

Investigating water resources of the desert: how isotopes can help

by R. Gonfiantini*

Newspapers and magazines from time to time write about the enormous reserves of water stored underground in the Sahara, whose rational exploitation would allow the agricultural development of the desert. Although the practical implementation of such projects is rather problematic, it is true that groundwater is relatively abundant under most of the Sahara (as well as in other deserts in the world), but it is seldom easily accessible. What do we really know about these resources of groundwater and how they have accumulated in areas where rainfall is so scarce? What do we know of the hydrological history of the desert? These problems are important for the correct evaluation and use of the groundwater in the desert. Isotope techniques help in their solution.

The term *desert* applies to all those arid regions of the world where rain is so scarce that the land cannot be permanently inhabited by man. Although the upper limit of precipitation usually assumed for deserts is 250mm a year, over most of the present deserts rains are less, and often much less, than 100mm per year – a limit which corresponds to about 15% of the precipitation over most of Europe – irregularly distributed in time and in space, and there are frequent years with no precipitation at all (hyperarid deserts). As a consequence, no fresh water bodies, like rivers and lakes, occur on the land surface and groundwater is generally so deep that it cannot be reached by the roots of plants or by dug wells. Permanent forms of animal and vegetal life are missing or very rare. Human settlements are scarce and can take place only in oases: depressions in the desert where the groundwater level reaches or approaches the land surface, so that the water can be easily used for irrigation and other purposes, even with primitive technical means.

Deserts occupy waste regions mainly in the latitude belts between 15° and 30°. The Sahara desert in northern Africa, the largest in the world, has a surface area of approximately 9 million km², which is comparable to that of the United States of America. Other large deserts are those of the Arabian Peninsula and Iran – which might be considered a continuation of the Sahara – the Turkestan desert in USSR; the Thar desert in India; the Gobi desert in China and Mongolia; the Great American Desert; and – in the southern hemisphere – the Kalahari desert in South Africa; the Great Australian Desert; and the Atacama desert in northern

Chile. The last, if relatively small in size, is certainly the driest: no precipitation has been recorded over most of it for more than one century.

Changes in climate

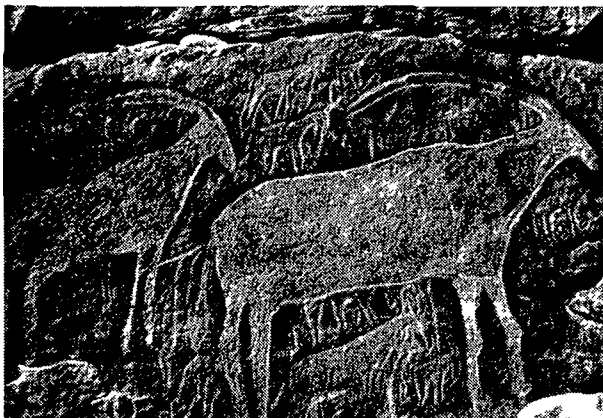
During the Earth's history, however, the climate has changed repeatedly, and the present deserts have not always been so arid, so devoid of life and of vegetation. Rock paintings and engravings and remains of human industry in many Saharan sites show that, in the past, the climate and environment was favourable to human life. This means that, sometime in the past, rains were relatively abundant and water easily available. The last of such "pluvial" periods, called "Humid Neolithic", lasted from approximately 7000 to 3000 years before the present-day. After that period conditions increasingly deteriorated, with the disappearance of surface water bodies, a gradual decrease in discharge of springs and a lowering of the water table. However, only 2000 years ago conditions were probably considerably better than those of today. The Roman legions were able to march twice across the Libyan desert to reach the large oasis of Wadi Ajal in the Fezzan and to fight against the Garamantes: the first time in the year 20BC, from Sabratha (65 km west of Tripoli) to Ghadames and then across the plateau of the Hamada-el-Hamra (Red Stone Desert) for a total of 1200 km; and the second time in the year 70AD, following a more easterly way, through the Al Jufrah oasis and the Jebel Sawda (Black Mountain).

South of the Sahara desert, between approximately 18° and 12° North, the rainfall does increase, although it remains rather scarce. But what is more important, the rains become a regular event in summer, coming from the northern displacement of the monsoon. Consequently, a scanty vegetation develops during the rainy season, which is sufficient for nomadic stock-raising. This is the region called Sahel, which means "shore" in Arabic, as the desert is likened to the sea. The Sahel habitat is however very frail: a year or two of scarce rains are sufficient to cause disaster, with the death by starvation of thousands of animals and, often, of people, especially children. Such tragic events have happened repeatedly over the last decade. Such events also cause the encroachment of the desert, which nowadays is a major worry to the Sahelian countries.

Groundwater the only resource

It is evident that to improve living conditions in the oases and the Sahel and to protect them from natural events, the first requisite is to secure sufficient supplies

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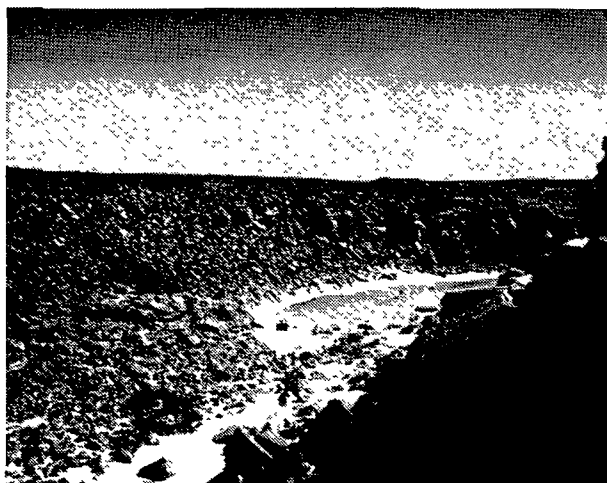
One of the finest rock engravings in the Wadi Zigzah (Fezzan, Libya), proving the occurrence in the past of an environment favourable to animal life.

of fresh water. Their source can obviously only be groundwater. All arid countries, therefore, have agriculture development programmes – often financed by the United Nations Development Programme (UNDP) – to study and assess their groundwater resources, and to drill wells for their exploitation. In these projects, isotope techniques have been repeatedly used to help assess correctly the resources of groundwater.

A basic problem in arid areas which often cannot be solved easily with conventional hydrological techniques is to find out if a given body of groundwater is actively recharged. In other words, will development simply mine the groundwater once and for all, or is it a renewable resource? The groundwater would be renewed by rain infiltrating the recharge area where the water-bearing geological formation (called an aquifer) is exposed on the land surface. Tritium determinations can often shed light on this problem.

Tritium is a radioactive isotope of hydrogen with mass 3 and a half-life of 12.43 years. Large quantities of it were injected into the atmosphere in the years

The present dry, bare bed of Wadi Zigzah. This river was probably flowing during the Upper Pleistocene (65 000 to 10 000 years ago) and the Humid Neolithic (7000 to 3000 years ago).



1952–1963 by atmospheric H-bomb tests. Before this period, the only tritium present in the environment was that produced by cosmic radiation, which only amounted to about 3–4 kg for the whole Earth. The tritium concentration reached its maximum in the 1963 spring rainfall, when values up to 1000 times the natural level were observed in the northern hemisphere. After 1963, the tritium concentration steadily decreased, because of the ban on thermonuclear explosions in the atmosphere.

The tritium concentration in natural waters, especially in groundwater, is generally very low. However, with the most advanced counting techniques one atom of tritium in 10^{18} atoms of hydrogen can be detected. A recently developed technique measures the helium-3 atoms produced from the decay of tritium with a mass-spectrometer. This has lowered the detection level by at least one order of magnitude, and possibly by two in the near future.

If tritium occurs, then the groundwater is clearly recent and has been recharged since 1952. Tritium can be used therefore to detect recharge which has occurred during the last three decades. However, due to the scarcity of rainfall in arid areas, such a length of time might not be statistically significant, or might be too short for the infiltrated water to reach the water table (the underground surface of shallow groundwater). As a matter of fact, shallow groundwater in the Sahara does not show any significant amount of tritium, thus indicating that modern recharge is negligible or has not yet reached the water table.

If infiltration occurs, however, one should be able to detect and evaluate it by means of variations in the tritium content of moisture in the soil above the water table. Results so far indicate that this method is reliable and promising, especially if used in connection with physical models describing water movement. To investigate the method further the IAEA has recently started a co-ordinated research programme. Financial support is provided by the Federal Republic of Germany through the Gesellschaft für Strahlen- und Umweltforschung (GSF). The programme will study the water infiltration processes in arid areas.

Another method of estimating the age of groundwater is to measure the amount of carbon-14 in dissolved inorganic carbon. Carbon-14 is a radioactive isotope of carbon with a half-life of 5730 years produced by cosmic radiation. The concentration of this radioactive isotope in modern atmospheric carbon dioxide is very low, of the order of 1 in 10^{12} atoms. Carbon is transferred from the atmosphere by plant photosynthesis and respiration to the soil and to groundwater, where it is dissolved mainly as bicarbonate. Dating groundwater, although complicated by the interaction of bicarbonate ions with the aquifer matrix, provides an indication as to whether we are dealing with very old water: the method is valid only for ages greater than 2000–3000 years. The upper limit is now about 30 000 years, but possibly this may be pushed up to

70 000 years and perhaps more with the development of new counting techniques, making use of the cyclotron or of the Van de Graaff accelerator.

A third isotopic tool, however, is perhaps the most attractive for groundwater studies in arid areas: the variations of the ratios of the stable isotopes deuterium/hydrogen and oxygen-18/oxygen-16 in water. It is now quite clear that in the past these ratios in rainwater have changed as the climate changed. Therefore isotopic ratios of groundwater which are considerably lower than those expected for modern precipitation, indicate that the groundwater is not recent and was recharged thousands of years ago, when the climate was more humid.

Ancient waters

In arid zones, and especially in the Sahara or in sub-Saharan areas, where the IAEA has carried out a number of hydrological investigations with isotope techniques under contract from other UN organizations (FAO, UNESCO, UNDP), the deep groundwater is generally very old. The carbon-14 content is frequently at or below 2% of the modern content, thus indicating an age greater than 20 000 years (taking into account the errors and the uncertainties inherent in the method). This would indicate that recharge probably occurred during the Pluvial period of the Upper Pleistocene (10 000 to 65 000 years ago). At higher latitudes this period corresponds to the last Glacial period, called Würmian and Weichselian in Europe and Wisconsinian in Northern America. Such a great age is also supported by the relative depletion in the heavy stable isotopes, deuterium and oxygen-18, which also indicates that recharge took place during a more humid period than today.

Observations similar to those just described have been made, for instance, for so-called "Continental Intercalaire" aquifer, the major water-bearing formation in the western Sahara: extending mostly in Algeria from the Atlas to the Ahaggar mountains, in the north-south direction; and from Tunisia and western Libya to the Wadi Saura valley, in the east-west direction. The total area is some 600 000 km², about 10% larger than that of France and seven times that of Austria. The amount of water stored in such an aquifer is enormous, in the order of thousands of cubic kilometers.

The Continental Intercalaire extends mostly in desert areas, often at great depths: for instance, in the proximity of Touggourt it is exploited by drilled wells whose screens (perforated sections) lie between 1500 and 1700m. The water head there is between 260 and 290m above the land surface and the water is hotter than 70°C, so that it needs to be cooled before being distributed. On the edges, where the formation outcrops, the carbon-14 increases, indicating the presence of younger water. A source of recharge which has been identified with the help of stable isotopes is the shallow aquifer of the Grand Erg Occidental. This is a vast sand-dune formation covering the north-western part of



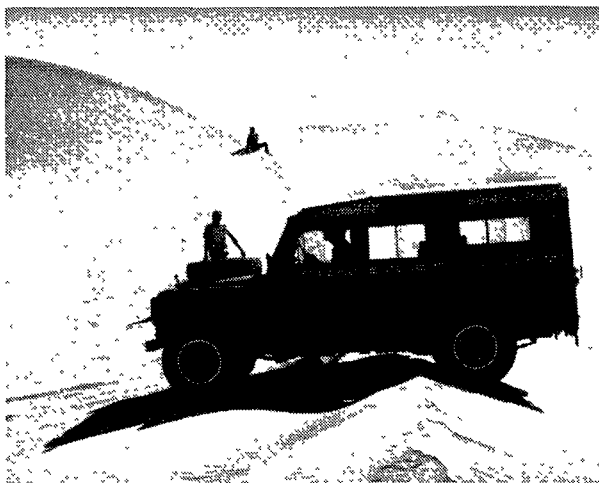
Artesian well at Wadi Qirzah.

the Continental Intercalaire, which was formed during the hyperarid period that followed the Upper Pleistocene Pluvial and preceded the Humid Neolithic. With the stable isotope technique also, the discharge of the Continental Intercalaire water into a shallower formation has been definitely confirmed in Tunisia, where the deep groundwater is ascending through the fault system of El Hamma.

These last examples also show how stable-isotope measurements can be used to identify the origin of groundwater and the hydraulic interconnections between aquifers. This type of information is obviously essential in any attempt to evaluate the balance of any water-bearing formation.

In a recent study in the Libyan Arab Jamahiriya, stable isotopes helped in the reconstruction of the regional groundwater flow. The main flow is from south to north in large aquifers (Palaeozoic, Kicla), which are being increasingly exploited as many new agricultural projects and experimental farms are established in several large oases from the Fezzan to the sea (Murzuk, Wadi Ajal, Wadi Ash Shati, Al Jufrah, Wadi Zamzam, etc.). Again, the groundwater is generally old (more than 20 000 years) according to carbon-14, and the relatively low content of deuterium and oxygen-18 also bears out

Sand dune desert (Erg) in Fezzan.





The village of Boutilimit in the Sahel of southern Mauritania.

this conclusion. The stable isotopes, in addition, helped in clarifying the interrelations between the various aquifers and in seeing how much groundwater came from different sources.

Scanty information

For many reasons, the study of the groundwater resources of arid zones is complex and difficult. Drilled wells, whose stratigraphic log can be used for a hydrogeological assessment of the various water-bearing formations, are generally scarce and often there are none over large areas; when they exist, the relevant documentation is sometimes lost or incomplete. The various types of data available (meteorological, climatological, hydrological, piezometric, etc.) are scarce considering the size of the areas involved. In addition, the time elapsed since the beginning of observations is often still too short, especially considering the unevenness and the infrequency of the

phenomena observed: for instance, little is known about rainfall over the desert, the mean value and the recurrence probability of rains exceeding a certain height; and therefore any evaluation of the groundwater renewal rate is questionable.

In this context, isotope techniques provide additional information which is not accessible by other means. The time-dependence of the isotopic composition of rainfall appears important, because it can shed light on the problem of modern recharge and evaluate groundwater age. Stable isotopes can be used as environmental tracers to follow the movement of groundwater over large distances. Compared with artificially injected tracers, environmental isotopes have the advantage of being injected continuously over the whole area of study, and therefore the results produced are valid in both spatial and time dimensions. With respect to other environmental tracers, like the chemical elements dissolved in water, the isotopes of hydrogen and of oxygen have the advantage of being much more conservative (except for tritium decay, the law of which is however well known), with negligible or limited interaction with the aquifer matrix, and to behave exactly as water, because they are incorporated in the water molecule.

The application of isotope techniques to hydrological studies in arid areas was thoroughly discussed at an Advisory Group Meeting convened by IAEA in 1978. Seventeen papers were presented, now published in the proceedings of the meeting (*Arid-zone hydrology: investigations with isotope techniques* STI/PUB/547, IAEA, Vienna, 1980), which summarize most of the data and the experience accumulated after about a decade of work in arid areas.

The Lake Um el Maih (Salt Mother) in the Ubari Sand Sea, Fezzan. A few other similar small lakes occur in this area occupying depressions between dunes, where the groundwater outcrops. Due to the high evaporation rate, the salt content in the lakes is always high and often reaches saturation level, with consequent formation of salt deposits mainly composed of sodium chloride. The salt is often collected and traded by the small communities living in the lake oasis.

