EVALUATION OF GROUNDWATER RECHARGE IN SEMI-ARID REGION OF INDIA USING ENVIRONMENTAL TRITIUM

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Abstract

Depth variations of environmental tritium and of soil moisture in the unsaturated zone of the semi-arid alluvial tracts of northern Gujarat (India) are measured and utilised to evaluate vertical groundwater recharge. Results obtained from the two different experiments carried out at an interval of two years are found to be in fair agreement. An average of recharge amounting to about 5 per cent is indicated.

The observed depth variation of tritium gives support to the view that the movement of soil moisture in this region is layered.

Introduction

Groundwater recharge, in general, occurs through a process of vertical infiltration and deep percolation to an unconfined aquifer, and through connected permeable strata located at a higher elevation to a confined aquifer. It is often possible to decide from the general hydrogeological considerations which mode is dominant. A preassessment of groundwater recharge is vital for proper planning of groundwater exploitation. But the problem is by no means easy or straightforward. Several conventional methods such as inventory, lysimetric and storage can be used, but in general they require the analysis of large amount of hydrological data on precipitation, surface run off, evapotranspiration, changes in groundwater storage, etc. The data on some of these are often inaccurate and questionable. Recently isotopic methods have also been utilised for recharge determination. These methods though supposedly direct require sophisticated methodology and are relatively new, therefore not well investigated as yet. A discussion of these methods has been given by Münnich[1] and Sukhija.[2]

The artificial isotope tagging method[3] involves the tagging of top moisture with tritium or deuterium and locating the depth of spike which moves down with the recharge water. Münnich *et. al.*[4] make use of environmental tritium also for the purpose. The 1963–64 tritium peak in the precipitation is made use of in the same way as is done in the case of artificial tagging method. But this method is applicable only when the soil moisture exhibits layered movement. The other method "Tritium Integral Method"[1] aims at finding out the total amount of bomb tritium in a profile underground (unsaturated and saturated zones) as a fraction of the total tritium precipitated since onset of the thermonuclear era (1952). The purpose of the present investigation is to explore the utility of the environmental tritium method in the alluvial semi-arid tracts of Northern Gujarat; the potentialities of the tritium method have hitherto been unexplored in such regions.

PHYSIOGRAPHY AND HYDROLOGY

The alluvial tracts of Gujarat, about 45,000 sq. km. area, are situated in semi-arid climate in western India (Fig. 1). The tracts are surrounded by Aravali hills in NNE and Saurashtra high lands in the west. In north-west alluvial plain merges into the Indian Desert and the Rann of Kutch. The area has an annual rainfall of about 70 cm, ranging from 50 to 100 cm, in different regions. The rainfall is peaked during the monsoon months of June to September. Except for the two rivers Narmada and Tapti which are perennial the rest of the streams run only during monsoon period. The main source of irrigation in the region is the groundwater; and its exploitation is increasing rapidly. This makes the evaluation of recharge in the region imperative.

Groundwater in the alluvial tracts occurs under water-table conditions at shallow depths and while that in deep aquifers under semi-artesian or artesian conditions. The productive aquifers are mainly sandy and they occur in pockets and lenses. General geohydrological considerations show that the main source of recharge to the aquifers is the vertical percolation of local rainfall.

In the past a few workers have made rough estimates of groundwater recharge in the region, using conventional methods. Some methods like inventory, storage, etc., though attempted, are essentially not applicable since adequate hydrological data for the region are not available. Our approach has been mainly experimental and direct, and is based on the environmental tritium method. Six sites, Ahmedabad, Balol, Kosamba, Sankeshwar, Taranga and Varahi (Fig. 1) were selected for this investigation. These sites are only rain irrigated as is the case for the large part of the area under study. The experiments were first undretaken in 1967 and repeated in 1969.

EXPERIMENTAL

A. Tritium Input Function

Tritium input function can be computed from the values of precipitation for different years /and their tritium concentration. Daily precipitation is routinely measured by India Meteorological Department at various locations. Monthly precipitation samples were separately collected at Ahmedabad since 1962 onwards; their tritium concentrations were measured at Bombay. In some cases one composite sample was made according to the weightage of precipitation in different months. Tritium concentrations of the samples were measured by converting the water into methane gas and subsequent counting in Oeschger type gas proportional counter[5], having a low background of 0·7 cpm. No enrichment step was needed.

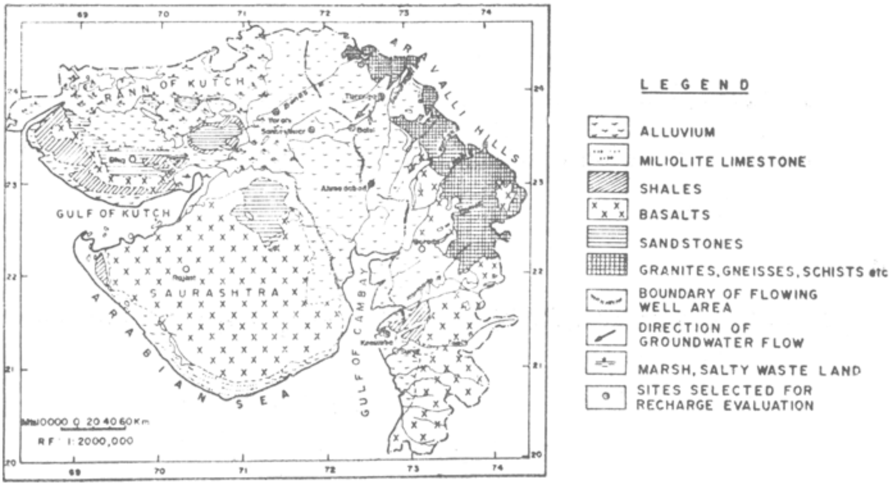

FIG. 1. Hydrogeology of Gujarat.

B. Tritium Percolation Function

Tritium percolation function can be computed from the values of moisture content at different depths in soil and the tritium concentration in this moisture. Soil samples were obtained by using a hand auger, Their moisture contents were determined by using conventional gravimetric and volumetric methods. Water was extracted from soil samples by distillation and its tritium concentration measured.

RESULTS

Recharge rates can be computed from the experimental data using (*a*) integral method and (*b*) peak method.

The integral method aims to determine the total amount of bomb tritium present in the profile as a fraction of the total tritium fallout. The fallout at a site is computed by summing up the products of monthly (or annual) precipitation and its tritium concentration. The summation is carried out for the period of 1952 (onset of thermonuclear era) to the time to which the investigation is carried out, *i.e.*, up to November 1967 for the first experiment and up to November 1969 for the second experiment.

We have

$$T = \Sigma A_i P_i$$

where

T = total tritium fallout (T.U. cm) ;

A_i = tritium concentration (T.U.) of precipitation in month i.

P_i = precipitation (cm) in month i.

Similarly, for the percolation function we have

$$t = \Sigma a_j m_j$$

where

t = total amount of tritium (T.U. cm) present in soil underground;

a_j = tritium concentration (T.U.) of soil segment j;

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

Since "T" represents the total fallout of tritium at a site and "t" is the amount that percolated (*i.e.*, which escaped the evapotranspiration and runoff losses), t/T represents the fraction of the rainfall that goes to recharge groundwater, *i.e.*, percentage recharge is given by

$$r = t/T \times 100.$$

The tritium concentrations have been measured for Ahmedabad precipitation only and that too only for the period 1962-70. At the remaining sites they have been assumed to be the same as that for Ahmedabad. The tritium values for the period 1952 to 1962 are computed by extrapolating from the Ottawa data. The average annual tritium concentration at Ahmedabad is seen to be about 1/5th of that at Ottawa for the years 1962–70. The values for the years 1952–62 have likewise been assumed to be 1/5th. Any discrepancy resulting from this extrapolation however is expected to cause only a small error in the computation of recharge since the extrapolated part forms a minor fraction of the total tritium fallout.

Figure 2 represents the measured and extrapolated tritium concentration (without decay correction) in precipitation at Ahmedabad for the period 1952 to 1970. Figure 3 shows the measured depth variation of soil moisture and its tritium concentration for Ahmedabad, Balol, Kosamba, Sankeshwar, Taranga and Varahi. The figure shows that the tritium content in the

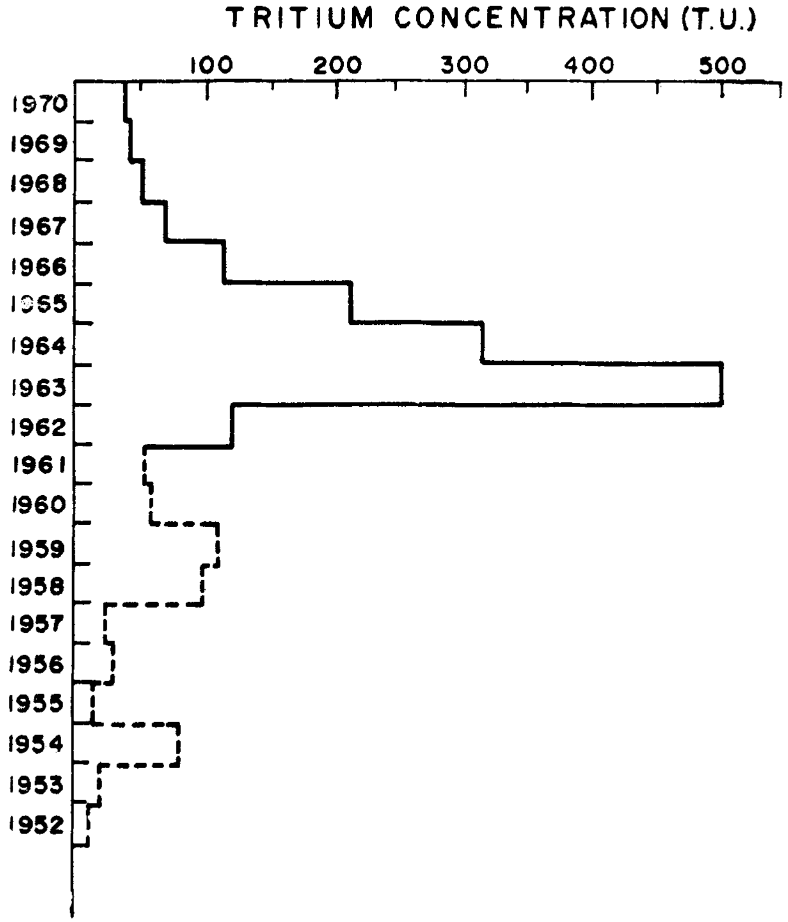

FIG. 2. Tritium concentration in Ahmedabad precipitation 1952–70,
——— Measured values;
------ Extrapolated from Ottawa data.

lower part of the profiles is negligible except in one case *i.e.*, Taranga. It is therefore possible to determine the total amount of tritium present in all profiles except that at Taranga where even at the level of water-table tritium concentration of water is very high (130 T.U.). The amount of tritium charged to saturation zone cannot be ascertained as the sampling was terminated at the water-table level. Hence the recharge obtained for Taranga by this method should represent the lower limit. Recharge rates computed for various locations are given in Table I. Results computed from the observations made in 1967 and then in 1969 are given separately.

RECHARGE EVALUATION BY THE PEAK METHOD

This method aims to locate the position of 1963 precipitation (having peak tritium concentration) in a soil profile in which it can be estimated that the movement of soil water has been layered. Recharge computations are made by finding out the total amount of water present up to the tritium peak position and comparing the amount with the total rainfall since 1963 to the time of investigation, *i.e.*, up to 1967 for the first experiment and up to 1969 for the second experiment. We have

$$r = \mathrm{S}/\mathrm{P} \times 100$$

where

r = recharge as a percentage fraction of rainfall,

S = soil moisture (cm) in the column from the surface to the depth where the tritium peak occurs,

P = precipitation during the period 1963 to the time of investigation.

In each profile (Fig. 3), a tritium peak can be identified though at different depths at different sites. In Table II are given the depths at which tritium peaks occur at various sites. The recharge computed as the ratio of moisture above the peak and the precipitation since 1963 are also given in the same table separately for the two experiments conducted in 1967 and in 1969.

DELINEATION OF DIFFERENT RECHARGE AREAS

On the basis of the measured recharge rates, climatic and geohydrologic considerations, it is possible to divide the investigated area into the following four zones.

TABLE I

Computation of recharge by "integral method"

Location	1967 Experiment			1969 Experiment		
	Tritium fallout 1952-1967 (T.U. cm) "T"	Tritium percolation 1952-67 (T.U. cm) "t"	Recharge (% precipitation) $r = \frac{t}{T} \times 100$	Tritium fallout 1952-69 (T.U. cm) "T"	Tritium percolation (1952-69) (T.U. cm) "t"	Recharge (% precipitation) $r = \frac{t}{T} \times 100$
Ahmedabad ..	144491	5457	3·8	104736	7493	7·6
Balol ..	79738	3248	4·1	77760	3196	4·1
Kosamba ..	179695	5303	3·0	169457	9232	5·4
Sankeshwar ..	65390	1301	2·0	60848	2497	4·1
Taranga ..	80919	3420	>4·2	77688	4789	>6·2
Varahi ..	61964	1910	3·1	57820	2264	3·9

TABLE II

Computation of recharge by "peak method"

Location	1967 Experiment				1969 Experiment			
	Peak at depth (cm)	Total moisture upto peak (cm) "S"	Total rain 1963-67 (cm) "P"	Recharge as fraction of rainfall S/P × 100	Peak at depth (cm)	Total moisture upto peak (cm) "S"	Total rain 1963-69 (cm) "P"	Recharge rate as fraction of rainfall S/P × 100
Ahmedabad ..	175-235	34	376	9·1	325-385	44	582	7·6
Balol ..	85-145	9	262	3·5	235-265	20	323	6·1
Kosamba ..	145-175	20	597	3·4	295-355	71	787	9·0
Sankeshwar ..	0- 85	7	214	3·4	175-205	11	263	4·3
Taranga ..	415-475	30	281	10·0	805-865	44	364	12·2
Varahi ..	0- 85	8	197	3·6	0-115	8	256	3·0

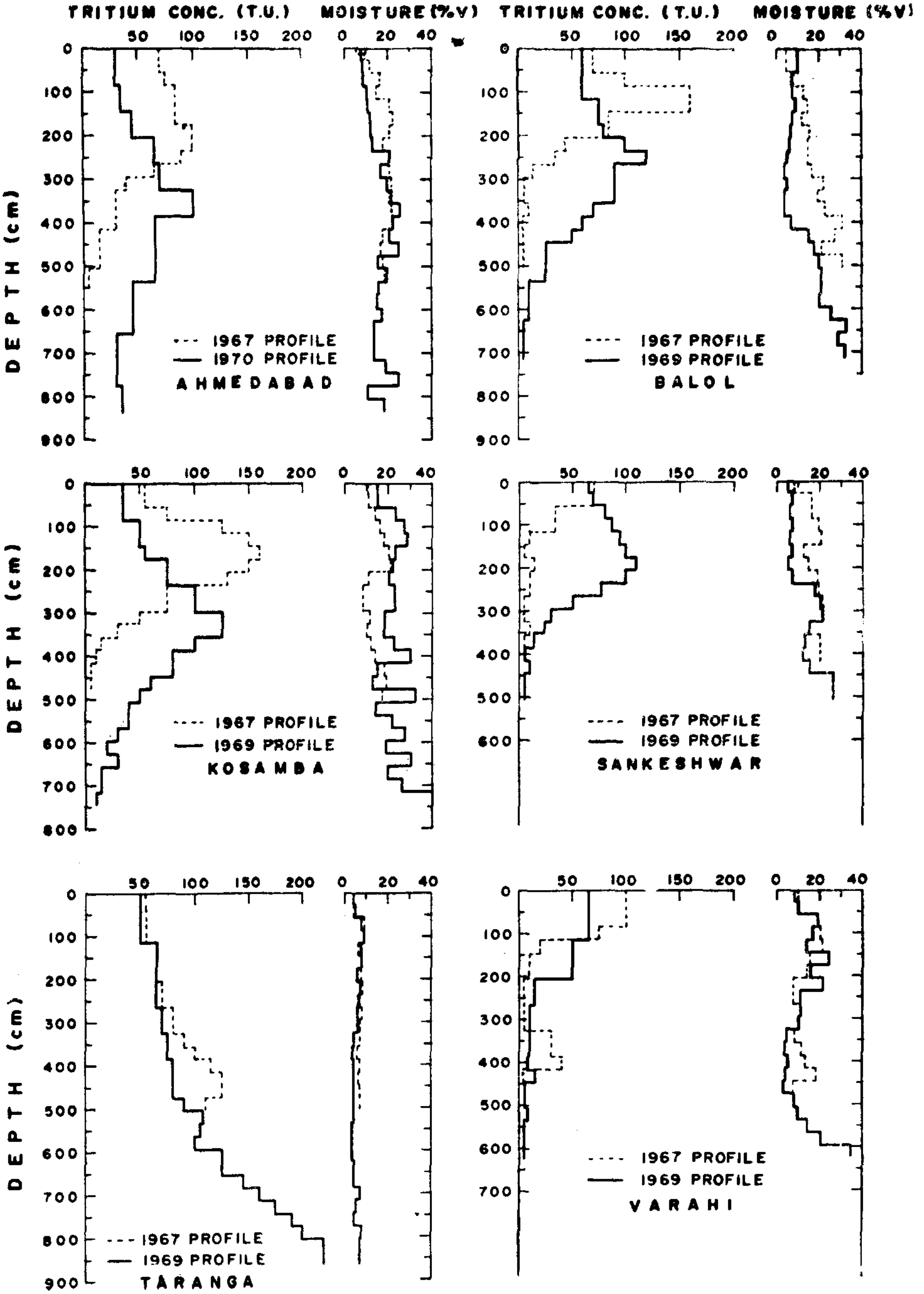

FIG. 3. Depth variation of tritium and soil moisture in alluvial tracts of Gujarat.

The north-west portion of the investigated area is represented by sites of Sankeshwar and Varahi. This zone is close to the Rann of Kutch and is almost arid. The temperature in summer is very high and results in very high evapotranspiration. The recharge is 3–4%.

The zone represented by sandy sites of Ahmedabad and Balol lies in the middle of the alluvial tracts and is relatively less arid than north Gujarat and has recharge of 5% rainfall.

The southern part of the tracts is represented by the site Kosamba where top soil has large clay content. Rainfall is more plentiful (125 cm). But due to poor infiltration the recharge is quite small.

The north-east part of the tracts is represented by the site Taranga lying at the foot of north-eastern hills and has high recharge. A recharge of 10–12% of local rainfall is indicated by the peak method. The top soil is largely coarse sand.

DISCUSSION

Of all the methods available for evaluating groundwater recharge, the environmental tritium method was found to be by far the most suitable in the area under investigation. The interconsistency of the results obtained from the integral method and peak method is fairly good; in any case, the uncertainties are far less serious than those involved in some of the conventional computations done for such purpose.

COMPARISON OF RECHARGE RATES : INTEGRAL AND PEAK METHODS

Table III shows the means of recharge rates from 1967 and 1969 experiments by the integral and the peak methods. It can be seen that the results obtained for Balol, Sankeshwar and Varahi agree fairly well, while those for Kosamba and Ahmedabad obtained from peak method show higher values. For Taranga, the integral method provides only the lower limit of recharge whereas the peak method gives the actual recharge value.

Overall recharge rates computed by the peak method represents an average for a relatively small duration (5–7 years) while the integral method provides the recharge averaged over last 15–17 years.

In principle, the integral method provides correct value of recharge (contributed exclusively by rainfall) even if the movement of water is not layered or even if the fields are irrigated by deep well water (free from H^3). But the results by the "integral method' are biased towards the years with

TABLE III

Comparison of recharge rates (percentage fraction of local rainfall): Different Methods

Location	Integral tritium	Peak tritium	Inventory	Dating	Emperical formulae	
	Mean of 1967–69 experiments	Mean of 1967–69 experiments			$r = (P-15)^{2/3}$ I R I formula	$R_A = P_A - KT_A$ Khosla's formula
Ahmedabad ..	5·7	8·3	2·5	5·0	9·6	Nil
Balol ..	4·1	4·8	..	do.	10·0	do.
Kosamba ..	4·2	6·7	30·0	do.	8·9	do.
Sankeshwar ..	3·0	3·8	Nil	do.	9·5	do.
Taranga ..	>6·2	11·1	..	do.	9·8	do.
Varahi ..	3·5	3·3	..	do.	9·5	do.

higher tritium contents in rainfall. The peak method essentially requires a layered movement of soil water, any deviation from this will lead to uncertainties. It can be seen that the peak tritium concentration in the profiles is approximately 1/3rd of 1963–64 tritium concentrations in precipitation. Such differences can be attributed to dispersion which results in mixing of moisture during its traverse through the soil.

COMPARISON OF RECHARGE RATES COMPUTED FROM DIFFERENT METHODS

Apart from the environmental tritium method, the inventory and dating methods and empirical formulae can also be used to evaluate vertical recharge in the area. The use of these methods is however only approximate.

The inventory method requires the data on precipitation, runoff and evapotranspiration. In the investigated area, satisfactory data on precipitation are available, but the data for runoff and evapotranspiration are lacking. Use is made of potential evapotranspiration data available from India Meteorological Department for the stations of Ahmedabad, Radhanpur and Surat.[7] Radhanpur data can be considered to be applicable for Sankeshwar and Varahi as well; and the Surat data for Kosamba because of their respective close proximity. The actual evapotranspiration is computed by using Thornwaite's method.[8] The basic principle is that actual evapotranspiration is assumed to be equal to the potential evapotranspiration for the months in which rainfall is greater than potential evapotranspiration and for the other months actual evapotranspiration is assumed to be the sum of rainfall and change in soil moisture storage. Recharge is simply calculated by the difference of rainfall and evapotranspiration; runoff is assumed to be zero. The results are shown in Table III.

A reasonable guess of recharge can be made by using the dating method. Measurements, carried over a few shallow and deep groundwater samples, show that the samples do not have measureable tritium ($\lesssim 5$ T.U.) and groundwater in the region can be said to be definitely older than 20 years. Carbon–14 and Silicon–32 dates obtained by Lal *et al.*[9] yield an average age of about 2,000 years for the water being pumped by State tube-wells. The groundwater ages obtained correspond to a mixture of groundwater from different aquifers being simultaneously tapped in the tube-well. To calculate the recharge rates knowledge of groundwater volume and the manner in which groundwater flows in the region are required. For investigated area there are no reliable estimates available for groundwater volume, yet a water column of 60 m can be assumed to be present on the basis of an average porosity of 30% for the 200 m alluvial thickness. An over-simplified model of vertically well-mixed water body is assumed. The adoption of this model is only due to the particular type of groundwater sampling and not because of actual groundwater mixing. Thus an average turnover time for groundwater is found to be 2,000 years and average recharge rate turns out to be 3 cm per year.

There are two empirical formulae which are often used for evaluating recharge in the alluvial tracts. One relation used by Irrigation Research Institute, Roorkee (India), is $I = (P-15)^{2/3}$ where I is recharge and P is precipitation in inches. It can be seen that the recharge rates computed from this formula range around 9–10% of local rainfall for all the sites. Another empirical formula used to obtain runoff (Surface + Subsurface) from rainfall and temperture can also be employed. According to this relation (called Khosla's formula),[10]

$$R_A = P_A - KT_A$$

where

R_A = annual runoff (surface + subsurface),

P_A = annual precipitation (inches),

K = constant for the catchment,

T_A = mean annual temp. (°F).

Recharge rates by different methods for different sites are compared in Table III. It can be seen that, for Ahmedabad the inventory method gives too low value of recharge and for Kosamba exceedingly high value. This is probably due to the assumption of zero runoff which is not applicable in the Kosamba area.

The dating method with all its uncertainties has given value of recharge which agrees well with the values obtained by the environmental tritium method. The recharge rates from empirical formula can hardly be relied upon since they give same result for all the sites (10% by IRI formula and nil by Khosla's formula). It would thus appear that direct experimental approach of the environmental tritium method makes it far more reliable despite the fact the peak method and the integral method show somewhat different results.

The environmental tritium methods are direct, convenient and do not involve uncertain computation and have the advantage of providing results averaged over a number of years.

MOVEMENT OF SOIL MOISTURE IN THE UNSATURATED ZONE

Our experiments, though mainly intended to evaluate recharge, elucidate the general premise on which the peak method works.

The observations at six selected sites in the alluvial tracts of Gujarat show that the depth variation of tritium in the unsaturated zone in year 1967 was replica of tritium variation in precipitation (since 1952). All the profiles show a general increase in the tritium concentration from surface downwards up to a certain depth where peak concentration occurs, and further deepdown the concentration gradually falls to negligible value. This disposition of tritium in profiles illustrates the layered movement of soil water.[4, 11] The peak tritium value locates the depth to which 1963–64 precipitation has percolated down. The rate of movement of the peak is seen to be different at different sites; it is about 0·5 m/year except for Taranga where it is 1 m/year. Sankeshwar and Varahi however have their peak tritium concentration close to the surface. The existence of peak at the top surface is difficult to understand in terms of layered movement of soilwater. The repeat experiments in 1969 showed that the tritium peaks had moved further down, without being much altered in their general shape. The rate of advance of the peak is about 0·5 m/year for Balol, Kosamba, Sankeshwar and Varahi. The maximum advance of the peak took place at Taranga, where it moved down by 2·75 m in two years time.

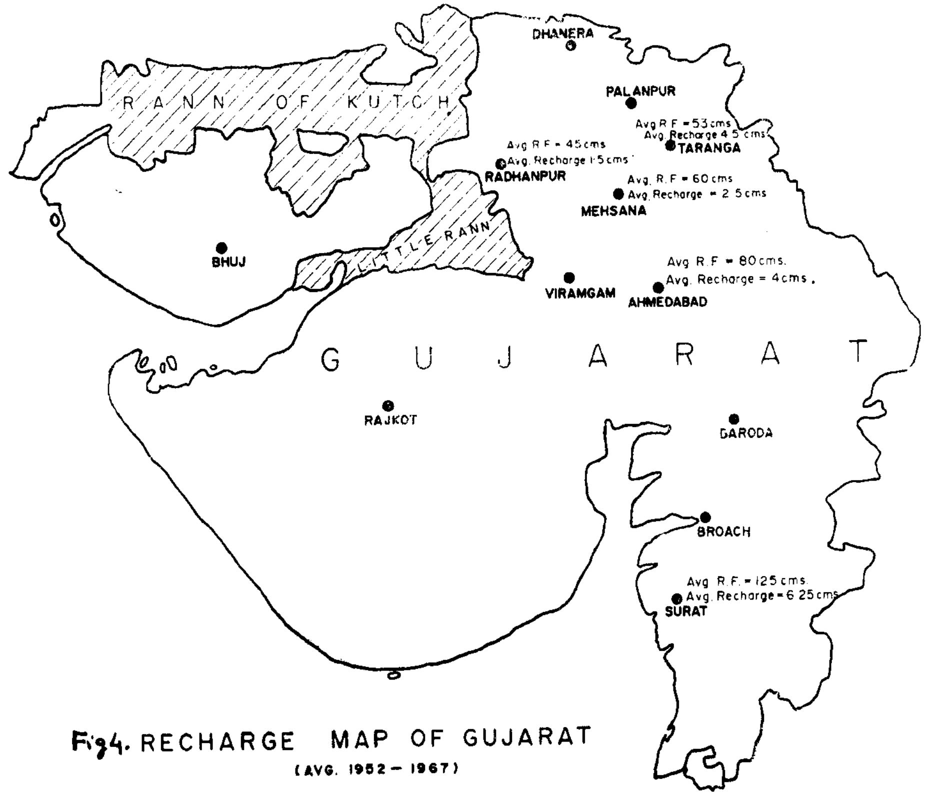

Fig 4. RECHARGE MAP OF GUJARAT
(AVG. 1952 – 1967)

CONCLUSIONS

Validity of the environmental tritium methods for evaluating vertical groundwater recharge has been ascertained for semi-arid area of alluvial tracts of Gujarat (India). The recharge rates computed by using the data obtained from 1967 and 1969 experiments agree fairly well. The recharge obtained by the peak method shows higher values. The recharge rates obtained by using integral method are found to vary between 3–5% of local rainfall at different sites (Fig. 4). It has been shown that the method can be used for delineating different recharge areas as well as for elucidating the soil-water movement.

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