Quantification of Natural Groundwater Recharge

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INTRODUCTION

Groundwater as a dependable source and its proximity to various users has led to indiscriminate extraction of this precious natural resource for agricultural, domestic and industrial uses. The rapid and uncontrolled use of groundwater has resulted in many problems. The intensive groundwater development has resulted in depletion in water levels, deterioration in water quality and availability of this resource. The development of groundwater resources in those areas therefore need to be regulated and augmented through suitable measures to provide sustainability. Since rainfall being the main source of recharge to groundwater, substantial volumes of surplus monsoon runoff that flows out into the sea has to be conserved and recharged to groundwater reservoir. The benefits result in terms of rise in water level and consequent increase in storage of the groundwater reservoir.

Ground water recharge is the process by which water percolates down the soil and reaches the water table, either by natural or artificial methods. The amount of water that may be extracted from an aquifer without causing depletion is mainly dependent upon the amount of ground water recharge. Besides rainfall, other sources of natural groundwater recharge include recharge from canals, rivers, streams, irrigation, ponds, etc. If the annual outflow from the aquifer is more than the annual groundwater recharge, the water table will decline and vice-versa. In order to maintain the sustainable groundwater table, it is necessary to limit the groundwater withdrawals to the groundwater replenishment. Figure 1 shows a schematic view of the groundwater system. With increasing groundwater extraction, development of artificial recharge structures is necessary in order to maintain the annual balance. A number of techniques of groundwater recharge estimation have been reviewed and presented (Kommadath, 2000).

TECHNIQUES FOR GROUNDWATER RECHARGE ESTIMATION

Estimation of groundwater recharge is probably the most difficult of all measures in the evaluation of ground water resources. Various methods of groundwater recharge estimation directly from precipitation are broadly classified into three - inflow, aquifer response and outflow methods according to how the studies are conducted (Kumar, 1977). The following methods are commonly used for estimating natural ground water recharge (Chandra, 1979):

- Soil water balance method
- Zero flux plane method
- One-dimensional soil water flow model
- Inverse modelling technique
- Ground water level fluctuation method
- Hybrid water fluctuation method
- Ground water balance method
- Isotope and solute profile techniques

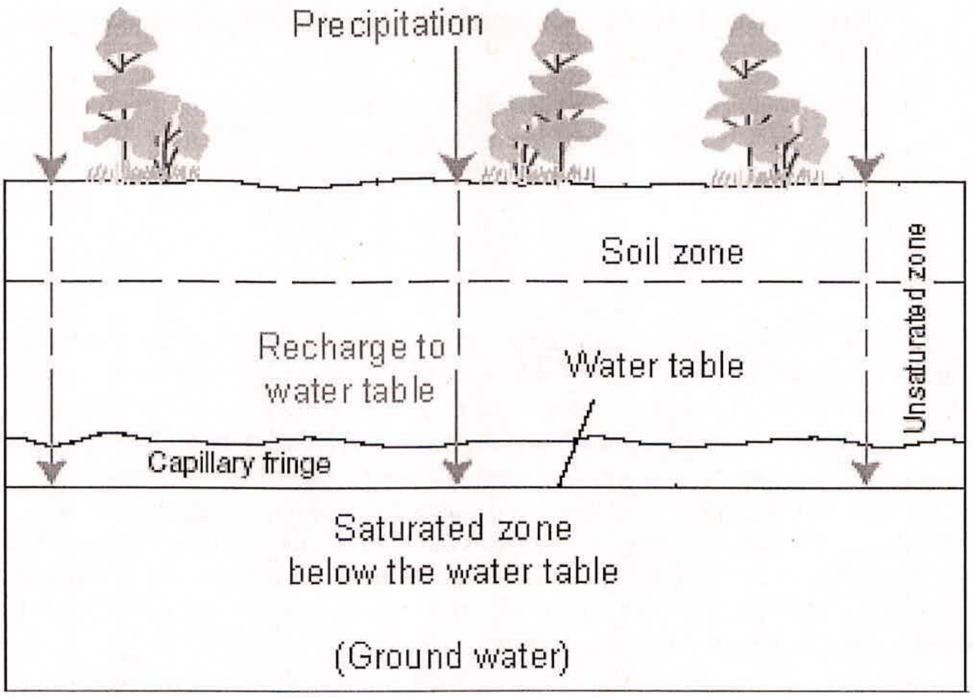

Fig 1. Schematic view of the groundwater system
(http://pubs.usgs.gov/circ/circ1186/html/gen_facts.html)

Soil Water Balance Method (Soil Moisture Budget)

This method is based on the water balance of the soil layer. The soil water balance can be expressed as

$$R = P - E_a + \Delta S - R_o \tag{1}$$

where R is recharge to groundwater, P is precipitation, Ea is actual evapotranspiration, ΔS is change in soil water storage, and Ro is surface runoff.

There are various techniques for estimating Ea, usually based on Penman-type equations can be used. Runoff can be estimated using the SCS-CN method. The data requirements of this method are large. When applying this method to estimate the recharge for a catchment area, the calculation should be repeated for areas with different precipitation, evapotranspiration, crop type and soil type. This method is of limited practical value, because ΔS is not directly measurable.

Zero Flux Plane Method

This method was first described in Richards et al. (1956) which relies on the location of a plane of zero hydraulic gradient in the soil profile. Recharge over a time interval is obtained by summation of the changes in water contents below the plant. The position of the zero flux plane is usually determined by soil matric-potential measurements using tensiometers to estimate the storage changes. Darcy's law is used to compute the unsaturated zone recharge which gives the flux q, defined as the volume of water per unit time passing through the unit area at any depth

$$q = -K(\theta).\frac{\Delta H}{\Delta z} \tag{2}$$

where $K(\theta)$ is unsaturated hydraulic conductivity, H is total water potential $= h(\theta) - z$, h is matric potential, z is depth below the ground surface, and θ is water contents.

Knowing the unsaturated hydraulic conductivity and potential gradient, the flux may be determined. The ZFP technique cannot be used when water fluxes are downward throughout the entire profile or when water storage is increasing because downward movement of a wetting front generally masks the zero flux plane. The ZFP technique is relatively expensive in terms of the required instruments and amount of data collection. This technique works best in regions where large fluctuations exist in soil-water content throughout the year and where the water table is always deeper than the ZFP.

One Dimensional Soil Water Flow Model

Groundwater recharge occurs as water moves downward through the unsaturated zone until it reaches the water table. Flow conditions in the unsaturated zone are far more complex than the flow mechanisms in a saturated aquifer. The equation of moisture retention curve is a non-linear relation to the water content. Since the moisture retention curve can only be determined experimentally, its true behaviour in practice is only known at a finite number of points. Two methods to obtain values at non-experimental points can be used. The best and most obvious method is by interpolation, but this method can only be successful in those cases where the experimental points are closely spaced. The most recent approach fits an equation to the experimental points. The equations commonly used are the Brooks and Corey function and the Van Genuchten (1980) function. The rate of flow in the unsaturated soil zone is given as

$$\mathrm{q} = -\mathrm{K}\left[1 - \frac{\Delta\psi}{\Delta \mathrm{z}}\right] \tag{3}$$

where K is the hydraulic conductivity, ψ is the matric potential, and z is the depth of soil layer. According to Van Genuchten (1980), the matric potential is expressed as,

$$\psi = \frac{1}{\alpha}\left[\mathrm{S_e^{n/(1-n)}} - 1\right]^{1/\mathrm{n}} \tag{4}$$

where α and n are curve fitting parameters. The parameter $1/\alpha$ is the air entry pressure. The relative saturation (Se) is defined as follows

$$\mathrm{S_e} = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{5}$$

where θr and θs are residual and saturated moisture contents, respectively.

$$K = \mathrm{K_0.S_e.L}\{1 + \alpha.\psi\}^2 \tag{6}$$

where K0 and L are curve fitting parameters.

Inverse Modelling Technique

Inverse modeling is used to estimate the groundwater recharge from the measured hydraulic heads. PEST (Doherty 1994) and UCODE (Poeter and Hill 1998) are various models used for this purpose. Additional information, such as base- flow discharge or groundwater dating, is also required in order to estimate recharge rates using inverse methods. The inverse modeling technique is a two-dimensional numerical technique to model the groundwater of the saturated zone. Current methods of calibrating ground water flow models are either direct or indirect. The indirect approach is essentially a trial and error procedure that seeks to improve an existing estimate approach of the parameters in an iterative manner, until the model response is sufficiently close to that of the real system. The direct approach treats the model parameters as dependent variables in a formal inverse boundary value problem.

Ground Water Level Fluctuation Method

Water level fluctuation method is an indirect method for computing the groundwater recharge from the water table fluctuation. In this method, water table rise during the monsoon season is used to estimate the groundwater recharge, provided that there is a distinct rainy season with the remainder of the year being relatively dry. The basic assumption is that the rise in the groundwater table in an unconfined aquifer is primarily due to the rainfall recharge arriving at the water table. It is recognized that pumping or irrigation during the monsoon season does not have any influence on the water table. This method is best applied over short time periods in regions with shallow water tables that show quick response to recharge. Groundwater recharge is estimated as

$$R = S_y \cdot \frac{\Delta h}{\Delta t} \tag{7}$$

where Sy = specific yield, h = water table height, and t = time under consideration.

This method neglects the subsurface inflow and outflow and assumes that every inflow and outflow is uniformly distributed over the area. This may be approximately true for the rainfall and even for the return flow from irrigation but it is rarely true for the abstraction from the aquifer. When pumping is reduced or ceases during the rainy seasons, a redistribution of ground water heads occurs so that part of the observed increase in water level may be due to normal well recovery. Since the above equation is dependent on the specific yield, the accuracy of this method depends on the specific yield which is very difficult to determine accurately.

Hybrid Water Fluctuation Method

Sophocleous (1991) proposed a hybrid water fluctuation approach for groundwater recharge estimation. This method is generally reliable for estimating natural ground water recharge in relatively flat areas with a shallow water table (less than 10 m). By associating water table rises with specific precipitation events and by combining the recharge estimates from the soil water balance analysis with the consequent water table rises, one can obtain effective storativity values for each recharge study site, especially after averaging several such values. The site-calibrated effective storativity value can then be used to translate each major water table rise tied to a specific storm period into a corresponding amount of ground water recharge. Estimation errors in the hybrid water fluctuation method are reduced by running a 'storm period' based soil water balance throughout the year in combination with the associated water level rise. This method gives better results than either of the two well-established approaches used singly.

Ground Water Balance Method

This method is based on the water balance approach, i.e. the difference in total inflow and outflow is equal to change in storage of aquifer. Mathematically the water balance may be described as

$$I - O = \frac{\Delta S}{\Delta t} \tag{8}$$

where I, O and ΔS are inflow, outflow and change in storage, respectively during time Δt. Considering the various inflow and outflow components as per our hydrological system, the ground water balance equation for a time period Δt may be written as

$$R_p + R_c + R_i + R_t + R_r + I_B - E_t - GW_d - O_r - O_B = \Delta S \tag{9}$$

where Rp is recharge from rainfall, Rc is recharge from canal, Ri is recharge from irrigation, Rt is recharge from tank, Rr is influent recharge from rivers, IB is inflow from other basins, Et is outflow through evapotranspiration, GWd is draft from groundwater, Or is effluent discharge to rivers, and OB is outflow from groundwater to other basins.

This equation is the general ground water balance equation for an unconfined aquifer in which the aquifer boundaries do not represent streamlines, i.e., they are not orthogonal to the equipotential lines. Hence, the lateral inflow and outflow must be accounted for the balance equation. Various components of the water balance equation are measured or computed using independent methods. The accuracy of the recharge estimation depends on the accuracy of computation of other components in the water-budget equation.

The water balance may be computed for any time interval. All components of the water balance equation other than the rainfall recharge are estimated. The rainfall recharge is calculated by substituting these estimates in the water balance equation. This approach is valid for the areas where the year can be divided into monsoon and non-monsoon periods and the water balance is carried out separately. The former yields an estimate of recharge coefficient and the latter determines the degree of accuracy with which the components of water balance equation have been estimated.

Isotope and Solute Profile Techniques

Isotopes 2H, 3H, 18O and 14C are commonly used to estimate the groundwater recharge. The first three most accurately simulate the movement of water, because they form a part of the water molecule. A radioactive tracer provides a means of tracing water movement through the unsaturated zone. In principle, any traces with negligible adsorption may be used, but tritium is preferred. Tritium may either be artificially introduced or environmental tritium may be used. However, environmental tritium has several disadvantages.

i) Tritium is not conservative but evaporative and is lost from the system by evapotranspiration.

ii) Contamination during sampling and processing is a factor, which is enhanced in remote areas and at low total moisture levels.

iii) Analysis is highly specialized and costly.

iv) Quantitative studies are difficult to achieve, since it is difficult to determine a tritium mass balance.

Other tracers are chloride, nitrate, bromide, chloride, atrazine, arsenic, chlorofluoro carbons, etc. The subsurface distribution of applied tracers is determined some time after the application by digging a trench for visual inspection and sampling or by drilling test holes for sampling. The vertical distribution of tracers is used to estimate the velocity (v) and the recharge rate (R)

$$R = v\,\theta = \frac{\Delta z}{\Delta t}\theta \tag{10}$$

where Δz is depth of the tracer peak, Δt is time between tracer application and sampling, and θ is volumetric water content. The minimum water flux that can be measured with applied tracers depends on the time between application and sampling and, in the case of surface-applied tracers, the root- zone depth.

Chloride Mass Balance

This technique is most widely used for estimating the low recharge rates mainly due to lack of other suitable methods. In this method chloride is used as an environmental tracer. An environmental tracer suitable for determining the movement of water must be highly soluble, conservative and not substantially taken up by vegetation. The chloride ion satisfies most of these criteria and is therefore considered a suitable tracer, particularly in coastal areas. This method provides point estimates of recharge estimates of recharge rates. The principle source of chloride in ground water is from the atmosphere.

The mass of chloride (Cl) into the system (precipitation and dry fallout, P) times the Cl concentration in rainfall (Cl_p) is balanced by the mass out of the system (vertical drainage, R) times the Cl concentration in drainage water in the unsaturated zone (Cl_{gw}) if surface runoff is assumed to be zero, i.e. $P.\ Cl_p = RCl_{gw}$

$$R = P.\frac{Cl_p}{Cl_{gw}} \tag{11}$$

where all concentrations are in mg/l.

The chloride method must be treated with caution. Recharge under conditions of extremely high rainfall with a long recurrence period, is likely to influence the chloride concentration of ground water to a high degree resulting in an over estimate of the mean annual recharge.

Regional Formulae for Natural Ground Water Recharge Estimation in India

Rainfall is the main source of ground water recharge in India. The commonly used methods for estimation of natural ground water recharge in India include empirical methods, ground water level fluctuation method and the ground water balance method. Various scientists and agencies have conducted research studies and correlated the groundwater levels with rainfall and derived empirical relationships for computation of natural recharge to ground water. Some of these empirical relationships under different hydro-geological setups in India are:

a) Chaturvedi Formula
b) Amritsar formula
c) Relationship of Krishna Rao

(a) Chaturvedi Formula

Based on the water level fluctuation and rainfall amounts in Ganga-Yamuna doab, Chaturvedi (1973) derived an empirical relationship for estimation of recharge as a function of annual precipitation (when rainfall exceeds 40 cm).

$$R = 2.0\,(P - 15)^{0.4} \tag{12}$$

where R is the net recharge due to precipitation during the year (inches), and P is annual precipitation (inches). This formula was later modified by further work at the UP Irrigation Research Institute, Roorkee as

$$R = 1.35\,(P - 14)^{0.5} \tag{13}$$

The Chaturvedi formula has been widely used for preliminary estimation of ground water recharge due to rainfall. It is clear from this formula that there is a lower limit of the rainfall below which the recharge is zero. The percentage of rainfall recharge commences from zero at P = 14 inches and increases up to 18% at P = 28 inches, and again decreases. The lower limit of rainfall in the formula may account for the soil moisture deficit, interception losses and potential evaporation.

These factors being site specific and hence one generalised formula may not be applicable to all the alluvial areas.

(b) Amritsar formula

Sehgal (1973) developed a formula for Irrigation and Power Research Institute, Punjab using regression analysis for certain doabs in Punjab. This formula holds good for areas were rainfall varies between 60 and 70 cm.

$$R = 2.5\,(P - 0.6)^{0.5} \tag{14}$$

where R and P are recharge and precipitation (inches), respectively.

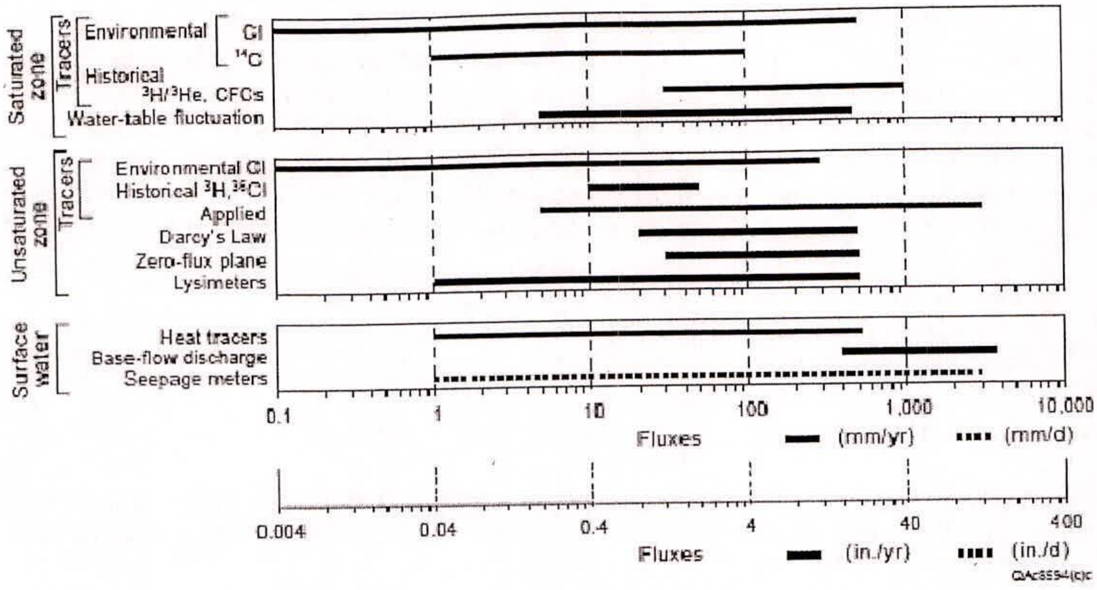

Fig. 2 Range of fluxes that can be estimated using various techniques

(c) Relationship of Krishna Rao

Krishna Rao (1987) developed the following empirical relationship to determine the ground water recharge in limited climatological homogenous areas in different parts of Karnataka as below

$$R = K(P - X) \tag{15}$$

This relationship is further regionalized based on precipitation as:

$$R = 0.20\,(P - 400) \qquad \textit{for areas} \qquad 400 \le P < 600\,mm$$

$$R = 0.25\,(P - 400) \qquad \textit{for areas} \qquad 600 \le P < 1000\,mm$$

$$R = 0.35\,(P - 600) \qquad \textit{for areas} \qquad P > 2000\,mm$$

Scanlon et al. (2002) have studied various techniques of groundwater recharge estimation based on regional scales, soil profile zone wise, temporal and spatial scales (Figs. 2 to 4). These techniques include those based on surface-water, unsaturated-zone and saturated zone data and can be based on physical, chemical, or numerical modeling approaches. These techniques vary in the space and time scales that they represent and in the range of recharge rates that they can estimate. Groundwater-tracer techniques are considered the most reliable estimators of recharge within the domain of specified assumptions. Techniques based on surface water and unsaturated- zone data provide estimates of potential groundwater recharge while techniques based on saturated zone analysis give actual groundwater recharge.

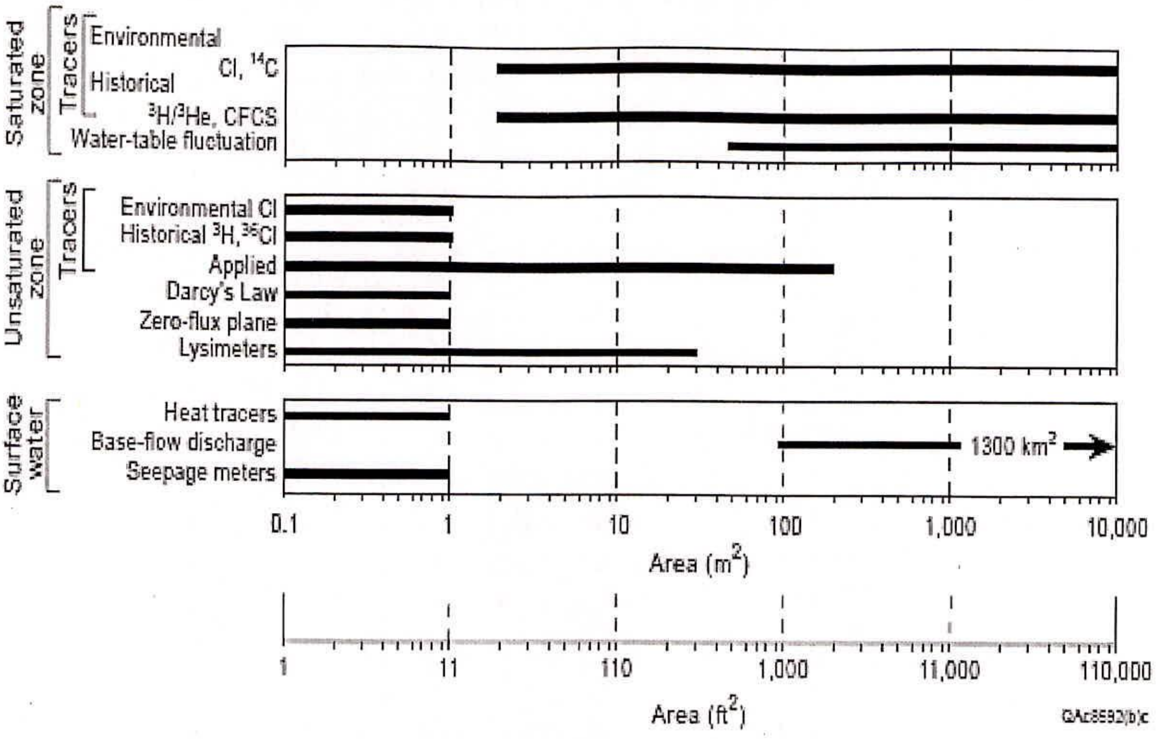

Fig. 3 Spatial scales represented by various techniques for estimating recharge

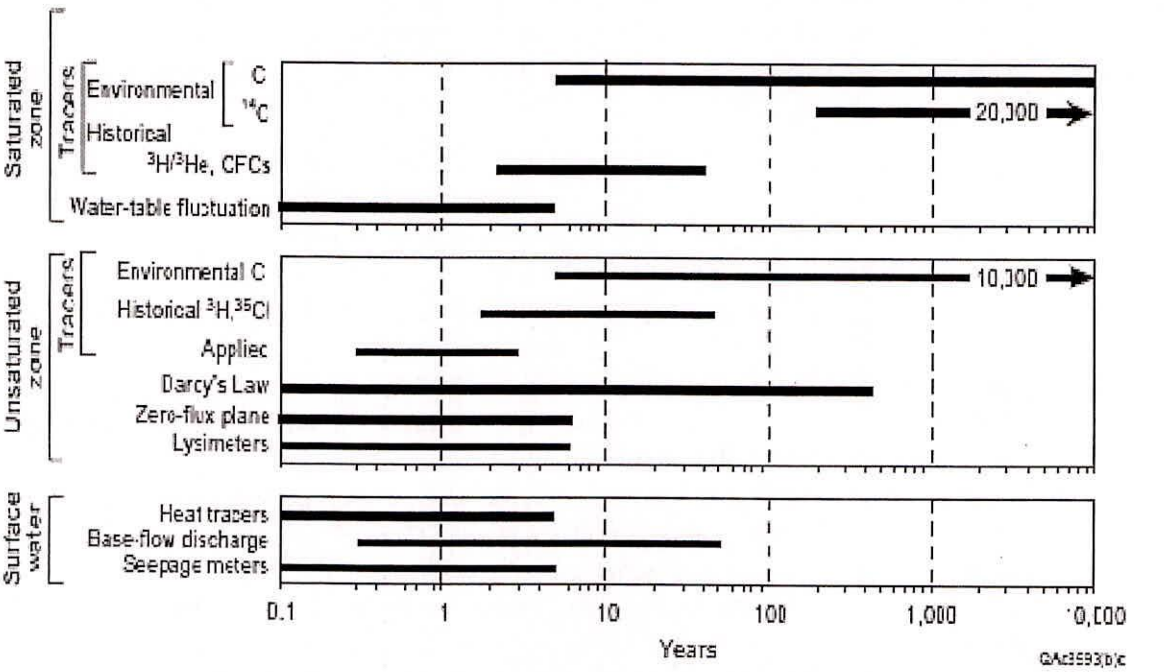

Fig. 4 Time scales represented by various techniques for estimation of recharge rates

Table 1. Techniques for estimating recharge in different regions (Scanlon et al., 2002)

Hydrologic Zone	Techniques	
	Arid & Semiarid Climates	Humid Climates
Surface Water	Channel water budget	Channel water budget
	Seepage meters	Seepage meters
	Heat tracers	Base flow discharge
	Isotopic tracers	Isotopic tracers
	Watershed modeling	Watershed modeling
Unsaturated Zone	Lysimeters	Lysimeters
	Zero-flux plane	Zero-flux plane
	Darcy's law	Darcy's law
	Tracers [Historical (^{36}Cl, ^{3}H), environmental (Cl)]	Tracers [Applied]
	Numerical modeling	Numerical modeling
Saturated Zone	-	Water table fluctuations
	-	Darcy's law
	Tracers [Historical (CFCs, ^{3}H, ^{3}He), environmental (Cl, ^{14}C)]	Tracers [Historical (CFCs, ^{3}H, ^{3}He), environmental (Cl, ^{14}C)]
	Numerical modeling	Numerical modeling

CONCLUSIONS

A number of techniques are available in literature for the estimation of groundwater recharge. Each technique has its own merits and demerits and also different accuracy levels. Choice of method depends on the availability of data type, temporal and spatial scales and the intended use. It is therefore necessary to have the basic knowhow of the different recharge processes and mechanisms and their importance in the study area. Economy also plays an important role for the recharge estimation. No single technique can be identified to give reliable and accurate results in different geographic regions. Hence, it is always advisable to apply more than one technique based on available input data.

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