Isotope hydrology: Investigating groundwater contamination

Environmental isotopes are used to study serious pollution problems

by V. Dubinchuk, K. Fröhlich, and R. Gonfiantini

During the past 100 years, groundwater has become an increasingly important source of water supply worldwide for domestic, agricultural, and industrial uses. The almost ubiquitous occurrence of water-bearing formations, the quality of groundwater, and the development of well-drilling techniques have all helped to bring this about.

Since it is naturally protected, groundwater has been immune from contamination for a long time. It has been cleaner and more transparent than surface water. From the time of Hipprocrates in the 5th century B.C., stagnant surface water, in fact, was believed to be the source of infirmities.

Lately, however, groundwater quality has worsened in many regions, with sometimes serious consequences. Decontaminating groundwater is an extremely slow process, and sometimes impossible, because of the generally long residence time of the water in most geological formations.

Major causes of contamination are poor groundwater management (often dictated by immediate social needs) and the lack of regulations and control over the use and disposal of contaminants. Agricultural practices, with the sometimes indiscriminate and frequently excessive use of fertilizers, herbicides, and pesticides, are among the most relevant sources of groundwater contamina-

Messrs Dubinchuk and Fröhlich are staff members in the isotope hydrology section of the IAEA Division of Physical and Chemical Sciences, and Mr Gonfiantini is Head of the section.

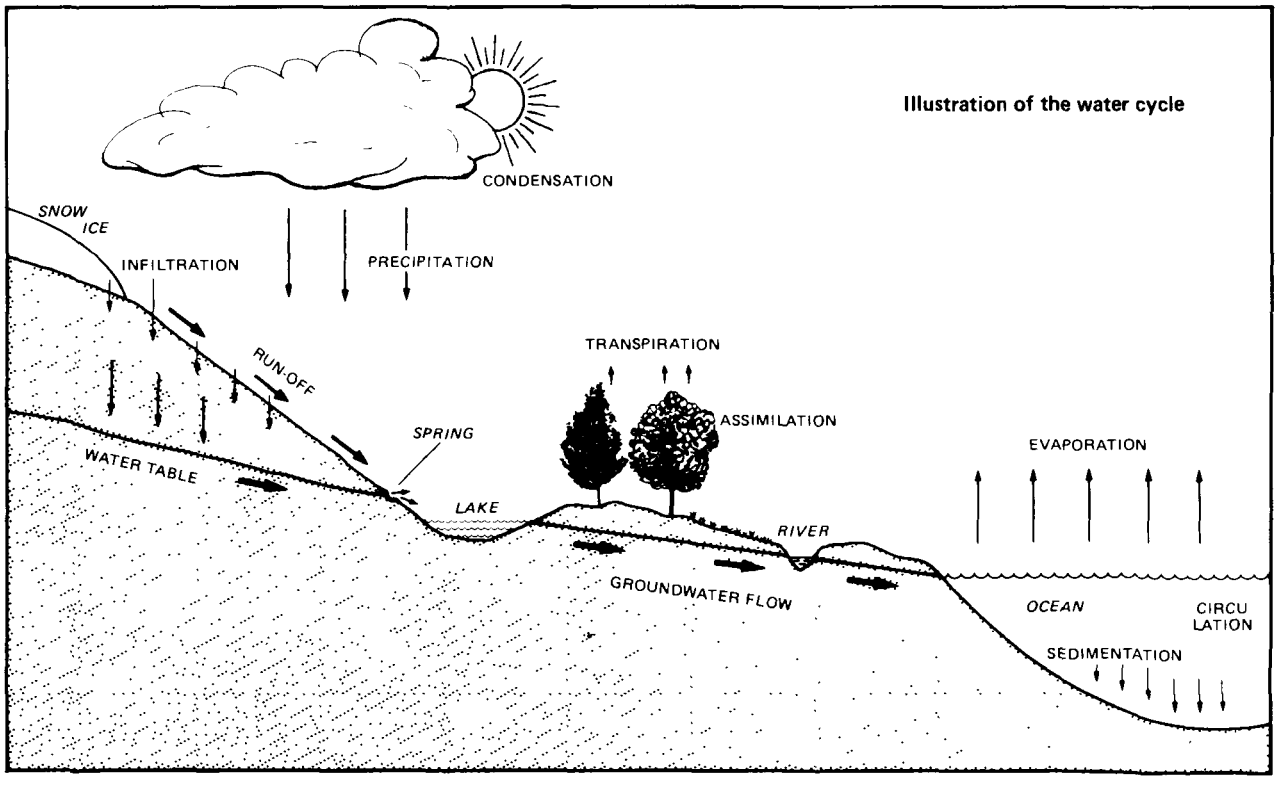


Illustration of the water cycle

tion. For instance, levels of nitrates often traceable to fertilizer usage are increasing in shallow aquifers.

Industrial and domestic contaminants are among the most dangerous. This is partly due to the fact that they are produced mainly in urbanized areas, where water demand is higher and groundwater exploitation more intense. Here, as the groundwater pressure is lowered, contaminated surface waters may be able to penetrate to depths where artesian pressure had previously prevented infiltration.

In coastal regions, over-development is frequently the cause of seawater encroachment and consequent groundwater salinization. In arid areas, over-development usually invites a rapid decline of groundwater resources, which are insufficiently recharged by prevailing climatic conditions. In addition, poorly designed irrigation schemes may hasten the salinization of soil, which eventually becomes sterile.

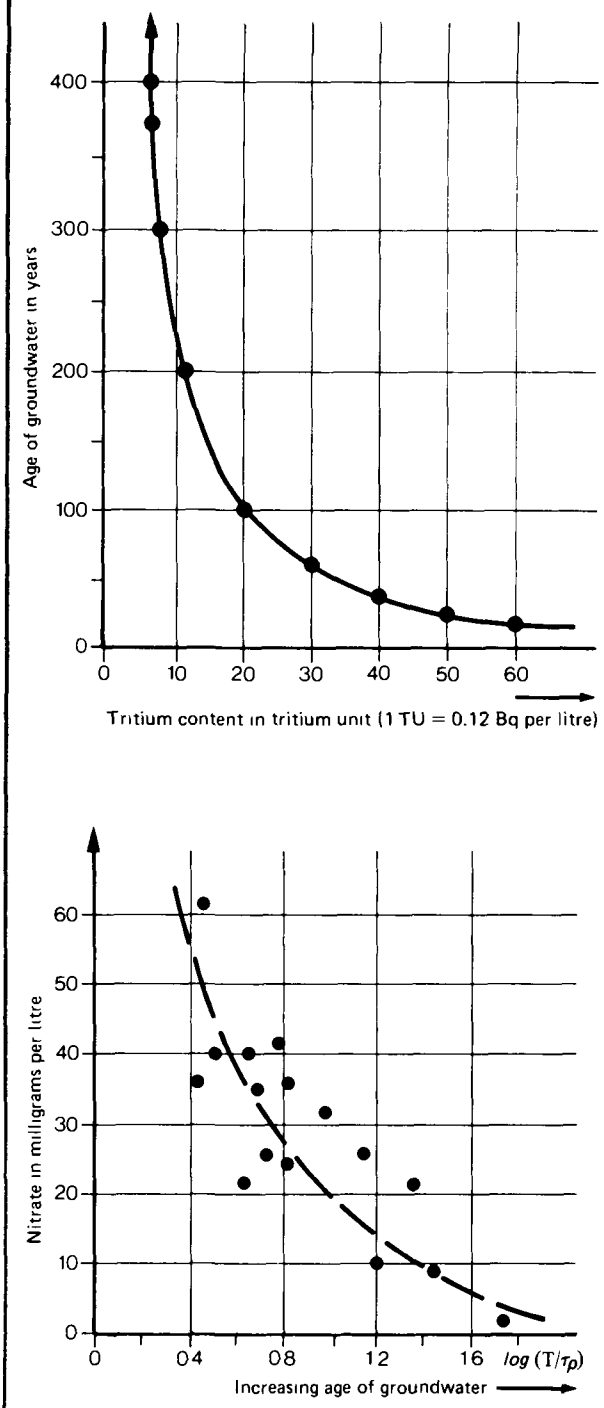
An investigation of groundwater in the Mexicali Valley in arid northwestern Mexico, for example, has helped researchers find the source of salinization. Chemistry alone could not solve the problem whether the groundwater's deterioration was being caused by poor irrigation practices or by bank infiltration from the Presal Morelos dam or Wellton-Mohawk drain. Using isotope techniques, investigators examined the linear correlations between concentrations of chloride and oxygen-18 and between the two heavy isotopes deuterium and oxygen-18. Results (reported in 1979 by Payne, Quijano, and Latorre) clearly indicated mixing with the Wellton-Mohawk drain, which was thus identified as the major source of contamination.

These and other types of problems have prompted an increasing demand for investigations directed at gaining insight into the behaviour of contaminants in the hydrological cycle. Major objectives are to prevent pollution and degradation of groundwater resources, or, if contamination already has occurred, to identify its origin so that remedies can be proposed.

Environmental isotopes

Environmental isotopes have proved to be a powerful tool for groundwater pollution studies. These isotopes are generally rare isotopes, both stable and radioactive, occurring in the environment in low and varying concentrations with respect to the most abundant isotope of the same element. Environmental isotopes are natural or man-made. In either case, their distribution in the environment is governed by natural processes. Although small, the variations in concentrations of environmental isotopes are measured with high accuracy and provide valuable information on hydrological systems.

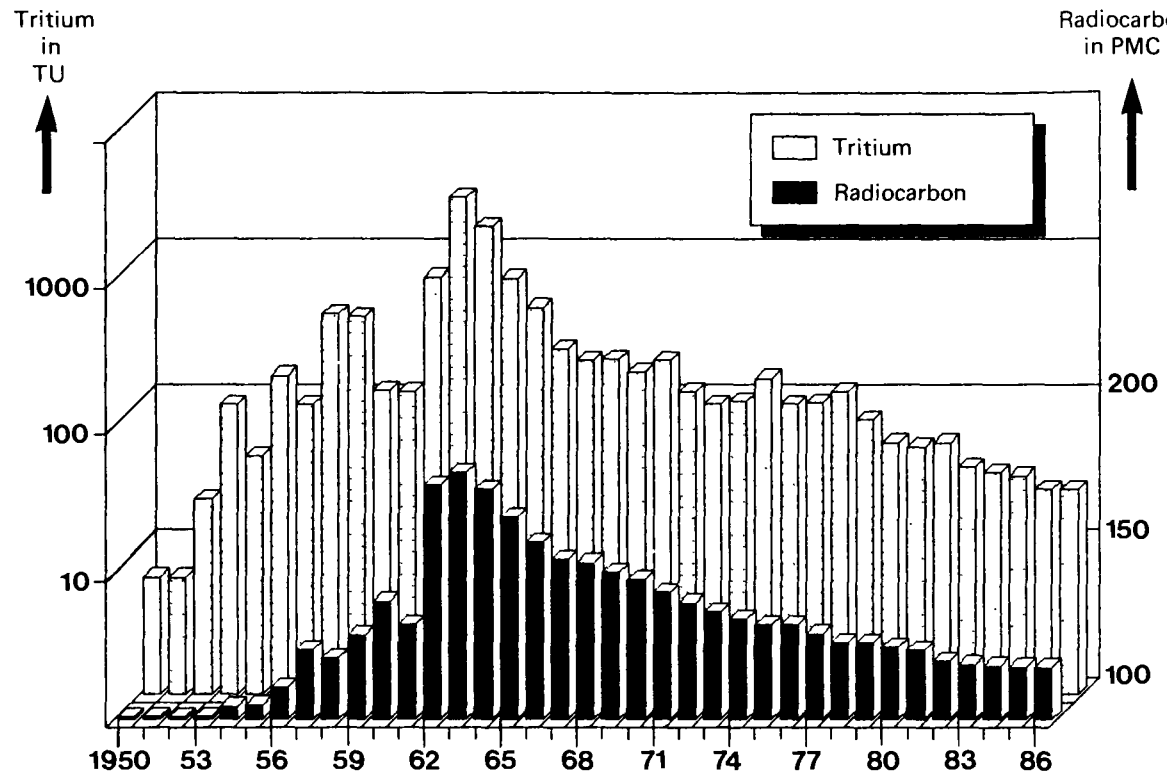
Processes in the hydrological cycle and interactions between the hydrosphere and atmosphere are responsible for isotopic variations observed in natural waters. *(See accompanying figure.)* As a general rule, stable iso-



Notes: T is the age of groundwater. τ_p is the time period between the occurrence of tritium from atmospheric weapons tests and the implementation of the field study.

These figures show the correlation between nitrate and tritium concentration observed in an unconfined Permian aquifer in the German Democratic Republic. The correlation indicates that the nitrate has been transported into the groundwater by the infiltration of rain water.

Tritium in precipitation and radiocarbon in atmospheric carbon dioxide in Middle Europe



Note: Tritium content in tritium unit (TU); 1 TU = 0.12 Bq per litre.
PMC = Per cent of modern carbon; 1 PMC = 0.23 Bq per gram carbon.

topes, which are invariant over time, are used to identify the origin of groundwater and mixing processes. Radioactive isotopes, whose decay over time can be detected, are used to assess the dynamics of groundwater. Chemical analysis generally provides complementary information and is carried out in parallel with the isotopic investigation.

Isotopes frequently used in hydrological investigations include tritium and carbon-14 which are naturally produced by secondary cosmic radiation. These have been injected into the atmosphere in large quantities by the atmospheric thermonuclear tests conducted until 1963 by the United Kingdom, United States, and USSR. Only minor amounts have been produced later by Chinese and French tests. *(See accompanying figure.)* The decrease of tritium and carbon-14 concentrations in precipitation and in atmospheric carbon dioxide after the Partial Test Ban Treaty of 1963 has provided new and invaluable insight into atmospheric processes.

Tritium, with a half-life of only 12.43 years, can be used to reveal the occurrence of modern groundwater recharge (that is, to detect recharge that has occurred over the past three decades). In addition to being of great hydrological importance, this information provides a tool to assess the potential risk of contamination of a given groundwater body. If tritium is present, the transit time of water from the recharge area to the aquifer is short, as is the residence time of groundwater in the aquifer. This lowers the chance of any contaminant dissolved in the recharge water to become adsorbed by the aquifer matrix. Consequently, the contamination risk is potentially high.

The movement of radionuclides in groundwater is one of the major subjects of investigation. Natural radionuclides of the uranium and thorium decay series enter groundwater through dissolution from the aquifer matrix. They can be used, under favourable circumstances, to assess the groundwater dynamics.

Incidentally, studies on the geochemical behaviour of these radionuclides are also of increasing interest for the assessment of nuclear sites, particularly nuclear waste disposal sites. The problem is to evaluate the rate of adsorption–desorption of these isotopes on various rock matrices and to determine the velocity of their migration, based on the knowledge of the migration velocity of the groundwater itself.

Stable isotopes of major elements used in environmental studies

Isotopes	*Abundance in natural compounds (%)*
Hydrogen-1	99.984
Hydrogen-2	0.015
Carbon-12	98.89
Carbon-13	1.11
Nitrogen-14	99.634
Nitrogen-15	0.366
Oxygen-16	99.76
Oxygen-18	0.2
Sulphur-32	95.02
Sulphur-34	4.21

A nuclear logging technique can help to determine the percolation rate of water in the unsaturated zone (the zone of the shallow aquifer above the water table). Coupled with environmental and artificial isotope data, the technique has been used in the Chernobyl area in the USSR to evaluate the time necessary for pollutants to reach groundwater from the land surface.

The IAEA has had a co-ordinated research programme since 1987 on the application of nuclear techniques to determine the transport of contaminants in groundwater. An isotope hydrology project is being launched within the framework of the IAEA's regional co-operative programme in Latin America (known as ARCAL). Main objectives are the application of environmental isotopes to problems of groundwater assessment and contamination in Latin America. In 1989, another co-ordinated research programme is planned under which isotopic and other tracers will be used for the validation of mathematical models in groundwater transport studies.

Radionuclides used in groundwater studies

Nuclide	Half-life (years)	Sources of production	Approximate initial activity concentration in groundwater (mBq per liter)
Tritium (Hydrogen-3)	12.4	Secondary cosmic radiation; atmospheric tests of thermonuclear devices; nuclear facilities (mainly reprocessing plants)	600 (before 1954)
Carbon-14	5730	Secondary cosmic radiation; atmospheric tests of thermonuclear devices; nuclear facilities (mainly reprocessing plants)	3
Silicon-32	105	Secondary cosmic radiation	5×10^{-3}
Chlorine-36	301 000	Secondary cosmic radiation; atmospheric tests of thermonuclear devices; natural nuclear reactions (subterranean)	3×10^{-3}
Argon-39	269	Secondary cosmic radiation; natural nuclear reactions (subterranean)	7×10^{-4}
Krypton-81	210 000	Secondary cosmic radiation	1×10^{-7}
Krypton-85	10.7	Nuclear facilities (mainly reprocessing plants)	less than 2×10^{-7} (before 1950)