

The Essential Role of Isotopes in Studies of Water Resources

One of the prerequisites for efficient management of a water resource is reliable information about the quantity, flow and circulation of water within the resource that is being exploited. During the past two decades, isotope techniques have come to play a major role in the qualitative and quantitative assessment of water resources.

In studies of surface water, isotope techniques are used to measure water runoff from rain and snow, flow rates of streams and rivers, leakage from lakes, reservoirs and canals and the dynamics of various bodies of water.

Studies of groundwater resources (springs, wells) today are virtually unthinkable without isotope techniques. Basically, these techniques are simple and relatively quick.

Among the many questions which may be asked of hydrologists about a given groundwater supply, often the most critical one concerns the safe yield so that the source will not run dry, or for a source to be "mined", the total yield.

Isotope techniques can be used to solve such problems as: identification of the origin of groundwater, determination of its age, flow velocity and direction, interrelations between surface waters and groundwaters, possible connections between different aquifers, local porosity, transmissivity and dispersivity of an aquifer. The cost of such investigations is often small in comparison to the cost of classical hydrological techniques, and in addition they are able to provide information which sometimes cannot be obtained by other techniques.

Isotope hydrology can be divided into two main branches: environmental isotope hydrology, which has become especially important in those regions of the world where basic hydrological data are insufficient, and artificial-isotope hydrology. The first branch uses isotope variations established in waters by natural processes, which can be observed and interpreted to solve some hydrological problems on the basis of the general knowledge of isotope variations in nature. Regional hydrological problems can be studied with environmental isotopes if (as is usually the case) natural conditions establish measurable variations in isotope concentrations of different waters.

Artificial-isotope hydrology makes use of radioactive isotopes that are injected into the system under investigation. The evolution of the isotope concentration is followed. The validity of the data provided by this technique is limited to a restricted area around the injection point and to the conditions present at the moment of injection. Nevertheless, measurements performed at a sufficient number of points and repeated at different times can provide a good description of the hydrological system investigated. Among the tracer techniques that have been developed, the single borehole method has proved to be a reliable means of determining quantitatively the aquifer parameters involved in groundwater supply.

The radioactive environmental isotopes of interest, tritium (hydrogen-3) and carbon-14, occur both naturally as the result of interaction of cosmic radiation with the atmosphere, and

artificially, created in explosions of nuclear devices. The man-made isotopes have been dispersed throughout the earth's atmosphere and their participation in the hydrological cycle is now regulated by natural processes.

Isotopes of oxygen and hydrogen, the chemical elements which constitute the water molecule are, in a certain sense, ideal geochemical tracers of water, because their concentrations are not subject to changes by interactions with the aquifer material. On the other hand, carbon compounds in groundwater may interact with the aquifer material, complicating the interpretation of the data.

Many natural processes cause variations of the isotopic composition of natural waters. Among them, the most important are evaporation and condensation. During the evaporation process, the light molecules of water, H_2^{16}O , are more volatile than those containing a heavy isotope such as deuterium (D) or oxygen-18 (^{18}O). Therefore, water which evaporates from the ocean has less deuterium and oxygen-18 than the ocean water.

When this atmospheric water vapour undergoes successive cooling and condensation in clouds and precipitation, the heavy molecules condense preferentially, and as a result, successive precipitations derived from the same initial vapour mass will be more and more depleted in deuterium and oxygen-18.

Because the degree of condensation of a vapour mass depends on the temperature, a relation between isotopic composition of precipitation and its temperature of formation should be expected. This dependency on temperature produces seasonal isotope variations in precipitation (winter precipitation is more depleted in heavy isotopes with respect to summer precipitation), latitude variations (high latitude precipitation is depleted with respect to low latitude precipitation) and altitude variations (the heavy isotope content of precipitation decreases with increasing altitude).

The last effect is especially important in regional hydrological studies. For instance, groundwaters deriving from recharge areas at different elevations may be differentiated on the basis of their isotopic content. The altitude effect may change from region to region but, in general, it is about 0.3% decrease in oxygen-18 content and 2.5% decrease in deuterium content per 100 metres increase in elevation.

With the evaluation of isotope data, many conclusions can be drawn, some of them unobtainable or difficult to ascertain by other methods. However, it should be emphasized that the use of these methods requires close collaboration with hydrologists in order to ensure a proper use and maximum interpretation of the isotope data. Probably the most important initial step is a clear definition of the problem, which, on the basis of the common hydrogeological investigational methods, may be expressed as which of a number of hypotheses is the most probable. The isotope method may then be used to indicate the hypothesis which is tenable or at least to eliminate some of the hypothesis made.

The second step is to decide whether environmental isotope techniques can contribute to the solution of the problem. In order to do this, one requires a basic understanding of the principles governing the environmental isotopic composition of natural waters. It may not always be possible to assess on purely theoretical considerations whether or not the isotopic method will be applicable, so it is common to make a small reconnaissance analysis of the waters from the project area to check the feasibility of the method.



Sampling water from a well in the Altiplano, Bolivia. Analysis of the isotopic composition of ground-water was carried out by the IAEA as part of a large-scale UNDP project that investigated the origin and movement of groundwater in the Altiplano. Photos: IAEA/Bryan Payne.

The IAEA provides assistance to countries in the application of isotope techniques in water resources studies and other hydrology field projects. The following examples of field studies are intended to give some idea of how these techniques are being applied to specific problems in various regions of the world. Most are discussed briefly, but in some cases a more detailed description has been given in order to demonstrate the application of environmental isotope techniques.

LATIN AMERICA

Nicaragua. Variations in the stable isotope composition of precipitation at different altitudes, the so-called altitude effect, have been used to answer the question of the origin or a particular water resource.

In Nicaragua, the Chinandega Plain covers an area of about 1100 square kilometres between the Pacific Ocean and the drainage divide of the Cordillera de Marrabios. Inwards from the coast, the topography rises gradually to an altitude of about 200 metres at a distance of 20 kilometres, after which the gradient becomes steeper with the maximum elevations at the crest of the Cordillera being 1745 metres. Samples of precipitation and groundwater were collected at different elevations in a transverse strip extending inland from the coast.

The results showed that shallow groundwater is recharged locally on the plain, but that deep groundwater in wells is recharged from precipitation in the mountains at elevations greater than 280 metres.

Ecuador. A recent Funds in Trust project, executed by the FAO, in Ecuador is designed to investigate the origin of groundwater using environmental isotopic techniques with the assistance of the IAEA.

Guatemala. A large-scale UNDP project in which the IAEA is participating is investigating the origin of groundwater in the area of Guatemala City, with the goal of increasing the capital city's water supply.

Bolivia. Appraisal of water resources in the Altiplano, Bolivia, has been made under a large-scale UNDP project, using environmental isotope analysis.

Mexico. A co-operative study between Mexico and the IAEA is investigating the origin of salinity in the groundwater in the Mexicali Valley. Isotopic techniques are being used also to evaluate the potential of the geothermal field in the Mexicali Valley. On the coastal plain south of Veracruz, environmental isotope techniques showed that most of the groundwater originates from infiltration of local rain fall rather than from the river that crosses the plain.

Cuba. Application of nuclear logging techniques for the development of groundwater resources is being carried out with the assistance of the IAEA.

Jamaica. A large-scale UNDP project for groundwater development has been carried out, with isotope analysis by the IAEA.

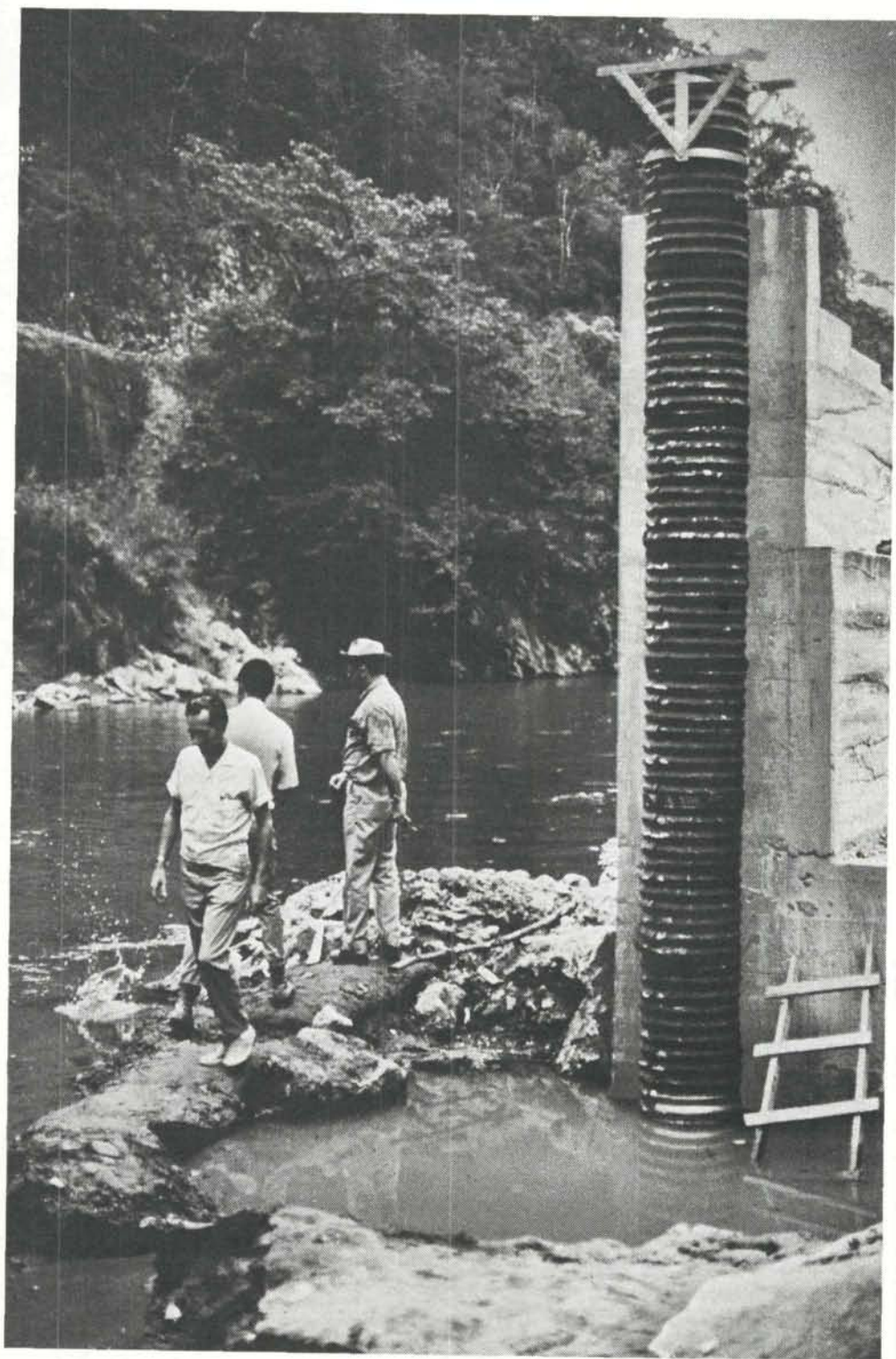
AFRICA

Algeria. A project in the Hodna Plain in Algeria used environmental isotope techniques to provide information on the recharge mechanisms of two aquifers one shallow, the other deep. A salt plain, the Chott-el-Hodna, occurs in the centre of the area where runoff from wadis in times of flood rapidly evaporates and leaves a salt deposit.

Both aquifers are recharged mainly by precipitation in the Hodna Mountains to the north. The rainwater is also carried by wadis to the plain where it partially infiltrates before reaching the Chott. Recharge of the shallow aquifer by infiltration from the wadis was demonstrated by the relatively high tritium concentrations found in the water sampled in the region of the wadis. In principle, the shallow aquifer may also be recharged by direct infiltration of precipitation falling on the plain itself. However, studies of water from wells in the plain far removed from the wadis revealed that the tritium concentration was much lower, thus suggesting that infiltration of direct precipitation was slight.

Another aspect of this study was the inter-relationship between the two aquifers. Although the altitudes of the recharge areas in the mountains were essentially the same, there was found to be a very significant difference in stable isotopic composition in samples of the

A water level recorder on a river in Jamaica where the IAEA carried out isotope studies for a UNDP project. ►





Lake Bassin Blanc, which lies in a volcanic crater on the island of Mauritius. Sample of water is being taken for isotope analysis.

deeper aquifer taken from artesian wells. Carbon-14 measurements suggested that this deeper water was recharged some tens of thousands of years earlier than the shallow aquifer. There was a correlation of oxygen-18 and carbon-14 with depth in the groundwater around the artesian wells. This is a clear indication that as water is taken from the deep aquifer, it is being recharged by the shallow aquifer.

Sudan. The unique value of the natural variations in the deuterium and oxygen-18 content of natural waters is that these variations can provide information on the origin of recharge to hydrological systems.

Near the site for a proposed new airport for Khartoum in Sudan, a new agricultural development was envisaged and the hydrology of that area had to be surveyed in order to secure water for the airport and the new development. In this case there was a distinction to be made between four sources of water. They were: water from (a) the Blue Nile, (b) the White Nile, (c) local precipitation, (d) groundwater inflow from bordering areas.

The differences in the environments of the headwaters of the Blue and White Nile rivers produce a significant difference in the respective stable isotope compositions of the two rivers, that of the Blue Nile being more depleted than that of the White Nile. Both river values were different from the stable isotopic composition of local precipitation. The values for groundwater in the area also were different from that of the local precipitation, indicating that recharge of the groundwater was not from local precipitation.



Water sample for environmental isotope analysis is taken at the top of a high waterfall in Mauritius.

Samples of groundwater to the east of the Blue Nile had a composition similar to that of the river indicating the effect of infiltration of river water up to about 10 kilometres from the river.

Further to the east the stable isotope data suggested that groundwater flow was in the opposite direction, that is from the north east. This water was much more depleted in stable isotopic composition and had a very low carbon-14 content thus suggesting recharge some thousands of years ago when the climatic regime was different from today. Between these two areas water was of a mixed type having much higher salinity.

These findings permitted the groundwater flow and recharge to be mapped, and helped to establish how much water could be used for the new developments.

Ethiopia. The level of Lake Baseyk, some 200 kilometres east of Addis Ababa, has risen 20 metres since 1972, and has threatened the rail and road link to the coast. Work has recently been completed to raise the level of both the railway and the road. The IAEA is co-operating with the Ethiopian Water Resources Authority on the possible application of isotope techniques to determine the source of the water causing the rise in the lake's level.

Libyan Arab Republic. A study of the movement and recharge of groundwater in several regions is being undertaken under a Funds in Trust Project executed by the FAO for the Libyan General Water Authority. The IAEA is assisting in the application of isotope techniques in the areas selected for the study.

Morocco. Environmental isotope techniques have been used to study the different modes of recharge to the aquifer in the Souss Valley in Morocco. An index of the stable isotope content was established for each of the potential sources of recharge — aquifers bordering the Valley, flood waters and precipitation. The results demonstrated that recharge from the aquifers bordering the Haut Atlas mountains is limited to a distance of about 5 kilometres into the plain. In the case of the Anti Atlas mountains, two important areas of recharge were defined, one to the south-west of Aoulouz towards Qued Tangarfa, and the other between Tazermmour and Oued Assads. The oueds from the Haut Atlas are effective sources of recharge only well into the plain where their gradients are much lower. The Oued Souss itself recharges the area to the south in a discontinuous manner, since along the bed of the river there are areas of infiltration and emergence of river water. Recharge by precipitation is limited mainly to the northern side of the Oued Souss.

Northern Sahara. An isotopic study of groundwater in the Northern Sahara in Algeria and Tunisia has been carried out. The Continental Intercalaire is the largest aquifer in the Sahara, covering an area of 600 000 square kilometres. The study confirmed the hypothesis that water from the Continental Intercalaire is moving through the fault system of

Mauritius — experimental borehole, sealed with concrete to prevent debris from falling in, is re-opened for sampling.

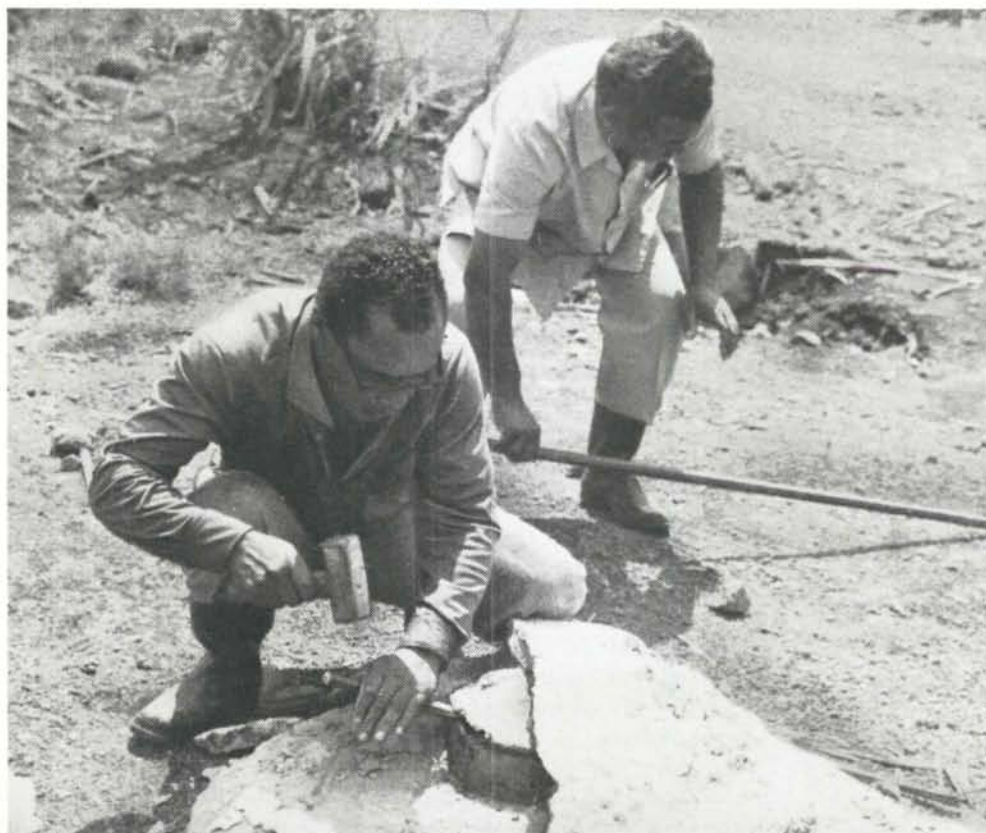


El-Hamma and Méddenine into the artesian aquifer (Complex Terminal) of the Golf of Gabès. Close to El-Hamma, the composition of the water has the same values as from the eastern part of the Continental Intercalaire. Moving eastwards, the oxygen-18 values gradually increase, which indicates mixture of water from local recharge.

Kenya. The characteristic stable isotopic enrichment of evaporated waters may be used to study possible inter-relations between lakes and groundwater. Lake Chala, a volcanic crater lake located on the south east slope of Mount Kilimanjaro having neither surface inflow nor outflow, was suspected to feed springs in the area. The lake has an area of about 4 square kilometres and a depth of 100 metres and a detailed survey demonstrated a homogeneous stable isotopic composition, characteristic of evaporated water, which did not vary with time.

It was found that the springs in the area have quite a different stable isotopic composition than the lake. It was therefore concluded that none of the springs received a major contribution of water from the lake. Based on the difference in stable isotopic composition between the lake and the springs, an upper limit of 6% of the individual discharges of the springs was placed on the possible contribution of lake water.

Cap of the borehole is removed.



The same principles have been applied to a study of the infiltration of water from Lake Chad to the groundwater close to the lake. Stable isotope data demonstrated that the proportion of lake water in the shallow groundwater in the dunes diminishes fairly rapidly moving away from the lake due to the recharge by infiltration of precipitation. Over the whole thickness of the aquifer there is a stratification of water due to the water originating from both the lake and infiltrated precipitation with the proportion of water derived from the lake increasing with depth.

Mauritius. As part of its Technical Assistance Programme, the IAEA is evaluating the potential use of environmental isotope techniques for studying the groundwater movements on this island in the Indian Ocean.

OTHER PROJECTS

Qatar. Under a UNDP/FAO project, the IAEA is investigating the recharge and rate of replenishment of groundwater in aquifers in northern Qatar. Depressions in the area are thought to be the main source of recharge. The project's goals are to assess available water resources and to assist the government in planning the development and management of the water resources in an integrated manner for domestic, industrial and agricultural use. Isotopic studies will provide data for estimating possible safe yields of water so that mining of existing groundwater will not occur and cause intrusion of saline water from deeper zones.

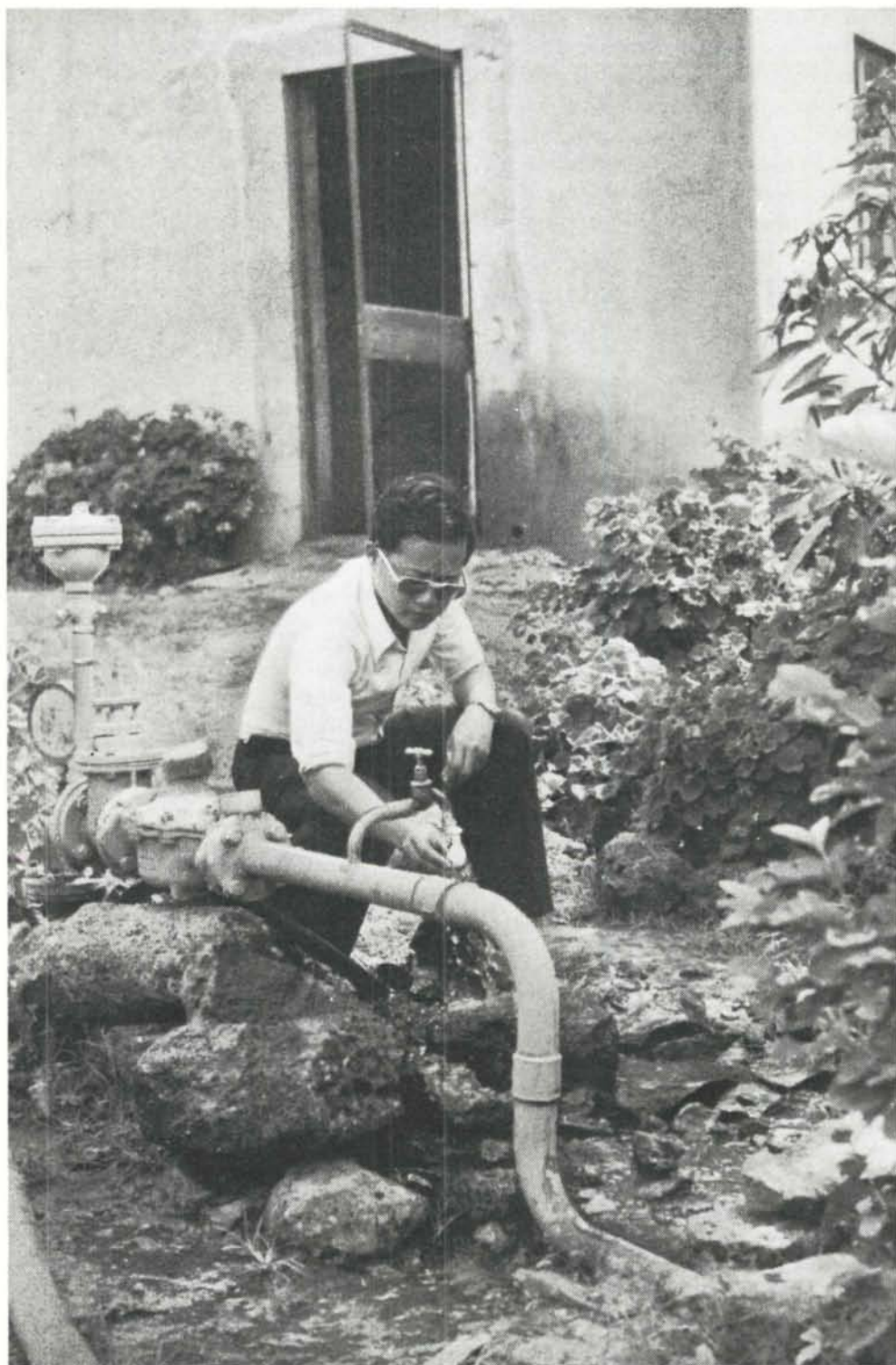
India. In a UNDP project, the IAEA is applying the environmental isotope techniques to help in evaluating the geothermal characteristics of two selected areas in the country.

Greece. Marathon Lake in the Kalamos area of Attica lies between the metamorphic Grammatikon system and the sedimentary Parnis system. The lake supplies water to the city of Athens, some 20 kilometres to the southwest. A group of springs near Kalamos on the coast north of the lake were recently investigated as a possible source of additional water supply for Athens. In order to develop this potential water supply, environmental isotope techniques were employed to find the origin or recharge area of the freshwater component of the spring discharge. The isotopic study was a collaborative effort by the International Atomic Energy Agency, the Greek National Institute for Geological and Mining Research and the Greek Atomic Energy Commission's Nuclear Research Centre, "Demokritos".

The problem was to determine if the Kalamos springs were recharged by the Grammatikon of the Parnis system. The elevation of the Grammatikon system rises to a maximum of about 590 metres, while that of the Parnis system reaches a maximum of nearly 1400 metres. This difference, therefore, suggested that owing to the altitude effect, there should be a significant difference in the stable isotopic composition of the waters from the two systems.

Analysis of water samples showed that isotopic composition of the freshwater of the Kalamos springs is similar to the values observed in the higher elevations of the Parnis system, and not the Grammatikon system. The isotope data also suggested that the groundwater moves across from the Parnis system into nearby areas of the Grammatikon system and thence in the direction of the Kalamos springs.

Water sample is taken from a well in Mauritius for environmental isotope analysis. ►



Crete. The development of groundwater in limestone aquifers often poses problems of whether various water sources in a given locality are part of a common system. An example of such a problem is a study made by the Agency in Crete. To the west of Heraklion is the Almyros spring which is partially saline during times of low discharge due to the intrusion of seawater. A number of test boreholes were drilled in the area with a view to the development of additional water supply for industrial use. The water in the boreholes was also partially saline, and the question was whether water from them came from the same freshwater system supplying the Almyros spring.

In the case of the Almyros spring, an increase in salinity is accompanied by an enrichment of the oxygen-18 component, which is exactly what one would expect for mixtures of varying proportions of fresh water and sea water. Samples from the boreholes showed no significant change in the oxygen-18 component with change in salinity. This showed that the salinity in the water from the boreholes was the result of mixing of fresh water and the saline water from the spring. It also showed that the fresh water tapped by the boreholes is not the same as that feeding the Almyros spring, which is recharged at a higher altitude.

Canary Islands. Isotopic measurements of groundwater were carried out by the Agency under a UNESCO/UNDP study of water resources on the Canary Islands. On Gran Canaria significant tritium content was found in the groundwater in the central part of the island, indicating that the water is of recent origin. On Tenerife, most of the groundwater did not show significant tritium content, which suggests that the water being exploited had its origin prior to 1952.

Republic of Korea. Stable isotope and tritium analyses were used in the volcanic island of Cheju, Republic of Korea, to characterize groundwaters with respect to time and place of recharge and to determine the nature of mixing of the different groundwater sources and estimate their residence times. From a preliminary sampling of 14 springs, eight wells and two streams from different parts of the island, nine points were chosen for periodic sampling. All the waters sampled contained appreciable amounts of thermonuclear tritium, thus indicating rapid circulation in the various groundwater systems. Upon the basis of their tritium content and stable isotopic composition, the waters were classified into a number of flow regimes.