

Isotopes in Groundwater Studies (semi-arid/arid regions)

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INTRODUCTION

The total amount of water on this earth is virtually constant but its distribution over time and space varies to a great extent. Wherever people live, they must have a clean and continuous water supply as a primary requirement to the human beings. The assessment of quality, supply, and renewal of resources of water is a well known problem, particularly in semiarid and arid regions, but it is becoming critical with increasing demand of fresh water due to alarming growth of population and rapid industrialization.

In the past few decades, sophisticated nuclear-hydrological instruments have been developed to measure accurately both radioactive as well as stable isotopes and accordingly various nuclear methods have been evolved. It is therefore, now very easy to solve many hydrological problems related to planning of water resources, agriculture, industry, and habitation using isotope techniques which were very difficult, sometimes impossible to tackle in the past.

Isotopes can be used to study the different facets of hydrologic cycle. However, the use of different types of isotopes, i.e., radioactive (artificial) -sealed or tracers, radioactive (environmental) or stable isotopes depends upon the type and requirement of the study to be carried out. The major applications of isotopes in Groundwater Hydrology that may be useful for arid and semiarid regions are listed below.

1. Groundwater recharge
2. Ground water flow velocity and direction (Dilution techniques)
3. Origin of groundwater
4. Recharge zones and sources to deeper aquifers
5. Effectiveness of artificial recharge measures
6. Groundwater salinization

The information on aquifer dynamics and soil erosion can be used to understand the availability of groundwater/replenishment, sustainability of springs, origin and source of groundwater, artificial measures to increase groundwater recharge, discharge of springs and control of soil erosion from the high erosion prone areas to manage the watersheds in an effective manner. Brief details of various applications of isotopes in groundwater management are discussed below.

ESTIMATION OF NATURAL GROUNDWATER RECHARGE

Groundwater recharge can be determined from water balance computations, from pumping over very long periods, from mass balance of different artificial or environmental tracers, or from hydraulic interpretations of the soil moisture movement below the active roots in the unsaturated zone. The hydraulically based methods, though highly developed in theory and practice, are hampered by the complex relationship between hydraulic conductivity and hydraulic gradient in the unsaturated zone. Tracer techniques have the advantage that old soil water can be

differentiated from relatively fresh water. A rather new way of estimating groundwater recharge is to use isotopes as tracers. The methodology of using artificial as well as environmental isotope tracers for estimating percolation rate and groundwater recharge is discussed here.

Mostly water table fluctuation approach is used to evaluate recharge to groundwater. But as the water table fluctuation may occur due to many processes like, vertically downward percolation of precipitation water, irrigation returnflow, percolation/seepage from surface water bodies/ pondings, draft of groundwater for irrigation, drinking, industrial and similar other purposes, flow of groundwater to river or vice-versa, leakage from shallow aquifers to deeper aquifers etc therefore, the water table fluctuation approach may lead to wrong predictions, if the information about the effect of individual parameter is not known. In such conditions, isotopes can be used to estimate the vertically downward component of recharge to groundwater without being influenced by any of the above said process.

ARTIFICIAL RADIOACTIVE ISOTOPE TRACERS FOR ESTIMATING GROUNDWATER RECHARGE

Radioactive isotopes that are produced artificially either in laboratory or in a reactor are known as artificial radioactive isotopes. These artificial radioactive isotopes can be used as water tracers. The artificial tracers have the advantage over environmental tracers that they are injected in a controlled way and that the concentrations are high enough to be easily detected. The disadvantage is that it is non-natural, which mean environmental hazard and that experiments can only be made at specific points and at specific times. The choice of artificial tracer should take into account that the tracer travels with the water and does not adsorb to the soil particles; in-situ detection is preferable and the tracer should be least toxic. Artificial tracer isotopes, which have been found useful as tracers in groundwater studies in a broad perspective include ^3H , ^{24}Na , ^{32}P , ^{36}Cl , ^{51}Cr , ^{60}Co , ^{82}Br , ^{86}Rb , ^{106}Ru , ^{131}I and ^{198}Au . The most commonly used artificial tracer isotope for groundwater studies is tritium (^3H) as HTO, which is applied below the root zone or in the groundwater depending on the purpose of the study. It was found by, for example Blume et al (1967) and Zimmermann et al (1967b) that the tracer should not be introduced at the surface because of the tracer losses by evapotranspiration. Among other radio isotopes that have been tried, ^{60}Co as $\text{K}_3\text{Co}(\text{CN})_6$ should be mentioned. Nair et al (1979) found no significant differences in the behaviour of the mentioned ^{60}Co complex and tritiated water in terms of retardation due to adsorption or molecular exchange with the interstitial water in the soil profile. However, ^{60}Co -EDTA (Ethylene Diamine Tetra Acetic Acid) complex was strongly retarded in comparison with the cyanide complex. On the other hand, Knutsson and Forsberg (1967) reported ^{51}Cr -EDTA to behave as an ideal tracer in soils free from montmorillonite. Still, the method of gamma-emitting tracers has to show its versatility in different geological settings. Therefore, ^3H as HTO is the only artificial tracer whose applicability is treated in more detail here.

Tritium Tagging Technique

Moisture Movement and Tracer Displacement

Soil water moves along a range of different pathways. Local field heterogeneity should bring about a considerable dispersion of pollutants or of a tracer. However, field experiments of Zimmermann et al. (1967a and 1967b) and Blume et al. (1967), showed "piston flow" type behaviour of soil moisture in nearly homogeneous soils; infiltrating water simply pushes the old water downward. This means that the soil moisture profile may change shape, but no newly percolated water bypasses water that has previously percolated below the root zone. In the above-mentioned experiments, the broadening of the peak of the injected tracer was of the same magnitude as expected by molecular diffusion only. Also, experiments conducted in the alluvial

tracers of north India by Bahadur et al(1977) showed broadening of the tracer peak comparable to the spread by molecular diffusion. It seems that if the flow is slow, the lateral mixing, mostly from molecular diffusion, in rather homogeneous soils between moisture packets having different flow velocities is quite effective, thus indirectly counteracting vertical dispersion.

In this context, it is necessary to distinguish between particle velocity, soil moisture flux, recharge rate and propagation rate of a disturbance. Particle velocity is the velocity of individual water molecules. The velocity depends on soil characteristics and moisture conditions. Typically the velocity is low, one to a few metres per year. In heterogeneous soils particle velocities vary within a large range.

Soil moisture flux or percolation rate is related to a fixed point at a fixed time. It is the "unsaturated Darcian velocity. A typical flux value is half a metre per year or less. Below the root zone, capillary tension gradients play only a minor role. The moisture content is at or above field capacity. The soil moisture flux corresponds to the unsaturated hydraulic conductivity. Increased flux at the lower root zone is not immediately recognised as groundwater recharge. The increased flux propagates down-wards with a propagation rate that depends on the moisture conditions in the soil profile. A typical propagation rate is a few metres per month, but it may be lower as well as higher. If the soil is initially dry the propagation rate is close to the particle velocity value, but if the initial soil moisture conditions correspond closely to the flux at root zone level, the propagation rate is fast giving a fast groundwater response to infiltration.

In the course of water infiltration, an injected or environmental tracer is carried along with the soil water. The position of the peak tracer concentration can be monitored in the soil profile; from the temporal displacement of the tracer a percolation rate or a moisture flux, and for certain conditions the groundwater recharge, can be estimated provided the measurements are taken below the root zone so that all water movements are directed downwards. Zimmermann and co-workers used deuterium and tritium. They called the method of tracing the peak tracer tagging technique. The principle of how percolation rates are determined from tracer monitoring is illustrated in Fig.1. Shortly after the tracer injection, the peak concentration is at depth z_1 and after a certain time it is found at depth z_2 . Provided no vertical mixing takes place during the downward movement, the mean moisture flux, q at the lower depth z_2 over the time period, Δt , between the two observations is,

$$q = \theta_v (z_2 - z_1) / \Delta t$$

Where, θ_v is the average volumetric moisture content between the two depths at the time of the first observation after reduction of eventual residual moisture content, i.e. interstitial water or water that adheres to the soil particles. This residual moisture content is generally believed to be negligible, except may be for very fine soils.

If the time period is a full season or full year, the moisture flux corresponds to the recharge over a season or year, although the particular soil water particles do not reach the groundwater during the particular year when the observations were made. A different technique for evaluating annual recharge when using stable environmental isotopes is to measure the soil moisture between two levels at which the soil water can be identified to originate from two events, preferably snowmelt, one year apart in time.

Methodology

Tritium is a radioactive isotope of hydrogen having half-life 12.32 years. Being a part of water molecule, tritium is commonly used as an artificial tracer for hydrological studies.

Although, the analysis of tritium activity requires some costly laboratory facilities but, keeping in view the low health hazard possibilities and accuracy in water tracing studies, its use is increasing in developing countries.

Tritium tagging technique was developed by Zimmermann et al (1967a,b), Blume et al (1967) and Munnich (1968a,b) with the assumption that the movement of soil moisture in a unsaturated zone is similar to piston type flow i.e., if any amount of water is added to the ground surface due to precipitation or irrigation, it will percolate by pushing equal amount of the water beneath it further down and so on such that an equal amount of the moisture of the last layer in the unsaturated zone is added to the groundwater. Although, it can be well understood that in case of unsaturated flow where air and water are found, which have entirely different properties, the movement of soil moisture can not be a piston type flow. Therefore, a number of questions have been raised by the various researchers (Datta *et al.*, 1990; Mookerjee, 1990; Singh and Kumar, 1993) on the assumption of piston flow movement and some evidences have been reported where the soil moisture flow does not follow the piston type movement. At the same time, it has also been mentioned that the results of recharge to groundwater determined using tritium tagging technique are comparable to those determined using gravimetric soil-moisture method. Therefore, there is no doubt about the validity and results obtained by using this technique.

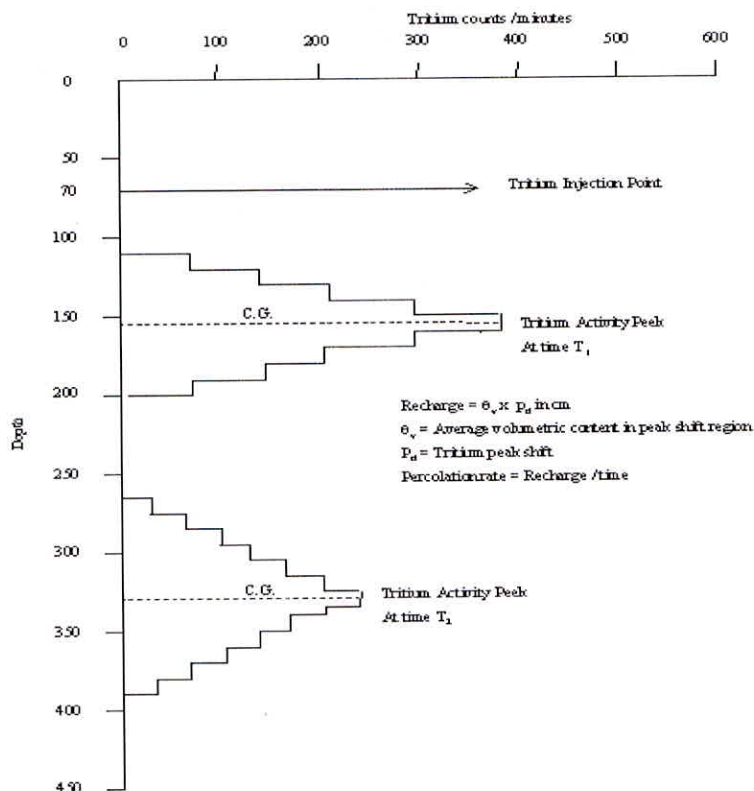


Fig. 1 Shifting of injected tritium with respect to the movement of infiltrated water.

In this technique, tritium is injected at a depth well below the root and sun-heating zone (70 to 100 cm) at selected site/s in the study area. The tritium injection site is left open for agricultural and other activities including natural variations. The soil samples are collected from different depths at the time of tritium injection from a nearby location for having the information of initial soil moisture conditions. The injected tritium is removed by collecting the soil samples from the tritium injection points at an interval of 10 cm. depth after a chosen time interval. These soil samples are analyzed to study the soil moisture and dry/wet density. The soil samples are

also subjected to distillation in order to get the tritiated water from the corresponding depths. The tritium activity is determined in the distilled water samples in order to know the movement of tritium peak. It has been noticed that the tritium peak obtained after the chosen period broadens due to diffusion, streamline dispersion and input water irregularities (Fig. 1). Therefore, the center of gravity of the broad tritium peak is considered to calculate the recharge to groundwater (Zimmermann *et al.*, 1967b). The recharge to groundwater is calculated by multiplying the tritium peak shift with the average volumetric moisture content obtained in the tritium peak shift region. The layout of the tritium injections is shown in Fig. 2.

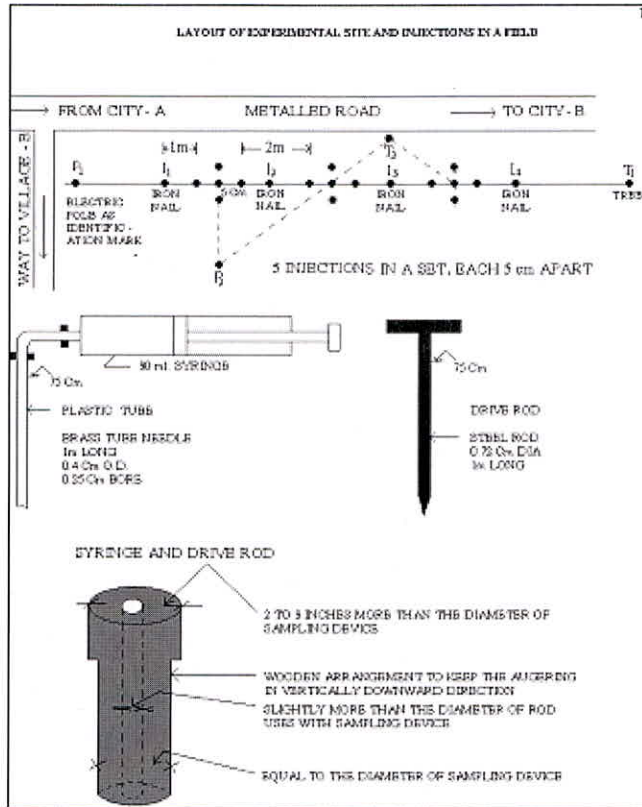


Fig. 2 Systematic diagram of injection layout and implements for artificial tritium injection at test site.

Zimmermann *et al.* (1967a, b) and Blume *et al.* (1967) found the downward moisture displacement for central European soils and climates, to occur at a rate of about 1 m/y, and the groundwater recharge to be about 200 mm/y. They considered the error in the recharge estimate to be less than 10%. Similar studies were carried out in India in the alluvial deposits of the Indo-Gangetic plain by Datta *et al.* (1973), by Bahadur *et al.* (1977) in the semi-arid regions around New Delhi and Athawale *et al.* (1980) in the Maner basin. These studies showed the applicability of tritium when the surface inputs come in heavy impulses, i.e., the monsoons. According to Datta *et al.*, the annual recharge for the area around Delhi region for 1971-72 was about 215 mm, which, however, is far from the estimated 33 mm/y by Eridsson (1976) based on chloride concentration in groundwater in Delhi. The poor agreement between the two different methods refutes, at least when monsoon rains are present, that recharge can be estimated with an accuracy of 10%. Bahadur *et al.* (1977) studied only the seasonal recharge due to the monsoon, but their data when extrapolated to yield annual recharge gave a value ranging from roughly 15 to 25 mm/y for 1973-1975.

The method described, using tracer input impulses, requires that the tracer is not retarded on its downward movement, or that the physics of the retardation is known. It is generally

accepted that tritium moves with the water, not being adsorbed and not being affected by any physical fractionation. In laboratory soil-column studies Knutsson and Forsberg (1967) found no significant adsorption or retardation of HTO in soils dominant in illite and kaolinite. However, tracer losses were found in bentonite and montmorillonite dominant soils.

ENVIRONMENTAL ISOTOPE TRACERS FOR ESTIMATING GROUNDWATER RECHARGE

Isotopes found in the atmosphere are known as environmental isotopes. These may be radioactive as well as stable in nature and both types can be used as water tracers. An environmental tracer has the advantage over an artificial tracer as it does not need to be injected and it is already a part of the environment. Environmental tracers can be used over large areas, but the concentrations are low and difficult to detect. Environmental isotope techniques are based on isotopic variations in time and space in natural water systems. These variations can be observed to gain information about the origin of water and about mixing conditions. The most commonly used environmental isotopic tracers in groundwater investigations are the radioactive carbon-14 and tritium, and the stable ones deuterium and oxygen-18. Carbon-14 is used for determining the age of very old groundwater.

Environmental Tritium Technique

The radioactive isotope of hydrogen, i.e. tritium, released from thermonuclear explosions in the atmosphere made possible a way of estimating groundwater recharge. The cosmogenically produced tritium is found entirely in atmospheric vapour and is brought down to earth's surface by precipitation. Before 1952, the tritium concentration in precipitation was low. When thermonuclear tests in the atmosphere began in 1952, tritium concentrations in precipitation suddenly increased and reached a record-high concentration in 1963-64 in the northern hemisphere. In India, the peak concentration of bomb derived tritium in 1963 was more than 1000 TU: in Sweden 2100 TU : (1 TU is equal to 1 atom of tritium in 10^{18} H atoms, or 0.12 Bq/l water). The fact that water originating from precipitation which has fallen before 1952 has lower tritium concentration than water contributed by more recent precipitation can be used when tracing groundwater.

Assuming that more recent infiltrating water pushes previously infiltrated water, the bomb tritium of the infiltrated precipitation of a particular year can be found in a soil profile. The tritium concentrations in the soil profile will be moderated due to dispersion and molecular diffusion. Among others, Munnich et al(1967), Sukhija and Shah (1976) in India, and Andersen and Sevel (1974) in Europe have used bomb-released tritium for the evaluation of groundwater recharge in Europe and India, respectively.

In this method, it is assumed that the amount of water from the soil surface to the soil depth, where the 1963-64 tritium peak is located, is the measure of recharge from that time until the time of investigation. In the other method, the tritium concentration of the water lost as evaporation of surface runoff as well as of the water percolating below the root zone is, at any time, assumed to equal the concentration of the precipitation. The accumulated percolation, R, which will contribute to groundwater recharge is simply given by,

$$R = P (M_s / M_p)$$

where P is accumulated rainfall since the beginning of the bomb tests, M_p is the total amount (per unit area) of tritium in the precipitation, and M_s is the amount of tritium found in the soil above the depth where the tritium concentration is at pre-1952 level. The method can be adjusted to be applied from the peak concentration time instead of from 1952, i.e. from 1964.

Stable Isotopes Technique

The stable isotopes oxygen-18 and deuterium in precipitation have long been known as potential tracers for natural waters yet they have been little exploited for measuring percolation. The flux of HDO and H₂¹⁸O from an open water body to the atmosphere is reduced relative to the flux of the lighter H₂¹⁶O because of the lower vapour pressure of the former species, which causes fractionation in evaporation and condensation processes. In cold climates seasonal stable isotopic composition of precipitation is rather well reflected in soil moisture. In semi-arids however, the isotope picture of soils is rather complex due to strong fractionation caused by high evaporation rates from the soil.

Soil water infiltrated during two periods with a time span of a year can be identified within a soil profile on the basis of stable isotopic composition of either deuterium (²H or D) or oxygen-18 (Fig. 3). Therefore, the total amount of percolated water during the year can be estimated simply by totalling the amount of soil water between the two depths where the soil water from the two periods is found. Reduction should be made for eventual residual water. Mathematically expressed, the annual percolation, R, which will later contribute to groundwater recharge, is

$$R = \int_{z_1}^{z_2} \theta_v dt$$

Where z_1 and z_2 are the identified depths and θ_v is the volumetric soil moisture content after reduction of eventual residual water. The method cannot be applied in areas where the groundwater level is shallow during some periods of the year.

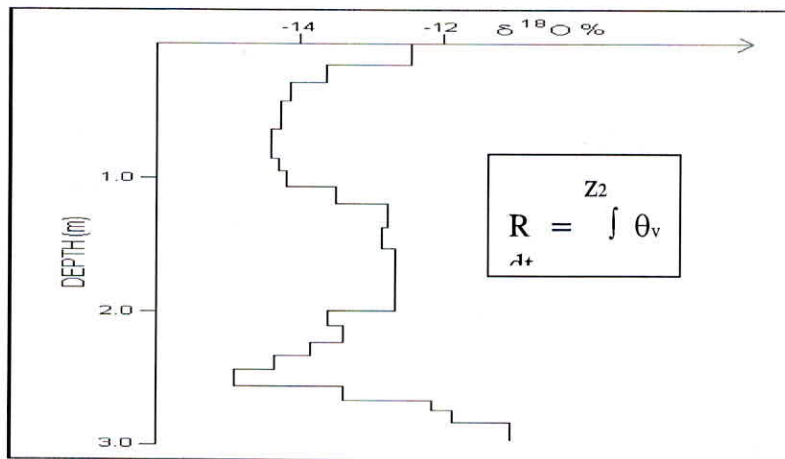


Fig. 3 Oxygen-18 profiles in soil moisture indicating patterns of infiltrated water in different years

The first attempt was made for estimating recharge to groundwater in sand dunes with depth fluctuations in deuterium in soil moisture profiles (Thoma et al., 1979). The seasonal variations of oxygen-18 in precipitation have been traced in the soil moisture and estimates of groundwater recharge and rates of moisture movement were estimated for Swedish glacio-fluvial deposits and moraine formations (Saxena, 1984). Now, this technique is used wherever the measurement of stable isotopes is possible.

Application of any of the two methods is restricted to sites where the water of peak tritium concentration has not yet reached the groundwater table. In fact the environmental tritium method was relatively more useful only until mid 1970s. Most of bomb tritium has by now

mixed with the groundwaters and the soil profiles have more or less a constant concentration of tritium.

CASE STUDIES

(a) Recharge to Groundwater in Bundelkhand Region of U. P., India Using Tritium Tagging Technique

The Bundelkhand region in India comprises 12 districts out of which 5 fall in Uttar Pradesh and 7 fall in Madhya Pradesh. The study area comprises of four districts, namely Jalaun, Banda, Hamirpur and Jhansi, covering an area of approximately 24079 km². Bundelkhand region of India falls in subtropical region characterized by hot and prolonged summer followed by rainy season and cold winter. The distribution of rainfall is not only erratic in the region but the same situation persists even in a small area, causing occasional drought conditions. District Jalaun, Banda and parts of Hamirpur (60%) and Jhansi (10%) are underlain by indo-gangetic marginal alluvium of quaternary age and comprise mainly sand of various grades, clay and clay mixed with kankar while the major parts of district Jhansi and about 40% area of district Hamirpur fall under rocky formation therefore, the surface soil is more compact in comparison to that in other two districts.

Bundelkhand region in India faces acute water deficiency due to higher losses of rain and surface waters. Although, the rainfall in this region is less in comparison to the surrounding region but it is much higher in comparison to the rainfall in semi arid regions. The groundwater reserves have been found very limited and groundwater level is also deep at number of places. Hence, it is treated as an undeclared semi-arid region in India. Keeping in view the prevailing conditions in Bundelkhand region, it is necessary to estimate the correct value of recharge to groundwater due to monsoon rains, which is the main source.

Tritium was injected at 25 sites before the start of monsoon rains. Soil samples were collected from the injected sites in the month of November and recharge percentages were determined. Since, sampling was carried out in November, the water input for the irrigation was also taken into account while determining the percentage of recharge. It is clear from the results obtained (Table- 1) that there is a wide variation in the values of recharge to groundwater. This variation may be due to different type of soil, topography, hydrogeology, groundwater level conditions, cropping pattern, rainfall pattern, evapotranspiration and several other local factors which are very difficult to account for. A sample plot of shifting of tritium activity and variation of soil moisture with depth are shown in Fig. 4.

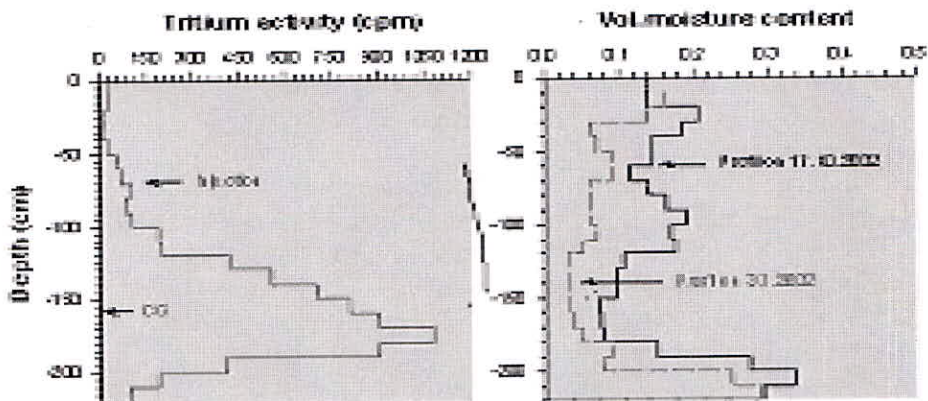


Fig. 4 Tritium and soil moisture profiles

Table 1: Rainfall + Irrigation and estimated recharge at different stations in the Bundelkhand region, U.P., India for the period from June, 1980 to November, 1980

Code	Station	District	Rain-fall + Irrigation (cm)	Estimated Recharge (cm)	Code	Station	District	Rain-fall + Irrigation (cm)	Estimated Recharge (cm)
1B	Bania Ka Purwa	Banda	72.16	13.12	2JA	Kad-aura	Jalaun	164.70	17.86
2B	Murwal	Banda	64.38	11.25	4JA	Jalaun	Jalaun	106.20	13.00
3B	Padmai	Banda	79.76	14.64	5JA	Rampura	Jalaun	134.30	34.00
4B	Tara	Banda	81.99	12.81	6JA	Konch	Jalaun	103.70	10.19
5B	Mrighani	Banda	91.99	19.87	1H	Muskara	Hamirpur	81.21	21.95
1J	Khillara	Jhansi	81.20	8.05	2H	Lal-pura	Hamirpur	95.18	22.04
2J	Siyoni Khurd	Jhansi	104.06	8.29	3H	Kuchhechha	Hamirpur	95.18	22.78
3J	Khirak	Jhansi	79.32	23.48	4H	Rewai	Hamirpur	111.77	11.60
4J	Khilli	Jhansi	88.05	16.15	5H	Eng-ohta	Hamirpur	71.90	6.09
5J	Baruwa Sagar	Jhansi	95.30	10.97	6H	Gatak Nahar	Hamirpur	81.20	7.31
6J	Panduwah	Jhansi	86.85	10.69	7H	Khanna	Hamirpur	81.21	15.50
7J	Manipur Moitra	Jhansi	99.40	6.35	8H	Bharwara	Hamirpur	76.21	18.98
8J	Mandori	Jhansi	92.50	11.78					

Mathematical Approach

Although large area can be covered at a time by using tritium tagging technique but, it is very difficult to carry out the field experiments every time for the evaluation of recharge to groundwater using this technique. Therefore, it is necessary to develop some mathematical formulation to calculate the recharge due to monsoon rains, if only the information on rainfall is available. But, it is also not advisable to develop an empirical relation using only one or more of

those hydrological parameters, which act as constants but affect the rainfall- recharge process. The authors have given emphasis to study the recharge to groundwater due to monsoon rains as major recharge to groundwater takes place during this season, otherwise, the method suggested here can also be applied for estimating recharge to groundwater during other seasons.

Groundwater recharge by rainfall is very complex process influenced by numerous surface and sub surface parameters including rainfall intensity, its frequency and several other local factors (e.g. vegetation cover, soil properties, etc.). Therefore, it is advisable that once, the recharge to groundwater due to rains and/or irrigation is determined using tritium tagging technique, a partly suitable mathematical approach can be developed which will be accounting for all the known and unknown factors affecting the rainfall-recharge process. However, the authors are not of the opinion that one should only follow this procedure, therefore, if the correct information of all the processes and parameters which affect the rainfall- recharge process are possible to obtain, a suitable mathematical model can be developed.

The recharge values were analyzed with respect to clay percentage, clay/sand ratio, water table fluctuation and rainfall data. It has been observed that the recharge values follow a unique logarithmic relationship with rainfall, for similar site conditions, while different relation is observed for the other set of sites. The plots of recharge values obtained at 25 sites in four said districts are shown in Fig. 5. The following two mathematical formulations fairly satisfy the variation of recharge values.

$$\begin{array}{lll} \text{Group A} & R_g = 29.316 \ln(P) - 111.259 & (r = 0.83) \quad (1) \\ \text{Group B} & R_g = 12.861 \ln(P) - 48.757 & (r = 0.85) \quad (2) \end{array}$$

where R_g is recharge to groundwater in cm, P is rainfall/precipitation in cm.

It is interesting to note that when the two different trends of variation were correlated with hydrogeological conditions, it has been found that recharge values for the sites which fall in the marginal alluvium region follow equation (1) and those which fall in the hard rock region follow equation (2). The plots of recharge values, calculated using Chaturvedi (Chaturvedi, 1973) and Amritsar formulae (Sehgal, 1973) and shown in Fig. 4, clearly indicate that Amritsar formula gives consistently higher estimates while the Chaturvedi formula seems to be partly applicable.

In addition, the mathematical approach has also been applied for Sabarmati basin and Mahi Command Area in Gujarat State for which Bhandari *et al.* (1986) have studied recharge to groundwater using tritium tagging technique. These investigators have developed empirical relation using precipitation and in some cases type of soil approaches. The equations for three trends that hold good as per the experimental data for Sabarmati basin are as follows:

$$\begin{array}{lll} \text{Group A} & R_g = 20.469 \ln(P) - 60.568 & (r = 0.80) \quad (3) \\ \text{Group B} & R_g = 14.345 \ln(P) - 42.376 & (r = 0.94) \quad (4) \\ \text{Group C} & R_g = 15.681 \ln(P) - 58.174 & (r = 0.92) \quad (5) \end{array}$$

The above two examples of Bundelkhand region and Sabarmati basin are indicative of the fact that, the net result is better if the area under question is subdivided on the basis of observed variations in the precipitation - recharge plots and equations are developed, than to treat them as one single unit and try to relate the recharge with other factors with poor statistical parameters. These mathematical formulations can be used to determine recharge to groundwater with respect to precipitation and irrigation during monsoon seasons in future.

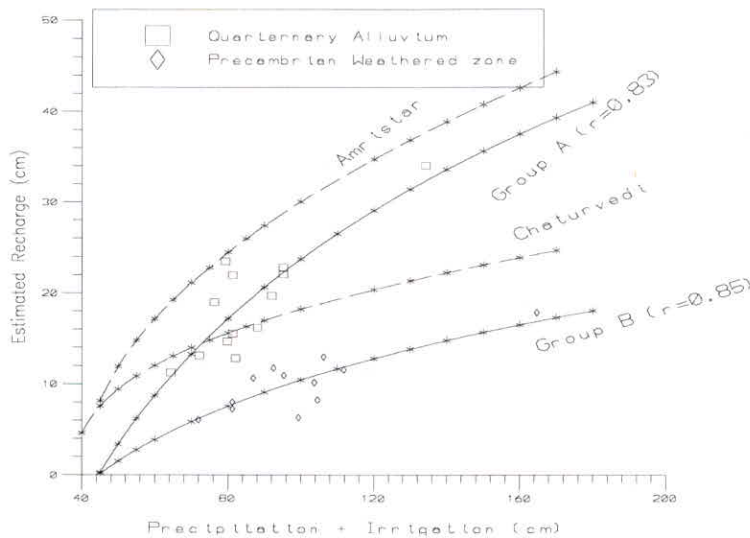


Fig. 5 Correlation of estimated recharge (cm) with precipitation

Discussion

From the results presented under the section 'mathematical approach' using tritium tagging technique, the following points emerged out.

i) It is clearly seen from the plots of recharge to groundwater with respect to rainfall for Bundelkhand region of Uttar Pradesh State and Sabarmati basin and Mahi Command Area in Gujarat State, India that a single empirical relation may not hold good for the whole region. Therefore, in order to explain the wide variations in the experimental results, it is advisable to consider the area under study in small sub-regions on the basis of observed trends in plots. Subsequently it may be verified in the field for the influencing parameters viz. hydrogeology, physiography and other local factors.

ii) The author is of the opinion that if reliable information on recharge to groundwater is required for any area, neither water table fluctuation approach nor empirical relation that has been developed for another area should be used. Instead tritium tagging technique which is simple and fairly accurate should be used to develop a separate empirical relation between rainfall and recharge for the area under question, to be used to estimate groundwater recharge in future.

(b) Recharge to Groundwater in Uppsala, Sweden Using Oxygen-18

Percolation rates in an Esker (glacio-fluvial formation) in Uppsala, Sweden have been estimated using the environmental isotope oxygen-18. Winter precipitation being depleted in oxygen-18 differs from summer precipitation in their oxygen-18 contents. Thus, meltwater is of relatively light isotopic composition. This oxygen-18 depleted water can be considered as a tracer of infiltrating melt water in the soil. After the melt period, water originating from rains of relatively high oxygen-18 content that eventually penetrates below the root zone "pushes" down the oxygen-18 depleted meltwater, which in turn further pushes down the older moisture (having high oxygen-18 content) contributed by the previous year's summer and autumn rains. Ideally, the infiltration an esker in Uppsala, where the depth to the groundwater table is about 4m, infiltrated meltwater from two consecutive melt periods was traced in the unsaturated zone providing estimates of annual recharge. The measured oxygen-18 profiles are shown in Fig. 3. In Fig.3, the melt periods of 1981 and 1982 can be distinguished in the soil moisture profile observed in May 1982. The first oxygen-18 depleted layer (average depth 65 cm and the front at

115 cm) represents snowmelt 1982, and the second depleted layer (average depth 235 cm and the front at about 265 cm) is due to contribution from the 1981 melt period. The total water present in between these two oxygen-18 depleted layers is the water, which has percolated below the root zone during one year. Soil moisture measurements showed the total soil water between the average depths of the two depleted layers to be 280 mm. This value agrees fairly well with the mean annual recharge arrived at by regional water balance studies (Eriksson, 1980). The recharge estimates obtained from this method are not more accurate than other methods, but it is possible to tell from which rain or snowmelt event the fairly deep soil water originates, and thus during which periods infiltrated water percolates below the root zone. The measurements from Upscale Esker are used as an example. In Fig.3, meltwater from the spring of 1982 is seen to be distributed from depth 15 to 115 cm. The average soil moisture content between these two depths is 0.18, giving a soil water contribution from 1982 snowmelt of 180mm. The meltwater from the spring of 1981 is found between 200 and 265 cm, where the average soil moisture content is 0.17, and thus the amount of percolated 1981 meltwater about 110 mm, whereas soil water between 115 and 200 cm amounting to about 120 mm is the contribution from percolation of rains.

For estimating the rate of moisture movement for relatively short periods, frequent sampling is required. Three oxygen-18 profiles observed during July, September and December 1982 are shown in Fig. 6. The infiltrated meltwater from the spring was observed at the average depth 115 cm in July, in the September at 155cm and in the December at 170cm. Thus, the rate of displacement of this depleted layer was during July-September 6.5 mm/d and during September- December 1.9 mm/d. The average moisture content between 115 and 155 cm was 0.11 in July. The average soil moisture flux at 155cm during July-September is found to be 0.72 mm/d. Knowing the average moisture content between 155 and 170 cm in September, 0.22, the average soil moisture flux September-December at 170 cm can be estimated as 0.42 mm/d. The average soil moisture flux or percolation rate at 170cm can be found from the oxygen-18 profiles for the full period i.e., July to September/ December. From the displacement rate 4.1 mm/d and the average soil moisture in July, 0.14, this percolation rate is 0.57 mm/d. Thus, the percolation rate during July-September must have been 0.77 mm/d, which is close to the percolation found at the depth of 155 cm for the same period. The computed percolation rates are summarized in Table 2. Using the environmental tracer technique, the contribution to groundwater recharge from different seasons can be determined and the origin of recharging water can be found. The exact time when the groundwater is recharged cannot be determined. But particle velocities of individual water molecules can be determined it. It is possible to estimate the time required for non-adhering conservative substances to reach the groundwater. The particle velocity below the root zone at the Uppsala Esker site as reported by Saxena (1984) varies only within a small range. The glacio-fluvial deposits are rather homogeneous. Newly percolated water does not bypass previously percolated water.

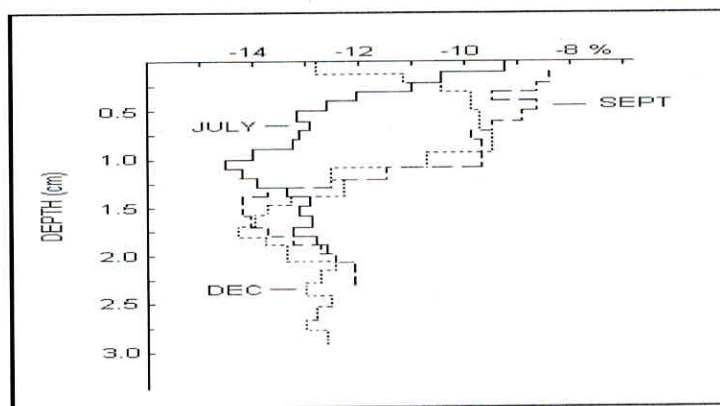


Fig. 6 O-18 profiles observed during different months

Table 2: Percolation rates (mm/d) in Uppsala Esker, autumn 1982, estimated from the measurement of O-18 concentrations and soil water content.

Level	July-Sept.	Sept-Dec	July-Dec.
155	0.72	-	-
170	0.77	0.42	0.57

The average velocity is 1.5-2 m/y, which means that it takes more than two years even for conservative non-adhering pollutants to travel with the percolating water from the ground surface to the groundwater table at about 4 m.

(c) Recharge to Groundwater in Gujarat, India, Using Environmental Tritium

The estimation of vertical component of recharge to groundwater by using environmental tritium differs in two ways from the injected tracer technique:

- i) Tritium input
- ii) Tritium measurement

As already stated that in case of environmental tritium, it is naturally injected in the soil system with precipitation while in case of injected tritium it is to be injected manually. As the activity of environmental tritium is not measurable using the system, which are used for injected tritium therefore, special equipment like, Ultra Low Level Liquid Scintillation Spectrometer is used to measure it. In this technique, soil samples are collected from the site of interest and tritiated water is obtained by vacuum distillation. In certain cases, where the tritium activities are not measurable, the water samples are enriched in order to increase the tritium concentration. Environmental tritium activity is measured with the help of special equipment, as stated above, in the tritiated water using Ultra Low Level Liquid Scintillation Spectrometer. The tritium activity is plotted with respect to depth along with moisture content. The total tritium activity is determined from the plot using the following relation.

$$\text{Recharge to groundwater} = \frac{\sum \text{Tritium concentration in TU} \times \text{Volumetric moisture content}}{T_p}$$

where, Ta = Total tritium activity observed; Tp = total tritium input through precipitation; TU = tritium unit; 1TU = $^3\text{H}/^1\text{H} = 10^{-18}$ (1 L of water with 1 TU activity emits 7.2 dpm or 0.12 Bq)

Physical Research Laboratory (PRL), Ahmedabad has carried out the study of groundwater recharge using environmental tritium in different parts of Gujarat, India. Results of a study carried out by PRL, Ahmedabad at few sites are given in Table-3 while the plots of observed environmental tritium activity are shown in Fig. 6.

Table-3: Estimated values of groundwater recharge using environmental tritium

Sl. no	Name of site	Avr. P.P.(mm)	Avr.G.W. (mm)	Recharge % of 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

GROUNDWATER FLOW VELOCITY AND DIRECTION

Single well and multi-well dilution techniques are employed using artificial radioactive isotopes to determine the ground water velocity and direction of flow. In fact single well dilution method, also called point dilution method can be used to determine both, the velocity and direction of flow using some special probe but multi-well method can be used to determine filtration velocity, transit velocity and direction of flow without using any special probe.

(i) Single Bore-Hole Dilution Technique

Single bore hole dilution technique can be employed to obtain direct measurement of filtration velocity in a water bearing formation under natural or induced hydraulic gradient. The filtration velocity interpreted in conjunction with other parameters can provide valuable information about an aquifer.

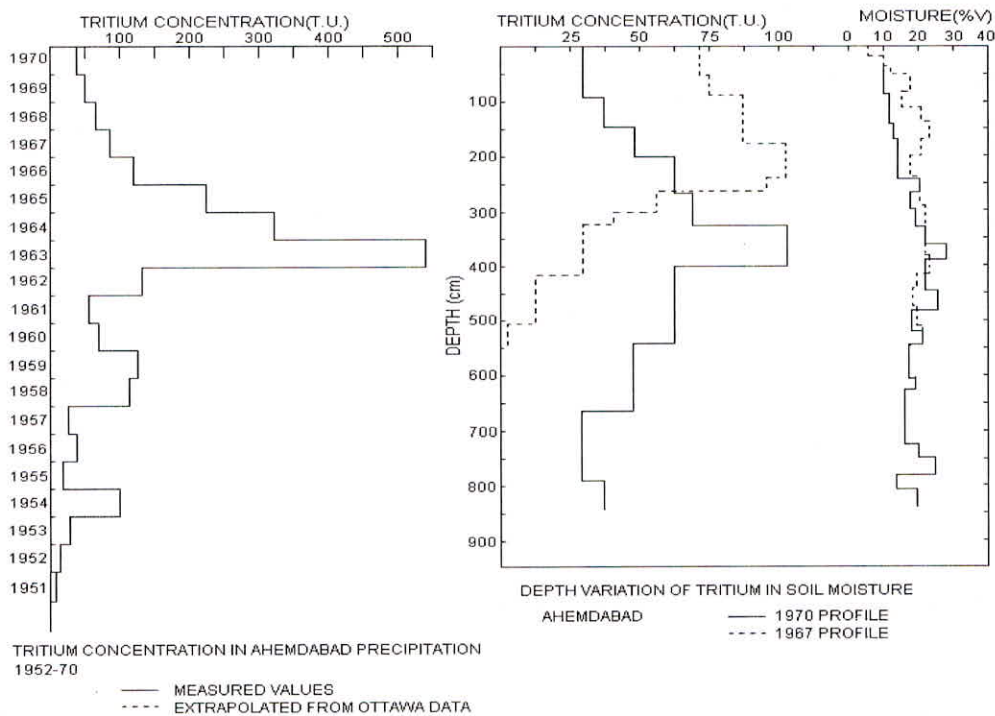


Fig. 6 Environmental tritium and soil moisture profiles source (PRL 1986)

Principle of the Technique

The dilution rate of the solution, which is homogeneously dispersed in a volume V in the bore hole is related to the horizontal water flow velocity V_f by the equation;

$$V_f = (\pi d/4\phi) \ln(C_0/C) \quad \dots(1)$$

where, 'd' is the diameter of bore hole, C_0 is the initial concentration of the tracer at time $T = 0$ and C is tracer concentration at time $T = t$ and ϕ is the distortion factor which compensate the effect deformation caused by the presence of the bore hole (distortion of flow lines takes place).

The value of ϕ depends on bore hole geometry and permeability in the area of bore hole (aquifer, filter tube and filter gravel used) and can be determined theoretically or through model experiments. But, for small bore hole say having diameter of 2", its value can

be taken 1, while for large diameter bore hole, its value may be taken 2 or even more. Other factors which affect the dilution rate of the tracer are vertical currents, artificial mixing of the tracer, molecular diffusion etc.. The effect of vertical currents may be avoided to some extent by isolating the dilution volume, while effect of the molecular diffusion of the tracer becomes important only for very low filtration velocities (5-10 cm/day) However, the author of this lecture has carried out several experiments taking different heights of water columns and established an empirical relation between filtration velocity observed and the average of the filtration velocities of different vertical currents. Therefore, the actual filtration velocity, if the filtration velocity could not be measured in situ by isolating the dilution volume, can be determined by using the empirical relation,

$$V_f = V_o \{1 - \exp(-hD/L)\}$$

where, V_o is the actual filtration velocity averaged over the filtration velocities of different currents, h is the height of water column in bore hole and D is the distance of the Bore Hole from the central line of canal or river. L is length of the one side curved surface of the canal or river. This relation is not valid in the case of natural ground water flow velocity measurements. The diffusion velocity in case of tritium has been observed very low, i.e., of the order of 0.5 cm per day by many investigators.

ii) Multi-well Dilution Technique

In this technique, the radioisotope is injected in one bore hole, may be called main bore hole, and either the probe is placed in another borehole made at some suitable distance or water samples are collected in the case of beta-emitting radioisotope. In fact, if the natural ground water velocity is to be observed, boreholes are made in a circle keeping the main bore hole again at the centre. By knowing the travel time of radio-isotope from main bore-hole to the borehole under observation, and distance of bore-hole, the velocity of transit is determined. The multiplication of specific yield of the soil strata with transit velocity provides the information of filtration velocity or groundwater flow velocity. Similarly, if the flow velocity is observed in all the bore holes made around the main borehole, the direction of flow will be the direction of bore-hole in which the maximum velocity will be observed.

ORIGIN OF GROUNDWATER

All groundwater of economic interest originates as precipitation. This means that the amount of recharge to a groundwater system related to its storage capacity determines the maximum available resources for exploitation. Under favourable conditions (that is, groundwater basins where the barrier boundaries and the inputs and outputs are well defined) it is possible to construct a simple conceptual model of the system to obtain a water balance. Nevertheless, in many cases recharge and water flow are rather complex and more information of the actual process is desirable. Knowledge of the recharge process is also important for preventing deterioration of water quality by salinization and pollution. The environmental isotopic methods provide a valuable approach to understand these complex phenomena as well as to test the validity of the alternative hypothesis. The application of the environmental isotope methods to understand the origin of groundwater w.r.t. its recharge is based on the spatial and temporal variability of the isotopic contents of water. The spatial variability can be grouped in four different topics

Altitude Effect

Groundwater recharge from high altitude either directly or by rivers draining high altitude catchment basins can be distinguished from recharge originating from low-altitude

precipitation due to altitude effect in precipitation. This effect is most useful in regimes having orographic precipitation, where there is a regular relationship between land-surface altitude and condensation temperature of precipitation (isotopic composition of heavier isotopes depletes in precipitation with increasing altitude). When saturated air moves upward it cools, which causes condensation. Consequently heat is released which counteracts cooling. The resulting change in temperature with altitude is called adiabatic lapse rate. The wet adiabatic lapse rate varies with altitude, but a value of $0.6\text{ }^{\circ}\text{C} / 100\text{ m}$ is reasonable. For ^{18}O , the temperature dependence during wet adiabatic cooling is about $0.5\text{ }_{\text{‰}} / ^{\circ}\text{C}$. The observed range of variation of $\delta^{18}\text{O}$ per 100 m is between -0.16 and $-0.7\text{ }_{\text{‰}}$ with an average value of $-0.25\text{ }_{\text{‰}}$ while for $\delta^2\text{D}$ per 100 m is between -1.0 and $-4.0\text{ }_{\text{‰}}$ with an average value of $-2.0\text{ }_{\text{‰}}$.

Latitude Effect

The stable isotope content of precipitation shows a marked dependence on latitude (depletes with increasing latitude) thus, groundwater replenished by rivers spanning significant latitude zones can be distinguished from local recharge.

Deuterium Excess

Another geographic effect on the stable isotope content that can be applied effectively is the shift in the D- ^{18}O relationship, relating to the source of atmospheric moisture. It has been noted that in the eastern Mediterranean and similar marine belts of rapid evaporation the resulting precipitation has a D - ^{18}O relation of $\delta\text{ D} = 8\ \delta^{18}\text{O} + 22$, quite different from the general northern hemisphere precipitation in which $\delta\text{ D} = 8\ \delta^{18}\text{O} + 10$. This difference can be used in the border areas of climatic zones, where precipitation on the coastal mountains can be of Mediterranean or oceanic origin.

Seasonal Recharge

In regions where temperature and precipitation are distinctly seasonal and groundwater flow occurs in crystalline or karstic rocks, the stable isotope content of groundwater may indicate the seasonal dependency of recharge and in some instances even the influence of specific large storm events. The stable isotope content can also be used to determine the ratio of seasonal recharge and base-flow of springs having such a composite discharge regime.

Dating of Groundwater

The dating of groundwater also helps in understanding the origin of groundwater i.e., of recent origin or old water. Many radioisotopes are produced in the environment by interaction of neutrons from cosmic rays with nitrogen. The nature of decay of these environmental radioisotopes can be used to detect the age of groundwater or other materials also. Radioisotopes mixed with water vapours in environment and enter into groundwater bodies with precipitation water.

Several groundwater dating techniques are available, but popularly, only two dating techniques are used for estimating age of groundwater.

- i) Tritium dating
- ii) Radiocarbon dating

The details of groundwater dating techniques are beyond the scope of this lecture, however, a brief idea will be provided to the readers/participants in this regard.

IDENTIFYING MODERN RECHARGE

Ground Water Dating With ^3H

Tritium is of special value in detecting recent recharge because of its short half-life of 12.32 years and because of high levels of tritium in the atmosphere since the beginning of atmospheric testing of thermonuclear devices in 1952.

- Tritium is produced due to the interaction of the cosmic rays produced neutrons in the upper atmosphere with nitrogen atoms;
$$^{14}\text{N} + ^1_0\text{n} = ^3_1\text{H} + ^{12}_6\text{C}$$
- Man-made, principally from the detonation of thermonuclear devices
- Environmental concentrations of tritium in natural waters are denoted as an isotope ratio in terms of tritium unit (TU)
- One TU has an isotopic ratio of $^3\text{H} / ^1\text{H} = 10^{-18}$
- One litre of water with a concentration of 1 TU produces 7.2 dpm (0.12 Bq)
- Direct age estimation using tritium is difficult due to variable input of tritium, since 1952.
- Tritium concentration in environment are routinely measured (monthly averages) at various gauging stations fixed by IAEA/WMO since 1961.
- Qualitative approach can be used to distinguish between old water (pre bomb) and waters containing at least a contribution of recent precipitation.

Tritium contents in the environment has reached to its normal value i.e., normally the natural level of tritium vary between 5 and 15 T.U. according to the geographical location of the area. The existence of tritium in a water sample is a definite proof of the presence of some components of modern recharge. Therefore, if tritium content is observed 10 T.U., the groundwater may be of recent origin and if we get 5 TU, then the groundwater may be 12.32 years old (uncorrected). One can measure age of groundwater upto 100 years using this technique. In some systems, where the discharge represents a variable composite of current-year recharge and older water of low tritium content, it is possible to calculate the ratio of the two components on the basis of periodic tritium sampling.

Isotopic profiles in the unsaturated zone can help in the evaluation of the infiltrated water, although disturbances introduced in the profiles by exchange with the atmosphere need further investigation. The tritium vertical stratification study can be also extended to the saturated zone, but here disturbances introduced by the horizontal groundwater flow should be taken into account. Injection of artificial tritium or other radioisotopes should also be considered when the detection of environmental tritium peaks is difficult.

Identifying Paleowater

Paleowater is the old groundwater (> thousands of years old that does not has dynamic recharge system at present). Owing to cooler and more humid conditions during the Pleistocene glaciations, reservoirs replenished during pluvial episodes are characterised by low deuterium excess, accompanied by relatively depleted ^{18}O and D contents as compared to modern recharge. This has been found true for North Africa and Middle East arid zones. It has been shown that a D-excess of 10 ‰ (as most frequently observed in modern precipitation) is produced with 70 ‰ (as often observed in old groundwaters in Africa and parts of the Middle East) is produced with about 85% of relative atmospheric humidity. However, caution should be exercised in using stable isotopes in identifying paleowater. Care should also be taken in the discussion of ^{14}C data which has to support the hypothesis on the occurrence of paleowater.

Groundwater Dating with ^{14}C

- Carbon-14 is a radioactive isotope of carbon.
- Its half life is 5730 years.
- Environmental C-14 produced in the upper atmosphere
$$^{14}\text{N} + ^1_0\text{n} = ^1_1\text{H} + ^{14}_6\text{C}$$
- C-14 is oxidized to CO_2 and becomes part of the atmospheric CO_2 reservoir.
- The activity of radiocarbon is measured in PMC (Percent Modern Carbon corresponds to the activity of carbon-14 which is equal to 13.56 dpm/gm and is treated as 100 PMC).
- For practical purposes, the activity of MC is 0.95 of the sp. activity of the carbon of oxalic acid (NBS)
- CO_2 enters into the water cycle by two main processes (neglecting direct dissolution)
 - (i) By pure chemical process of dissolution buffered by solid carbonate
 - (ii) By biochemical production of CO_2 and bicarbonate

The use of ^{14}C as a dating tool of groundwater is based on the following decay equation

$$A = A_0 e^{-\lambda t} \quad \text{and hence}$$
$$t = 8270 \ln A_0/A_t$$

where, A_0 and A_t are the initial and final ^{14}C activities respectively.

In routine ^{14}C dating, initial ^{14}C content is known by analysis of tree rings. However in hydrology the situation is much more complicated, the origin of C in water is less certain than that it is for plant and animal carbon.

By knowing the PMC value (also referred as pMC), one can calculate the age of the water sample. For example, if we get C-14 activity as 100 pMC, the groundwater is of recent origin or has direct contact with natural C-14 reservoir and if we get 50 pMC, the groundwater is 5730 years (uncorrected) old. One can measure age of groundwater upto 40,000 years using C-14 dating technique. However, groundwater age calculation using C-14 dating is neither simple nor very accurate as several corrections are to be done before arriving at any conclusion. Therefore, while dating groundwater using C-14 dating techniques, the factors like chemical (dilution) and isotopic (exchange), dissolved carbon of pure biogenic origin and dissolved carbon of mixed origin should be taken into account. Many different models have been suggested in the literature for predicting the initial ^{14}C activity. The carbon-14 method can be used for dating groundwater in the range 3000 to 40,000 a.

Recharge Zones and Sources of Aquifers and Springs Recharge Zones

Groundwater forms the most important resource of potable water as it is believed to be safe, free from pathogenic bacteria and from suspended matter. However, the deeper aquifers are becoming increasingly important with the increase in urban area and density of urbanisation. The area of groundwater recharge varies inversely with the density of urbanisation in urban areas. Thus the shallow aquifers are either drying -up or being contaminated in densely urbanized areas in the country. This leads to the more dependency on deeper aquifers which have not been given due importance so far from investigation point of view. Our most of the observations and investigations are limited to the shallow aquifers. Thus, the deeper aquifers for which recharge zones are located in remote or areas quite away from the area of utilization, may be suffered adversely by the various anthropological activities, that may either reduce the recharge area or contaminate the recharge source. It has increased the concern on groundwater resource mapping and its management that requires the identification of recharge-zones to deeper aquifers. In fact, the deeper aquifers not only cater the maximum need of fresh water at present but these will also

be the potential source of fresh water in future when the shallow aquifers will either be dried up or contaminated in densely populated areas and metropolitan cities. Once the recharge zones are identified, these can be protected from the anthropogenic activities and the most important recharge source can be given due importance for its better management.

Environmental isotopes like ^3H (tritium-3), ^{14}C (carbon-14), ^2H (deuterium-D), and ^{18}O (oxygen-18) are used to identify the recharge zones and recharge sources to aquifers and springs. Geohydrological details like groundwater level conditions, geological cross sections etc., and water quality data like major and minor ion chemistry, physico-chemical parameters etc., are used as supporting tools. Groundwater samples are collected from different aquifers for the measurement of ^3H , ^4C , ^2H , and ^{18}O . The dating of groundwater using Tritium and Carbon-14 provide information of recharge zones, groundwater flow velocity and flow pattern while the D and O-18 (δD and $\delta^{18}\text{O}$) analysis help in understanding the contribution of different recharge sources and also to pinpoint the most important recharge source.

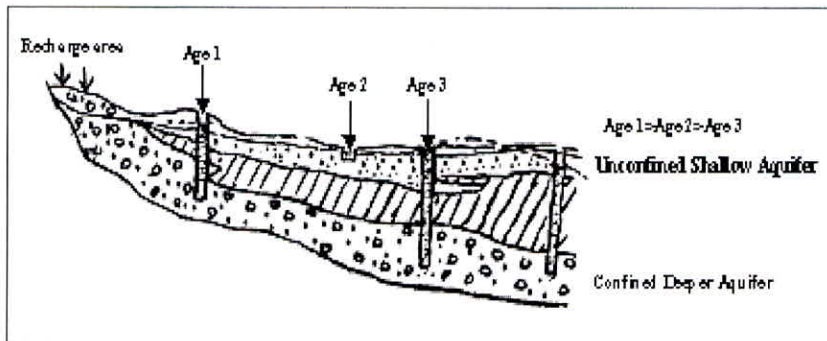


Fig. 6a Representation of recharge and discharge zones in confined aquifers

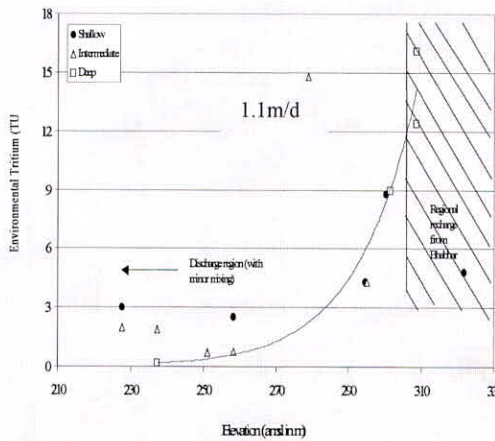


Fig. 6b Variation of environmental tritium concentrations with elevation in Solani-Ganga interfluves

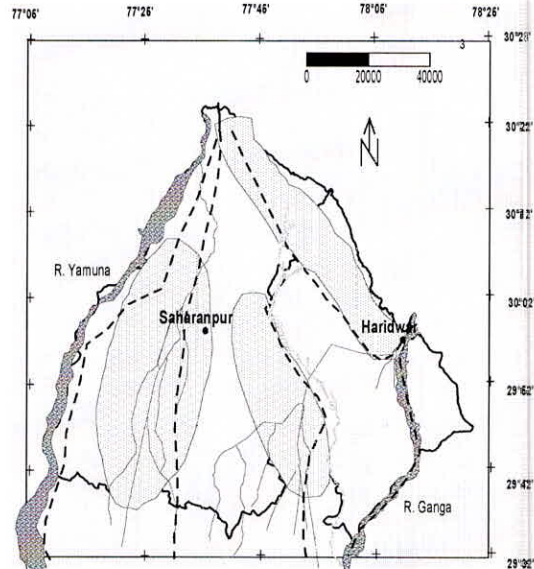


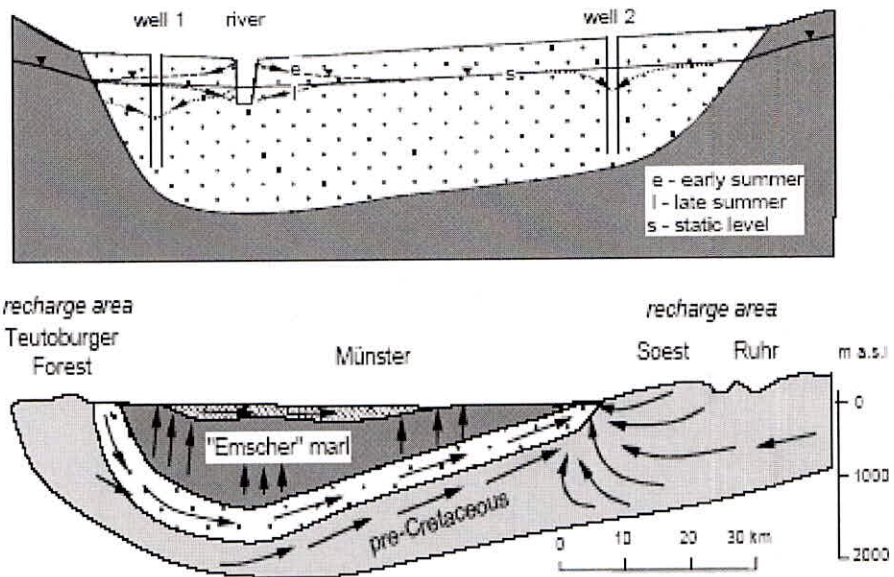
Fig. 6c Map showing different recharge zones identified on the basis of environmental tritium concentrations.

Recharge Sources

Change in oxygen and hydrogen isotopes composition in precipitation with change in altitude (altitude effect) enables to determine the average elevation of recharge zone for a spring

or aquifer. In regions where direct and rapid infiltration of rain occurs, the composition of the groundwater will have isotope ratio as that of the precipitation or slightly enriched due to evaporation effect during the process of infiltration as when evaporation precedes, the heavier isotope gets enriched in water phase. The analyses of stable isotopic composition together with that of dating using radioisotopes gives a reliable 'fingerprint' whereby to identify each group of water of different sources. Water infiltrated at higher altitude and is transmitted over long distances will show depleted $\delta^{18}\text{O}$ and low tritium compared to water infiltrated from local precipitation.

The isotopic index of different possible sources is determined and then using two or three box model [$m_p = (\delta^{18}\text{O}_{\text{gw}} - \delta^{18}\text{O}_p) / (\delta^{18}\text{O}_{\text{ch}} - \delta^{18}\text{O}_p)$], the proportion of different sources are identified. Based on the maximum contribution, the important source to be protected is finalized.



Mixing and movement of waters from different sources

Case Study-I

A study was conducted in the Uttarakhand state along the Bhagirathi River by the National Institute of Hydrology, Roorkee (Uttarakhand) to identify the recharge areas and source of the springs. The groundwater (hand pump), rainwater and springwater samples were collected (Fig. 1) and the spatial distribution of $\delta^{18}\text{O}$ for riverwater, groundwater was plotted from Goumukh to Devprayag.

The local meteoric water line (LMWL) was developed for Bhagirathi river catchment as shown in figure-2 using the monthly weighted average isotopic values of precipitation. The equation for LMWL is given by:

$$\delta D = 8.0 \delta^{18}\text{O} + 11.5$$

The altitude effect in isotopic composition of precipitation was established by plotting the yearly weighted average $\delta^{18}\text{O}$ values of precipitation with respect to altitude (Fig. 3). The altitude effect of $-0.004 \text{‰} / 100\text{m}$ was found in $\delta^{18}\text{O}$ in the study area. The $\delta^{18}\text{O}$ and δD values of spring water were plotted along with the LMWL for the study area (Fig. 4).

Isotopic values of some of the springs fall on the LMWL indicating no evaporation effect. Therefore, altitudes of recharge areas were estimated directly applying the altitude effect as given in Table-1, while the isotopic values for those springs which fall on the evaporation lines (EVP1 & EVP2) were determined by extending the line towards the LMWL. After getting the real values of $\delta^{18}\text{O}$ for such springs, the altitude of recharge area has been determined as given in Table-2.

Table 1. Isotope characterization of shallow aquifers

Area type	Site name & height above mean sea level (m)	$\delta^{18}\text{O}$ (‰)		TU	Interfluvial type	Possible recharge sources
		Local rainfall (*)	Groundwater			
Tarai-Plains Away from rivers and canal network.	Chhutmal-pur (295)	-6.8	-5.8	<i>Intermediate aquifer</i> TU= 17.8)	Solani-Yamuna	100% local precipitation recharge Enrichment due to evaporation.
Plains, Close to Canal	Roorkee (265)	-6.7	-7.6	--		Rainfall - 73% & Canal Seepage 27%
Plain region. Away from rivers and canal system	Gagalhedi (280)	-6.7	-5.3	7.2		100% local precipitation recharge
	Nakud (263)	-6.7	-5.5	11.7		100% Local precipitation recharge.
Plains near river Yamuna	Toda (247)	-6.6	-6.7	--		Rainfall - 96% & Canal seepage 4%
Plains close to River Ganga	Chandpuri Kalan (228)	-6.5	-7.8	3.0	Solani-Ganga	87% from Middle Siwalik (~700m) & 13% from local precipitation

Table 2. Isotope characterization of deeper aquifers in Solani-Yamuna Interfluvial

Region	Site name and height above msl (m)	$\delta^{18}\text{O}$		TU	Recharge source
		Local rainfall (*)	Ground-water		
Siwalik foot hills	Nagal Kothari (417)	-7.1	-9.0	11.1	100% precipitation recharge at Upper Siwalik (~1000m msl).
	Timli (550)	-7.7	-8.0	10.4	100% recharge from Middle/Upper Siwalik (~700m)
Tarai-Plain interfringe	Chhutmalpur (295)	-6.8	-7.3	1.8	100% recharge at Lower Siwalik (~450m)
Plains near Upper Ganga Canal	Roorkee (265),	-6.7	-8.8	5.0	14% recharge from shallow aquifer ($\delta^{18}\text{O} = -7.6$) + 86% from Upper Siwalik (~1000m)
	Purkazi (232)	-6.5	-7.1	10.7	83% local precipitation ($\delta^{18}\text{O} = -6.5$) + 17% canal ($\delta^{18}\text{O} = -10$)
Plains, near the river Yamuna	Nakud (263)	-6.7	-7.3	ND	100% precipitation recharge from Lower Siwalik (450m).

(*) - Isotope index in precipitation is estimated by considering an altitude effect of 0.31‰ decrease per increase in altitude of 100 meters in $\delta^{18}\text{O}$.

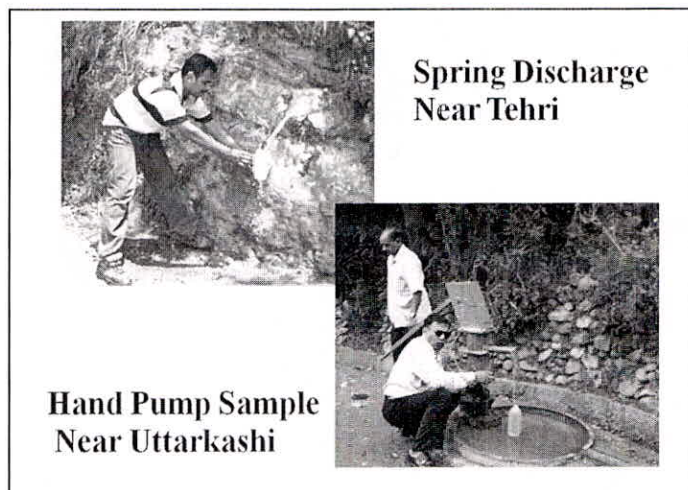


Fig. 1. Collection of water samples from a spring and a handpump

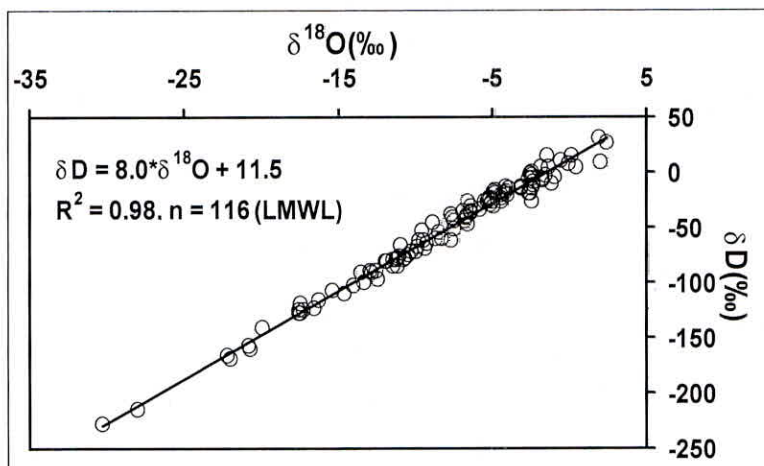


Fig. 2. Local meteoric water line (LMWL) for Bhagirathi river basin

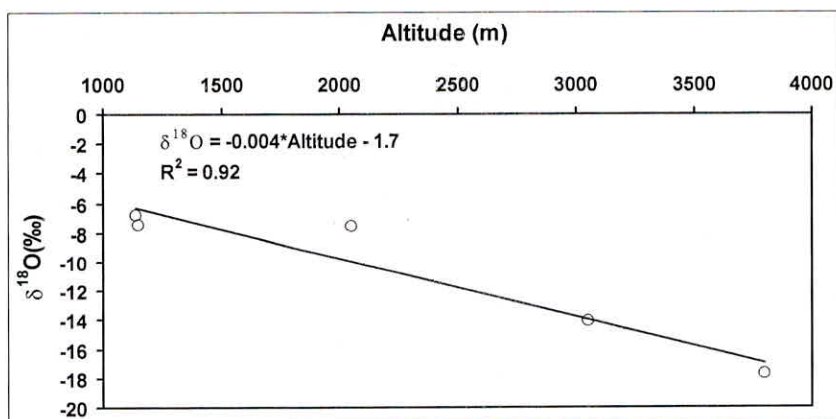


Fig. 3. Altitude effect on isotopic composition ($\delta^{18}\text{O}$) of precipitation in Bhagirathi river basin

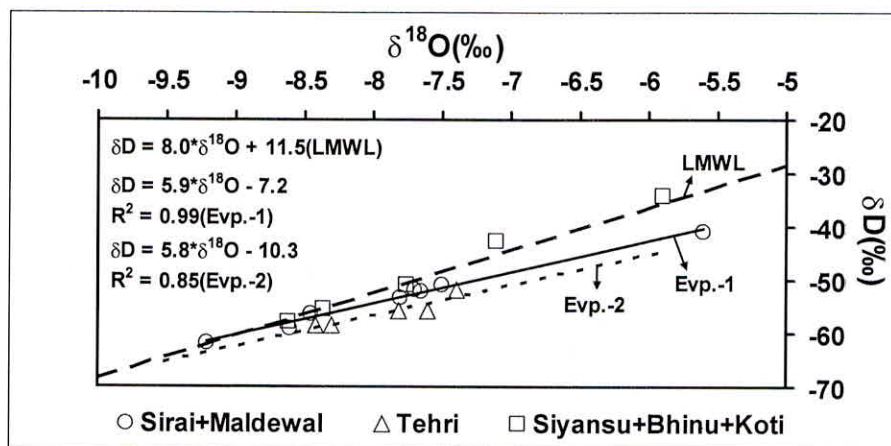


Fig. 4 Plot of isotopic values of different springs along with LMWL

Table 1. Altitude of recharge zones of springs whose isotopic values fall on LMWL

Spring name (altitude in m)	Spring $\delta^{18}O$ (‰)	Precipitation $\delta^{18}O$ (‰)	Difference $\Delta \delta^{18}O$	Projected altitude of recharge area above the location of spring (m)	Altitude of recharge area (m)
Siyansu (752)	-7.76	-4.76	-3.0	748	1500
Bhinu (1256)	-7.1	-6.78	-0.32	244	1500
Koti (1450)	-8.6	-7.55	-1.05	260	1710

The environmental tritium contents in groundwater ranges from 7.5 to 13 TU in the study area, which are almost similar to tritium contents, observed in precipitation. It reveals that the groundwater is of recent age. Because of this, most of the springs and hand pumps do not sustain the whole year (Table 3).

Table 2. Altitude of recharge zones of springs whose isotopic values fall on Evaporation Lines (EVP1 & EVP2)

Spring name (altitude in m)	Spring $\delta^{18}O$ (‰)	Precipitation $\delta^{18}O$ (‰)	Difference $\Delta \delta^{18}O$	Projected altitude of recharge area above spring location (m)	Altitude of recharge area (m)
Tehri (640)	-9.3	-4.3	-5.0	1245	1885
Sirai (658)	-9.2	-4.4	-4.8	1202	1860
Maldewal (755)	-8.45	-4.8	-3.65	917	1672

Table 3. Environmental tritium contents in groundwater, river and rainfall in the study area

Groundwater	Uttarkashi	Syanshu	Devprayag	Rishikesh	Range
3H (TU)	13	10.7	12.4	7.5	7.5-13.0
River	Gangotri	Uttarkashi	Devprayag		
3H (TU)	14	12	11		11-14
Rainfall	Uttarkashi	Devprayag			
3H (TU)	13	12			12-13

Case Study-II

In another study conducted jointly by Isotope Applications Division, Bhabha Atomic Research Centre, Mumbai and Himalayan Environmental Studies and Conservation Organization, Dehradun on the identification of recharge areas at Gauchar area of Chamoli (Shivanna et al., 2008).

Stable isotope data of precipitation collected from three different heights of the valleys, viz. 1180, 990 and 800 m amsl, during September 2004 show that $\delta^{18}\text{O}$ varied from -10.0 to -8.2‰ and δD varied from -69.2 to -56.3‰ . The isotopic composition of spring water varied from -7.7 to -7.0‰ for $\delta^{18}\text{O}$ and from -57.9 to -50.3‰ for δD . It is observed that most of the isotopic values of the precipitation samples do not fall on the GMWL. The best-fit line for the precipitation samples was plotted to construct the LMWL.

The equation for LMWL is given by:

$$\delta\text{D} = 6.8 \times \delta^{18}\text{O} + 0.3 \quad (r^2 = 0.98, n = 6)$$

Compared to GMWL, LMWL has lower slope and intercept showing evaporation effect. This is because during precipitation, the raindrops might have undergone evaporation. The samples from high-altitude springs fall on the LMWL, indicating recharge by precipitation prior to evaporation. The equation of the evaporation line (EL) is given by:

$$\delta\text{D} = 5.2 \times \delta^{18}\text{O} - 17.6 \quad (r^2 = 0.93, n = 4)$$

For estimating the altitude effect, the stable isotopic compositions of the precipitation samples were plotted against their corresponding altitudes. The altitude effect was calculated as the inverse of the slope of the best-fit line. It was found to be -0.55‰ for $\delta^{18}\text{O}$ and -3.8‰ for δD per 100 m rise in altitude. Generally, the discharge rates of springs ranged from 0.7 to 120 l/min during the monsoon season, which reduced to 0.2–99 l/min within a month after the monsoon. The discharge measurements indicated that all the springs responded instantaneously to the precipitation events.

During summer, most of the high-altitude springs dry up, whereas low-altitude springs continue to discharge with low rates. This shows that low-altitude spring discharges were a mixture of groundwater and precipitation, whereas only precipitation contributed to the high-altitude springs. This is further corroborated by hydrochemical data. The tritium content of the low-altitude springs was about 9.5 TU, whereas it was about 11.5 TU for high-altitude springs. This slight variation in tritium content can be attributed to relatively longer residence time of groundwater in low-altitude springs compared to that of high altitude springs. The enrichment in isotopic composition of high-altitude springs compared to that of precipitation during September 2004 was due to the contribution from initial rains during July 2004. Hence recharge altitude for these springs could not be estimated. Since the values of the low-altitude springs fall on an EL, their isotopic composition before evaporation was calculated by extrapolating the EL to intersect the LMWL. The corrected isotopic composition of these springs was -10.7 and -73‰ for $\delta^{18}\text{O}$ and δD , respectively. Using this corrected isotopic composition, the recharge area of the low-altitude springs was determined and it was found to be 1250 m amsl.

The topography and geology of the area suggests that the presence of thin, weathered, top soil cover underlain by hard and compact quartzite, phyllite and granite with a steep gradient does not allow the rainwater to percolate down, and hence the spring waters were mostly derived from seepage waters. Based on geology, geomorphology, hydrochemistry and isotope information of the study area, the possible recharge zones to the springs in valleys 1, 2 and 3

were located at altitudes of 1270, 1330 and 1020 m amsl respectively. At these identified altitudes, water-conservation and artificial recharge structures like subsurface dykes (5 nos) in valley-1, check bunds (2 nos) in valley-2 and a few trenches in valley-3 were constructed for rainwater harvesting (Figure 5a). Monthly spring discharge measurements were carried out during December 2004–April 2005 before the construction of the structures and also during the same period in the following year, after the construction. The cumulative discharge rate of ten springs was found to be increased from 375 to 708 l/min during the post-monsoon period. It was found that the discharge rates had not only increased considerably, but also were sustainable even during the dry period. In addition to the existing springs, two new springs also appeared close to the subsurface dykes (Figure 5b). The cumulative discharge rate of these new springs was about 67 l/min. The significant increase in the spring discharge rates, their longer duration and formation of new springs can be attributed to proper identification of recharge areas and implementation of artificial recharge structures.

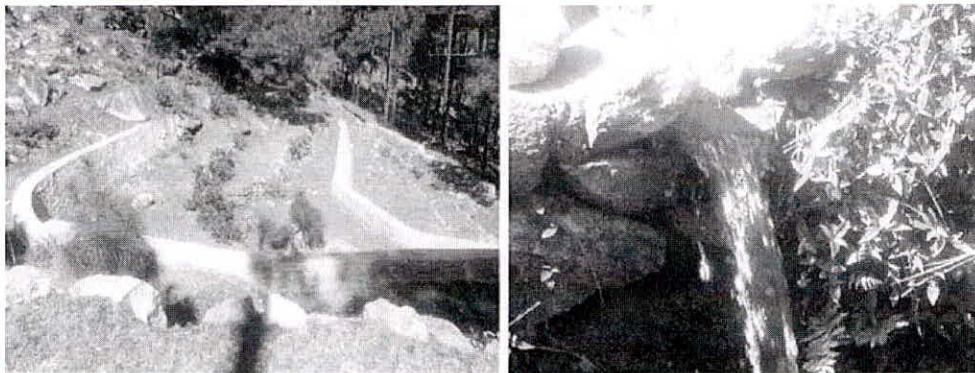


Fig . 5a, Subsurface dykes; b, New spring that appeared subsequently

Effectiveness of Artificial Recharge Measures

Depletion of groundwater table at a faster rate in most of the urbanized area and in semiarid/arid regions has drawn the attention of water resources managers. This situation has also arisen in areas where surface water bodies such as rivers, canals and natural or artificial lakes/ reservoirs do not exist. In order to mitigate the increasing shortage of groundwater, artificial recharge of groundwater by making earthen bunds, through injection wells or roof top rainwater harvesting programs have been given priority by the concerned organizations and individuals. However, the effectiveness of these programs has not been assessed at the desired scale as it is difficult using conventional techniques. Isotope techniques have the potential to assess the effectiveness of these programs using environmental isotopes.

The effectiveness of artificial recharge measures can be studied with the use of environmental isotopes (either δD or $\delta^{18}O$ and 3H , if required) provided the artificially recharged water has different isotopic composition than the natural recharge. However, if the same water is used for artificial recharge through prolonged infiltration by constructing earthen bunds, the isotopic composition of ponded water is changed due to evaporative enrichment. The isotopic indices (δD or $\delta^{18}O$) of precipitation, groundwater (without artificial recharge component), surface water being used for artificial recharge are determined and then the isotopic composition of the groundwater (from the study area) are determined at different time intervals (minimum monthly frequency). The use of two component model can reveal the percentage of mixing of artificially recharged water at different time. If the groundwater samples are collected from different locations around the site/s of artificial recharge, then the effect and extent of recharge (%) can be determined in different directions. 3H values of groundwater can confirm the recent recharge due to artificial measures.

An example of Ozar Watershed study in District Nasik, Maharashtra

The results of $\delta^{18}\text{O}$ analysis for groundwater, precipitation and canal water samples are given in Table-1. The distribution of $\delta^{18}\text{O}$ in groundwater and the groundwater flow pattern in the Ozar watershed is shown in the Figure 2a. The groundwater samples collected for environmental tritium analysis were carried out by liquid scintillation counting and were found in the range of 14-16 TU. These values are comparable to the Hatnur Canal (~12.6 TU), the water of which is used for artificial recharge through earthen channels, and much different from the rainfall in the area which show a typical value within the range of 5 to 6 TU. The Hantur Canal originates from the Tapi River which drained a large area. Therefore, it can have different T.U. values (high and low) depending upon the sources of water and time period.

We have observed high T.U. values in canal water. The groundwater, being mostly recharged through the canal water, also has T.U. values comparable to canal water. However, the T.U. values of canal water might be higher during certain other period during which samples could not be collected, but the higher values of groundwater reflect it. The T.U. in rainwater could not be observed more than 5T.U. in Ozar watershed. Therefore, it is inferred that the groundwater is dominated by recharge from canal water through earthen channels and rainfall recharge component is comparatively very less. Moreover, the data reflect that the groundwater is young with negligible aquifer storage.

It is seen from Table 1 that the most depleted and enriched $\delta^{18}\text{O}$ values of the groundwater in Ozar watershed are -2.2% and 0.0% respectively. If we compare the monthly average values of $\delta^{18}\text{O}$ (neglecting spatial variations) of groundwater with the surface impoundment i.e., the earthen channels that carry canal water, it is seen that in the month of June, the groundwater is more depleted than the surface water (Fig. 2(b)). This indicates the effect of evaporation on surface water that results in the enrichment of isotopic composition. In the month of July, the isotopic values of both systems get closer probably due to mixing of water from earthen channels that infiltrated during the month of June as enrichment in isotopic composition of groundwater is clearly seen (Fig. 2(b)).

The evaporation effect further enriched isotopic contents of small quantity of water stored in channels due to no supply from canal in the month of August, while the groundwater also show a little enriching trend due to delayed contribution from precipitation and channel water.

In the month of September, the input from canal is provided to the earthen channels therefore, the isotopic contents of channel water comparatively deplete and so in the Ozar watershed. However, the $\delta^{18}\text{O}$ of groundwater in the month of October is found identical to that of the earthen channel in the Ozar Watershed. This fact clearly indicates that major recharge to the groundwater is from the impoundments across the channels locally called as Bandharas. The contribution from rainfall or canal (channel) to groundwater is determined using the following relation based on $\delta^{18}\text{O}$ values of end members.

$$m_{\text{ch}} = (\delta^{18}\text{O}_{\text{gw}} - \delta^{18}\text{O}_{\text{p}}) / (\delta^{18}\text{O}_{\text{ch}} - \delta^{18}\text{O}_{\text{p}}) \quad \text{or} \quad m_{\text{p}} = (\delta^{18}\text{O}_{\text{gw}} - \delta^{18}\text{O}_{\text{ch}}) / (\delta^{18}\text{O}_{\text{p}} - \delta^{18}\text{O}_{\text{ch}})$$

where, m_{p} and m_{ch} are the contributions of precipitation and channel water to groundwater respectively while $\delta^{18}\text{O}_{\text{gw}}$, $\delta^{18}\text{O}_{\text{p}}$, and $\delta^{18}\text{O}_{\text{ch}}$ are the corresponding oxygen-18 values of groundwater, precipitation and channel water (Table 2)

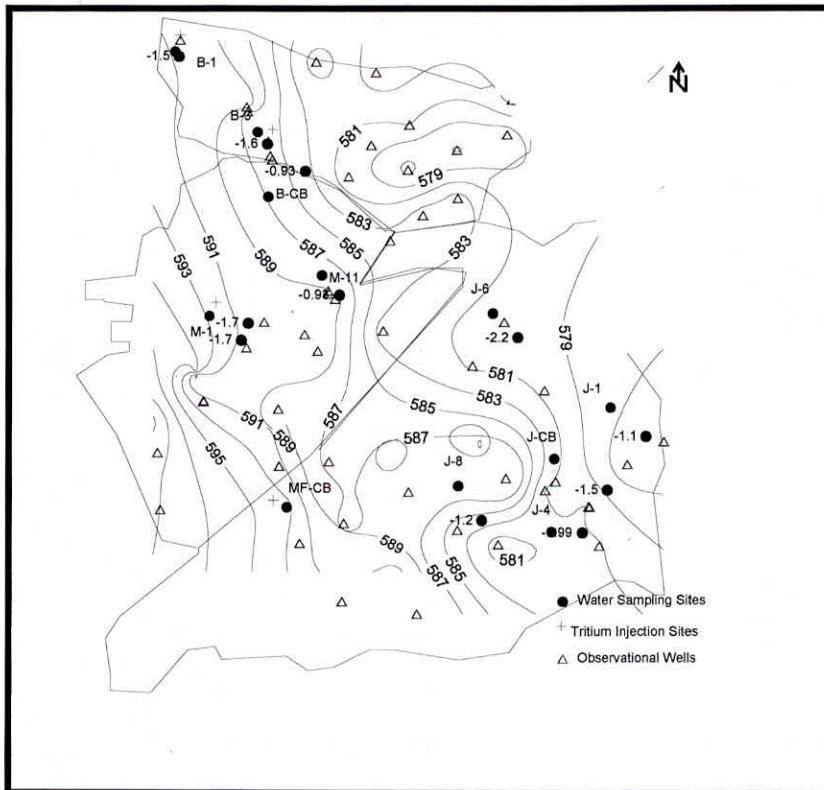


Fig. 2(a) Groundwater level contours in the post monsoon season of 1997, stable isotope ($\delta^{18}\text{O}$) composition (‰) of groundwater in the Ozar watershed, Nashik

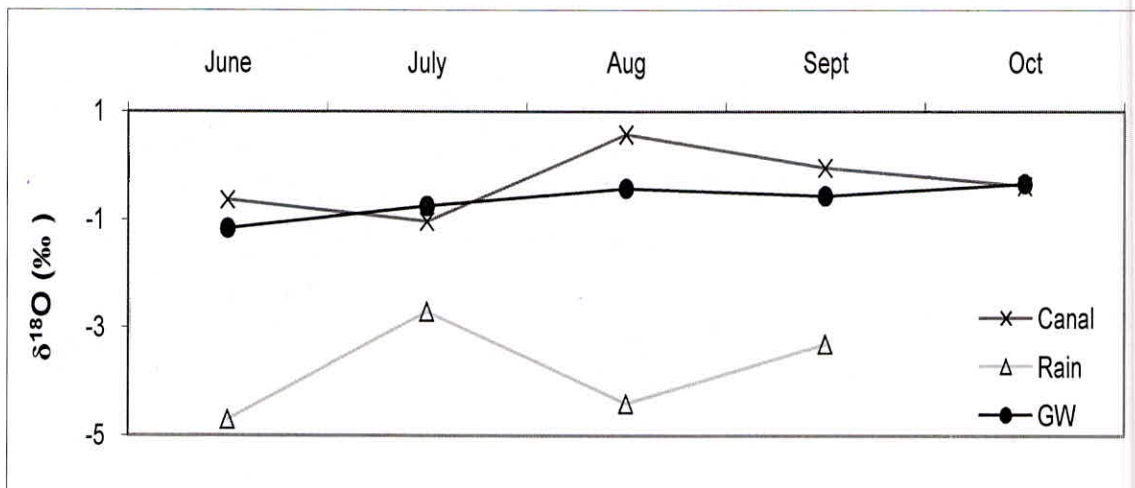


Fig. 2(b) Variation of $\delta^{18}\text{O}$ of channel water, groundwater and precipitation with time in Ozar watershed, Nashik

Table 1: Results of $\delta^{18}\text{O}$ for groundwater, precipitation and canal water samples collected from Ozar watershed

S. No.	Society	Well No.	$\delta^{18}\text{O} \text{‰}$				
			Jun-2000	Jul-2000	Aug-2000	Sep-2000	Oct-2000
1	Mahatma Phule	M-1	-1.7	-0.8	-1.3	-0.5	0.1
2	Mahatma Phule	M-11	-0.9	0.0	-0.9	-0.4	-0.5
3	Banganga	B-1	-1.5	-0.5	0.3	-1.1	1.8
4	Banganga	B-3	-1.6	-0.8	0.0	-0.4	-0.2
5	Jay Yogeshwar	J-1	-1.1		-1.1	-1.3	-1.3
6	Jay Yogeshwar	J-4	-1.0	-0.7	-1.2	-1.2	-0.6
7	Jay Yogeshwar	J-6	-2.2	-0.3	-1.2		-1.6
8	Jay Yogeshwar	J-8	-1.2	-1.3	-0.4	-1.2	-1.1
	Average of well samples		-1.4	-0.6	-0.7	-0.9	-0.4
9	Rain		-4.7	-2.7	-4.4	-3.3	-
10	Earthen Channel	Near M1	-0.4	-0.7	0.5	0.3	0.6
11	Earthen Channel	Near B3	-0.3	-1.4	0.6	-0.4	-0.9
12	Earthen Channel	Near J-1	-1.2	-1.0	0.65	0.0	-0.8
	Average of channel samples		-0.6	-1.0	0.6	0.0	-0.4

Table 2: Recharge percentage due to canal water supplied through channels and rainfall in different months

Recharge in (%) due to	June	August	September	October
Canal or Channel (M_{ch})	80	74	73	100
Rainfall (M_p)	20	26	27	0

Figure 2(c) clearly indicates the percent contribution of rainfall to groundwater in Ozar watershed. The percent of artificial recharge to groundwater through earthen channels can be estimated by subtracting percent of rainfall recharge from 100 as shown in Fig. 2(c). A straight line relation between the amount of rainfall and $\delta^{18}\text{O}_p$ values also enables to determine the percent contribution of rainfall to groundwater.

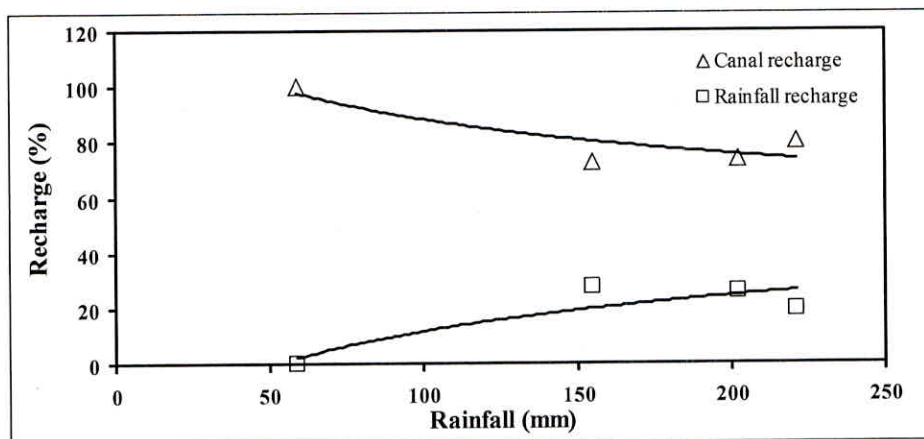


Fig. 2(c) Percent recharge to groundwater due to rainfall and canal water in Ozar watershed

SURFACE WATER AND GROUNDWATER INTERACTION

The river and groundwater interaction may be studied by groundwater modeling, channel water balance, isotope mass balance method and/or by statistical method using the river and groundwater water level fluctuation data. The statistical method based on Darcy's law involves analyses of the river water levels and groundwater levels adjacent to the river. Here, we will discuss only isotope mass balance method.

Principle

The approach is based on the fact that if the rivers originates at higher altitudes and has a different stable isotopic composition than that of groundwater that is recharged by infiltration of local precipitation then stable isotopes can be used to understand river and groundwater interaction. In most of the cases, the stable isotope ^{18}O is utilized for determining the contribution of groundwater to the river flow. If R_g and R_r are the isotopic composition of the groundwater and the river, respectively and m_g and m_r are the fractions of ground water and river, respectively in the admixture, while R_{am} is the isotopic composition of the admixture, then the isotopic balance and mass balance equations can be written as

$$m_g R_g + m_r R_r = R_{am} \quad \text{and} \quad m_g + m_r = 1$$

From the above two equations, we have

$$m_r = (R_{am} - R_g) / (R_r - R_g)$$

Therefore, by knowing the value of R_g , R_r , and R_{am} , the fraction of river water mixed with ground water can be evaluated. In addition, environmental tritium can be used to understand the contribution of the Yamuna River to the groundwater in the study area as the mixing of river water reduces the groundwater ages.

Case Study of the Yamuna River

The present study is being carried out using isotope mass balance method. Isotopic tracers provide a mean for identifying the actual mass transport of water in the hydrologic cycle. The approach is based on the fact that the river Yamuna originates at higher and normally has a different stable isotopic composition than that of groundwater being recharged by infiltration of local precipitation. In case of a mountainous river, the river transports water, which has generally been originated from precipitation falling at higher elevations than the area where the surface-groundwater relation is under investigation. The difference in isotopic composition of these waters is due to altitude effect. The isotopic composition for ^{18}O in precipitation changes between -0.2 and -0.3 ‰ per 100 m with altitude. Thus, the stable isotopic composition of the river water is more depleted than that of groundwater derived from infiltration of local precipitation. This distinct difference helps in identifying the contribution of one to the other.

The studies carried out by NIH, Roorkee and few others have revealed that the river Yamuna has stable isotopic signatures ($\delta^{18}\text{O}$) in the range of -8 ‰ to -9 ‰ while the groundwater in Delhi region varies between -6 ‰ to -7 ‰ where recharge due to precipitation dominates. Therefore, stable isotopes of hydrogen and oxygen have been used to determine the contribution of groundwater to river or vice versa at the selected locations in the study area.

In case of river Yamuna contributing to the groundwater regime, there are two possible sources of recharge to groundwater, viz. infiltration of local precipitation and infiltration of river water. In such conditions, the accuracy of the estimate of the proportion of infiltrated river water

depends upon the accuracy of the estimates of stable isotopic indices of these two potential sources of recharge and the difference between these indices. An estimate of the river index has been made on the basis of samples from the river during the monsoon season, as this is the time when majority of the recharge in the river banks take place.

The estimation of the index for recharge due to infiltration by local precipitation may be based on measurements of groundwater away from the influence of the river or, if sufficient data are available, on the peak value of the skewed frequency distribution. If the errors in estimates of the indices of the two potential sources of recharge are not greater than the analytical error, then the accuracy in the estimate of the proportion is better than 10%. In practice, the limitations of the method are not in the method itself, but in the availability of meaningful samples.

Establishment of sampling Stations

In the first phase, existing shallow groundwater abstraction points such as hand-pumps and shallow tubewells were identified along the riverbed along one section on both the sides of the river. As the sufficient observation wells were not available and also measurement of water levels was not possible, ten piezometers were installed along one section during April 2007 to June 2007. Five of the piezometers were installed on the Delhi side and other five on the UP side to monitor the effect of pumping on groundwater conditions (Fig. 1).

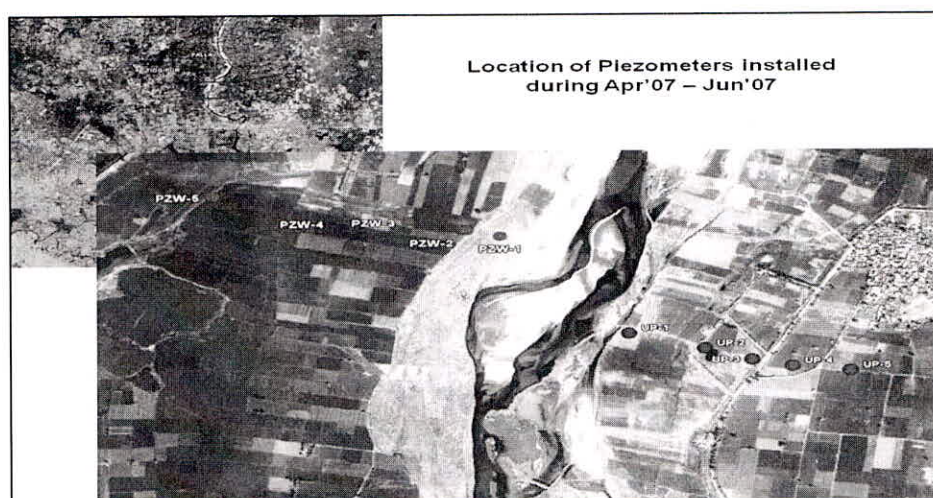


Fig. 1 Location of piezometers installed on both the sides of the river to study the effect of pumping

Water Sampling and Water Level Monitoring

Oxygen and hydrogen isotopes are invaluable to hydrological studies as these are part of the water molecule itself. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values may be used to assess evaporation during recharge, stream – aquifer interconnectivity, and mixing between different bodies of water within the basin. Similarity of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values between stream and aquifer may indicate interconnectivity, whereas isolated aquifers may contain waters with different $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values. Stable isotope systematics of waters around surface water bodies may be used to trace movement of seepage into / from nearby groundwater systems. Groundwater samples are being collected at an interval of 7 days (every Sunday) from piezometers on Delhi side and at an interval of 14 days (every alternate Sunday) from piezometers on UP side. While collecting the samples water levels are also monitored in the piezometers (Fig. 2).

A few more water samples are being collected on both the sides. Also samples from one ranney well and one tube well are also collected to check the component of river water in the water being pumped from the area. Most of the piezometers show declining water levels from November onwards, except piezometer PZ-5, which shows some erratic behaviour. In Aug 2008 all the piezometers were submerged due to heavy flood in the Yamuna River.

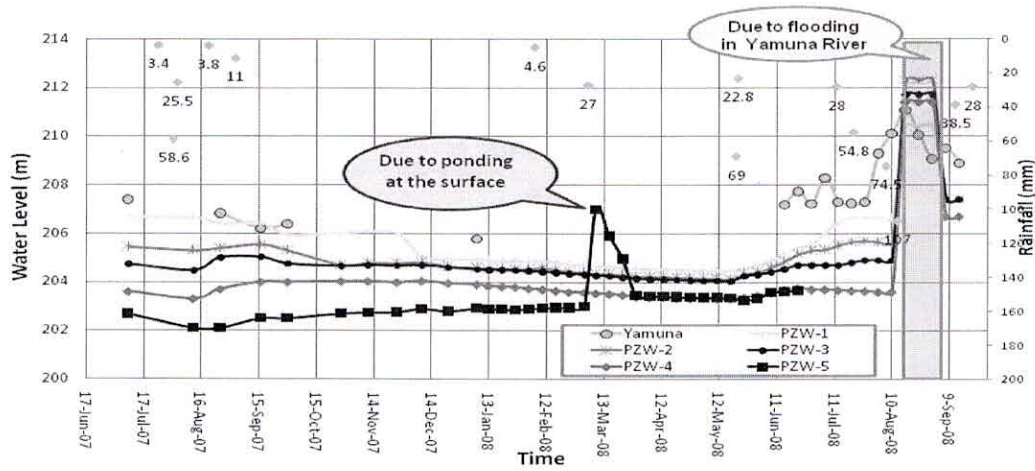


Fig. 2 Variation of water levels on the Delhi side

Groundwater Table in the Palla Area of Yamuna Floodplain (Jul'07 - Sep'08)

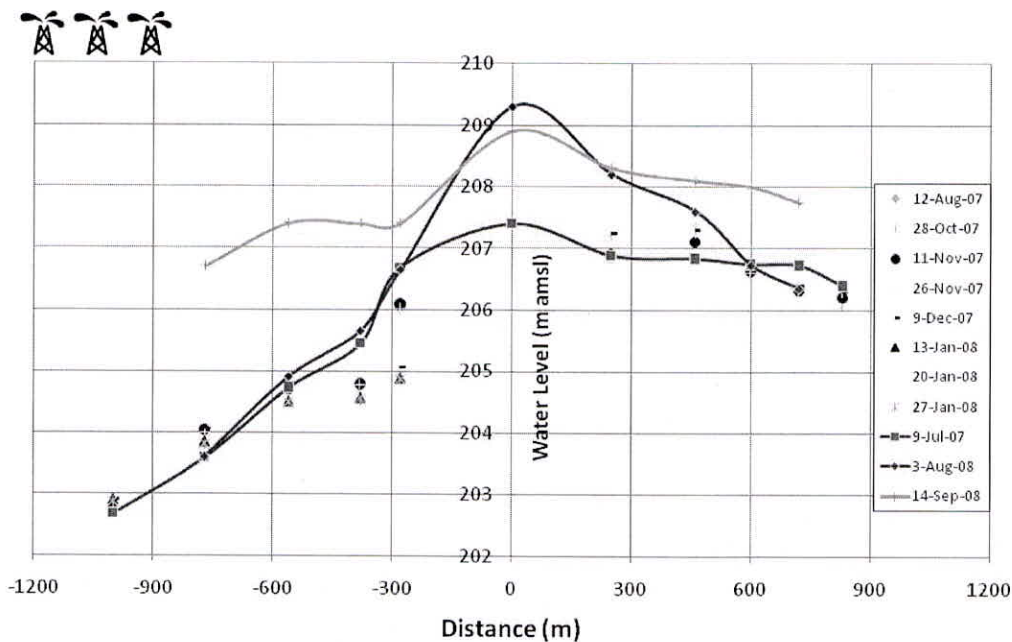


Fig. 3 Position of water table on both sides of the River Yamuna

It has been observed that the decline in water table is more on the Delhi side than on the UP side (Fig. 3).

Isotopic variations in groundwater

As mentioned earlier, samples for isotopic analysis were collected from the piezometers and existing hand pumps and shallow tube wells in the area. The samples were analysed for ^{18}O and D at Stable Isotope Laboratory of National Institute of Hydrology, Roorkee.

The variation in $\delta^{18}\text{O}$ with time at various piezometers, groundwater and Yamuna River water are shown in Fig. 4. It can be seen from the figure that the composition of groundwater remains almost stable in the range of 6.8 to 7.1‰, whereas, water from other sources show large variation.

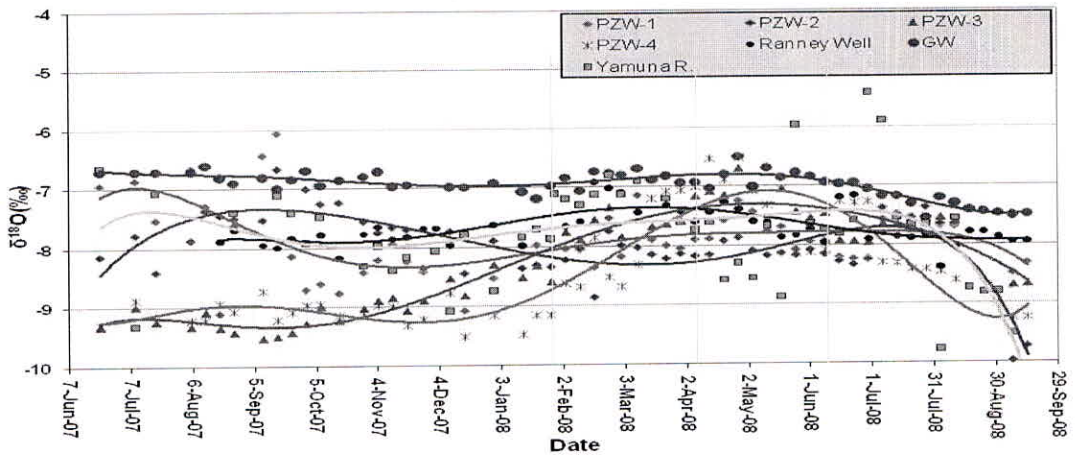


Fig. 4 Variation of $\delta^{18}\text{O}$ with time in waters of Palla area

Closer look at the data reveals that PZW-1, the piezometer installed closest to the river shows signatures of the river water but more stable than the river (Fig. 5). Further, the dip in $\delta^{18}\text{O}$ value on 9th July can be seen to move in the groundwater from river towards riverbank (line of pumping), with a velocity of about 2m/day in the river channel and 1m/day in the floodplain (Fig. 6). Rain water were also collected for analysis of isotopic composition and $\delta^{18}\text{O}$ in the rain varies from -0.41‰ to -7.41‰ .

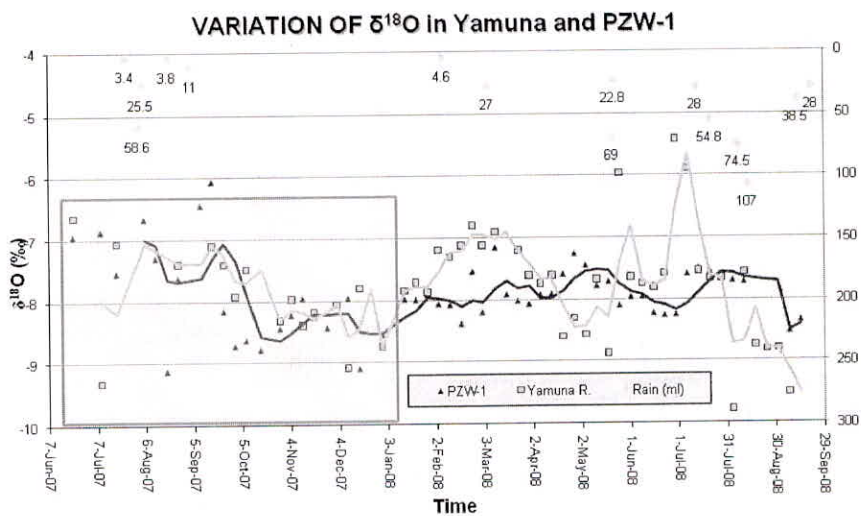


Fig. 5 Isotopic variation in PZW-1 and River Yamuna

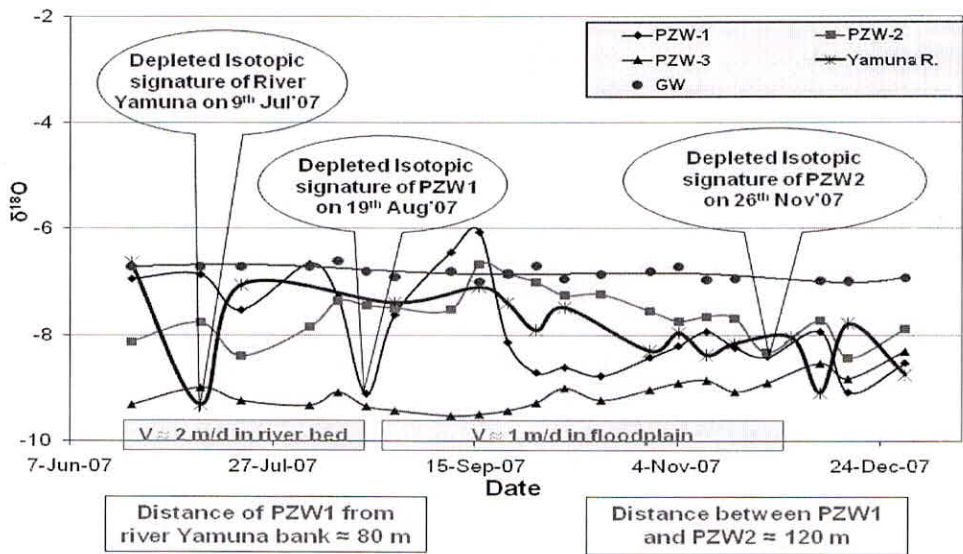


Fig. 6 Movement of depleted peak of $\delta^{18}\text{O}$ from PZW-1 to PZW-2

Based on the $\delta^{18}\text{O}$ variation in groundwater, the river water and the ranney well, the component of river water in the pumped water has been computed. The percentage of water from the floodplain in various months is given in table below.

Table ($\delta^{18}\text{O}$ value of the Yamuna River = -9.5‰)
Component of Surface Water in Pumped water in Palla Area

Month	$\delta^{18}\text{O}$ in Ranney Well Water (‰)	$\delta^{18}\text{O}$ in Ground water (‰)	Flood Plain water in pumped water (%)
Aug-07	-7.9	-6.8	41
Oct-07	-7.9	-6.9	43
Dec-07	-7.8	-7.1	33
Feb-08	-7.1	-6.9	9
Apr-08	-7.4	-6.8	24
Jun-08	-7.6	-6.9	30
Aug-08	-8.0	-7.4	32

If the total water pumped by the Ranney wells and the tube wells is considered as 30 mgd, then the component of water from floodplain varies between 12.9 mgd (in Oct'07) to 2.7 mgd (in Feb'08), which is equivalent to $0.565 \text{ m}^3/\text{sec}$ and $0.118 \text{ m}^3/\text{sec}$ respectively.

GROUNDWATER POLLUTION (SALINIZATION)

The build-up of salinity in groundwater and soil represents a major wastage of natural resources in arid and semi arid zones. The salinity of groundwater may occur due to several processes, but, two of them are of major importance, i.e., i) salts leached by percolating water. These salts may be evaporative - deposits, aeolian transported salts (usually of marine origin) or products of weathering of surface rocks and soils. ii) Saline surface water, sea-water, brines and connate water.

Conventionally, ionic ratios such as Na^+/Cl^- , $\text{Ca}^{+2}/\text{Mg}^{+2}$, $\text{SO}_4^{-2}/\text{Cl}^-$ etc. are used to study the source of salinity. However, after transport of the salts by percolating water to the water table and after primary mixing with saline waters, the chemistry of the water may undergo further secondary changes which may make it difficult to identify precisely the mechanism of salinization. The problem of identifying the mechanism of salinization becomes more acute in irrigated areas in arid zones. Leaching is usually local and the soluble salts may not be transported very far. This is partly due to the low rainfall and also the high evaporation rates which are characteristic of arid zones, tend to concentrate salts in the groundwater. Furthermore, surface drainage systems may be poorly developed, having no outlet to permanent stream.

The use of environmental isotopes, D and ^{18}O , allow distinction of leaching from evaporation. Since leaching causes no isotopic change, whereas evaporation leads to isotopic enrichment. Further, the S-34 ($\delta^{34}\text{S}/\delta^{32}\text{S}$) isotope provides very clear picture about the salinity of marine origin. The isotopic approach is particularly useful in coastal areas where all salinity ultimately originates from marine environment so that little chemical distinction exists between salinity originating for example, from sea spray or from direct sea water encroachment from surface lagoons or connate sea water. The stable isotopes in the study of salinization mechanism have been extensively used by various workers abroad but it has been tried very less in India.

CASE STUDIES OF THE ARID REGIONS OF WESTERN RAJASTHAN, INDIA

The Thar desert in Rajasthan extends from the western side of the Aravalli mountain ranges upto the limit of the Indus valley in Pakistan.(Fig.1) It covers 60% of area of the Rajasthan state. Having ~ 38% of the state's population with a density of 84 persons/ km^2 , this is one of the most populated desert regions of the world. The constantly increasing human and livestock population is putting tremendous pressure on the available natural resources.

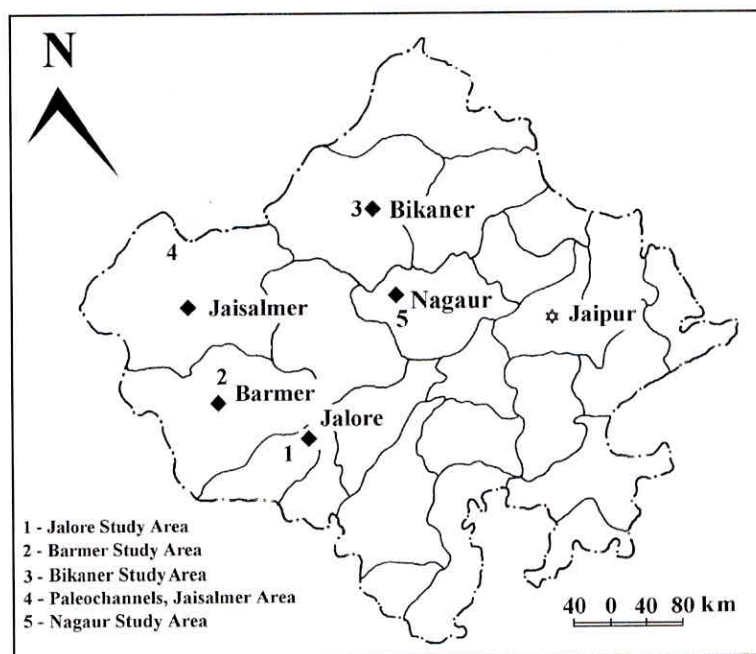


Fig. 1 Map of Rajasthan

The land is characterized by sand dunes with inter dunal plains in the north, west and south and alluvium in the central and eastern parts. Streams are very few, ephemeral in nature and confined mostly to the rocky parts of the desert, the prominent being the Luni river in the south west region. Precipitation is low (100 to 200mm) and erratic with frequent droughts.

The main source of water in the area is groundwater. The region faces acute shortage of potable water and village women have to fetch water from many kilometers away to meet domestic requirements. At many places the groundwater is brackish or saline. Efforts are being made by the state groundwater department to study known groundwater resources and explore potential ones in the region.

In groundwater management particularly in arid regions like western Rajasthan it is important to know the presence of modern recharge and to estimate the recharge rate to avoid over exploitation of the groundwater resource. In such areas the problem is to know whether a given groundwater body is being actively recharged, i.e. whether it is a renewable resource? This could be studied using environmental isotopes, for example, if a particular groundwater body contains tritium significantly above 5 TU, then it has been recharged in the post thermonuclear era (i.e after 1952). Tritium can hence be used to detect recharge, which occurred during the last 4 decades. However, due to scarcity of rain in these areas, high potential evaporation and low infiltration of water through the unsaturated zone, the shallow groundwater may not receive any modern recharge and this is usually indicated by low tritium content. Environmental carbon-14 could be used to date very old waters i.e paleowaters upto an age of ~ 40, 000 years. A number of hydrological studies have been carried out mostly in the Sahara using isotope techniques and it has been observed that the deep groundwater is generally very old. The carbon-14 content indicates an age greater than 20,000 years before present (BP). Such a great age was also supported by a relative depletion in the deuterium and oxygen-18 of these groundwater. From these studies it was concluded that that episodic large scale recharge corresponding to humid phases or pluvials occurred in these areas. The article reviews our experiences on the application of isotope techniques in understanding groundwater recharge process and effect of overexploitation of groundwater in arid western Rajasthan.

1. Groundwater recharge process

The possible groundwater recharge process in arid areas like Rajasthan may be

- a) Direct recharge of precipitation through the unsaturated zone
- b) Indirect recharge through river channels from flash floods or from irrigation canals etc.
- c) Paleoclimatic recharge during humid episodes in the past.

a) Direct recharge of precipitation to the groundwater was studied in Jodhpur and Barmer districts of western Rajasthan using artificial tritium tracer as HTO in the unsaturated zone. The results showed the tracer displacement and hence the groundwater recharge was found to be negligible due to low rainfall (~200mm) during the study periods of 1982 –84 and 1990 –92 respectively. Hence for arid areas the artificial tracer method which determines on an annual basis for short duration may not be useful and may be combined with other methods such as environmental ^3H , ^{36}Cl and chloride methods. In these methods results are derived from long term average of recharge. In a study carried out under an IAEA- coordinated research programme on 'Isotope based assessment of groundwater renewal and related anthropogenic effects in water scarce areas' [8], the isotopic content and chemistry of water infiltrating through unsaturated zone to the groundwater body has been used to estimate groundwater recharge. Soil cores were collected up to a depth of 12m in 3 sites in Barmer district of Rajasthan, using a hand drilling unit and soil water extracted for deuterium, oxygen-18, tritium and chemical analysis. Mean annual rainfall in the area was 241mm. The investigation was carried out in collaboration with Groundwater department Jodhpur. Groundwater recharge estimates by environmental chloride method compared well with tritium method and gave a mean value of 14 mm. From the $\delta^{18}\text{O}$ profiles with depth at the sites, depleted $\delta^{18}\text{O}$ values observed at a depth of ~2m and ~4.5m [Fig.2] could be due to heavy rains during 1998 and 1994 respectively. Unsaturated zone profile

could be used to provide a record of recharge history as interpreted for profiles from Cyrus and northern Senegal.

b) In arid areas indirect recharge through wadis (river channels) could be an important mechanism for groundwater recharge. Environmental isotopes ^2H , ^{18}O , ^3H and ^{14}C were employed to identify the recharge process in Jalore area of Western Rajasthan. Jalore district is situated adjacent to Barmer district in the south – west part of Rajasthan. The study area [Fig.3] receives a mean rainfall of $\sim 380\text{mm}$ and is drained by the Sukri river, a tributary of the Luni river system, which is ephemeral in nature.

The younger alluvium, which is present mostly along the river course, is unconsolidated to semi consolidated, coarse to fine sand and gravel. Older alluvium of sub-recent to Pleistocene age, formed by semi-consolidated to consolidated, medium to coarse sand with clay lenses, caliche and rock fragments, is observed away from the river course. Sand and shale fragments are encountered at deeper horizons. Study of subsurface geology indicates the presence of fault along which the Sukri river is flowing

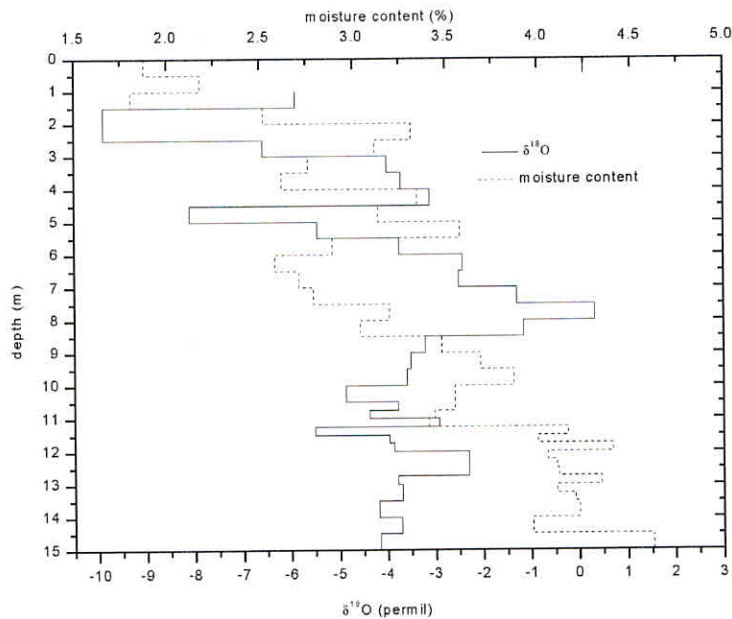


Fig. 2 $\delta^{18}\text{O}$ profile with depth at Sihania site

A number of water samples from shallow ($<50\text{m}$) and deep wells were collected for chemistry and environmental isotopes. From chemical analysis, it is observed that the shallow and deep groundwater, from near the river course are generally fresh and of Na-HCO_3 type. Shallow and deep groundwaters away from the river course are brackish and NaCl type. From fig.4, it is observed that the isotopic composition of the samples may be grouped into 3 sets. Shallow groundwaters along the river course are isotopically enriched and fall in group C. Shallow groundwaters which are away from the river course and located in the western and south western part of the study area have comparatively depleted stable isotopic values and form group B. These samples have tritium concentrations ranging from 1.4 to 4.8 TU. Group A contains both shallow and deep well samples and have most depleted stable isotope values.

It is observed that samples with depleted ^{18}O values have low tritium contents and vice versa. It is also seen that old waters with low tritium values have high chloride values (800 to 1000 ppm), whereas recent water with high tritium values have low chloride content. This indicates

that the groundwaters near the river course are fresh waters with enriched stable isotopic composition and high tritium values showing presence of modern recharge. The groundwaters away from the river course are brackish, have depleted stable isotope and low tritium contents and thus seem to represent old waters. It was concluded from the study that the shallow aquifer receives recharge through river channels during episodic floods caused by intense rain events (amount effect). Some parts of the shallow aquifer also receive recharge from the deep confined aquifer by upwelling through subsurface fault zones in the area. The deep aquifers are generally old water recharge during cool and moist periods in the past.

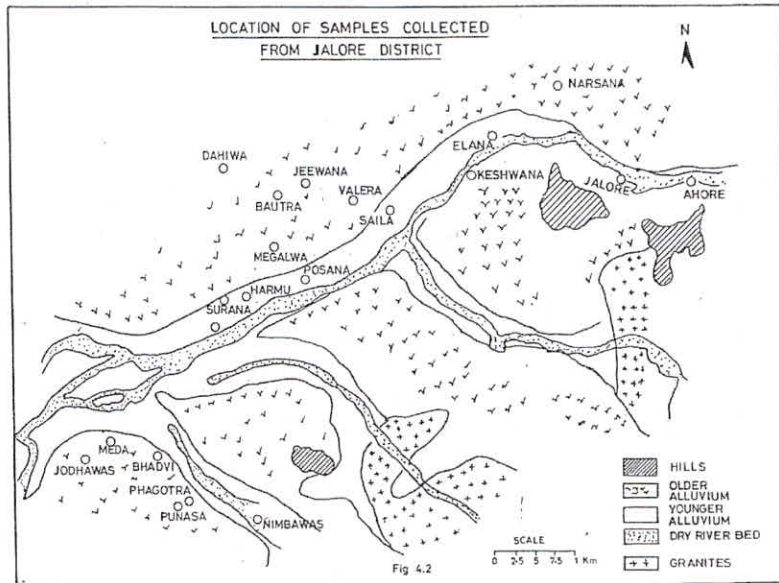


Fig. 3 Location of samples from Jalore area, Rajasthan

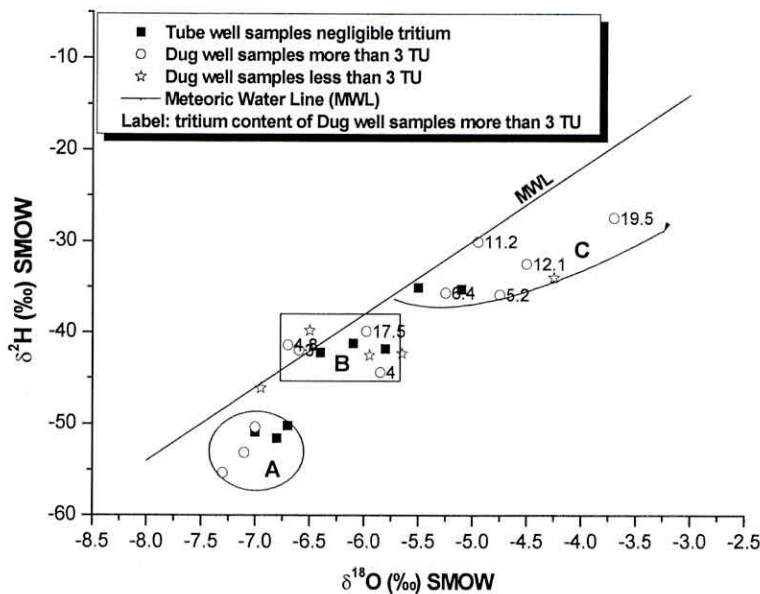


Fig. 4 $\delta^2\text{H} - \delta^{18}\text{O}$ plot of samples from Jalore area

Buried courses of rivers (paleochannels) are important as they have good groundwater potential. Interpretation of satellite imagery of the western parts of Jaisalmer district in Rajasthan revealed the buried course of a river in the NE-SW direction. Field investigations along one such course showed that in spite of highly arid condition, comparatively good quality groundwater

was available along the course, below 30m depth. Groundwater away from the course was saline. The course was seen to have a link with the dry bed of the Gaggar river in the north-east, while in the south-west it was met with or even cut across the surviving courses of Hakra or Nara rivers in Pakistan. The above course was thought to belong to the legendary river Saraswati of Himalyan origin, mentioned in many early literary works and known to have existed before 3000 a BP. To confirm the above senario, an environmental isotope study was initiated in collaboration with Groundwater Department of Rajasthan. Samples were collected from existing dugwells, hand pump and tube wells in the area (Fig.) for $\delta^2\text{H}$, $\delta^{18}\text{O}$, ^3H , ^{14}C as well as chemical analyses. The stable isotope ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) results show that the groundwater samples from the area have enriched values compared to Himalayan rivers. ^{14}C model age of the dug well samples is less than 5000 years and of tube well samples range from 5000 to 20,000 years (Fig.5). There is trend of increase in the ^{14}C age of groundwaters along a stretch in the suspected course, and from the relative ages, a groundwater velocity of about 5 m/a may be inferred. A possible recharge area for the groundwaters in the study area may be the dry bed of river Ghaggar, part of which is in Pakistan.

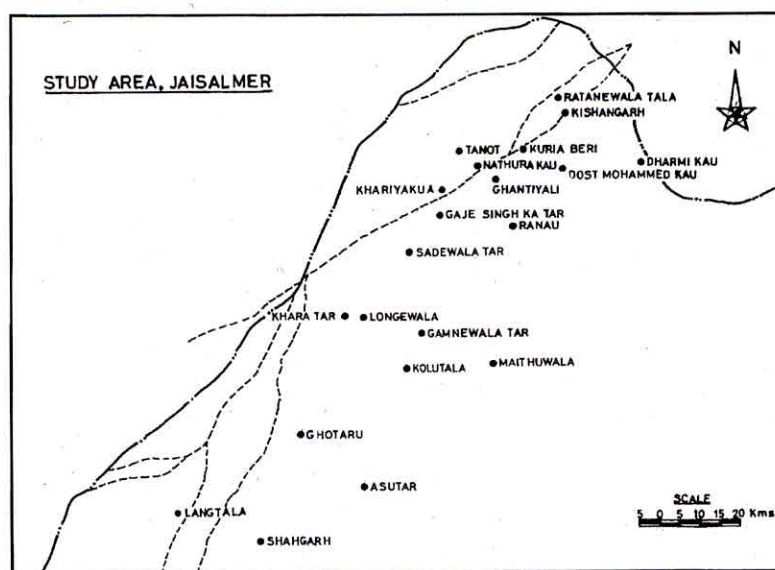


Fig. 5 Map showing location of samples in Jaisalmer

To study any possible linkage between the dry river bed and the study area, groundwater samples were taken from Ganganagar area in the northern part of Rajasthan. Isotope analyses of the samples showed that the groundwater in the area was extensively affected by irrigation waters. Thus the results showed that direct head water connection to the groundwater in the study area from present day Himalayan sources seemed to be remote. The stable isotopes, tritium and radiocarbon values indicated that the groundwaters were old waters.

Beyond this area in all directions the deep aquifer becomes brackish or saline. The aquifer is Tertiary sandstone, which occurs at different depths. Isotope results show that the deep groundwater (depth > 100m) has depleted $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values compared to the shallow groundwater (Fig.8). They have negligible ^3H and ^{14}C contents range from 22 to 50 pmC. Model ^{14}C ages of these groundwaters range from 4000 to 9500 a BP. Hence the deep fresh groundwater seems to represent paleowaters recharged during a cooler and more humid climate. This is further confirmed by palaeontological studies [14,15], which showed that during the early and mid Holocene humid climate existed in Rajasthan.

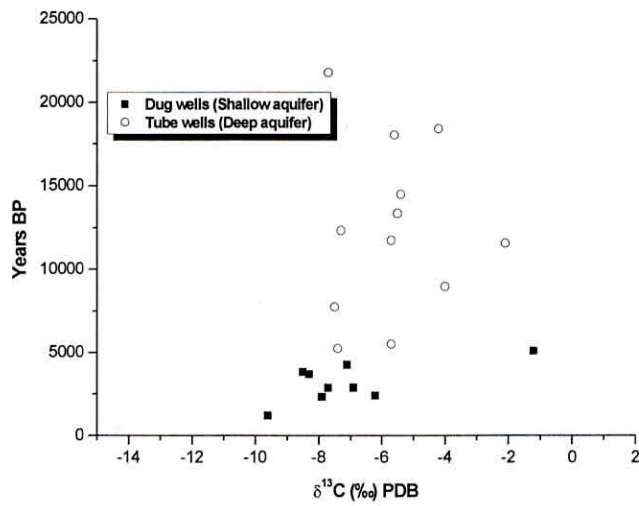


Fig.6 Carbon-14 age Vs $\delta^{13}\text{C}$ of samples from Jaisalmer

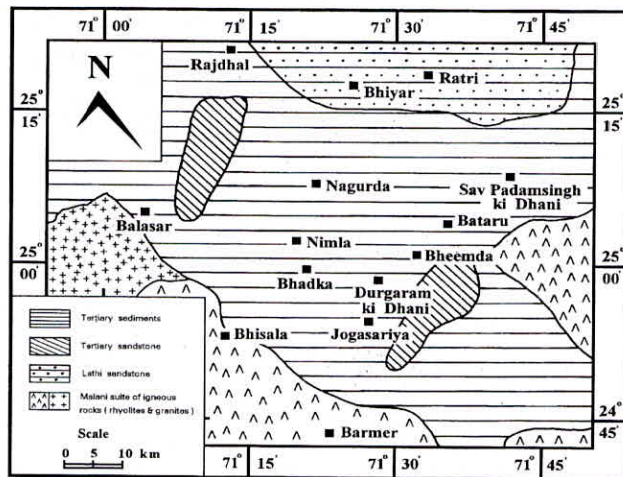


Fig. 7: Location map of sample from Bhadka-Bheemda area

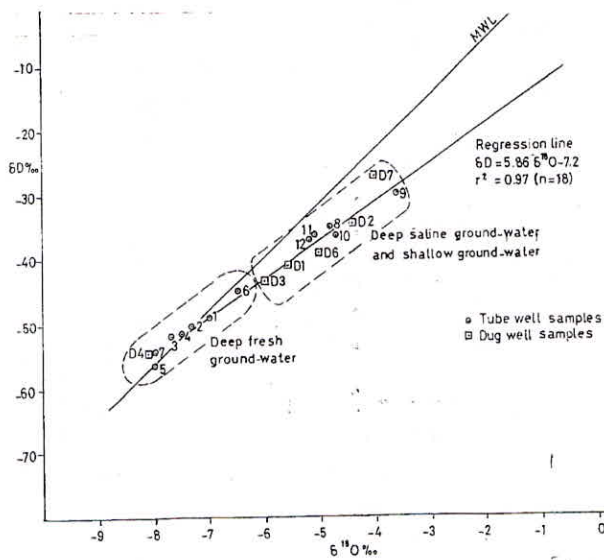


Fig. 8: δD $\delta^{18}\text{O}$ plot of samples from Bhadka-Bheemda area

Environmental isotopes ^2H , ^{18}O , ^3H , and ^{14}C were used to understand the groundwater recharge process in the Bhadka- Bheemda area in Barmer district in Western Rajasthan[13]. In Bhadka – Bheemda area (Fig. 7) the deep aquifer is generally fresh compared to the shallow aquifer.

2. Effect of over exploitation of groundwater

The increasing demand of water supply for various purposes has lead to heavy exploitation of groundwater resources in many parts of the world. This is particularly so in arid areas where limited water resources are being exploited with adverse effects of rapid lowering of water table and deterioration of water quality. For example in Bikaner town in Western Rajasthan, the groundwaters from the Eocene sandstone aquifer are extensively exploited and water levels have been declining. The shallow wells in the above areas are mostly under unconfined condition whereas the deep wells are under semi confined condition. Isotope study [16] showed that the shallow and deep wells have generally similar $\delta^2\text{H}$, $\delta^{18}\text{O}$ and negligible ^3H .

The ^{14}C model ages of the deep wells vary from modern to 9500 years BP. Similar $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of the shallow groundwater and young groundwater encountered in some deep well samples indicates mixing of the shallow and deep zone waters due to heavy exploitation of groundwater in the area. Similarly in Bhadka- Bheemda area the isotopic and chemical characteristics was studied to understand their response due to long term exploitation of groundwater [17]. 3 sets of groundwater samples were collected during 1987, 1996 and 2000 from the area and analysed for isotopes and chemistry. Fig.9 shows the electrical conductivities of tube well samples for the 3 sampling campaign. From the figure it can be seen that groundwater generally becomes more brackish with time.

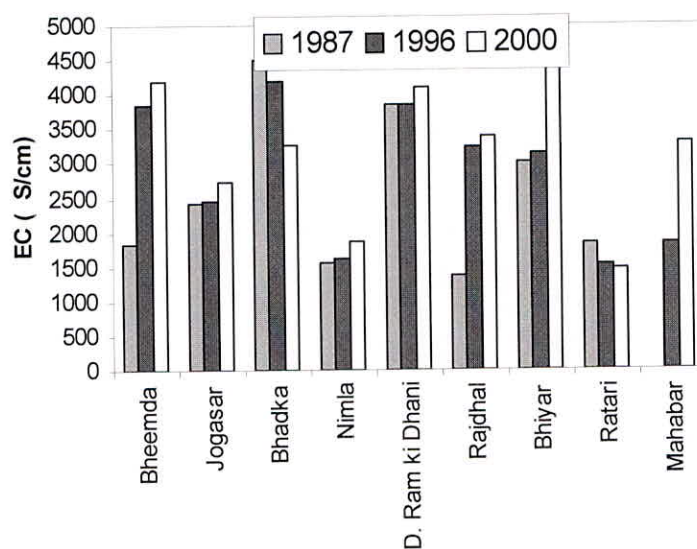


Fig.9 EC of tube well samples during 1987, 1996 & 2000

Fig.10 shows $^{14}\text{C} - \delta^{18}\text{O}$ plot of groundwater samples from the area during the 3 periods. $\delta^{18}\text{O}$ enrichment is observed in many of the well samples with time. Also ^{14}C values show lower values with time. This indicates influx of older waters from adjacent areas which are brackish/ saline and have enriched $\delta^{18}\text{O}$ signatures.

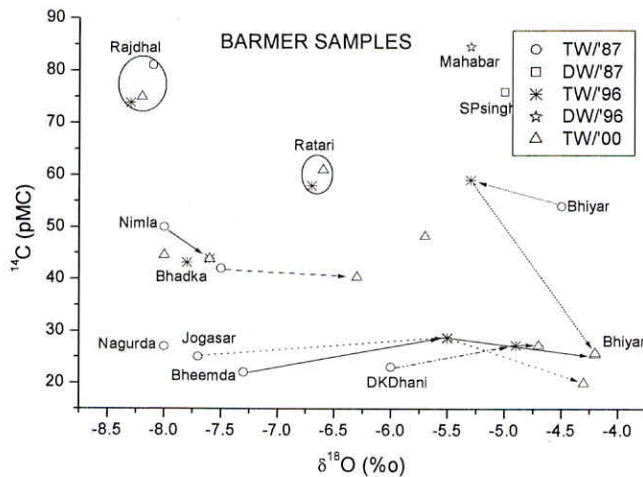


Fig.10 ^{14}C - $\delta^{18}\text{O}$ of samples during 1987, 1996 & 2000

In another example in a limestone belt which extends from Bilara to Phalodi in Western Rajasthan groundwaters are being heavily exploited for irrigation and domestic purposes. The isotope results [18] show that modern recharge is possible in the southern part of the area through the Luni river which is ephemeral. In the central part the groundwater contains negligible ^3H and ^{14}C indicates an age of ~2000 years BP (Table 1). In Phalodi area in the north the groundwater contains negligible ^3H and ^{14}C showing a maximum age of 4000 years indicating paleorecharge. Time series analysis of the tritium data of some of the well samples (Table 1) showed decreasing trend. This may be due to overexploitation of groundwater in the central part leading to influx of older water from the north.

REFERENCES

- Andersen, L.J. And T.Sevel, 1974: Six years' environmental tritium profiles in the unsaturated and saturated zones, Gronhoj, Denmark, Proc. IAEA Symp. Isotope Techniques in Groundwater Hydrology, 9-13 March, Vienna, 3-20.
- Athawale, R.N., Murti, G.S. And R.Chand, 1980. Estimation of recharge to the phreatic aquifers of the Lower Maner Basin, India, by using the tritium injection method. J.Hyd: vol. 45, 185-202.
- Bahadur, J., Saxena, R.K. And P.Mookerjee, 1977: Soil moisture movement and groundwater recharge by tritium tracer tagging technique. Proc. Indian Acad.Sci.Ser. A 85, 462-471.
- Bakliwal, P. C. and Grover, A.K. Signature and migration of Saraswati river in Thar desert, Western India, Rec. Geo. Surv. Ind., V 116, (1988), 77-86.
- Balistreri, L.S., and J.W. Murray. 1984. Marine scavenging: Trace metal adsorption by interfacial sediment from MANOP site H1. Geochim. Cosmochim. Acta 48:921-929.
- Bhandari, N., Gupta, S. K., Sharma, P., Premsagar, Ayachit, V. & Desai, B. I. (1986) Hydrogeological investigations in Sabarmati and Mahi basins and Coastal Saurashtra using radioisotope and chemical tracers. *Tech. Rep., HILTECH, Roorkee, India.*
- Blume, H.P., Zimmermann, U., And K.O. Munnich, 1967: Tritium tagging of soil moisture: the water balance of forest soils. Proc. Symp. Isotope and Radiation Techniques in Soil Physics, 12-16 June 1967, Istanbul. IAEA, Vienna, 315-332.
- Chaturvedi, R.S. (1973) A note on the investigation of groundwater resources in western districts of Uttar Pradesh, *Annual Report, UPIRI, Roorkee*, 86-122

- Datta, P.S., Goel, P.S., Rama And S.P. Sangal, 1973: Groundwater recharge in Western Uttar Pradesh. Proc. Indian Acad. Sci. 72 A 1.
- Datta, P.S., Mookerjee, P., Chandrasekaran, H. & Mukherjee, T.K. (1990) Variability in groundwater recharge through the unsaturated zone. *Bull. of Radiation Protection*, **13**(1), 127-130.
- Dietrich, W.E., and T. Dunne. 1978. Sediment budget for a small catchment in mountainous terrain. *Z. Geomorphol.* 29:191-206.
- Dincer, T., Payne, B.R., Florkowski, T., Martinec, J., And E. Tongiorgi, 1970: Snowmelt runoff from measurements of tritium and oxygen-18, *Water Resour. Res.* 6., 110-124.
- Eriksson, B., 1980: The water balance of Sweden: Annual mean (1931-60) of precipitation, evaporation and runoff. Swedish Meteorol.Hydrol.Inst.Report, RMK 18, (in Swedish).
- Eriksson, E., 1976: The distribution of salinity in groundwaters of the Delhi region and recharge rates of groundwater. Proc. Advisory group meeting on the interpretation of environmental isotopes as hydrochemical data in groundwater hydrology. IAEA. Vienna, 171-177.
- Errmann, A. And W. S Tichloer, 1980: Groundwater- runoff relationships, *Catena* 7, 251-263.
- Fontes, J. Ch. And Edmonds, W.M., The use of Environmental isotope Techniques in arid Zone Hydrology – a critical Review, UNESCO, Paris, (1989).
- Geyh, M. A. and Ploethner, D., An applied palaeohydrological study in Cholistan, thar Desert, Pakistan, application of Tracers in Arid Zone Hydrology (Proceedings of the Vienna Symposium, August 1994), IAHS Pub. No. 232, 1995, 119-127.
- Ghose, B., Kar, A and Hussain, Z, The lost courses of Saraswati river in the Great Indian Desart: New evidence from Landsat imagery. *The Geographical J.*, London, Vol. 145 (3), (1979), 446-451.
- Hawley, N., J.A. Robbins, and B.J. Eadie. 1986. The partitioning of 7-beryllium in fresh water. *Geochim. Cosmochim. Acta* 50:1127-1131.
- Hydrological barrier studies, Stage 2., Cad, IGNP, 1989-90, Government of Rajasthan, (1991).
- Kar, A., Remote sensing of buried former streams in the extremely arid terrains of Jaisalmer, Indian desert, for water and salinity. Proc. Seventh Asian Remote Sensing conference, Seoul, Korea, B2/1-B2/9, (1986).
- Knutsson, G. And H.G. Forsbert, 1967: Laboratory evaluation of ⁵¹Cr-EDTA as a tracer for groundwater flow. Proc. IAEA Symp. Isotopes in Hydrology, 14-18 Nov. 1966. Vienna, 629-651.
- Mookerjee, P. (1990): New concept of profile moisture and depth of injection in tritium tagging technique for evaluation of groundwater recharge as a component of the water balance equation. *Bull. of Radiation Protection*, **13**(1), 147-150
- Monitoring of water table-Stage 1, Drainage trials and demonstration Stage 1, Hydrological barrier studies Stage 1, Status Report (1991-1992), Government of Rajasthan, (1992).
- Munnich, K.O., Roether, W. And L. Thilo, 1967: Dating of groundwater with tritium and C-14. Proc. IAEA Symp. Isotopes in Hydrology, 14-18 Nov. 1966, Vienna, 305-319.
- Munnich, K. O. (1968a) Moisture movement measured by isotope tagging. In: *Guide book on nuclear techniques in hydrology*, IAEA, Vienna, 112-117
- Munnich, K. O. (1968b) Use of nuclear techniques for the determination of groundwater recharge rates. In: *Guide book on nuclear techniques in hydrology*, IAEA, Vienna, 191-197

- Nair, R.A., Pendharkar, A.S., Navada, S.V. And S.M. Rao, 1979: Groundwater recharge studies in Maharashtra. Development of isotope techniques and field experience. Proc. Symp. Isotope Hydrology, 19-23 June 1978, Neuherberg, IAEA, Vienna, 803-826.
- Olley, J.M., A.S. Murray, D.H. Mackenzie, and K. Edwards. 1993. Identifying sediment sources in a gullied catchment using natural and anthropogenic radioactivity. *Water Resour. Res.* 29:1037-1043.
- Owens, P.N., D.E. Walling, and Q. He. 1996. The behaviour of bomb-derived caesium-137 fallout in catchment soils. *J. Environ. Radioactivity* 32:169-191.
- Owens, P.N., D.E. Walling, and G.J.L. Leeks. 1999. Use of floodplain sediment cores to investigate recent historical changes in overbank sedimentation rates and sediment sources in the catchment of the River Ouse, Yorkshire, UK. *Catena* 36:21-47.
- PRL, 1986: Hydrogeochemical investigations in Sabarmati and Mahi basins and coastal Saurashtra using radioisotopic and chemical tracers, Published by HILTEC, NIH, Roorkee
- Robbins, J.A. 1978. Geochemical and geophysical applications of radioactive lead. p. 285-393. *In* J.O. Nriagu (ed.) *Biogeochemistry of lead in the environment*. Elsevier, Amsterdam.
- Robbins, J.A., P.L. McCall, J.B. Fisher, and J.R. Krezoski. 1979. Effect of deposit feeders on migration of ^{137}Cs in lake sediments. *Earth Planet. Sci. Lett.* 42:277-287.
- Ritchie, J.C., and J.R. McHenry. 1990. Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review. *J. Environ. Qual.* 19:215-233
- Rodhe, A., 1984: Groundwater contribution to stream flow in Swedish forested till soil as estimated by oxygen-18. Proc. Symp. Isotope Hydrology in Water Resources Development, IAEA, Vienna, 55-66.
- Saxena, R.K., 1984: Seasonal variations of oxygen-18 in soil moisture and estimation of recharge in esker and moraine formations. *Nordic Hydrology.* 15, 235-242.
- Sehgal, S. P. (1973) Groundwater resources of Punjab state, *III Annual Research Session of CBIP, New Delhi*
- Singh, B. P. & Kumar, B. (1993) Is it correct to assume that soil moisture movement in unsaturated strata is a piston flow. *Abs. Vol., Intl. Conf. on Hyd. & Water Resour., Dec. 20-22, New Delhi, India.*
- Sklash, M.G. And R.N. Farvolden, 1979: The role of groundwater in stream runoff. *J. Hydrol.* 43, 45-65.
- Sukhija, B.S. And C.R. Shah, 1976: Conformity of groundwater recharge rate by tritium method and mathematical modelling. *Ibind.* 30. 167-178.
- Thoma, G., Esser, N. Sonntag, C., Weiss, W. And J.Rudolph, 1979: New technique of in-situ soil moisture sampling for environmental isotope analysis applied at Pilat sand dune near Bordeaux. Proc. Symp. Isotope Hydrology, 19-23 June, 1978, Neuherberg, IAEA, Vienna, 753-768.
- Valdiya, K.S., Raiver Piracy, *Resonance*, 5, (1996), 19-28.
- Wallbrink, P.J., A.S. Murray, J.M. Olley, and L.J. Olive. 1998. Determining sources and transit times of suspended sediment in the Murrumbidgee River, New South Wales, Australia using fallout ^{137}Cs and ^{210}Pb . *Water Resour. Res.* 34:879-887.
- Wang, K., and R.J. Cornett. 1993. Distribution coefficients of ^{210}Pb and ^{210}Po in laboratory and natural aquatic systems. *J. Paleolimnol.* 9:179-188.
- Walling, D.E., and J.C. Woodward. 1992. Use of radiometric fingerprints to derive information on suspended sediment sources. p. 153-164. *In* *Erosion and sediment transport monitoring programmes in river basins*. Publ. 210. IAHS, Wallingford, UK.

- Walling, D.E., P.N. Owens, and G.J.L. Leeks. 1999. Fingerprinting suspended sediment sources in the catchment of the River Ouse, Yorkshire, UK. *Hydrol. Process* 13:955–975.
- Zimmermann, U., Munnich, K.O. And W. Roether, 1967A: Downward movement of soil moisture traced by mean of hydrogen isotope. *Geophysical Monograph No.11. Isotope Techniques in the Hydrological Cycle* (Stout, G.E., ed.) Amer. Geophys. Union. Washington 1967, 28-36.
- Zimmermann, U.,Munnich, K.O. & Roether, W. (1967a) Downward movement of soil moisture traced by means of hydrogen isotopes. *Am. Geophys. Union, Geophys. Monogr.*, **11**, 28-36.
- Zimmermann, U., Ehhalt, D. & Munnich, K. O. (1967a) Soil water movement and evapotranspiration; changes in the isotopic composition of the water. In: *Isotopes in hydrology*, IAEA, Vienna, 567-584.