Developing isotope techniques for water exploration in the Sahel

A project in Senegal, Mali, Niger, and Cameroon helps scientists learn more about the Sahel's limited water resources

by Jean François Aranyossy, Didier Louvat, and Mokdad Maksoudi

Periods of drought affecting the Sahelian region during the last two decades underline the precarious nature of surface water reserves and the need for more systematic use of groundwater resources. Over the years, extensive programmes have been initiated for the exploitation of groundwater throughout the Sahel region, in line with recommendations issued for the International Drinking Water Supply and Sanitation Decade. In the course of a few years, thousands of boreholes have been drilled, notably under numerous "rural water supply" schemes.

However, the aquifers tapped in haste proved in many cases to be both qualitatively and quantitatively vulnerable. As a result, parallel global studies were initiated with a view to exploring water resources in these countries. These studies were directed at all aspects of hydrology and hydrogeology so as to develop water management models based on the fullest possible knowledge of aquifer characteristics.

Within this context, the IAEA in the early 1980s started its first activities on hydrogeology in Mali, Niger, and Senegal through its technical co-operation programme. These activities included, first of all, local aquifer studies with environmental isotopes. The studies were found to be particularly useful for obtaining specific information on, for example, relationships between aquifers and between surface water and groundwater, and the existence or absence of recent recharge. Moreover, the IAEA established the basic infrastructures needed for the application of artificial tracer techniques and the use of nuclear instrumentation in hydrology and hydrosedimentology.

Several factors underscored the need for coordinating the scientific activities already being carried out under existing bilateral projects. Firstly, the "horizontal" flow of information was very poor in spite of the similarity between the hydrological and hydrogeological problems encountered in the three countries. Secondly, political frontiers do not generally follow the boundaries of the hydrological basins, so that the same aquifer can be shared between several countries. Thirdly, the costly infrastructure established by the IAEA in certain countries deserved to be utilized at the regional level.

To meet these concerns, an African regional project was launched 4 years ago on the development of isotope and nuclear techniques in hydrology in the Sahelian countries. Its main objectives were to further broaden ongoing studies in the participating countries; to strengthen training; to promote exchange of information on various previous studies; to foster co-operation between the different institutes involved in these studies; and to reinforce the infrastructures established by the IAEA and their utilization in the region.

After 4 years of operation, the project has yielded important results, much to the credit of the active collaboration of all the counterparts. This article reports on major areas of research and the principal results recorded so far.

Joint topical studies on water problems

In hydrology, attempts to model groundwater resource management in arid and semi-arid regions generally meet with difficulties. These difficulties are mainly associated with estimating recharge and actual evaporation, and the scanty information that is available on hydrodynamic characteristics and conditions at aquifer boundaries.

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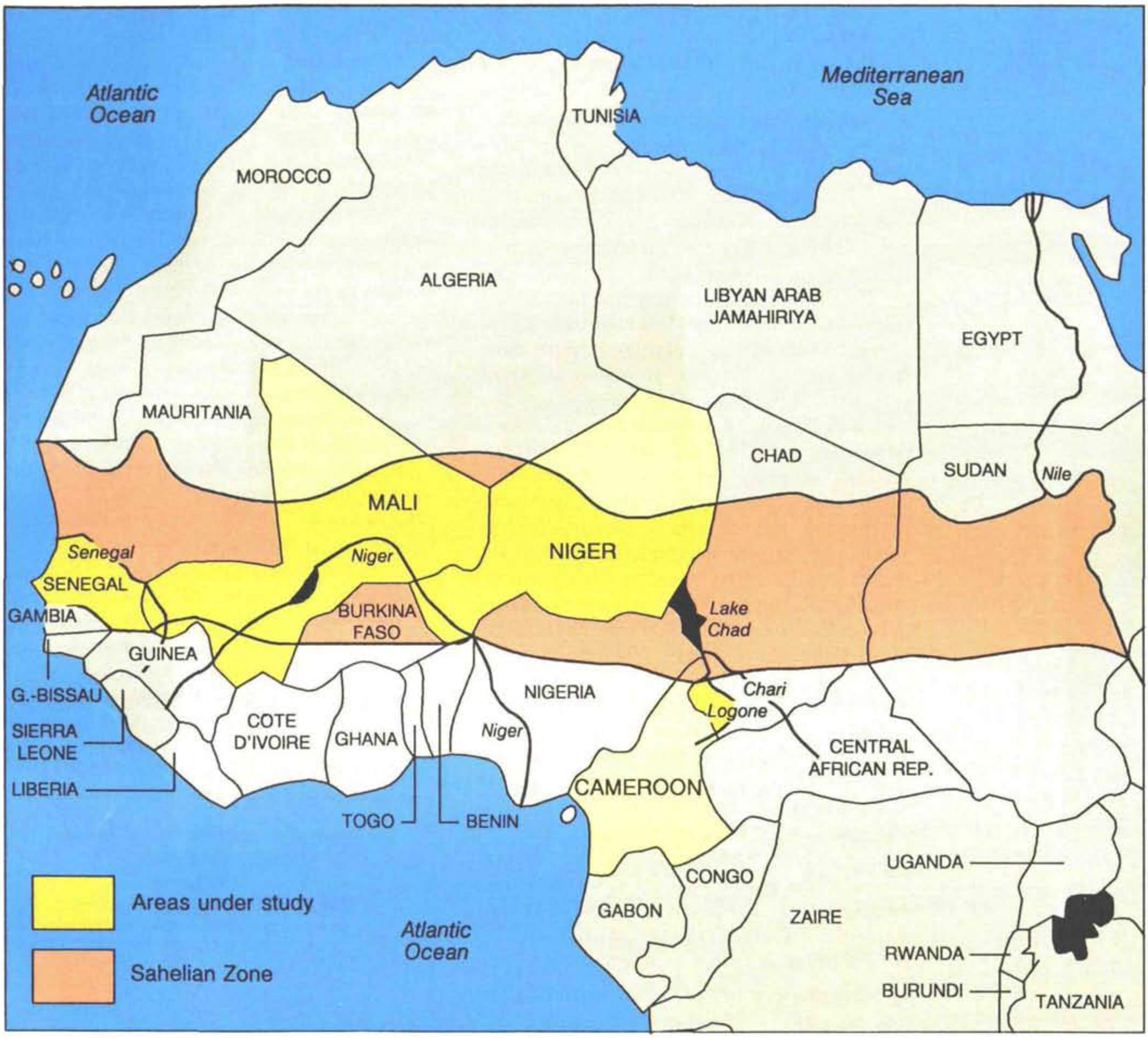


The Sahelian zone is located in areas having rainfall limits of between 50 and 500 millimetres a year. Precipitation is irregular, severe periods of drought are recurrent, and surface water is scarce. One sustainable source of fresh water is found in huge sedimentary aquifer formations that were filled during past humid periods in Northern Africa. Today, these natural reservoirs of groundwater are being extensively studied and explored, often with the use of isotope techniques as in the case of the IAEA's regional project involving Senegal, Mali, Niger, and Cameroon.

In the hot desert sun of the Bilma region in eastern Niger, a project research team takes sand dune samples required for isotopic analyses of soil moisture. The information enables quantification of water losses from the deep aquifer's water table by evaporation through the unsaturated zone.

Under the regional project, these problems are tackled by means of joint topical studies, which have reached different stages of progress in different countries.

● ***Surface water-groundwater relationship.*** The big rivers and the few large permanent lakes (Lake Guiers in Senegal, the interior delta of the Niger river in Mali, and Lake Chad) are the only bodies of perennial surface water in the Sahelian zone. They therefore play an important part in the traditional economy of the region.

The commissioning of large hydraulic structures (for example, the Manantali dam on the Senegal river) will undoubtedly promote more rational use of the water. However, we know very little about the consequences which this regulation of water flow will have on the natural recharge of aquifers in the valley's alluvial formations, or about the regional sedimentary aquifers. One research objective is to determine the mechanisms of natural recharge of the aquifers in the alluvial formations and in the regional sedimentary aquifers contiguous to them. This is important for assessing the consequences that river dams might have on recharge.

Initial results obtained along the Niger tend to indicate that the river's influence on the recharge of aquifers at the level of Tombouctou in Mali would extend at most to a few tens of kilometres. Results further indicate that the river's influence would be less at Niamey in Niger, where the low–flow channel seems to be virtually isolated from the alluvial aquifers. In Senegal, studies being carried out in collaboration with the French Office for Scientific and Technical Research Overseas (ORSTOM) have shown that Lake Guiers and the adjacent aquifers are almost fully isolated from one another.

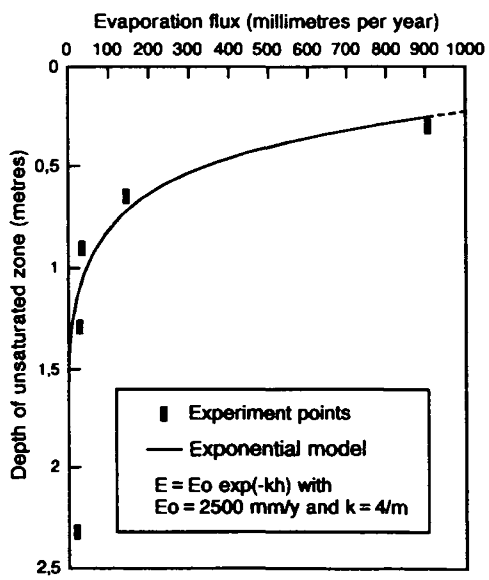
● ***Transfer of water to the unsaturated zone.*** These studies are based essentially on an interpretation of the chemical and isotope profiles of the water retained by the soil between the surface and the groundwater table. The application of these methods has been developed mainly in Senegal and Niger in collaboration with the British Geological Survey and the Hydrology and Isotope Geochemistry Laboratory, University of Paris XI in France.

Estimate of effective infiltration. The search for the peak of tritium from past atmospheric thermonuclear tests is now virtually inapplicable in humid temperate zones (because the tritium has usually reached the water table). However, the research method is still very useful in arid and semi-arid zones where infiltration is slight and the unsaturated zone is very thick. This has been demonstrated at a depth of 25 metres by research in north Senegal. The calculations of effective infiltration agree with those resulting from the chloride balance between rain water and the water in the unsaturated zone.

Estimate of evaporation losses. From theoretical studies and experiments carried out in the laboratory, or in sediment columns under natural conditions, it is known that evaporation concentrates heavy isotopes mainly at the front between the dominant zones of liquid and vapour transfer. An estimate of evaporation losses under steady–state conditions can be derived from mathematical modelling of the profiles of stable isotopes in the unsaturated zone. Furthermore, the infiltration rate can be evaluated by determining the chloride balance between rain water and the water in the unsaturated zone. Experiments carried out in various semi-arid regions of Africa, and recent results obtained in the hyper-arid region of Bilma in Niger, show that this evaporation decreases very rapidly with the depth of the water table. *(See graph.)* Surface evaporation would only be a few dozen millimetres when the water table is situated at a depth of two metres. In natural discharge zones of large regional water tables, the best way to prevent evaporation of millions of cubic metres of water would thus be to pump and use the water so that the piezometric level is lowered.

● ***"Very old" groundwater and palaeohydrology.*** In the Sahelian region there are huge groundwater resources in the big regional

Estimate of evaporation flux through unsaturated zone



The graph compares results from experiments and mathematical modelling for the hyper-arid region of Bilma, Niger.

aquifers. In a large part of these aquifers, the initial isotopic studies have demonstrated the presence of fossil water whose recharge period goes back to more than 40 000 years (the limit for carbon–14 dating) and which can therefore be called "very old". Hence the study of these aquifers requires new techniques using very long-lived isotopes (chlorine–36 and uranium isotopes) and labelling elements suitable for palaeohydrological conditions, such as the noble gases.

Chlorine–36 is used for dating very old groundwater because it has an extremely long lifetime (its half–life is 3.01 x 10^5 years) and because chlorides are highly soluble and possess conservative properties in geochemical reactions. However, the application of chlorine–36 requires a thorough knowledge of the aquifer's geochemistry because it arises from a variety of sources (cosmic, previous thermonuclear tests, and terrestrial, both sub–surface and deep). Under favourable geochemical conditions, a knowledge of the initial activity of uranium–234 (whose half–life is 2.5 x 10^5 years) enables application of the standard radioactive decay dating formula. The dissolution of noble gases (argon, xenon, krypton, and neon) in the infiltration water depends primarily on the ambient temperature. The resulting concentration then remains theoretically constant because of the chemical inertia of these elements. Thus by determining their concentration in fossil water, the climatic conditions which prevailed at the time of recharge of the aquifers can be reconstructed.

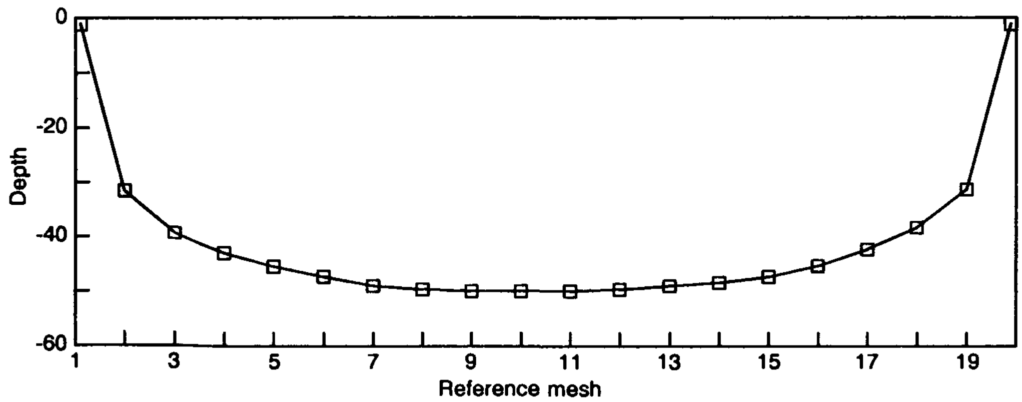
These techniques are now being used by the African participants in the project, in collaboration with specialized laboratories in Europe (the Hydrology and Isotope Geochemistry Laboratory at the University of Paris XI, France, and the School of Chemistry at Bath University, United Kingdom), for the study of Maastrichtian (Senegal) and Continental Intercalaire (Mali and Niger) aquifers.

● ***Origin of the piezometric depressions.*** The discovery of large piezometric depressions dates back to the 1950s, when the early hydrogeological studies took place in Africa. Since then numerous examples have been described throughout the Sahel region—for example, the aquifers in the Ferlo region in Senegal, those of the Nara graben, Gondo, and Azaouad in Mali, of Trarza in Mauritania, of Kadzell in Niger, and of Yaérés (region of Lake Chad) in Cameroon.

So far none of the different theories put forward to explain this phenomenon has found general agreement. The discussion is not a purely academic one, however, because for long-term management it is necessary to select a conceptual circulation model and to know the conditions at the boundaries of these large aquifers.

Several studies on this topic are in progress under the regional project. The preliminary results obtained in Senegal, Mali, and Cameroon seem to show that an imbalance between infiltration and evapotranspiration plays a predominant role. A mathematical simulation model taking this hypothesis into account has been developed as part of the project, in collaboration with a Senegalese teacher–researcher. It reproduces in

Modelling results of observed piezometric depressions



Notes: Results are of a numerical simulation, transient state, with alimentation through boundaries (river or lake). Mesh are 20 kilometres in length.

The graph depicts the shape of the piezometric level of an unconfined aquifer after 8000 years of deficient precipitation.

a satisfactory manner the form of the observed piezometric depressions. *(See graph.)*

Hydrology and hydrosedimentology

Hydrology. The hydrology of the Sahelian countries is characterized by a very sparse surface network; only the very large water courses (mainly the Niger, Senegal, Logone, and Chari rivers) are perennial, while violent and sporadic floods during the rainy season (from June to September) fill the network of flood flats which are dry for the rest of the year. This characteristic creates considerable difficulties for measurements of liquid flow.

Mali, which undoubtedly has the largest network of small non-perennial water courses, was the first to profit by the introduction of artificial tracer techniques for liquid flow measurements. It now has a competent team and the equipment needed to carry out field operations. This team is the only such specialized unit in the region and is now capable of operating abroad and of training technicians from other countries.

Under the regional project, several workshops and practical field training sessions for engineers and technicians have been held in Mali. *(See box.)*

Hydrosedimentology. The Sahelian water courses transport considerable sediment masses. These settle in the surface reservoirs, thereby reducing their capacity and lifetime. The torrential flow of the water courses makes it difficult to assess sediment transport by conventional methods.

To help solve this problem, the IAEA provided Mali with a hydrosedimentology laboratory comprising a conventional unit and a nuclear instrumentation unit. The nuclear unit includes a sediment gauge to measure sedimentation rates (laboratory measurements); a gauge for *in situ* measurement of suspended sediments (specially adapted for mapping sedimentary deposits in reservoirs and canals); and a gauge for *in situ* measurement (and continuous automatic recording) of the concentration of suspended sediments in water courses.

The laboratory is now operational and has two functions. It performs studies for the Directorate of Water Resources and outside bodies, and it provides theoretical and practical training for final-year students at the National School of Engineers in Bamako.

Regional information exchanges

Regularly holding scientific meetings and regional workshops is the best way to exchange experiences, share results, and to train engineers from the various national agencies involved in the project. Within this framework, project activities have included:

- An hydrology course in Bamako in August 1987, where 15 engineers and technicians from Mali, Niger, and Senegal were trained in tracer techniques for the measurement of water courses.
- A regional workshop on the development of isotope techniques in hydrology and hydrogeology in Niamey in November 1988. It was attended by 38 participants from 8 countries, and 24 papers were presented that dealt with the development of isotope techniques in the region and gave many examples of application.
- A regional training course on the application of isotope techniques in water resources development, in Dakar, in June 1989. It was organized by the IAEA and United Nations Educational, Scientific, and Cultural Organization (UNESCO) and attended by 10 participants associated with the regional project.
- Two new training courses of long duration in hydrology and hydrosedimentology in Mali during 1990 and 1991.
- A regional workshop on nuclear hydrosedimentology in Bamaka in December 1990, which provided training for two engineers from each participating country.

In early 1990, an exchange programme began involving technicians and engineers-researchers. Specifically, a Malian expert presented a series of lectures on nuclear sedimentology at Dakar; a Senegalese researcher participated in a field mission to Niger; and a scientist from Niger gave a training course in Dakar on geographic data analysis and automatic cartography.

Future aims and prospects

In accordance with recommendations of the first co-ordination meeting (Bamako, December 1989), the project now aims to develop:

- Equipment and operational support to infrastructures so as to promote a progressive increase in the region's analytical self-sufficiency, as well as regional utilization of existing laboratories;
- Documentation and training support through more exchanges of technicians between participating countries and by the project personnel's more active participation in regional workshops, seminars, and conferences;
- Greater financial resources for activities by increasing the IAEA's contribution and by seeking contributions from other international agencies, and/or countries through bilateral co-operation.

In that context, four new technical co-operation projects have been approved by the IAEA in 1991 in Mali, Senegal, and Niger within the framework of regional project activities. In particular, they will facilitate the

In the Ferlo region of northern Senegal, wells dug between 60 and 100 metres deep are the main sources of water. One focus of hydrological research is whether groundwater is being recharged by atmospheric precipitation.

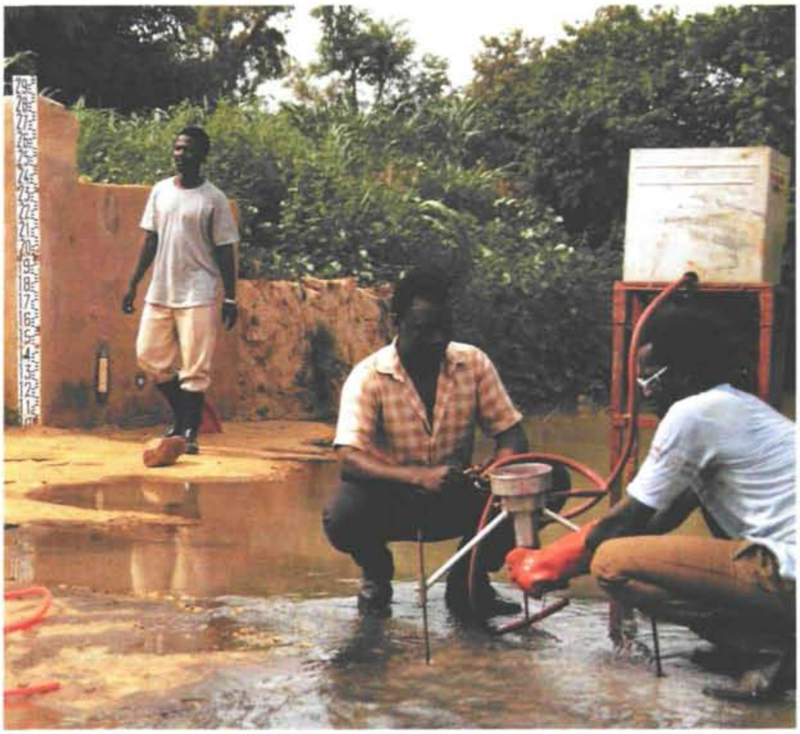
application of hydrological tracing techniques in Senegal and Niger, as well as continuation of that activity in Mali; and strengthening of various laboratories and promotion of their use on a regional basis.

Thus, the carbon–14 laboratory installed by the IAEA in Niamey will be provided with a new liquid scintillation counter. Very soon, it will be used to analyse samples taken in the region for hydrological and archaeological purposes. Additionally, the nuclear hydrosedimentology laboratory in Bamako could be used for studies outside Mali, and the University of Dakar's soil laboratory, which has a vacuum distillation extraction line, will process samples which would previously have been sent to Europe.

In areas of research and training, four regional workshops for local training already have been planned. One workshop will focus on studying the unsaturated zone (Dakar, November 1991); another on the preparation and measurement of carbon–14 (Niamey, 1992); a third on hydrochemistry (Yaoundé, 1992); and a fourth on mathematical modelling in hydrogeology (Dakar). In addition, a regional research activity for evaluating the rate of recharge and evaporation of unconfined aquifers in the Sahel area has been proposed for external financing.

Beneficial collaboration

Given the regional project's relatively limited financial resources, it would hardly have been possible to achieve the results to date had it not been for hydrology projects that were already under way in these countries, and the close cooperation which has emerged with national, bilateral, and international bodies. The project especially has benefitted from the work of the main counterparts. They include Senegal's Geology Department at Dakar University, and its Directorate of Water Resource Studies, Ministry of Water Resources; Mali's Ministry of Water Resources and Energy, and the National School of Engineers, Bamako; Niger's Geology Department, Niamey University, and the Directorate of Water Resources, Ministry of Water Resources; and Cameroon's Yaoundé Institute of Geological and Mining Research. Also highly valuable has been the collaboration with the United Na-



A Malian specialist trains a scientific fellow on the use of tracer dilution techniques to assess the dynamics of sediment transport in the Dourou river basin in Mali. In the background on the wall, a small nuclear gauge has been placed to continuously record sediment transport when the river floods.

Activities	Senegal		Mali		Niger		Cameroon	
Study of aquifers with environmental isotopes	Cap Vert, Horst Ndiass	(1)	Fractured aquifers in basement				Mt. Mandaru	(2)
	Casamance	(1)	Bougoni, Kolokani	(1)	Liptako, Aïr	(1)		
	Ferlo	(2)	Regional aquifers (Continental Terminal and Continental Intercalaire)				Yaérés plain	(2)
	Eastern Senegal	(3)	Nara, Azaouad Gondo	(2) (1)	Irhazer Eastern Niger	(1) (2)		
Relationship between surface water and groundwater	Casamance Senegal river	(2) (2)	Niger river Interior delta	(2) (3)	Niger river Niamey	(2) (2)	Alluvial plain	
Unsaturated zone	Louga Ferlo	(2) (2)	Azaouad	(2)	Niamey Bilma	(2) (3)	Yaérés	(3)
Very old water	Casamance Ferlo	(2) (2)	Nord Azaouad	(2)	Irhazer Plain	(2)		
Piezometric depressions	Ferlo	(2)	Nara, Azaouad	(2)	Kadzell	(3)		
Specific activities	Isotopic study of organic matter		Surface hydrology		Study on origin of nitrates			
Laboratories	Unsaturated zone Hydrochemistry	(2) (3)	Hydrochemistry Hydrosedimentology	(1) (2)	Hydrochemistry Carbon–14	(1) (2)	Hydrochemistry	(2)
Seminars, workshops, training	Isotope hydrology Unsaturated zone workshop Mathematical model workshop	(1) (3) (3)	Hydrology workshop Hydrology training Sedimentology workshop Sedimentology training	(1) (2) (3) (3)	Isotope hydrology Hydrochemistry workshop Carbon–14 workshop Carbon–14 training	(1) (3) (3) (3)		
New activities	Use of artificial tracers	(3)			Use of artificial tracers kori Téloua	(3)		

Note: Numbers in parentheses indicate activities completed (1), in progress (2), and planned (3) under the regional project.

Activities of the Sahelian regional project

tions Development Programme's (UNDP) water resources projects in the three countries, the Canadian International Development Research Centre (IDRC), the French Fonds d'Aide à la Co-opération, the Swiss Institut Universitaire Etudes Développément (IUED), and the French Office for Scientific and Technical Research Overseas (ORSTOM).

Early on, this base of support enabled selection of research projects of common interest to the countries on the basis of detailed analyses of regional hydrological and hydrogeological problems, and of the possibilities of applying nuclear techniques to them. Other activities were selected in view of their local potential and importance. *(See table.)*

Apart from specific results achieved, the regional project has made valuable contributions to the implementation of existing scientific programmes. This has been done by supplying equipment and isotope analyses, by providing experts and consultants, and by awarding training fellowships. As importantly, regional co-operation has been facilitated by the presence of a resident expert and the emphasis placed upon frequent exchange of technical information. Channels have included the publication and dissemination of all scientific results; exchanges of lecturers, engineers, and specialized technicians between countries; and the organization of training courses, regional workshops, and seminars on a regular basis.

Through these activities and others, the project is helping national scientists and engineers in the Sahel to build the technical foundation for effective exploration and management of their region's precious water resources.