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ENVIRONMENTAL ISOTOPES FOR HYDROLOGICAL INVESTIGATIONS

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SUMMARY

In this report it is proposed to review the status of applications of environmental isotopes in hydrological investigations. These include tritium(H^3) and Carbon-14(C^{14}), naturally occuring isotopes and stable isotopes Deuterium(D) and oxygen-18(O^{18}). In some cases measurements of environmental isotopes of only few samples may provide important hydrological information which could be obtained only with difficulty or not at all by other methods. For example, the detection of tritium in ground water proves that ground water was formed after 1953-54 and origin of different waters is given by variation in stable isotopic contents. Applications of environmental isotopes are useful for dating ground water by using tritium and Carbon-14, evaluation of ground water recharge by measuring environmental tritium profile in soil water and studying interconnections between surface and subsurface waters. Other applications of environmental isotopes employ stable isotopes of Deuterium and oxygen-18 to identify source of recharge, to study effect of local surface bodies on the ground water and lake evaporation studies.

Variation in the concentration of stable isotopes in rainwater is due to evaporation and condensation processes. Depletion in stable isotope composition is also observed with decreasing temperature and with increasing latitude. The effect of latitude, altitude and distance from sea on environmental isotopes is briefly discussed in this report.

Stable isotopic composition of water is measured using Mass spectrometerand environmental tritium is measured by Liquid scintillation spectrometer and also by Proportional counters. Electrolytic enrichment is compulsory for counting very low activities. The measurement of these environmental isotopes is a vast subject and is not discussed

in this report. Attempts have been made to present a review of environ mental isotopes in hydrological investigation covering briefly application in many fields and water balance studies of lakes and reservoir in particular.

1.0 INTRODUCTION

Nuclear methods were first applied to hydrological problems by nuclear scientists and the advent of the inexpensive supply of radioactive isotopes in the early 1950's increased the interest in these techniques. Largely as a result of the coordinating work of the International Atomic Energy Agency(IAEA) hydrologists became involved in these developments. Nuclear methods now provide a valuable additional tool to complement the wide range of techniques already available to the practical hydrologist.

Nuclear techniques are based on one or other two approaches. The first depends on the ability to detect very low concentrations of radioactive elements and often to carry out such detection insitu in the field. The second approach makes use of the properties of the nuclear radiations and measurements of their attenuation or interaction as they pass through the media. Radioactive isotopes are normal elements with a nuclear configuration which is unstable. During their transformation to a stable form they emit α-particles, β-particles and γ-radiations. The α-particle is a helium nucleus and owing to its very short range in material, is of no direct application in hydrology. The β-particle is an electron ejected from the nucleus with an energy expressed as thousands or millions of electron volts (Kev, Mev). Low energy β-particles (~ 10 Kev) penetrate only a few tens of microns of water while high energy particles (~ 1 Mev) will penetrate several centimeters. Some of the most important isotopes used in hydrological studies emit only low energy β-particles and efficient detection requires the measurement of samples in the laboratory. Gamma radiation is an electromagnetic radiation emitted by some radioactive isotopes in conjunction with α or β particles. It

is highly penetrating (50 cm to 100 cm in water) and hence a detector immersed in water measures the radiation originating in a large volume which results in a very high sensitivity of measurement. Neutrons are not normally emitted from radioisotopes and sources rely on a secondary reaction using the α particles from a radioisotope to react with the nucleus of a beryllium atom to release a neutron. A radioactive source decays with time and emits a decreasing amount of radiation. The decay is exponential and is expressed in terms of the half life of the source. Over the period of one half-life, the amount of radiation emitted decreases by a factor of two. Radioactivity is expressed in terms of the Curie (Ci) where one Curie is 3.7×10^{10} disintegrations per second. Practical units are the millicurie (mci, 10^{-3} ci) and microcurie(μ ci, 10^{-6} ci).

Some radioisotopes occur in nature while others are artificially produced in a nuclear reactor. The obvious examples of natural radioisotopes are uranium and thorium with very long half-lives of 4.5×10^{9} years and 1.4×10^{10} years respectively. Other isotopes are constantly produced by the action of cosmic radiation in the atmosphere. Two of these, that are of major importance in hydrology are tritium and carbon-14. Tritium is an isotope of hydrogen of nuclear mass 3 and since it is incorporated in the water molecule as tritiated water (HTO) it forms an almost perfect tracer of water. This unique property is the reason that at least half of the water tracing applications are based on tritium. In addition to the truely occuring radioisotopes, there is another world wide source of radioactivity in the environment which arises from thermonuclear weapon tests. These have been carried out since about 1954 and have caused the release of tritium, carbon-14 and other fission products as caesium-137 and strontium-90

into the stratosphere and biosphere. The release of these isotopes have provided the hydrologist with tracers which can be used in long term studies of water behaviour. The hydrogen and oxygen components of water consists of a mixture of stable isotopes. The hydrogen is principally protium (^{1}H) but includes a fraction of approximately one part in 3200 of deuterium (^{2}H). Similarly oxygen is principally ^{16}O and contains a fraction of one part in 500 of ^{18}O. Highly accurate measurements of changes of these fractions are of value in providing information about the origin and history of the measured water.

The environmental isotopes include naturally occuring radio-isotopes and stable isotopes which are used to investigate water behaviour. The isotopes of particular interest are:

(i) Tritium

(ii) Carbon-14

(iii) Stable isotopes, $^{18}O/16_{0}$ and $D/_{H}$ ratios.

The wide distribution of these isotopes provide a series of techniques for large scale hydrological investigations which provide unique information on long term water movement. Tritium in the form of water molecule (HTO) enters the hydrological cycle as rainfall. The concentration due to this source is 5 to 10 T.U.(Tritium Units) where a tritium unit is defined as one tritium atom to 10^{18} normal hydrogen atoms and result in 7.2 disintegrations per minute per litre of water. The concentration of tritium is extremely difficult to measure and requires refined laboratory equipment which includes a method of electrolytic enrichment of tritium and low level counting laboratory. Proportional gas counters may be used to detect tritium in slightly lower concentrations while tritium in higher concentration is preferably counted on liquid scintillation spectrometer in the liquid phase.

2.0 REVIEW

Enrivonrmental isotopes of natural or artificial origin are present in natural waters in varying proportions, these proportions depend on natural processes which can not be controlled by man. The isotopes normally used in hydrology are ^{18}O, ^{2}H, ^{3}H, ^{13}C, ^{14}C, ^{34}S, ^{15}N and ^{234}U . Following table lists some of the important isotopes and their occurance.

ELEMENT	ISOTOPE	AVERAGE NATURAL CONTENT %	HALF-LIFE YEARS
Hydrogen	^{1}H	99.985	Stable
	^{2}H = D (Deuterium)	0.015	Stable
	^{3}H = T (Tritium)		12.26 Yr.
Carbon	^{12}C	98.89	Stable
	^{13}C	1.11	Stable
	^{14}C		5730 Yr
Oxygen	^{16}O	99.76	Stable
	^{17}O	0.04	Stable
	^{18}O	0.20	Stable

2.1 Stable Isotopes of Hydrogen and Oxygen

Among the stable isotopes, oxygen-17 is not used as its variation is exactly similar to those of oxygen-18 and its measurement, which is more complex than that of oxygen-18, does not provide any useful additional information. Oxygen and hydrogen isotopes are ideal hydrochemical tracers for the study of certain problems, because they

are incorporated in water molecule. These isotopes have been used to obtain a better theoretical and practical understanding of groundwater. Demand is increasing for better understanding of hydrologic systems to facilitate management of water as a resource and to evaluate environmental problems. The distribution of isotope species in water provides information on sources of groundwater, on flow paths, mixing and on physical and chemical characteristics of aquifers.

For an isotope to be useful in hydrology, the following characteristics are desirable. First, the relative mass difference of common to rare isotopes of the element should be large. Isotopes of heavy elements may not show significant separation in nature because the difference of their weight. Second, the abundance of the rare isotopes must be substantial and in contrast with the dominant isotope. Third, occurance of some natural process modifies the relative abundance of an element is isotope in a system. Because absolute meàsurement of isotope ratios is analytically difficult, relative isotopic ratios are measured instead. For example, variations of D/H ratio are 5 to 8 times bigger in natural waters than those of $^{18}O/16_O$, however, variations of $^{18}O/16_O$, can be measured with a precision ten times higher than those of D/H. $^{18}O/16_O$ of a sample is compared to $^{18}O/16_O$ of a standard maintained by the International Atomic Energy Agency (IAEA). The symbol δ (delta) designates relative difference in connection with units of per mil ($^{o}/_{oo}$) and is written as:

$$\delta^{18}_{O} = (R \text{ sample} / R \text{ standard} - 1) \times 1000$$

$$= \frac{R \text{ sample} - R \text{ standard}}{R \text{ standard}} \times 1000$$

where $R = {}^{18}O / {}^{16}O$

For example, $\delta^{18}O = -11\ ^{o}/_{oo}$ means that the sample contains 11 parts per thousand less ^{18}O than the standard, $\delta^{13}C$, $\delta^{34}S$, δD and $\delta^{15}N$ are defined in a similar manner. $R_{standard}$ is also denoted as R_{smow} Standard SMOW has the isotopic composition of average oceanic water which constitutes the initial and the final point of all the important hydrological circuit. The isotopic ratios are measured by mass spectrometry, the normal measurement precision is less than 1% for the D/H ratio and 0.1% for $^{18}o/16_{o}$ ratio.

2.1.1 Variation in stable isotopic content of groundwater

The stable isotope content of groundwater is normally equal or near to the average content of precipitation in the recharge area. The differences of D and is more or less contemporary groundwaters correspond, therefore, to those of precipitation in recharge zones. If, for example, the recharge zones of two aquifers are at different altitudes, the isotopic composition of water from the two aquifers will also differ. When the age of ground water is more than a few thousand years, their heavy isotopic content may be noticeable different from that of the actual recharge waters, this is due to intervening climatic variations, and especially changes in temperature and humidity. If the ground waters are recharged by surface waters, their isotopic composition can be affected by the partial evaporation to hich the waters may have been subjected before infiltration. In this case, the waters will be enriched in heavy isotopes(less volatile) and their values of δD and δ_{o}^{18} will no longer have a linear relation and isotopic composition of ground water will provide information on its origin.

2.1.2 Variation in stable isotopic content of Precipitation

Water vapour which evaporates from the ocean is depleted in deuterium and oxygen-18 content with respect to oceanic water as $HD^{16}O$ and $H_2{}^{18}O$ are less volatile than $H_2{}^{16}O$. When the atmospheric vapour is subjected, following cooling, to successive condensation producing snow and precipitation, the heavy isotopes condense first and the remaining vapour is more and more depleted for D and O^{18} Therefore, successive precipitations are also more depleted of heavy isotopes. Since the degree of condensation depends on the temperature, one should expect that the values of δ_D and $\delta^{18}O$ are correlated with the temperature of formation of precipitation. Correlation with temperature gives rise to isotopic variations according to season, winter rain is depleted by heavy isotopes in comparison with summer rain. The heavy isotope content of rain decreases with altitude and also get affected due to variations in latitude. Thus rainfall at colder temperatures, higher altitudes and latitudes and greater distance from the ocean will be characterized by isotopically lighter δD and $\delta^{18}O$ values.

Both the absolute and relative amounts of these isotopes change when water is removed by phase changes. For example, during condensation water molecules containing the lighter isotope have a higher vapour pressure and hence enrich the gas phase, while the heavier isotope forms precipitation more readily. Equilibrium phase changes affect deuterium and ^{18}O in a constant ratio and their values are linearly related in rainwater according to a general world wide equation

$\delta D = 8\ \delta^{18}O + 10$ (Craig, 1961)

Condensation is an equilibrium reaction, where as kinetic effects

became more important during evaporation which results in additional fractionation. Fractionation is a process that separates the isotopes of an element. The depletion or enrichment of a heavier isotope relative to lighter one is reflected by different δ values. Fractionation process are the result of physical and chemical reactions. Owing to different thermodynamic properties, molecules with different masses have different rates of diffusion, evaporation, condensation, freezing and melting. Thus phase changes such as condensation of rain separate the isotopes in physical fractionation. Chemical fractionation occurs due to the different bond energies of different isotopic molecules. Heavier isotopes prefer a higher bond strength than lighter isotopes, so the isotopes may be separated in chemical reactions. There are two types of chemical fractionation, kinetic and equilibrium.Kinetic fractionation is due to relative velocity and vibrational frequency of the molecules and is irreversible.In equilibrium chemical reactions, the isotopes are continuously exchanged rather than separated by unidirectional movement. The heavy isotopes are enriched in the compound that will hold the isotope most strongly. The solid phase is enriched in the heavier isotopes according to equilibrium fractionation. Physical and chemical fractionation thus affect the isotopic ratios of a system. Fast reactions tend to accentuate kinetic effects and slow reactions accentuate equilibrium effects. Lakes and open systems have δ D and δ^{18}O values that deviate from the world wide rainfall line because they are subjected to evaporation. Repeated evaporation and condensation leads to progressively lighter isotopic values in the vapour phase.

2.2 Tritium

Tritium is one of the heavy isotope of hydrogen and has one proton and two neutrons. It is produced in the atmosphere by interaction of cosmic rays. Since 1953, this has also been formed in thermonuclear explosions and due to atomic bomb explosions. The tritium content of the atmosphere and water increased significantly and is now one of the most important isotope used to identify recent ground water movement.

2.2.1 Variation of tritium in precipitation

Since 1953, when thermonuclear weapon testing started an enormous quantity of artificial tritium got injected into the atmosphere. As a result, the amount of tritium in precipitation increased from 5TU to 5000-10,000 TU in 1963-64 and afterwards began to decrease, more or less regularly following suspension of explosions.

2.2.2 Variation of tritium in subterranean waters

Due to short half life and low concentration of tritium in precipitation before 1953 it is present in recent ground waters in noticeable quantities. In general, the following practical rule can be established

(i) If the amount of tritium is less than 3-5 TU the water dates before 1953.

(ii) The amount is more than 20TU, the recent component is preponderant.

(iii) If the amount is made up of between 5 and 20TU an important quantity of recent water is present mixed with old water.

The study of the time variation of the amount of tritium may

give important information on water circulation time and on the behaviour and characteristics of the reservoir. Tritium content if measured in the wells at various depths may establish layering of ground water by different ages.

2.3 Carbon Isotopes

The most commonly measured isotopes of dissolved constituents in groundwater are ^{13}C and ^{14}C in the organic carbon species(HCO_3 CO3, H2CO3, CO2, aq.) ^{14}C is a radioactive isotope produced indirectly in the atmosphere by interaction of cosmic rays and in recent years also by thermonuclear weapon testing. The amount of ^{14}C in a natural sample is expressed in modern percentages, that is to say in percentage of the amount of ^{14}C in plant carbon before 1890, since that time ^{14}C in plant carbon before 1890, since that time ^{14}C in atmospheric CO2 has slightly decreased due to production of CO2 by industrial combustion(fossil fuel does not contain ^{14}C) and recently it has begun to increase following the nuclear explosions. The amount of ^{13}C is expressed in $\delta^{13}C‰$ and is compared to the PDB standard which has a ratio $^{13}C/12_C$ more or less equal to the average ratio of marine limestone(which gives $\delta^{13}C=0$). Atmospheric CO2 carbon has an average value of $\delta^{13}C \sim -7‰$ and that of biogenic origin has$\sim -25‰$ due to the isotopic fractionation in chlorophyllic synthesis, however significant variations in the ratio $^{13}C/12_C$ is observed in different plants.

The age of ground water can be determined by measuring the decay rate and dilution factors of ^{14}C concentration. Water as old as 40,000 years can be dated with ^{14}C techniques now available. Practionation of ^{13}C, a stable isotope, provides information on carbonate solution that causes the dilution of ^{14}C. In addition, photosynthesis,bacterial

activity and other chemical reactions cause fractionation of carbon isotopes that help in identifying the source of carbon. ^{14}C is measured with proportional counters in the gas or liquid phase. ^{13}C is measured by mass spectrometry, with a precision of $\pm$ 0.1 $o/_{oo}$

2.4 Applications of Environmental Isotopes

In the last two decades both the use of environmental and of man made isotopes has proved to be quite a reliable tool in hydrological investigations. Isotopes have wide applications both in surface water and ground water problem. In brief, isotope techniques provide the potential of routine operation to the following areas of application:

(i) Investigation of changes in soil moisture content.

(ii) Process in the unsaturated zone .

(iii) Investigation of recharge mechanisms and origin of recharge.

(iv) Quantitative recharge estimates .

(v) Groundwater movement and storage.

(vi) Dispersion in surface waters.

(vii) Sediment transport .

(viii) Stream flow gauging .

(ix) Seepage losses from reservoirs.

(x) Watershed investigations .

(xi) Snow and glacier melt studies.

(xii) Water balance studies of lakes and reservoirs etc.

There are numerous applications and could not be even listed. First five applications can be reviewed under the head of investigations in the unsaturated zone covering studies on changes in soil moisture content, recharge estimates and origin of recharge and finally

movement of ground water, flow direction and flow velocity. Last seven applications can be studied under surface water studies covering origin of salinity and water pollution studies. Attempts have been made to review the application of environmental isotopes particularly to water balance studies of lakes and investigations connected to unsaturated zone in this report. It is however not possible to explain studies on ground water and surface waters under distinct heads as 'water' is one and can not be studied in isolation. It is clearly seen from the studies taken by various scientists with a multipurpose approach and the same is reviewed.

2.4.1 Water balance studies in lakes and reservoirs.

Reservoirs are large water supply systems. The dynamic properties of a reservoir are the overall water balance and the mixing pattern. In applying isotope techniques the identification of the mixing pattern can be investigated, for instance by injection of a tracer pulse at the inlet and measuring the response at the outlet, or any other points of interest. An alternate technique offers labelling of the whole water volume by a tracer whose concentration is diluted by inflowing water. A check on decrease of concentration with time results in the overall turnover time of the system. In the event of considerable evaporation it is in principle possible to use two different tracers simultaneously, one like tritium as a constituent of water molecule underlying evaporation and a second one whose concentration is enriched by evaporation. In comparing the dilution rates of both concentrations, the amount of evaporation may be calculated.

However, general constraints for the use of radio isotopes as tracers in lake investigations are the considerable activities required,

which demand costly radiation protection procedure and that is why naturally occuring radioisotopes and stable isotopic investigations are preferred. Further the composition of environmental isotopes is governed by the water balance of a reservoir. For instance, the enrichment of the heavy isotope content of the water molecule depends upon evaporation losses. But unlike other components of the water balance the isotopic content of water lost by evaporation can not be measured directly. Therefore for calculating water balance tenable estimates of the isotopic composition of evaporating moisture are necessary which should be based on data of previous experiments conducted and modified for the meteorological conditions of the reservoir under investigation.

Leakage from a reservoir creates problems in reducing the amount of available water and affects the structural stability of the hydraulic works. Leakage may occur through the foundation of the dam site or through the geological formations in which the reservoir is bedded. According to experiences of the last two decades, nuclear techniques are applicable for leakage studies in the reservoir itself or in the surrounding aquifer. The principal advantage of some tracers in these investigations in the in-situ monitoring of the injected tracer cloudes. The determination of the ratio of stable isotopes in both ground water and surface water may trace paths of seepage and indicate flow lines. Similarly the increased tritium values in the ground water due to enrichment of surface water may indicate seepage and its path from the reservoir by determining environmental tritium of both surface and ground water. The use of environmental isotopes could alone give the necessary information to trace the seepage paths of dams and reservoirs. The water balance of lakes and reservoirs can be calculated

by using the following isotopic balance equations

$$\frac{dV_L}{dt} = \Sigma I_i + P - \Sigma O_j - E \qquad \ldots(1)$$

where

I_i = rate of inflow of the i^{th} source

O_j = rate of outflow of the j^{th} outflow component.

t = time

P = precipitation rate

E = evaporation rate and

V_L = Volume of surface water body.

ΣI_i may be written as $I_s + I_G$, the surface and ground water inflow rates and ΣO_j as the sum of O_s and O_G as surface and Ground water outflow rates. Equation (i) thus can be rewritten as

$$\frac{dv_L}{dt} = I_s + I_G + P - O_s - O_G - E \qquad \ldots(2)$$

The equation (i) & (ii) can be rewritten in termsof deltas representing isotopic composition of particular components as

$$\frac{d(\delta_L V_L)}{dt} = \Sigma I_i \delta I_i + P \delta_P - \Sigma O_j \delta O_J - E \delta E \qquad \ldots.(3)$$

and

$$\frac{d(\delta_L V_L)}{dt} = I_s \delta_s + I_G \delta_s + I_G \delta_G + P \delta_P - O_s \delta_L - O_G \delta_L - E \delta_E \qquad \ldots(4)$$

These equations can also be expressed in terms of water height instead of volume. Calculation of water balance by employing these equations is based under assumption of a well mixed water body i.e. $\delta O = \delta L$

The isotopic content of evaporating moisture δE, is usually most diffi-

cult to estimate. Although it is difficult to evaluate evaporation directly using this approach(Zimmermann and Erhalt, 1970) but valuable information can be obtained about terms in the water balance(Dincer, 1968; Gat, 1970). In particular, estimates of ground water inflow can often be obtained using this technique. Craig and Gordon(1965) developed an expression for evaluating δ E whose simplified formula is given as follows

$$\delta E = (\alpha \delta^{*} \delta L - h\delta_{A} - \epsilon) / (1-h+10^{-3}\Delta\epsilon) \quad \ldots(v)$$

where δ L = Isotopic content of a well mixed reservoir of water subject to evaporation.

δ A = The isotopic content of atmospheric water vapour.

α^{*} = The equilibrium isotopic fractionation factor for the temperature at the interface.

h = The relative humidity normalized to the temperature at the interface.

ϵ = Total isotopic enrichment expressed in per mil[$\epsilon = 10^{3}(1-\alpha^{*}) + \Delta\epsilon$]

$\Delta\epsilon$ = Kinetic enrichment expressed in per mil.

$1-\alpha^{*}$ = Equilibrium enrichment

The majority of investigators use the temperature of the surface water for determining α^{*} and h. Allison et.al. (1979) showed intheir experiment that the non-normalized relative humidity determined for air temperature gives a better fit to the pan data than the normalized one determined for the temperature of surface water as the mean surface water temperature is not easily measurable for large reservoirs where as the long term averages of the air temperature does not differ very

much from that of surface water. Several workers have attempted to make estimates of δ_E for natural water bodies by using an index lake where water balance is known (Dincer, 1968), or small pans in thermal equilibrium with the lake (Gat, 1970; Welhan and Fritz 1977). Welhan and Fritz measured the change in the isotopic composition of water remaining in small pans after evaporation and the data collected was used to estimate δ_E. Allison et.al. (1979) modified this approach and developed alternative techniques for the evaluation of δ_E. Assuming the isotope content of atmospheric vapour, δ_A, to be in equilibrium with the mean isotope content of precipitation i.e.

$$\delta A = \alpha^* \delta P - \epsilon^*$$

$$\text{or} \quad \delta A = \alpha^* \delta P - 10^3(1-\alpha^*) \qquad \ldots(vi)$$

and the kinetic enrichment for ^{18}O (after Vogt,1976) may be given as

$$\Delta\epsilon_{18} = (14.3 \pm 0.4)\ (1-h)\ ^{o}/_{oo}$$

It is known that the isotopic contents of evaporating water bodies in $\delta^{18}O$ versus δD diagrams lie on the so called evaporation lines. The end point of the evaporation line corresponds to the case without outflow. The initial point, on the other hand, corresponds to the case of negligible evaporation. Brief description of the interpretation of some case studies is given by Zuber(1983) for various lakes. Zimmermann, Turner, Fontes, Dincer and Kumar et al studied water balance of some lakes and the summary of the studies is given in the following paragraphs.

(i) Lake Chala

It is a volcanic crater lake of Tanzania having an area of 4.2 km^2 and volume 3.7 x $10^8 m^3$ and maximum depth of 100 meters. The lake has no surface inflow and outflow. The water balance of this lake was

determined by Payne(1970) by whole body tracing with tritium. No quantitative interpretation of the stable isotope data was attempted by Payne. Zuber(1983) interpreted stable isotope data quantitatively and estimated the real value of outflows and turn over time of the lake. It was also pointed out that inaccuracy in calculating evaporation rates limit the accuracy of measuring outflow.

(ii) Burdur, Egridir and Beysehir lakes

Dincer(1968) determined isotopic content of the evaporating water for the Burdur lake situated in Turkey and used this an index for estimating isotope balances of Egridir and Beysehir lakes. Zuber(1983) solved isotopic balance of Burdur lake and had disagreement with the estimates given by Dincer. A need of further investigation was suggested for the proper management of lake water.

(iii) Lake Titicaca

Fontes et.al.(1979) studied isotopic balance of lakes Titicaca, Bolivia. Titicaca is a large tropical lake located at high altitude on the Andean Altiplano having an area of 8100 km^2. Its mean depth is 107 metre, maximum depth 281 metre and volume 866 km^3. On the basis of 5 years period of observations on water budget, it was indicated that the evaporation accounts for 98% of water losses where as 2% in lost through a surface outflow. Precipitation provides 58% of the input, where as stream inflow was estimated as 42%. Isotopic data and tritium depth profiles(Grabczak 1980) indicated that the isotopic composition of the lake is farely constant and the reservoir can be treated as well mixed.

(iv) Lake Waid

This lake is situated in Federal Republic of Germany and is an artificial reservoir without surface in and outflow. Its volume is

about 2.6 x 10^6 m^3 and mean depth of 11.8 metres. Lake being of recent origin has not reached steady state in its isotopic composition. Detailed study was performed by Zimmerman(1979) and analytical solutions for determining the equilibrium isotopic content of the lake water and the evaporation rate were given. Zuber (1983) reinterpreted the data and calculated that the lack of conventional data on evaporation did not allow complete calculation of the water balance.

(v) bagry Lake

It is an artificial reservoir located near Cracow ,Poland. Its mean depth is 4.5-5.0 metre, maximum depth 8.0 metre and volume 1.2x10^6 m^3. The lake has no surface in flow and outflow. Its turnover time is of interest because of the proposed development of the lake as a recreation object. Water level showed a change of about 0.6 meter over a period of 4-5 years. The lake remains covered with ice for about two months in a year. Zuber (1983) estimated the isotopic balance of the lake and determined the apparent kinetic enrichment of deuterium. The turn over time (5.1±0.8 years) calculated by isotopic method was in agreement that of calculated by other classical methods.

(vi) Lake Kainji

Zimmermann etal (1976) studied the mixing and layering of lake Kainji using deuteriuim content of inflow, outflow and the water in reservoir. Lake is situated in Nigeria was formed after the Kainji dam was constructed on Niger river. Owing to the dependence of the fishery of the lake on the annual cycle of water renewal, the question of the degree and of the pattern of mixing of flood with stored water had become of considerable significance to an understanding of seasonal

changes in the fishery of the lake. Zimmermann et al concluded that lake can not be regarded as a completely mixed lake. Good mixing conditions occur, when the reservoir is near its maximum level. It is slightly mixed at minimumn level. The isotope method has been successfully employed as a promising tool for solving water balance of the lake.

The apparent kinetic enrichment for deuterium was estimated by craig and Gordon(1965) for some of the lakes by fitting the calculated evaporation line to the observed isotope content of lake water. The parameters needed for the roughest estimate are the isotopic composition of the input, relative humidity and the air temperature . One can get best results by improving the estimate of the isotopic composition of the atmospheric vapour.

(vii) Blue Lake

Blue lake is small maar lake situated in Australia in the Karstic region. It provides municipal water supply for a population of about 20,000 inhabitants. The lake has a volume of 3.8×10^7 m^3 out of which about 15% is consumed every year by the inhabitants and lake gets recharged almost entirely by ground water. Turner et.al(1984) studied the water balance of this lake by using stable isotopes and tritium. Concentrations of the environmental isotopes ^3H ^{18}O, ^2H and ^{14}C in the lake water and in the recharging ground water were measured to establish water balance. The groundwater inflow and outflow rates and residence time of water in the lake were estimated. Total ground water inflow to the lake by tritium mass balance did not differ much of that calculated by deuterium mass balance equation.

(viii) Ramappa and Ghanpur lake

Kumar et al(1982) studied water balance of Ramappa and Ghanpur

lakes of the lower manner basin situated in Andhra Pradesh, India Isotopic ratios of lake water samples show a considerable relative enrichment due to evaporation. Well water samples did not show any such enrichment. Various other local tanks in the area were also studied. It was indicated that water which has reached zone of saturation does not show evaporation effect.

The use of Helium-3 and radon 222 along with H^3, ^{18}O and deuterium (the most frequently used isotopes) is found useful. Measuring tritium and hellium-3 content in lakes Erie, Huron and Ontario, Torgersen et.al. (1977) studied the hypolimnion(age) of lakes and mixing across the thermocline. Weisss(1979) also measured tritium and helium-3 in the constance lake to investigate vertical mixing.

Tritium and stable isotopes were used as powerful tools for investigating meromiotic lakes. Craig (1973) studied Tanganyika. It was confirmed that its deep water is enriched in heavy stable isotopes with respect to shallow water. An enrichment in heavy isotopes in deep water is observed also in another large meromiotic lake of the African Rift lake Malawi by Gonfiantini et.al.(1979).

Rn^{222}, an another environmental isotope has found recent application in studying vertical mixing in lakes. It is produced by α -decay of Ra^{226} and has half life of 3.83 days. Rn^{222} method has been used to investigate vertical and horizontal mixing in the Greifensee, a swiss lake near Zurich by Imboden and Emerson(1977).

Shallow lakes for which mixing patterns have been investigated with environmental isotopes are lake Chad in Africa ,(Fontes et.al.1970) and lake Neusiedl in Austria(Rank et.al.1979). Isotopes have found their most useful application in lake balance studies in the determination of sub-surface in-and outflow, normally difficult to evaluate

otherwise. Water balance of lakes is made up of several components:inflow from surface runoff and precipitation, outflow by river, subsurface in-and outflow of groundwater and outflow by evaporation. The determination of subsurface in-and outflow is possible in principle only in isotopically well mixed lakes, in which evaporation has significantly raised the heavy isotope content with respect to inflow. An evaluation of the water lost by evaporation was attempted by Fontes and Gon fiantini(1967) for two small ephemeral lakes in the western Sahara, Algeria. Lake Kinneret in Israel was investigated first by Gat(1970) and later by Lewis (1979). Dincer(1968) has reported the isotopic composition of three Turkish lakes (Burdur, Egridir and Beysehir). Direction of subsurface outflow was measured in a small lake in the Federal Republic of Germany by Stichler and Moser(1979). Zimmerman (1979) studied two small artificial lakes in the Federal Republic of Germany, the water balance of which consits of groundwater in flow, evaporation and subsurface outflow by using stable isotopes. An other interesting application of isotope methods in lake studies is that of Dincer et.al(1979) to evaluate the fraction of water lost by plant transpiration in the Okawango swamps, Botswana with respect to the total evapotranspiration losses.

The examples discussed above show the difficulties of obtaining reasonably good accuracies in determining the water balance of lakes with isotope techniques and are found useful in revealing and evaluating losses to ground water, for which it is probably the best method available. In the past only few attempts were made to use environmental isotopes in this field but the same methods which have shown promise in lakes and reservoir investigations are applicable.

2.4.2 Investigations to study unsaturated zone

For studying the unsaturated zone, it is necessary to investigate the changes in soil moisture content, recharge mechanism and origin of recharge, quantitative estimates of recharge and finally the movement of ground water. At farm level the knowledge of water balance is some times quite insufficient for the determination of the quantity of water to be applied for irrigation. The water balance problem as such is directly or indirectly linked with detailed investigations on evaporation, transpiration, soil moisture etc. The displacement of irrigated water with in the soil profile is of prime importance to get final information on water leaving the root zone and potentially recharging ground water aquifers. To estimate the downward flow of water in the unsaturated zone, irrigated water may be lebelled by well selected ratio-tracer and its spread in the soil may be measured by monitoring the movement of the tracer.

The same can be achieved by using stable isotopes as they provide excellent means for studying the ions and water movement in soil profiles. Soil moisture movement in the unsaturated zone has been widely studied by using tracers. Zimmermann et.al(1967a & b) used HTO and HDO as labelled molecules of water for soil moisture movement studies. During the course of infiltration, the tracer is carried along with the moving soil moisture. The monitoring of the isotopes provide estimates of recharge. However, the use of environmental stable isotopes of the water molecule containing ^{18}O and D have not been seriously attempted to study moisture movement in the unsaturated zone.

Emiliani(1955) analysed deep sea cores for ^{18}O content to study the temperature changes. During Valdivia-cruises. In the Red Sea, a

14 metre piston core was recovered and used to provide excellent material for paleontological and paleoenvironmental studies. The temperature and salinity of Red Sea water varied considerably during the last several thousand years due to variations in the amount of exchange with the Gulf of Aden at the Strait Ob Babel Mandeb. The Red Sea sediments should therefore incorporate ideal founal and isotopic records especially for studies of effects due to eustatic sea level changes. Knowledge of the regional distribution of the stable isotopes, oxygen-18 and deuterium in natural waters is useful in determining "Classifying parameters" to characterize the inventory for the natural water resources in the areas. Stable isotopes have been successfully applied to delineate the origin of waters (Craig,1963),especially in areas where geothermal activity valcanism and rift tectonics include hot spring thermal brine phenomena. Craig applied stable isotope technique to many geothermal areas of the world and found that metoric water overwhelmingly dominates recharge of most geothermal systems. Attempts were made to delineate recharge area in Neyveil Lignite Mine area, India, using natural tritium by Lal(1964-65). Results were not reported.

Zimmermann et.al(1967a & b) used HTO and HDO as labelled molecules of water for soil moisture movement studies. Depth distribution of Deuterium(D) was studied resulting from water evaporating from the surface of a column of saturated soil. The depth of penetration of water enriched with deuterium was determined by a balance between the upward pore-water velocity, the evaporation flux and the downward diffusion of HDO. Good agreement was observed between calculated and observed profiles of deuterium concentration. The low level of thermonuclear tritium in ground water from the saturated zone of the chalk aquifer throughout much of its intake area has been recognised a major anomaly

British hydrology. The tritium profile of pore-water from the unsaturated zone at the Berkshire site(Smith et.al.1970) suggested that about 85% of the total flow of vadose groundwater was by intergrannular seepage at a mean rate of less than 0.9 m/year, contradicting the widely held concept that fissure-flow dominated downward movement. Gupta and Nijampurkar(1974) reported ground water ages using environmental tritium, carbon-14 and silicon-32. Bahadur et.al(1974) used ^{3}H, ^{2}H and ^{18}O environmental isotopes and demonstrated their usefulness in studying the local and regional hydrological problems of semi-arid regions of Gujarat and Rajasthan. High tritium values in shallow aquifer of Gujarat indicated that the aquifer is fast replenished by rainfall. The absence of bomb tritium in confined groundwaters of Gujarat and samples collected at more than 14 metres below the water table in Rajasthan shallow aquifer showed that these waters are older than twenty years, Deuterium and oxygen-18 data of Rajasthan groundwaters indicated that the aridity enriches the stable isotopes. Water of artesian aquifer showed some enrichment which could be due to evaporation before recharge or mixing with some ponded water. Use of environmental isotopes was suggested for studying transit and turnover times of reservoir, ground water flow patterns and salinity problems in Indian arid conditions.

In one of the few studies reported on both ^{18}O and D in the unsaturated zone, Dincer et.al. (1974) measured stable isotope profile of water held in dune sands in the Sahara Desert. It was found that the ^{18}O - D slope was ~ 2.0, much lower than the value of ~ 5 usually obtained for open water bodies subject to evaporation. Gonfiantini et.al. (1974) reported a slop of 2.9 for a shallow ground water body in Algeria attributed to salinity effects. Foster (1975) used environmental tritium to investigate the rate of ground water movement in

the British Chalk and other physically comparable formations. It could explain the anomalously low levels of thermonuclear tritium observed in the saturated zone of Chalk aquifer with important implications for pollution control. Tenu et.al. (1975) utilized environmental isotopes to determine the underground water pattern in the aquifer of Barremean - Jurrassic limestones, representing the main water supply for south Dobrogea region. Both the groundwaters (Barremian - Jurrassic and Senonian aquifers) and surface water (Danube river, situtghiol lake and Black sea) were analysed for ^{18}O, D, ^{13}C and ^{14}C contents. Recharge area, flow velocity and direction were determined.

Athavale and Murti (1975) used environmental tritium for estimating recharge to ground water of Raikal, Andhra Pradesh by analysing soil core profiles for thermonuclear tritium content. Gianni cortecci and Jan Dowgiallo (1975) studies mineral and thermal groundwaters of poland. Sutides on the Oxygen isotopic behaviour of sulphate water system and on the bacterial fractionation of oxygen and sulphur in the reduction of sulphate and the oxydation of sulphide and sulphure were carried out. The measurement of ^{18}O and ^{34}S contents of the sulphate dissolved in underground waters provide information on its origin and on the sulphate, sulphide reduction and oxydation processes occured. In case of water showing $\delta^{18}O > o$, a closed system is considered. Oxygen isotopic positive correlation with the dissolved sulphates and the environmental waters prove the lack of mixing with recent infiltrating waters. Analysis of brines, thermal and cold mineral water come from various old aquifers and are an admixture of relict seawater with infiltration meteoric water. The oxygen and the sulphur isotopic compositions of the analysed sulphate were found higher than the modern sea water sulphate. Allison and Huges (1975) used the tritium concen-

tration of groundwater samples to estimate the amount of water moving laterally into an aquifer and the local recharge.

Schoell and Risch (1976) used ^{18}O content of the Shells as useful tracer for correlating of core material. Increase in ^{18}O concentration during times of reduced exchange and higher salinity was reflected in the isotopic composition of foraminifera shells. Enrichment of ^{18}O content by about $0.6^{o}/_{oo}$ was observed of the Red Sea deep water as compared to inflowing waters from the Gulf of Aden. The application of ^{18}O analysis to deep sea sediments provided information on correlation of cores, establishment of a tentative time scale > 30,000 years by comparihg the ^{18}O record with other well dated records and evaluation of more details on the paleo-environment of the Red sea. Martin Schoell and Eckhard Faber (1976) carried out analysis of oxygen - 18 and deuterium to characterize natural water from the NE-Africanrift triangle. It was concluded that hot springs derive from two water sources, the present day meteoric waters and palea waters deplected in heavy isotopes.

Environmental tritium was used by D.Dan Rabinowitz et.al. (1977) as a hydrological tool in the Roswell basin, New Mexico. It was the early work in Central New Mexico that pioneered the use of environmental tritium as a regional groundwater tracer. The maximum age of groundwater in the northern part of the Raswell artesian basin was estimated. It was concluded that the movement of water underground from out crop area to discharge point was much faster. Study was undertaken to have quantitative estimates of recharge, transmissivity and groundwater flow velocity and flow in a complex aquifer system. Hydrological parameters were computed on the basis of tritium data and were correlated with lithalogic, hydrologic and structural features in the basin. The average dispersion constant, porosity and effectiveness

of the aquifer were determined. Porosity was calculated by Darcy's law,

$$Vs = (K/\theta)\ (d\emptyset/ds)$$

using the average velocity, some known local transmissivities and the measured value of hydraulic gradient. The velocity is the particle flow velocity and not the Darcy velocity. Transmissivities were obtained by pumping tests. The hydraulic gradients were taken from potentiometric surface contour maps. Recharge was computed in the Roswell basin using non linear precipitation & recharge relationship.

Allison and Hughes (1978) measured the mean annual recharge by measuring tritium and chloride concentration within the soil profile and obtained good agreement. Thomas et.al(1978) used deuterium profiles to estimate annual recharge probably due to seasonal variation of deuterium in precipitation. Calf(1978) analysed water samples of the Mereenie sand stone aquifer and Alice springs of Australia for chemical, radio carbon, stable carbon, deuterium and oxygen-18 composition to investigate recharge to the aquifer system.

Radhakrishnan Nair et.al(1978) evolved a simple stable isotope approach for investigating the extent of artificial recharge in the command area of shindawane percolation tank in the Pune district(India). This tank was constructed with an specific purpose for the artificial replenishment of ground water for lift irrigation in small agricultural tracts. Since the hydrological system of a percolation tank consists of an evaporating body contributing to a non evaporating ground water system, stable isotopes have offered an elegant approach to study the effectiveness of the tank and delineate the extent of its beneficial

effect. Following is the isotope balance equation used by Radhakrishnan Nair et.al. for estimating contribution of surface water (ms) to the well water,

$$m_s = \frac{R_{PG} - R_{G(d,t)}}{R_{PG} - R_{L(t-td)}} = 1-mg$$

R_{PG} = Isotopic composition of pure groundwater sampled beyond the recharge zone of the tank

$R_{G(d,t)}$ = Isotopic composition of the admixture of a distance 'd' from the tank and time 't'

$R_{L(t-td)}$ = Isotopic composition of the tank water that is found at a distance 'd' at any time 't'

t = average travel time of seeping water to reach distance 'd'

m_g = original ground water fraction in well water.

Cortecci et.al.(1978) studied several thermal springs emerging from the volcanic cover in the campi Flegrei area and presented the isotopic analysis of water and dissolved sulphate(H,O,T and S isotopes) It was suggested that the analysed spring waters are formed by mixing in different proportions of two components: water of marine origin filling the volcanic cover and coming form the Tyrrhenian sea and a meteoric water. This mixing model was also confirmed by tritium content.

Craig(1978), utilised the constituent composition and carbon and oxygen isotopes for CO_2 in the unsaturated zone gases to provide an independent means of determining what chemical reactions occured during an extended artificial recharge experiment on the high plains of Texas. Gas samples were collected at different depths beneath a water spreading basin to see what effect recharging water had on the unsaturated zone atmosphere.

Sukhija (1976,78,81 & 1982) carried out environmental tritium studies to demarcate recharge areas and to know the source of recharge. Allison(1982) developed a relation between ^{18}O and deuterium in water in sand columns undergoing evaporation. It was suggested that arid zone ground waters are getting replenished by local recharge. Kumar et.al(1982) employed stable isotopes to know the origin of geothermal water and to suggest area of recharge for Puga and Manikaran geothermal areas in India. The stable isotopic studies of water indicated in that the water is predominantly of meteoric origin. δ D contents of Puga thermal waters are more or less similar to that of local meteoric water, however $\delta^{18}O$ values show an oxygen shift of about 3‰ towards positive values, which is generally a characteristics feature observed in deep water circulating through high tempe-

rature environments.

Allison and Barnes(1983) studied water balance of arid and semi-arid areas. A new method was developed for estimating evaporation from a bare surface based on enrichment of natural deuterium. Evaporation rate from the dry salt lake in central Australia was estimated (63 mm per year). Allison et.al(1983) reported experimental data on the depth distribution of the stable isotopes of ^{18}O and deuterium in soil water for columns of soil undergoing evaporation. Under steady state and isothermal conditions in dry soil, isotope concentration rises from a low value at the soil surface to a maximum in the region where liquid transport of water dominates. The concentration then falls exponentially. Good agreement was observed between observed isotope profiles and those calculated by theory. Wurzel(1983) used tritium as a tracer to study the recharge of sabi valley alluvial basin in Zimbabwe by measuring tritium over a period of 15 years. Herraez and Llamas(1983) estimated annual recharge over the Madrid basin using environmental isotopes. The sedimentary basin of Madrid having an area of about 6000 km^2 is a tectonic depression filled with detrital deposits of tertiary age. The thickness of these continental deposits is more than 3000 metre in the deepest parts. Annual mean recharge over the whole basin was estimated at 60 mm per year. Environmental isotopes used were Tritium, Deuterium, oxygen-18, Carbon-13 and Carbon-14. Gupta(1983) studied the distribution of environmental tritium, deuterium and oxygen-18 in the unsaturated zone and the underlying sandy phreatic aquifer in the high pine forests of the Rhine valley near Hiedelber, West Germany.

Saxena(1984) studied soil moisture with an objective of estimating vertical ground water recharge and moisture movement in swedish

eskersand moraines by estimating the seasonal variations of ^{18}O in precipitation. Oxygen-18 was used as a natural tracer to estimate recharge in different types of soils of uppsala. The differing values of ^{18}O in summer and winter precipitation in south Sweden by about 6-8‰ SMOW, giving the soil moisture a distinct isotopic profile. The temporal displacement of soil moisture layers depleted or enriched in ^{18}O was used to calculate seasonal and annual recharge. Collection of soil samples, vacuum distillation of soils and others details have been given by Saxena and Dressie(1984). Campana and Simpson(1984) estimated groundwater residence times and recharge rates using Discrete-state compartment(DSC) model of ^{14}C data. Vertical flow in the aquifer and long term average annual recharge were estimated. Residence time of about 100-15000 years was measured. Salameh and Rimawi (1984) investigated the chemical and isotopic composition of the thermal springs along the east flank of the rift valley of Jordan. The evaluation and interpretation of the chemical and isotopic data provide the informaotion about the origin of the spring water and the source of heat and of abnormal concentrations of dissolved solids.

Gerhard Andres and Richarge Egger(1985) estimated recharge rates of deep ground water by using a new and inexpensive tritium interface method. The depth of the interface between tritium bearing and tritium free ground water with the hydraulic conductivity of the aquifer and the duration of authropogenic tritium input were used to calculate recharge rates in the Bavarian Molasse Basin. Allison et.al(1985) investigated the rates and mechanism of local recharge in semi arid environment beneath two major landscape settings in the Murray basin south Australia. River Murray and its tributories constitute the largest river system in Australia. Increase in the

salinity of this river particularly in its lower reaches is of great concern. How the saline ground water moves in response to changed hydrologic input is the subject of study. Allison carried out this study to investigate the rates and mechanism of recharge in an area where ground water salinities are variable. Mazor(1985) used stable and radioactive isotopes as specific tracers to know proportions of intermixing water types, recharge altitude, depth of circulation and mode of flow etc. Sharma and Hughes (1985) monitored environmental chloride, deuterium and oxygen-18 in the deep coastal sands of Austr-alia with an objective to estimate average recharge to ground water. The stable isotope data deuterium and oxygen-18 showed some isotopic enrichment due to evaporation of the rainfall. The overall small enrichment of isotope in the unsaturated zone suggested that water loss by evaporation is a relatively small component of the total water loss and as such reliable estimates or recharge can not be made from the stable isotope data.

Besides the applications of environmental isotopes to water balance studies, soil moisture studies, recharge and recharge mecha-nism, origin of recharge, evaporation ground water flows, which have been summarised in the section 2.4.1 and 2.4.2, there are many other applications where environmental isotopes alone do not provide suffi-cient information. One of the potential application is discharge measurements of the surface water flows by repeated applications of radiotracers at various points upstream, here the application of radio isotopes can be performed either into canal itself or in the surrounding ground water. It is important to note that environ-mental isotope technique are applicable if the isotope composition of surface and ground water is different. The other field of appli-

cation is seepage losses, losses of water due to seepage and evaporation of surface water bodies are from 20-80% during the transport. Their proper estimation is an important aspect in making decisions for efficient management. In the past, only few attempts have been made to make use of nuclear techniques in the field. Here same methods which have shown promise in lake and reservoir studies are applicable. The selection of radio tracer or stable isotopes is important. The information obtained by one tracer is not enough and use of multitracer technique must be adopted. Gap left by one is filled by another

For example, in case of seepage estimation the use of both environmental isotope techniques and injected tracer technique may be valuable.

Special problem of water conveyance particularly in urban environment are due to the introduction of sewage influents into irrigation water supplies. Confluence dynamics of rivers with various degree of pollution can be studied by employing environmental isotopes. Utilisation of stable and radioactive isotopes in monitoring and predicting pollutants in groundwater systems provide partial and some times complete answer to specific questions concerning the flux of water or pollutants within the hydrological systems. Great emphasis must be given to the applicability of nuclear techniques in ground water pollution problem, however some work has already been done in this field. Nuclear techniques are mostly independent, reliable, useful and partly unique in their applications. Injected tracers have significant advantages over the environmental tracers however environmental isotopic approaches may be proved most suitable in tackling various problems of pollution such as flow velocity vectors in an aquifer, dilution, type of aquifer, climatic conditions, dispersi

on coefficient downward movement of contaminants through the unsaturated zone, stream aquifer exchanges, defining of protection zones. Problems of dating ground water, snow and glacier melt studies also employ environmental isotopes, radio isotopes and stable isotopes. The use of fluoroscent dye tracers along with radio isotopes and environmental isotopes that is a 'multitracer approach' may solve the problems which can not either be solved by conventional techniques.

3.0 REMARKS

In this report, an attempt has been made to review the status and potentialities of environmental isotopes in hydrological investigations. The use of environmental isotopes in relation to the various hydrological and hydrogeological problems for the assessment of the available water potential, study of dynamic behaviour etc. have been proved very useful. The technique is rather used when we either do not have any solution or difficult to reach a correct solution using conventional methods. The interpretation and evaluation of the isotope data in conjunction with the basic hydrological data provided an answer to the various problems of utmost importance for the appraisal and development of water resources.

Combined approach must be preferred for example, in case of studying interconnection between surface and subsurface waters the application of tritium could provide additional useful supporting information to arrive at conclusions by studying stable isotopes alone. For the regioal groundwater investigations, additional use of Carbon-14 may enable interpretation regarding recharge area and direction. The other one, the most important application of isotopes is injected tracer technique, where isotopes can be injected intentionally into the system under study. Isotopes can be choosed to behave exactly like the traced material and should be easily detected. The use of artificially produced radioisotopes is recommended for measurement of flow in surface streams and canals, ground water flow velocity and direction, study of interconnection between aquifers, between surface and subsurface water bodies, studying reservoir dynamics turn over rates, seepage of canals and leakage of dams and reservoirs, discharge measurements etc. Studies

carried out by tracer dilution techniques are in principle cheap and direct as compared to stable isotopic measurements which are very expensive to use. Some problems like estimation of aquifer characteristics, filtration velocity etc. can only be solved by using injected tracer technique however estimation of stable isotope content may provide additional information. Thus environmental isotope methods will be proved very valuable if used in conjunction with artificially produced isotopes and dye tracers.

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