Water and earth sciences: Isotopes in the field

Countries are applying stable and radioactive elements to help track and solve hydrological problems

by Roberto Gonfiantini and Gert Hut

Nuclear techniques using isotopes are precise, modern tools for studying water resources. They can provide an adequate solution to the problem of the origin, distribution, and properties of water in a given region, especially when they are combined with all other tools available to hydrologists, hydrogeologists, and geochemists.

Modern isotopic research in hydrology, on the one hand, is based on the discovery by W.F. Libby in 1946 of the natural abundance of carbon-14 and tritium, and, on the other, on the experimental and theoretical work, appearing in 1947, of H.C. Urey and J. Bigeleisen concerning the fractionation effects for stable isotopes. Although the first publications on the natural abundance of isotopes in water appeared within a few years, it was not until the 1960s that isotope hydrology became a separate field of research.

The IAEA entered this field soon after its establishment (30 years ago this July) at the encouragement of many well-known scientists. It fortunately coincided with a rapid development in the area of applications of isotope techniques.

This development now has been reflected in the proceedings of seven symposia on the use of isotope techniques in water resources development organized by the Agency, several of them in co-operation with the United Nations Educational, Scientific and Cultural Organization (UNESCO). The first symposium was held in Tokyo in 1963, the last one was held in Vienna from 30 March to 3 April 1987. It was attended by more than 160 scientists from 45 countries and three international organizations.

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Photo above:
Much attention is being devoted to assessing water resources in arid countries of Africa and other regions. (Credit: BRGM, France)

Artificial and environmental isotopes

An ideal water tracer should have a behaviour as similar as possible to that of the water and, at the same time, it should be easily detectable — possibly *in situ* — and easily injectable over large regions of a hydrogeological system.

Artificial isotopes emitting gamma radiation possess some of these characteristics — they are easily detectable — while environmental isotopes — whose measurement is more difficult — are injected over the entire system by natural processes.

Isotopes such as tritium, deuterium, and oxygen-18 are part of the water molecule and therefore have a behaviour which is identical — or almost so — to that of the bulk of water in the system.

A specific field of isotope hydrology is based on the interaction of radiation with matter. A typical example is that of radiation emitted by a source that is absorbed by sediment transported in suspension by river water. The radiation absorbed is proportional to the suspended sediment concentration. Important information about sediment transport has been obtained using this technique.

In 30 years of investigations and applications of isotopes to case studies, a considerable amount of information and knowledge has been accumulated. Therefore, a skilled isotope hydrologist should be able to select those isotopes and techniques most suitable to the hydrological problem to be solved. For example, artificial isotopes are injected in a given point of a hydrological system and monitored in other points of it, generally not too far away, where they are expected to show up. The time

The tritium gas preparation system is among the analytical tools at the IAEA's isotope hydrology laboratory in Vienna. (Credit: Katholitzky for IAEA)

elapsed between the injection and the detection, as well as the shape of the isotope concentration curve at the detection points, provide detailed and precise information on the behaviour of the system (on the conditions prevailing during the experiments). Considerable skill is required to plan the experiment correctly.

The situation is different for environmental isotopes. They are either natural or man-made (or both at the same time) but their distribution in the hydrological cycle is governed by natural processes. Therefore, their injection occurs all over the hydrological system, continuously or at least during long periods of time. Studies with environmental isotopes generally are carried out over large bodies of water — rivers, lakes, groundwater — and conclusions are drawn on their major characteristics, which are valid for a long time. The theoretical background and the interpretation of the data of environmental isotopes are usually rather complex and require considerable experience and a multidisciplinary approach.

For groundwater in aquifers, the concentration of deuterium and oxygen-18 (stable isotopes) can often be used to distinguish different water bodies and to determine the origin of the water. This is done in relation to the corresponding stable isotope concentration in the precipitation infiltration in the aquifer's recharge area. Sometimes the stable isotope concentration in the aquifer can be related to infiltration in a period with different climatic conditions.

Different stable isotopic compositions of water from rivers originating in mountains and from local precipitation can be used to determine the mixing of precipitation and rivers in groundwater. The change of the stable isotopic composition of stagnant water in lakes is often used to determine the evaporation rate of the lake.

Age determinations of water

An important point of interest is the residence time of water in an aquifer, also called the "age" of the water. Several radioactive isotopes can play a role — depending on their half-lives — to settle the question of how long ago the water under consideration was in contact with the atmosphere. Very young groundwater means that replenishment can depend on the rainfall in a certain year and that a dry season can be followed by a lack of groundwater. The other extreme, very old groundwater, can imply no replenishment and therefore mining of the groundwater.

Tritium, a radioactive isotope of hydrogen with a half-life of 12.43 years, is present in very low natural concentrations. This is on the order of a few picocuries per litre. Due to the atmospheric thermonuclear bomb tests in the 1950s and 1960s the concentration of tritium in precipitation increased drastically; in some cases it reached almost 1000 times natural levels. After the Test Ban Treaty, the tritium concentrations returned to values that are now almost equal to pre-bomb values. This tritium "signal", if it entered the groundwater, is used to determine whether the water has an age "post or pre-bomb".

Carbon-14, with a half-life of 5730 years, is an environmental isotope very often used for age determination. A serious problem is that the carbon atom is not a part of the water molecule, but of the bicarbonate ion dissolved in the water. Because of this, the water chemistry has to be taken into account.

The bicarbonate in groundwater is thought to be composed of carbon from two different sources: one from humus in the soil, infiltrated with the precipitation, and the other from marine carbonate in the aquifer and dissolved by the groundwater. The first carbon contains carbon-14 since it is in equilibrium with the carbon dioxide produced in the soil by plant respiration and composition of organic matter; the marine carbonate has no carbon-14 any more. For an age determination, the initial carbon-14 concentration, that of the recently infiltrated water, has to be known. Therefore, several models have been developed to determine the fraction of "modern" and "old" carbon. In these models, the different carbon concentrations of humus and the marine bicarbonate are used, for example.

Carbon-14's half-life limits the range of dating to approximately 50 000 years. The concentration of carbon-14 in modern carbon is already so low (10^{-12}), that the measurement is conventionally done by decay counting. After approximately 10 half-lives, and a carbon-14 concentration of 0.001 of that of modern carbon, the analytical technique no longer has the required accuracy. The development of accelerator mass-spectrometry, by which technique the carbon-14 ions are counted directly using a tandem Van de Graaff accelerator, in principle enables dating beyond that limit, and the use of a smaller sample size. In practice, however, machine contamination has restricted dating to about the same range as with decay counting.

To extend the range of dating, another isotope with a longer half-life has to be found. Chlorine-36, for example, has a half-life of 305 000 years. The water- and geo- chemistry were thought to be simple. However, the concentration of chlorine-36 is so low that tremendous amounts of water had to be processed before a decay measurement could be done. The development of accelerator mass-spectrometry has improved the situation, since much smaller amounts of chlorine are required. The results obtained over the past 5 years or so indicate that, in many cases, the geochemistry is much more complicated than expected.

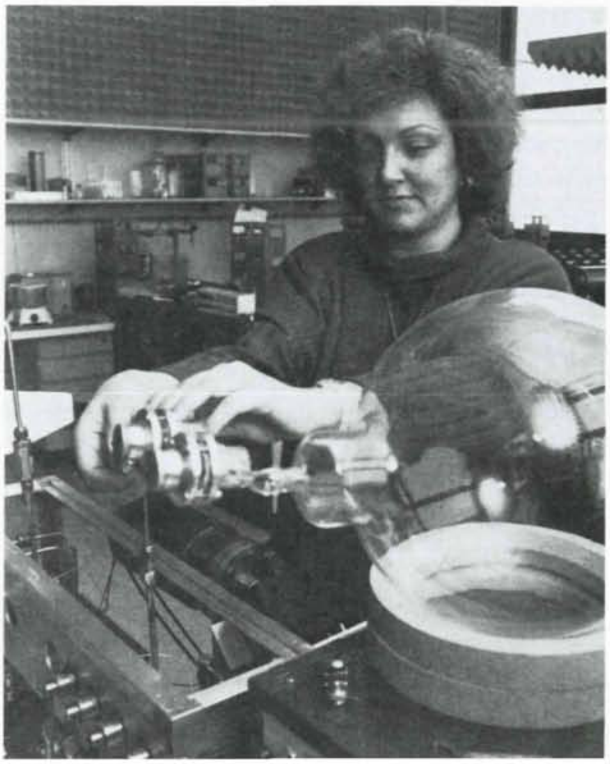
In some situations, however, encouraging results have been obtained. An example is the application of chlorine-36 measurements in the Australian Great Artesian Aquifer. The developments in this field will enable the study of large aquifers like those of Continental Intercalaire in the Sahara (about 600 000 square kilometres) or Botacatu in Brazil (about 1 000 000 square kilometres).

IAEA support and activities

All types of applications of isotope techniques to hydrology have been supported by the Agency since the inception of its programme. This support consists of provision of experts, equipment, and training to carry out the field work and all the necessary analytical support directly in the country concerned. However, in the case of environmental isotope applications, only a limited number of countries have laboratory capabilities to perform the analyses: In this case, they are carried out at the Agency's isotope hydrology laboratory, located in Vienna. The IAEA also encourages the development of new techniques and the refinement of those already in use, both in terms of analytical improvements and more elaborate theoretical approaches to data interpretation.

Examples of applications carried out with Agency support are innumerable. Some of the most important ones have been done in recent years or are currently being done.

• *Northern Africa.* At the beginning of the 1980s, the United Nations Development Programme (UNDP) started a project in the three Maghrebian countries in Northern Africa — Algeria, Morocco, and Tunisia — with the objective of assessing the water resources, especially groundwater, since the countries are largely arid or semi-arid. In addition, a part of the work programme was devoted to techniques to increase water resources: for example, the artificial recharge of groundwater; the purification and re-utilization of used water; the evaluation of land erosion and the suspended sediment transport following it in ways that may strongly shorten the life of artificial reservoirs. The Agency decided then to establish a parallel regional project in the three countries for applying isotope techniques to study some of these problems, taking advantage of the important infrastructure that had been set up for the UNDP project. This was advantageous for both parties. Studies were carried out in the Tunisian and Algerian Sahara to determine the age and the dynamics of groundwater in the two major aquifers — the Continental Intercalaire and the Complexe Terminal — which in principle may help in establishing the mathematical models and planning the exploitation. In view of the very old age of the groundwater, which was replenished more than 30 000 years ago during the Pleistocene, it is now planned to use chlorine-36 as a dating tool.



Maria da Conceição Ribeiro Vieira, of Portugal, during her scientific fellowship training at the IAEA's isotope hydrology laboratory in Vienna. (Credit: Katholitzky for IAEA)

In the bed of the Wadi N'Fis close to Marrakesh, artificial isotopes were used to investigate the water movement in an experimental infiltration site for groundwater recharge. These studies showed that the decantation and precipitation of suspended sediments in the first basin did not occur with the required efficiency due to short circuits in the water circulation. The first basin's configuration was then changed accordingly so that sediments would be deposited in it and not in successive basins, with, as a consequence, a decreased rate of infiltration.

In a site near Tunis, tritiated water was reinjected together with used water to check the purification efficiency of soil and the propagation of reinjected water in the aquifer. This study is still not completed, but the results so far are sufficient to demonstrate the validity of the method, and especially the validity of tritium as an ideal water tracer.

● *Asia and the Pacific.* In several countries and regions, co-ordinated research programmes in isotope hydrology are being financed by Member States and executed by the Agency. One programme in Asia and the Pacific, financed by Australia, includes research projects in the Republic of Korea, Indonesia, Thailand, Malaysia, and Sri Lanka. This programme will be concluded this year with a workshop in China.

● *Latin America.* Another co-ordinated research programme, this one financed by the Federal Republic of Germany, aims to build up the use of isotope techniques in hydrology in Latin America. Ten countries are participating in this programme — Argentina, Bolivia, Brazil, Chile, Colombia, Cuba, Dominican Republic, Ecuador, Guatemala, and Mexico. It will conclude in 1987 with a seminar in Mexico City. Another programme, financed by Italy, has the objective of showing the potential of isotope and geochemical techniques in geothermal exploration. Participating countries include Argentina, Bolivia, Colombia, Costa Rica, Ecuador, Guatemala, Peru, and Venezuela. Most Latin American countries have important geothermal resources, which so far are exploited only in Mexico and El Salvador. Mexico, which will soon join the programme, today is the third producer of geothermal electricity in the world, after the United States and the Philippines and before Italy.*

Water resources in arid countries

Special attention has been dedicated to groundwater resources assessment in arid countries. Isotopes are in fact one of the most powerful tools to investigate the occurrence of groundwater recharge and to identify fossil groundwater — that is, water that has been replenished under more humid climatic conditions of the past.** Studies have been conducted with Agency support in many arid countries in Africa and Asia. Recently, two regional projects have been launched, one in three western African countries — Mali, Niger, and Senegal — and another in eastern Africa, including Egypt and Sudan. This second programme is financed by the Federal Republic of Germany.

Training support

Training is also strongly supported by the Agency. This year, for the first time, group training has been organized by the isotope hydrology section consisting of lectures, laboratory training, and scientific work on a field project. Fellows from Albania, Egypt, Colombia, Portugal, Philippines, Jordan, Sudan, Cyprus, and Indonesia are participating in this training experiment. If successful, it will be repeated so that more scientific fellows are able to participate.

Water symposium attracts high interest

To help solve practical problems, hydrologists, geochemists, and other scientists are increasingly using both stable and radioisotopes as useful, sometimes unique, research tools at aquifers, lakes, reservoirs, rivers, and estuaries. Isotopes — elements in the environment or artificially produced — are used as tracers to describe water properties and characteristics and to assess prospects of supplies under different climatic and geographical conditions. They are also applied to study water and sediment movements, salinization, and pollution, for example. Important isotopes in hydrological investigations are deuterium (hydrogen-2) and oxygen-18, both of which are stable, and tritium (hydrogen-3) and carbon-14, which are radioactive.

At an international symposium in Vienna from 30 March to 3 April 1987, more than 160 scientists and researchers from 45 countries and three international organizations reviewed the use of these nuclear and related techniques in hydrological investigations. Jointly sponsored by the IAEA and the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the symposium featured reports and papers on research and field studies being carried out in more than 30 countries in Africa, Europe, Latin America, and other regions. The symposium was the seventh in a series since 1963 that has been organized by the IAEA to foster exchange of scientific information and research results in this important field. Through its technical co-operation programme, research contracts, and other mechanisms, the Agency has also been providing direct financial support and expert assistance to hydrological projects around the world. Co-operation with UNESCO has been established within the framework of an international hydrological programme that aims to help developing countries effectively apply techniques and tools for solving local and regional water problems.

Proceedings of the symposium will be published later this year.

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* See "Isotopes in geothermal energy exploration", *IAEA Bulletin*, Vol. 25, No. 2 (1983).

** See "Investigating water resources of the desert: how isotopes can help", *IAEA Bulletin*, Vol. 23, No. 1 (1981).