Artificial radioisotopes in hydrological investigation

A review of specific applications

by Antonio Plata-Bedmar

Artificial radionuclides have been contributing for more than 30 years to the investigation of hydrological problems. A considerable amount of information and knowledge has been accumulated during this period of time, and we are now in a sound position to make an evaluation of the real contribution of these techniques and its possibilities in the future. Hydrological problems are frequently very complex and many different techniques have to be applied for their investigation. None of the developed techniques can be neglected *a priori*; this is also the case of radioisotope techniques which occupy a complementary but important place in this context.

Radioisotopes are used in hydrology in two different ways: as sealed sources of radiation, and as tracers.

Radioactive sealed sources

Different kinds of gauges containing radioactive sealed sources have been developed for specific hydrological purposes. The operation of these gauges is based on the interaction of radiation with matter which may provide information on the solid medium related to the water flow. The following methods are the most important:

- ***Measurement of the concentration of the sediments transported in suspension by river water.*** This transport represents more than 75% of the total solid transport of rivers and very often raises problems of great economical importance, for instance, for the life of artificial reservoirs. No adequate solution is provided by the known conventional methods. Several nuclear gauges have been developed for these purposes using americium-241 and caesium-137. The concentration of sediments is registered automatically over long periods of time (fixed gauges) or is manually measured (portable gauges). Further development of fixed gauges is needed in order to improve its performance and reliability and to reduce its cost.

- ***Measurement of thickness and density of layer of deposited sediments.*** The interest of this method is related to the maintenance of navigation channels in harbours and estuaries (dredging operations), as well as to the colmatation of reservoirs, especially in arid and tropical zones where the highest rates of transported sediment are registered. No conventional techniques exist which can give the information provided by these gauges.

Some nuclear gauges are commercially available, which allows obtaining density profiles of the layer of deposited sediments. The variation with time of these profiles gives information on the dynamics of the deposition. Further development is also needed in order to upgrade the measuring technique in the usually adverse field conditions.

- ***X-ray fluorescent analysis of sediment.*** Radioactive gamma sources are used to excitate the characteristics of X-rays of the heavy elements ($Z > 20$) contained in sediment samples. The identification and semi-quantitative analysis of these elements are achieved. The combined use of these techniques with other analytical methods, for example, activation analysis, makes it possible to identify the origin of sediment transported by rivers.

- ***Well-logging methods.*** The natural gamma logging method has reached extensive diffusion and is widely used for hydrological and geological investigations. The method allows for the identification of clay layers, which is very important in order to obtain permeability profiles in alluvial and colluvial aquifers as well as to identify fractures filled with clay in the case of fractured rock aquifers. On the other hand, the logging methods neutron-neutron and gamma-gamma are mainly used in

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Photo above: Measurement of groundwater flow velocity in Nicaragua by the dilution method.

connection with irrigation studies and to investigate infiltration processes at the unsaturated zone, which are especially interesting in the case of arid zones. The neutron-neutron method gives profiles of the water content in the soil, which corresponds to porosity profiles in the saturated zone. The gamma-gamma method gives wet density profiles of the formation from which the porosity can also be evaluated for the saturated zone. The need for specially constructed boreholes seriously limits the use of these methods for hydrological purposes.

Radioactive tracers

Hydrological problems which demand the use of artificial tracer techniques are apparent in all countries of the world. Many of these problems can only be investigated by means of radioactive tracers. The need for tracers is mainly a consequence of the large variability with time and space of relevant parameters of water systems. This variability frequently makes it difficult to obtain reliable values of the parameters which are responsible for the behaviour of water in the system under investigation, especially when precise information is absolutely necessary. In these cases, the use of tracers may provide the only available solution.

● *Tracing of sediments.* The investigation of the transport of sediments by water flow based on the use of labelled sediments can be considered as a highly developed technique. Suspended sediments can be easily labelled using gold-198, iron-59, or hafnium-181 as a tracer, for example, and the deposition of these sediments at the bottom of water bodies can be investigated. The technique is of interest in studies concerned with deposition in harbour zones, estuaries, reservoirs and infiltration ponds for artificial recharge of water.

Considerable experience has been accumulated in the past on the use of artificial radioactive tracers for the determination of bed load transport in rivers and seas. Several radionuclides are available for sediment labelling; they include scandium-46, lanthanum-

Typical tracer applications

Below are some of the most important and typical applications of artificial radioactive tracers. It should be noted that frequently they must be combined with other techniques (environmental isotopes, hydrochemistry, and other conventional hydrological techniques) to obtain the required information.

Surface water

● Flow-rate measurements in rivers and open channels. Many requirements of flow-rate measurements can only be given by means of tracer techniques. Radioactive tracers are mostly appropriate for the measurement of large flow rates between 50 and 1000 cubic metres per second. For lower flow rates other non-radioactive tracers may be used advantageously. Calibration of turbines in hydro-electrical power plants and calibration of gauging stations in rivers can be mentioned as typical examples.

● Dispersivity studies in rivers, lakes, estuaries and seas, mainly, connected with water pollution problems. Dispersion coefficients obtained through these experiments are frequently used to adjust mathematical or hydraulical models.

● Residence time measurements and mixing characteristics in lakes.

● Dynamics of river basins including the determination of transit times of water. Environmental tracers (for example, stable isotopes of water) can help in these studies.

● Problems connected with the use of water for irrigation purposes, including loss of water in channels; identification and evaluation of return flow; and partial contribution of water coming from different sources.

● Tracing of polluted water in order to investigate the self-purification capabilities of different surface water bodies.

● Connection with groundwater (leakage of surface water bodies) for which environmental isotopes are frequently also basic tools.

Groundwater

● Infiltration studies of the unsaturated zone. Artificial tritium is the only choice for these studies. The information is obtained through vertical profiles of the injected tritium measured at different intervals.

● Determination of parameters of aquifers through single- and multi-well tracer tests, including flow velocity determination by point dilution and transit time methods; identification and measurement of vertical flow inside wells; determination of the direction of the groundwater flow; determination of effective porosity and permeability in combination with pumping tests; determination of dispersion coefficients of aquifers; distribution of fractures (vertical profiles) in fractured aquifers.

● Investigation of the dynamics of karstic systems.

● Many local or regional problems on the dynamics of karstic systems can only be studied by means of artificial tracers. Generally the tracer is injected in a given part of the system and monitored in sites where it is expected to arrive. Many experiments of this type have been carried out over the last 30 years using fluorescent and radioactive tracers. Apart from determining the flow pattern of the water, semi-quantitative information can be obtained on the volume of the groundwater reservoir.

● Tracing of geothermal fluids re-injected into the geothermal field after they have been exploited. The fate of the re-injected fluid is investigated.

● Tracing of water injected into aquifers during artificial recharge processes. The dynamic behaviour of the injected water, which includes mixing with previously existing water, is obtained. Furthermore, these methods can give information on the chemical evolution of the injected water (important if we are dealing with waste waters) and on some hydrological parameters of the aquifer (total porosity, velocity of the natural groundwater flow, and dispersivity).

Investigation of dam seepage at the Maguaca reservoir, Dominican Republic.

barium-14, silver-110m, gold-198, iridium-192, and zirconium-neodymium-95. In the case of fine sediments, radioactive glasses are usually used (scandium-46).

Qualitative and quantitative information can be obtained. In the case of river beds, the mass transport of sediments is determined, although the large variability of the grain size makes the investigation somewhat difficult. When dealing with the sea, the technique is more appropriate for the study of local problems, for example, in connection with dredging operations (assessment of dumping sites) or beach protection.

● ***Tracing of water.*** The use of artificial tracers to investigate the flow of water was initiated more than 2000 years ago. Many non-radioactive tracers have been used and, at present, fluorescent products, dyes, and less frequently, some ionic chemicals, lycopodium spores, and certain bacteria play an important role in water tracing. Some artificially produced radionuclides have also been used during the last 30 years for this purpose. The most important are iodine-131, bromine-82, chromium-51, cobalt-58, gold-198, and tritium.

The comparison of the radioactive tracers with the non-radioactive tracers can be summarized as follows: Advantages of radioactive tracers include limited life (no permanent contamination of water is produced); detection *in situ* for gamma emitters (indispensable for some applications); high sensibility of detection (tracing of large volumes of water with small amounts of tracer); and better stability (possibility of use with highly polluted water and in cases of large sediment charges).

Disadvantages include the need for authorization of its use; occasional difficulties for its acquisition (short half-life tracers cannot be stored); and handling risks.

Special attention should be paid to tritium in view of the fact that it is the only known isotopic artificial tracer for water (the tracer is incorporated in the water molecule). For many tracer experiments, tritium is the only choice in spite of its long half-life (12.43 years) and its being a pure beta emitter (which is impossible to detect *in situ*). When dealing with tracing of groundwater flow, only tritium has the same behaviour of water and gives reliable quantitative information. Furthermore, artificial tritium is inexpensive, easy to handle (practically without any risk), and can be detected without enrichment at a concentration of 0.2 microcuries per cubic metre (0.003 microcuries per cubic metre after electrolytical enrichment).

Typical applications

Two main characteristics of artificial tracer experiments determine the types of problems for which these tracers are appropriate: (1) The volume of water that can be labelled is limited and frequently represents only a small fraction of the total volume existing in the water system. (2) The time available for the experiment is usually limited and very often determined by the dynamics of the investigated water system. Experiments with a duration longer than 1 year are very seldom.

For these reasons the following types of problems are most frequently tackled by means of artificial tracers:

● Problems concerning water systems with a very rapid water flow, as is the case with most surface water systems and many groundwater systems in fractured rocks.

● Local problems affecting small areas (no more than several square kilometers), where precise and exhaustive hydrological information is necessary. This occurs in many hydrological problems related to civil engineering.

● Local experiments of large water bodies with the aim of obtaining general information valid for the whole system on the basis of the integration of point data.

Civil engineering

Artificial radioactive tracers are important tools for investigating many civil engineering problems related with water. Integrated studies are usually necessary which include the use of different techniques. One important example of such problems is the investigation of leakage in reservoirs and lakes. Many tracer techniques have been especially developed for these types of studies. They include interconnection experiments between reservoirs and downstream emerging waters; use of tracers which are absorbed at the bottom of reservoirs to detect zones of water infiltration; gauges for the localization of infiltration zones at the bottom based on flow direction measurements; gauges for the measurement of the point infiltration rate at the bottom of reservoirs; and single-well techniques to detect groundwater flow through the adjacent formations.

Furthermore, some artificial tracer techniques can be used to investigate the suitability of sites for dam construction to predict leakage problems. In other cases, similar investigations can be carried out in connection with, for example, the construction of tunnels or the foundation of important buildings and bridges.

Mine flooding

Many investigations have been carried out in the past using all types of artificial tracers to obtain information on the origin and pathways of water emerging into mines. Generally, integrated studies using different techniques are needed for this purpose. Artificial tracers, together with environmental isotopes, play the main role for these studies, especially when the water may come from different sources. Frequently, the connection of surface water bodies with the mine water has to be investigated. In other instances, the investigation tends to define the water flow going towards the mine in order to pump out the water before emerging in it.

IAEA activities

The IAEA has a long tradition in promoting and supporting the use of nuclear techniques in this field. Many technical co-operation projects and research contracts that cover nearly all the topics mentioned here have been awarded by the IAEA over the last 30 years.

At present, the IAEA is supporting several studies which involve the use of artificial radioisotopes. Projects concern water pollution of a lake in Guatemala; irrigational water in Romania; sediment transport and deposition in Southeast Asia and Brazil; leakage of lakes and dams in Chile and the Dominican Republic; mine flooding and groundwater pollution in Nicaragua; and dispersivity of the estuarian flow in connection with water pollution in Argentina (advisory services only).

Future of techniques

The experience accumulated during the last 30 years has proved that important benefits can be derived from the utilization of artificial radionuclides for the investigation of hydrological problems. Unfortunately, however, there are difficulties in using this technology due to the restrictions imposed in many countries on the use of radioactive materials. The utilization of these techniques is generally in the hands of the nuclear organizations and no possibility exists for transferring this technology to organizations dealing directly with hydrological studies. The collaboration between both kinds of organizations is not always satisfactory. There are even countries where the use of artificial radionuclides for hydrological investigations has been absolutely forbidden.

On the other hand, experience has proven that the use of this technology involves generally no or very limited risks for the population. Yet nuclear regulations which are in force in many countries impose excessively severe restrictions because they have been promulgated by basically taking into account other nuclear activities for which the type and level of risks are completely different. Specific regulations for the use of radioactive material in environmental studies based on the evaluation of the real risks would help immensely for future development of this technology.