

**THE ROLE OF HYDROLOGY
AND HYDROMETEOROLOGY
IN THE ECONOMIC DEVELOPMENT
OF AFRICA**

**LE RÔLE DE L'HYDROLOGIE
ET DE L'HYDROMÉTÉOROLOGIE
DANS LE DÉVELOPPEMENT ÉCONOMIQUE
DE L'AFRIQUE**

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NUCLEAR TECHNIQUES IN GROUNDWATER EXPLORATION

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ABSTRACT

The principles of the use of environmental isotope techniques, depending upon the natural variations of deuterium, oxygen-18, tritium and carbon-14, are described. Examples of applications are drawn from studies on the African Continent.

RESUME

Les principes déterminant l'emploi des techniques des isotopes naturels dépendant des variations naturelles du deutérium, de l'oxygène-18, du tritium et du carbone-14, sont décrites. Les exemples de ces applications proviennent d'études faites sur le Continent Africain.

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INTRODUCTION

Nuclear techniques are one of the recent technological developments in hydrology which can help solve hydrological problems and contribute to a better understanding of hydrological phenomena. The wide range of techniques available to the hydrologist are discussed in a guidebook (IAEA-1963) which outlines the principles of application to specific hydrological problems. In groundwater studies the techniques include the use of nucleonic instruments and injected radioactive tracers and the use of a group of techniques based upon the natural variations of environmental isotopes in waters of the hydrological cycle. Nuclear logging methods fall in the first group and have been used in the petroleum industry for some time, but relatively limited use has so far been made by the hydrologist. It is hoped that a recent report (IAEA-1971) will generate interest in the use of these methods.

Environmental isotope techniques are already being used in a number of UNDP Special Fund projects in countries on the African continent, mainly by co-operative arrangements between IAEA and FAO, UNESCO and WHO. Bearing this in mind and the limitations on length, this paper is limited to a brief discussion of the principles of application of these relatively new methods.

Environmental isotopes may be defined as those isotopes, both radioactive and stable, which occur in the environment in varying concentrations and over which the investigator has no direct control. At present, the commonly used environmental isotopes are the stable isotopes deuterium and oxygen-18 and the radioisotopes tritium and carbon-14. The first three isotopes are part of the water molecule and as isotopic tracers constitute the only real water tracers available to the hydrologist. All other water tracers are present in a dissolved form and, therefore, are subject to loss by precipitation, adsorption and exchange.

Environmental isotopes have two immediate advantages over the use of injected radioisotope tracers. First, there are no problems of health and safety, and second, since the waters of different parts of the hydrological cycle are labelled with these isotopes, it is possible to make much larger scale studies than are possible with injected radioisotopes. Many applications are available and there is a continuing refinement and development of techniques.

OCCURRENCE OF STABLE ISOTOPES IN NATURAL WATERS

Deuterium and oxygen-18 occur in the oceans in concentrations of about 320 p.p.m. and 2000 p.p.m. for the molecular species HDO and H₂¹⁸O respectively. In practice, the isotope ratios D/H and ¹⁸O/¹⁶O are measured in a mass spectrometer; the data being expressed as per mil deviations (δ_D , δ_{18O}) from a standard. The accuracy of measurement is about ± 2.0 and ± 0.2 for deuterium and oxygen-18 respectively.

Owing to the difference in vapour pressures and diffusion velocities in air of the different isotopic species of water, fractionation takes place when water changes state. Water vapour in equilibrium with liquid water is depleted in the heavy isotopic species with respect to the liquid phase. Thus, precipitation and, therefore, river waters and most groundwater are depleted in deuterium and oxygen-18 as compared with the isotopic composition of the oceans. This isotopic depletion becomes more marked with increasing latitude, distance from the sea and altitude due to the continuous removal of the heavier isotopic species by precipitation.

In a given region, a seasonal variation of the isotopic composition of precipitation is seen which closely parallels the variation in air temperature, so that precipitation in winter is more depleted in the heavy isotopes than in summer. However, these seasonal variations are soon smoothed out during passage to the groundwater table. This is due to the dispersion taking place during movement through the unsaturated soil zone and also to the fact that not all precipitation reaches the groundwater system due to run-off and evapotranspiration which is not uncommon in arid and semi-arid areas.

Craig showed that the isotopic composition of precipitation at a large number of stations in the world approximately obeys the following relation:

$$\delta_D = 8 \delta_{18} + 10 \quad (1)$$

Water which has been subjected to evaporation does not plot on the line given by equation 1. When water is subjected to evaporation the isotopic composition changes so that the remaining water is enriched with respect to the heavy isotopic species. However, the relative change for the deuterium and oxygen-18 is different from that in condensation processes so that a slope of 4 to 6 is observed.

OCCURRENCE OF TRITIUM IN NATURAL WATERS

Tritium, the radioisotope of hydrogen, has a half-life of 12.26 years and is a soft beta emitter (E_{\max} 18 kev). Its occurrence in precipitation arises from two sources. The first, a natural one, is the production by cosmic radiation. Estimates of the concentration in precipitation vary, but are of the order of 10 T.U. (1 T.U. = T/H $\times 10^{18}$). The second source is man-made and is derived,

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since 1952, principally from the detonation of thermonuclear devices. This production has swamped the former by injecting periodic pulses into the atmosphere which has resulted in the labelling of waters of the hydrological cycle with an amount of tritium which can easily be measured. Tritium concentrations in precipitation reached a maximum in 1963 in the northern hemisphere.

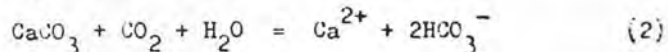
The concentration of tritium in precipitation at any given location varies with season and exhibits a maximum in late spring and early summer. Knowledge of this variation is necessary when estimating the tritium concentration of water which is effective in recharging an aquifer. Tritium concentrations are also dependent upon geographic location. At a given time the concentrations are greater at higher latitude and more continental locations.

OCCURRENCE OF CARBON-14 IN GROUNDWATER

Carbon-14 has a half-life of about 5,730 years and, like tritium, is produced by cosmic radiation and from thermonuclear devices. The carbon-14 is oxidized to carbon dioxide and mixes rapidly with the atmospheric carbon dioxide reservoir. Any material that uses or reacts with carbon dioxide will contain a constant amount of carbon-14 as long as the material is in equilibrium with the atmospheric carbon-14 reservoir. After removal from contact with this reservoir, the carbon-14 content of the material will be subject to radioactive decay.

The carbon in groundwater is present in the form of dissolved carbon dioxide, bicarbonate and carbonate, bicarbonate being the predominant form at the pH of most groundwaters. In order to obtain a true age from the measurement of the carbon-14 content of a sample of groundwater, it is necessary to know what proportion of the total dissolved carbon species is derived from soil-air carbon dioxide which contains carbon-14. The remaining proportion is derived from non-biogenic carbon which contains no carbon-14 so that the radiocarbon age of a water sample will be falsely greater than its true age.

The $^{13}\text{C}/^{12}\text{C}$ adjustment technique permits an estimation of the carbon derived from soil-air by measurement of the $^{13}\text{C}/^{12}\text{C}$ ratio of the dissolved carbon species.



In the above equation 2 which represents the solution of limestone, the carbon in the soluble bicarbonate is partly derived from the carbon dioxide derived from soil-air containing carbon-14, and partly from the carbon-14 free carbonate. The relative proportions may be determined from the $^{13}\text{C}/^{12}\text{C}$ ratio of the bicarbonate if the isotopic ratio for both limestone and soil-air carbon dioxide are known. Values for limestone are known quite well and a number of measurements of the other parameter indicate the range of values to be expected.

APPLICATION OF ENVIRONMENTAL ISOTOPE TECHNIQUES

Before a discussion of the various uses it should be emphasized that the optimum benefit is obtained if the isotope techniques are used in conjunction with conventional hydrological methods, as is the

case in the Special Fund projects mentioned earlier. Isotope techniques are often very valuable in substantiating a hypothesis based on hydrological data, or even deciding between alternative hypotheses.

The stable isotopic composition of a groundwater sample is valuable for classification and providing information on the origin of the water. Although there is a marked seasonal variability in the stable isotopic composition of precipitation, considerable smoothing occurs during infiltration through the soil and during transit through basins. Consequently, groundwater usually has a fairly consistent isotopic composition characteristic of its origin. This is true for granular aquifers, but not necessarily so when the flow is through fractures and tubular openings such as in karst and volcanic rocks, when some of the seasonal variability may be retained. An illustration of the value of stable isotope data is provided in a current UNDP project, executed by FAO, in Hodna, Algeria, where the stable isotope composition of the phreatic and artesian aquifers was found to be different, which excluded the hypothesis that the artesian aquifer was recharging the phreatic aquifer by leakage.

The change in isotope composition induced by evaporation of surface waters is of value in studying the relation of surface water to groundwater. An application of this type has been made on the border between Kenya and Tanzania (Payne, 1970). The isotope composition of Lake Chala which straddles the border was completely different to springs in the area. These results refuted the hypothesis that the springs received a significant proportion of their recharge from the lake. This type of application is particularly valuable when competing demands for the water are under consideration.

The hydrology of Lake Chad and the surrounding area is also being investigated by isotopic methods (Fontes *et al.*). The enriched stable isotope composition of the lake water owing to evaporation has demonstrated that leakage to groundwater is limited to areas quite close to the lake where mixing also takes place with rain water recharged on the sand dunes. The stable isotope data also demonstrate the stratification of water in the phreatic aquifer and the influence of flood water from the Chari river, the major source of supply to the lake, on the neighbouring phreatic aquifer.

The half-life of tritium limits its use in groundwater studies to shallow aquifers or in fractured rocks where movement is relatively rapid. The presence of thermonuclear tritium is a unique tool for testing hypotheses related to recharge. Investigations in arid and semi-arid areas often pose the question as to whether or not active recharge is taking place. In the example of the Hodna project cited earlier the highest tritium concentrations in the phreatic aquifer were observed near wadis, thus confirming that these are probably the major source of recharge to the aquifer. Elsewhere in the aquifer the tritium concentrations were rather low indicating that direct recharge by precipitation is probably rather low. The same technique is being applied in a UNDP project executed by WHO in Senegal. Tritium has demonstrated the existence of recharge in a number of the aquifers under investigation.

Attempts to interpret measured tritium values in terms of the time since recharge of the water sampled is complicated for two principle reasons. Firstly there is uncertainty in the tritium value to be used at the time of recharge and this is particularly so in the cases

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of water recharged since the early 1950's owing to the production of tritium by thermonuclear devices. Secondly, from the hydrological standpoint, a sample of water most likely represents a mixture of waters of different ages owing to the dispersive and mixing processes which have taken place since recharge. Therefore the dynamics of the aquifer are better considered in terms of transit time rather than age. In practice quantitative data require a time series of observations which are then matched with computed tritium concentration curves derived from different models postulated for the system.

Clearly the use of environmental tritium is limited to systems having relatively short transit times. Thus in studies in semi-arid and arid areas and particularly in confined aquifers, we find that carbon-14 measurements are required. Such studies are currently being made in a number of countries on the African continent, including Algeria, Chad, Senegal, Sudan and Tunisia. The carbon-14 data are normally interpreted in terms of groundwater velocity from which a figure for the regional mean permeability may be derived. It is considered that estimates of the latter parameter are more realistic than the extrapolations to a given area from pumping tests.

Carbon-14 data have also been used in a study of an artesian aquifer on the south coast of South Africa (Vogel). The low flow rate of 0.7 m/y estimated is presumed to be due to the fact that very little water can escape through the confining layers to the ocean. The same author has also estimated groundwater velocities in two aquifers in the central arid region of southern Africa where the water is in crystalline and consolidated rock covered by a thick layer of Kalahari sand.

CONCLUSIONS

Nuclear techniques provide the hydrologist with a powerful tool not only to solve routine problems, but also problems for which no solution was known before. Environmental isotope techniques, which are the subject of this paper, depend upon the fact that water can be identified by its composition thus giving the hydrologist a whole range of potential applications only some of which have been briefly touched upon. For example, no mention has been made of the use of stable isotope data in determining the source of salinity in saline waters, a problem which is difficult to resolve without recourse to isotope data.

Although nuclear techniques are not being used as yet as widely as their potential indicates, the number of studies in Africa has reached the stage where data from one study is also of benefit to other studies in the area. In addition to the work of the IAEA in co-operation with other specialized agencies there are probably about seven other groups actively engaged in isotope studies in Africa. These efforts will no doubt contribute to a wider awareness of the capabilities of these techniques and thus to their wider use as an additional tool for the hydrologist.

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