column of unit cross sectional area, then the amount in cm, contained between the injected and the displaced position is given by equation

$$m(d) = \bar{m} \times d$$

where $\bar{m}$ is average moisture content of soil layers expressed in cm of water per cm of soil column. This is the amount of soil water which infiltrated during the period of observation through unit cross sectional area. An equal amount of water is added to ground water as recharge.

If soil cores are obtained for soil moisture/density determination in sections of 10 cm, $\bar{m}$ may be calculated by summing up the moisture content of individual sections.

$$\bar{m} = \frac{(W_2-W_3)\ D/\ (W_2-W_1)}{n}$$

where n is number of sections examined in the 'd' cm section of the core. The % recharge of the precipitation p to the ground water can be calculated using the expression

$$R = \frac{\bar{M} \times d}{P} \times 100.$$

4.0 REVIEW

In recent years, the use and application of nuclear techniques in hydrology has been well recognised. Nuclear techniques in hydrology are mainly isotope based. In particular, the use of isotopes is being actively introduced into hydrological research and field investigations like recharge to groundwater, moisture content, porosity, sediment movement and transport, measurement of rate of flow, snow packs, erosion etc.

The first planned significant discussion at international level on hydrological application of isotopes was conducted by a panel of experts (from 6-9 November 1961 in Vienna at the International Atomic Energy Agency headquarters). After that, several thorough attempts have been made in this direction and now several nuclear techniques employing stable and unstable isotopes (both artificial and natural) are used. Also, International Atomic Energy Agency has introduced international symposium after every four years on the use of isotope techniques in the field of hydrology.

In this report an attempt has been made to briefly review the status of ground water recharge studies using tracer techniques.

Both natural and artificial tracers have been employed in the country and abroad to study the soil moisture transport and estimate the direct recharge to the groundwater. The methods most commonly used are:

(i) Isotopic tracer injection method

(ii) Environmental tracer method

Two direct methods using environmental and artificial tritium developed by Munnich and his Coworkers (Zimmermann et al., 1965, 1966, 1967; Munnich et al., 1967: Munnich, 1968) are noteworthy contribution to recharge determination methods. Since the first demonstration of such an application by Munnich and his colleagues, many researchers have explored the utility of the methods in diverse climatic and hydrological conditions.

The tritium injection method of estimation of recharge is based on the assumption that the soil moisture moves downwards in discrete layers. Any fresh layer of water added near the surface, due to precipitation or irrigation would percolate by pushing an equal amount of water beneath it further down, and so on, such that the moisture of the last layer in the unsaturated zone is added to the groundwater. In this technique, the moisture at certain depth of the soil profile is tagged with tritiated water. The tracer moves downwards along with the infiltrated moisture due to subsequent precipitation or irrigation. A soil core from the injection site is collected after a certain interval of time and the moisture content and tracer concentration are measured on samples from various depth intervals. Many examples of this technique have appeared in the literature describing studies particularly in Europe and India.

Early field studies in this direction were carried out under the humid central European conditions (Blume et al., 1967). The technique of injection was however, by sprinkling of tritiated water on the soil. The apparent recharge has been calculated on one type of forest soil which shows that the apparent recharge was very high in the early stages because of root activity. When the tracer peak reached below the root zone the apparent recharge became more representative of ground water recharge.

Saxena and Dressie (1984) have used natural oxygen-18 and injected tritium for the estimation of ground water recharge and moisture movement in sandy formations. Rates of soil moisture movement and recharge estimates by these two independent tracers have been compared and the agreement was found to be quite good. It is also reported that ^{18}O- depleted soil moisture derived from two years successive snow melt periods can be used to estimate yearly recharge.

Since the early seventies, a large number of recharge measurement were carried out in India using injected tritium method. The pioneering work in India using this technique was carried out by the group of Rama, Goel and Datta. The first measurement were carried out in western Uttar Pradesh (Datta et al.,1973), and were later extended to Haryana and Punjab (Tanwar et al., 1974: Datta, 1975; Goel et al., 1975, 1977). All these measurements were carried out in the Indo - gangetic alluvial plains. The results of these studies have been summarized in a review article by Athavale (1980):

TABLE 1: RECCHARGE MEASUREMENTS IN WESTERN U.P., PUNJAB AND HARYANA

S.No.	Zone	No. of injection sites	Average rainfall (cm)	Average recharge (cm)	Variation in recharge (cm)
1.	Western U.P.	45	99	21.5	3-55
2.	Punjab	21	46	6.2	2-20
3.	Haryana	14	47	6.4	0-20

The Physical Research Laboratory at Ahmedabad also took up this work in Sabarmati basin (Datta et al., 1977, 1978: Bhandari et al., 1982). A number of measurement made in the Sabarmati basin of Gujarat show that the average recharge to the unconfined aquifer in a two year period (1976-78) was about 8% of the total water input. It was concluded that the spatial variability in the downward movement of soil moisture within the basin was governed by the amount of silt and clay (≤ 45 microns) content of the soil.

Datta et al. (1979) made a basinwise comparison of recharge rates in parts of Indo-Gangetic Plains and Sabarmati alluvial plains and concluded that comparatively lower recharge in Sabarmati Basin may be ascribed to higher evapotranspiration and difference in hydrometeorological parameters such as rainfall distribution, temperature etc. The comparative study has brought out that it is possible to develop empirical relationship to estimate groundwater recharge for each region within which soil characteristics and hydrometeorological factors can be reasonably taken to be uniform. Since these factors vary significantly from basin to basin and sometimes within parts of a basin, extrapolation of such empirical formula developed for a given region to other region may lead to erraneous estimates of recharge. Development of a comprehensive formula incorporating all variable factors controlling groundwater recharge is rather difficult and therefore, it is desirable to treat each region individually.

A number of areas in Southern India have also been investigated by 'the group of Athavale at National Geophysical Research Institute, Hyderabad. They have estimated recharge to the pheratic aquifers of lower Maner Basin (Athavale et al., 1978) by using the tritium injection method and have correlated the recharge values with local water table fluctuations and sand content of the soils. The experiments done by them also indicated that the depth selected for injecting tritium does not play any critical role in the final estimate of recharge values, if the area is devoid of wild growth of shrubs and plants. From their experiment it is inferred that in general soil moisture after passing below the root zone layers is not affected during the hot period, as long as water table is sufficiently deep . Mention should also be made of the work in the sandstone area of the Lower Manner Basin (Athavale et al., 1980) in Andhra Pradesh and some other basins which are in the granitic terrain of the peninsular shield. In the Lower Maner Basin (1600 K^2), 26 tritium injections were made. An average recharge value of 10 cm

(5 to 24 cm) was obtained for a rainfall of 125 cm. This 8% recharge compares well with the observations of water table fluctuations. Studies have also been carried out by them in different basins covered grantitic rocks such as Vedavati basin, Noyil, Ponnani and Vattamalai Karai basins and the Mar Venka basin (Athavale et al., 1983). Recharge measurements have also been carried out in two Deccan trap basalt covered basins, namely Godavari - Purna basin and Kukadi basin (Athavale et al., 1983). Results of these studies have been summarised by Athavale (1983) and are shown in table 2.

TABLE 2 :RECHARGE MEASUREMENTS IN INDIA USING INJECTED TRITIUM TECHNIQUE

Sl. No.	Location	No. of Recharge measurements in a year	Average rainfall (cm)	Mean Recha- (cm)
1.	Punjab	21	46.0	6.2
2.	Delhi	8	71.4	19.3
3.	Haryana	14	47.0	6.4
4.	Western U.P.	45	99.0	21.5
5.	Jalaun (U.P)	4	80.0	21.2
6.	Sabarmati basin	23	78.0	11.0
7.	Godavari Purna basin	24	65.2	5.6
8.	Kukadi basin	19	61.2	4.6
9.	Lower Maner Basin	26	125.0	10.0
10.	Marvanka basin	19	55.0	4.2
11.	Vadavati basin (Lower Hagari sub-basin)	44	56.5	0.65
12.	Vedavati basin (W. Suvarnamukhi sub-basin)	19	56.5	3.9
13.	Noyil basin	21	71.5	6.9
14.	Vattamalai Karai basin	2	46.0	6.1
15.	Ponnani basin	9	132.0	6.1

Nigam et al. (1980) carried out such studies in Jalaun district of Uttar Pradesh in order to explore the possibilities of future ground water development in the area to augment present irrigation facilities which have more or less protective nature. The results of their study have been given in Table 3.

TABLE 3 : RECHARGE MEASUREMENTS IN JALAUN DISTRICT, U.P.

Sl.	Name of Site	Recharge Calculated by tritium shift method (cm)	Recharge calculated by water table fluctuation method (cm)
1.	Kalpi	15.97	- 5.81
2.	Madaripur	22.02	+ 3.15
3.	Ait	29.82	- 1.50
4.	Baragaon	14.65	- 5.04

The difference between recharge calculated by tritium peak shift method and water table fluctuation method has been reported due to flow of groundwater from/ to the river.

The group at National Research Laboratory of IARI has been using this technique in studying recharge conditions in their agricultural research farms (Bahadur et al., 1977). Experiments have been conducted in fields treated with sodium chloride under controlled conditions (Bahadur et al., 1974) to study the pattern of moisture distribution and movement in relation to plant productivity. Arora et al. (1974) selected five different locations to study deep drainage below 150-180 cm depth in irrigated wheat fields under wet and dry conditions. They concluded that tritium tagging method of soil moisture is rather a simple, easy and less laborious task to determine deep drainage, compared to the conventional methods making use of tensiometers. Singh et al. (1979) carried out some recharge studies in Gandak command area. Sharma and Gupta (1985) estimated 6-14% recharge in the thar Desert of Rajasthan, India.

Many investigators had encountered situations of negative recharge or exfiltration (Goel et al., 1975 ; Nair et al., 1978). In these cases, the tracer maximum shifted to a position above the injection layer. Since in such cases the moisture content being low ($\leq$ 5% or so), the evaporation effect causes such an upward movement. In some other cases, the authors preferred to locate the centre of gravity of the tritium profile whenever the position of the maximum concentration could not be properly defined. The above situation indicate deviations from the piston flow model concept. The results still have validity since they can qualitatively indicate the existence of recharge or otherwise. Considering the large spatial variation of recharge figures within small area of 100 km^2 or so, the proof of downward movement of soil moisture, even if piston flow conditions are not satisfied has considerable hydrological significance.

Among the other injected tracers, deuterium in the form of heavy water can also be used as an injected tracer. It has all the advantages and disadvantages of tritium or tritiated water. However, so far no serious attempt of using deuterium for studying flow in the unsaturated zone has been made. The main reason is that laboratory measurement of deuterium is much more complicated and laborious as compared to measurement of artificial tritium with liquid scientilation counter.

Cobalt-60 in the form of $K_3Co(CN)_6$ has been used under field conditions, after detailed laboratory investigations, by the Isotope Hydrology group of Bhabha Atomic Research Centre (Rao, 1982). The main advantage of using this tracer is that its movement can be monitored in situ through gamma-logging in a borehole adjacent to the injection site. The half life of ^{60}Co is 5.3 years. It, therefore, seems to be a potentially good tracer for studying the unsaturated zone.

The tracer was first tested in column studies carried out in laboratory. Cobalt - 58, which is a much shorter lived isotope as compared to cobalt-60, was used for the purpose (Rao, 1978; Nair et al., 1977). The first field measurements were made in the Tapti alluvial tract in Maharashtra (Nair et al., 1979). The results have been compared with those with the tritium tracer which shows that the cobalt peak was ahead of the tritium peak possibly due to anion exclusion in the clayey soil.

In addition to injected tracers, environmental tracers have also been successfully used for groundwater recharge measurements. The most commonly used environmental tracer is tritium. The occurrence of tritium in precipitation originates from two causes : (i) Production by interaction of high energy cosmic radiation with the atmospheric gases. It is estimated that tritium concentration in precipitation is of the order of 5-10 T.U. (ii) Man-made detonation of thermo-nuclear devices and atmospheric release of waste from nuclear power plants.

The presence of tritium in groundwater indicates that at least some of the water has been recharged during the last few decades. During the early years of environmental tritium measurements, the converse conclusion, that absence of tritium implied that recharge was not occuring, failed to take into account that the unsaturated zone might be so deep that the recharging water had not yet reached the water table. Today the presence of tritium still provides atleast qualitative information on recharge. In the early 1960s the concentration of tritium in precipitation reached a maximum after the moratorium on the atmospheric testing of thermonuclear devices. This peak in tritium has been used for studying the infiltration of water through the unsaturated zone and for estimating the average recharge over the period from the peak in concentration in 1963 to the time of measurement of the tritium profile with depth.

Smith et al. (1970) utilised the method for studying soil water movement and recharge in chalk and clay profiles. The marked peaks in the chalk and clay profiles indicates that intergranular seepage dominates the downward movement of the water and recharge occurs by replenishment of the summer soil moisture deficit by autumn rainfall.

Anderson and Sevel (1974) investigated the infiltration rate and movement of water in the unsaturated zone using environmental tritium in precipitation and subsurface water. From the results tritium balance for the unsaturated zone during the period 1966-72 have been set up.

Ataken et al. (1974) carried out experiments in a shallow unconfined aquifer composed of fine to coarse sand, in the alluvial plain of the upper Rhine River, FRG. The observations reached to a maximum of 75 m depth but were concentrated in the top 15 m of the ground. A groundwater recharge rate of 164 mm yearly was deduced from the results.

Sukhija (1972) found from tritium measurements of pore water extracted from cores in the alluvial tracts of Gujarat that peak concentration was clearly identifiable and was moving through the unsaturated zone at a rate of about 0.5 m yr^{-1} Using such studies Sukhija and Rama (1973) estimated that only small fraction (5-10%) of the rain infiltrates to become part of groundwater in different parts of Gujarat. Results of their studies are given in table 4.

TABLE 4 : RECHARGE MEASUREMENTS IN GUJARAT

Sl.	Location	Average precipitation (mm)	Average groundwater recharge	
			(mm)	% Rainfall
1.	Varahi	450	13 - 18	2.9.-4.0
2.	Sankeshwar	500	10 - 25	2.0-5.0
3.	Balol	600	25	4.2
4.	Taranga	530	50 - 60	9.4-11.3
5.	Ahmedabad	800	32 - 40	4.0-5.0
6.	Kosamba	1250	38 - 60	3.0-4.8

A comparative study of recharge rates determined over an interval of two years 1967-1969 in a semi-arid region of western India(Gujarat) has also been attempted by Sukhija et al. (1976) using the environmental tritium method and those computed using a diffusion - tube unsteady groundwater flow model for a part (Mehsana district) of the selected area. The results shows a fair agreement between the recharge rates determined by the two altogether different techniques.

Sukhija et al. also carried such studies in Lower Maner Basin falling in Karim nagar district of Andhra Pradesh (Sukhija, 1978) and Vedavati River Basin situated partly in Karnataka and partly in Andhra Pradesh (Sukhija et al., 1980).

In a similar study Athavale and Murti (1980) identified the tritium peaks produced in Indian precipitations as a result of Chinese thermonuclear tests and used this identification in estimation of recharge in some parts of Andhra Pradesh.

Allison and Hughes (1972, 1974) investigated recharge to groundwater under pasture and forest at a site on the Gambier Plain, southern Australia by making use of environmental tritium. For several sites a long a groundwater streamline, the mean tritium concentration of groundwater beneath the forest was found to 1.8 TU, while that under pasture was 12 TU. These results lead to the conclusion that there is virtually no recharge to groundwater beneath the forest.

Allison and Hughes (1978, 1988) have also used chloride as an environmental tracer for studying fluid movement in semi-arid area of southern Australia. They have carried out measurement of chloride and environmental tritium in vertical soil sections and used these measurements in the estimation of recharge. A change in land use from Eucalyptus scrub to cropping with wheat was shown to have caused considerable change in the mechanism of the movement of soil water and the amount of deep drainage. Chloride concentrations of soil water have been used to show the mean annual amount of deep drainage increases from less than 0.1 to ~ 3 mm yr^{-1} following clearing of the native vegetation. The concentration of environmental tritium in soil water beneath the native vegetation was consistent with the hypothesis that some relative recent water (post 1960) has penetrated to depths of at least 12 m along channels occupied by living roots. Where the native vegetation has been cleared, no water which fell as rain since 1960 was found at depths greater than 2.5 m.

Vogel et al. (1974) carried out recharge measurements in parts of South Africa. Edmunds and wright (1979) used stable and radio isotope results of Sirte and northern Kufra basins, Libya to determine the Holocene and late pleistocene.

Schmalz and Polzer (1969) and Foster (1975) have used the natural tritium concentrations of water samples collected from geologic deposits to gain insight into groundwater recharge through unsaturated strata. Hendry (1983) reported the character of groundwater movement through the unsaturated and saturated zones of a glacial till, southern Alberta, Canada. From the study, he has concluded that water, which entered the subsurface environment from ground surface after 1953, has migrated to the lacustrine - till contact viz intergranular seepage and fracture flow and that fractures are transmitting post-1953 recharge water to depths within the underlying slowly permeable unsaturated and saturated till. In addition, diffusion of tritium from the fractures into the adjacent matrix material appeared to occur both above and below the water table.

Issar et al. (1984) examined the contribution of different pathways of recharge to the groundwater in the Negev desert, the southern arid part of Israel by means of isotope and chemical signatures which are imprinted on the water. In regions covered by sand dunes, with no perennial vegetation cover, it was found that evaporation amounts to about 30%, while 70% of the rain water infiltrates into the subsurface. In dune areas covered by deep-rooted vegetation, all water flowing into the subsurface may be transpired by the vegetation. In limestone area, recharge to groundwater was of the order of 2% and was mainly through gravel-filled river beds by flood water.

Recently Delcore (1987) utilised environmental tritium to gain quantitative information on the rate of groundwater recharge to homogeneous and heterogeneous unconfined aquifers of U.S.A.

Andres and Eggar (1985) described a new tritium interface method for determining the recharge rate of deep groundwater using the aquifer in the Bavarian Molasse basin. The depth of the interface between tritium-bearing and tritium-free groundwater, together with the hydraulic conductivity of the leaky layer overlying and aquifer and the duration of anthropogenic tritium inputs, were used to calculate recharge rates of 1-6 ls^{-1} km^{-2} for the study area. Recharge rates obtained using the tritium interface method for deep groundwater were compared with those obtained from a mathematical groundwater simulation model. The presence of anthropogenic tritium in pumped samples established that the ^{14}C - dated Holocene and Pleistocene groundwater in undisturbed areas and especially in abstraction areas is regenerated by long-term infiltration of recent groundwater from the overlying Neogene and Quaternary aquifers. In the main abstraction areas of Munich and Augsburg the deep groundwater is still sufficiently regenerated from quaternary aquifers at recharge rates of 10.0 and 7.5 $1\ s^{-1}$ km^{-2}, respectively.

Winter (1986) reported the importance of topography on the shape of the groundwater table. Based on water level elevation in lakes and in piezometers completed in the underlying water-table aquifer, winter concluded that recharge was concentrated in topographic lowlands in during area between lakes.

Field experiments have been performed on a sand dune near Socorro, New Mexico to investigate the significance of topography on soil-water movement (Stephens et al., 1985; McCord and Stephens, 1987). Two separate experiments have been conducted. which shows that there are horizontal components to soil moisture flow. In the first experiment bromide tracer was buried at different depths in the profile beneath a steep slope (23%). Following periods of rainfall, the soil was sampled and analysed for bromide. Contours of equal solute and unpumped groundwater concentration clearly showed evidence of soil-water movement nearly parallel with the topographic slope. In the second experiment moisture content was measured by the neutron scattering method to depths of about 5.8 m at three locations along transverse transect across the dune. The monitoring location were located at the dune crest, on the slope, and in a swale at the base of a slope. Following a major rainstorm, there was very little increase in soil moisture beneath the crest, a significant increase in moisture occured on the slope, and a gradual increase in moisture in the swale to an amount which exceeded the recorded amount of rainfall. No runoff has been observed at this site during over three years of monitoring. The results of these two experiments suggest that horizontal components of the unsaturated flow may contribute significantly to depression focused recharge beneath lowlands within sand dune area, perhaps including those studied by winter (1986).

Dincer et al. (1974) studied natural recharge rates in sand dunes in Saudi Arabia using tritium. Their results indicated a mean recharge of 23 mm a^{-1}, about 35% of the annual rainfall, for the period 1963 - 1972 in the Dahna sand dune in Saudi Arabia. Allison et al. (1975) used chloride concentrations from core samples to determine that recharge to a cleared sand dune area is as much as 1.4 cm yr^{-1} in a semi-arid area in south Australia where mean annual precipitation is about 30 cm yr^{-1}.

In recent years the use of unsaturated stable isotope profiles in field investigations has become widespread. Recently Barnes and Allison (1988) summarised the development of an analytical model for movement of the stable isotopic species of water in unsaturated soils. Initially investigations were aimed at examination of isotopic modifications to water which infiltrated through the unsaturated zone to the water table (Zimmermann et al., 1967). More recently, investigations have been aimed at using stable isotopes to determine the distributed groundwater recharge rate (Dincer et al., 1974 ; Saxena and Dressie, 1983; Saxena, 1987) and recharge mechanisms (Bath et al., 1982; Fontes, 1983; Issar et al., 1985; Darling and Bath, 1988, Darling et al., 1987).

For areas where there is a marked seasonal temperature cycle, (e.g. those with cool to temperate climates), the isotope concentrations of rainfall are seasonally "tagged" because of the temperature dependence of isotope concentrations of precipitation (White, 1983; Rodhe, 1987; Saxena, 1987). Thus, recharge waters from successive seasons can be identified in deep unsaturated profiles where piston flow is the dominant mechanism of water movement, although diffusive attenuation of the signal is to be expected. Measurements of recharge rates in the unsaturated zone have been made by successive observations of isotope profiles, or by observing the displacement between successive seasonal inputs (Thoma et al., 1979; Bath et al., 1982). By observing the displacement following one years's infiltration, an estimate of that year's recharge can be obtained by integrating the water content profile over that interval.

For this method to be useful, it is necessary that the isotopic signature of rainfall changes over the year, that there is significant recharge during both summer and winter periods, and that measurement are made beneath the root zone. The first of these requirements may make the technique unsuitable for areas with equatorial or maritime climates where there is little differentiation between seasons, whereas the second excludes arid and semiarid climates, where rainfall is vary variable, and no rain may fall for long periods. The technique appears to be most successful when recharge is high (200-300 mm yr^{-1} or more). An additional advantage in such areas is that the root zone is usually shallow, and sampling can be carried out near the surface. If the recharge rate is low, or the depth of roots is large, the size of the isotopic peaks will be reduced by diffusion. Alternatively, if a record of the isotopic concentration of precipitation is kept, it may be possible to identify the passage of water from particular events through the soil profile (Dincer et al., 1974). This method would be suitable for arid zones, except that the meteorological stations collecting isotope samples in these regions are relatively sparse, and rainfall variability and climatic difficulties generate special sampling problems in these areas.

Although much has been said about the relative merits of the piston flow model (Zimmermann et al., 1967; Sharma and Hughes, 1985) it is clear that it will remain a good model during unsaturated flow conditions. Macropore flow can only occur under saturated conditions, and for pores which are directly connected to the surface. For distributed recharge, bypass flow through macropores will only occur when the rainfal intensity exceeds the saturated hydraulic conductivity of the soil matrix.

If ignificant flow does occur through macropores and cracks, the soil matrix which is sampled may be bypassed, and thus will not reflect the true recharge rate. Bath et al. (1982) and Darling and Bath (1988) have used stable isotopes in this way to compare flow mechanisms in the English chalk. In order to explain tritium and solute profiles, as well as the stable isotope data, they considered a model involving a continuum of pore sizes. They observed similar isotope profiles at significantly different sites, with the profiles tending towards uniformity after a certain depth. The depth at which uniformily was obtained varied with the recharge rate, and this uniformity was attributed by them to effects of dispersion. For high recharge rates seasonal cyclicity was preserved for several meters. Whereas for lower rates (< 200 mm yr^{-1}) the cyclicity was damped.

Fontes (1983) summarized a number of experimental field investigations into flow mechanisms in the unsaturated zone using a variety of tracers, including stable isotopes. Lysimeter studies on a number of different soils, with either natural rainall or irrigation, showed only partial piston flow, and evidence of quite complicated interactions between water in large and small pores within the soil matrix.

Stable isotope work involving investigations into pathways for infiltration has been mostly semi quantitative, with little use made of the considerable body of literature available on macropore flow (White, 1985). Stable isotopes are ideal tracers for both field and laboratory investigations of this kind, and closer cooperation between those using stable isotopes on the one hand and those attempting to drive quantitative models of water movement in complex porous media on the other, would appear to offer scope for a more detailed examination of the process involved. A model of isotope movement involving both evaporation and infiltration is necessary and it is essential that heterogeneity be realistically accounted for (Jury, 1988) if field observations are to be accurately interpreted.

Allison (1987) has recently reviewed methods of estimating groundwater recharge in arid and semi-arid regions, including the use of stable isotopes. In these regions, distributed recharge through the unsaturated zone is thought to be strongly biased towards the heavier rainfall events, with little or no deep percolations from the more numerous smaller events. The critical size of the events which will produce significant recharge will depend on the effect of capillary rise of soil water to the surface i.e. on the rain size (Dincer et al., 1974). Allison et al. (1983) observed that for four dunes in the Australian arid zone, having different mean annual rainfall, the enrichment of the deep soil water of the unsaturazted zone relative to the local Meteoric Water Line appeared to be related to an independent estimate of the recharge rate. A very simple model of recharge through the dune suggested that this enrichment should be proportional to the inverse of the square root of the recharge rate, and this was found to be consistent with the data. The approach is somewhat empirical and has not been corroborated with other data so far.

5.0 CONCLUSION

Isotope techniques are without doubt an accepted tool, for a broad spectrum of applications in hydrology. In the foregoing discussion we have seen how tracer techniques can be used to estimate groundwater recharge. Often the cost towards such investigations in generally considered relatively small compared to the conventional hydrological techniques. The present status of ground water recharge studies in reviewed with the accent on techniques which are most frequently used. Applications of such techniques are grouped under two categories: (i) applications of intentionally introduced tracers and (ii) applications of environmental isotope techniques.

The past three decades has made considerable progress on the use of tracer techniques for the estimation of groundwater recharge. Tritium has been found to be very useful radioactive tracer for understanding the flow pattern and infiltration rate of moisture in the unsaturated zone and also for quantifying the recharge to the saturated regime. The recharge estimates obtained by using tritium as a tracer are found to be broadly in agreement with those obtained from hydrometeorological studies or hydrogeological measurements.

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