Isotopes in groundwater hydrology

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ABSTRACT Isotopes in groundwater hydrology give a direct insight into the movement and distribution processes within the aquifer. Groundwater in its natural state contains environmental isotopes and conclusions may be drawn from their abundance variations. The isotopes commonly employed in groundwater investigations are the heavy stable isotopes of the water molecule, deuterium and oxygen-18 and the radioactive isotopes, tritium and carbon-14. The stable isotopes are excellent indicators of the circulation of water, while the radioactive isotopes are of special value in detecting the residence time, assuming no contamination of the water has occurred. The application of these techniques in connection with surface and groundwater in Sudan are discussed briefly. It can be concluded that these techniques complement the more traditional hydrological and hydrogeological methods employed in water resource investigations and that their use should be encouraged.

Application des isotopes du milieu dans l'hydrologie des eaux souterraines

RESUME L'utilisation des isotopes du milieu dans le domaine de l'hydrologie des eaux souterraines offre la possibilité d'obtenir une meilleure compréhension des processus de mouvement et de distribution dans l'aquifère. Les eaux souterraines contiennent naturellement des isotopes du milieu et on peut en tirer des conclusions par rapport aux quantités existantes. Les isotopes normalement utilisés pour les recherches dans le domaine des eaux souterraines sont les isotopes très stables et lourds de la molécule d'eau, deutérium et oxygène-18, et les isotopes nucléaires, tritium et carbone-14. Les isotopes stables sont d'excellents indicateurs pour préciser la circulation d'eau alors qu'avec les isotopes nucléaires on peut déterminer avec plus de précision le temps de rétention en supposant qu'il n'y a pas eu de contamination de l'eau. L'application de ces techniques aux études concernant l'eau de surface et l'eau souterraine au Soudan est brièvement discutée. On peut en conclure que ces techniques complètent les méthodes hydrologiques et hydrogéologiques traditionnelles qui sont utilisées pour les recherches dans le domaine des ressources en eau et l'application de ces nouvelles techniques doit être encouragée.
INTRODUCTION

Isotopes, when used in groundwater hydrology give a direct insight into the movement and distribution processes within aquifers. Groundwater, in its natural state, contains environmental isotopes and conclusions may be drawn from their abundance variation. Many hydrologists do not use nuclear techniques because they lack knowledge of the principles involved and the potential benefits. The object of the present paper is to give a general idea of the application of environmental isotopes in hydrological studies.

Techniques used in hydrology may be classified into three groups (Payne & Halev, 1968): environmental isotopes, artificial isotopes, and application of sealed radioactive sources. Environmental isotopes are discussed briefly in the present paper.

Isotope hydrology provides complementary information on the type, origin and age of groundwater. If the isotope content does not change within the aquifer, it will reflect the origin of the water, particularly the location, period and processes of recharge. If the isotope content changes along groundwater paths, this will reflect the history of the water, particularly the mixing, salinization and discharge processes.

There is an International Atomic Energy Agency/World Meteorological Organization (IAEA/WMO) global network, which samples precipitation on a monthly basis, the samples being analysed for deuterium, oxygen-18 and tritium. The available global data, showing the time and areal distribution of stable and unstable isotopes provide a basis for more detailed investigations.

ISOTOPES - GENERAL COMMENTS

A molecule of water consists of two atoms of hydrogen and one atom of oxygen. However not all the atoms of hydrogen and oxygen are the same. Most of the hydrogen atoms have atomic mass one (\(^1\)H), but a small number, referred to as isotopes, appear to have atomic mass two (\(^2\)H = D), known as deuterium, and even three (\(^3\)H = T), tritium. In the same way the normal oxygen atoms (\(^16\)O) are accompanied by isotopes of mass 17 and 18.

Stable isotopes

The principal heavy stable isotopic components of water are HD\(^{16}\)O, and H\(_2\)\(^{18}\)O. The isotopic composition of a water sample is expressed as the per mille deviation of the isotopic ratio, \(R = \text{D/H or }^{18}\text{O}/^{16}\text{O}\) from that of a standard. The standard of reference in general use is an arbitrary point of reference called SMOW (Standard Mean Ocean Water). The data are thus expressed as delta (\(\delta\)) units, defined by

\[
\delta = \frac{R - R_{\text{SMOW}}}{R_{\text{SMOW}}} \times 10^3 \text{ o/oo}.
\]

Whenever water changes state, through condensation or evaporation, an isotopic fractionation occurs, mainly because the heavy isotopic components, HD\(^{16}\)O and H\(_2\)\(^{18}\)O, have lower vapour pressures than H\(_2\)\(^{16}\)O.
Thus moisture evaporated from a lake is depleted in deuterium and oxygen-18 relative to the surface water. Analysis of precipitation and water not subjected to evaporation shows a good linear relationship between the deuterium and oxygen-18 given by

$$\delta D = 8\delta^{18}O + y$$

The excess of deuterium ($y$) is normally $+10$ but this may vary. Waters which have been subjected to evaporation are found to fall below the general line of slope 8 and slopes of between 4 and 6 have been observed.

Radio-isotopes

Isotopes with unstable nuclei are called radio-isotopes and, in reaching a stable nuclear configuration, they undergo radioactive disintegration or decay. This process is spontaneous and cannot be changed by external influences. The rate of decay is unique for each radio-isotope and is described by the half-life ($T_1$) which is the time required for one half of the radioactive atoms to decay. The half-life of tritium is 12.3 years and that of carbon-14, 5730 years.

Tritium, is the radioactive isotope of hydrogen which occurs in precipitation, and originates from two processes, one natural and the other artificial. Tritium is, to a large extent, added to the atmospheric moisture by natural inflow from the stratosphere. However, large quantities have been added by man when detonating thermonuclear devices as was observed at Khartoum in 1963 (IAEA, 1981b), see Fig.1.

![Tritium variation in precipitation at Khartoum](image)

**FIG.1** Tritium variation in precipitation at Khartoum.

APPLICATION OF ENVIRONMENTAL ISOTOPES

General

The isotopes commonly employed in groundwater investigations are the heavy stable isotopes of the water molecule, deuterium and oxygen-18 and the radioactive isotopes, tritium and carbon-14 (IAEA, 1981a; Fritz & Fontes, 1980), see Table 1.
Deuterium and oxygen-18 have been studied extensively in precipitation; generally the highest counts are found in tropical areas with a decrease towards the poles.

The stable isotopes are excellent indicators of the circulation of water, while the radioactive isotopes are of special value in detecting the residence time, assuming no contamination of the water has occurred.

In nature, most groundwater is renewed by the direct infiltration of precipitation and surface water or by subsurface inflow, and thus originates from precipitation. Owing to evaporation and exchange processes, the isotope content and time and space distribution can change during the transition from precipitation to groundwater and sometimes in the groundwater itself.

The average precipitation data and the distribution of the stable isotopes correlate with the groundwater isotope composition. The origin and movement of subsurface waters. The short half-life of tritium provides valuable information on recent recharge whereas the long half-life of carbon-14 dates slow-moving groundwater. Generally, if the water sample is shown to have a significant tritium content, the water is either of subrecent age (younger than 50 years) or, more likely, is a mixture of older and recent water. The carbon-14 and tritium data, when used with hydrogeological data, enable us to decide about the possible water sources. The combined carbon-14 and tritium data have only provide relative age limits, and cannot give absolute groundwater ages since, for example, the mixing ratio of old and young water and the tritium content of the original precipitation are unknown.

Examples
Data are available related to the use of environmental isotopes in various (semi-)arid regions of Africa (IAEA, 1978, 1981a). Some
results in connection with surface and groundwater in Sudan are shown in Fig.2, and discussed below.

The isotopic composition of surface water samples from the White Nile reflects the equatorial rains of central Africa. Similarly the isotopic composition of samples from the Blue Nile reflect the rains from the high altitude of the Ethiopian Plateau. Both White and Blue Nile values for deuterium and oxygen-18 are slightly increased by evaporation (Fritz & Fontes, 1980).

Two groundwater samples were taken at a depth of 150 m, the first, sample A, being from a well near to the White Nile for which a comparison of isotopes with those found in the river indicate recent recharge. The second, sample B, was taken at some considerable distance from the Blue Nile and the very low isotopic values reflect a more humid and cooler period of recharge. Carbon dating indicates that this groundwater is some 15,000 years old.

The isotopic composition of precipitation at Khartoum is also
shown in Fig.2. The point plotted is the total weighted mean for 1962-1965 inclusive, and 1973-1976 inclusive, for stable isotopes deuterium and oxygen-18. The variation in tritium for the same period is shown in Fig.1.

For reference purposes, the SMOW (Standard Mean Ocean Water) reference point and a plot of the general precipitation line are also given together with a present day surface water sample from the River Rhine in the Netherlands, which reflects temperate European climatic conditions.

CONCLUSIONS

Groundwater, in its natural state, contains environmental isotopes and conclusions may be drawn from the distribution variations.

The distribution of the stable isotopes, deuterium and oxygen-18, of groundwater correlated with average isotopic data of precipitation define the origin and movement of subsurface waters. Radio-isotopes, such as tritium, provide valuable information on recent recharge whereas carbon-14 data show slow-moving groundwater.

The use of isotope techniques which complement hydrochemical and hydrogeological studies should be encouraged in both surface water and groundwater resource development.

REFERENCES


IAEA (1981a) Stable Isotope Hydrology, Deuterium and Oxygen-18 in the Water Cycle. IAEA, Vienna, Austria.

IAEA (1981b) Statistical Treatment of Environmental Isotope Data in Precipitation, IAEA, Vienna, Austria.